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New Radiocarbon Dates for the Vedde Ash and the Saksunarvatn Ash from Western Norway

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The Vedde Ash Bed (mid-Younger Dryas) and the Saksunarvatn Ash (early Holocene) are important regional stratigraphic event markers in the North Atlantic, the Norwegian Sea, and the adjacent land area. It is thus essential to date them as precisely as possible. The occurrence of the Saksunarvatn Ash is reported for the first time from western Norway, and both tephras are dated precisely by AMS analyses of terrestrial plant material and lake sediment at Kråkenes. The Vedde Ash has been previously dated at sites in western Norway to about 10,600 yr B.P. It is obvious in the Younger Dryas sediments at Kråkenes, and its identity is confirmed geochemically. The mean of four AMS dates of samples of *Salix herbacea* leaves adjacent to the tephra is 10,310 ± 50 yr B.P. The Saksunarvatn Ash is not visible in the early Holocene lake sediment at Kråkenes. After removal of organic material and diatoms, the identity of the tephra particles was confirmed geochemically, and their stratigraphic concentration was estimated. From curve matching of a series of seven AMS dates of terrestrial plant macrofossils and whole sediment, the radiocarbon age of the ash is 8930–9060 yr B.P., corresponding to an age of 9930–10,010 cal yr B.P. (7980–8060 cal yr B.C.).

INTRODUCTION

The Vedde Ash, (mid-Younger Dryas; Mangerud *et al.,* 1984), correlated with Ash Zone I in the North Atlantic (Ruddiman and McIntyre, 1981), and the early Holocene Saksunarvatn Ash (Mangerud *et al.,* 1986) are widespread in the North Atlantic–Norwegian Sea region (Fig. 1). Both originated in Iceland (Mangerud *et al.,* 1984, 1986; Kvamme *et al.,* 1989; Norddahl and Haflidason, 1992; Björck *et al.,* 1992; Lacasse *et al.,* 1995). Some of the Vedde Ash was transported on sea ice and only released and deposited when the ice melted (Ruddiman and McIntyre, 1981; Fillon *et al.,* 1991; Austin *et al.,* 1995). Thus the ash appears more widespread than its airborne plume (Fig. 1). The time lag between atmospheric and ice-rafted deposition is not considered significant within the available dating precision (Kvamme *et al.,* 1989).

The Saksunarvatn Ash, unlike the Vedde Ash, was not ice rafted and has a more restricted distribution (Fig. 1). It has been recorded in Iceland and the ocean to the northeast and east; in lake sediments on the Faeroe, Shetland, and Orkney Islands; in northern Germany; and in the Greenland ice sheet. We report the occurrence of the Saksunarvatn Ash for the first time from western Norway, at Kråkenes (Fig. 1).

The quoted ages of the two ashes currently rely mainly on conventional dates of bulk sediment samples from several sites, a few AMS dates of the Vedde Ash (e.g., Bard *et al.,* 1994) and Saksunarvatn Ash (e.g., Björck *et al.,* 1992; Ingólfsson *et al.,* 1995), and mean values for these dates (Table 1). As the Vedde and Saksunarvatn tephras are important regional stratigraphic event markers within the North

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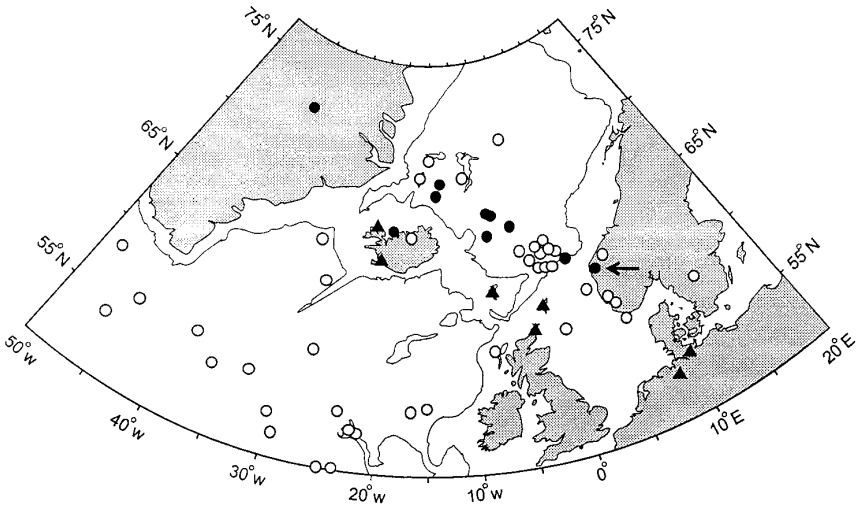

FIG. 1. Map of the North Atlantic ocean and northwestern Europe showing the known occurrence of the Vedde Ash and the Saksunarvatn Ash. ○, Vedde; ▲, Saksunarvatn; ●, both ashes together; —, 1000 m isobath. Kråkenes is indicated by the arrow. Sites for the Vedde Ash in the North Atlantic are taken from Ruddiman and Glover (1972), Ruddiman and McIntyre (1981), Kvamme *et al.* (1989), and Bard *et al.* (1994); in the Labrador Sea from Fillon *et al.* (1981) and Hillaire-Marcel *et al.* (1994); in the Norwegian–Greenland Sea from Sigurdsson and Loebner (1981), Sejrup *et al.*, (1989), Sjøholm *et al.*, (1991), Haflidason *et al.* (1990), Koç Karpuz and Jansen (1992), Koç *et al.* (1993), Schrader *et al.* (1993), and Haflidason (1994); on the adjacent land areas in Iceland from Björck *et al.* (1992) and Norddahl and Haflidason (1992); in western Norway from Mangerud *et al.* (1984); and in the Greenland ice sheet from Grønvold *et al.* (1995). Sites for the Saksunarvatn Ash in the North Atlantic are from Sjøholm *et al.* (1991), Haflidason *et al.* (1990), Koç Karpuz and Jansen (1992), and Haflidason *et al.* (1995); in Iceland from Björck *et al.* (1992), Sigurgeirsson and Leosson (1993), and Ingólfsson *et al.* (1995); in the Faeroe Islands from Jóhansen (1977) and Mangerud *et al.* (1986); in the Shetland Islands from Bennett *et al.* (1992); in the Orkney Islands from Bunting (1994); in Germany from Merkt *et al.* (1993); and in Greenland from Grønvold *et al.* (1995).

Atlantic region, it is essential that they be dated as precisely as possible. The lake sediments at Kråkenes permitted detailed sampling of terrestrial plant material across both tephra layers. The AMS dates obtained are the most precise age estimates currently available.

As the tephras have been found in both continental and marine sediments, they can be used to estimate the reservoir age of marine organisms by subtracting the terrestrial ^{14}C age from the marine ^{14}C age (Bard *et al.*, 1994; Haflidason, 1994; Austin *et al.*, 1995). These tephras can also now be

TABLE 1
Estimates of the Age of the Vedde Ash and the Saksunarvatn Ash in ^{14}C yr B.P.

Site	^{14}C age (yr B.P.)	Method of dating[a]	Reference
		Vedde Ash	
Kråkenes	10,310 ± 50	AMS, TPM (mean of 4)	This paper
Møre area, Norway	ca. 10,300	AMS, PM (mean of 2 sites)	Bard *et al.* (1994)
Møre and Hordaland, Norway	10,600 ± 60	Bulk sediment (mean of 4 sites)	Mangerud *et al.* (1984)
Southern Sweden	9945 ± 115	AMS, TPM	Wohlfarth *et al.* (1993)
		Saksunarvatn Ash	
Kråkenes	8930–9060	AMS, TPM, and sediment	This paper
Saksunarvatn, Faeroe Islands	9000–9100	Sedimentation rate between bulk dates	Mangerud *et al.* (1986)
Saksunarvatn, Faeroe Islands	9380 ± 130	Bulk sediment dates	Jóhansen (1977)
Northern Iceland	ca. 8900	Mean of AMS on sediment and mosses	Björck *et al.* (1992)
Southwest Iceland	ca. 9000	Conventional, TPM	Ingólfsson *et al.* (1995)
Shetland	ca. 9300	Sedimentation rate between bulk sediment dates	Bennett *et al.* (1992)
Northern Germany	ca. 8700	Pollen stratigraphy	Merkt *et al.* (1993)

[a] AMS, accelerator mass spectrometry ^{14}C date; TPM, terrestial plant material; PM, plant material.

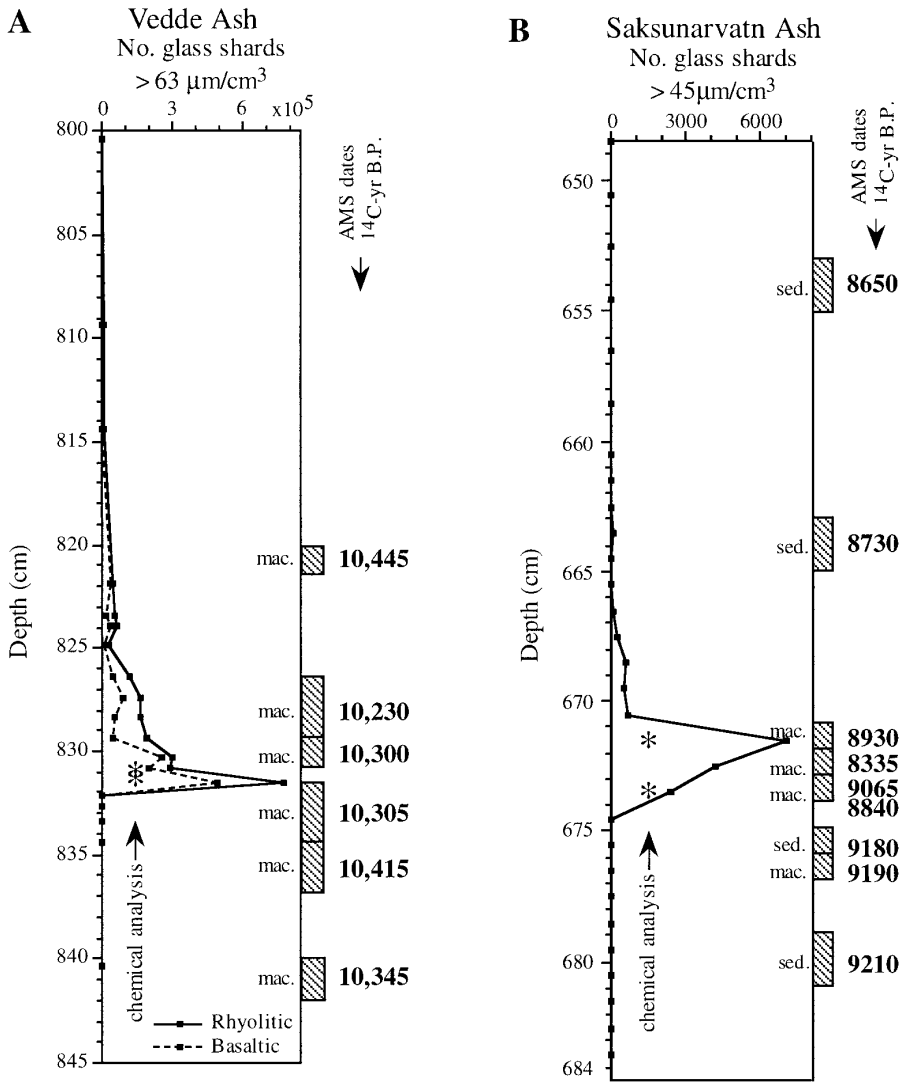

FIG. 2. Stratigraphic distribution of the Vedde (A) and Saksunarvatn (B) tephra particles at Kråkenes, together with the AMS radiocarbon dates associated with them; dates were obtained from terrestrial plant macrofossils (mac.) and bulk sediment samples (sed.).

used for comparing radiocarbon years and dendrochronologically calibrated radiocarbon years against the Swedish varve chronology (e.g., Wohlfarth *et al.,* 1993) and the GRIP ice-core chronology (Grønvold *et al.,* 1995).

CHARACTERIZATION OF THE TEPHRAS AT KRÅKENES

The Vedde Ash at Kråkenes

Kråkenes Lake lies at 38 m altitude on Vågsøy island, western Norway (Fig. 1). A Younger Dryas glacier in the lake's catchment led to the deposition of laminated lacustrine silts and sands (see Larsen *et al.* (1984) for further details). Sediment cores were taken from the southeast basin of the lake, where the silts are finer and mixed with terrestrial material, including plant macrofossils, derived largely from the steep slopes of the huge moraine to the south (Birks *et al.,* 1996).

The Vedde Ash Bed is visible in the middle of the Younger Dryas sequence (Mangerud *et al.,* 1984; Larsen *et al.,* 1984). It is a distinct layer about 0.5 cm thick, browner than the gray silts, and of a contrasting firm, coarse nature, with a sharp lower boundary. The morphology and color of the volcanic glass shards are typical of the Vedde Ash Bed, as described previously by Mangerud *et al.* (1984). The stratigraphic distribution of the tephra particles in the core was determined by examining the sand-size fraction ($\geqslant$63 μm) in a known volume of sediment under a stereo-micro-

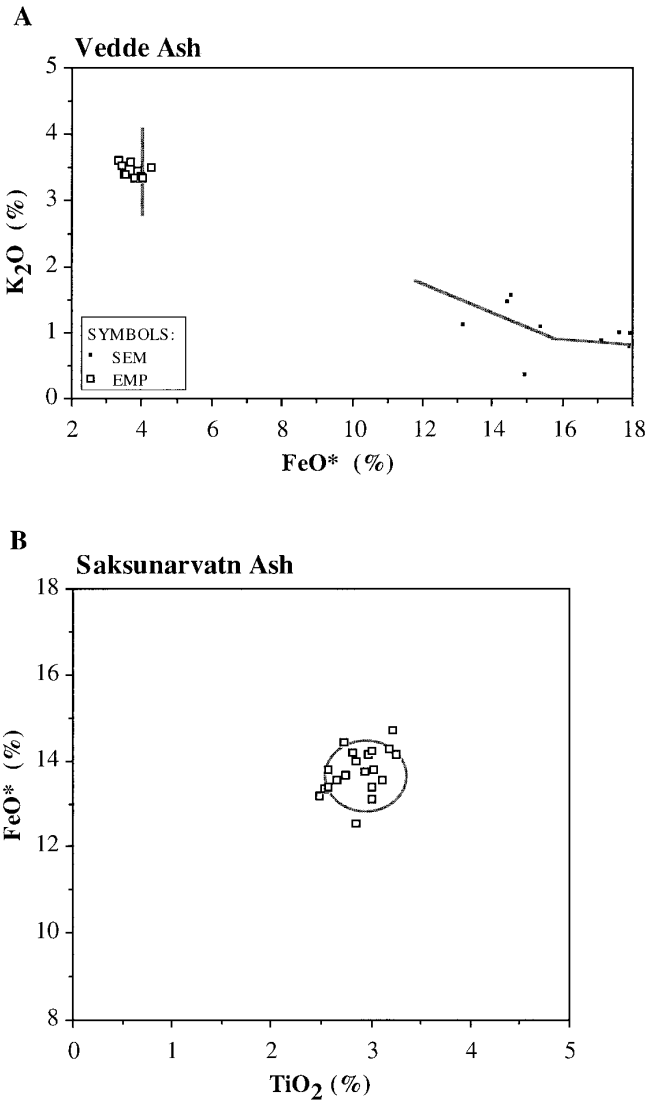

FIG. 3. Chemical characterization of the ashes at Kråkenes, using an electron microprobe (EMP) and a scanning electron microscope connected to an energy dispersive spectrometer (SEM). The analyses have been normalized to 100% by weight. The locations of the samples are shown in Figure 2. (A) Vedde Ash. Estimates of FeO* and K_2O. Lines show the highest frequency of distribution previously determined for the rhyolitic and basaltic-intermediate shards (Mangerud *et al.,* 1984; Kvamme *et al.,* 1989). (B) Saksunarvatn Ash. Estimates of FeO* and TiO_2. Circle is distribution of values determined for Saksunarvatn tephra particles from Saksunarvatn, Faeroe Islands (Mangerud *et al.,* 1986).

scope and estimating its concentration (Fig. 2A). The identity of the glass shards was also confirmed geochemically (Fig. 3A; Table 2).

The Saksunarvatn Ash at Kråkenes

The Holocene sediment at Kråkenes is fine diatom-rich organic mud (gyttja) (loss-on-ignition ca. 30%) produced within the lake, and with only a small component of inwashed terrestrial material. The Saksunarvatn Ash is not visible; to locate it, 1-cm-thick contiguous samples were taken from the core at a level estimated to date ca. 9000 yr B.P. The organic material was digested with H_2O_2, and the diatoms were removed by ultrasonic vibration. The concentration of the tephra particles was then estimated using a stereo-microscope (Fig. 2B), and they were characterized geochemically (Fig. 3B, Table 2).

RADIOCARBON DATING OF THE KRÅKENES TEPHRAS

Methods

During the entire Younger Dryas interval, quantities of *Salix herbacea* (dwarf willow) leaves from the adjacent slopes were washed into Kråkenes Lake along with minerogenic matter. The leaves are ideal material for AMS radiocarbon assay. Short segments of core (1–3 cm) adjacent to the Vedde Ash were suspended in water and washed over a sieve of 125 μm mesh. *S. herbacea* leaves were picked out under a stereo-microscope, cleaned of silt and other contamination, and air-dried. They were radiocarbon dated at Uppsala (Figs. 2A and 4; Table 3).

Remains of terrestrial plants in the early Holocene sediment are rare. Coarse material was sieved out of contiguous samples 1 cm thick, as above. Identified plant remains of various taxa of undoubted terrestrial origin (Table 3) were extracted and air-dried immediately. There were such small amounts of identifiable material in some of the samples that samples of whole sediment were taken in addition (Figs. 2B and 5). All the samples were dated at Trondheim and Uppsala (Table 3).

Terrestrial plant macrofossils were pretreated according to the standard acid–alkali–acid procedure in order to eliminate carbonates from any sediment matrix, absorbed recent atmospheric CO_2, and humics. The soluble humic fraction was extracted from the sediment samples by hot NaOH and precipitated with concentrated HCl. The CO_2 obtained by combustion with CuO (800°C, 5 min) was catalytically (Fe) converted to graphite (Hut *et al.,* 1986). Three of the sediment samples (TUa-1006A, 1007A, 1008A) were originally intended to be dated conventionally and were combusted in a flow system used for large samples. However, due to the low carbon content, these samples were also graphitized and measured by the AMS technique. The relatively large dating uncertainties for these samples (Table 3) are caused by combustion contamination correction.

The AMS measurements were performed with the Uppsala EN-tandem accelerator (Possnert, 1990). A small fraction of the CO_2 gas was used for determination of the natural mass fractionation, $\delta^{13}C$, by conventional mass spectrometry

TABLE 2

Major Element Chemical Analysis of Volcanic Glass Shards from Kråkenes at Two Depth Intervals

Sample No.	SiO_2	TiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	Total
				Saksunarvatn Ash (673.5 cm) (EMP)						
1	49.98	2.67	12.59	14.18	0.20	5.11	10.05	2.94	0.49	98.23
2	50.00	3.07	12.58	13.33	0.19	5.31	10.79	2.66	0.41	98.33
3	50.67	2.80	11.75	13.13	0.23	4.74	9.50	2.30	0.45	95.57
4	50.43	2.52	13.19	13.30	0.17	5.97	11.00	2.62	0.37	99.57
5	49.30	2.58	12.66	13.18	0.15	6.02	10.56	2.75	0.24	97.43
6	49.75	2.94	12.63	13.95	0.24	5.26	9.89	2.94	0.46	98.06
7	50.10	2.93	12.65	13.37	0.21	4.84	9.79	2.75	0.44	97.08
9	50.46	2.82	12.83	12.35	0.23	5.90	10.73	2.92	0.39	98.64
10	48.74	2.50	12.96	13.05	0.24	6.31	10.75	2.61	0.41	97.57
11	49.94	3.12	12.04	14.28	0.16	5.15	9.62	2.33	0.51	97.15
12	49.22	2.48	12.47	13.34	0.21	5.92	10.04	2.66	0.37	96.71
13	49.31	2.66	12.79	13.29	0.23	5.75	10.09	2.72	0.38	97.21
14	49.73	2.92	12.74	13.03	0.30	5.40	10.04	2.72	0.48	97.35
15	49.38	2.87	12.41	13.63	0.17	5.19	9.78	2.63	0.42	96.48
16	50.23	3.15	12.68	14.07	0.08	5.27	10.18	2.54	0.43	98.62
17	50.85	2.83	13.19	13.85	0.24	4.89	9.64	3.14	0.54	99.16
18	48.31	2.92	11.14	12.80	0.25	8.30	11.27	2..20	0.31	97.51
19	48.63	2.72	12.65	13.65	0.14	5.57	9.96	2.47	0.50	96.28
20	49.82	2.44	12.80	12.97	0.21	6.24	10.99	2.58	0.32	98.36
23	49.80	3.17	12.57	13.79	0.33	5.05	9.77	2.47	0.52	97.45
				Vedde Ash (831.5 cm) (EMP)						
80	70.98	0.32	13.13	3.64	0.25	0.16	1.48	4.90	3.51	98.37
81	71.11	0.29	13.04	3.32	0.23	0.20	1.21	4.21	3.43	97.04
82	70.26	0.31	12.94	3.43	0.16	0.23	1.44	4.72	3.28	96.77
83	70.00	0.29	12.60	3.62	0.08	0.17	1.47	4.39	3.21	95.83
84	71.18	0.26	13.32	3.43	0.20	0.18	1.33	5.07	3.33	98.29
85	68.69	0.33	12.60	3.17	0.06	0.21	1.42	5.52	3.43	95.44
87	71.11	0.31	12.89	3.89	0.18	0.23	1.28	4.60	3.29	97.78
88	69.85	0.25	12.87	3.74	0.34	0.21	1.48	4.38	3.32	96.43
89	70.66	0.23	12.93	3.66	0.14	0.20	1.46	4.74	3.25	97.28
90	71.84	0.28	13.19	4.21	0.13	0.24	1.31	4.37	3.47	99.03
92	69.36	0.27	12.92	3.85	0.13	0.21	1.32	4.19	3.18	95.42
				Vedde Ash (831.5 cm) (SEM)						
1	46.52	4.63	12.45	15.31	0.97	4.04	6.83	3.52	1.10	100.00
2	49.34	3.85	12.68	14.37	0.38	4.00	8.32	4.38	1.48	100.00
3	45.10	5.03	12.05	17.06	0.30	4.24	10.78	3.05	0.90	100.00
4	50.73	3.89	12.91	14.48	0.59	3.22	8.59	3.49	1.57	100.00
6	49.91	2.96	14.52	13.10	0.00	4.44	8.56	4.57	1.13	100.00
7	46.22	5.00	11.55	17.97	0.00	3.82	10.47	3.09	0.78	100.00
8	45.17	4.54	12.46	17.57	0.62	3.91	10.83	3.16	1.00	100.00
14	47.78	4.97	11.85	17.44	0.00	4.41	11.29	2.76	0.99	100.00
15	45.03	5.28	11.88	17.94	0.00	4.41	11.29	2.76	0.99	100.00

Note. The chemical analyses were performed with a standard wavelength dispersal (EMP) technique (Cameca-SX 50 microprobe), with an accelerating voltage of 15 kV, a beam current of 5 nA, and a beam diameter of 5–10 μm. The chemical analyses on the basaltic part of the Vedde Ash were performed on a scanning electron microscope (SEM) (JEOL-6400) connected to an energy dispersive spectrometer (TRACOR NORTHERN 5600, series II), with an accelerating voltage of 18 kV. All analyses are expressed in weight percent and total iron as FeO*. Natural and synthetic minerals and glasses were used as standards.

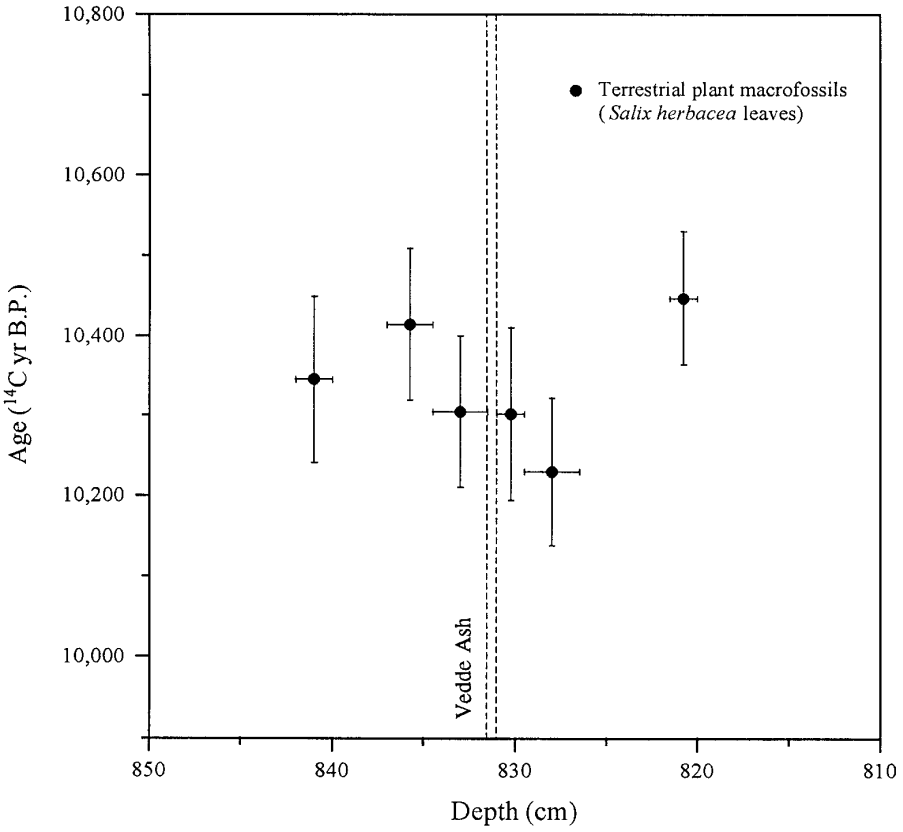

FIG. 4. Radiocarbon dates vs depth across the Vedde Ash layer at Kråkenes (indicated at 831–831.5 cm), all on *Salix herbacea* leaves. Horizontal bars are the depth span of the sample, vertical bars are 1 standard deviation of measurement.

(VG OPTIMA spectrometer). The results are summarized in Table 3.

Age of the Vedde Ash

The mean of the four AMS dates closest to the Vedde Ash (Fig. 4, Table 3) is 10,310 ± 50 yr B.P. An attempt to calibrate this age in calendar years has not been made because of the preliminary nature of the available calibration curve beyond the limit of the dendrochronological data (Stuiver and Reimer, 1993). However, this ash is found in the GRIP ice-core at Summit, Greenland (Grønvold *et al.,* 1995) at a depth corresponding to 11,980 ± 80 ice-core yr B.P.

The mean sedimentation rate over the whole Younger Dryas interval at Kråkenes is 1.5–2 mm yr^{-1}. The four dates used to calculate the age of the Vedde Ash were obtained from contiguous samples spanning 10.5 cm, likely to have accumulated in 50–70 yr (no rapid-deposition sand layers are present). The radiocarbon dates with their one standard deviation probabilities are internally consistent, indicating a high degree of precision and consistency of this age estimate for the Vedde Ash. The slight variability between the dates (Fig. 4) could express errors related to sampling and measurement, but it may also reflect as yet unknown variations in Younger Dryas atmospheric ^{14}C content, which are highly probable in this climatically and oceanographically unstable interval. In this context, the ^{14}C ages of the two dates for samples 10 cm distant from the ash bed are well inside the expected range.

The date of 10,600 yr B.P. usually quoted for the Vedde Ash is based on the mean of conventional bulk sediment dates from four sites in western Norway (Mangerud *et al.,* 1984). A recent estimate of ca. 10,300 yr B.P. was made by Bard *et al.* (1994) from a mean of six rather widely varying AMS dates from two sites in the same area. This result agrees closely with our new precise estimate and implies that the date obtained by Wohlfarth *et al.* (1993) from southern Sweden is too young (Table 1).

Age of the Saksunarvatn Ash

The ^{14}C results from bulk sediment are concordant with those from macrofossils, indicating no significant error in dating the sediments due to, e.g., ''old'' carbon or roots (Fig. 5; Table 3). Therefore, the sediment dates are considered as reliable as the macrofossil dates. The date for terrestrial plant

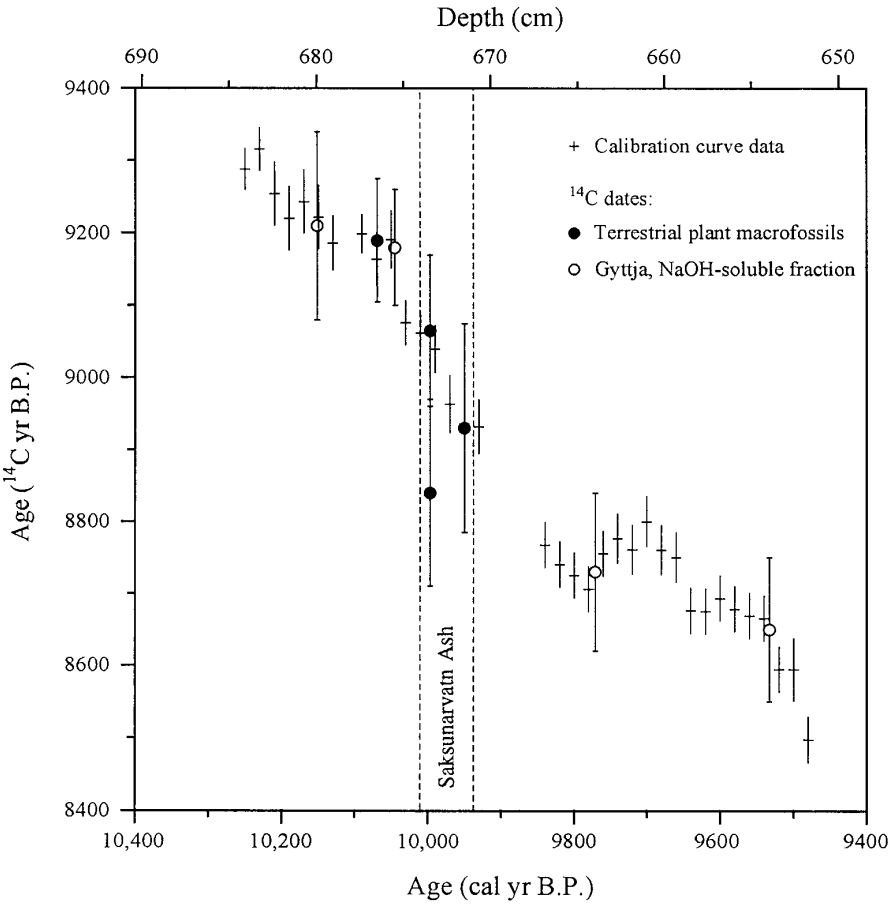

FIG. 5. Radiocarbon dates (circles) vs depth (upper scale) across the Saksunarvatn Ash layer at Kråkenes (indicated between 671–674 cm). Samples all span 1 cm depth. Vertical bars are 1 standard deviation of measurement. Radiocarbon ages versus calibrated age (lower scale) from the dendrochronological calibration curve (Stuiver and Reimer, 1993) are shown with crosses. The Kråkenes dates are matched to the calibration curve data by varying the scale and the chronological position of the depth (upper) axis (see text).

macrofossils from 672–673 cm is clearly too young and is thus omitted from consideration.

The seven ^{14}C dates around the ash layer are within the range of dendrochronological calibration. Comparison of the dates with calibration data (Stuiver and Reimer, 1993) was done to find the chronological position of the dates that yields the minimum sum of squares for the differences between the sample dates and the calibration data. The best fit is obtained with a sedimentation rate of 0.42 mm yr^{-1}, assumed to be constant throughout this segment (Fig. 5). The calibrated age of the Saksunarvatn Ash layer is 9930–10,010 cal yr B.P. (7980–8060 cal yr B.C.), corresponding to radiocarbon ages in the range 8930–9060 yr B.P. The rapid sedimentation rate at Kråkenes during the early Holocene has allowed this high precision.

Our age determination for the Saksunarvatn Ash agrees well with estimates from the Faeroe Islands-type site (Mangerud *et al.*, 1986) and Iceland (Björck *et al.*, 1992; Ingólfsson *et al.*, 1995). Other estimates of the ^{14}C age of the Saksunarvatn Ash are given in Table 1. The Saksunarvatn Ash is reported from the GRIP ice core, with an age of 10,180 ± 60 ice-core years (Grønvold *et al.*, 1995). This age is somewhat older than our result (170–250 ± 60 yr). The difference could be due to inaccuracies in estimating the dendrocalibrated age at Kråkenes, to the ice-core age, or to a combination of both.

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TABLE 3
Radioarbon Dates Relating to the Saksunarvatn Ash (671–674 cm) and the Vedde Ash (831–831.5 cm) at Kråkenes

Laboratory reference	Depth (cm)	Material dated	Identity of TPM	Dry weight (mg)	Sample size (mg carbon)	^{14}C age (yr B.P.)	δ^{13}C (‰ PDB)
			Saksunarvatn Ash				
TUa-1006A	653–655	Gyttja, sol.		1800	1.7	8560 ± 100	−29.8
TUa-1007A	663–665	Gyttja, sol.		1600	1.7	8730 ± 110	−28.3
Ua-3423	671–672	TPM	*Betula pubescens* fruits, *Betula* budscales and leaf fragments, bark of *Salix* or *Betula*, *Salix* seed, *Empetrum* seeds and leaves, terrestrial mosses (*Hylocomium splendens, Aulacomnium palustre, Racomitrium, Dicranum*)	3.3	0.8	8930 ± 145	−29.3
Ua-3424	672–673	TPM	*B. pubescens* fruits, *Betula* male catkin scales, female catkin scale, budscales, bark fragments, *Empetrum* seeds and leaves, terrestrial mosses as above, carbonized mosses and plant remains	3.8	1.6	8335 ± 95	−27.1
Ua-3425	673–674	TPM	*B. pubescens* fruits, *Betula* male catkin scale, budscales, leaf fragments, *Salix* bud, *Empetrum* seeds and leaves, terrestrial mosses as above, carbonized mosses	3.4	1.5	9065 ± 105	−27.1
Ua-3426	673–674	TPM	*Sphagnum*	3.1	1.0	8840 ± 130	−30.8
Ua-3427	675–676	Gyttja, sol.		112	3.0	9180 ± 80	−27.2
Ua-3428	676–677	TPM	*B. pubescens* fruits, *Betula* male catkin scales, budscales, bark, leaf fragments, *Empetrum* leaves, *Comarum palustre* seed, terrestrial mosses as above, carbonized mosses	5.8	2.4	9190 ± 85	−27.4
TUa-1008A	679–681	Gyttja, sol.		2000	1.9	9210 ± 130	−29.1
			Vedde Ash				
Ua-3400	820.0–821.5	TPM	*Salix herbacea* leaves	26.3	3.6	10,445 ± 85	−28.6
Ua-3401	826.5–829.5[a]	TPM	*S. herbacea* leaves	23.5	3.9	10,230 ± 90	−28.7
Ua-3402	829.5–831.0[a]	TPM	*S. herbacea* leaves	14.1	1.9	10,300 ± 110	−28.6
Ua-3403	831.5–834.5[a]	TPM	*S. herbacea* leaves	18.7	4.1	10,305 ± 95	−28.3
Ua-3404	834.5–837.0[a]	TPM	*S. herbacea* leaves	23.0	3.9	10,415 ± 95	−28.5
Ua-3405	840.0–842.0	TPM	*S. herbacea* leaves	28.4	4.1	10,345 ± 105	−28.8

Note. Gyttja, sol., organic lake sediment soluble in NaOH; TPM, terrestial plant macrofossils; PDB, Pee Dee Belemnite.
[a] Used for mean age.

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