CARBON ISOTOPE VARIATIONS AND CHRONOLOGY OF THE LAST GLACIAL-INTERGLACIAL TRANSITION (14–9 ka BP)

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ABSTRACT. We present $\delta^{13}C$ data from both bulk organic sediment samples and terrestrial plant macrofossils from five high-resolution sedimentary sequences from the United Kingdom from which extensive multiproxy data sets have been obtained. These span the last glacial-interglacial transition. Chronological control has been provided by radiocarbon dating and/or tephrochronology. The results demonstrate that significant shifts in bulk organic $\delta^{13}C$ can be identified at key climatic transitions in most of the sites. The data are affected by site-specific influences that restrict their use as chronological markers. However, terrestrial plant macrofossil records are more consistent and reveal shifts that appear to be synchronous and which therefore offer a basis for interregional correlation as well as significant paleoenvironmental information.

INTRODUCTION

The last glacial-interglacial transition (14–9 ka BP) was characterized by marked climatic fluctuations around the north Atlantic seaboard (Walker 1995) that may have had global effects (Peteet 1995). Following deglaciation at the end of the last cold stage, temperatures increased to levels comparable to today (Late Glacial Interstadial: *ca.* 14.5–12.6 ka cal BP). An abrupt climatic deterioration known as the Younger Dryas stadial (*ca.* 12.6–11.4 ka cal BP) was marked by significant readvance of glaciers in the Northern Hemisphere, followed by significant warming during the early Holocene (post-11.4 ka cal BP). However, precise dating of events during this period is complicated by both systematic factors (*e.g.*, radiocarbon plateaus (Ammann and Lotter 1989; Wohlfarth 1996)) and site-specific controls (*e.g.*, mineral carbon error, hard water error (Lowe 1991)).

A knowledge of carbon cycling at local and regional scales is crucial to our understanding of events during the last glacial-interglacial transition since it bears on the reliability of ^{14}C age estimates. $\delta^{13}C$ of bulk organic carbon from lacustrine sediments has been routinely used as an index of fractionation and other effects (*e.g.*, Hammarlund 1993). However, the interpretation of $\delta^{13}C$ values is complicated by factors including, in lake sediments, carbon isotope fractionation within the water body (Herczeg and Fairbanks 1987), silicate dissolution (Vogel and Ehhalt 1963), aqueous productivity (Hollander and McKenzie 1991), input of terrestrially derived carbon (Mook 1980) and organic matter decomposition (Deines 1980). Nevertheless, a marked shift in bulk organic $\delta^{13}C$ has been observed by several authors at the transition from the Younger Dryas into the Holocene (Håkansson 1986; Hammarlund 1993), suggesting that this feature could provide an independent chronological control.

In an attempt to reduce the uncertainties in the interpretation of $\delta^{13}C$ values, several authors have turned to the use of terrestrial plant macrofossils. The $\delta^{13}C$ content of plant material is a measure of plant metabolism during the lifetime of the plant. The discrimination of ^{13}C relative to ^{12}C is controlled by the ratio of internal and external CO_2 concentrations (c_i/c_a) in the leaf (Farquhar *et al.* 1989). Although the environmental controls on the c_i/c_a ratio are not completely determinate (because it is not possible to distinguish, for example, between the effects of atmospheric moisture and temperature (Schleser 1995)), the use of terrestrial material at least avoids uncertainties over source material. Significant shifts in $\delta^{13}C$ have been observed during the last glacial-interglacial transition using a variety of fossil types (Becker, Kromer and Trimborn 1991; Leavitt and Danzer

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1992; Beerling 1996; Vernet *et al.* 1996), suggesting some overarching environmental control, and providing a basis for correlation.

The problem with these studies, however, has been the limited stratigraphic resolution of the period concerned. Here we present new $\delta^{13}C$ data sets for five sequences in the United Kingdom that span the last glacial-interglacial transition. The $\delta^{13}C$ measurements were obtained from the same plant genus (*Carex*). Accelerator mass spectrometry (AMS) ^{14}C dates were obtained from terrestrial plant macrofossils and converted to a calibrated time scale using CALIB 3.0 (Stuiver and Reimer 1993). A newly developed tephrochronology (Lowe and Turney 1997) for the United Kingdom provides an additional check on correlation of some of the sequences. Combining these procedures provides one of the strongest tests yet of the extent to which $\delta^{13}C$ shifts in the Late Glacial are synchronous.

METHODS

Several sites were investigated on a north-south transect across the United Kingdom (Fig. 1). Borrobol and Tynaspirit West are infilled kettle basins from which samples were obtained by coring.

Fig. 1. Site locations within the United Kingdom

The other three sites (Whitrig Bog, Gransmoor and Llanilid) provided full exposures of the last glacial-interglacial transition sediment sequences that were sampled using monolith tins. It was possible to isolate sufficient terrestrial plant material from Gransmoor (Walker, Coope and Lowe 1993; Lowe *et al.* 1995) and Llanilid for AMS ^{14}C dating (Table 1). Due to an age inversion within the Younger Dryas at Llanilid (caused by reworking processes), some of the radiometric measures based on the humin extract (reported by Walker and Harkness (1990)) have also been used. All ^{14}C analyses were performed at the NSF-Arizona AMS facility, except those obtained from humin, which were analyzed using liquid scintillation counting of benzene at East Kilbride. Unfortunately, no ^{14}C dates are yet available for the Borrobol and Tynaspirit West sequences. Two dates from

TABLE 1. ^{14}C ages and equivalent calibrated ages determined for Llanilid and Gransmoor. Note the sudden decrease in age for both ^{14}C and calibrated dates between 62 and 70 cm (Llanilid) and 142 and 160 cm (Gransmoor), marking the onset of the Younger Dryas (Björck *et al.* 1996; Hajdas *et al.* 1997).

Lab code	Depth (cm)*	Organic component	^{14}C age (yr BP)	$\delta^{13}C$ PDB ± 0.1‰	Calibrated age (cal BP) at 1 σ confidence†		
					Maximum	Median	Minimum
Llanilid							
SRR-3466	176	Humin	9320 ± 60	−29.1	10,370	10,300	10,205
SRR-3465	133	Humin	9570 ± 60	−28.9	10,901	10,800; 10,750; 10,580	10,480
SRR-3464	126	Humin	9850 ± 65	−27.6	11,009	11,000	10,984
SRR-3463	123	Humin	9920 ± 65	−28.5	11,203	11,010	10,997
AA-17669	80	Terrestrial	10,665 ± 85	−27.9	12,697	12,600	12,487
AA-17670	78	Terrestrial	10,990 ± 85	−28.9	13,002	12,910	12,813
AA-17671	74	Terrestrial	10,885 ± 75	−28.0	12,896	12,810	12,720
AA-17672	70	Terrestrial	10,585 ± 75	−28.9	12,612	12,510	12,406
AA-17673	62	Terrestrial	11,200 ± 150	−28.8	13,271	13,110	12,956
AA-17674	56	Terrestrial	11,185 ± 85	−27.2	13,194	13,090	12,998
AA-17675	52	Terrestrial	11,290 ± 95	−29.2	13,315	13,200	13,091
AA-17676	46	Terrestrial	11,395 ± 85	−28.8	13,423	13,310	13,201
AA-17677	40	Terrestrial	11,400 ± 95	−27.6	13,437	13,310	13,198
AA-17678	36	Terrestrial	11,290 ± 85	−27.2	13,305	13,200	13,099
AA-17679	24	Terrestrial	11,480 ± 100	−30.3	13,534	13,400	13,273
AA-17680	22	Terrestrial	11,605 ± 85	−27.3	13,670	13,530	13,412
AA-17681	16	Terrestrial	12,035 ± 85	−27.5	14,196	14,040	13,884
Gransmoor							
AA-13299	40	Terrestrial	10,150 ± 80	−28.6	12,068	11,840	11,265
AA-13298	50	Terrestrial	10,215 ± 90	−29.5	12,192	12,000	11,703
AA-13297	60	Terrestrial	10,355 ± 75	−29.0	12,365	12,240	12,077
AA-13296	70	Terrestrial	10,835 ± 80	−27.5	12,853	12,760	12,667
AA-13295	85	Terrestrial	10,340 ± 85	−29.2	12,356	12,210	12,034
AA-13293	101	Terrestrial	10,565 ± 75	−28.8	12,592	12,490	12,382
AA-13292	115	Terrestrial	10,385 ± 75	−29.7	12,401	12,280	12,130
AA-13291	135	Terrestrial	10,275 ± 90	−29.2	12,279	12,110	11,881
AA-13290	142	Terrestrial	10,575 ± 80	−29.5	12,606	12,500	12,389
AA-12005	160	Terrestrial	11,355 ± 80	−25.6	13,374	13,260	13,166
SRR-4920	169	Wood	11,475 ± 50	−27.2	13,492	13,390	13,302
AA-12004	170	Terrestrial	11,195 ± 80	−25.5	13,200	13,100	13,012
AA-12003	178	Terrestrial	10,905 ± 75	−26.2	12,915	12,830	12,740
AA-12002	188	Terrestrial	11,300 ± 80	−25.8	13,312	13,210	13,113
AA-12001	205	Terrestrial	11,565 ± 85	−24.8	13,622	13,490	13,371

*Due to the lack of any prominent feature in the Llanilid profile, "depth" is defined as height above an arbitrary point at the base of the sequence.

†All dates were calibrated using CALIB 3.0 (Stuiver and Reimer 1993).

Whitrig Bog merely confirm its Late Glacial age. All ^{14}C dates were calibrated using CALIB 3.0 (Stuiver and Reimer 1993). These dates were then used to develop age-depth relationships for each sequence using regression equations (Fig. 2).

Bulk organic samples were extracted from all five sequences for $\delta^{13}C$ analysis; *Carex* sp. fruits (trigonous) were extracted from the Gransmoor and Llanilid sites. Bulk organic samples were acid-washed with 10% HCl and the *Carex* sp. fruits (trigonous) were cleaned manually under a biological

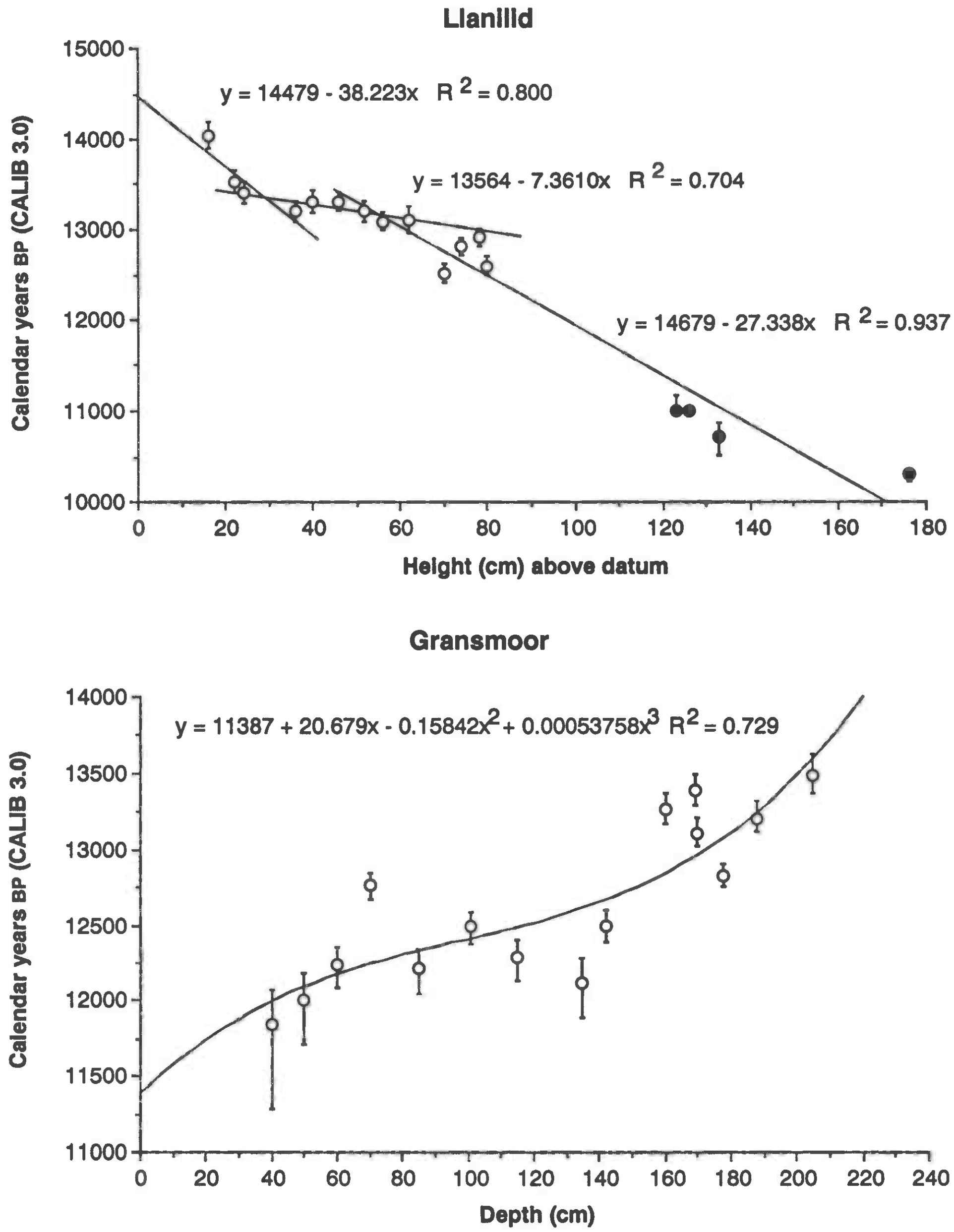

Fig. 2. Age-depth relationships developed for Llanilid and Gransmoor. o = dates based on terrestrial plant material. ● = dates based on the humin fraction of the bulk sediment. The age ranges at 1 σ confidence are also shown.

microscope and washed thoroughly using distilled water. All samples were dried at <50°C. Samples were sealed and heated through a temperature cycle (reaching 900°C) in evacuated quartz tubes with silver foil and CuO. The evolved CO_2 was cryogenically trapped and vacuum distilled. Measurements were made on a VG Optima isotope ratio mass spectrometer and to an overall analytical precision of 0.1‰. In keeping with established practice at the NERC Radiocarbon Laboratory, the ^{13}C enrichment values were calibrated directly against and calculated with respect to the international standard NBS-19. The reported results (denoted as $\delta^{13}C_{PDB}$ and quoted at 0.1‰ precision) are numerically indistinguishable from their equivalent $\delta^{13}C_{VPDB}$ values, *viz.*, $\delta^{13}C_{PDB} = 1.00195 \times \delta^{13}C_{VPDB}$ (Coplen 1994).

In addition, it was possible to quantify the concentrations of microtephra in the three Scottish sequences (Borrobol, Tynaspirit West and Whitrig Bog) using a relative density flotation technique (Turney, in press). Work is now underway to investigate Gransmoor and Llanilid for the presence of microtephra layers. Geochemical analyses of the shards was undertaken using wavelength dispersive spectrometry on a Cambridge Instruments Microscan 5 at Edinburgh University, the results of which will be reported elsewhere.

Results and discussion

The bulk organic $\delta^{13}C$ values are plotted in Figures 3 and 4. Those at Llanilid and Gransmoor have been plotted using the calibrated time scale. Note that the ages were derived from the appropriate

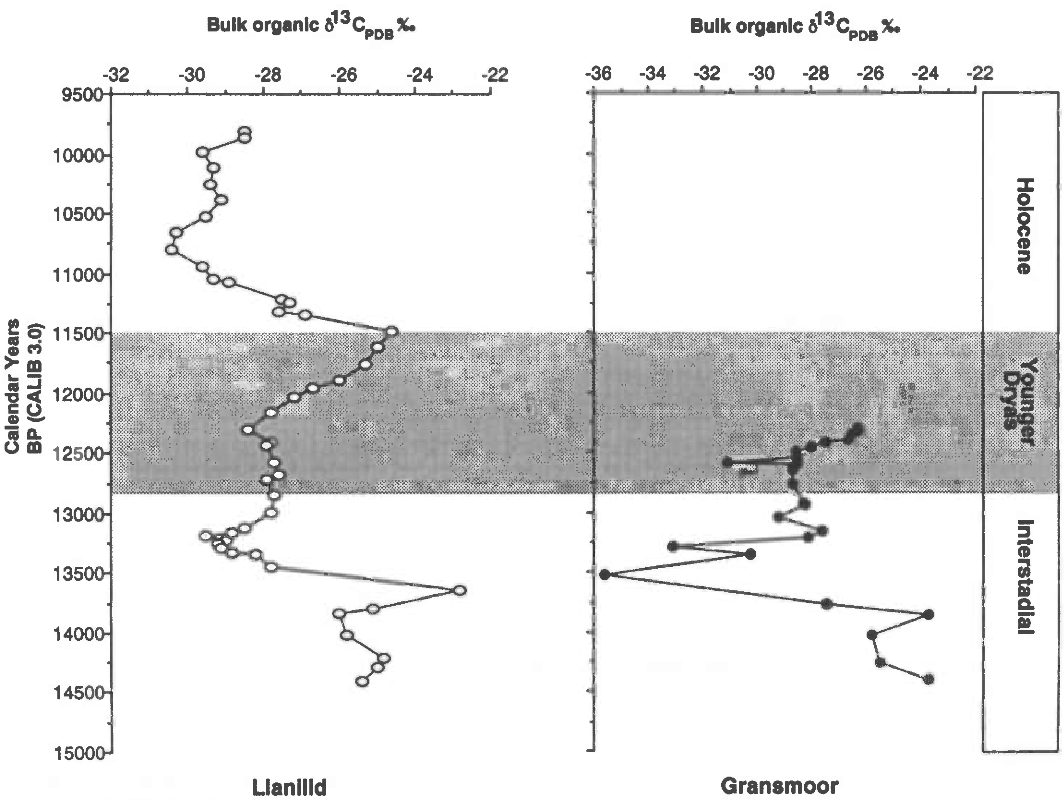

Fig. 3. Bulk organic $\delta^{13}C$ for Llanilid and Gransmoor on a calibrated time scale (using Stuiver and Reimer 1993). Ages were determined using the age-depth relationships shown in Figure 2. Climatic phases have been identified according to multiproxy data and ^{14}C ages. $\delta^{13}C$ for Llanilid were reported by Harkness and Walker (1991).

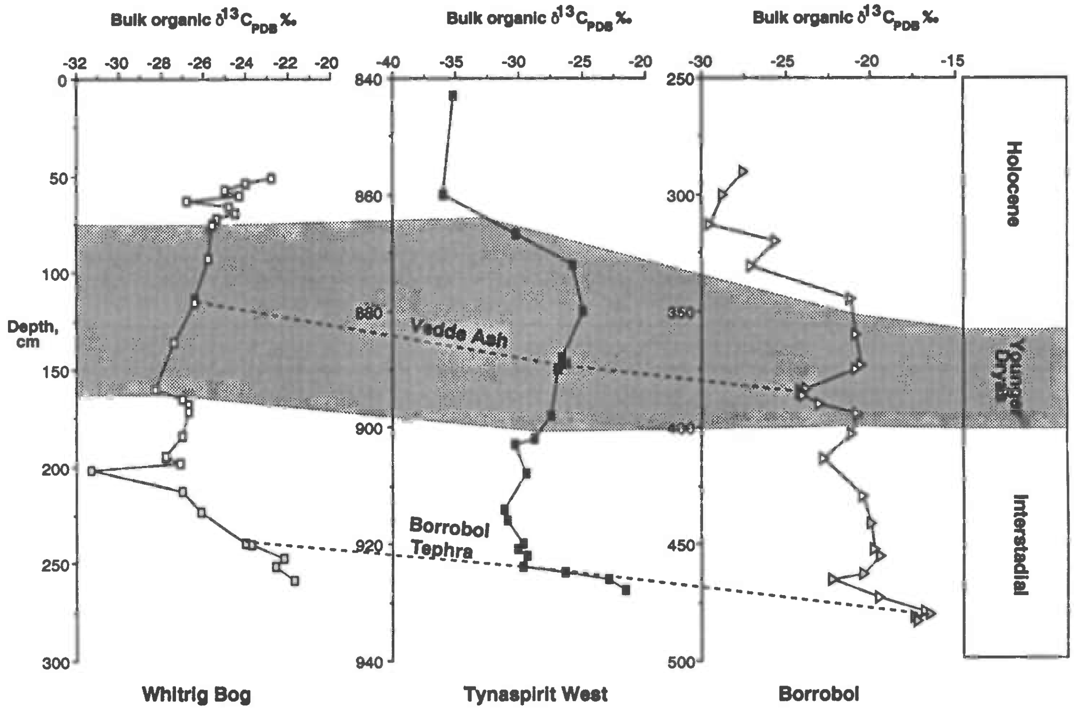

Fig. 4. Bulk organic $\delta^{13}C$ for Whitrig Bog, Tynaspirit West and Borrobol against depth but with microtephra horizons. Climatic phases have been identified according to multiproxy data.

age-depth relationship shown in Figure 2. Borrobol, Tynaspirit West and Whitrig Bog have been plotted using depth, though with correlation between the sequences based on two geochemically defined ash horizons.

The results from Llanilid (Harkness and Walker 1991) demonstrate that, following deglaciation (*ca.* 14.5 ka cal BP) a heavy isotope signature dominates, reflecting low productivity in the basin and the influence of silicate dissolution (Vogel and Ehhalt 1963). At *ca.* 13.7 ka cal BP, basin productivity and catchment vegetation increased with a characteristic shift to lighter values. This was maintained until the start of the Younger Dryas chronozone (*ca.* 12.5 ka cal BP), during which period a deterioration in climate destroyed the vegetation mat and reduced basin productivity. Erosion increased and with it the effect of bicarbonate from silicate dissolution. The termination of the Younger Dryas is clearly marked (*ca.* 11.5 ka cal BP) by a reversion to lighter $\delta^{13}C$ values as the catchment vegetation and basin productivity recovered.

The same broad trends can be seen at most sites, though there are some discrepancies. For instance, at Whitrig Bog the transition from the Younger Dryas into the Holocene is marked by a reverse trend, *i.e.*, there is an *increase* in ^{13}C content. This site is rich in marl at this transition, suggesting that carbonate formation (possibly biogenic) could be responsible for this trend. At Borrobol, the $\delta^{13}C$ values of the Younger Dryas appear to get lighter, possibly due to a total closedown of lake productivity and an increased relative effect of inwashed "fossil" terrestrial vegetation.

The upper of the two ash layers identified in the three Scottish sites has been determined to be Vedde Ash, which is known to have erupted at *ca.* 12.0 ice core ka BP (Grönvold *et al.* 1995). The lower tephra has been identified in Scotland for the first time and has been named the Borrobol Tephra (after the site in which it was first found) (Lowe *et al.*, in press). Its precise age is unknown, as it has not yet been reported for sites outside Scotland but it is estimated to date to *ca.* 12.5 ka BP. The tephra horizons provide a basis for precise correlation among the three sites. The Borrobol Tephra is particularly important as it demonstrates that although all three Scottish sites show a decrease in ^{13}C content in the early Interstadial, the Borrobol site appears to lag behind the others.

The $\delta^{13}C$ signatures of *Carex* sp. fruits (trigonous) from the Gransmoor and Llanilid sequences are shown in Figure 5, based on the age-depth relationships determined in Figure 2. The suggested synchroneity between the two data sets (within the precision of ^{14}C dating) and the degree of compatibility throughout the last glacial-interglacial transition are striking. The onset of the Younger Dryas (based on multiproxy evidence and the marked shift in ^{14}C and calibrated ages) provides additional support for the synchroneity of the trends. The heavy values probably indicate high moisture stress and/or high temperatures with the converse being the case for light $\delta^{13}C$ values. This is in strong agreement with isotopic trends in Greenland ice core data (Bard *et al.* 1996) suggesting a high degree of synchroneity in climatic developments across the entire North Atlantic region. In addition, the resolution is considerably enhanced compared with other terrestrial $\delta^{13}C$ records (*e.g.*, Vernet *et al.* 1996). The only apparent anomaly in $\delta^{13}C$ trends occurs within the Younger Dryas chronozone (post-12.5 ka cal BP) where the Gransmoor $\delta^{13}C$ values are relatively complacent, whereas the Llanilid data has marked oscillations. Research is now underway to attempt to replicate these trends in at least two other high-resolution sequences from the United Kingdom.

Conclusion

We measured bulk organic $\delta^{13}C$ in five sequences spanning the last glacial-interglacial transition within the United Kingdom. Although shifts are commonly observed across climatic boundaries, as

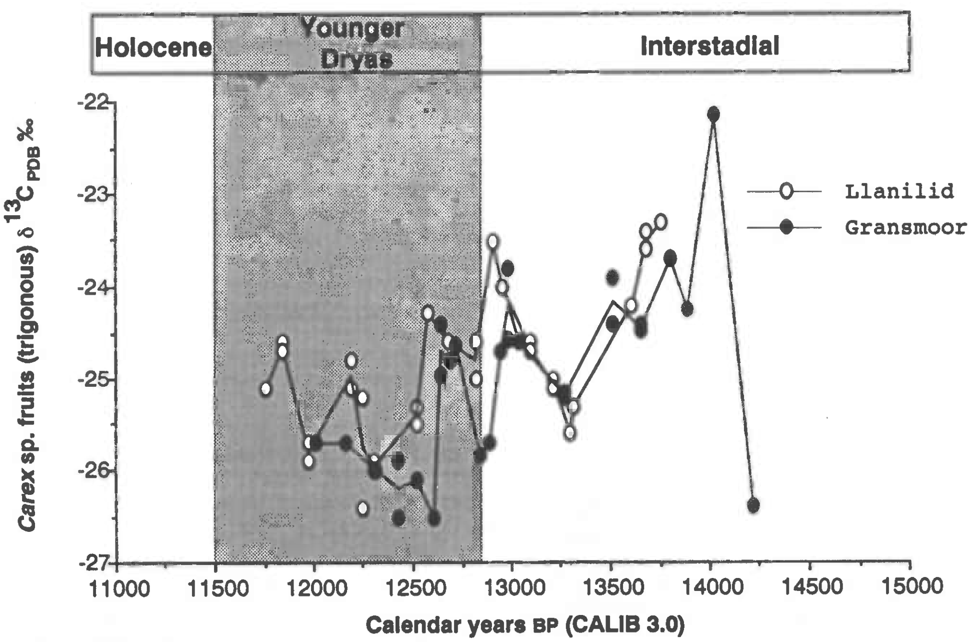

Fig. 5. *Carex* sp. fruits (trigonous) $\delta^{13}C$ for Llanilid and Gransmoor. Ages were determined using the age-depth relationships shown in Figure 2.

reported in the literature, their chronological use is limited. Either the shifts are not observed at all the sites or they do not appear to be synchronous, suggesting that site-specific factors are important.

Consistent trends in $\delta^{13}C$ variations are obtained from organ-specific measurements based on terrestrial plant macrofossils. The data strongly suggest that some environmental (meteorological) parameter was controlling the $\delta^{13}C$ shifts. If our interpretations are correct, the behavior of $\delta^{13}C$ in plant material in the United Kingdom during the last glacial-interglacial transition was controlled by regional climatic variations, and these appear to have been synchronous with climate variations inferred from the Greenland ice-core records. There are also close parallels between the $\delta^{13}C$ shifts in Gransmoor and Llanilid and paleotemperature variations inferred for these sites using the mutual climatic range (MCR) method applied to fossil beetle remains (Coope 1977; Coope and Lemdahl 1995; Turney 1997). Striking though the $\delta^{13}C$ data are, there is still room for improvement through 1) better screening of fossil material, 2) more replication of $\delta^{13}C$ measurements from each sample, 3) higher sampling resolution, 4) more comprehensive ^{14}C dating programs, and 5) extension of the tephrochronological work in the United Kingdom. Improvement in these procedures is likely to lead to robust paleoenvironmental data sets with $\delta^{13}C$ variations being one of the key proxy indicators.

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References

Ammann, B. and Lotter, A. F. 1989 Late-Glacial radiocarbon- and palynostratigraphy on the Swiss Plateau. *Boreas* 18: 109–126.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G. and Rougerie, F. 1996 Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature* 382: 241–244.

Becker, B., Kromer, B. and Trimborn, P. 1991 A stable-isotope tree-ring timescale of the Late Glacial/Holocene boundary. *Nature* 353: 647–649.

Beerling, D. J. 1996 ^{13}C discrimination by fossil leaves during the late-glacial climate oscillation 12–10 ka BP: Measurements and physiological controls. *Oecologia* 108: 29–37.

Björck, S., Kromer, B., Johnsen, S., Bennike, O., Hammarlund, D., Lemdahl, G., Possnert, G., Rasmussen, T. L., Wohlfarth, B., Hammer, C. U. and Spurk, M. 1996 Synchronised terrestrial-atmospheric deglacial records around the North Atlantic. *Science* 274: 1155–1160.

Coope, G. R. 1977 Fossil coleopteran assemblages as sensitive indicators of climatic changes during the Devensian (Last) cold stage. *Philosophical Transactions of the Royal Society of London* B280: 313–340.

Coope, G. R. and Lemdahl, D. 1995 Regional differences in the Lateglacial climate of northern Europe based on coleopteran analysis. *Journal of Quaternary Science* 10: 391–395.

Coplen, T. B. 1994 Reporting of stable hydrogen, carbon and oxygen isotopic abundances. *Pure and Applied Chemistry* 66: 273–276.

Deines, P. 1980 The isotopic composition of reduced organic carbon. *In* Fritz, P. and Fontes, J.-C., eds., *Handbook of Environmental Isotope Geochemistry.* Volume 1. *The Terrestrial Environment.* Part A. Amsterdam, Elsevier: 329–406.

Farquhar, G. D., Ehleringer, J. R. and Hubick, K.T. 1989 Carbon isotope discrimination and photosynthesis. *Annual Review of Plant Physiology and Plant Molecular Biology* 40: 503–537.

Grönvold, K., Oskarsson, N., Johnsen, S. J., Clausen, H. B., Hammer, C. U., Bond, G. and Bard, E. 1995 Ash layers from Iceland in the Greenland GRIP ice core correlated with oceanic and land sediments. *Earth and*

Planetary Science Letters 135: 149–155.

Hajdas, I., Bonani, G., Bodén, P., Peteet, D. M. and Mann, D. H. (ms.) 1997 A rise in the atmospheric ^{14}C content at 11,000 BP – a world-wide marker for the onset of the Younger Dryas. Paper presented at the 16th International ^{14}C Conference, Groningen, The Netherlands, 16–20 June.

Håkansson, S. 1986 A marked change in the stable carbon isotope ratio at Pleistocene-Holocene boundary in southern Sweden. *Geologiska Foreningens i Stockholm Forhandlingar* 108: 155–158.

Hammarlund, D. 1993 A distinct $\delta^{13}C$ decline in organic lake sediments at the Pleistocene-Holocene transition in southern Sweden. *Boreas* 22: 236–243.

Harkness, D. D. and Walker, M. J. C. 1991 The Devensian Lateglacial carbon isotope record from Llanilid, South Wales. *In* Lowe, J. J., ed., *Radiocarbon Dating: Recent Applications and Future Potential.* Quaternary Proceedings No. 1. Cambridge, Quaternary Research Association: 35–43.

Herczeg, A. L. and Fairbanks, R. G. 1987 Anomalous carbon isotope fractionation between atmospheric CO_2 and dissolved inorganic carbon induced by intense photosynthesis. *Geochimica et Cosmochimica Acta* 51: 895–899.

Hollander, D. J. and McKenzie, J. A. 1991 CO_2 control on carbon-isotope fractionation during aqueous photosynthesis: A paleo-pCO_2 barometer. *Geology* 19: 929–932.

Leavitt, S. W. and Danzer, S. R. 1992 $\delta^{13}C$ variations in C_3 plants over the past 50,000 years. *In* Long, A. and Kra, R. S., eds., Proceedings of the 14th International ^{14}C Conference. *Radiocarbon* 34(3): 783–791.

Lowe, J. J. 1991 Stratigraphic resolution and radiocarbon dating of Devensian Lateglacial sediments. *In* Lowe, J. J., ed., *Radiocarbon Dating: Recent Applications and Future Potential.* Quaternary Proceedings No. 1. Cambridge, Quaternary Research Association:19–25.

Lowe, J. J., Coope, G. R., Harkness, D. D., Robson, G., Sheldrick, C., Turney, C., Walker, M. J. C. and Watson, C., in press, Establishing the rate and magnitude of ecosystem responses to climatic variations during the last glacial-interglacial transition. *Journal of the Geological Society.*

Lowe, J. J., Coope, G. R., Sheldrick, C., Harkness, D. D. and Walker, M. J. C. 1995 Direct comparison of U.K. temperatures and Greenland snow accumulation rates, 15 000 – 12 000 yr ago. *Journal of Quaternary Science* 10: 175–180.

Lowe, J. J. and Turney, C. S. M. 1997 Vedde Ash layer discovered in small lake basin on Scottish mainland. *Journal of the Geological Society of London* 154: 605–612.

Mook, W. G. 1980 Carbon-14 in hydrogeological studies. *In* Fritz, P. and Fontes, J.-C., eds., *Handbook of Environmental Isotope Geochemistry.* Volume 1. *The Terrestrial Environment.* Part A. Amsterdam, Elsevier: 49–74.

Peteet, D. 1995 Global Younger Dryas? *Quaternary International* 28: 93–104.

Schleser, G. H. 1995 Parameters determining carbon isotope ratios in plants, *In* Frenzel, B., ed., *Problems of Stable Isotopes in Tree-rings, Lake Sediments and Peat-bogs as Climatic Evidence for the Holocene.* Paläoklimaforschung, Palaeoclimate Research 15. Stuttgart, Gustav Fischer Verlag: 71–96.

Stuiver, M. and Reimer, P. J. 1993 Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. *In* Stuiver, M., Long, A. and Kra, R. S., eds., Calibration 1993. *Radiocarbon* 35(1): 215–230.

Turney, C. S. M., in press, Extraction of rhyolitic component of Vedde microtephra from minerogenic lake sediments. *Journal of Paleolimnology.*

Turney, C. S. M. (ms.) 1997 Isotope stratigraphy and tephrochronology of the last glacial-interglacial transition (14–9 ka BP) in the British Isles. Ph.D. thesis, University of London.

Vernet, J.-L., Pachiaudi, C., Bazile, F., Durand, A., Fabre, L., Heinz, C., Solari, M.-E. and Thiébault, S. 1996 Le $\delta^{13}C$ de charbons de bois préhistoriques et historiques méditerranéens, de 35 000 BP à l'actuel. Premiers résultats. *Surface Geosciences (Paleoenvironment/Prehistory)* 323: 319–324.

Vogel, J. C. and Ehhalt, D. 1963 The use of the carbon isotopes in groundwater studies. In *Radioisotopes in Hydrology.* Proceedings of the Symposium on the Application of Radioisotopes in Hydrology, Tokyo, 1963. Vienna, International Atomic Energy Agency: 383–395.

Walker, M. J. C. 1995 Climatic changes in Europe during the Last Glacial/Interglacial Transition. *Quaternary International* 28: 63–76.

Walker, M. J. C., Coope, G. R. and Lowe, J. J. 1993 The Devensian (Weichselian) Lateglacial palaeoenvironmental record from Gransmoor, East Yorkshire, England. *Quaternary Science Reviews* 12: 659–680.

Walker, M. J. C. and Harkness, D. D. 1990 Radiocarbon dating the Devensian Lateglacial in Britain: New evidence from Llanilid, South Wales. *Journal of Quaternary Science* 5: 135–144.

Wohlfarth, B. 1996 The chronology of the last termination: A review of radiocarbon-dated, high-resolution terrestrial stratigraphies. *Quaternary Science Reviews* 15: 267–284.