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Late-glacial and Holocene palaeoceanography of the North Icelandic shelf

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ABSTRACT: High-resolution gravity cores and box cores from the North Icelandic shelf have been studied for palaeoceanographic history based on lithological and biostratigraphical foraminiferal data. Results from two outer shelf cores covering the last 13.6 k ^{14}C yr BP are presented in this paper. The sediments accumulated in north–south trending basins on each side of the Kolbeinsey Ridge at water depths of ca. 400 m. Sedimentation rates up to 1.5 m kyr^{-1} are observed during the Late-glacial and Holocene. The Vedde and Saksunarvatn tephras are present in the cores as well as the Hekla 1104. A new tephra, KOL-GS-2, has been identified and dated to 13.4 k ^{14}C yr BP, and another tephra, geochemically identical to the Borrobol Tephra, has been found at the same level. At present, the oceanographic Polar Front is located on the North Icelandic shelf, which experiences sharp oceanographic surface boundaries between the cold East Icelandic Current and the warmer Irminger Current. Past changes in sedimentological and biological processes in the study area are assumed to be related to fluctuations of the Polar Front. The area was deglaciated before ca. 14 kyr BP, but there is evidence of ice rafting up to the end of the GS-1 (Greenland Stadial 1, Younger Dryas) period, increasing again towards the end of the Holocene. Foraminiferal studies show a relatively strong GS-2 (pre-13 kyr BP) palaeo-Irminger Current, followed by severe cooling and then by unstable conditions during the remainder of the GI-1 (Greenland Interstadial 1, Bølling–Allerød) and GS-1 (Younger Dryas). Another cooling event occurred during the Preboreal before the Holocene current system was established at about 9 kyr BP. After a climatic optimum between 9 and 6 kyr BP the climate began to deteriorate and fluctuate. Copyright © 2000 John Wiley & Sons, Ltd.

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KEYWORDS: Palaeoceanography; Foraminifera; tephrochronology; climatology; North Atlantic.

Introduction

Very few high-resolution marine records have been available from Iceland in spite of its critical location in the North Atlantic with respect to both oceanographic and atmospheric frontal systems. The present paper reports the first detailed shallow marine data from the extensive, mud-dominated North Icelandic shelf. These data fill some gaps in the knowledge of the position and migrations of the Late-glacial and Holocene frontal systems, which have been central issues in palaeoclimatic studies in the northern North Atlantic region and Iceland since the mid-1970s on both short and long time-scales (e.g. Ruddiman and McIntyre, 1973; CLIMAP Project Members, 1976; Eiríksson, 1985; Eiríksson and Geirsdóttir, 1991).

The modern oceanographic surface circulation close to Iceland is dominated by the Irminger Current (Fig. 1), which forms a clockwise gyre around Iceland (Stefánsson, 1962; Hopkins, 1991; McCave *et al.*, 1995). The Irminger Current branches off the North Atlantic Current to the southwest of the Iceland–Faeroe Ridge and carries warm and saline water towards the polar front north of Iceland, where it meets the East Icelandic Current. Today, the East Icelandic Current forms a cold, seasonally variable low-salinity tongue of surface water occasionally extending to the North Icelandic shelf. It is derived partly from the East Greenland Current and partly from the counter-clockwise gyre of the Iceland Sea (Stefánsson, 1962; Malmberg and Jónsson, 1997; Swift and Aagaard, 1981). Lateral and vertical mixing as a result of the parallel flow of the Irminger Current and East Icelandic Current and winter cooling leads to the formation of an intermediate water mass in the Iceland sea which disintegrates by spring or summer. The present foraminiferal faunal distribution suggests that the North Icelandic shelf is affected by the Irminger Current down to at least 500 m water depth.

The circulation off North Iceland is affected partly by the north–south trending, actively spreading Kolbeinsey Ridge,

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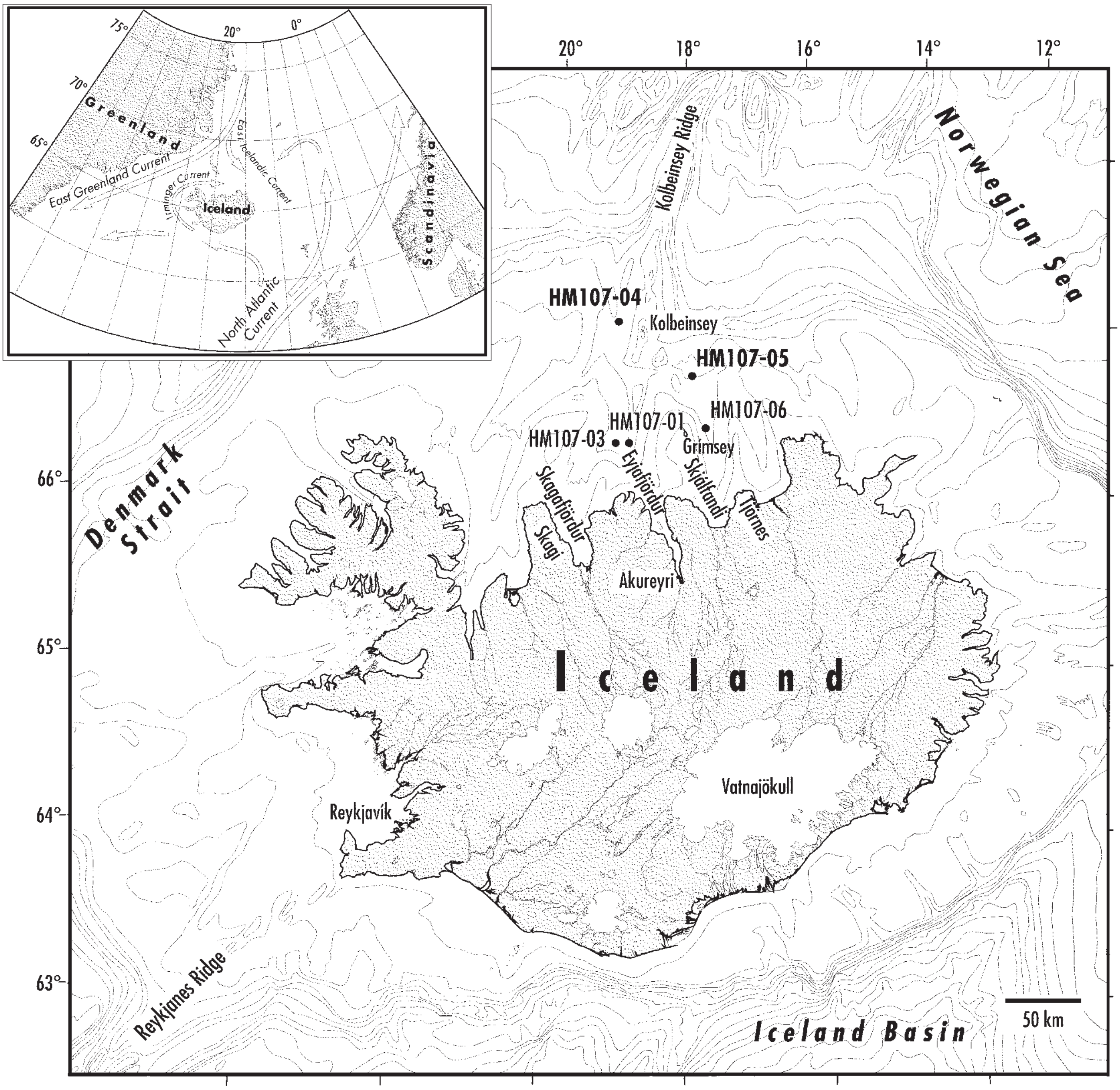

Figure 1 Location map of the research area with an inset map showing the regional surface circulation. Contour intervals at 100 m.

which forms a rather shallow barrier on the outer shelf. The Irminger Current is partly channelised by seamounts and islands and local current velocity anomalies are formed across it. The ridge presumably formed a more dramatic barrier during the Last Glacial Maximum and the Late-glacial as a result of eustatic lowering of sea-level (Fairbanks, 1989). The rough topography of the ridge may have reached an altitude of 100–200 m a.s.l. For this reason, the modern circulation pattern is unlikely to be directly analogous to the Late-glacial or Early Holocene scenarios. Local volcanism also has been affected by environmental factors related to sea-level (Lackschewitz and Wallrabe-Adams, 1991).

The North Icelandic shelf is distinctly a boundary region where past changes of the oceanographic Polar Front may be expected to be registered in the sedimentary record. The sensitivity of the Late-glacial sedimentary record to changes in oceanic circulation has been demonstrated for the area around Iceland (e.g. Sarnthein *et al.*, 1995; Voelker *et al.*, 1998). Similarly, the origin and distribution of sedimentary particles and the faunal distribution on the North Icelandic shelf are clearly related to oceanographic conditions, in particular current velocities, temperature and salinity. In addition, there are active volcanic processes related to the Icelandic hot spot, producing tephra which may be emplaced as air-fall deposits, by ice rafting or subaqueous flows, depending on the physical conditions during the eruptions and on the local topography.The present-day oceanographic conditions reflect strong variablity in sedimentation patterns (e.g. see the discussion in Henrich *et al.*, 1995). These authors found that the Irminger Current is characterised by high planktonic productivity, contrasting strongly with the very low productivity and inorganic sediment concentration of the East Icelandic Current. Sites in the region therefore may act as critical indicators for changes in both the ocean circulation and volcanic events.

This paper is based on material from cores located off separate drainage regions in Iceland with respect to terrestrial sediment input. The western sites lie in a topographic continuation of Eyjafjördur, which drains an unglaciated region of Iceland, whereas the sites to the east of Kolbeinsey Ridge are close to fjords fed by glacial rivers from the Vatnajökull ice cap. The results were obtained through a research project (PANIS – Palaeoenvironments on the North Icelandic Shelf) with the objective to obtain data on palaeoceanography, sedimentation and volcanic history of the Late-glacial and the Holocene periods of the North Icelandic shelf. Important proxies include biostratigraphy of benthic and planktonic Foraminifera sedimentological parameters such as grain size, mineralogy and geochemistry of tephra layers. Age control is obtained with a number of accelerator mass spectrometry (AMS) ^{14}C dates and through correlation with isochronous regional tephra horizons.

The sedimentary records of core sites HM107-04 and HM107-05 (Figs 1 and 2), which are presented in this paper, extend back to ca. 13.6 kyr BP, covering the Late-glacial, the Pleistocene–Holocene transition and the Holocene. Observed oceanographic changes are compared with terrestrial data from Iceland and ice-core records from Greenland for the corresponding period. We discuss the records in terms of Greenland ice-core events (Björck *et al.*, 1998) instead of the classic chronostratigraphical terminology (Mangerud *et al.*, 1974), but retain the latter in parentheses for the sake of clarity.

Sampling and methods

A total of six gravity cores from the North Icelandic shelf were obtained in 1995 on the HM107 BIOICE cruise with *RV Haakon Mosby* (Fig. 1). Twelve kHz echosounder and 3.7 kHz echosounder penetration profiles were run in order to select appropriate locations for the core stations. The present paper presents the two northernmost cores in the area, one on each side of the Kolbeinsey Ridge, core HM107-05 (66°54′08″N, 17°54′19″W) from 396 m water depth and core HM107-04 (67°13′38″N, 19°03′00″W) from 458 m water depth covering the time span back to almost 14 kyr BP. The results are presented in Figs 2–12 and summarised in Fig. 13.

Before splitting, the cores were X-rayed and measured at 1 cm intervals for magnetic susceptibility. This was followed by visual inspection and photographing of the split cores. Shear strength was determined with a Swedish cone fall penetrometer before subsampling 1-cm-thick slices for the foraminiferal and sedimentological analyses. Carbonate and organic carbon contents were determined by gas volumetric method on bulk samples at 20-cm intervals, and water content was determined at 10-cm intervals. Grain-size distribution was obtained by wet sieving and pipette analysis down to 10 ϕ at 5-cm intervals, and the mineralogy is based on grain counts of over 300 grains in the $>$125 μm fraction of the sieved sample. In addition to the 5 cm prefixed subsampling interval, all potential tephra horizons observed during visual inspection of the cores were subsampled for tephrostratigraphical analysis. Segments of these potential tephra horizons were wet-sieved using 1000 μm, 125 μm and 63 μm sieves and tephra grain counts undertaken on the 125–1000 μm fraction both for these segments and for the intervals selected for grain-size distribution (see Figs 7 and 11). The chemical analyses of the tephra grains were performed with a standard wavelength dispersal technique, either on a Cameca-SX 50 microprobe or on an ARL-SEMQ microprobe, with an accelerating voltage of 15 kV, a beam current of 10 nA (determined by a Faraday Cup), and a beam diameter of 6–10 μm.

The samples for foraminiferal analysis, each representing 1 cm sediment, were extracted at 10-cm intervals and washed through 1000, 125 and 63 μm sieves according to the methods described by Feyling-Hanssen *et al.* (1971) and Knudsen (1998). The Foraminifera were concentrated from the 125–1000 μm dry fraction by means of the heavy liquid CCl_4 (specific gravity 1.6 g cm^{-3}). Total foraminiferal assemblages were analysed in the 125 μm fraction by counting at least 300 specimens of benthic as well as planktonic Foraminifera, when possible. The sediment successions of the two cores are subdivided into benthic assemblage zones following the definition by Salvador (1994). In order to find the exact level of the faunal changes, samples at every 1 cm interval were analysed around each zone boundary. This gives a time resolution of 20–50 yr cm^{-1} (see below). The palaeoecological interpretations are based on comparisons with modern faunal distributions.

This paper presents only an overview of the foraminiferal faunal distribution in the two cores, including the relative occurrences of selected benthic species and the total contents of benthic and planktonic specimens per 100 g dry sediment. The benthic percentages (see Figs 8 and 12) are calculated on the basis of calcareous species only, because the preservation of arenaceous species in the material is poor. The two species *Islandiella norcrossi* (Cushman) and *Islandiella helenae* Feyling-Hanssen and Buzas, which both belong in arctic waters, are not easily distinguished in the present material. They are, therefore, presented together as one group in the diagrams (see Figs 8 and 12). It appears that most of the specimens belong to *I. norcrossi*.

The planktonic Foraminifera in the material consist mainly of sinistrally coiled *Neogloboquadrina pachyderma* (Ehrenberg), but a few per cent of dextrally coiled *N. pachyderma* as well as *Turborotalita quinqueloba* (Natland), *Globigerinita glutinata* (Egger) and *Globigerina bulloides* d'Orbigny also occur in part of the succession. Detailed studies of the planktonic assemblages as well as their stable isotopic compositions are in progress.

The benthic foraminiferal zones are used in the following as a stratigraphical framework for the description of the sediments.

Chronology

Radiocarbon dates

No chronological framework was available for the shelf sediments off North Iceland prior to this study, and the stratigraphy was unknown. Tephrochronology and AMS ^{14}C dating of either molluscs, planktonic or benthic Foraminifera are used to establish detailed chronology and correlation between cores HM107-05 and HM107-04. Important tephra markers have been identified in both cores, in particular the Saksunarvatn and the Vedde ashes. A total of 25 AMS ^{14}C dates have been undertaken, 16 for core HM107-05 and nine for core HM107-04 (Table 1 and Fig. 2). In the present context we apply the modern reservoir age value of 400 yr (Andersen *et al.*, 1989) as a correction for all AMS ^{14}C dates. Zero age is assumed for the top of both gravity cores. This assumption is based on a correlation of the tops of each gravity core with corresponding box cores. Stained (living) Foraminifera in the box cores show zero age for the coretops. For core HM107-04 this is also supported by the position of the Hekla 1104 tephra in the record (see below).

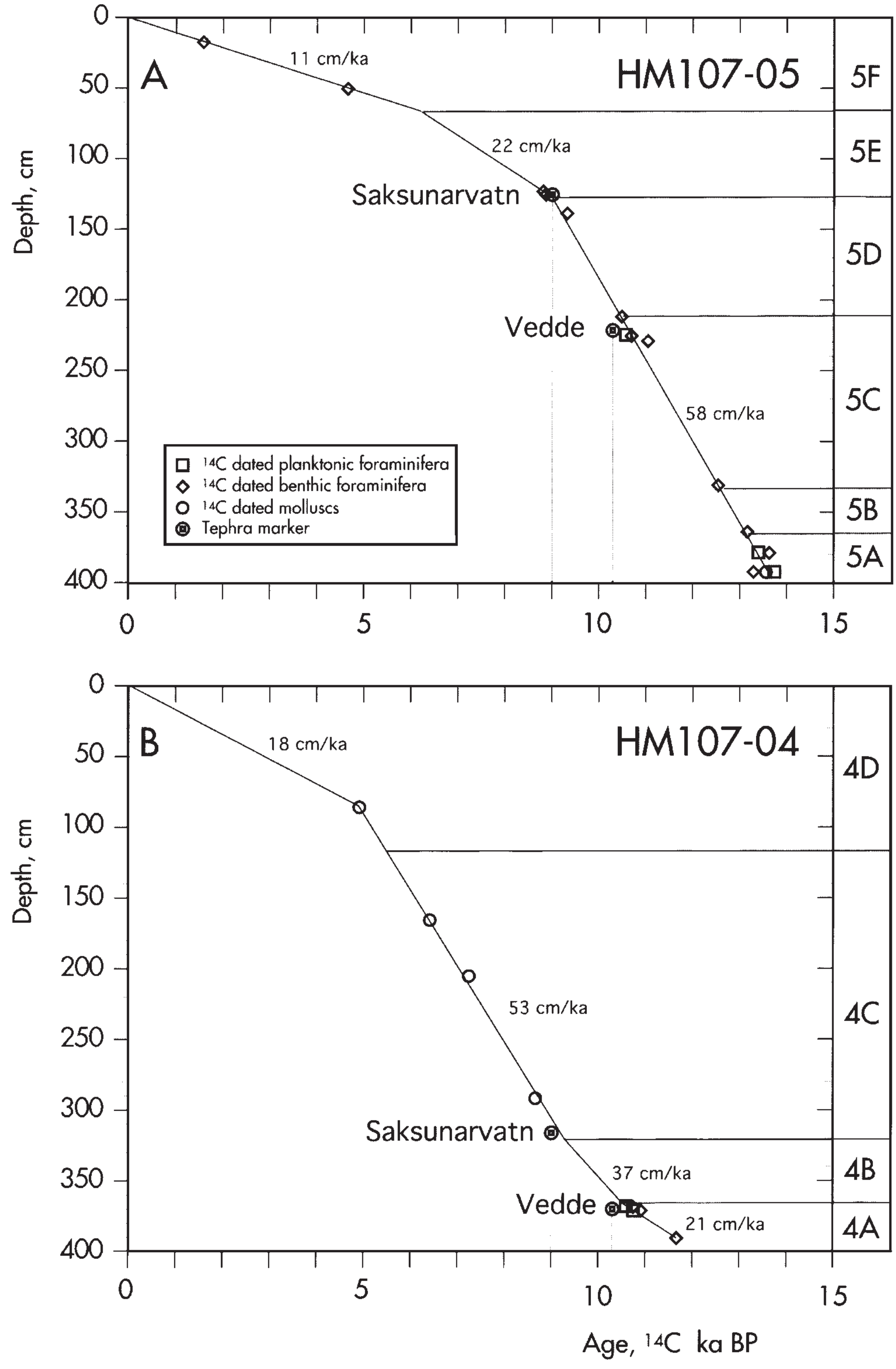

Figure 2 Age–depth diagram for cores HM107-05 (2A) and HM107-04 (2B). The AMS ^{14}C datings (Table 1) based on either molluscs, planktonic or benthic Foraminifera are used as a basis for the reconstruction of linear segments in the age–depth model (see also section on chronology). The Vedde (10.3 kyr BP) and the Saksunarvatn (9.0 kyr BP) tephras are also plotted. Benthic foraminiferal zones are indicated on the right-hand side.

An age model for core HM107-05 is shown in Fig. 2A. In addition to the AMS ^{14}C dates, the Saksunarvatn (Mangerud *et al.*, 1986; Björck *et al.*, 1992; Ingólfsson *et al.*, 1995; Birks *et al.*, 1996) and the Vedde (Mangerud *et al.*, 1984; Bard *et al.*, 1994; Birks *et al.*, 1996) tephras have been plotted. In the absence of constraining dates or marker horizons, we have chosen to let sedimentation rates change at biozone boundaries that reflect palaeoceanographic changes and probably therefore coincide with changes of sedimentation rates. The following assumptions have been made for each line segment. Zero age for the top of the core is included in the calculation of a regression line fitted through available dates down to the biozone boundary 5E–5F. A regression line fitted to the remaining ^{14}C dates is drawn from the base of the core up to the biozone boundary 5D–5E, and a straight line between the two regression lines is then used to connect the age–depth line across biozone 5E.

Figure 2B shows an age–depth relationship for core

Table 1 Radiocarbon dates in cores HM107-05 and HM107-04 from the North Icelandic shelf. The datings were carried out at the AMS ^{14}C Dating Laboratory, University of Aarhus, Denmark. The age calibration is based on Stuiver and Reimer (1993)

Sample	Depth (cm)	Laboratory number	Material	^{14}C age (BP)	Reservoir corrected age (400 yr)	Calibrated age ±1 SD	$\delta^{13}C$
HM107-04	87–88	AAR-4202	Mollusc, *Siphonodentalium lobatum*	5345 ± 55	4945 ± 55	3710, BC 3780–3660 BC	+1.7
HM107-04	165–166	AAR-2932	Molluscs, *Thyasira equalis, Yoldiella* sp.	6830 ± 60	6430 ± 60	5410–5340 BC 5430–5280 BC	−2.0
HM107-04	207–208	AAR-4203-2	Mollusc, *Siphonodentalium* sp.	7700 ± 100	7300 ± 100	6120–6060 BC 6190–6000 BC	+1.3
HM107-04	292–293	AAR-3384	Mollusc, cf. *Siphonodentalium lobatum*	9075 ± 60	8675 ± 60	7670–7620 BC 7870–7570 BC	+1.0
HM107-04	369–371	AAR-4421	Foraminifera, total benthic fauna	11100 ± 80	10700 ± 80	10680 BC 10780–10580 BC	−0.3
HM107-04	369–371	AAR-4422	Foraminifera, *Neogloboquadrina pachyderma* sinistral	10980 ± 90	10580 ± 90	10560 BC 10670–10440 BC	+0.1
HM107-04	371–373	AAR-4424	Foraminifera, *Neogloboquadrina pachyderma* sinistral	11160 ± 90	10760 ± 90	10740 BC 10840–10630 BC	+0.1
HM107-04	371–373	AAR-4423	Foraminifera, total benthic fauna	11290 ± 110	10890 ± 110	10860 BC 10980–10750 BC	−0.7
HM107-04	391–392.7	AAR-4418	Foraminifera, total benthic fauna	12040 ± 80	11640 ± 80	11620 BC 11760–11500 BC	−0.6
HM107-05	18–19	AAR-3381	Foraminifera, total benthic fauna	2015 ± 45	1615 ± 45	AD 430 AD 410–535	−1.1
HM107-05	49–51	AAR-4117	Foraminifera, total benthic fauna	5050 ± 45	4650 ± 45	3490–3370 BC 3500–3360 BC	−0.9
HM107-05	122–125	AAR-4419	Foraminifera, total benthic fauna	9190 ± 80	8790 ± 80	7900–7750 BC 7950–7700 BC	−1.7
HM107-05	125–128	AAR-4420	Foraminifera, total benthic fauna	9250 ± 70	8850 ± 70	7940 BC 7980–7740 BC	−1.4
HM107-05	137–141	AAR-3380	Foraminifera, total benthic fauna	9730 ± 60	9330 ± 60	8390–8350 BC 8420–8260 BC	−1.1
HM107-05	212–213	AAR-3382	Foraminifera, total benthic fauna	10900 ± 100	10500 ± 100	10470 BC 10600–10320 BC	−1.1
HM107-05	224–227	AAR-4118	Foraminifera, *Neogloboquadrina pachyderma* sinistral	10970 ± 60	10570 ± 60	10550 BC 10640–10450 BC	+3.0
HM107-05	224–228	AAR-4119	Foraminifera, total benthic fauna	11090 ± 80	10690 ± 80	10670 BC 10770–10570 BC	−0.5
HM107-05	228–231	AAR-3379	Foraminifera, total benthic fauna	11440 ± 90	11040 ± 90	11010 BC 11100–10910 BC	−0.8
HM107-05	331–334	AAR-4116	Foraminifera, total benthic fauna	12920 ± 80	12520 ± 80	12730 BC 12920–12540 BC	−1.3
HM107-05	364–366	AAR-4115	Foraminifera, total benthic fauna	13560 ± 90	13160 ± 90	13740 BC 13900–13560 BC	−1.2
HM107-05	379.5–381	AAR-3377	Foraminifera, *Neogloboquadrina pachyderma* sinistral	13790 ± 120	13390 ± 120	14060 BC 14250–13870 BC	−1.1
HM107-05	380–381	AAR-3378	Foraminifera, total benthic fauna	14010 ± 120	13610 ± 120	14360 BC 14540–14170 BC	−0.9
HM107-05	393–394.3	AAR-3375	Foraminifera, *Neogloboquadrina pachyderma* sinistral	14100 ± 140	13700 ± 140	14470 BC 14670–14270 BC	−1.3
HM107-05	393–394.3	AAR-3376	Foraminifera, total benthic fauna	13690 ± 100	13290 ± 100	13920 BC 14100–13750 BC	−1.2
HM107-05	393–394.3	AAR-3383	Molluscs, *Yoldiella lenticula Thyasira gouldi*	13980 ± 90	13580 ± 90	14320 BC 14470–14170 BC	−1.3

HM107-04. The position of the tephra markers Vedde and Saksunarvatn are also depicted. The following assumptions have been made for each line segment. Zero age for the top of core HM107-04 is connected with the uppermost ^{14}C date with a straight line. The segment from this date down to biozone boundary 4B–4C is based on a regression line based on the four available ^{14}C dates. The lowermost segment, in biozone 4A, is also a regression line fitted to the five ^{14}C dates in that zone. The two regression lines are then connected with a straight line across biozone 4B.

It appears that our reservoir correction of 400 yr overestimates the age of the Vedde Ash by ca. 350 yr (HM107-05) and ca. 400 yr (HM107-04), respectively (Figs 2 and 13). This indicates that a 750–800 yr reservoir age should be applied at that level. A 700 yr correction has been adopted for the Late-glacial in other regions of the North Atlantic (Austin *et al.*, 1994; Bard *et al.*, 1994; Haflidason *et al.*, 1995). At present, the uncertainties in projecting this correction factor in either direction do not justify a general reservoir age correction of 750–800 yr for the Late-glacial in North Icelandic waters, however.

Tephra markers

Five potential tephrochronostratigraphical marker horizons have been identified in the two cores. The Vedde Ash horizon forms a distinctive layer in both cores, with a sharp lower boundary and a thickness of ca. 2 cm in core HM107-04 and ca. 5 cm in core HM107-05. The geochemical linkage of these layers to the Vedde Ash regional chronostratigraphical horizon is emphasised in Figs 3 and 4. The Saksunarvatn tephra is also a distinctive layer, with a rather well-marked lower boundary and a thickness of 2–3 cm in both cores. The geochemical relationship to the Saksunarvatn tephra in the Faeroe Islands is shown in Fig. 4.

Two rhyolitic tephra layers, Hekla 1104 (Larsen and Thorarinsson, 1978) and a tephra layer chemically identical to the Borrobol Tephra (Lowe and Turney, 1997; Turney *et al.*, 1997), are identified in core HM107-04 and core HM107-05, respectively. These are not visible in the core sections, but have been isolated through microscopic work, where both the petrography and the particle concentrations were applied to select the respective depth intervals (Figs 7 and 11). The geochemical linkage to the source data is stressed in Fig. 3. It should be noted that the Borrobol Tephra layer, the age of which has been estimated to 12.26 kyr BP in lake sediments on the Scottish mainland (Lowe *et al.*, 1999), gives a considerably lower age than the present rhyolitic tephra in the marine core (close to 13.4 kyr BP, see discussion below).

A distinctive, ca. 2–3-cm-thick tephra layer with a sharp lower boundary was found at the same depth level as the Borrobol Tephra in core HM107-05 (382–379 cm). This is a tholeiitic basaltic tephra layer of a fairly homogeneous composition (Table 2) dated to ca. 13.4 kyr BP (see Fig. 7 and Table 1). The geochemistry is similar to the tholeiitic composition produced by a Mid-Atlantic ridge system (Maalöe, 1979) and a strong candidate for this volcanic source is the Kolbeinsey Ridge system (Fig. 1). This tephra layer has not been described previously as a distinctive tephra horizon in any marine or terrestrial sediment sections, and in the present study it is given the informal name KOL-GS-2.

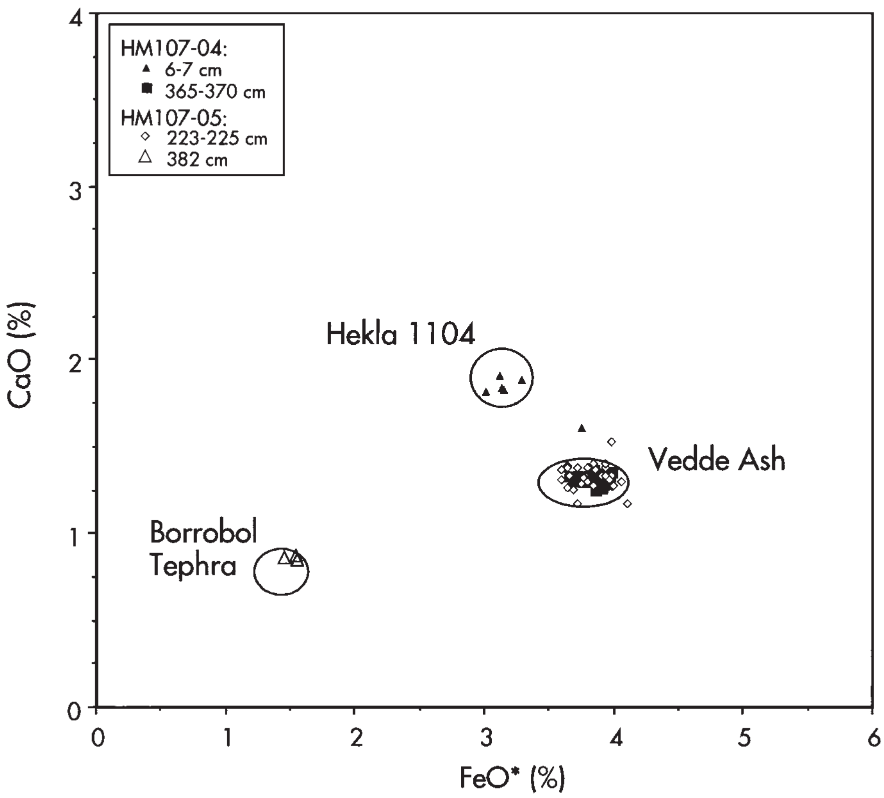

Figure 3 Geochemical characterisation of the rhyolitic components studied in cores HM107-04 and HM107-05 plotted as wt. % of FeO* versus CaO on a variation diagram. Total iron is expressed as FeO*. The encircled areas mark the main geochemical distribution of the Vedde Ash population (Mangerud *et al.*, 1984; Kvamme *et al.*, 1989), the Hekla 1104 population (Sigurdsson, 1982) and the Borrobol Tephra population (Lowe and Turney, 1997; Turney *et al.*, 1997). The depth location of the samples is shown in Figures 5 and 7 for core HM107-05 and in Figures 9 and 11 for core HM107-04.

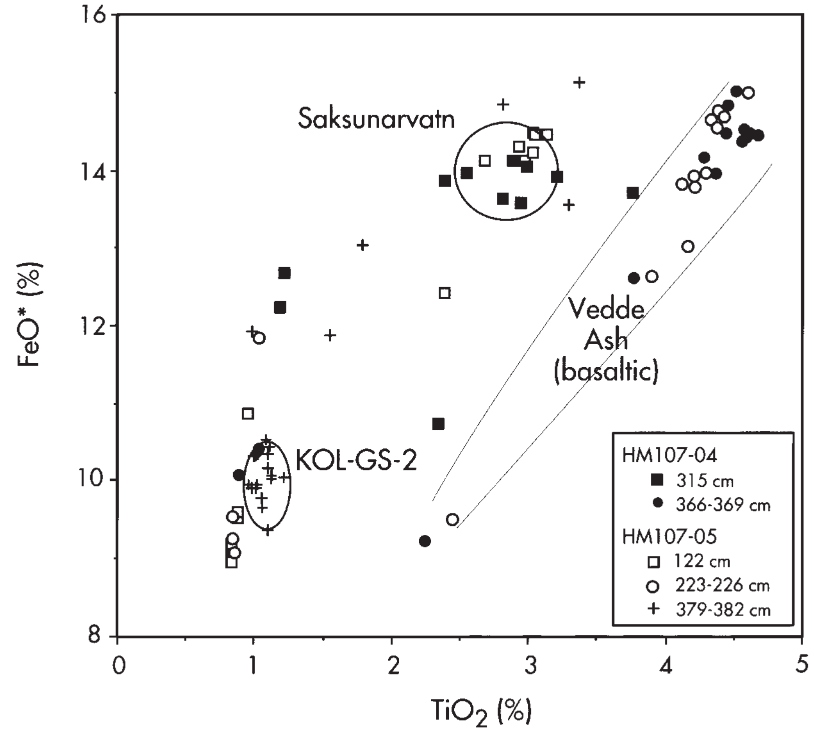

Figure 4 Geochemical characterisation of the basaltic components identified in cores HM107-04 and HM107-05 plotted as wt. % of TiO_2 versus FeO* on a variation diagram. Total iron is expressed as FeO*. The encircled areas mark the main geochemical distribution of the Saksunarvatn ash population (Mangerud *et al.*, 1986; Ingólfsson *et al.*, 1995) and the enriched population of tephra layer KOL-GS-2 (Table 2). The two semiparallel lines bracket the highest frequency of the basaltic component within the Vedde Ash horizon (Mangerud *et al.*, 1984; Kvamme *et al.*, 1989). The depth location of the samples is shown in Figures 5 and 7 for core HM107-05 and in Figures 9 and 11 for core HM107-04.

Table 2 Major element chemical analysis of volcanic glass shards (>125 μm) from core HM107-05, depth intervals of 379–382 cm (KOL-GS-2). All analyses are expressed in weight per cent and total iron as FeO*. Natural and synthetic minerals and glasses were used as standards. Mean values are given at the bottom of the table in bold with 1 SD below. For methods, see text

SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
48.92	1.09	14.71	9.38	0.17	8.36	12.82	2.10	0.09	0.30	98.64
48.95	1.11	14.90	10.44	0.22	8.19	13.00	2.14	0.11	0.29	99.35
49.05	1.06	14.98	9.65	0.21	8.77	12.58	2.10	0.07	0.26	98.73
48.90	0.98	15.22	9.90	0.25	8.55	12.74	2.04	0.11	0.21	98.91
48.64	1.01	14.61	9.92	0.18	8.47	12.61	2.08	0.08	0.30	98.09
49.90	1.21	14.37	10.05	0.20	8.20	11.77	2.46	0.12	0.28	98.57
49.14	0.95	14.93	9.97	0.23	8.57	12.74	2.00	0.10	0.26	98.88
49.17	1.02	15.04	9.97	0.19	8.57	12.82	2.07	0.12	0.29	99.25
49.07	1.12	14.96	10.04	0.19	8.46	12.44	2.15	0.09	0.32	98.84
48.84	1.00	15.12	10.32	0.24	8.45	13.00	2.17	0.07	0.32	99.57
48.99	1.12	14.86	10.08	0.19	8.62	12.57	2.16	0.10	0.27	98.96
48.78	1.10	14.64	10.16	0.12	8.28	12.69	2.18	0.11	0.27	98.33
49.37	1.05	15.03	9.79	0.21	8.50	12.84	2.09	0.10	0.25	99.23
49.17	1.10	14.82	10.34	0.24	8.49	12.50	2.18	0.09	0.22	99.15
48.99	1.02	15.03	10.35	0.19	8.62	12.58	2.19	0.08	0.25	99.29
49.17	1.02	14.87	10.36	0.30	8.53	12.63	2.20	0.10	0.30	99.47
49.37	0.95	14.93	9.95	0.19	8.68	12.72	2.07	0.08	0.34	99.29
49.27	1.08	14.84	10.53	0.23	8.51	12.64	2.12	0.10	0.27	99.59
49.09	**1.06**	**14.88**	**10.07**	**0.21**	**8.49**	**12.65**	**2.14**	**0.09**	**0.28**	
0.28	0.07	0.20	0.29	0.04	0.15	0.27	0.10	0.01	0.03	

Core HM107-05 east of Kolbeinsey Ridge

Sediments

Core HM107-05 is located in a trough to the east of the Kolbeinsey Ridge, about 90 km offshore (Fig. 1), which is connected to the Skjálfandi Bay in North Iceland. Today, Skjálfandi Bay is fed by a glacial river draining the Vatnajökull ice cap.

The lower part of core HM107-05 shows a relatively

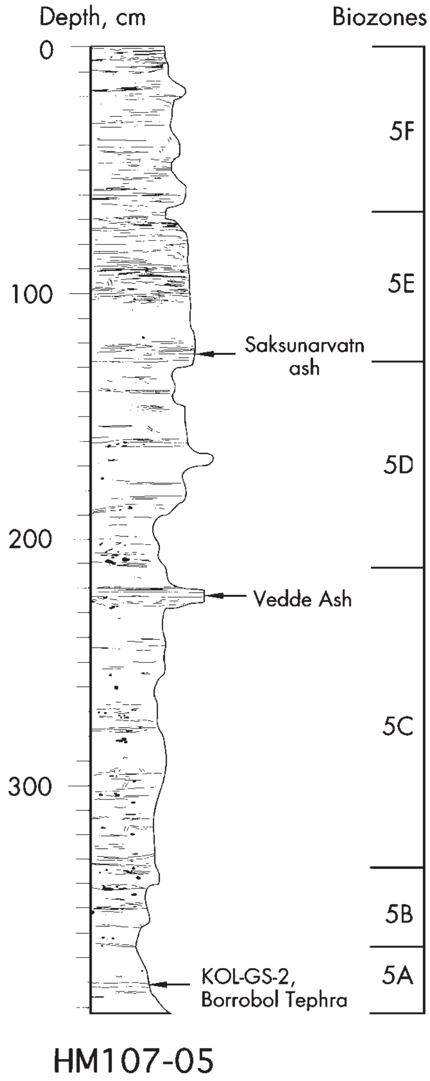

Figure 5 Lithology of core HM107-05, based on X-ray photographs and grain-size analyses. The right-hand side of the column reflects changes in mean grain size. Black lines and objects represent all laminations and pebbles (shown in double size) seen on the X-rays (see text for discussion). Benthic foraminiferal biozones are shown on the right-hand side of the diagram.

massive deposit up to 230 cm depth (Fig. 5). Above that, the Vedde tephra forms a discrete layer that shows up clearly on both the X-ray photographs and visually. Strong laminations are also observed at tephra marker levels around 390–380 cm (KOL-GS-2 and Borrobol Tephra), and at 130–120 cm (Saksunarvatn). The interval 120–105 cm, just above the Saksunarvatn tephra, appears to be massive, whereas the uppermost 105 cm show relatively strong laminations, particularly in the interval 105–60 cm. Subvertical burrows are observed throughout the core, but they are not very common.

A few levels of pebble concentrations are observed on the X-ray photographs. These pebbles are embedded in the mud matrix and are considered to represent ice-rafted material. The strongest concentration is observed in the interval 365–330 cm, coinciding with biozone 5B. Between 330 and 210 cm there are fewer pebbles, being unevenly scattered with four to five levels of higher frequency. Between the Vedde and the Saksunarvatn tephras there are three distinct levels of pebble concentrations, but no pebble concentrations are observed above the Saksunarvatn tephra in core HM107-05.

The mean grain size is relatively stable at ca. 15 μm (Fig. 6), except for the very lowest samples, increasing slightly up to the Vedde tephra. The mean remains low after the deposition of the Vedde up to 190 cm where it jumps up to over 20 μm. The sand fraction increases significantly at the same level. The Vedde and Saksunarvatn tephras form peaks in both the sand fraction and the mean grain size. Coinciding with biozone 5E (ca. 9–6 kyr BP), the lower part of the post-Preboreal Holocene displays a relatively high mean grain size, decreasing and beginning to fluctuate in the uppermost 60 cm which were deposited after 6 kyr BP.

Although the sand fraction has some visible effects on the mean grain size, the sortable silt fraction curve displays a trend that is similar to the mean curve, indicating that the silt fraction is the controlling factor. The sortable silt fraction may be taken as an indication of current strength at the sea floor (McCave *et al.*, 1995), and a plot of the silt to clay ratio averaged over the biozones shows a clear relationship (Fig. 6). The grain-size parameters show relatively strong currents during deposition of the basal part of core HM107-05, coinciding with biozone 5A, dropping sharply in zone 5B and remaining low during the zones 5C and 5D. Apparently, the bottom current was reduced and generally has been unstable during the last 6 kyr BP (zone 5F) relative to the period 9–6 kyr BP (zone 5E).

The mineralogy of core HM107-05 is characterised by tephra peaks and distinct variation in IRD content. The percentage of mineralogical fractions is given in Fig. 6, but the amount per gram sediment in Fig. 7. Rhyolitic tephra is a minute component below the Vedde, where the >125 μm rhyolitic fraction jumps to over 10^5 grains per gram of sediment. Rather high background levels of redeposited rhyolite grains are observed to the top of the core, especially up to the Saksunarvatn tephra (Fig. 7). Interestingly, the concentration of >125 μm rhyolite shards is low immediately after the primary Vedde tephra, increasing to a second, rather sharp peak ca. 40 cm higher in the core. Continued influx of butterfly shaped sand-sized Vedde shards for the remainder of the Holocene is thought to originate from storm generated erosion events or earthquake triggered slurries from the rugged, and partly very shallow Kolbeinsey Ridge. Owing to their shape and low bulk density, the shards are thought to be prone to preferential erosion relative to basaltic tephra, behaving rather like autumn leaves.

The magnetic susceptibility curve for core HM107-05 (Fig. 6) is characterised by low values in zone 5A, rising through zone 5B hand in hand with decreased water content, and remaining high through zones 5C to 5E, apart from a major drop coinciding with the Vedde Ash. Slightly below the 5E–5F boundary, the susceptibility starts to fall, and drops sharply in the uppermost 20 cm. This is explained by increasing water content and lack of compaction. The shear-strength values are generally very low and apart from peaks at tephra markers and sandy intervals, the sediment is not compacted and clearly has not been overburdened by overriding glacier ice. The carbonate content shows a broad correspondance to foraminiferal productivity (see Fig. 8).

Biostratigraphy

Six foraminiferal assemblage zones have been established in core HM107-05 (Zones 5A–5E, Fig. 8). The age of each of

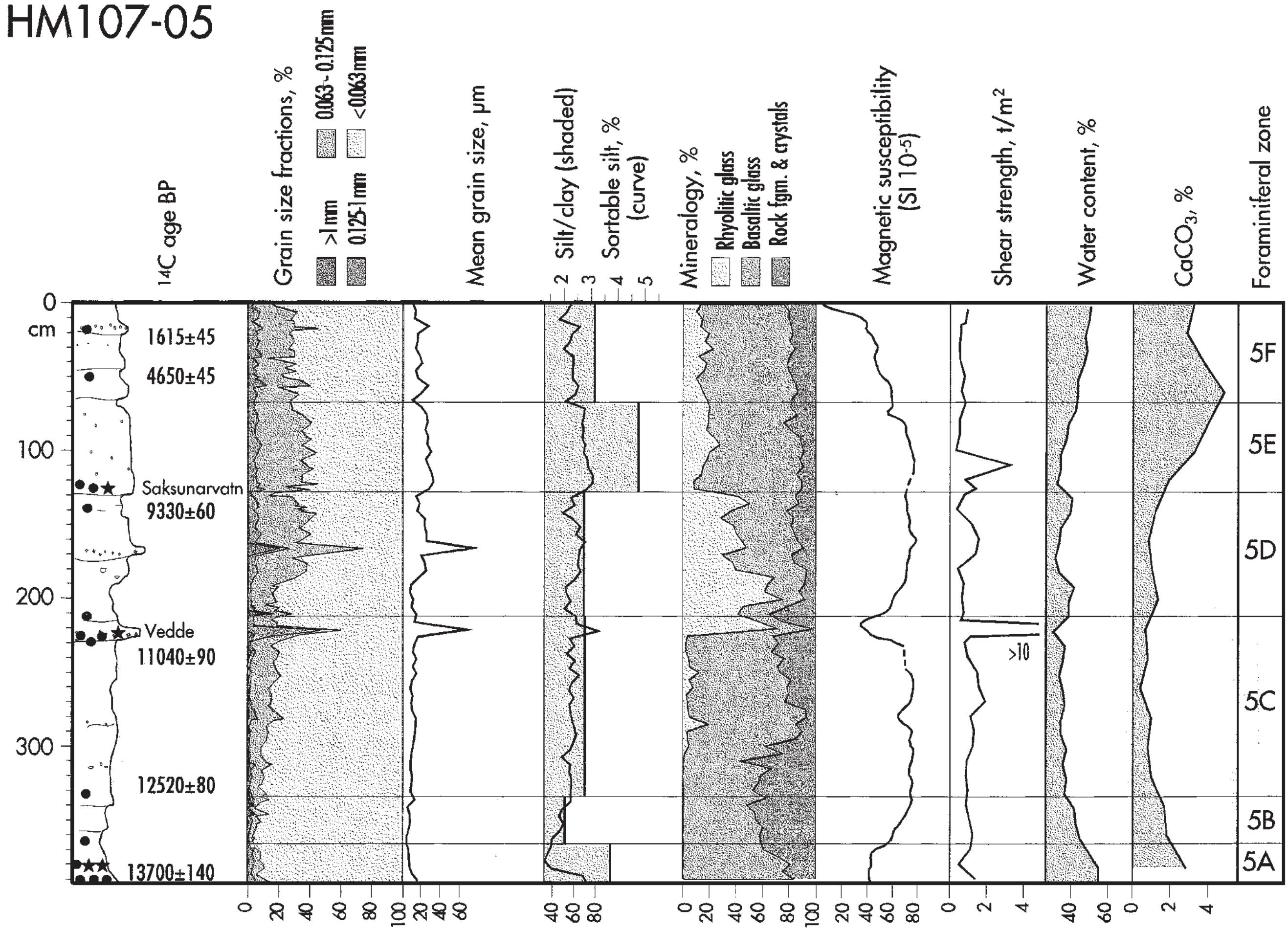

Figure 6 Sedimentary parameters in core HM107-05. The levels of AMS ^{14}C dates in the core are indicated by dots on the lithological column, while well defined tephra layers (the Borrobol, KOL-GS-2, Vedde and Saksunarvatn tephras) are marked with stars (see also Figs 5 and 7). Selected dating results are also indicated (reservoir corrected by 400 yr).

the zone boundaries is calculated by graphical interpolation from the age–depth model segments (Fig. 2).

Zone 5A (394.3–366 cm; ca. 13.6–13.1 kyr BP)

Zone 5A is rich in both benthic and planktonic Foraminifera (Fig. 8). *Cassidulina neoteretis* Seidenkrantz is the dominant species, and *Pullenia bulloides* (d'Orbigny), *Melonis barleeanus* (Williamson) and *Alabaminella weddellensis* (Earland) are common, together with a relatively high amount of *Cassidulina reniforme* (Nørvang) and the group Miliolida. *Cassidulina neoteretis* and *P. bulloides* are common species in chilled Atlantic water masses (Steinsund, 1994; Seidenkrantz, 1995). Their occurrence in Zone 5A together with *A. weddellensis,* as well as several other species typical for the Atlantic waters south of Iceland today, are taken as an indication of a strong influence of the palaeo-Irminger Current to the region towards the end of Stadial GS-2 (pre-Bølling). The high amount of Miliolida in Zone 5A also points to a high salinity.

Zone 5B (366–334 cm; ca. 13.1–12.6 kyr BP)

There is a marked change in fauna at the transition to Zone 5B. *Cassidulina neoteretis* almost disappears, together with the other Atlantic water indicators, and these are replaced by high-arctic species such as *C. reniforme, I. norcrossi/helenae* and *Nonionellina labradorica* (Dawson) (e.g. Nørvang, 1945; Steinsund, 1994; Hald and Korsun, 1997). Harsh conditions are also indicated by the high amount of *Elphidium excavatum* (Terquem) as the arctic form *clavata* (e.g. Feyling-Hanssen, 1972; Hald *et al.*, 1994). The number of benthic Foraminifera is still relatively high but decreasing, whereas planktonic Foraminifera almost disappear. Thus, there is a faunal indication of a total shift in the water mass influence at the transition to Zone 5B. The palaeo-Irminger Current has been cut off, and cold bottom waters are entering the region during the initial part of Interstadial GI-1 (Bølling–Allerød). The extremely sparse planktonic fauna could be a result of seasonal ice cover in the area (Kohfeld *et al.*, 1996).

Zone 5C (334–212 cm; ca. 12.6–10.5 kyr BP)

Zone 5C contains a fluctuating amount of the Atlantic water indicator *C. neoteretis,* but all the other common species in the assemblages are arctic, i.e. *C. reniforme*, *E. excavatum*, forma *clavata*, *I. norcrossi/helenae* and *N. labradorica*. Thus, there seems to have been a fluctuating influence of the palaeo-Irminger Current to the area during the remaining part of GI-1 (Bølling–Allerød) and GS-1 (Younger Dryas), even though it never reached a similar high level as seen in Zone 5A. Sample 223–222 cm, which is taken within the Vedde tephra, was totally barren (Fig. 8), but a close examination of the assemblages on both sides of the Vedde tephra

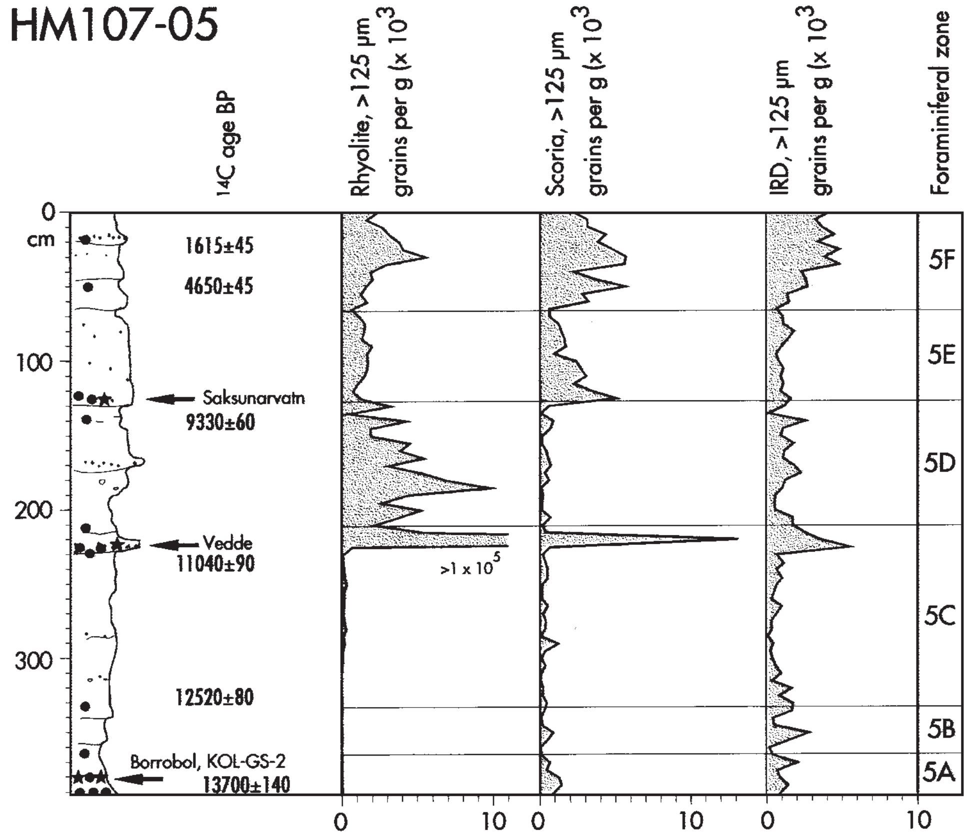

Figure 7 Mineralogy of the >125 μm sand fraction in core HM107-05. The levels of AMS ^{14}C dates in the core are indicated by dots on the lithological column, whereas well-defined tephra layers (the Borrobol, KOL-GS-2, Vedde and Saksunarvatn tephras) are marked with stars. The arrows indicate levels of chemical analyses (Figs 3 and 4). Selected dating results are also indicated (reservoir corrected by 400 yr).

shows that *C. neoteretis* is especially common in this interval of Stadial GS-1 (Younger Dryas). This is taken as an indication of a short-term increase in the influence of the palaeo-Irminger Current, an interpretation that is also supported by a marked increase in planktonic specimens during the same period of time. Most of Zone 5C is, however, very poor in planktonic Foraminifera, presumably as a result of seasonal ice-cover in the region.

Zone 5D (212–128 cm; ca. 10.5–9.0 kyr BP)

There is a very abrupt change in fauna again at the transition to Zone 5D, when *C. neoteretis* almost disappears. The assemblage in the lower part of Zone 5D is characterised by the same high-arctic species as found in Zone 5B. There is, however, a gradual decrease in some of the arctic species, especially *C. reniforme* and *E. excavatum* forma *clavata*, and an increase in the percentages of *M. barleeanus* towards the upper part of the zone. The Zone 5D assemblages, thus, indicate an initial abrupt cooling of the bottom waters at about 10.5 kyr BP. This is followed by a gradual change in environmental conditions in the upper part of the Preboreal, presumably owing to a return of Atlantic water from the palaeo-Irminger Current. An almost total lack of planktonic fauna indicates that there might have been major seasonal ice cover in the region.

Zone 5E (128–67 cm; ca. 9.0–6.2 kyr BP)

Zone 5E is characterised by a gradual increase in the amount of both benthic and planktonic Foraminifera. *Melonis barleeanus*, which is connected to a high supply of nutrient-rich water, is dominant in Zone 5E, and there is a slight increase in *C. neoteretis* and in *Trifarina fluens* (Todd) and, in the upper part, also in *P. bulloides*. This faunal composition, together with the appearance of some subpolar planktonic Foraminifera, indicate an increase in the influence of the palaeo-Irminger Current. Relatively high temperatures, a gradually increasing salinity, and a high influx of nutrient-rich water, therefore prevailed in the area during this Holocene 'climatic optimum'.

Zone 5F (67–0 cm; ca. 6.2–0 kyr BP)

There is a continuous increase in the percentages of *T. fluens* and *P. bulloides* in Zone 5F. This is taken as an indication of a high nutrient supply and a relatively high salinity in the area (e.g. Steinsund, 1994). A high nutrient supply is also supported by the continuous relatively high percentages of *M. barleeanus* (e.g. Mackensen *et al.*, 1985; Caralp, 1989). The decrease in the amount of Foraminifera and the reappearance of *E. excavatum* forma *clavata* towards the top of the zone presumably indicate a gradual change to less favourable, colder and fluctuating conditions.

Core HM107-04 west of Kolbeinsey Ridge

Sediments

Core HM107-04 is located on a level stretch of a north–south trending trough on the western margin of the Kolbein-

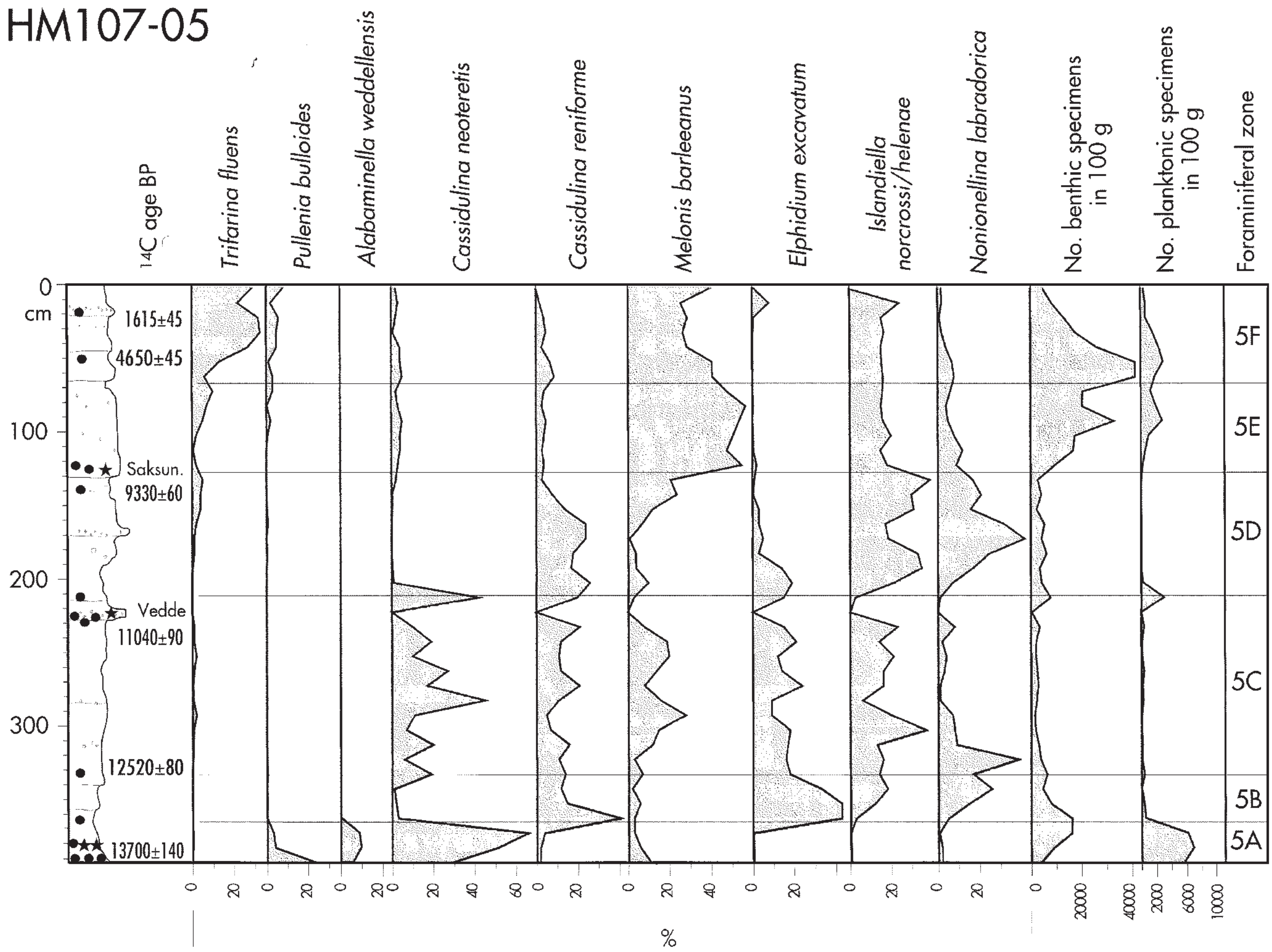

Figure 8 The relative frequency of selected benthic foraminiferal species and the number of benthic and planktonic specimens per 100 g dry weight in core HM107-05. The levels of AMS ^{14}C dates in the core are indicated by dots on the lithological column, whereas well-defined tephra layers (the Borrobol, KOL-GS-2, Vedde and Saksunarvatn tephras) are marked with stars (cf. Figs 5 and 7). Selected dating results are also indicated (reservoir corrected by 400 yr).

sey Ridge, about 120 km offshore (Fig. 1). Towards the south this trough is shifted eastwards at 67°N and then connects to the Eyjafjardarall trough, which locally reaches 700 m depth, reversing the gradient from land to the core site. This reduces the likelihood of turbidity currents from the inner shelf and fjords in North Iceland to the core site.

Visual inspection and X-ray photographs show a relatively massive deposit with minor structures except at tephra horizons. Both the Vedde and Saksunarvatn tephras are easily discerned on the X-ray photographs. Laminations are most prominent in the interval between these two tephras, corresponding to biozone 4B (Fig. 9). Another interval with strong laminations is seen between 235 and 205 cm, and a third one upwards from 105 cm, corresponding to the base of biozone 4D. Ice-rafted pebbles are common below and above the Vedde Ash, and small pebble concentrations are observed just above 300 cm, and in the interval 220 to 200 cm.

The mean grain size of sediments penetrated by core HM107-04 is relatively uniform, in the 10–20 μm mud range (Fig. 10). Tephra layers are responsible for distinct sand peaks at just above 370 cm (Vedde Ash), 317 cm (Saksunarvatn tephra) and at 70–65 cm (Fig. 11). Several other peaks contain volcanic grains, but they appear to be mixed, e.g. at the 130–110 cm interval. Apart from the tephra peaks the core as a whole displays three clearly defined levels of sand content (Fig. 10). The lowest interval (392–315 cm) has sand-fraction values around 20%, corresponding to biozones 4A and 4B (including the Preboreal). The mean grain size varies considerably, only partly because of the Vedde tephra. The mineralogy of this interval has a relatively strong percentage of rock fragments and crystals in the >125 μm range, interpreted as ice-rafted debris (Figs 10 and 11). The second interval (315–120 cm) has less than 10% sand and a very stable mean grain size. The sand mineralogy of this interval is relatively uniform. The uppermost interval (120–0 cm) shows increased sand with 10–20% values and rather unstable mean grain size. This interval is characterised by a strong increase in >125 μm crystals and rock fragments, interpreted as ice-rafted debris, but there is also an increase in rhyolitic glass content, probably as a result of Late Holocene Hekla eruptions. The Hekla 4, Hekla 3 and Hekla 1104 (Larsen and Thorarinsson, 1978) have all been identified in this area from core HM107-03 (Fig. 1) (Eiríksson *et al.*, 1998). This increase starts at ca. 6 kyr BP. At 115 cm there is a very marked peak in the content of rock fragments, crystals and altered glass. This event occurred at 5.5 kyr BP according to the age model presented in Fig. 2.

A plot of the sortable silt fraction is included (Fig. 10) mainly to illustrate the difference between sedimentation at core sites HM107-04 and HM107-05. If the sortable silt fraction is taken to indicate the strength of the sediment transporting current, the bottom currents were generally much weaker on the west side of the Kolbeinsey Ridge than

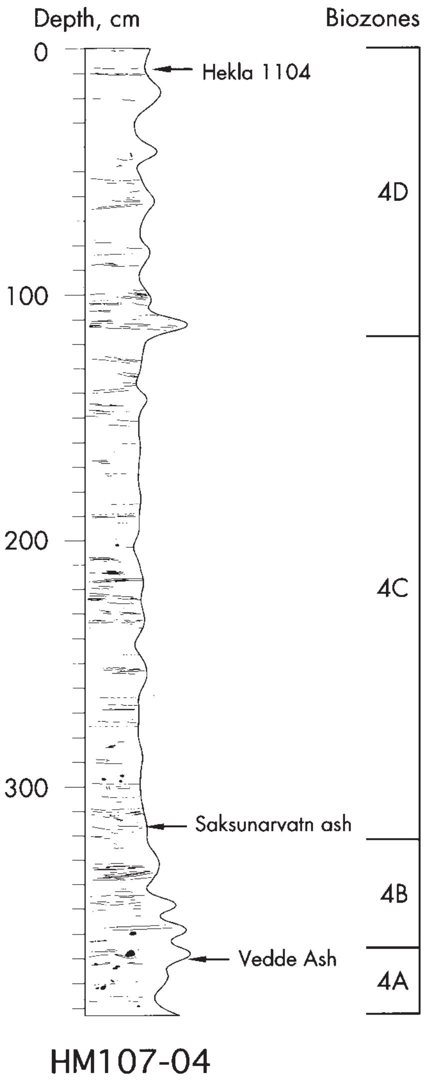

Figure 9 Litholgy of core HM107-04, based on X-ray photographs and grain size analyses. The right-hand side of the column reflects changes in mean grain size. Black lines and objects represent all laminations and pebbles (shown in double size) seen on the X-rays (see text for discussion). Benthic foraminiferal biozones are shown on the right-hand side of the diagram.

at site HM107-05, where the values are generally over 60%. There is a slight upward fall in the sortable silt fraction at site HM107-04, indicating decreasing bottom current velocities towards the end of the Holocene.

The magnetic susceptibility curve (Fig. 10) shows a general upward decrease in susceptibility. The water content curve shows an inverse trend, and probably explains most of the susceptibility decrease being related to reduced compaction. A sharp drop in susceptibility at 370 cm coincides with the rhyolite peak of the Vedde Ash, containing relatively few magnetic minerals. A small peak at 320 cm corresponds to the Saksunarvatn tephra layer, coinciding with a relatively high basaltic tephra content (Fig. 11). There is an increase in susceptibility above 120 cm that coincides with the end of the low sand fraction interval. The shear strength of the sediment is extremely low except at the sandy tephra unit at 370 cm and the relatively coarse grained basal part. There is no indication that the sediment has ever been overridden by a grounded glacier. Total carbonate content is clearly low during the Late-glacial and Preboreal, increasing upward through most of the Holocene, but displaying some variability and reduction towards the top.

Biostratigraphy

Four foraminiferal assemblage zones have been established in core HM107-04 (Zones 4A–4D, Fig. 12). The age of each of the zone boundaries is calculated by graphical interpolation from the age-depth model segments (Fig. 2).

Zone 4A (392.7–366; ca. 11.8 to ca. 10.5 kyr BP)

Zone 4A is characterised by a high content of arctic species such as *C. reniforme*, *E. excavatum* forma *clavata*, *I. norcrossi/helenae* and *N. labradorica*. There is, however, a dominance of *C. neoteretis* in the upper part of the zone. As in HM107-05, dense sampling around the Vedde tephra shows that this dominance occurs both below and above the tephra layer. There is also a peak in the amount of planktonic Foraminifera in the same interval. As shown for core HM107-05 this would indicate a relatively high influence of the palaeo-Irminger Current in the region during part of GS-1 (Younger Dryas).

Zone 4B (366–322 cm; ca. 10.5–9.3 kyr BP)

There is an abrupt change to a high-arctic benthic fauna at the transition to Zone 4B. *Cassidulina neoteretis* almost disappears and arctic species become dominant. This indicates that extremely cold bottom-water masses are entering area, and that the palaeo-Irminger Current does not reach the area during early Preboreal time. A change towards higher contents of *M. barleeanus* towards the top suggests a later increase in the input of nutrients. Planktonic Foraminifera are totally absent in Zone 4B, presumably as a result of seasonal sea-ice cover during the Preboreal, as also seen at core site HM107-05.

Zone 4C (322–117 cm; ca. 9.3–5.5 kyr BP)

The assemblages in Zone 4C correspond to those found in Zone 5E at site HM107-05, except that the amount of the Atlantic water indicator *C. neoteretis* is higher at HM107-04, whereas the amount of the arctic species *I. norcrossi/helenae* is lower. This presumably is the result of the location of this site being to the west of the Kolbeinsey Ridge, i.e. closer to the source of the palaeo-Irminger Current. The amount of planktonic Foraminifera is generally high, but increasing through Zone 4C. The planktonic assemblage also contains a considerably higher amount of warmer water (subpolar) species than seen at site HM107-05 during the same period. An interesting feature in Zone 4C is a short-term cooling, which is documented by an increase in the high-arctic species *C. reniforme* and *I. norcrossi/helenae* at around 213–206 cm in the core. A sample from 208–207 cm is dated at 7.3 kyr BP (Table 1). The exact faunal development through this interval is being studied in detail.

Zone 4D (117–0 cm; ca. 5.5–0 kyr BP)

An increase in *T. fluens* and *I. norcrossi/helenae* in Zone 4D indicates gradually colder and more saline conditions

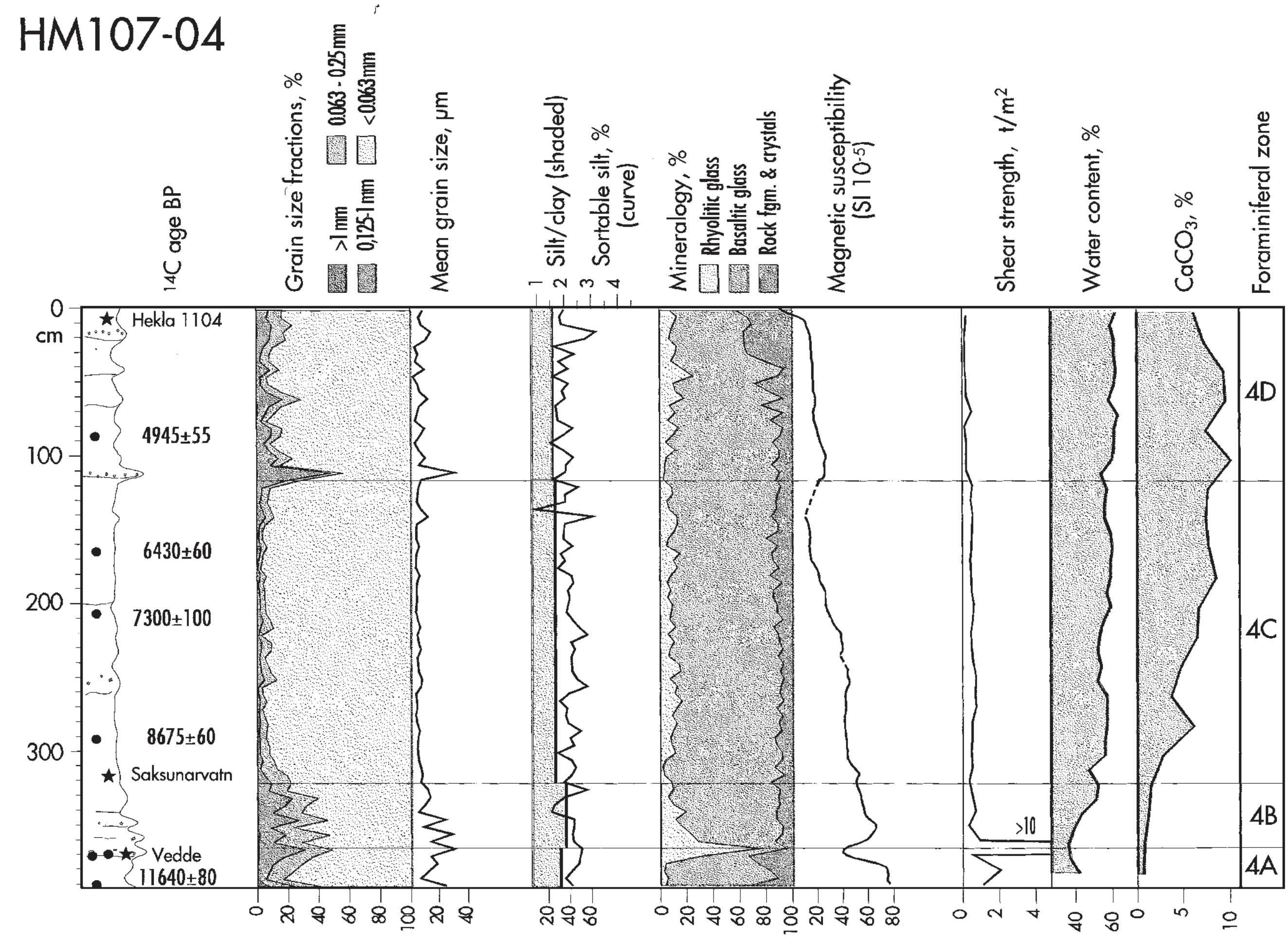

Figure 10 Sedimentary parameters in core HM107-04. The levels of AMS ^{14}C dates in the core are indicated by dots on the lithological column, whereas well-defined tephra layers (the Vedde, Saksunarvatn and Hekla 1104 tephras) are marked with stars. Selected dating results are also indicated (reservoir corrected by 400 yr).

after about 5500 yr BP. Even the opportunistic, arctic species *E. excavatum* forma *clavata* reappears towards the top of the zone. This is considered an indication of decreasing influence from the palaeo-Irminger Current. The influence of Atlantic waters is, however, always higher in the area west of the Kolbeinsey Ridge than at site HM107-05. This is suggested by relatively higher contents of *C. neoteretis* and lower amounts of the arctic *T. fluens* and *I. norcrossi/helenae* at HM107-04. There is a high, but fluctuating amount of both benthic and planktonic Foraminifera through Zone 4D, decreasing towards the top. An increase in percentages of sinistrally coiled *G. pachyderma* through this zone also points to gradually less influence of the palaeo-Irminger Current and a higher influence of the East Greenland Current in the region (e.g. Johannesen *et al.*, 1994).

Discussion

Quite intensive environmental changes are recorded in the shelf sediments north of Iceland during the past 14 kyr BP. Many of the changes in faunal and sedimentary parameters are thought to be related to temporal changes in the relative strength of the Irminger and East Icelandic currents, probably reflecting the changes in the pattern of the global thermohaline circulation.

This discussion focuses on major changes between time slices in the North Icelandic shelf cores and a comparison of these with the well-established coeval event stratigraphy in the northern North Atlantic region, particularly the Greenland ice-core record and the Nordic Seas, as well as the terrestrial development in Iceland. Major palaeoenvironmental events in the North Icelandic shelf records are schematically presented in Fig. 13 on a radiocarbon time-scale.

Greenland Stadial 2 event (GS-2)

Sediments deposited during the GS-2 event were penetrated only at site HM107-05 on the North Icelandic shelf. Biozone 5A (13.6–13.1 kyr BP, pre-Bølling, Fig. 13) represents a period with relatively strong bottom current activity (high silt/clay ratio). The species composition of rich benthic faunas indicates that there was a strong inflow to the area of relatively warm Atlantic water with high salinity. The immigration of several southern species at this time is especially remarkable because most of these never appear in the area again, not even during the Holocene 'climatic optimum'.

A high amount of planktonic Foraminifera in the same pre-Bølling interval, however, is totally dominated by the high arctic *N. pachyderma* sinistral, indicating that the surface waters must have been more influenced by the cold East Icelandic Current and that the water masses were strati-

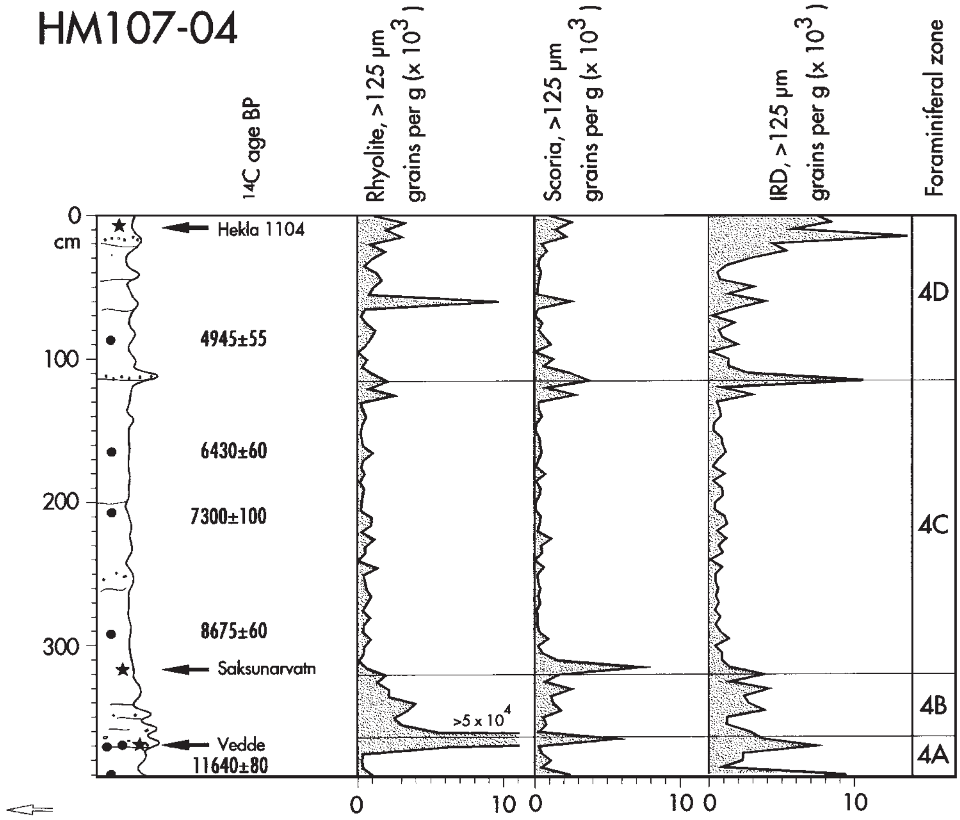

Figure 11 Mineralogy of the >125 μm sand fraction in core HM107-04. The levels of AMS ^{14}C dates in the core are indicated by dots on the lithological column, whereas well-defined tephra layers (Vedde, Saksunarvatn and Hekla 1104 tephras) are marked with stars. The arrows indicate levels of chemical analyses (Figs 3 and 4). Selected dating results are also indicated (reservoir corrected by 400 yr).

fied. Since about 13.1 kyr BP the environmental signals from bottom and surface assemblages seem to be similar and environmental changes appear to occur simultaneously. This is taken as an indication of vertical mixing of the water column, which also occurs at present in the area.

A strong pre-Bølling palaeo-Irminger Current also has been suggested by Sarnthein *et al.* (1995) on the basis of isotopic data from deep-sea cores in the North Atlantic, and supported by data from a core to the northwest of Iceland (Voelker *et al.*, 1998). In a study of climatic and oceanographic changes in the North Sea region, Rochon *et al.* (1998) registered a noticeable cooling of surface water masses from about 14.0 to 13.3 kyr BP (calculated to a 400 yr reservoir correction), coinciding with the Oldest Dryas in terrestrial northern Europe. In the GRIP record the long, cold stadial between Interstadials 2 and 1 (Johnsen *et al.*, 1992), referred to as Greenland (Isotope) Stadial 2 (Björck *et al.*, 1998), ends with a particularly cold episode (GS-2a) that corresponds to the time interval covered by biozone 5A on the North Icelandic shelf. Thus, the available data indicate that the cooling event in Greenland and northern Europe was accompanied by warming of the seas to the west and north of Iceland, indicating a northward bulge of the Polar Front in the western North Atlantic. This would indicate a partial westward deflection of the North Atlantic Current and strengthening the palaeo-Irminger Current. Oceanic modelling work in progress at the Nansen Environmental and Remote Sensing Centre in Bergen, Norway, indicates that increased strength of the Norwegian Current into the Norwegian Sea leads to cooling of the Iceland Sea north of Iceland, and, inversely, that a reduction of the Norwegian Current leads to warming of the Iceland Sea (Helge Drange, personal communication, 1999).

Two tephra units were identified in the GS-2 sediment record of core HM107-05, the KOL-GS-2 and a tephra with chemical composition identical to the Borrobol Tephra (Lowe and Turney, 1997; Turney *et al.*, 1997). The age of this latter tephra in core HM107-05 is considerably older than indicated for the Borrobol Tephra at the type locality (12.26 kyr ^{14}C BP; Lowe *et al.*, 1999). If the two chemically identical tephras were derived from one eruption, a marine reservoir correction of over 1500 yr would be indicated. This would imply a GI-1 age for biozone 5A. Further work is needed, however, to clarify the age difference of the Borrobol Tephra in the two areas.

The KOL-GS-2 is described here for the first time. It was probably erupted on the Kolbeinsey Ridge, but the regional extent is unknown. A study of the sedimentary record close to the Kolbeinsey Ridge further north indicated a total dominance of Kolbeinsey Ridge derived tephra (Lackschewitz *et al.*, 1994). The KOL-GS-2 is the only discrete tephra layer from the Kolbeinsey Ridge that has been identified so far in the study area. All sand-sized rhyolitic material found in the cores is thought to be derived from Iceland as there are no known silicic volcanoes on the Kolbeinsey Ridge.

Greenland Interstadial 1 event (GI-1)

The GI-1 event (Bølling-Allerød) is generally warm with a very abrupt shift at the GS-2–GI-1 boundary. In the GRIP ice-core, it comprises three warm subevents separated by two cold spells (Johnsen *et al.*, 1992).

A remarkable change in both sediment and fauna occurs in core HM107-05 at 366 cm depth. This level is dated to

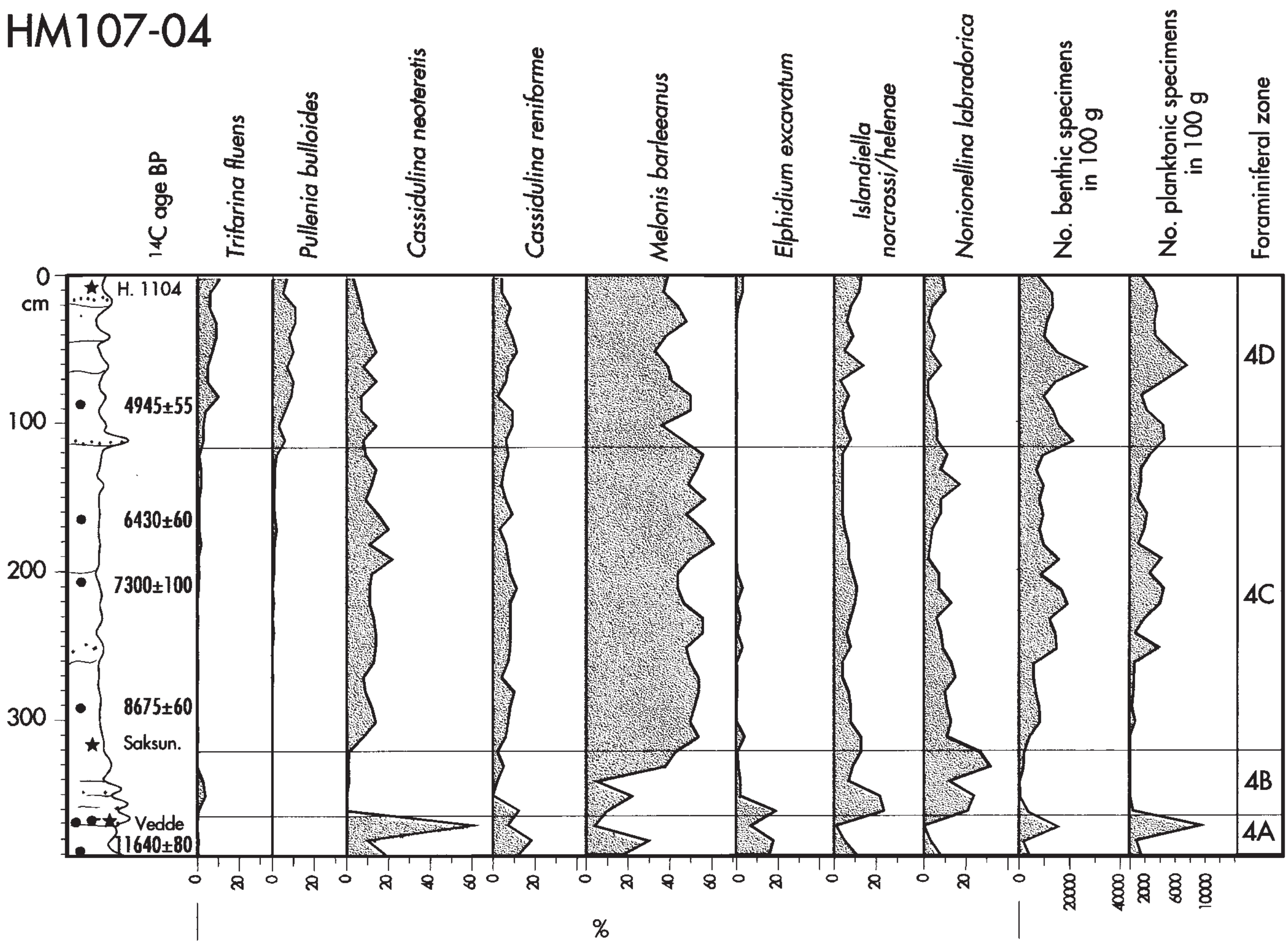

Figure 12 The relative frequency of selected benthic foraminiferal species and the number of benthic and planktonic specimens per 100 g dry weight in core HM107-04. The levels of AMS ^{14}C dates in the core are indicated by dots on the lithological column, whereas well-defined tephra layers (the Vedde, Saksunarvatn and Hekla 1104 tephras) are marked with stars. Selected dating results are also indicated (reservoir corrected by 400 yr).

13.1 kyr BP and corresponds approximately to the radiocarbon age of the beginning of the Bølling–Allerød chronozones. The foraminiferal assemblage in biozone 5B indicates that the palaeo-Irminger Current was greatly reduced in the region north of Iceland, and that seasonal ice cover occurred in the area. The sediments contain a number of basaltic pebbles that indicate ice rafting, either from icebergs derived from calving glaciers in Iceland or drifting coastal ice floes. Biozone 5B is correlated with the first warm subevent of the GI-1, the GI-1e (cf. Björck *et al.*, 1998).

Again, the sudden cooling and inferred reduction of the palaeo-Irminger Current is apparently contrary to the climatic change in the Nordic Seas and in the Greenland ice-core record. There is no doubt, however, that the same climatic event is involved, but the repercussions are longitude dependent. Kroon *et al.* (1997) found that the Bølling period was characterised by a high influx of warm and salty water into the eastern North Atlantic, presumably leading to an intense deep-water formation in the Nordic Seas and restoration of the Atlantic salinity conveyor belt after the last glacial period (see also Boyle and Keigwin, 1987; Sarnthein *et al.*, 1994). This sudden change may have led to general instability in the circulation pattern north of Iceland. The very cold benthic fauna probably indicates increased sea-bed influence of Norwegian Sea Deep Water (NSDW) along and partly across the outer realms of the shelf. The westward deflection of the North Atlantic Current leading to a strenghening of the palaeo-Irminger Current as proposed for the upper part of GS-2 is thus no longer in effect during the initial phase of the GI-1 event. This fits with the modelling results referred to earlier (Helge Drange, personal communication, 1999).

The extremely harsh conditions indicated by biozone 5B are followed in biozones 5C and 4A (base of core HM107-04 west of Kolbeinsey Ridge) by a dominance of arctic species but a fluctuating amount of Atlantic water indicators. This is taken to imply a strong East Icelandic Current but periodic influx of a strengthened palaeo-Irminger Current.

Recent research and compilations of the glacial and vegetation history of Iceland during the last termination (Norddahl, 1991; Ingólfsson, 1991) indicate deglaciation of coastal regions and transgression at the start of the GI-1 (Bølling), with sea temperatures below 5°C, followed by a glacial readvance (Einarsson and Albertsson, 1988; Ingólfsson, 1988) which traditionally has been correlated with the Older Dryas chronozone. According to Rundgren (1995), terrestrial data from North Iceland indicate that the waters immediately north of Iceland were seasonally ice-free during the Allerød interstadial. Data from Southwest Iceland (Geirsdóttir and Eiríksson, 1994; Sveinbjörnsdóttir *et al.*, 1993), however, show that the upper part of the GI-1 experienced glaciation to sea-level, with a continued transgression leading to glacier retreat at the GI-1 to GS-1 (Allerød–Younger Dryas) transition.

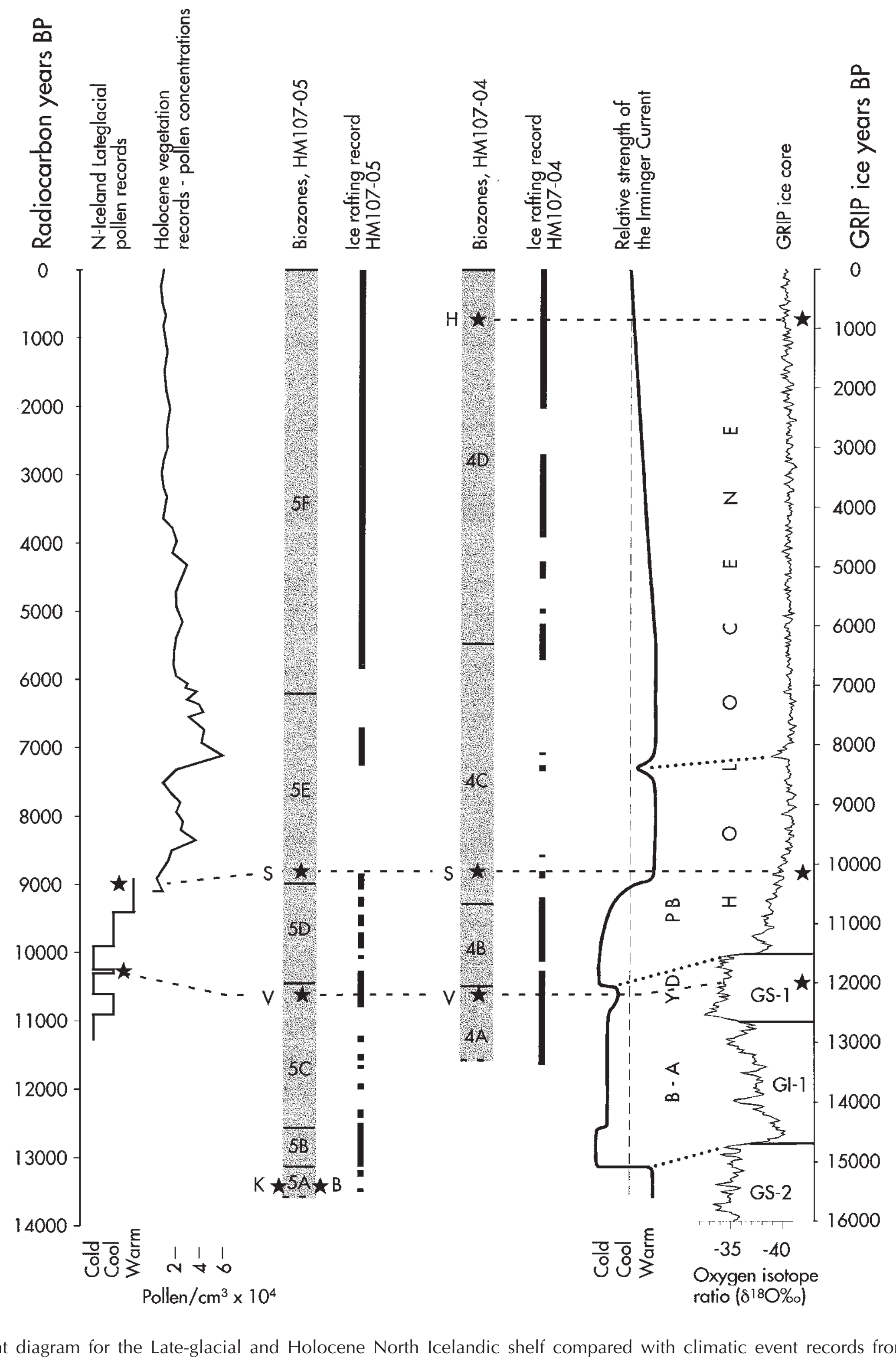

Figure 13 Event diagram for the Late-glacial and Holocene North Icelandic shelf compared with climatic event records from terrestrial Iceland and Greenland. Radiocarbon dated events and biozone boundaries are correlated to the time-scale on the left-hand side of the diagram. The GRIP ice-core years are shown on the right-hand side, as well as the oxygen isotope event record (Johnsen *et al.*, 1992; Johnsen *et al.*, 1995). Tephra markers identified in the ice, either as acidity peaks (Clausen *et al.*, 1997) or glass shards (Grönvold *et al.*, 1995) are marked with stars. The North Icelandic Late-glacial pollen records are based on lacustrine sediments (Rundgren, 1995), containing the Vedde and Saksunarvatn tephra markers (marked with stars). The Icelandic vegetation records are based on pollen work in bogs and lacustrine sediments (Hallsdóttir, 1995). Threshold levels for IRD in cores HM107-05 and HM107-04 at $1.2 \times 10^3 > 125$ μm grains g^{-1}, and pebbles seen on X-ray photographs are also included. Tephra markers are marked with stars in respective biozones (H = H 1104; S = Saksunarvatn ash; V = Vedde Ash; K = KOL-GS-2; B = tephra with Borrobol chemistry). The curve for the relative strength of the palaeo-Irminger Current is based on benthic and planktonic Foraminifera as well as sedimentary parameters such as laminations, sortable silt content, mean grain size. B–A = Bølling–Allerød, YD = Younger Dryas, PB = Preboreal.

Greenland Stadial 1 event (GS-1)

The Vedde Ash is present as a discrete marker horizon in both cores HM107-05 and HM107-04. This, together with several ^{14}C dates, allows a correlation with the Greenland Stadial 1 event (Younger Dryas). The age of the event (Fig. 13) is probably overestimated by 350–400 yr in the present study owing to reservoir age uncertainties (see discussion above). The base of the GS-1 event is not clearly seen in the faunal record. According to the depth–age diagram (Fig. 2) the base of the Younger Dryas chronozone would occur at 243 cm depth in core HM107-05 and at 376 cm in HM107-04 (with a reservoir correction of 400 yr).

The GS-1 event is characterised by a continued strong East Icelandic Current with fluctuating influx of the palaeo-Irminger Current and seasonal sea-ice cover, as in the upper part of the GI-1 event (Allerød). There is faunal evidence, both in surface and bottom waters, of an especially strong palaeo-Irminger Current during a short period of time around the Vedde event (both before and after) in both cores. There is, however, no evidence of any palaeoceanographic change on the North Icelandic shelf associated with the eruption, as suggested by Rochon *et al.* (1998). With the present time resolution of the faunal changes it is not possible to make a closer comparison with the Younger Dryas fluctuations observed in the eastern Atlantic by Kroon *et al.* (1997).

Pollen records from North Iceland, extending back to ca. 11.3 kyr BP (Rundgren, 1995) show a marked warming at ca. 10.9 kyr BP, close to the Allerød–Younger Dryas chronozone boundary (Fig. 13), with subsequent cooling at 10.6 kyr BP. In accordance with the present results, another warm event is indicated by the pollen data at the Vedde Ash level (10.3–10.25 kyr BP), although Rundgren (1995) interpreted this part of the pollen record as being redeposited. In addition, shallow-marine records from southwest Iceland, dated to the Younger Dryas, show clearly that there was an influx of relatively warm Atlantic water for at least part of the period (Eiríksson *et al.*, 1997).

In core HM107-05 there is a secondary peak of rhyolitic grains with Vedde composition above the primary peak (Fig. 7). Using the age model presented in Fig. 2, the delay amounts to at least 800 yr. This has important implications for the use of the Vedde as a marker in the North Atlantic, because there cannot have been any immediate air-fall deposition of the Vedde Ash on the sea-floor in regions of sea-ice cover. Recent data show that the lag time between eruption and release at the glacier margin of tephra buried in the accumulation region of present-day Vatnajökull, Iceland (Fig. 1) may be up to 800 yr (Larsen *et al.*, 1998).

The Holocene

In both cores HM107-05 and HM107-04 there is a very abrupt change in benthic Foraminifera associated with the end of GS-1, which is close to 10.5 kyr BP according to the age model presented in Fig. 2. The zones 5D and 4B, respectively, are marked by the disappearance of the Atlantic species *C. neoteretis* and a dominance of arctic species. The sediments are relatively strongly laminated with levels of pebble concentrations, indicating minimal bioturbation and ice-rafting events. Some of the laminations may reflect meltwater events from the disappearing Icelandic glaciers. Planktonic Foraminifera are practically absent in the sediments ascribed to the Preboreal, perhaps indicating significant presence of sea-ice. The assemblages in the upper part of the Preboreal, however, indicate a gradually greater influence of the palaeo-Irminger Current.

According to Rundgren (1995), the climatic conditions in coastal regions of North Iceland were cool with long seasons without sea-ice in the lower part of the Preboreal, changing to warm with possibly no sea-ice in the upper part. Preboreal readvances have been identified in North Iceland (Norddahl and Haflidason, 1992), southwest Iceland (Eiríksson *et al.*, 1997) and South Iceland (Hjartarson and Ingólfsson, 1989; Geirsdóttir *et al.*, 1996).

The abrupt cooling of the North Icelandic shelf waters at the transition to the Preboreal occurs at the same time as the initiation of warm water influx in the eastern North Atlantic (e.g. Lehman and Keigwin, 1992) and isotopic indication of warmer climate in the GRIP ice-core (Johnsen *et al.*, 1992). Again, this presumably is the result of the markedly intensified deep-water formation, leading to an influx of NSDW across the outer part of the shelf area.

Faunal changes immediately before the deposition of the Saksunarvatn tephra, which in the present material is dated at ca. 8.8 kyr BP, indicate an influx of relatively warm, saline and nutrient-rich water as a result of strengthening of the palaeo-Irminger Current. Faunal indication of temperatures higher than today occurs throughout biozones 5E and 4C, corresponding to a Holocene 'climatic optimum' between ca. 9 and 6 kyr BP in this area. Comparing the two sites on each side of the Kolbeinsey Ridge, the westernmost site (HM107-04) has clearly enjoyed warmer conditions. This is consistent with the present-day conditions in the area. Generally, the circulation became much more stable in the seas north of Iceland after the Preboreal.

A similar early Holocene temperature maximum has been reported from the northwest Atlantic and the Denmark Strait (e.g. Balsam, 1981; Kellogg, 1984). Both in that region and in the Iceland Sea (Koç Karpuz and Schrader, 1990) a general decrease in temperture started at about 6 kyr BP, corresponding to the present results from the North Icelandic shelf. Recent temperature calculations from the GRIP ice-core, however, indicate the 'climatic optimum' on Summit, Greenland, to be as late as 8–5 cal. kyr BP (Dahl-Jensen *et al.*, 1998). In the eastern Nordic Seas the cooling after the Holocene 'climatic optimum' occurred as late as about 4 k ^{14}C yr BP (Koç *et al.*, 1993; Sejrup *et al.*, 1995).

In core HM107-04 there is evidence of a short-term cooling, documented by abundance peaks of arctic benthic Foraminifera. The event is dated to 7.3 kyr BP. This cooling presumably corresponds to the distinct isotopic minimum (Fig. 13) seen at 8.2 cal. kyr BP in the Greenland ice-core records (Alley *et al.*, 1993; Dansgaard *et al.*, 1993), which also has been registered recently in the Norwegian Sea (Klitgaard-Kristensen *et al.*, 1998). For this event, the term 'GH (Greenland Holocene)-8.2 event' has been suggested by Walker *et al.* (1999). Clearly, the oceanographic conditions of the area were no longer out of phase with the Greenland and eastern North Atlantic records.

The uppermost biozones (5F, from 6.2 kyr BP and 4D, from 5.5 kyr BP) reflect continued dominance of relatively warm, saline water in the area, but with a gradual cooling and fluctuating conditions. The western area remained warmer throughout. In both cores the sortable silt fraction is generally lower, and fluctuates more strongly than in the sediments deposited during the first half of the Holocene (Figs 6 and 10). This indicates increasingly sluggish currents and increased influence of the East Icelandic Current. The base of biozone 4D in core HM107-04 is marked by an interval with relatively strong laminations, the corresponding interval in core HM107-05 documents a relative reduction of laminations. This between-site variability reflects the fact that the cores sites are located in different oceanographic settings. The bottom currents appear to be generally much stronger at the easternmost site.

A comparison of the North Icelandic shelf data with the Holocene vegetation succession in Iceland (reviewed by Hallsdóttir, 1995) shows a remarkable agreement (Fig. 13). Low-arctic heath vegetation began at 9.7 kyr BP, and at 8.5 kyr BP a subalpine birch forest had started to develop in North Iceland. This forest became dense from 7.2 to 6 kyr BP, but was abruptly halted with a transient reappearance of heath vegetation around 7.5 kyr BP (Fig. 13). A sharp reduction of woodlands took place at 6 kyr BP, and the climatic implications of vegetational changes indicate unstable conditions on a millennial time-scale during the latter half of the Holocene.

A review of the Holocene environmental history of Iceland describes increasing frequency of glacier expansions in North Iceland for the past 5–6 kyr BP (Gudmundsson, 1997). This is in accordance with the present marine records of increasing IRD content in the North Icelandic shelf sediments, indicating increased sea-ice since 6 kyr BP (Fig. 13). The reconstructed temperature history for the Greenland ice sheet also shows a clear cooling with several oscillations after 5 cal. kyr BP (Dahl-Jensen *et al.*, 1998).

Conclusions

The data from the North Icelandic shelf show that there is significant longitudinal difference across the North Atlantic in the climate response to major Late-glacial events recorded, for example, in the Greenland ice-core records. The apparent regional synchronicity of terrestrial and atmospheric deglacial records in the North Atlantic region (Björck *et al.*, 1996) is not borne out by the marine data from the North Icelandic shelf. The southward shift of the Polar Front was not uniform across the North Atlantic Ocean—instead the form of the Polar Front changed in a see-saw fashion during the Late-glacial. Apparently, triggering events in the Nordic seas have repeatedly caused a northward bulge of the oceanographic Polar Front around Iceland while the eastern part moved south, so that the eastern and western parts moved in a see-saw fashion rather than performing a simple north–south shift. After the Preboreal, however, the North Icelandic shelf oceanographic record appears to reflect the regional pattern of the North Atlantic.

The main conclusions on the Late-glacial and Holocene palaeoceanographic evolution north of Iceland are:

1. the North Icelandic shelf segment from Kolbeinsey to Grímsey was deglaciated prior to ca. 14 k ^{14}C yr BP and has not been subjected to grounded ice cover since that time;
2. the palaeo-Irminger Current was relatively strong from at least 13.6 kyr BP until 13.1 kyr BP — this coincides with a strong meltwater event in the Nordic seas and reduced thermohaline circulation;
3. the transitions to the GI-1 (Greenland Interstadial 1, Bølling–Allerød) and to the Preboreal are associated with severe cooling events in the study area, indicating an initial reduction of the palaeo-Irminger Current at the onset of strong NSDW formation and strengthening of the thermohaline circulation;
4. a relatively stable oceanographic system, analogous to the present-day scenario, was established in the waters north of Iceland at ca. 9 kyr BP, with one distinct cooling event at 7.3 kyr BP (8.2 cal. kyr BP);
5. a distinct cooling trend and increased oceanographic instability occurred from ca. 6 kyr BP.

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