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^{14}C AND OTHER PARAMETERS DURING THE YOUNGER DRYAS COLD PHASE

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ABSTRACT. Pollen analysis as well as $^{18}O/^{16}O$ results on lake marl show that the Younger Dryas climatic period, between about 11,000 and 10,300 BP, was the last vigorous cold phase of the Würm Glacial. Detailed ^{14}C analyses from a peat bog near Wachseldorn (Switzerland) point to a ^{14}C anomaly in this period. Further indication of a ^{14}C anomaly is given by the observation that, during the Younger Dryas period, the sedimentation rates in several lakes apparently were higher than in adjacent periods; an explanation might be that the ^{14}C time scale was compressed between 11,000 and 10,000 BP, *ie,* the atmospheric $^{14}C/C$ ratio varied. If real, this suggested ^{14}C variation would probably be connected to the climatic events during this transition period from Later Glacial to Postglacial.

INTRODUCTION

Measurements on dendrochronologically dated tree-rings made it possible to reconstruct the history of the atmospheric $^{14}C/C$ ratio of the last 8000 years (Nobel Symposium 12; these proceedings). The results proved the existence of ^{14}C variations of different frequencies and amplitudes, a finding of great geophysical importance. A direct or indirect relation between atmospheric ^{14}C levels and climate has been suggested and discussed repeatedly (de Vries, 1958; Damon, 1968; Suess, 1970). If such a relation indeed exists, especially pronounced ^{14}C variations can be expected to have occurred during the transition period from Glacial to Postglacial, about 14,000 to 9000 BP.

Several years ago, we noticed that ^{14}C dates on peat profiles exhibit irregularities around 10,000 BP, *ie,* at the boundary between the pollen zones Younger Dryas (the last and vigorous cold phase of the Würm ice age) and Pre-Boreal. The end of the Late Postglacial and beginning of the Postglacial is often considered to have occurred around 10,000 BP. We, therefore, decided to perform detailed ^{14}C analyses on a peat bog near Wachseldorn (Switzerland) which is known from pollen analysis, to have grown continuously during the whole Late Glacial and Postglacial time. The data are presented below, together with the results of pollen analysis. Furthermore, general environmental conditions during the Younger Dryas cold phase, as inferred, eg, from $^{18}O/^{16}O$ data in lake carbonate sediments, are discussed.

The Wachseldorn peat bog

Description of the area

The area of Schwarzenegg-Wachseldorn-Heimenschwand is situated in the Swiss Plateau (fig 1) at an altitude of about 920m to 1030m asl. The greatest part of the bedrock of this area consists of Nagelfluh, a tertiary conglomerate. It is covered by deposits of the Riss and Würm glacial. The landscape was strongly formed by the activities of the Aare

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and Emme glaciers during the Würm glacial which left well marked moraines and large basins on the various plateaus. The material of the ground moraine is very clayey, so that the water hardly ran off, making the formation of bogs possible. The peat growth of these bogs was also favored by considerable precipitation, a typical feature of this area.

At the beginning of the last century, large raised bogs still existed in this region. Their original extension was estimated by Früh and Schröter (1904) to about 2.24km^2. During the last century, the strange landscape of bogs attracted botanists, since the raised bogs were harboring several very rare plant species which are considered relicts from the ice age. However, considerable peat cutting was started in the last century and was intensified in our century, so that today the large raised bogs have been destroyed except for a few remnants. Nearly all rare plant species became extinct.

Pollen-analytic investigations and ^{14}C studies

Keller (1928) was the first to examine the pollen content of two sections of this area. Later, Heeb studied the formation of the raised bogs as well as the vegetational history of this area by means of pollen analysis (Heeb and Welten, 1972). These studies showed that the raised bog Wachseldorn-Untermoos is especially suited for palynologic research. At the northwestern margin of the remaining peat area, Heeb could take

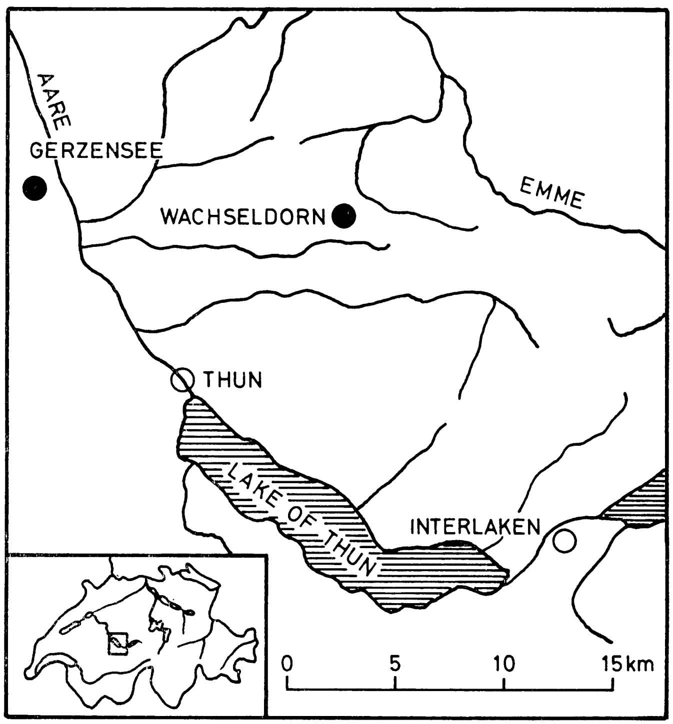

Fig 1. Map of the area of investigation: Switzerland, with area of detailed map.

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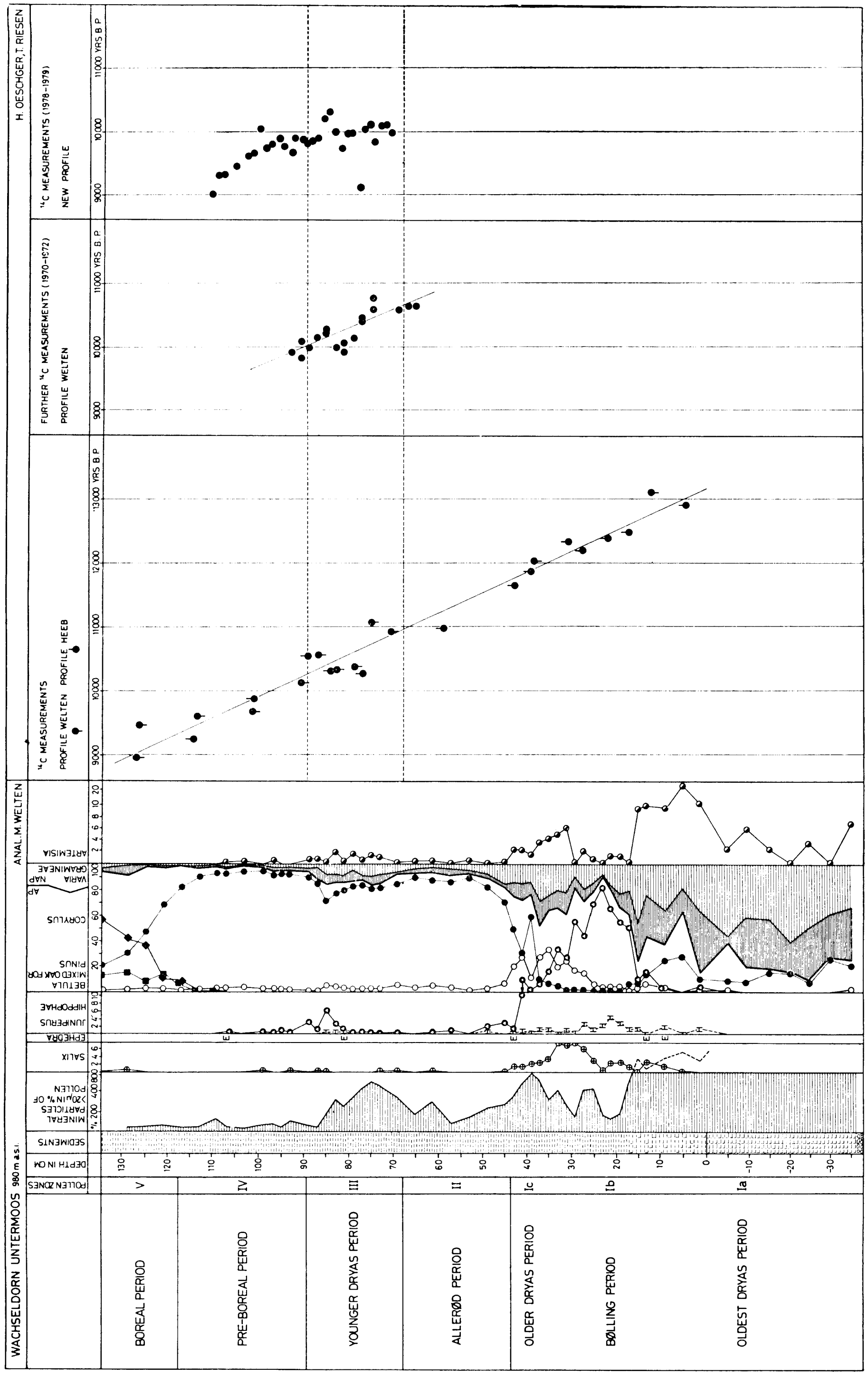

Fig 2. Pollen profile and ^{14}C results of the Wachseldorn peat bog. The pollen profile and the center ^{14}C profile belong to the samples taken by Welten; the other ^{14}C profiles were adjusted by means of the pollen-analytic results.

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excellent samples at a peat wall for pollen analytic studies and ^{14}C dating. The pollen-analytic results, as well as the ^{14}C dates, showed that formation of the Cyperaceae-Hypnaceae peat started at the beginning of the Bølling s l period. Peat growth continued then during the entire Late Glacial and Postglacial time. Thus, this raised bog seemed very suitable for ^{14}C dating.

After the early death of K Heeb in 1970, Welten took another profile from the same wall for pollen analysis. In figure 2, this pollen diagram is presented in a reduced form. The complete diagram will be published later. Since the ^{14}C dates in the profile of Heeb (Heeb and Welten, 1972) as well as in the profile of Welten showed certain anomalies in the section of the Younger Dryas period and in the transition to the Pre-Boreal period, a third profile was taken from the same peat wall in November 1978 in order to repeat dating of the sediments of these periods.

The Late Glacial vegetation history of the area of Wachseldorn

The diagram shows that classical succession of Late-glacial vegetation stages, as demonstrated also in other pollen-analytically examined profiles from various regions of Switzerland. The bottom part of the profile is to be attributed to the Oldest Dryas period (Ia). The vegetation of this cold period following the melting of the glaciers was formed mainly by grasses, sedges, and other herbs, especially by *Artemisia*.

There were hardly any trees in the landscape of Wachseldorn. It is possible that the change of sediments from clay to peat represents the border between the periods Oldest Dryas (Ia) and Bølling s l (Ib). This change of sediments was chosen as the basis for height measurements. Improvement of climatic conditions at the beginning of the Bølling s l induced the spread of *Juniperus* in the Wachseldorn area. *Salix, Hippophaë,* and *Betula* became frequent, too, while *Artemisia* and other herbs of the Late Glacial flora were pushed back. During the climatic deterioration of the Older Dryas period (Ic), herbs became more dominant again and the relative abundance of mineral particles in the sediment points to a more open vegetation. During the Allerød period (II) pine forests dominated in the whole area. As a result of cooling during the Younger Dryas period (III) various herbs of the Late Glacial flora reappeared and *Juniperus* spread again. Larger deposition of mineral particles indicates a more open forest. The Pre-Boreal period (IV) is marked by a strong domination of *Pinus* and the appearance of the first warmth-requiring tree species. The extension of *Corylus* and of trees of a mixed oak forest marks the transition to the Boreal period (V).

^{14}C analyses

As mentioned above, three peat profiles were taken at Wachseldorn, the first by Heeb, the second by Welten, and the third, "new" profile in November 1978 by Welten and Oeschger. Pollen analysis was performed on all three profiles enabling relationships and, thus, comparisons of ^{14}C results of the different profiles (fig 2). Minor uncertainties in synchronization cannot, however, be avoided.

The first ^{14}C dates on the profiles of Heeb and Welten (furthest left ^{14}C profile, fig 2) were measured routinely. No special efforts regarding accuracy and precision were made. An irregularity in the ^{14}C dates appeared in the Younger Dryas period, with an abrupt decrease in ^{14}C age from about 11,000 to 10,300 BP, and a minor increase back to about 10,500 BP at the end of Younger Dryas.

In order to examine the ^{14}C levels in more detail, further ^{14}C analyses were than performed on Welten's profile, concentrating on the time interval of interest (center ^{14}C profile, fig 2). The results exhibited a similar pattern, though shifted by 200 to 300 years towards younger ^{14}C ages. The reason for this difference is not certain; eg, small errors in the background count rate assumed for calculating the ^{14}C ages might be responsible.

Precision ^{14}C measurements were performed on the profile collected in 1978. Preparation of the samples consisted of treatment with HCl,

TABLE 1

1978 Wachseldorn peat samples-radiocarbon dates

Height above clay horizon (cm)	Laboratory number	Radiocarbon age in years BP Counter I	Counter II	Average
98.5-100.0	B-3332	8983 ± 55	9031 ± 55	9007 ± 39
97.0- 98.5	B-3333	9291 ± 55	9327 ± 55	9309 ± 39
95.5- 97.0	B-3334	9312 ± 43	9293 ± 56	9304 ± 34
92.5- 94.0	B-3336	9421 ± 64	9468 ± 58	9446 ± 43
89.5- 91.0	B-3338	9669 ± 58	9537 ± 59	9604 ± 41
88.0- 89.5	B-3339	9655 ± 76	9652 ± 69	9653 ± 51
86.5- 88.0	B-3340	10,016 ± 51	10,073 ± 60	10,040 ± 39
85.0- 86.5	B-3341	9733 ± 58	9776 ± 60	9754 ± 42
83.5- 85.0	B-3342	9847 ± 61	9774 ± 50	9803 ± 39
82.0- 83.5	B-3343	9871 ± 62	9915 ± 68	9891 ± 46
80.5- 82.0	B-3344	9783 ± 59	9750 ± 52	9764 ± 39
79.0- 80.5	B-3345	9621 ± 60	9707 ± 38	9682 ± 32
77.5- 79.0	B-3346	9921 ± 51	9857 ± 49	9888 ± 35
76.0- 77.5	B-3347	9882 ± 75	9867 ± 62	9873 ± 48
74.5- 76.0	B-3348	9784 ± 54	9846 ± 61	9811 ± 40
73.0- 74.5	B-3349	9857 ± 63	9864 ± 61	9861 ± 44
71.5- 73.0	B-3350	9894 ± 46	9909 ± 58	9900 ± 36
70.0- 71.5	B-3351	10,253 ± 60	10,154 ± 61	10,204 ± 43
68.5- 70.0	B-3352	10,324 ± 65	10,309 ± 52	10,315 ± 41
67.0- 68.5	B-3353	10,182 ± 59	9977 ± 60	10,081 ± 42
		9961 ± 56	10,026 ± 55	9994 ± 39
65.5- 67.0	B-3354	9797 ± 58	9702 ± 59	9750 ± 41
64.0- 65.5	B-3355	9970 ± 59	9994 ± 57	9982 ± 41
62.5- 64.0	B-3356	9987 ± 48	9987 ± 42	9987 ± 32
61.0- 62.5	B-3357	9222 ± 55	8984 ± 56	9105 ± 39
			8836 ± 55	8836 ± 55
59.5- 61.0	B-3358	10,004 ± 60	10,081 ± 59	10,043 ± 42
58.0- 59.5	B-3359	10,201 ± 51	10,039 ± 62	10,136 ± 39
		10,076 ± 68	10,110 ± 57	10,096 ± 44
56.5- 58.0	B-3430	9851 ± 47	9837 ± 65	9846 ± 38
55.0- 56.5	B-3431	10,100 ± 64	10,092 ± 62	10,096 ± 45
53.5- 55.0	B-3432	10,041 ± 80	10,162 ± 69	10,110 ± 52
52.0- 53.5	B-3433	9997 ± 53	9911 ± 59	9959 ± 39

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NaOH, again HCl, and rinsing with distilled water. The samples were dried at 100°C. Conversion to CO_2 was follwed by synthesis of methane, our counting gas. Each sample was measured successively in two 1 liter copper proportional counters equipped with external guard counters. Operated at 4905mb, the copper counters have modern net effects of 35.4cpm and 32.9cpm, respectively, and background counting rates of 0.8cpm and 0.6cpm, respectively, in our underground laboratory (*cf* Loosli, Heimann, and Oeschger, 1980). Results covering peat samples ranging between 52cm and 100cm above the clay horizon and corresponding to the critical era are listed in table 1 and plotted in figures 2 and 3. Agreement between the measurements in the two counters is generally excellent. Discrepancies could partly be eliminated by third and fourth measurements. Sample B-3357 definitely must be prepared and measured again. $\delta^{13}C_{PDB}$ values for the 1978 profile were –29.3‰ on the average which lead to an age correction of about –70 years. This must be considered when the 1978 profile is compared to the two earlier profiles for which no $\delta^{13}C$ measurements were performed and no ^{13}C correction applied. Since those samples can be assumed to show similar $\delta^{13}C$ values, the ^{14}C dates of the two earlier profiles should be corrected by about 70 years toward younger ages for comparison with the 1978 profile.

Results for the "new" profile confirm the earlier ones with regard to the second half of Younger Dryas. A peak of about 300 ^{14}C years

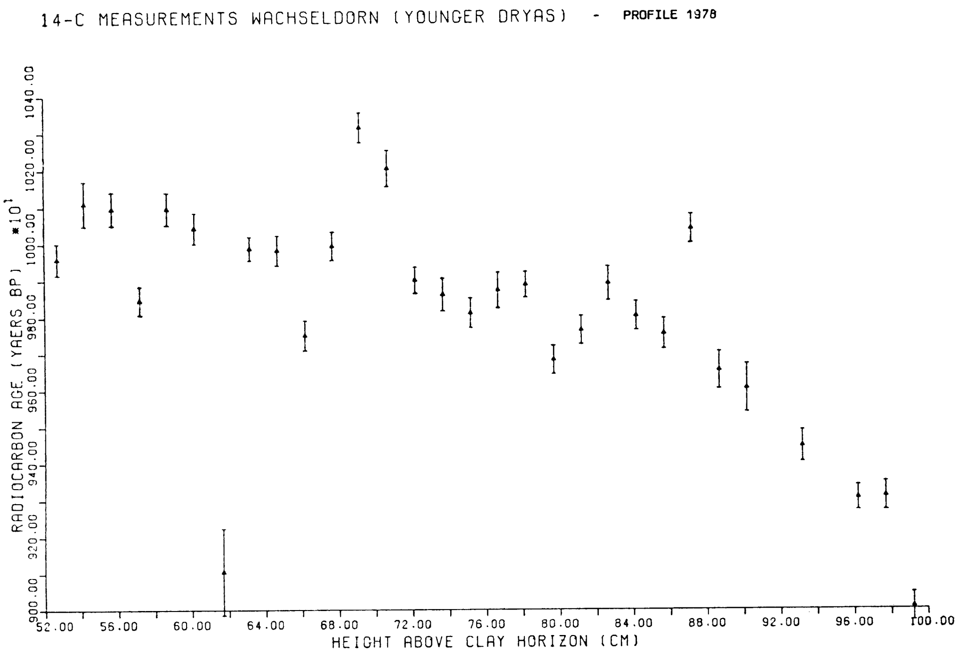

Fig 3. ^{14}C measurements Wachseldorn profile 1978. Younger Dryas period corresponds to peat layers between 50cm and 75cm above clay horizon. Note that the height scales of figures 2 and 3 are for different peat sections.

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toward older ages is observed at the end of the Younger Dryas. Data for the first half of the Younger Dryas appear too young, compared to the earlier profiles. Several ^{14}C results at the lower end of the 1978 profile have been omitted in figure 2 because pollen from younger vegetation periods indicates contamination in those horizons. Although no allochthonous pollen was found in the horizons for which ^{14}C data are shown in figure 2 and 3, the lower layers might also be contaminated. This would explain the difference from the former profiles.

The results of all three ^{14}C profiles together strongly suggest that there was a marked ^{14}C anomaly during the Younger Dryas cold phase, *ie,* between 11,000 and 10,000 BP (conventional ^{14}C years). There are possibly some disturbances in the peat which also may have affected the ^{14}C profiles, eg, irregular peat growth. However, a varying rate of peat growth cannot explain a reversal of the ^{14}C time scale as observed at Wachseldorn.

Further evidence for a ^{14}C anomaly

We noticed that for several profiles of lake marl, the sedimentation rate during the Younger Dryas was surprisingly large compared to other time intervals. Lake marl is formed when aquatic plants withdraw CO_2 from the lake water and consequently, solid carbonate is precipitated. Unfortunately, no ^{14}C dates exist yet for these profiles (they do not contain enough organic matter). Thus, sedimentation rates must be determined from indirect dating by comparing their pollen diagrams with those of ^{14}C dated peat sections. In a number of ^{14}C dated peat sections in Switzerland (Welten, 1972) the following average ^{14}C ages of pollen zone boundaries were found: 13,300 BP for the boundary Oldest Dryas/Bølling (Ia/Ib), 11,000 BP for Allerød/Younger Dryas (II/III), 10,300 BP for Younger Dryas/Pre-Boreal (III/IV), and 9100 BP for Pre-Boreal/Boreal. Based on these dates, the mean (apparent) sedimentation rates in Lake Gerzensee (fig 4) were 3.4cm per 100 years during the first interval (Ib + Ic + II), 8.3cm per 100 years during the Younger Dryas, and 2.5cm per 100 years in the Pre-Boreal phase (IV, 130 to 165cm).

One explanation for this anomaly might be a much higher input of allochthonous sediments during the Younger Dryas because of thinner vegetation cover during this cold phase. Such an increased input is indicated for the Wachseldorn peat bog by a higher percentage of mineral particles (see fig 2). A significantly higher river input of material during the Younger Dryas should have led to a higher percentage of non-carbonate sediment, as it is observed during the Oldest Dryas (Ia) when productivity, and, therefore, sedimentation of lake marl, was still low. The nearly constant carbonate content (fig 4) contradicts this view, however. In profile Gerzensee III, carbonate content of the sediment was always more than 80 percent after the beginning of pollen zone Ib (Bølling) including the Younger Dryas. We also observed anomalously high sedimentation rates during the Younger Dryas in other lake marl profiles. The values are given in table 2. Carbonate content was measured also at Chirens, and it also remains constant there over the entire time span Ib to IV.

Thus, using the indicated ^{14}C data for the pollen zone boundaries, the sedimentation rate during the Younger Dryas seems to be two to three times higher than in adjacent periods, in at least four different lakes. It is difficult to see why such a systematic fluctuation should occur, since allochthonous sediment input cannot be made responsible. An explanation for variation of the apparent sedimentation rate might be

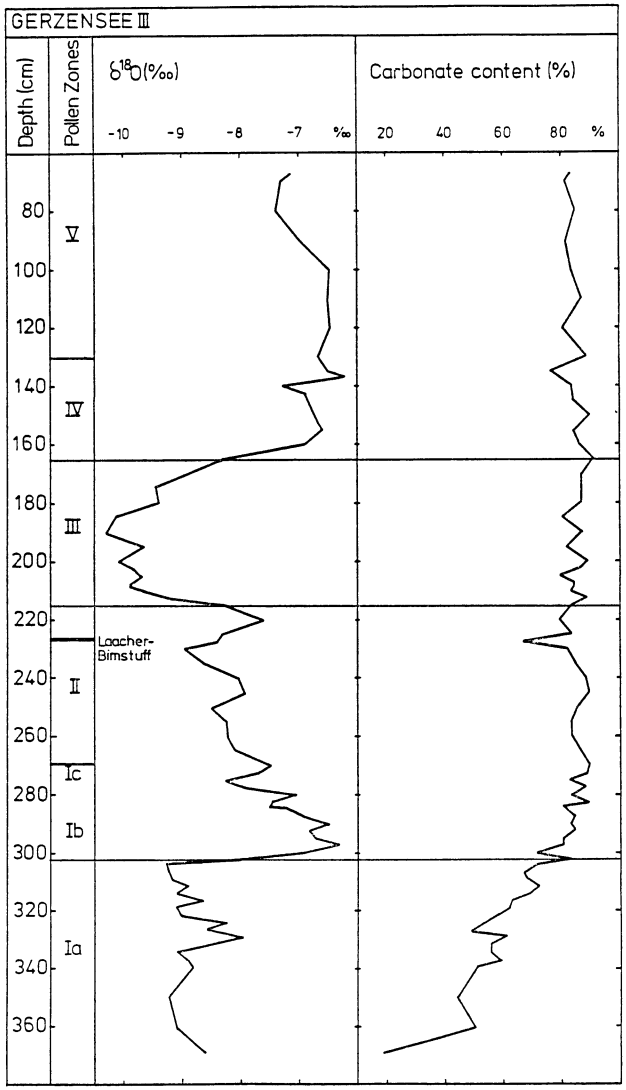

Fig 4. $\delta^{18}O$ and carbonate content (percent of dry sediment by weight) for lake marl from Lake Gerzensee (profile Gerzensee III).

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that the Younger Dryas period lasted considerably longer than assumed. This would imply that the ^{14}C time scale was strongly compressed between 10,000 and 11,000 ^{14}C years BP.

There are not many ^{14}C studies covering the age range considered here with which our results can be compared. Comparison of ^{14}C dates with varve countings for Lake of the Clouds (Stuiver, 1970) yielded some evidence for a fluctuation of the ^{14}C level around 10,000 BP. Further work will be necessary to see if the observed anomaly of sedimentation rates is indeed due to a fluctuating atmospheric $^{14}C/C$ ratio.

Discussion of environmental conditions during the Younger Dryas period

$^{18}O/^{16}O$ variations in precipitation as recorded in lake sediments

An empirical relationship exists between $^{18}O/^{16}O$ ratios in meteoric precipitation and temperature. As has been shown by detailed measurements, $^{18}O/^{16}O$ profiles in polar ice reflect the climate history back to the last Interglacial (eg, Dansgaard and others, 1969). In temperate latitudes, $^{18}O/^{16}O$ variations in precipitation are recorded in authigenic lake carbonates (lake marls or mollusk shells). These carbonates are formed in the lake and therefore reflect oxygen isotopic composition of the lake water at the time of their formation. There is an isotopic fractionation between the water and the precipitated carbonate, so that the $^{18}O/^{16}O$ variations in water and carbonate are not quantitatively the same, but they go in the same direction. A detailed discussion is given by Eicher and Siegenthaler (1976). Here, we base our findings on the observation that in warmer periods $^{18}O/^{16}O$ ratios are higher than in cooler periods.

Material from the Wachseldorn bog is not suited for such analyses. Therefore, we will discuss results obtained at a site nearby. In figure 4, $^{18}O/^{16}O$ ratios measured in profile III of Lake Gerzensee, a small lake still existing today (fig 1) are given, together with the relative carbonate content of the dry sediment. The $^{18}O/^{16}O$ ratios are given as deviations ($\delta^{18}O$) in per mil from the standard PDB. In a previous publication

TABLE 2

Sedimentation rates of lake marl in cm per 100 years

Location	Ib+Ic+II	III	IV	Pollen analysis by	Reference
Gerzensee III (Switzerland)	3.8	7.1	2.9	Eicher	This paper
Faulenseemoos (Switzerland)	4.4	10.0	—	Welten	Eicher and Siegenthaler, 1976
Leysin (Switzerland)	2.4	6.0	2.1	Welten	unpublished
Tourbière de Chirens (French Alps)	5.9	13.6	2.9	Wegmüller	Eicher, Siegenthaler, and Wegmüller, 1980

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(Eicher and Siegenthaler, 1976) $\delta^{18}O$ values obtained on another profile (Gerzensee II) from the same lake were discussed in detail, together with results from pollen analysis. The results of Gerzensee III are very similar to those of Gerzensee II.

Three transitions between pollen zones are strongly marked in $\delta^{18}O$ by abrupt shifts of 2 to 3‰: the transitions Ia/Ib (Oldest Dryas/Bølling), II/III (Allerød/Younger Dryas), and III/IV (Younger Dryas/Pre-Boreal). On the other hand, the Older Dryas period (Ic) considered from pollen studies as possibly not a very distinct cool phase, is not clearly recognizable in the $\delta^{18}O$ profile, so that the interval Ib-Ic-III appears as a more or less uniform and static climatic period. The general decrease of $\delta^{18}O$ can partly be explained by a simultaneous $\delta^{18}O$ decrease in the oceans, due to the addition of abundant meltwater from the ^{18}O-depleted ice sheets.

A remarkable feature of the Younger Dryas period is the abruptness of the climatic changes which is most clearly demonstrated in the ^{18}O results from Gerzensee as well as from a number of other sites (Eicher and Siegenthaler, 1976; Eicher, Siegenthaler, and Wegmüller, 1980; Eicher, unpub). In view of the length of the Younger Dryas, only about 700 years according to ^{14}C dating, transitions from warm to cold and vice versa must have occurred within about one century or less, while before and after each transition, the climate was relatively stable. This would remain true even if the ^{14}C age scale were distorted in that period.

The main points of interest, then, in the $\delta^{18}O$ results from lake carbonates are 1) the observation that during the Younger Dryas, the climate was markedly different from the adjacent periods (*cf* also, Moore, 1979), 2) that onset and end of the Younger Dryas occurred abruptly. At present, we can only try to speculate about the cause of such drastic, rapid environmental changes.

Possible causes of the suggested ^{14}C variation

Three causes of variations of the atmospheric $^{14}C/C$ ratio (Suess, 1970) appear possible: 1) changes in the ^{14}C production rate due to changing geomagnetic field, 2) changes in the ^{14}C production rate due to the modulation of galactic cosmic rays by solar activity, 3) changes in the terrestrial carbon system.

During the late Pleistocene, geomagnetic field strength seems to have been generally lower than in the Holocene, leading to higher atmospheric $^{14}C/C$ ratios and too young ^{14}C dates (Barbetti, 1980). Barbetti notices that there should be compressions in the ^{14}C time scale from ~12,000 to 10,000 BP. Available geomagnetic data are, however, still sparse.

Since 10,000 BP marks the transition from the Glacial to the Postglacial, a connection between suggested ^{14}C variation and climatic change appears probable. For varying solar activity, this connection is evident: it would simultaneously affect ^{14}C production and terrestrial climate. A causal relation could certainly exist between observed climatic fluctuations and changes in the global carbon cycle, the third proposed mechanism (see Siegenthaler, Heimann, and Oeschger, 1980, for a discussion).

Measurements on polar ice cores suggest that atmospheric CO_2 concentration was lower during the Glacial than now (Berner, Oeschger, and Stauffer, 1980). Such a reduction would, for a constant ^{14}C production rate, imply a higher atmospheric $^{14}C/C$ ratio. Thus, all three suggested causes seem plausible in explaining ^{14}C variation around 10,000 BP.

CONCLUSION

^{14}C analyses on peat from the peat bog near Wachseldorn provide evidence that the atmospheric $^{14}C/C$ ratio fluctuated by several percent around 10,000 ^{14}C years BP. This is supported by several profiles of lake marl that exhibit much higher apparent sedimentation rates during the Younger Dryas than during adjacent time periods, if the ^{14}C time scale is used as a basis.

The results presented here must be substantiated by further studies. We plan to make further ^{14}C analyses on other peat profiles, and on profiles of lake marl. The history of atmospheric $^{14}C/C$ ratio around 10,000 BP is of special interest because that time marks the end of the Late Glacial, the beginning of the Postglacial, and the occurrence of drastic environmental changes.

Finally, this work shows that peat, although not as ideal as tree rings, is suitable for studying the history of atmospheric ^{14}C contents.

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