^{14}C AMS DATING OF ICELANDIC LAKE SEDIMENTS

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ABSTRACT. We report an age-depth profile for the sediments of the Lake Hestvatn, southern Iceland, based on ^{14}C analyses of the organic fraction of bulk sediment samples, molluscs and foraminifera. Our age-depth curve is supported by the occurrence of the well-dated Vedde ash in the lowermost part of the sediments. Comparison of foraminifera dates with the age of the Vedde ash indicates a reservoir age of *ca.* 400 yr. The results suggest that the sediments at Hestvatn accumulated in a marine environment until *ca.* 8700 BP and thereafter in freshwater.

Owing to the lack of terrestrial macrofossils and the low concentration of molluscs and foraminifera, we were forced to attempt to date most of the core with the organic fraction of the bulk sediment samples. We found, however, that this fraction is not homogeneous in density or ^{14}C age. We believe that during sample pretreatment we managed to isolate a light organic fraction, which closely represents the true age of the sediment, whereas the denser fraction yields ages that are too high. This age diversity may to some extent be explained by the large drainage area of the lake, from which plant remains of different ages may have been washed into the lake.

INTRODUCTION

The location of Iceland in the North Atlantic, at the boundaries of major air and ocean masses, has made it an important research area for regional and global paleoclimatic studies. During the last three years the joint Icelandic/USA initiative within the Paleoclimate of Arctic Lakes and Estuaries (PALE) program has focused on this region and now conducts diverse paleoclimatic studies in southern, western and northwestern Iceland. The major objective of the PALE program is to reconstruct both spatial and temporal environmental changes since the deglaciation of Iceland, based on continuous and high-resolution data. This is accomplished by studying numerous sediment cores obtained from lakes lying on a transect from southern to northwestern Iceland, and by extensive ^{14}C dating.

In this study, we report ^{14}C results from the sediments of the lake Hestvatn, southern Iceland (Fig. 1), where seismic survey has identified sediments up to 45 m in depth, and suggested a change from marine to lacustrine deposition at *ca.* 10–12 m depth (Geirsdóttir and Harðardóttir 1995). The main objective of our measurements was to establish a depth-age model for the lake basin and specifically to date the transition from marine to lacustrine sediments.

The scarcity of macrofossils forced us to base most of the ^{14}C dates on the organic fraction of bulk samples—a procedure that seemed acceptable as Icelandic lakes are noncalcareous. Also, we can check the reliability of the dates, as the lakes studied in southern Iceland are located close to the active volcanic zone. Their sediments thus include abundant tephra layers (*ca.* 70 in each core) deposited during volcanic eruptions. The tephras make correlation within and between lake basins easy. Many of the layers that are younger than *ca.* 6000 BP have been ^{14}C-dated in nearby soil sections and represent valuable chronological control in the lake sediments.

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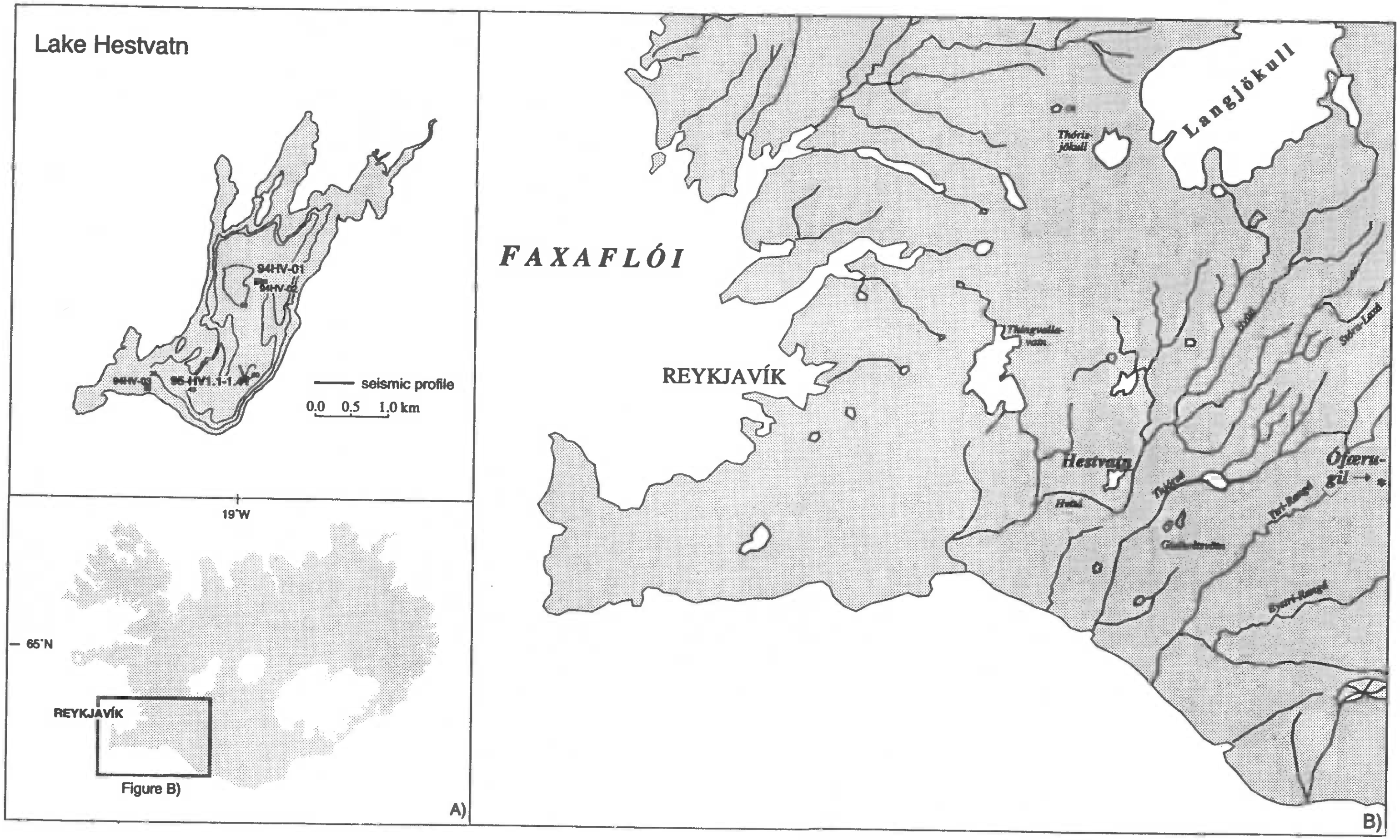

Fig. 1. Map of Iceland showing the location of Hestvatn and other localities mentioned in the text

METHODS

Coring

The uppermost 5.7 m of the Hestvatn sequence was obtained by the Nesje gravity coring system (Nesje 1992). With the help of the Coring Company of Iceland we obtained an additional long core (95HV-1.1-1.4) (Geirsdóttir and Harðardóttir 1996, 1997), which is an extension of the former Nesje cores although they do not overlap. The diameter of the Nesje core is 7 cm, but that of the long additional core is 3.5 cm. Unfortunately there is a 3.8 m gap between the lowermost Nesje core and the long core. The long core was obtained in four sections (HV1.1–HV1.4) and there is a strong indication from our ^{14}C results that the uppermost samples in each section were contaminated by younger sediments as a consequence of the coring process (see Fig. 4).

Sample Preparation

We pretreated the bulk sediment samples with 1M HCl for 2–3 h in order to remove inorganic carbon, followed by rinsing with distilled water. After this pretreatment the sediment samples were centrifuged. The suspected marine sediment samples settled in the centrifuge tubes into two distinct layers: a pale gray fraction above and a dark gray fraction below (Fig. 2). The reason for the layering is thought to be the greater density of the organic content of the lower fraction, which may be more mineralized and which would therefore precipitate faster. Within the lacustrine sediments the layering was not so obvious, but a gradual change from top to bottom of the centrifuge tube was observed. When possible, both upper (less dense) and lower (denser) layers were sampled for ^{14}C measurements. Carbon from all samples was transformed to CO_2 by combustion with CuO in an evacuated vial at 900°C.

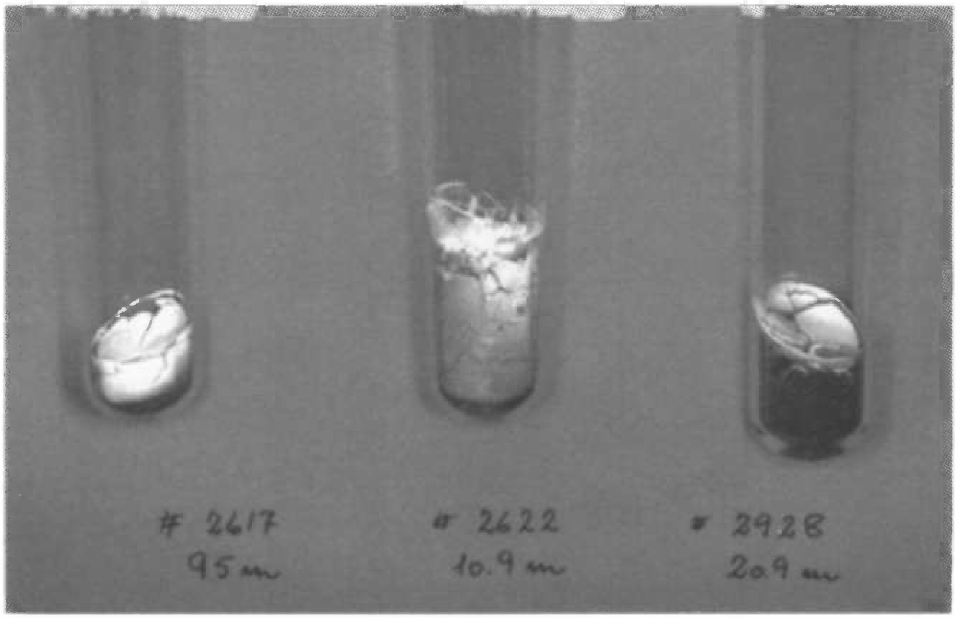

Fig. 2. During pretreatment with HCl the organic part of the marine sediment samples settle into two distinct layers; a light-colored fraction on top and a darker fraction below. The reason for the layering is probably higher density of the organic content of the lower fraction, which may be more mineralized and therefore precipitates faster. When lacustrine samples were centrifuged, the layering was not as obvious but a gradual change from top to bottom was observed.

For the shell fragments we followed the normal rinsing procedure. In order to eliminate possible surface contamination, the outer 25% of the sample was removed by etching with HCl and any organic carbon present was dissolved away by treatment with a $KMnO_4$ solution for 16–20 h at 80°C. We processed the sediment samples for foraminifera by dry-sieving sediment on a mesh diameter of 100 μm. The foraminifera were then picked out individually from the dry <100 μm sediment fraction. The CO_2 of the carbonate samples was liberated with 100% phosphoric acid in an evacuated vial at 25°C.

This CO_2 was then partly used for $\delta^{13}C$ measurements at the Science Institute, University of Iceland, and partly converted to graphite using a cobalt catalyst (Vogel *et al.* 1984) for ^{14}C measurements at the Aarhus AMS Dating Laboratory (Andersen *et al.* 1989).

RESULTS

Table 1 gives the results of our ^{14}C and $\delta^{13}C$ measurements on the organic fraction of bulk sediment samples, shell fragments and foraminifera. Figure 3 illustrates the ^{14}C results for the lacustrine part of the core down to 5.7 m, compared with the known ^{14}C ages of the identified tephra layers, which have previously been dated in nearby soil sections. The diagram shows that the organic fraction of

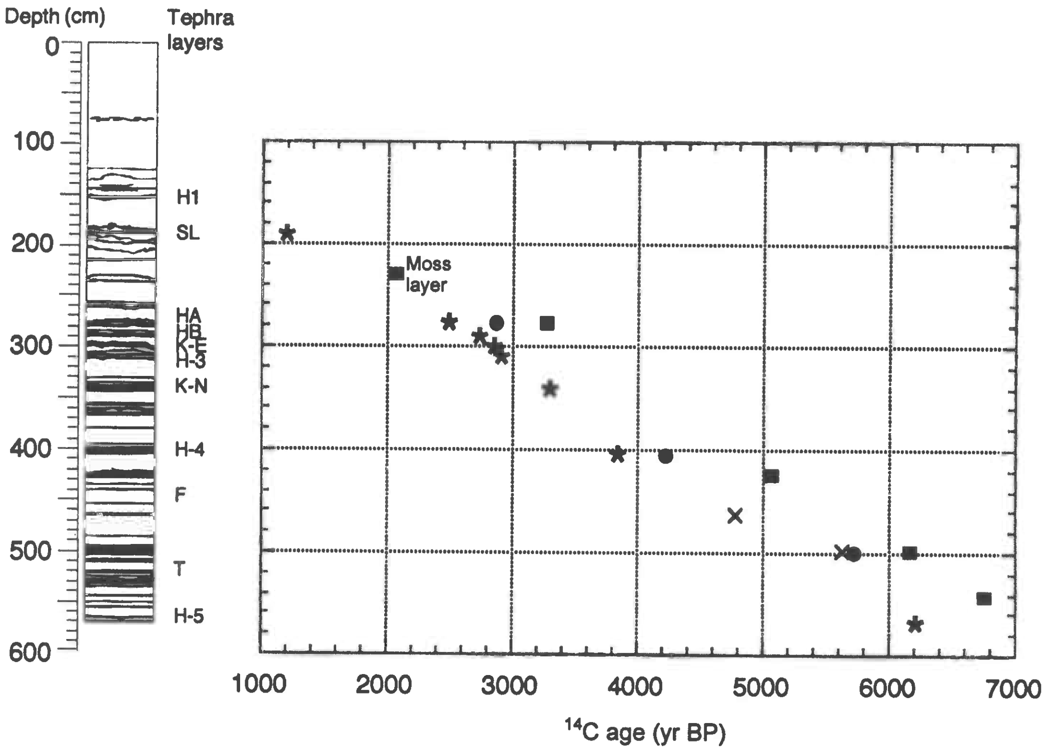

Fig. 3. The organic fraction of previously dated bulk sediment samples from the Hestvatn sequence always yields higher ^{14}C ages (by *ca.* 700–900 BP) than the soil sections nearby. When only the less dense component of the sample separated after treatment with HCl is dated, the results are closer (250–400 yr) to the age given by the neighboring sections. ^{14}C dates from: ● = AMS Laboratory, University of Århus; ✱ = dated tephra in soil sections; ■ = AMS laboratory, University of Colorado-Lawrence Livermore, cores 94&95HV; ✕ = AMS laboratory, University of Colorado-Lawrence Livermore, core 94-VGHV01.

bulk sediment samples from the Hestvatn sequence, measured previously by CAMS at Lawrence Livermore National Laboratories, always yields ^{14}C ages *ca.* 700–900 BP older than the tephra layers. However, the only moss-layer we found, which was measured at CAMS, lies much closer to the tephra ages, differing by *ca.* 250 BP. We observed similar discrepancies for the bulk samples prepared at Aarhus, where only the less dense part of the organic fraction was used for ^{14}C measurements (Fig. 3).

TABLE 1. ^{14}C and δ^{13}C for the Lacustrine and Marine Sediments in the Hestvatn Cores Obtained at the Aarhus AMS Laboratory.

Cores	Cum. depth (cm)	^{14}C age (yr BP) of organic fraction			^{13}C ‰ org	^{14}C age (yr BP) of shell (s) / foraminifera (f)*	^{13}C ‰ carb. (PDB)
		Upper fraction	Lower fraction	Mixed fraction			
94-HV01	278.5	2875 ± 45 (AAR-3474)	--	--	−22.0	--	--
	404.7	4230 ± 70 (AAR-3475)	--	--	−22.8	--	--
	499.5	5765 ± 55 (AAR-3476)	--	--	−23.8	--	--
HV95-1,1	951	6220 ± 90 (2617-1.1)	6740 ± 80 (AAR-2617-1.2)	--	−24.5	--	--
	1033.5	9800 ± 90 (AAR-2620)	--	--	−24.7	--	--
	1086.5	8890 ± 120 (AAR-2622-1.2)	11,640†	9700 ± 130 (AAR 2622-1.1)	−21.2	--	--
HV95-1,2	1241.5	6050 ± 90(m) (AAR-2624-2)	8170 ± 100(m) (AAR-2624)	--	--	--	--
	1324.5	--	--	9230 ± 75 (AAR-2626)	−24.8	--	--
HV-95-1,3	1609.5	8670 ± 120 (AAR-2627-1)	--	--	--	--	--
	1670.5	9330 ± 130 (AAR-2628-1)	--	--	--	--	--
	1730.5	8990 ± 190 (AAR-2629-1)	--	--	--	--	--
	1810.5	10,420 ± 140 (AAR-2630-1)	--	--	--	--	--
HV-95-1,4	1896	6760 ± 100 (AAR-2797)	--	--	−23.2	--	--
	1898	12,420 ± 240 (AAR-2799)	--	--	−21.9	10,070 ± 75 (AAR-2798) (f)	−1.16
	1918	--	--	--	--	10,110 ± 130 (AAR-3565) (s)	−0.64
	2033	--	--	--	--	10,640 ± 80 (AAR-3566) (s)	−1.05
	2056	--	--	--	--	10,480 ± 140 (AAR-2927) (s)	--
	2089	7660 ± 150 (AAR-2928-1)	--	--	--	10,690 ± 140 (AAR-2928-2) (f)	--

*Marine carbonate ^{14}C ages have not been corrected for the reservoir age.
†Estimated after measurements on upper layer and mixed layers.

The ^{14}C ages of the organic fraction of the bulk sediment samples from the marine section of the core (Table 1) range from 6050 BP to 12,420 BP. In the three cases in which we were able to measure separately the ages of both fractions that formed during pretreatment, the denser component was found to be older by (respectively) 500, 2000 and 3000 yr.

We found shell fragments at only three locations in that part of the core below 18.95 m. In addition, sufficient foraminifera for dating were only present in two further adjacent samples (Table 1). Their dates, which range from 10,070 to 10,690 BP, lie broadly in a conformable sequence and are also consistent with the position in the core of the well-dated Vedde ash (10,300 BP (Bard *et al.* 1994)) at 20.88 m.

Where there was enough material the $\delta^{13}C$ values of the organic fractions were measured. We obtained normal values for terrestrial C_3 plants (−21.2 to −24.8‰). The $\delta^{13}C$ results for the foraminifera and molluscs range from −0.4 to −1.2‰.

Figure 4 shows the age profile for the Hestvatn sequence, in which only the ages of the less dense component of the bulk sediment samples are used. We have also omitted dates from material taken from the top section of each segment of the core, which we suspect became contaminated during the coring process. We suggest that the age of the less dense component is closer to the "true" age of the sediment and that the denser material that separated during centrifuging represents some older, more mineralized plant or other remains washed into the lake or marine environment.

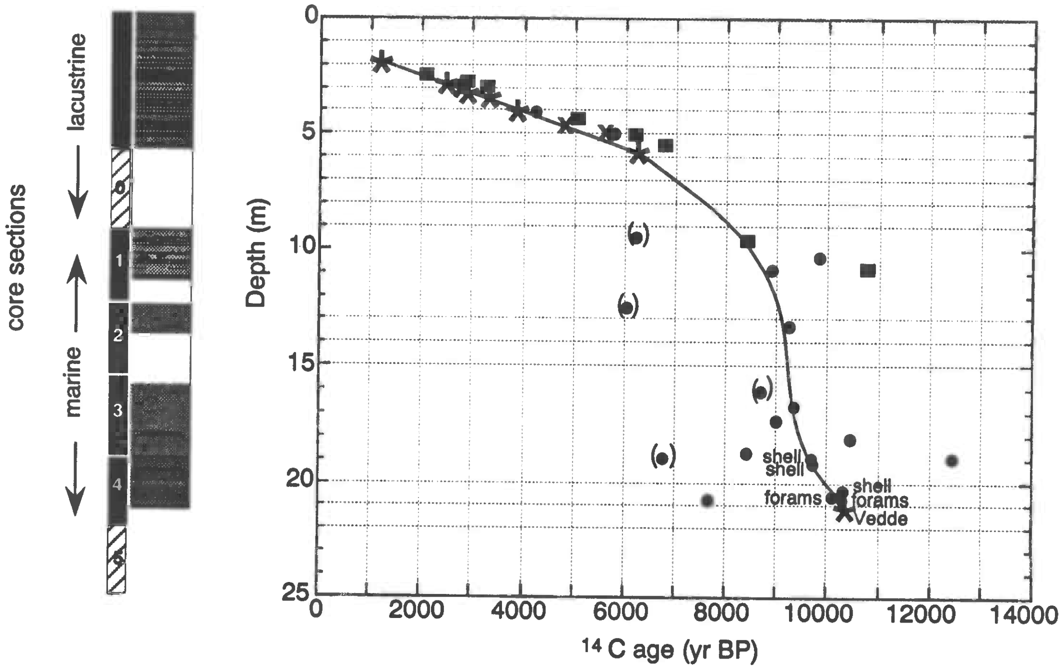

Fig. 4. Age-depth curve for the Hestvatn. In our model we use the younger ages for the bulk sediment samples (see text), omitting however the dates at the top of the core that we suggest are contaminated with younger sediments. An additional point in our age-depth curve is provided by the microprobe identification of Vedde Ash grains. The ^{14}C age of the Vedde Ash is 10,300 BP (Bard *et al.* 1994), which corresponds well with the dates in the lowermost part of our section. The marine carbonate ^{14}C ages have been corrected for the reservoir age of 400 yr. (●) = uppermost samples from core sections; other symbols as in Fig. 3.

DISCUSSION

The nonhomogeneity of organic material we report here for the Hestvatn sediment sequence has not been noted earlier in Iceland, where in general the ^{14}C method has been used successfully to date lake sediments. For example, dates from the thick lacustrine sedimentary sequences exposed in the Ófærugil ravine, situated west of the volcano Hekla, *ca.* 40 km east of Hestvatn (Fig. 1) yield ages in the range 3830 ± 50 to 8980 ± 190 (Jóhannesson, Grönvold and Sveinbjörnsdóttir 1994). No difference in ^{14}C age between the humic fraction and the plant macrofossils was detected in any of the samples analyzed. The dates were also consistent with the local tephrochronology. Another example of successful ^{14}C dating of Icelandic lake sediments is given by Björck *et al.* (1992), who report six ^{14}C ages of bulk sediment samples giving fairly consistent results, also agreeing with previously known tephrochronology. They also reported a transition from glacial facies with high sedimentation to postglacial conditions with reduced accumulation.

The nonhomogeneity of the organic material is consistent with pollen analyses of the sediments, which revealed a high percentage of corroded *Betula* pollen (9–25%; Geirsdóttir *et al.* 1995), indicating reworking.

The age diversity may to some extent be explained by the large drainage area of the lake, from which plant remains of different ages have been washed into the lake. It is, however, also possible that the high ages reflect geothermal influences, as today warm springs are located at the northern shore of the lake. The catchment area is also close to the volcanic zone of the southern lowlands where geothermal activity is widespread. Sveinbjörnsdóttir *et al.* (1992) report an age excess of up to 8 ka for aquatic plants living in geothermal water, whereas terrestrial plants living close to boiling geothermal springs were unaffected by the geothermal activity.

The bottom part of our age-depth curve is fixed by the five results obtained from shells and foraminifera from the narrow interval 10,070 to 10,690 BP. An additional point is provided by the microprobe identification of Vedde Ash grains in this part of the core (Karl Grönvold, personal communication). The age of the Vedde Ash (10,300 BP; Bard *et al.* 1994) corresponds well with the dates obtained on the carbonate samples using a reservoir correction of 400 yr. However, Bard *et al.* (1994) estimated the atmosphere-sea surface ^{14}C difference at the time of the Vedde event to be *ca.* 700–800 yr. This difference in reservoir age may indicate that the seawater environment at the Hestvatn site was not fully marine, in agreement with the low δ^{13}C results of the foraminifera and molluscs (Table 1).

According to our age-depth model, the transition from marine to lacustrine sediments occurs at 8700 BP (Fig. 4). The lower marine part of the Hestvatn sequence exhibits several abrupt changes in lithology between massive mud and sand. The latter includes high concentrations of volcanic glass and probably accumulated during very short periods, possibly during jökulhlaup events (Harðardóttir, Geirsdóttir and Sveinbjörnsdóttir 1996). Evidence of such episodes is abundant in terrestrial sections dating from deglacial times *ca.* 20 km west of the lake (Geirsdóttir, Harðardóttir and Eiríksson 1997).

CONCLUSION

1. The ^{14}C dating of the Hestvatn lacustrine and marine sediments shows a great variation in ^{14}C ages detected within the organic part of the bulk sediment samples. However, if the dense fraction of the organic sample is excluded, we obtain a consistent age model without inversions. We emphasize the importance of measuring separately the ^{14}C age of all fractions if the bulk sediment sample

fractionates under the pretreatment procedure. The less dense fraction of the Hestvatn bulk sediment samples gives ^{14}C ages closest to the "true" age of the sediment.

2. Dates from molluscs and foraminifera indicate that they are deposited *in situ* within the Hestvatn sediments and give very important reference points at the bottom part of our age-depth curve. The ^{14}C ages are consistent with a 400-yr reservoir age.

3. According to our age-depth curve, the boundary between marine and lacustrine sediments occurs at *ca.* 8700 BP.

4. The bottom part of our age-depth curve (22–12 m; 10,300–9100 BP) accumulated at a rate of *ca.* 1 m 100 a^{-1}, whereas the uppermost part of the marine sequence (9100–8700 BP) was deposited more rapidly, at *ca.* 1.75 m a^{-1}

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