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AMS ^{14}C DATING ON THE FOSSVOGUR SEDIMENTS, ICELAND

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ABSTRACT. Several new AMS ^{14}C dates on shells from the Fossvogur sea sediments in southern Iceland are reported. Up till now, researchers have assumed that the Fossvogur sediments formed during the last interglacial period (Eem), some 100,000 years ago. However, a recent ^{14}C determination from this location yielded an age of ca 11,000 yr. Because of the importance of these sediments for the Quaternary chronology of Iceland, further sampling for ^{14}C dating was subsequently initiated. The present results on several shell samples collected from the Fossvogur layers strongly indicate that these sediments were formed during the warm Allerød period toward the end of the last glaciation.

INTRODUCTION

Great variation in geologic stratigraphy has made Reykjavík, the capital city of Iceland, one of the best known localities reflecting the uppermost Quaternary chronology of Iceland. Most of the area is covered by basaltic lavas (Reykjavík olivine basalt) generally believed to have formed during the Holstein interglacial, some 300,000 years ago (Jónsson, 1973) (Figs 1 & 2). This lava overlies the Elliđavogur sediments, which have also been assumed to have formed during the Holstein period (Einarsson, 1968). The Fossvogur sediments are considerably younger. In his pioneering work, Pjeturss (1904) first suggested that the Fossvogur layers were formed in an interglacial period during the Pleistocene. Since then, it has been assumed that these layers were from the beginning of the last interglacial period, Eem, and therefore, ca 100,000 to 120,000 years old. This age was not questioned as the sediments are very hard with carbonate fillings in fissures and cavities and some of the shells contain calcite precipitates. Further, moraine and glacial striations on top of the sediments indicate reglaciation after the formation of the sediments. These observations and the fact that the cold Older Dryas stage (12,000 BP) is well established in Scandinavia, have labeled the Álftanes end moraine, the outermost moraine in the Reykjavík district, the *locus typicus* for the Older Dryas stage in Iceland (Einarsson, 1968).

The first ^{14}C date on shells from the Fossvogur sediments was Lu-2599: 11,530 ± 100 BP (Hjartarson, 1987; Håkansson, 1987). This unexpected result was questioned by some who claimed that a single ^{14}C result was not reliable. Because of the importance of these sediments for the Quaternary chronology of Iceland, further sampling for ^{14}C dating was subsequently initiated.

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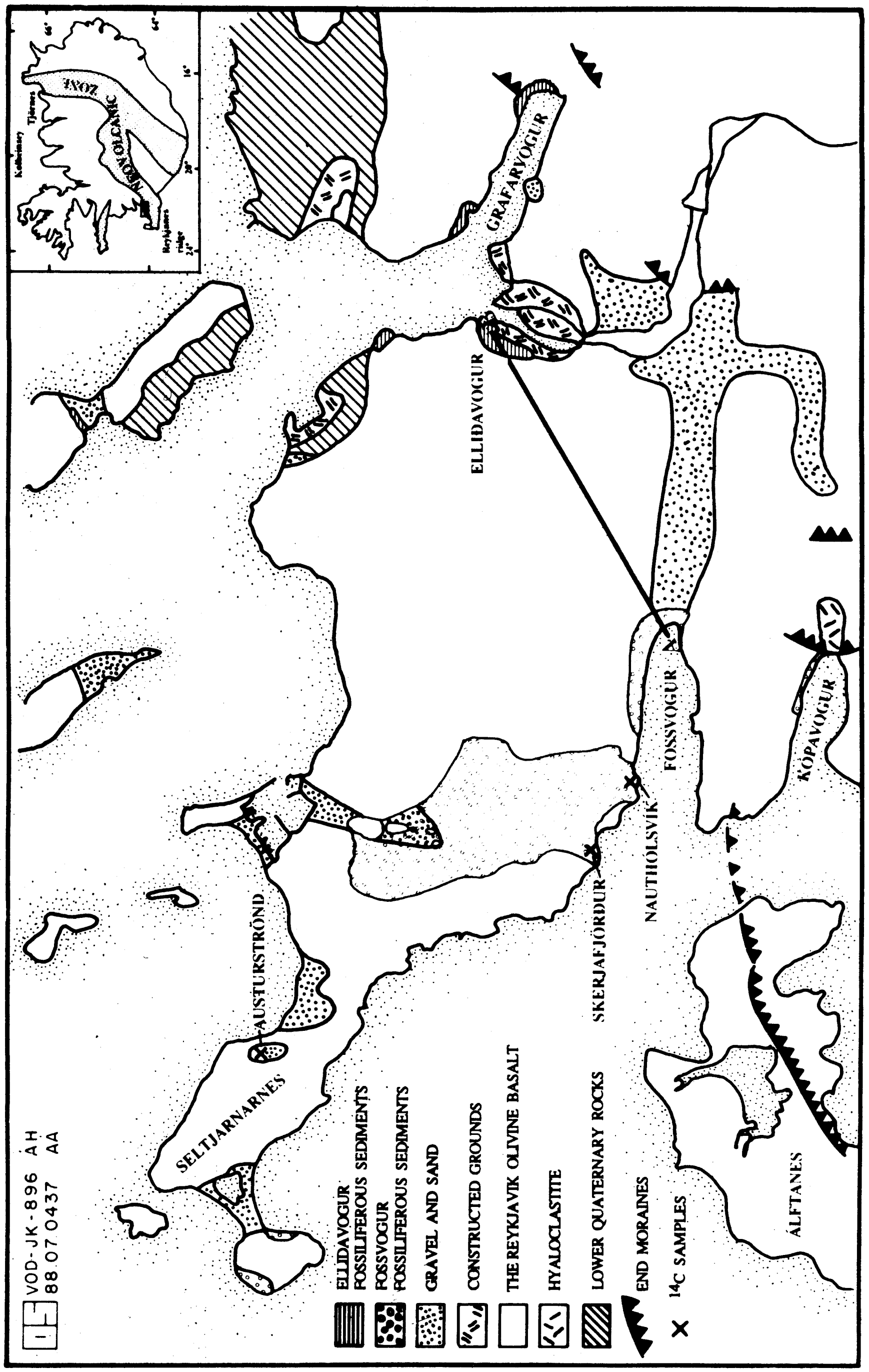

Fig. 1. Geologic map of the Reykjavík district, Iceland. A-B, see Fig 2.

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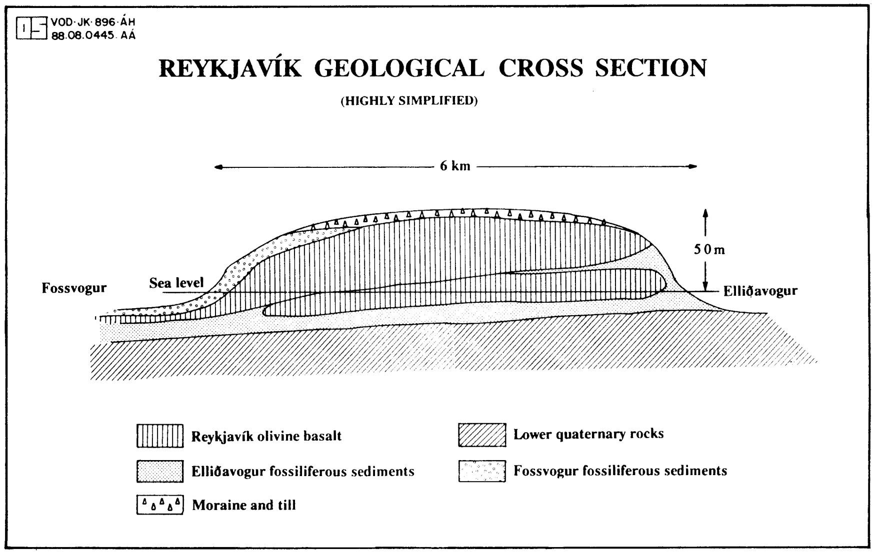

Fig 2. Highly simplified cross-section (A-B Fig 1), showing the Fossvogur fossiliferous layers in relation to the main stratigraphic units in the Reykjavík area

SAMPLE COLLECTION

The Fossvogur layers are generally 3 to 4m thick, and they cover ca 2km of the coast south of Reykjavík. Similar layers are also found in Kópavogur, Seltjarnarnes and Grafarvogur (Fig 1) (Hjartarson & Guðjónsson, 1984). Both coastal-marine and glacial formations occur in the sediments, according to Geirsdóttir (1979), who has studied the sedimentology of the Fossvogur layers. Nineteen species of shells have been identified in the sediments, all of which presently live around Iceland, indicating a similar sea temperature at the time of formation (Einarsson, 1968).

Nine *in situ* mollusk samples *(Mya truncata* L) were collected and analyzed for ^{14}C and $\delta^{13}C$ (6 from Skerjafjördur and 3 from Nauthólsvík). The Nauthólsvík samples (AAR-2 and AAR-12) were collected from the Fossvogur layers, just above the beach in Nauthólsvík at ca 3m asl. The shells were small and thin; a thicker shell collected from a tephra layer at 2m asl, ca 50m west of AAR-2 and AAR-12 represents the third Nauthólsvík sample (AAR-13). The Skerjafjördur samples were collected from the Fossvogur layers where these emerge on the beach as a shell-rich and very hard layer at 0m asl, ca 700m west of the sampling site in Nauthólsvík. One sample *(Mya truncata* L) was taken at Austurströnd, Seltjarnarnes from a shell-rich sand and gravel layer (8m asl), which directly overlies the Reykjavík olivine basalt.

MEASUREMENTS

The samples were ^{14}C dated at the accelerator mass spectrometry facility at the University of Aarhus, Denmark where the system was developed and applied to measurements of ^{14}C and the relatively short-lived radionuclides ^{22}Na, ^{24}Na, ^{31}Si and ^{32}Si (Heinemeier *et al,* 1987; Thomsen *et al,* 1987; Thomsen *et al,* 1988).

The following sample preparation procedure was applied: the outer 20–30% of the shell carbonate was removed with 1N HCl; the samples were then heated in demineralized water at 90°C overnight to remove organic particles (Mook & Streurman, 1983). CO_2 was evolved by treatment with 85% phosphoric acid under vacuum. For some of the samples, the released CO_2 was separated into two fractions corresponding to the inner and outer part of the shell to provide an indication of possible contamination (Mangerud, 1972). The CO_2 was then converted to ca 1mg graphite using a cobalt catalyst (Vogel *et al,* 1984).

The ion source which is used for ^{14}C dating is a new version of the ANIS sputter ion source (Thomsen *et al,* 1988) with a sample wheel which holds eight cathodes. The switching between samples in the wheel is done in a few seconds via the computer which controls the tandem accelerator. These graphite targets yielded $^{12}C^-$ negative ion intensities of 5–10μA. To avoid loading of the accelerator when the most abundant carbon istope ^{12}C is injected, a pulsed electrostatic deflector at the LE end of the accelerator is activated during the measurements of ^{12}C, reducing the intensity of this isotope by two orders of magnitude.

In the ^{14}C dating experiments, all the dipole and quadrupole magnetic fields on the tandem accelerator system are switched, under computer control, to allow for ^{12}C, ^{13}C and ^{14}C sequential measurements at the target position at the end of the dating beam line (Heinemeier *et al,* 1986). Since no attenuation is applied to ^{13}C, this isotope is expected to be measured with slightly higher precision than ^{12}C. Therefore, the measured ratio between ^{14}C and ^{13}C is used in the age calculation for the sample by comparison with a known standard, whereas, at present, the ratio $^{13}C/^{12}C$ is used only to monitor the performance of the AMS system.

The standard samples were prepared from the old NBS oxalic acid standard. Samples prepared from Icelandic Double Spar (ca 15Myr old) were used as ^{14}C blanks to measure the ^{14}C background from the accelerator and the graphitization process. For the three-day measurements, the background remained constant with a $^{14}C/^{13}C$ ratio of 3‰ relative to the modern standard, corresponding to a ^{14}C age of 46,000 BP. Figure 3 shows $^{14}C/^{13}C$ ratios measured in 5 runs on the oxalic acid standard and 10 runs on different Icelandic shell samples of unknown age. Since the two isotopes are not measured simultaneously, the ratios are corrected for small variations in ion source output by interpolation. The $^{14}C/^{13}C$ ratio for the standard remains constant within statistical uncertainty and the ages of the different shell samples (derived from $^{14}C/^{13}C$ ratios) are identical within experimental errors. The relative $^{13}C/^{12}C$ ratios agreed with those measured by conventional mass spectrometry to an accuracy which allows us to use the statistical uncertainty from the ^{14}C counting as a measure of the error in the age determination.

Age calculation is done after Stuiver and Polach (1977), but, as we use the $^{14}C/^{13}C$ rather than the $^{14}C/^{12}C$ ratio in our calculation, their expression is rewritten as:

$$T_s = -8033 \cdot \ln\left\{\frac{(^{14}C/^{13}C)_s(^{13}C/^{12}C)_s}{0.95(^{14}C/^{13}C)_{ox}(^{13}C/^{12}C)_{ox}}\left(\frac{1-0.025}{1-0.019}\right)^2\left(\frac{1+\delta^{13}C_{ox}/1000}{1+\delta^{13}C_s/1000}\right)^2\right\}$$

which to first order may be reduced to:

$$T_s = -8033 \cdot \ln\left\{\frac{(^{14}C/^{13}C)_s}{0.95\ (^{14}C/^{13}C)_{ox}}(1-[\delta^{13}C_s-\delta^{13}C_{ox}+12]\cdot 10^{-3})\right\}$$

where ox refers to the oxalic acid standard and ($^{14}C/^{13}C$) to the background corrected ratios.

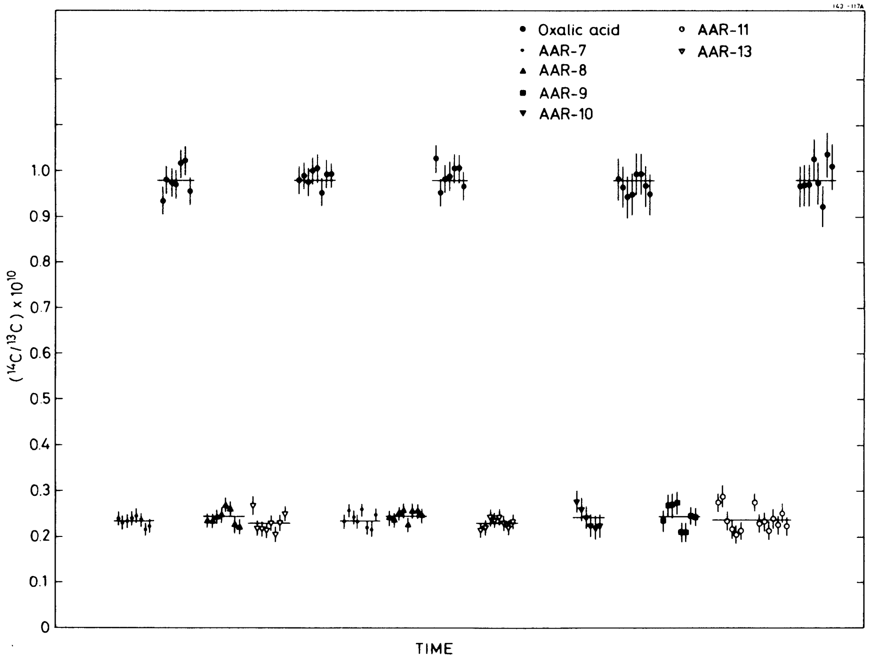

Fig 3. $^{14}C/^{13}C$ ratios measured in 5 runs on the oxalic acid standard and 10 runs on different shell samples. The $^{14}C/^{13}C$ ratio for the standard is constant within the statistical uncertainty and the isotopic ratio for the different shell samples are identical within the experimental errors.

Table 1 lists the conventional ^{14}C ages of the samples, some of which were divided into outer and inner fractions. Table 1 also includes $\delta^{13}C$ values, measured by conventional mass spectrometry at the Science Institute, University of Iceland.

TABLE 1

^{14}C and $\delta^{13}C$ determinations for samples from Reykjavík, Iceland

Sample	Location	Fraction	Age (BP)	$\delta^{13}C$ (‰ PDB)
AAR-2A		Outer	12,360±330	
AAR-2B		Inner	11,840±210	1.67
AAR-2C	Nauthólsvík	Inner	11,800±150	
AAR-12			11,330±140	1.28
AAR-13			11,580±150	0.88
AAR-6			11,400±160	1.74
AAR-7			11,380±140	2.29
AAR-8	Skerjafjördur		11,130±120	0.74
AAR-9			11,190±270	2.01
AAR-10			11,170±330	2.83
AAR-11			11,320±180	2.27
AAR-3A	Austurströnd	Outer	10,290±210	1.49
AAR-3B		Inner	10,180±150	

DISCUSSION

Conventional ^{14}C ages given in Table 1 need to be corrected for the reservoir effect of sea water, which causes marine mollusks to appear older than contemporary terrestrial material (Mangerud, 1972). The reservoir age of the coastal waters of SW Iceland has been calculated on recent shells (Lu-2006, -2009, -2010) (Håkansson, 1983) to yield a mean reservoir age of 375 ± 25 yr. Håkansson (1983) also calculated reservoir ages from previously published activity values for recent mollusks from Iceland. Broecker & Olson (1961) measured three samples (L-576C, -576H, -576I), with values of 500 ± 35 yr. Krog and Tauber (1973) found a reservoir age of 330 ± 60 yr for SW Iceland (K-330). In the following, we use a reservoir age of 400 yr for SW Iceland, assuming the same seawater reservoir age for the end of Pleistocene and today. When this correction is applied to Table 1, the Nauthólsvík and Skerjafjördur samples date to ca 11,000 BP, whereas the Austurströnd sample dates to 9800 BP. In agreement with Hjartarson (1987), this suggests that the Fossvogur sediments were not formed during the Eem, but toward the end of the Pleistocene.

Glacial striations and moraine on top of the layers indicate that the sediments formed prior to a cold period. Also, all the subfossiliferous species identified in the sediments live around Iceland today, suggesting similar sea temperatures. A comparison has been made with former estimates of temperature variations towards the end of the Pleistocene to determine if the ^{14}C dates agree with earlier paleoclimatic studies.

For several decades, studies of $\delta^{18}O$ variations in glacial ice cores have led to the establishment of past and present climate conditions (Paterson & Hammer, 1987), as $\delta^{18}O$ is strongly temperature-dependent; it is depleted during cold and enriched during warm periods. Seasonal variation in $\delta^{18}O$ is preserved in Greenland ice for thousands of years, and thus, alternating warm and cold periods during the Pleistocene in the Northern Hemisphere are well established. Figure 4 shows the $\delta^{18}O$ profile of lime sediments from

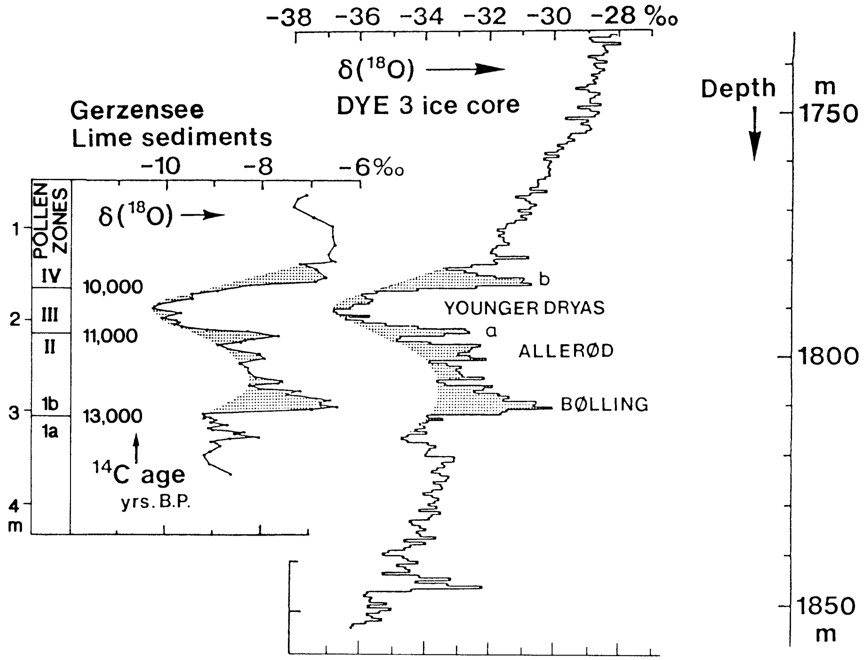

Fig 4. $\delta^{18}O$ profiles of lime sediments, from Lake Gerzensee, Switzerland (Eicher, 1980), and of an ice core drilled at Dye 3 in southern Greenland (Dansgaard *et al,* 1985). The profiles show climate variations at the end of the Pleistocene and into postglacial time. a) ^{14}C dates of the Skerjafjördur and Nauthólsvík samples; b) ^{14}C age of the Austurströnd sample on the ^{14}C time scale of the Lake Gerzensee profile, based on measurements on pollen zones (Wegmüller & Welten, 1973; Oeschger *et al,* 1984).

Lake Gerzensee in the pre-Alpine region of Switzerland (Eicher, 1980), and from the Greenland ice core, drilled at Dye 3 in southern Greenland (Dansgaard *et al,* 1985). The profiles demonstrate the climate variations during the end of the Pleistocene into postglacial time. Both profiles show interstadial oscillations Bølling/Older Dryas/Allerød (Older Dryas is not very distinct here). Younger Dryas, the last glacial advance, is very well established on both profiles. These data suggest that the climate variations were identical in Europe and thus can be applied to Iceland. According to ^{14}C dating of pollen zones, the beginning of Bølling is 13,000 BP and the end of the cold phase, Younger Dryas, is 10,000 BP (Eicher & Siegenthaler, 1976; Oeschger *et al,* 1984). Figure 4 shows that the Skerjafjördur and Nauthólsvík samples (a) originate from the end of Allerød, which according to Wegmüller and Welten (1973) is at ca 11,000 BP. Consequently, the moraines on top of the Fossvogur sediments formed during the cold younger Dryas stage, whereas the Austurströnd, Seltjarnarnes sample (b) formed during the mild climatic conditions after Younger Dryas. These results suggest that the Álftanes end moraine, hitherto assumed to be the *locus typicus* for Older Dryas, in fact originates from the cold period (Fig 4) shortly after the end of Younger Dryas.

We conclude that the Fossvogur sediments were not formed during the last interglacial period, Eem (120,000 BP), but at 11,000 BP, during the end of Allerød. This leads to a revision of the late Pleistocene time scale of the Reykjavík district and indicates more extensive glaciation of that area at the very end of the Pleistocene than earlier assumed.

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REFERENCES

Broecker, WS and Olson, EA, 1961, Lamont radiocarbon measurements VIII: Radiocarbon, v 3, p 176–204.

Dansgaard, W, Clausen, HB, Gundestrup, N and Johnsen, S, 1985, Dating and climatic interpretation of two deep Greenland ice cores, *in* Langway, CC, Oeschger, H and Dansgaard, W, eds, Greenland ice core: Geophysics, geochemistry and the environment: Am Geophys Union, Geophys Mono 33, Climate processes and climate sensitivity (Maurice Ewing ser), p 71–76.

Eicher, U, 1980, Pollen- und Sauerstoffisotopenanalysen an spätglazialen Profilen vom Gerzensee, Faulenseemoss und vom Regenmoos ob Boltigen: Mitt Naturforsch Ges in Bern, v 37, p 65–80.

Eicher, U and Siegenthaler, U, 1976, Palynological and oxygen isotope investigations on Late-Glacial sediment cores from Swiss lakes: Boreas, v 5, p 109–117.

Einarsson, Th, 1968, Jarđfraeđi. Saga bergs of lands: Reykjavík, Heimskringla, 335 p (in Icelandic).

Geirsdóttir, Á, 1979, Fossvogslögin: BSc thesis, Univ Iceland, 72 p (in Icelandic).

Heinemeier, J, Hornshøj, P, Larsen, G, Nielsen, HL, Olesen, S, Rud, N, Stensgaard, R and Thomsen, MS, 1986, Accelerator mass spectrometry at Aarhus, *in* Hedges, REM and Hall, ET, eds, Proc AMS Workshop: Oxford Research Lab Archaeol, p 53–59.

Heinemeier, J, Hornshøj, P, Nielsen, HL, Rud, N and Thomsen, MS, 1987, Accelerator mass spectrometry applied to $^{22,24}Na$, $^{31,32}Si$, and ^{14}C: Nuclear Instruments & Methods, v B29, p 110–113.

Hjartarson, Á, 1987, Chronology of the glacial history of the Reykjavík area, *in* Conference on the Late Glacial history of Iceland, Proc, Reykjavík April 28, 1987: Geol Soc Iceland, p 4–5 (in Icelandic).

Hjartarson, Á and Guđjónsson, S, 1984, Reykjavíkurhöfn. Jarđfraeđi vid Sundin bla: Natl Energy Authority, internal rept OS-84034/VOD-04, 35 p (in Icelandic).
Håkansson, S, 1983, A reservoir age for the coastal waters of Iceland: Geol Fören Stockh Förh, v 105, p 64–67.
Håkansson, S, 1987, University of Lund radiocarbon dates XX: Radiocarbon, v 29, no.3, p 353–379.
Jónsson, J, 1973, Grágrýtiđ: Náttúrufr, v 42, p 21–30 (in Icelandic).
Krog, H and Tauber, H, 1973, C-14 chronology of Late- and Postglacial marine deposits in North Jutland: Denm Geol Survey Yearbook, p 93–105.
Mangerud, J, 1972, Radiocarbon dating of marine shells, including a discussion of apparent age of Recent shells from Norway: Boreas, v 2, p 143–172.
Mook, WG and Streurman, HJ, 1983, Physical and chemical aspects of radiocarbon dating: PACT, no. 8, Strassbourg, p 31–55.
Oeschger, H, Beer, J, Siegenthaler, U, Stauffer, B, Dansgaard, W and Langway, CC, 1984, Late glacial climate history from ice cores: Am Geophys Union Mono 29, p 299.
Paterson, WSB and Hammer, CU, 1987, Ice core and other glaciological data, *in* North America and adjacent oceans during the last deglaciation, The geology of North America: Geol Soc America, v K-3, p 91–109.
Pjeturss, H, 1904, Athugasemd um jarđlög í Fossvogi og vàđar à nágrenni Reykjavàkur: Tàmarit àsl Bókmenntafélagsins, v 25, p 49–57.
Stuiver, M and Polach, HA, 1977, Discussion: Reporting of ^{14}C data: Radiocarbon, v 19, no. 3, p 355–363.
Thomsen, MS, Heinemeier, J, Hornshøj, P and Rud, N, 1987, Isotopic ratio of $^{22,24}Na$ measured by accelerator mass spectrometry: Nuclear Instruments & Methods, v B28, p 433–437.
Thomsen, MS, Heinemeier, J, Hornshøj, P, Nielsen, HL and Rud, N, 1988, Accelerator mass spectrometry applied to ^{32}Si: Nuclear Instruments & Methods, v B31, p 425–432.
Wegmüller, S and Welten, M, 1973, Spätglaziale Bimstufflagen des Laacher Vulkanismus im Gebiet der westlichen Schweiz und der Dauphiné (F): Eclogae geol Helv, v 66, p 533–541.
Vogel, JS, Southon, JR, Nelson, DE and Brown, TA, 1984, Performance of catalytically condensed graphite for use in accelerator mass spectrometry: Nuclear Instruments & Methods, v B5, p 289–293.