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A calendar age estimate of the Younger Dryas-Holocene boundary at Kråkenes, western Norway

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Abstract: The Younger Dryas/Holocene transition (YD/H) in the sediments of Kråkenes Lake, western Norway, is well marked both lithologically and palaeobiologically at 756.5 cm in the investigated core. A series of 70 AMS radiocarbon dates on terrestrial plant macrofossils and the NaOH-soluble fraction of lake sediment was measured between 585 and 840 cm, covering the time span *c.* 10 440 to 7915 BP on the radiocarbon timescale. Forty-three of these dates above 760 cm were wiggle-matched against the German oak-pine dendro-calibration curve (IntCal 93) with recent corrections in both the oak and the pine sections. With an increase in age of the pine dendro-series of 200 ± 20 yr, the calendar age of the YD/H lithostratigraphic boundary at Kråkenes is estimated to $11\,530^{+40}_{-60}$ cal. BP. By using a date of 9750 BP (11 170 cal. BP) on the transition between the 10 000 and 9600 ^{14}C plateaux as a time marker, this result is compared with recent results from other archives. It is consistent with many of them, including the GRIP ice core, German pine series, Lake Gościąż, south Swedish lakes, and Baltic varves, suggesting that the Younger Dryas-Holocene transition in the North Atlantic region occurred within the range 11 500–11 600 cal. BP.

Key words: AMS radiocarbon dating, radiocarbon calibration, wiggle-matching, Younger Dryas-Holocene transition, lithological boundary, Kråkenes, Norway

Introduction

The transition from the last glacial period in northwest Europe (Weichselian) to the present interglacial, the Holocene, was characterized by several climatic reversals, the largest and longest of which was the millennial scale Younger Dryas (YD) stadial. The description and dating of these oscillations are important for understanding and modelling the mechanisms that could influence the rapid climatic changes during the lateglacial. Dates for the boundaries associated with the YD/Holocene transition (YD/H) have been obtained from a variety of natural archives in the Northern Hemisphere in which evidence of climatic changes is preserved, but the results are slightly different (e.g. Goslar *et al.*, 1995a; Wohlfarth, 1996; Björck *et al.*, 1996). To resolve the causes of the discrepancies it is essential to correlate the results from the different dating methods correctly, and to refine them so that the chronologies are as precise as possible.

Detailed sequences of radiocarbon dates on lake sediments (e.g. Ammann and Lotter, 1989; Lotter, 1991; Goslar *et al.*, 1995b) and tree rings (e.g. Becker and Kromer, 1986; 1993), have revealed so-called radiocarbon plateaux, centred on 12 600, 10 400, 10 000, and 9600 BP (Before Present; 1950). They reflect periods of atmospheric ^{14}C decrease, which in the lateglacial are thought to be primarily associated with increased ocean upwelling (e.g. Stuiver and Braziunas, 1993). Consequently, growing plants incorporate the same ^{14}C activity as plants that died in preceding decades or centuries. The Younger Dryas-Holocene transition falls within the 10 000 BP ^{14}C plateau and it is thus impossible to radiocarbon date it more precisely within the duration of the plateau, which lasted about 400 calendar years according to annually varved lake sediments (Ammann and Lotter, 1989; Lotter, 1991). The implications for the chronology and interpretation of events occurring within the plateaux timespans are discussed by

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Lotter (1991), Becker and Kromer (1993) and Bartlein *et al.* (1995).

Dendrochronology has provided a direct comparison between radiocarbon and calendar years throughout the Holocene, thus enabling radiocarbon dates to be calibrated to calendar years (e.g. Stuiver and Reimer, 1993). The precision of lake-sediment dating can be greatly improved by the 'wiggle-matching' technique on a close series of radiocarbon dates (Pearson, 1986). The pattern of radiocarbon dates is fitted to the dendrochronological time series so that the sums of squares of the differences between the two datasets are minimized (Pearson, 1986). Dating of floating tree-ring chronologies is typically done by this method. In sequences without an independent annual timescale (e.g. non-laminated sediments) the sedimentation rate needs to be estimated (van Geel and Mook, 1989; Day and Mellars, 1994; Pilcher *et al.*, 1995; Oldfield *et al.,* 1997). By this means, the 10 000 BP ^{14}C plateau in unlaminated lake sediments can be penetrated, and the Younger Dryas-Holocene transition can be positioned in calendar years. This will then allow direct comparison with other calendar chronologies from, for example, tree-rings, ice cores and lacustrine varves.

Taking this approach, we have used AMS (Accelerator Mass Spectrometry) for close-interval fine-resolution radiocarbon dating of an exceptionally thick Younger Dryas-Holocene limnic sequence from Kråkenes. Kråkenes Lake (62°02′N, 5°00′E), on the west Norwegian coast (Figure 1), possesses several characteristics ideal for an investigation of the Younger Dryas-Holocene transition (Larsen *et al.*, 1984; Birks *et al.*, 1996a). It is in southern Scandinavia, where the Younger Dryas event was first recognized and named, and where it is most strongly manifested lithostratigraphically and biostratigraphically (Mangerud *et al.*, 1974). Moreover, the climatic change at the Holocene boundary is more abrupt, better defined, and of larger amplitude along the western seaboard of Europe than in most other areas (Lowe *et al.*, 1994). The lithostratigraphical boundaries of the Younger Dryas in the lacustrine sediments at Kråkenes are sharp (Figure 2), due to direct minerogenic input from the small cirque glacier that existed during the Younger Dryas on the mountain to the south. The rate of sedimentation is high, allowing detailed temporal sampling-resolution. There are abundant *Salix herbacea* (dwarf willow) leaves in the lateglacial and earliest Holocene sediments that can be used for AMS dating. The chronostratigraphical suitability of the sediments is enhanced by the presence of both the Vedde and Saksunarvatn tephras (Birks *et al.*, 1996b).

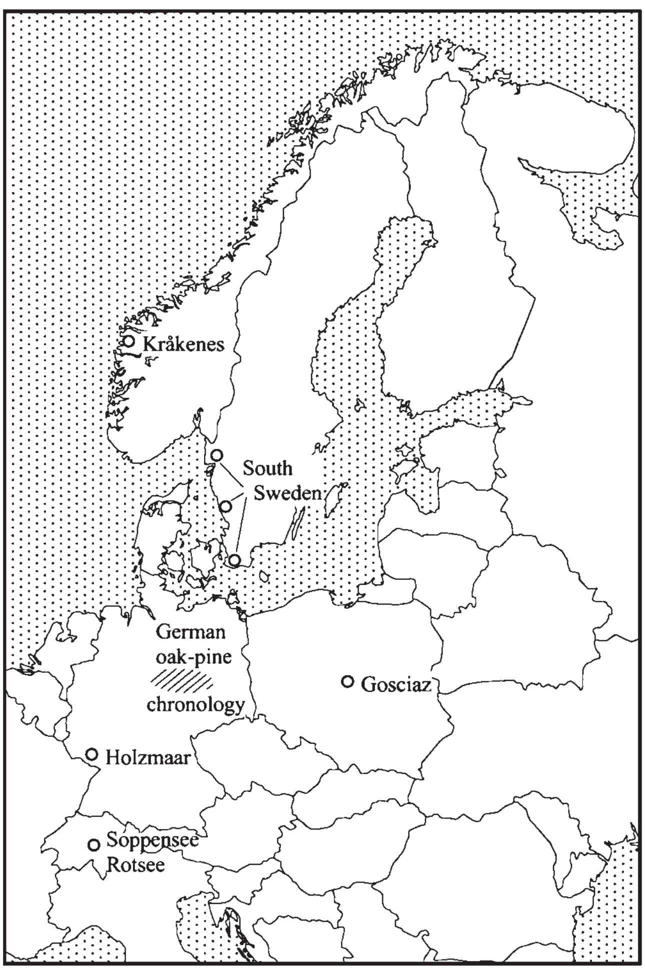

Figure 1 Map showing the location of Kråkenes in western Norway, and other places mentioned in the text.

Although our sequence of dates covers the transition between the Younger Dryas and the Holocene, we take the sharp and distinct lithostratigraphic change from laminated silts to unlaminated increasingly organic sediments at 756.5 cm in the investigated core at Kråkenes (Figure 2) as the local boundary between the Younger Dryas and the Holocene. The lithostratigraphic change occurred as a result of the final melting of the cirque glacier. However, the glacier presumably melted in response to a rise in temperature that probably started about a decade earlier, in order to melt the ice. There is also a biostratigraphical response by aquatic organisms in the lake to this warming (Birks, 1997) that starts 10–20 years before the lithostratigraphic boundary at 756.5 cm.

Past climate changes cannot be observed directly and their detection depends upon changes registered in proxy data. As Watson and Wright (1980) discuss, each proxy will have a lag in response time depending on (a) the amount of temperature increase, (b) the rate of temperature increase, as different thresholds of reaction are passed, and (c) different sensitivities and thresholds to change in different systems (Wright, 1984). Climate itself changes over a period of time. In Greenland ice, the Younger Dryas-Holocene shifts in climate proxies (Alley *et al.*, 1993; Taylor *et al.*, 1997) occurred on decadal timescales, but the Holocene temperature rise of 7°C reconstructed from $\delta^{18}O$ measurements took 50 years (Dansgaard *et al.*, 1989). The increase in ring width of central German pine trees associated with Holocene warming took place over 60 years (Björck *et al.*, 1996). The timing and rates detectable in other archives depends on the resolution of their chronology, and on the threshold and speed of response of the recorded proxies. Therefore, we consider the change from Younger Dryas to Holocene conditions as a transition between the two states. In contrast, the lithological change at Kråkenes is defined here as the local boundary between the Younger Dryas and the Holocene in the stratigraphical sense (Salvador, 1994). It is distinct and simultaneous throughout the lake, and may have occurred over a very short period of time (probably less than one year). In this paper we focus on the dating of this boundary as a well-defined event within the Younger Dryas-Holocene transition. The lithostratigraphic change is equally sharp in numerous other lakes in the area, even those not receiving discharge from a glacier (Kristiansen *et al.*, 1988). It has also been used to define the YD/H boundary in south Sweden (Björck *et al.*, 1996).

In the Møre area of western Norway, the Younger Dryas-Holocene boundary is usually clear in the lithostratigraphy, with a sharp transition from greyish minerogenic Younger Dryas sediments to browner, more organic Holocene sediments. The transition has been consistently radiocarbon dated to about 10 000 BP. The associated pattern of changes in the pollen stratigraphy is also consistent (e.g. Larsen *et al.*, 1984; Johansen *et al.,* 1985; Kristiansen *et al.*, 1988; Svendsen and Mangerud, 1990; Birks, 1994). High percentages of *Salix* pollen are characteristic of the Younger Dryas, accompanied by a range of herbs of cold and wet, open habitats. Above the Holocene boundary, pollen percentages

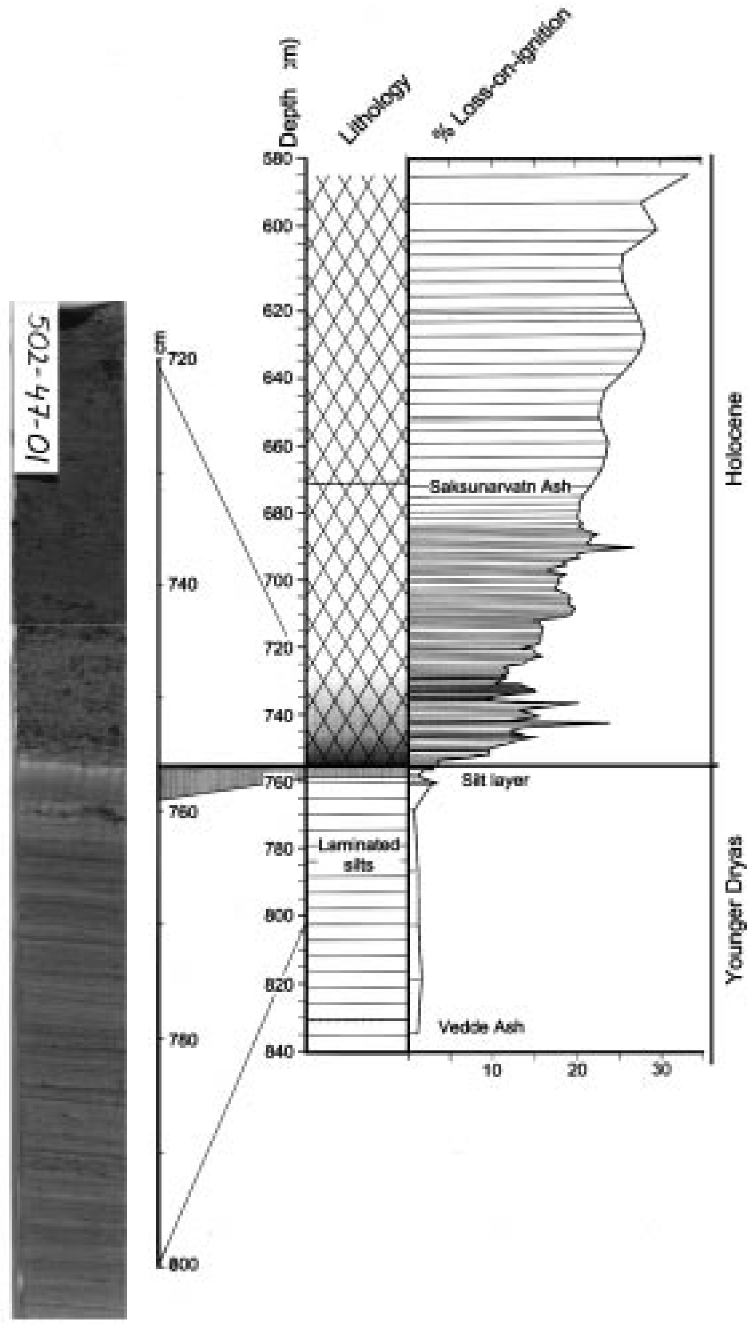

Figure 2 Lithostratigraphy of Kråkenes core 502-47-01, and percentage loss-on-ignition at 550°C. The laminated Younger Dryas silts, the 2.5-cm homogenous silt layer at the top of the Younger Dryas, and the leaf layers (dark streaks) in the early Holocene are visible in the photograph of the core (720–800 cm). The silt content declines during the early Holocene, and the gyttja appears homogenous above 700 cm. The Vedde Ash is visible, but the Saksunarvatn ash can only be detected microscopically (Birks *et al.*, 1996b).

of *Salix* and open-ground herbs fall sharply, and there is usually a peak of Cyperaceae, often accompanied by a peak of Gramineae, and sometimes also of *Rumex* and other pollen types derived from 'tall herbs'. This phase is followed by a characteristic increase in the abundance of fern spores, that remain abundant thereafter, and a relatively short phase of *Empetrum* pollen abundance. The subsequent rise in *Betula* pollen percentages (and influx where estimated) reflects the establishment of open birch woodland. Similar successions have been recorded in pollen diagrams from further south in Norway (see Birks, 1994), although fern spores tend to be less abundant. The Younger Dryas-Holocene transition is also characterized in the Møre area by an increase of aquatic plants and algal productivity (*Pediastrum* and/or *Botryococcus*). The pollen and macrofossil changes recorded at Kråkenes (H.H. Birks *et al.*, unpublished data) associated with the lithological change (Figure 2) conform to this regional pattern, and the high rate of sedimentation at this site has allowed a detailed reconstruction of the biotic responses and vegetational succession initiated by the climatic change at the beginning of the Holocene (Birks, 1997).

The sediment cores from Kråkenes Lake used in the present study contain 168 cm of laminated Younger Dryas silt overlain by 756 cm of Holocene sediments with a high organic content, mainly algal gyttja and terrestrial macrofossils (Figure 2). Unfortunately most of the YD laminations are not annual varves (Kårevik Stalsberg, 1995), so our estimated mean rate of YD sediment accumulation depends on the calendar-age estimates of the duration of the Younger Dryas of 1100 years from other sites (e.g. Wohlfarth, 1996). Both the site and the multidisciplinary study in progress on the Kråkenes sediments are described in more detail in Birks *et al.* (1996a) and references therein.

Radiocarbon dating

The first radiocarbon dates from Kråkenes Lake were conventional dates on bulk sediments (Mangerud *et al.*, 1979; Larsen *et al.*, 1984). The possibility of dating small amounts of terrestrial plant macrofossils (TPM) by the AMS-technique stimulated in 1993 a comprehensive dating project based on the abundance of *Salix herbacea* leaves preserved in the sediments (Gulliksen *et al.*, 1994).

Samples from the core were 1 cm thick from the Holocene, but varied up to 2 cm thick in the YD, depending on the thickness of laminations. After suspension of the sediment samples in water the leaves and other terrestrial plant macrofossils were sieved out (125 μm mesh). Separation and identification under a stereomicroscope were followed by cleaning and air drying. Pretreatment of the leaves followed the standard AAA-technique, i.e. hot acid-alkali-acid, to remove humic acids and carbonates of non-contemporaneous origin. The residual material was combusted with CuO as the oxidizing agent and graphitized in a forced circulation system (Hut *et al.*, 1986).

Dating of lake sediments by conventional radiometric measuring technique at Trondheim is normally done on NaOH-soluble organic constituents. Although it has been demonstrated that a variety of problems can affect the dating of gyttja (e.g. Olsson, 1986), the non-calcareous algal gyttja of the Holocene sediments at Kråkenes should be well suited for the dating of NaOH extracts. Comparative dating of both terrestrial plant macrofossils (TPM) and gyttja extracts around the Saksunarvatn tephra yielded very consistent ages (Birks *et al.*, 1996b), and it was therefore decided to strengthen the chronological framework of the Younger Dryas-Holocene transition by including a series of dates on gyttja extracts. These were obtained by treatment with hot NaOH (80°C, >4 hrs) followed by precipitation of the humic fraction with conc. HCl. Combustion and conversion to graphite were as for the TPM samples, and carbon amounts well above 1 mg were obtained for all gyttja samples. Our assumption of negligible influence from old carbon on the gyttja samples is confirmed by the fact that the 9600 BP ^{14}C plateau is reproduced with no significant age difference between the gyttja dates and the calibration curve data (Figure 3).

Samples were prepared at the radiocarbon laboratories at Trondheim (prefix TUa-) and Uppsala (Ua-) (Table 1), and AMS measurements were performed with the Uppsala EN-tandem accelerator (Possnert, 1990). Natural mass fractionation, δ^{13}C, was measured on separate aliquots of CO_2 from the samples at the Department of Geology, University of Bergen, or at Uppsala (Table 1).

Results

The dating results are listed according to increasing sediment depth in Table 1. The position of the YD/H lithostratigraphic boundary is at 756.5 cm, the Vedde Ash is between 831 and 831.5 cm, and the Saksunarvatn Ash is at 671–674 cm (see Figures 2 and 3).

The Younger Dryas-Holocene transition is expected to be within the range of the dendrochronological calibration curve, close to the end of the ~10 000 BP ^{14}C plateau (Kromer and Becker, 1993). With our stratigraphical sequence of closely spaced radiocarbon dates, wiggle-matching of the sequence against the calibration curve should provide accurate estimates of calendar ages for the samples. The sequence is positioned so that the sum-of-squares of the differences between the dates and the calibration data is minimized. To wiggle-match a sequence lacking an independent time control such as is provided by varves or tree-rings, the sedimentation rate must be known in order to translate the depth between samples into chronological intervals (van Geel and Mook, 1989). In this case it is therefore necessary to vary both the position of the sequence and the sedimentation rate to find the best possible match (Pilcher *et al*., 1995; Oldfield *et al.*, 1997).

Calibration data in the actual age range are based on German oak and pine chronologies that have recently been revised. Forty-one tree rings, missing in the Hohenheim oak chronology at 7191 cal. BP, have been discovered (Kromer *et al.*, 1996) and 54 tree rings have also been added at 9741 cal. BP (M. Spurk and B. Kromer, personal communication). An extension of the oak series and addition of more trees to the pine series have now made it possible to obtain a reliable link by matching the ^{14}C patterns of the overlapping sections. The result is that the pine series is now 200 $\pm$ 20 yr older than the IntCal 93 data (M. Spurk and B. Kromer, personal communication). This implies that the estimated shift of 120 $\pm$ 80 yr of Björck *et al.* (1996) is verified to be 105 $\pm$ 20 yr. The IntCal 93 calibration data-set was corrected accordingly for our calculations.

The macrofossil dates adjacent to the lithostratigraphical boundary are quite ambiguous (Figure 3; Table 1). Therefore, it was decided to give preference to the gyttja AMS dates because these show a more coherent pattern. A data set combining 39 gyttja dates between depths 585 cm and 760 cm with four dates on terrestrial macrofossils from 670–677 cm (Birks *et al.*, 1996b) was used. These samples are indicated in Table 1. As a first approach, a constant sedimentation rate was assumed throughout the whole depth range. When plotting the fitted data, systematic divergencies between the dates and the calibration data were observed, indicating – as expected – that the sedimentation rate had varied. To estimate the pattern of rate variation, the data set was split into running groups of eight samples (typically spanning 35 cm) along the sequence. In depth intervals with a high sample density the number of samples was increased to span a minimum of 25 cm. By matching each group to the calibration data approximate sedimentation rates over different depths were obtained (Figure 4). Although the data points are scattered, they clearly indicate the depths where sedimentation rate changes.

The loss-on-ignition (LOI) curve (Figure 2) changes rapidly and rather irregularly in the early Holocene. There are three major sediment components involved; minerogenic material washed in from the unstable catchment, organic material produced *in situ* by lake productivity, and inwashed terrestrial organic material that occurs in substantial quantities between 755 and 740 cm, consisting mainly of *Salix herbacea* leaves and mosses that are visible in the photograph in Figure 2. It is difficult to explain in detail the changes in the relative balance between the three components, but it is likely that the leaf layers cause the irregularities in the LOI curve, as this becomes more regular after leaf deposition decreases above 740 cm. Organic lake productivity increased dramatically at the YD/H transition, and it is likely that it increased throughout the early Holocene as the lake ecosystem became established (Birks, 1997). With a high silt input at the start of the Holocene, it is probable that the sedimentation rate was high up to about 730 cm. If the rate of silt and terrestrial organic input then decreased more rapidly than the autochthonous organic sedimentation was increasing, this may have resulted in a lower sedimentation rate between 700 and 680 cm. Subsequently, aquatic organic productivity was sufficiently high to increase the sedimentation rate to values approaching the Holocene average of 0.07 cm yr^{-1}. By this time there was minimal silt input, and the 70% of the sediment not combusted at 500°C consists mostly of biogenic silica, clay, and other non-organic components.

A sedimentation rate model was established by using fixed depth positions for the shifts in rate, based on the results from the group wiggle-matching, and with constant sedimentation rates between these positions as variable parameters. For the late part of the Younger Dryas useful calibration data are lacking, and rates

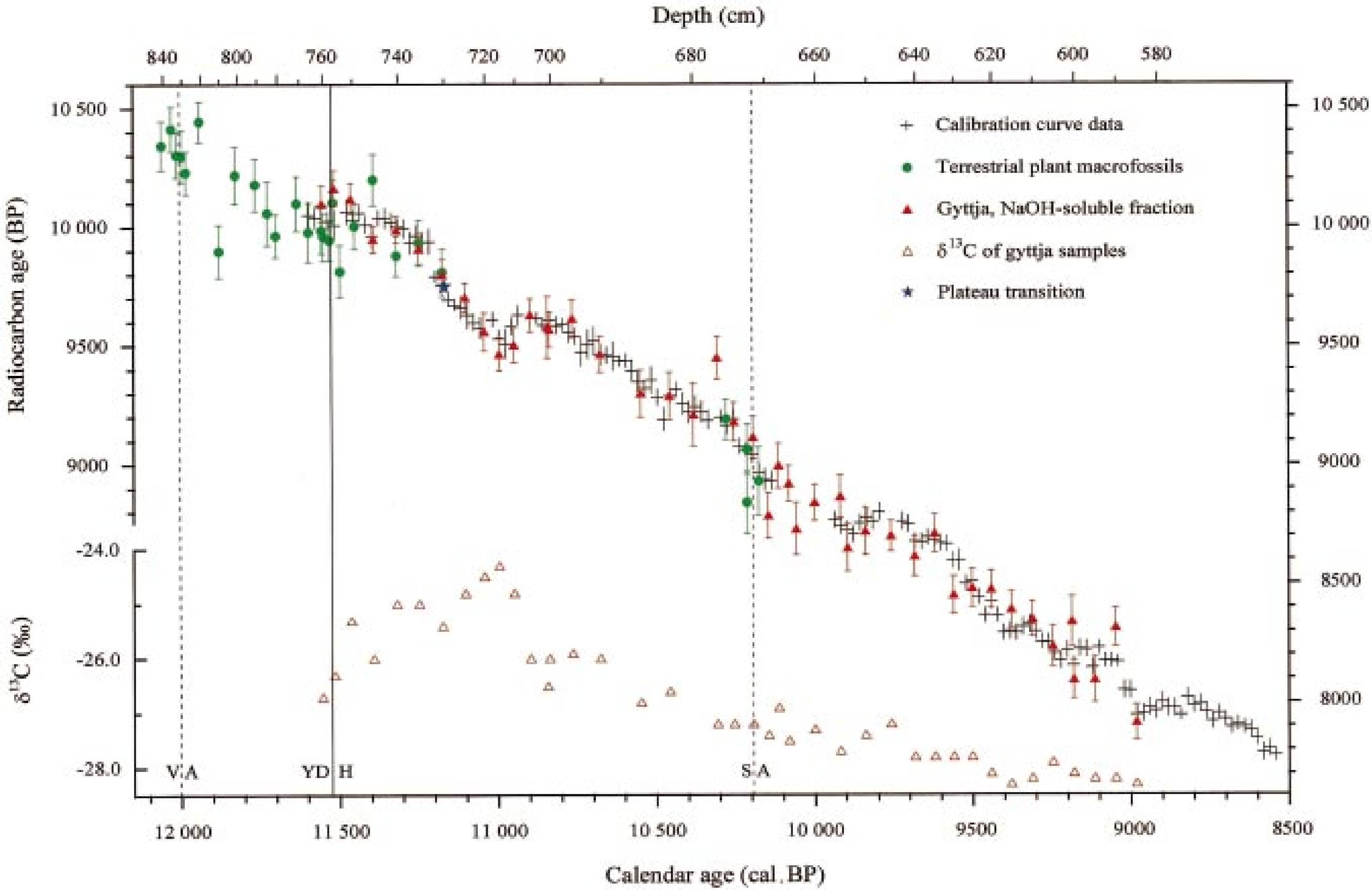

Figure 3 Radiocarbon dates and $\delta^{13}C$ values from Kråkenes Lake. Calibration data (IntCal 93) are corrected for recent additions to the oak and pine chronologies, resulting in an increase in the age of the pine chronology of 200 ± 20 yr. Calendar ages for radiocarbon samples are obtained by wiggle-matching of the dates with a variable sedimentation rate model (see text), as reflected by the non-linear depth scale. For depths below 800 cm a rate of 0.17 cm $yr^{\pm 1}$ is assumed. Positions of the Younger Dryas-Holocene boundary (YDH), the Vedde Ash (VA) and the Saksunarvatn Ash (SA) are indicated, and the blue star is the position chosen for the Plateau Transition reference point.

Table 1 Radiocarbon AMS dates from Kråkenes Lake. Materials dated are terrestrial plant macrofossils (TPM) and the NaOH-soluble fraction of gyttja (Gyttja, sol). All samples were measured in Uppsala (Ua-). Prefix TUa- indicates samples preparted in Trondheim. Two samples measured by the conventional dating technique are included (T-)

Lab. ref.	Depth (cm)	Material dated	Sample size (mg carbon)	^{14}C age (years BP)	$\delta^{13}C$ (‰ PDB)	Comments
Ua-3429	585–586	Gyttja, sol.	3.0	7915 ± 75	−28.3	Used for wiggle-matching
Ua-3430	590–591	Gyttja, sol.	2.4	8315 ± 80	−28.2	Used for wiggle-matching
Ua-3431	595–596	Gyttja, sol.	3.2	8095 ± 95	−28.2	Used for wiggle-matching
Ua-3432	600–601	Gyttja, sol.	3.2	8095 ± 80	−28.1	Used for wiggle-matching
T-10829A	600–602	Gyttja, sol.	365	8340 ± 105	−29.8	Conventional radiometric date
Ua-3433	605–606	Gyttja, sol.	2.6	8235 ± 85	−27.9	Used for wiggle-matching
Ua-3434	610–611	Gyttja, sol.	2.6	8350 ± 75	−28.2	Used for wiggle-matching
Ua-3435	615–616	Gyttja, sol.	3.6	8390 ± 75	−28.3	Used for wiggle-mtching
Ua-3436	620–621	Gyttja, sol.	3.0	8475 ± 80	−28.1	Used for wiggle-matching
Ua-3437	625–626	Gyttja, sol.	3.7	8480 ± 80	−27.8	Used for wiggle-matching
Ua-3438	630–631	Gyttja, sol.	3.8	8450 ± 80	−27.8	Used for wiggle-matching
Ua-3439	635–636	Gyttja, sol.	2.2	8710 ± 80	−27.8	Used for wiggle-matching
Ua-3440	640–641	Gyttja, sol.	3.7	8615 ± 85	−27.8	Used for wiggle-matching
Ua-3441	645–646	Gyttja, sol.	2.4	8700 ± 65	−27.2	Used for wiggle-matching
Ua-3442	650–651	Gyttja, sol.	2.3	8720 ± 100	−27.4	Used for wiggle-matching
TUa-1006A	653–655	Gyttja, sol.	1.7	8650 ± 100	−29.8	Combusted as conventional sample
Ua-3443	655–656	Gyttja, sol.	3.8	8865 ± 90	−27.7	Used for wiggle-matching
Ua-3444	660–661	Gyttja, sol.	2.7	8840 ± 75	−27.3	Used for wiggle-matching
TUa-1007A	663–665	Gyttja, sol.	1.7	8730 ± 110	−28.3	Combusted as conventional sample
Ua-3445	665–666	Gyttja, sol.	3.6	8920 ± 75	−27.5	Used for wiggle-matching
Ua-3446	667–668	Gyttja, sol.	2.9	8995 ± 95	−26.9	Used for wiggle-matching
Ua-3447	669–670	Gyttja, sol.	2.1	8785 ± 95	−27.4	Used for wiggle-matching
Ua-3423	671–672	TPM, fruits, seed etc.	0.8	8930 ± 145	−29.3	Used for wiggle-matching
Ua-3424	672–673	TPM, fruits, seed etc.	1.6	8335 ± 95	−27.1	Obvious outlier
Ua-3448	672–673	Gyttja, sol.	3.6	9115 ± 90	−27.2	Used for wiggle-matching
Ua-3425	673–674	TPM, fruits, seed etc.	1.5	9065 ± 105	−27.1	Used for wiggle-matching
Ua-3426	673–674	TPM, *Sphagnum*	1.0	8840 ± 130	−30.8	Used for wiggle-matching
Ua-3427	675–676	Gyttja, sol.	3.0	9180 ± 80	−27.2	Used for wiggle-matching
Ua-3428	676–677	TPM, fruits, seed etc.	2.4	9190 ± 85	−27.4	Used for wiggle-matching
Ua-3449	677–678	Gyttja, sol.	3.8	9450 ± 90	−27.2	Used for wiggle-matching
TUa-1008A	679–681	Gyttja, sol.	1.9	9210 ± 130	−29.1	Combusted as conventional sample
Ua-3450	682–683	Gyttja, sol.	2.0	9290 ± 100	−26.6	Used for wiggle-matching
TUa-1165A	685–686	Gyttja, sol.	2.3	9300 ± 100	−26.8	Used for wiggle-matching
TUa-1166A	690–691	Gyttja, sol.	2.8	9465 ± 75	−26.0	Used for wiggle-matching
TUa-1167A	695–696	Gyttja, sol.	3.3	9615 ± 80	−25.9	Used for wiggle-matching
TUa-1168A	700–701	Gyttja, sol.	3.1	9570 ± 75	−26.0	Used for wiggle-matching
T-10830A	700–702	Gyttja, sol.	365	9580 ± 130	−26.5	Conventional radiometric date
TUa-1169A	705–706	Gyttja, sol.	4.6	9330 ± 70	−26.0	Used for wiggle-matching
TUa-1170A	710–711	Gyttja, sol.	2.2	9505 ± 75	−24.8	Used for wiggle-matching
TUa-1171A	715–716	Gyttja, sol.	2.9	9465 ± 70	−24.3	Used for wiggle-matching
TUa-1172A	720–721	Gyttja, sol.	1.8	9560 ± 80	−24.5	Used for wiggle-matching
TUa-1173A	725–726	Gyttja, sol.	3.5	9705 ± 60	−24.8	Used for wiggle-matching
TUa-1174A	730–731	Gyttja, sol.	2.2	9800 ± 65	−25.4	Used for wiggle-matching
TUa-593	730–731	TPM, *Salix* leaves	2.9	9810 ± 100	−29.0	
TUa-780	735–736	TPM, *Salix* leaves	1.6	9935 ± 95	−28.0	^{13}C not measured, mean value
TUa-1175A	735–736	Gyttja, sol.	2.7	9910 ± 65	−25.0	Used for wiggle-matching
TUa-1176A	740–741	Gyttja, sol.	4.4	9990 ± 55	−25.0	Used for wiggle-matching
Ua-3406	740–741	TPM, *Salix* leaves	3.0	9880 ± 85	−28.1	
TUa-605	745–746	TPM, *Salix* leaves	2.2	10200 ± 110	−28.4	
TUa-1177A	745–746	Gyttja, sol.	5.2	9950 ± 55	−26.0	Used for wiggle-matching
TUa-588	749–750	TPM, *Salix* leaves	3.2	10005 ± 95	−28.6	
TUa-1178A	750–751	Gyttja, sol.	3.7	10120 ± 65	−25.3	Used for wiggle-matching
TUa-595	753–754	TPM, *Salix* leaves	2.5	9815 ± 110	−29.0	
TUa-1179A	755–756	Gyttja, sol.	2.0	10165 ± 75	−26.3	Used for wiggle-matching

Continued

Table 1 Continued

Lab. ref.	Depth (cm)	Material dated	Sample size (mg carbon)	^{14}C age (years BP)	δ^{13}C (‰ PDB)	Comments
TUa-584	755–756.5	TMP, *Salix* leaves	3.5	10105 ± 95	−28.5	
TUa-594	756.5–758	TPM, *Salix* leaves	3.3	9945 ± 85	−28.0	^{13}C not measured, mean value
TUa-585	759.5–760	TPM, *Salix* leaves	3.1	9960 ± 100	−29.1	
TUA-1180A	760–760.5	Gyttja, sol.	1.9	10100 ± 75	–26.7	Used for wiggle-matching
TUa-590	760–761	TPM, *Salix* leaves	3.3	9985 ± 95	−28.2	
Ua-3414	765–767	TPM, *Salix* leaves	1.3	9980 ± 125	−28.0	^{13}C not measured, mean value
Ua-3410	770–772.5	TPM, *Salix* leaves	1.9	10100 ± 115	−28.4	
TUa-782	870–781	TPM, *Salix* leaves	1.5	9965 ± 90	−29.3	
Ua-3415	784–768	TPM, *Salix* leaves	1.1	10060 ± 135	−28.0	^{13}C not measured, mean value
TUa-598	790–792	TPM, *Salix* leaves	1.8	10180 ± 110	−28.0	^{13}C not measured, mean value
TUa-783	801–802	TPM, *Salix* leaves	1.3	10220 ± 120	−29.5	
Ua-3411	809–811.5	TPM, *Salix* leaves	1.5	9900 ± 110	−28.0	^{13}C not measured, mean value
Ua-3400	820–821.5	TPM, *Salix* leaves	3.6	10445 ± 85	−28.6	
Ua-3401	826.5–829.5	TPM, *Salix* leaves	3.9	10230 ± 90	−28.7	
Ua-3402	829.5–831	TPM, *Salix* leaves	1.9	10300 ± 110	−28.6	
Ua-3403	831.5–834.5	TPM, *Salix* leaves	4.1	10305 ± 95	−28.3	
Ua-3404	834.5–837	TPM, *Salix* leaves	3.9	10415 ± 95	−28.5	
Ua-3405	840–842	TPM, *Salix* leaves	4.1	10345 ± 105	−28.8	

must be evaluated by other means. Several independent estimates for the duration of the Younger Dryas are close to 1100 years (Wohlfarth, 1996). At Kråkenes these sediments span 168 cm, giving an average rate of 0.15 cm yr^{-1}. In our model we assumed a decreasing sedimentation rate, from 0.17 cm yr^{-1} at depth 800 cm to 0.125 cm yr^{-1} at the YD/H transition at 756.5 cm. The sedimentation rates in the five other blocks along the sequence were varied during the wiggle-matching of the complete data set, resulting in the pattern of sedimentation rate shown by the solid line in Figure 4. The data in Figure 3 are plotted according to the best fit obtained by this matching. The YD/H lithostratigraphical boundary at 756.5 cm corresponds to 11 525 cal. BP.

An alternative fit was done by using the nine data points in the depth range 710–750 cm that coincide with the steep slope on the calibration curve forming the transition between the 9600 BP and the 10 000 BP ^{14}C plateaux (Figure 3). A contour plot for χ^2 confidence intervals at 68, 60, and 50% levels (Figure 5) shows two possible date ranges for the 750.5 cm depth at the 68% level. The best fit is at 11470^{+30}_{-55} cal. BP, with 11 350 ± 30 cal. BP as an alternative. Evaluation of the sedimentation rate for the first 6 cm of the Holocene (756.5–750.5 cm) is obviously critical to the accuracy of the boundary dating. Our sedimentation rate model prescribes an average of 0.1 cm yr^{-1}, i.e. 60 years for the actual 6 cm. If allowance is made for both the earliest Holocene rate of *c*. 0.07 cm yr^{-1} and the Younger Dryas average of 0.15 cm yr^{-1}, the 6 cm equals 60 ± 20 yr. This results in an estimated date for the YD/H transition of 11530^{+40}_{-60} cal. BP, or alternatively 11 410 ± 40 cal. BP, both at a 68% confidence level, and with the uncertainty of ±20 yr in the positioning of the pine chronology included. The older date, containing the best fit, is considered to be the best estimate.

Discussion

Kråkenes Lake

While the dated lithostratigraphic boundary is very sharp at 756.5 cm depth, there is some biotic evidence pointing towards an earlier small climatic improvement around 762 cm depth (Birks, 1997). This is 2.5 cm below a 3-cm layer of massive silt at the top of the YD sequence (Figure 2). The lack of structures indicates that this silt layer may have been deposited by an instantaneous event, possibly flooding associated with the rapid drainage of an ice-dammed lake in the cirque. The initial weak warming episode and the lithostratigraphic boundary at 756.5 cm are within 10–20 calendar years (simultaneous within the dating precision). We conclude therefore that the best estimate of the age of the YD/H boundary and transition is 11530^{+40}_{-60} cal. BP, which thus occurs ~360 calendar years before the plateau transition (see below and Table 2).

The δ^{13}C values plotted in Figure 3 are those obtained on gyttja samples. The very variable loss of material during pretreatment of the *Salix* leaves implies that the isotopic composition of these samples possibly depends more on the degree of humification of the samples than on environmental parameters. The δ^{13}C values of the whole gyttja samples increase after the YD/H to a maximum at *c*. 10 800 cal. BP, before a long-term decrease (Figure 3). This may be due to increasing water-use efficiency by terrestrial plants and thus less discrimination against ^{13}C during CO_2 uptake in response to increasing temperature. Terrestrial macrofossils (e.g. *Salix herbacea* leaves) are abundant in the sediments up to 740 cm (Figure 2) and other substantial terrestrial macrofossils (e.g. of *Salix*) are common up to 720 cm (H.H. Birks, unpublished data). Freshwater algal carbon tends to be lighter in δ^{13}C than terrestrial-derived carbon (Ariztegui and McKenzie, 1995). At Kråkenes, the rise and decline in δ^{13}C may be explained most simply by the relative changes in the amounts of terrestrially derived and within-lake derived carbon in the sediments, according to the balance between allochthonous and autochthonous organic material, that also influences the sedimentation rate.

Comparison with other sites/archives

The most recent estimates for the calendar year age of the Younger Dryas-Holocene transition derived from various sources are compared in Table 2. The plateaux on the radiocarbon calibration curve at 9600 and 10 000 ^{14}C yr BP should be globally synchronous events, as they relate to global changes in atmospheric ^{14}C concentration, and should be detectable in closely

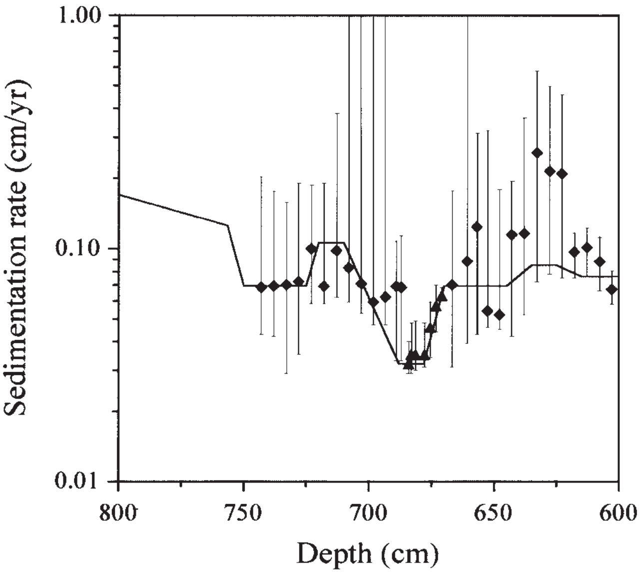

Figure 4 Sedimentation rate variation in Kråkenes Lake obtained by wiggle-matching running groups of samples. Each group spans 25–35 cm of sediment thickness with a group size of eight samples when applicable. Symbols are plotted at the average depth for each group. The error bars show 68% confidence intervals according to a χ^2 test, except for the 670–685 depth range (filled triangles) where inclusion of two outlying measurements make 80% confidence limits necessary. Large error bars are associated with ^{14}C plateaux where the data are invariant to different sedimentation rates. The solid line shows the sedimentation rate pattern after wiggle-matching the complete data set of 43 samples (see text).

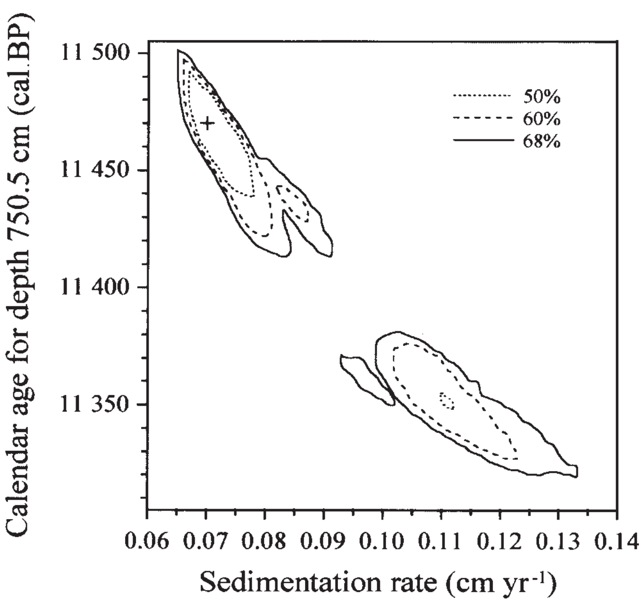

Figure 5 Confidence contours for the calendar age of 750.5 cm and for the sedimentation rate for depth range 710–750 cm, obtained by wiggle-matching of the Kråkenes data. Different confidence levels are shown by different types of line. The best fit is indicated by the + symbol.

dated material. Thus the end of the 10 000 BP plateau is a marker against which to compare the dating of the YD/H boundaries estimated from the different archives (see, for example, Stocker and Wright, 1996). However, for practical purposes, it is more reliable to use a radiocarbon date in the plateau transition (PT) as a marker, because it is difficult to establish the plateaux extremities sufficiently precisely, even in our fine-resolution series of radiocarbon dates (compare the macrofossil and gyttja dates in Figure 3). A point on the plateau transition can, however, be recognized relatively easily by radiocarbon dating, as this stratigraphic level has a unique ^{14}C age. Therefore, for comparison of different ^{14}C archives we have used 9750 ^{14}C BP, equivalent to 11 170 cal. BP (Table 2). Ice-core and Baltic varve levels are dated independently of radiocarbon by counting annual layers.

The generally slight differences in the age estimates of the Younger Dryas-Holocene transition described below and in Table 2 may be attributable to errors or imprecision in the identification of the boundaries and in their dating, to dating of different events within the transition, and to systematic divergencies between dating methods (varve counting, dendrochronology, ice-core chronology, radiocarbon dating etc.). However, there may also be real differences in the ages of the transitions being dated. This may be caused by different sensitivity and response times to an initial climatic change, in, for example, the ocean, in terrestrial vegetation, in the isotopic composition of precipitation in Greenland, and in the isotopic composition of lake carbonate in Switzerland and Poland (see Wright, 1984). The differences may also be due to geographically different rates or amplitudes of the climatic changes themselves, thus causing a time-transgressive reaction in, for example, vegetation or lake sediments, as the different thresholds for causing stratigraphically detectable changes in biological, geological and atmospheric systems are passed.

Laminated lake sediments

At Lake Gościąż (Poland) wiggle-matching of the ^{14}C dates of the annually laminated lake sediments to the oak dendrochronology placed the YD/H transition at 11 440 ± 120 cal. BP (Goslar *et al.*, 1995b). When available data (T. Goslar, personal communication) close to the plateau transition are wiggle-matched against the corrected dendrocalibration pine data, we obtain a YD/H boundary estimate of 11 460 cal. BP (Table 2). This is consistent with Goslar *et al.*'s (1995b) date, when this is corrected for the 41 yr that were missing from the oak chronology at 7191 cal. BP. This may suggest that the YD/H at Lake Gościąż is slightly later than at Kråkenes, the Swedish Lakes, the German pines and the GRIP aricives. However, the Gościąż radiocarbon dates are rather scattered, and our wiggle-match estimate could easily be altered by further data.

The floating chronology of the varved sediments at Soppensee (Switzerland) is positioned by wiggle-matching of AMS dates of terrestrial plant macrofossils to the German oak chronology, and corrections are applied for several unlaminated intervals (Hajdas *et al.*, 1993). The YD/H boundary is defined by pollen changes observed in another core (Lotter, 1991), and cross-correlated to the dated core. It is surprising that the end of the YD in Soppensee is placed after the end of the 10 000 BP plateau (Table 2) (Wohlfarth, 1996), whereas the correlated pollen-zone boundary precedes the end of the plateau by 250–300 years in the radiocarbon dated sequence from nearby Rotsee (Lotter, 1991; Figure 2).

The YD/H transition in Holzmaar (Germany) is dated by Hajdas *et al.* (1995) by wiggle-matching AMS dates of terrestrial macrofossils from a laminated sediment sequence of *c.* 6500 years to the combined oak and pine chronology of Kromer and Becker (1993). Using uncorrected calibration data, they obtained an age estimate of 11 490 cal. BP for the boundary as defined by pollen stratigraphical and lithological changes (Zolitschka *et al.*, 1992). Matching of the Holzmaar data in the range 4500–11 500 cal. BP to the corrected IntCal 93 calibration data gives a best fit at 11 555 cal. BP, but with a χ^2-value outside the 68% confidence level. This is 385 years before the plateau transition and is in fair agreement with Kråkenes (Table 2).

When a correction of 80 years (S. Björck, personal communication) is added to the estimate of the age of the YD/H boundary in unlaminated south Swedish lakes (Björck *et al.*, 1996) using the YD/H lithostratigraphic change and a series of radiocarbon dates, the result is very close to the Kråkenes estimate (Table 2). The fast Fourier transform smoothing through the AMS

Table 2 Comparison of age estimates of the Younger Dryas-Holocene transition and comparison with the Plateau Transition (PT)

Archive	Boundary definition	Dating method	YD/H age (cal. BP)	YD/H-PT cal. yr	References
Kråkenes Lake	LITH	^{14}C-WMP	$11\,530^{+40}_{-60}$ (2)	360	This work
Lake Gościąż	^{18}O, VEG	VC/^{14}C-WMO	11 460 ± 120 (1)	310	Goslar *et al.* (1995b) (see text)
Soppensee	VEG	VC/^{14}C-WMO	11 027 ± 69 (2)	~−140	Hajdas *et al.* (1993)
Holzmaar	VEG	VC/^{14}C-WMOP	11 490	~320	Hadjas *et al* (1995) (see text)
S. Swedish lakes	LITH, VEG	^{14}C	11 530–11 480	360–310	Björck *et al.* (1996)
German pines	^{13}C, ^{2}H	DEND	11 250 (2)	~80	Kromer and Becker (1993)
German pines	Ring width	DEND	11 530–11 470	360	Björck *et al.* (1996)
Swedish varves	IMR	VC	11 440		Wohlfarth (1996)
GRIP ice core	^{18}O	VC	11 510 ± 70		Johnsen *et al.* (1992)
GISP2 ice core	^{18}O	VC	11 640 ± 280		Alley *et al.* (1993)
	Δ^{14}C change	DEND, VC	11 500 (2)	330	Stuiver *et al.* (1991)

^{18}O, ^{13}C, ^{2}H – Changes in isotopic compositions.
LITH – Changes in lithology of sediment.
VEG – Biostratigraphical changes, pollen assemblage zones.
IMR – Changes in ice margin recession rate.
WMP – Wiggle-matching against pine dendochronology.
VC – Varve counting.
YD/H – Younger Dryas-Holocene transition.
WMO – Wiggle-matching against oak dendrochronology.
DEND – Dendrochronology.
PT – Plateau transition, 9750 ^{14}C BP; 11 170 cal. BP (2).
^{14}C – Radiocarbon dating.
(1) – Corrected for missing oak rings at 7191 cal. BP (41 years).
(2) – Corrected for missing oak rings and revised oak-pine connection (total 200 years).

radiocarbon series they used to match against the dendrocalibration curve is not a direct wiggle-matching, and relies on assumed constant sedimentation rates between fixed points (Björck *et al.*, 1996).

German pines

Some type of environmental change is indicated in the isotopic changes (^{13}C and ^{2}H) measured in wood samples from the pine chronology. The beginning of a marked increase in the δ-values at 11 250 cal. BP (Table 2) has been interpreted as the YD/H transition (Becker *et al.*, 1991; Kromer and Becker, 1993). This is rather close to the end of the 10 000 BP plateau and ~280 years later than our boundary. However, the interpretation of the isotopic change, and its relation to climatic change, is as yet uncertain. Reduced carbon isotope discrimination and hence a rise in δ^{13}C in the plants is probably a result of an increase in water-use efficiency that is most likely brought about by reduced soil moisture causing stomatal closure (Leavitt and Long, 1986; Depouey, 1995). Increased atmospheric CO_2 concentrations over the YD/H transition (Beerling *et al.*, 1995) may also lead to a reduction in stomatal density and increased water-use efficiency, reinforcing the effect. There is widespread evidence for periods of low lake-water levels close to the YD/H transition in Switzerland, Poland, south Germany, Austria and further north in the Netherlands and south Sweden (Gaillard, 1985, and references therein; Pazdur *et al.*, 1994). At Kråkenes, there seems to be little evidence for any cooling related to the proposed PreBoreal Oscillation (e.g. Björck *et al*., 1996), but there is evidence for a summer-dry interval that finished coincident with the end of the 9600 BP ^{14}C plateau. This may be related to the widespread evidence of a dry interval in Europe at this time. We speculate that the isotopic change in the German pines (Becker *et al.*, 1991) also reflects this European dry interval, and is an indirect effect rather than a direct expression of the Holocene temperature rise. Indeed, evidence of a more continental climate is found in the tree-rings themselves between 10 000 and 9000 ^{14}C BP (Becker and Kromer, 1993). An increase in ring width observed in the German pines between 11 530 and 11 470 cal. BP is now suggested to be a response to the Holocene warming (Björck *et al.*, 1996; S. Björck, personal communication).

Swedish varves

The Swedish Time Scale, extending *c.* 13 000 years back from present, is constructed from a large number of correlated clay varve sequences. The first rapid rate of ice-sheet retreat in central Sweden, that is possibly the response to the first Holocene warming, is tentatively positioned at *c.* 11 440 varve yr BP (Strömberg, 1994; timescale adjusted by Wohlfarth, 1996) (Table 2). However, the oldest part of the Swedish varve chronology is poorly connected (Wohlfarth, 1996; personal communication) and this age will probably be revised.

Ice cores

The δ^{18}O records from the GRIP and GISP2 ice cores at the Greenland summit (Johnsen *et al.*, 1992; Alley *et al.*, 1993) display major and rapid changes reflecting similar climate fluctuations to those described from continental Europe. By counting annual layers the YD/H transition is dated to 11 510 ± 70 GRIP ice-core yr BP, and 11 640 ± 280 GISP2 ice-core yr BP. If the estimate of Birks *et al.* (1996b) for the Saksunarvatn Ash is corrected by the addition of 200 years, the result is 10 210 ± 30 cal. BP for the first occurrence of the ash in the sediment. On the revised GRIP timescale (S. Johnsen, personal communication) the age of the Saksunarvatn Ash in the GRIP ice core (Grønvold *et al.,* 1995) is 10 240 ± 30 ice-core yr BP. The two ages are remarkably close.

Conclusions

This radiocarbon study at Kråkenes has tackled several problems in dating the Younger Dryas-Holocene transition. In order to determine and model the global mechanisms operating at the last glacial termination, a precise calendar timescale is essential (e.g. Björck *et al.*, 1996; Stocker and Wright, 1996) for tracking the times and rates of change, locally, regionally and globally, and for modelling the mechanisms of change during this unstable transitional period. However, one result of the mechanisms, particularly those involving changes in ocean circulation, is the variation in atmospheric ^{14}C concentration that leads to radiocarbon plateaux, thus making detailed dating by radiocarbon impossible in the absence of direct comparisons with independent, calendar timescales. The best of these for this time period is the dendrocalibration curve (Becker and Kromer, 1993). This is undergoing revisions (e.g. Kromer *et al.*, 1996) that will lead to a more precise ^{14}C chronological calibration. In combination with other shorter calibration series such as Lake Gościąż (T. Goslar, personal communication) and the Cariaco Basin (Hughen *et al.*, 1998), the precision of the chronology of lateglacial climatic changes and the responses to them will be enhanced.

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