PAPERS FROM THE WORKSHOP ON PAGES CHRONOLOGIES

from the Workshop on PAGES (Past Geological Changes) Chronologies, 14 August 1994, 15th International Radiocarbon Conference, Glasgow, Scotland; Wim Mook, Sessions Chairman

https://doi.org/10.1017/S0033822200014788 Published online by Cambridge University Press

[RADIOCARBON, VOL. 37, NO. 1, 1995, P. 53–62]

THE ^{14}C AGE OF THE ICELANDIC VEDDE ASH: IMPLICATIONS FOR YOUNGER DRYAS MARINE RESERVOIR AGE CORRECTIONS

W. E. N. AUSTIN,[1] *EDOUARD BARD,*[2] *J. B. HUNT,*[3] *DICK KROON*[1] *AND J. D. PEACOCK*[4]

ABSTRACT. Increased marine ^{14}C reservoir ages from the surface water of the North Atlantic are documented for the Younger Dryas period. We use terrestrial and marine AMS ^{14}C dates from the time of deposition of the Icelandic Vedde Ash to examine the marine ^{14}C reservoir age. This changed from its modem North Atlantic value of *ca.* 400 yr to *ca.* 700 yr during the Younger Dryas climatic event. The increased marine reservoir age has implications for both comparing climatic time series dated by ^{14}C and understanding palaeoceanographic changes that generated the increase.

INTRODUCTION

We discuss here a correction applied to marine radiocarbon ages to compensate for the "marine reservoir age effect". For the present-day ocean, the sea-surface ^{14}C reservoir age is on the order of 300–400 yr at low latitudes, rising to 1200 yr at higher latitudes in the southern ocean and the North Pacific. High-latitude surface waters are old because of upwelling of subsurface water, whose ^{14}C is not reset to atmospheric values. By contrast, no surface ^{14}C gradient is present between 40° and 70°N in the North Atlantic Ocean. The apparent natural ^{14}C age of these surface waters is almost constant at *ca.* 400 yr. This is linked to the northward advection of surface and thermocline waters from lower latitudes that travel through the Gulf Stream and North Atlantic current systems. Modern marine samples from coastal British waters suggest that the conventional ^{14}C ages obtained are typically too old and that a correction factor of 405 ± 40 yr should be applied (Harkness 1983). This correction factor is generally applied to all conventional marine ^{14}C ages (*eg.*, Stuiver, Pearson and Brazunias 1986; Peacock and Harkness 1990) to facilitate comparison with terrestrial ^{14}C ages.

The study of paired terrestrial and marine samples has demonstrated that the reservoir ages have varied during the Holocene, although it is characterized by a rather stable climate (for the Pacific Ocean, see Southon, Nelson and Vogel (1990); for the Atlantic, see Talma (1990) and Moore, McCormac and McCormick (1994)).

By contrast, the last deglaciation was a period of intense climatic and oceanographic changes that have profoundly affected the global carbon cycle. As evidenced in ice cores and deep-sea and continental sediments, the sizes of the major carbon reservoirs (atmosphere, biosphere and oceans) during the last deglaciation were quite different from their steady-state sizes today. In addition, the rates of exchange between these reservoirs were also probably different because of changes in deep-sea ventilation, wind speed and sea-ice distribution. All these changes must have left some imprint on the distribution of ^{14}C, which is today the most suitable tracer for studying the dynamics of the global carbon cycle.

New evidence suggests that the marine reservoir age may have differed significantly during the last glacial/interglacial transition. Specifically, we have compared the ^{14}C ages of shallow marine mollusks from the Hebridean Shelf of northwest Scotland and the apparent ages of the Icelandic Vedde ash from this region and elsewhere in the North Atlantic.

[1]Department of Geology and Geophysics, University of Edinburgh, West Mains Road, Edinburgh, EH9 3JW, Scotland
[2]CEREGE, JE 192 and FU CNRS 17, Université d'Aix-Marseille III, Europole de l'Arbois, BP 80, 13545 Aix-en-Provence, CEDEX 4, France
[3]Department of Geography and Geology, Cheltenham and Gloucester College, St. Georges Place, Cheltenham, GL5 OPP, England
[4]18 McLaren Road, Edinburgh, EH9 2BN, Scotland

The extremely high sedimentation rates, with nearly 500 cm of sediment representing the Younger Dryas (YD) interval, allow us to resolve the Vedde ash into a single, stratigraphically well-constrained horizon within British Geological Survey vibrocore 57/-09/46 (Fig. 1) (*cf.* Selby 1989; Austin 1991; Peacock *et al.* 1992; Hunt *et al.*, in press; Kroon and Austin, in press; Austin and Kroon (ms.).)

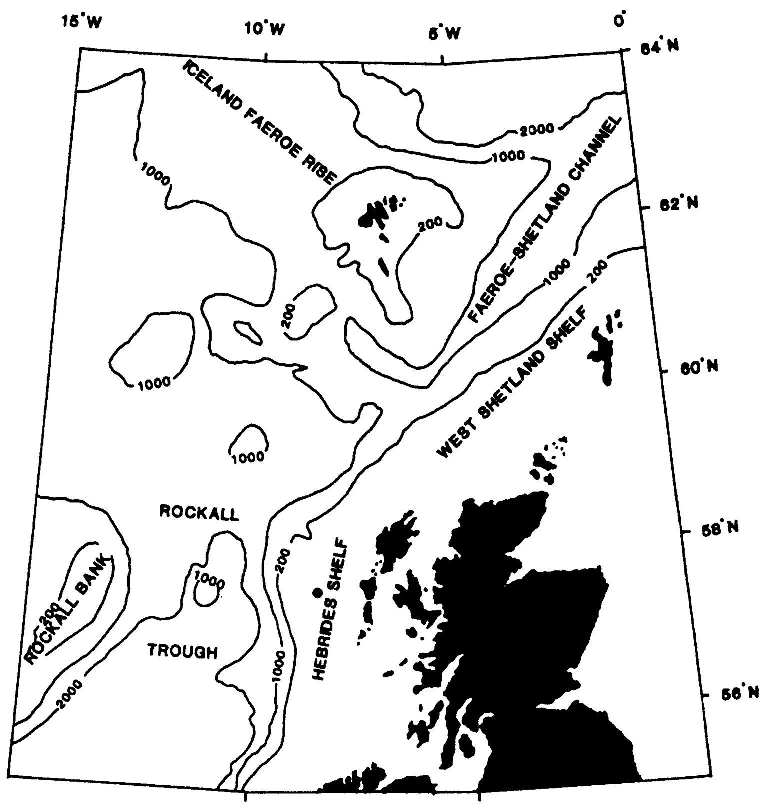


Fig. 1. Location map and bathymetry of core VE 57-09-46 (water depth 156 m)

Methods and Results

We extracted molluscan samples from washed and dried bulk sediment samples and identified them by species before submitting them for accelerator mass spectrometry (AMS) ^{14}C analyses. The samples were processed by the NERC ^{14}C laboratory at East Kilbride, according to the procedures outlined by Gillespie, Hedges and Humm (1986) and prepared targets analyzed at Oxford (OxA) and Toronto (TO). Table 1 lists the results of the ^{14}C measurements. These data show a largely conformable sequence, with ^{14}C ages decreasing upwards through the core from 11,400 ± 70 yr BP (conventional ^{14}C yr) at a core depth of 565–568 cm to 10,380 ± 100 BP at a core depth of 47–51 cm.

We did not find evidence for the Late Glacial Interstadial–YD boundary at the base of this core. However, a nearby core (57/-09/89) from the margins of the St. Kilda Basin contains a longer record (Peacock *et al.* 1992) that yields a conventional ^{14}C age of 11,440 ± 120 measured on *Parvicardium ovale* underlying this regionally well-defined climatostratigraphic boundary. This suggests that the base of the core, at a depth of 579 cm, is almost coincident with the basal YD boundary.

TABLE 1. ^{14}C Ages Obtained by AMS on Mollusks from Core VE 57-09-46

Lab no.	Species	Core depth (cm)	Conventional ^{14}C age (yr BP)*
VE57-09-46			
OxA-2786	*Acanthocardia echinata*	47–51	10,380 ± 100
OxA-2787	*Nuculoma belotti*	105–130	10,580 ± 100
TO-3127	*Nuculoma belotti*	206–209	10,610 ± 70
TO-3128	*Nuculoma tenuis*	230–233	10,970 ± 70
OxA-2788	*Nuculoma belotti*	480–500	11,420 ± 120

*Ages are conventional ^{14}C ages (*i.e.*, normalized for $\delta^{13}C$ but not corrected for reservoir age).

The YD-Holocene boundary is clearly defined by lithological and faunal evidence at a core depth of 85 cm (Austin 1991). It would therefore appear that almost the entire YD is present in this core and that it spans a period of >1000 ^{14}C yr (Johnsen *et al.* 1992; Alley *et al.* 1993). This interval is represented by nearly 500 cm of sediment, suggesting an average YD accumulation rate of 0.5 cm yr^{-1} within the central St. Kilda Basin. Our evidence suggests that sedimentation rates did not remain constant during the YD. The best fit for the age-depth data is a second-order polynomial curve, with an r^2 value of 0.94 (Fig. 2). This fitted curve suggests that sediment accumulation rates were considerably higher during the early part of the YD, falling from 1.7 cm yr^{-1} at 570 cm to >0.3 cm yr^{-1} above 100 cm. From this fitted curve, we can derive an expression for the age-depth relation within core VE 57-09-46 during the YD

$$\text{conventional } ^{14}C \text{ age} = 10212 + 3.146\,(\text{depth cm}) - 1.695 \times 10^{-3}\,(\text{depth cm})^2 . \qquad (1)$$

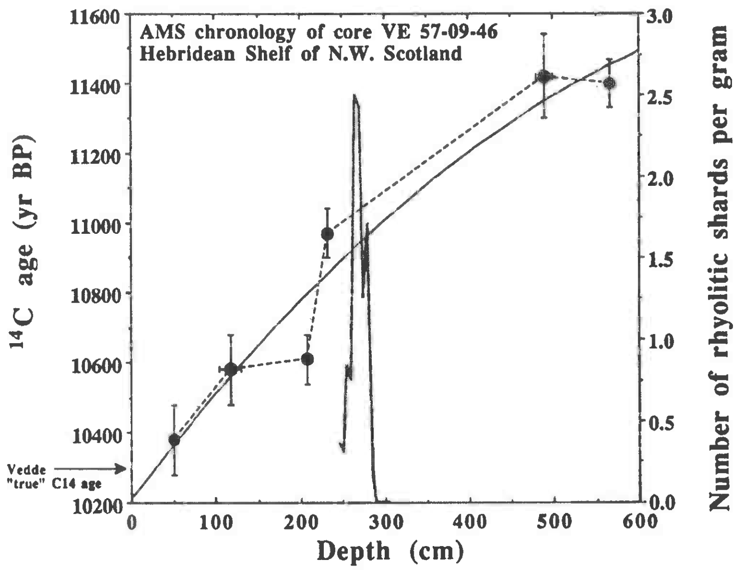


Fig. 2. ^{14}C age vs. depth model for core VE 57-09-46. The concentration of rhyolitic shards is indicated on the right axis. The ^{14}C age of the Vedde eruption is *ca.* 11,000 BP, based on the dates on mollusks. The true ^{14}C age of the eruption is 10,300 BP, based on data obtained in terrestrial sediments (Bjorck *et al.* 1992; Bard *et al.* 1994; Gulliksen *et al.* 1994; Wohlfarth, Bjorck and Possnert 1995).

The peak of clear acidic shards is centered around a core depth of 265 cm, with their first appearance at 285 cm and a gradual decline in shard numbers upward to 230 cm. These shards exhibit the typical "winged" morphologies associated with the rhyolitic Vedde ash (Fig. 3). These tephra can be correlated with the Rhy 1 shards studied by Kvamme *et al.* (1989) within North Atlantic Ash Zone 1 (NAAZ1) and with the Vedde ash described from lacustrine sediments in western Norway by Mangerud *et al.* (1984).

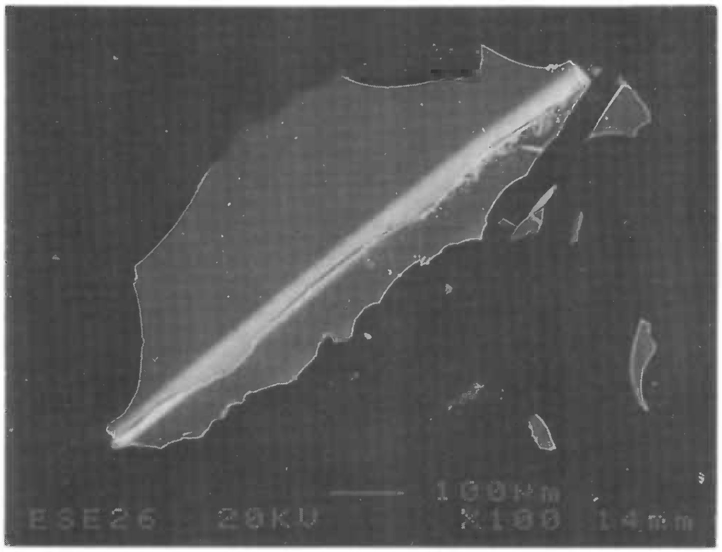


Fig. 3. SEM photomicrograph of a typical rhyolitic Vedde Ash shard

We determined the geochemistry of the tephra by electron microprobe analysis according to methods outlined by Hunt *et al.* (in press), who measured the basaltic tephra at the University of Edinburgh; H. Haflidason and W. Austin measured the acidic component of the Vedde ash at the University of Bergen, Norway. For our counts of clear, acidic, winged shards (Fig. 2), we used those with a sieved size of >250 μm. Figure 4 presents the results of the geochemical analyses, which agree with previously published analyses of the rhyolitic fraction of the Vedde ash (Mangerud *et al.* 1984; Kvamme *et al.* 1989).

We also recognized, in this core, three distinct basaltic populations, all geochemically indicative of an Icelandic origin (Kvamme *et al.* 1989) at depths between 340 cm and 100 cm (Hunt *et al.*, in press). Two of these basic populations, STK-1 and STK-2, are basaltic tholeiites and can be correlated with 1 Thol. 1 (similarity coefficient (s.c.) = 0.95) and 1 Thol. 2 (s.c.= 0.98), respectively. The third, STK-3, is a transitional alkali basalt and can be correlated with 1 Tab 1 (s.c.= 0.95). The latter is thought to represent the basic component of the Vedde ash. We are currently re-examining this core in an attempt to resolve the basaltic populations into a stratigraphic sequence of eruptive events. Earlier investigations by Selby (1989) and Peacock *et al.* (1992) suggest that this is possible.

Attributing a ^{14}C age to the Vedde ash eruption is not trivial because the ages are not directly measured on the shards. Potential problems include the depth of the dated mollusks while living, bioturbation, reworking of older sediment and ice rafting of ash shards. The living depth of the dated shells strongly affects the accuracy of the sediment chronology. However, the species chosen for AMS dating are small nuculacean bivalves that usually live at or a few cm below the sediment surface (*cf.*

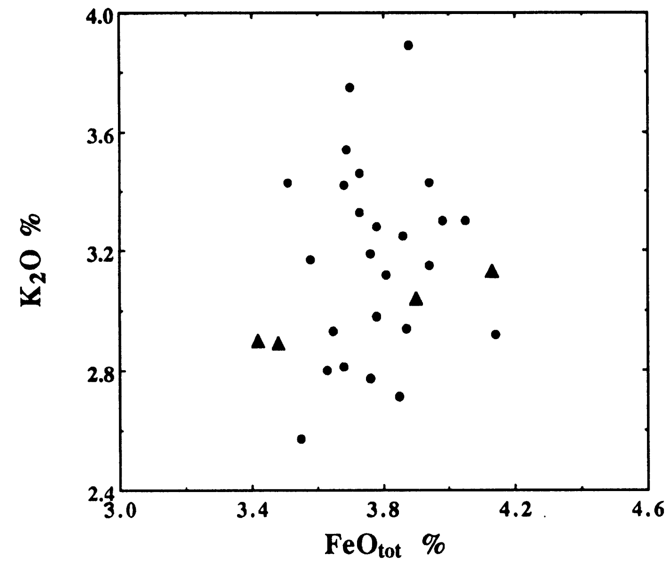


Fig. 4. K2O *vs.* FeO_{tot} geochemical plot characterizing the Vedde Ash shards. ● = the Vedde Ash observed in Norway (Mangerud *et al.* 1984); ▲ = shards from core VE 57-09-46.

Yonge and Thompson 1976). Consequently, it is safe to assume that no systematic lag is created between the age of the shells and the true age of the sediment.

As bioturbation models clearly show (*e.g.*, Berger and Heath 1968), there is an initial downward transport from the sediment surface related to the mixed layer depth (usually <10 cm for the deep ocean). Fortunately, however, in a shelf area characterized by extremely high sedimentation rates on the order of 1 cm yr^{-1}, the bioturbation should be negligible, creating a maximum lag on the order of a decade for a bioturbation depth of 10 cm.

Nielsen, Heinemeier and Rud (1994) demonstrated convincingly that the sand-sized fraction of sediment can be continuously reworked through a process of lateral transportation to the site of deposition. They studied coastal cores from the Skagerrak region characterized by extremely high sedimentation rates (on the order of 1 cm yr^{-1}), observing significant and systematic discrepancies (ranging from several centuries to a few millennia) between the AMS ^{14}C ages obtained on mollusks and those measured on benthic foraminifera. Their interpretation is that the sand-sized foraminifera are continuously eroded from older marine deposits, transported and redeposited at the site, and that they are, on average, older than the true age of the sediment, which is given by the shells.

The shelf sediments from the St. Kilda region are also characterized by extremely high accumulation rates on the order of 1 cm yr^{-1}. Following the same line of reasoning as Nielsen, Heinemeier and Rud (1994), the shells of mollusks are immobile, and thus in place, whereas the sand-sized ash shards (>250 μm) have been reworked over a depth of *ca.* 30–40 cm. The true depth of the Vedde ash deposition should thus be its deepest occurrence in the sediment column, 285 cm, corresponding to a shell age of *ca.* 11,000 BP. An initial entrainment by bioturbation (<10 cm) would reduce the depth to *ca.* 275–285 cm.

On the continent, the volcanic ash was windblown (Mangerud *et al.* 1984), whereas in the deep-sea sediments, the ash shards were also rafted by drifting sea ice, which could have further delayed deposition (Ruddiman and Glover 1972). The >250 μm size of the shards counted from core 57/-09/46 lie (at a distance of nearly 1000 km from Iceland) outside the size-distance relations for the subaerial fallout of tephra, according to the data from Fisher (1964) and Walker (1971). The high accumulation rate observed in St. Kilda sediments provides a unique opportunity to quantify this age delay between wind deposition and ice rafting. From Figure 2, it is clear that the shards are spread over a depth of 30–40 cm, a stratigraphic spread probably due to reworking. Assuming that the spread results from delayed deposition by icebergs and sea ice, it is possible to calculate an upper bound of *ca.* 30–40 yr for the duration of this ice-rafting effect. For the depth range 230–285 cm, this represents a period of 125 yr, whereas a 30-cm spread centered upon 265 cm represents a maximum of 70 yr. These simple calculations confirm the statement by Kvamme *et al.* (1989) that the delay in deposition was only a few years, and that the rhyolitic tephra can indeed be used as a geologically instantaneous time marker.

Based on the observed depths of the Vedde ash and the ^{14}C age-depth relation (Eq. 1), we can date the earliest occurrence at 285 cm to 10,970 BP, the peak in shard concentration at 265 cm to 10,930 BP, and the last occurrence at 230 cm to 10,850 BP. Taking into account the different phenomena described above, the best estimate of the age of the Vedde eruption is, thus, on the order of 11,000 BP (275–285 cm).

Comparison with Other Estimates of the Vedde Ash ^{14}C Age

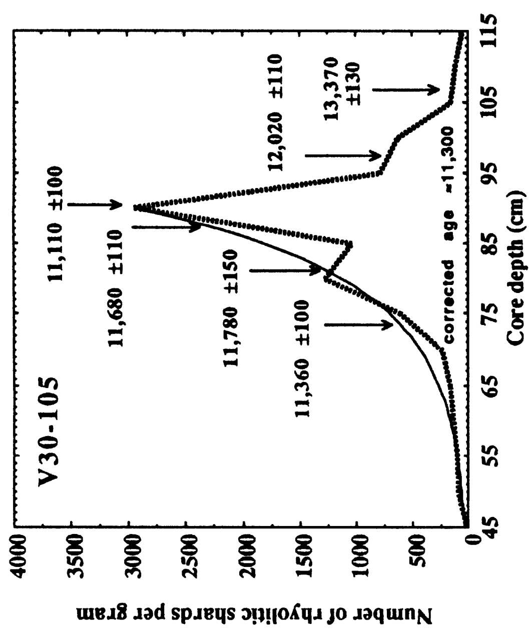
Most of the age determinations of the Vedde ash layer were obtained from lacustrine sediments. The recent use of the AMS technique has enabled more accurate dating of selected terrestrial macrofossils, at the same time minimizing or eliminating the hard-water effect. Recent studies conducted on lacustrine sediments from Iceland (Björck *et al.* 1992), Norway (Bard *et al.* 1994, Gulliksen *et al.* 1994) and Sweden (Wohlfarth, Björck and Possnert 1995) indicate that the Vedde ash eruption occurred at *ca.* 10,300 BP. By comparing this age with the one determined in the St. Kilda area (close to 11,000 BP), we conclude that during the YD, the reservoir age at this location was on the order of 700 yr, whereas it is now on the order of 400 yr.

This new estimate of the reservoir age essentially agrees with those determined by using the same rationale for deep sea cores (Bard *et al.* 1994). In that case, the reservoir age is more difficult to quantify, since bioturbation also generates a significant age difference between ash layer and foraminifera. However, after correction for a bioturbation bias, it appears that the North Atlantic reservoir age was a few centuries greater than today (700–800 yr instead of 400–500 yr). Figure 5 gives three examples of deep-sea sediment cores in the Vedde ash layer section that have been AMS-dated; bioturbation displacement of ash shards is evident in each. The magnitude of the age bias between ash and foraminifera depends on the sedimentation rate and the bioturbation mixing depth (estimated from the exponential decrease of the ash concentration). For each core it is possible to derive a corrected ^{14}C age for the Vedde ash deposition on the order of 11,000–11,100 BP (Bard *et al.* 1994). Sediment reworking should not have a major effect on the study of these deep-sea sediments because additional proxies ($\delta^{18}O$, transfer function SSTs) were obtained on the samples that were used for AMS dating. These other measurements independently confirmed that the AMS-dated foraminifera were indeed living during the YD. Moreover, both ash shards and foraminifera would be reworked, because both are mobile when subject to reworking.

IMPLICATIONS FOR NORTH ATLANTIC PALEOCEANOGRAPHY

The finding that North Atlantic reservoir ages were larger during the YD has two important implications. First, it limits our ability to compare climatic time series dated by ^{14}C on foraminifera or

https://doi.org/10.1017/S0033822200014788 Published online by Cambridge University Press



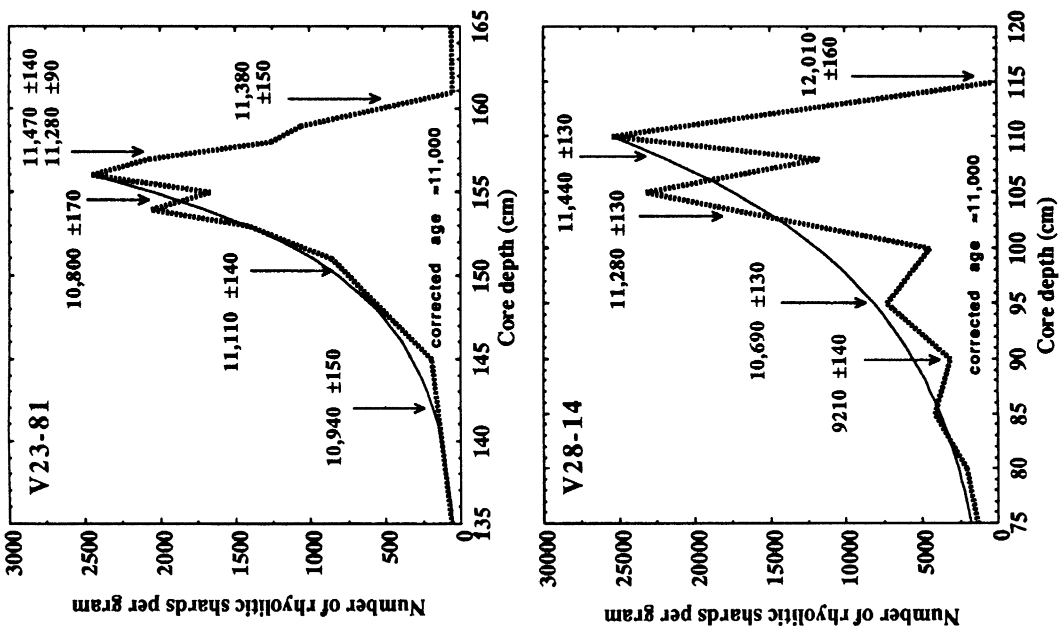


Fig. 5. Distribution of rhyolitic glass shards and conventional ^{14}C ages obtained on deep-sea cores V23-81, V28-14 and V30-105 (from Bard *et al.* 1994). Exponential fits of the distribution tails were used to calculate bioturbation depths for each core. Under each curve is given the ^{14}C age of the Vedde eruption, corrected for the effect of bioturbation (see Bard *et al.* 1994).

mollusks with other time series obtained in other oceanic areas or in continental deposits. The clues to the causes of the deglacial climatic changes will probably come from precise determinations of leads between the time series obtained in the different compartments of the ocean-atmosphere system. During the last deglaciation, the major climatic changes occurred as very abrupt steps (within a few centuries) and it is now crucial to provide ^{14}C ages at this level of accuracy.

As an example, consider the North-Atlantic record of core Troll 3.1 (Lehman *et al.* 1991; Lehman and Keigwin 1992), which has been extensively cited and compared with continental and ice-core chronologies. In Troll 3.1 sediments, the YD boundaries are well marked by sharp changes in $\delta^{18}O$ and in the relative abundance of the polar foraminifera *Neogloboquadrina pachyderma* (sinistrally coiled). The ^{14}C chronology is based on a regular sequence of *ca.* 10 AMS ages for the last 15 ka. The authors have used a constant reservoir correction of 440 yr, resulting in remarkable YD start and end dates of 11,280 BP and 10,530 BP, respectively (Lehman and Keigwin 1992). These ages are much older than the consensus values for these well-recognized climatic boundaries, 11 and 10 ka BP (Mangerud *et al.* 1974; Hajdas *et al.* 1993; Goslar *et al.* 1994). Peacock and Harkness (1990) suggest that polar waters returned to the seas adjacent to Scotland by *ca.* 10,850 BP and were present until *ca.* 10,200–10,100 BP. The discrepancy in Troll 3.1 could be removed by invoking larger reservoir ages during the last deglaciation (Stuiver and Brazunias 1994).

Second, it affects our understanding of the mechanisms that generated the increase in reservoir age. Today the North Atlantic is characterized by a reservoir age on the order of 400–500 yr, whereas all other high-latitude oceans show larger reservoir ages of 500–1000 yr (Stuiver, Pearson and Brazunias 1986; Bard 1988; Southon, Nelson and Vogel 1990). This major difference is linked to the northward advection of surface and thermocline waters from lower latitudes that travel through the Gulf Stream and North Atlantic current systems. After recirculation and winter convection, this water flux ultimately feeds the North Atlantic deep water (NADW).

Consequently, any change in the North Atlantic reservoir age is probably a response to variations in the NADW formation process and/or changes in the rate of ocean-atmosphere gas exchange. During the cold/warm swings of the last deglaciation, both processes changed dramatically, and the observed effect is probably the combined result of a decrease of NADW flux (Boyle and Keigwin 1987; Keigwin *et al.* 1991) and an increase of North Atlantic sea ice (Koc-Karpuz, Jansen and Haflidason 1993).

Acknowledgments

We thank S. H. Nielsen and M. J. Moore for useful discussions and review of the manuscript. W. A. and D. K. acknowledge an NERC grant (GST/02/723). W. A. also acknowledges a BP/RSE fellowship.

REFERENCES

Alley, R. B., Meese, D. A., Shuman, C. A., Gow, A. J., Taylor, K. C., Grootes, P. M., White, J. W. C., Ram, M., Waddington, E. D., Mayewski, P. A. and Mielinski, A. G. 1993 Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature* 362: 527–529.

Austin, W. E. N. (ms.) 1991 Late Quaternary benthonic foraminiferal stratigraphy of the western UK continental shelf. PhD dissertation, University of Wales: 205 p.

Austin, W. E. N. and Kroon, D. (ms.) The Lateglacial palaeoceanographic evolution of the Hebridean continental shelf, NW Scotland. In Andrews, J. T., Austin, W. E. N. and Bergsten, H. E., eds., *The Lateglacial Paleoceanography of the North Atlantic Margins*. Geological Society Special Publication. Submitted.

Bard, E. 1988 Correction of accelerator mass spectrometry ^{14}C ages measured in planktonic foraminifera: Paleoceanographic implications. *Paleoceanography* 3: 635–645.

Bard, E., Arnold, M., Mangerud, M., Paterne, M., Labeyrie, L., Duprat, J., Mélières, M. A., Sonstegaard, E., Duplessy, J. C. 1994 The North Atlantic atmosphere-sea surface ^{14}C gradient during the Younger Dryas climatic event. *Earth and Planetary Science Letters* 126: 275–287.

Berger, W. H. and Heath, G. R. 1968 Vertical mixing in pelagic sediments. *Journal of Marine Research* 26: 134–143.

Björck S., Ingolfsson, O., Haflidason, H., Hallsdottir, M. and Anderson, N. J. 1992 Lake Torfdalsvatn: A high resolution record of the North Atlantic ash zone 1 and the last glacial-interglacial environmental changes in Iceland. *Boreas* 21: 15–22.

Boyle, E. A and Keigwin, L. 1987 North Atlantic thermohaline circulation during the last 20,000 years linked to high-latitude surface temperature. *Nature* 330: 35–40.

Broecker, W. S. 1992 Defining the boundaries of the Late-Glacial Isotope episodes. *Quaternary Research* 38: 135–138.

Fisher, R. V. 1964 Maximum size, median diameter and sorting of tephra. *Journal of Geophysical Research* 69: 341–355.

Gillespie, R., Hedges, R. E. M. and Humm, M. J. 1986 Routine AMS dating of bone and shell proteins. *In* Stuiver, M. and Kra, R., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2A): 451–456.

Gulliksen, S., Possnert, G., Mangerud, J. and Birks, H. (ms.) 1994 AMS ^{14}C dating of the Krakenes Late Weichselian sediments. Paper presented at the 15th International ^{14}C Conference, 15–19 August 1994, Glasgow, Scotland.

Goslar, T., Arnold, M., Bard, E. and Pazdur, M. F. (ms.) 1994 Variations of atmospheric ^{14}C levels around the Late Glacial/Holocene boundary. Paper presented at the 15th International ^{14}C Conference, 15–19 August 1994, Glasgow, Scotland.

Hajdas, I., Ivy, S., Beer, J., Bonani, G., Imboden, D., Lotter, A.F., Sturn, M. and Suter, M. 1993 AMS radiocarbon dating and varve chronology of Lake Soppensee: 6000 to 12000 ^{14}C yr BP. *Climate Dynamics* 9: 107–116.

Harkness, D. D. 1983 The extent of natural ^{14}C deficiency in the coastal environment of the United Kingdom. *In* Mook, W. G. and Waterbolk, H. T., eds., Proceedings of the International Symposium on ^{14}C in Archaeology. *PACT* 8: 351–364.

Hunt, J. B., Fannin, N. G. T., Hill, P. G. and Peacock, J. D., in press. The tephrochronology and radiocarbon dating of North Atlantic Late Quaternary sediments: An example from the St Kilda Basin. *Geological Society Special Publication.*

Johnsen, S. J., Clausen, B., Dansgaard, W., Fuhrer, K, Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Stauffer, B. and Steffenson, J. P. 1992 Irregular glacial interstadials recorded in a new Greenland ice core. *Nature* 359: 311–313.

Keigwin, L. D., Jones, G. A., Lehman, S. J. and Boyle, E. A. 1991 Deglacial meltwater discharge, North Atlantic deep circulation, and abrupt climatic change. *Journal of Geophysical Research* 96(9): 16811–16826.

Koc-Karpuz, N., Jansen, E. and Haflidason, H. 1993 Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian Seas through the last 14 ka based on diatoms. *Quaternary Science Reviews* 12: 115–140.

Kroon, D. and Austin, W. E. N. in press. High resolution marine records of the last glacial/interglacial transition from the Hebridean margin, N.W. Scotland. *Proceedings of the Royal Dutch Academy of Science.*

Kvamme, T., Mangerud, J., Furnes, H. and Ruddiman, W. 1989 Geochemistry of Pleistocene ash zones in cores from the North Atlantic. *Norsk Geologisk Tidsskrift* 69: 251–272.

Lehman, S. J., Jones, G. A., Keigwin, L. D., Andersen, E. S., Butenko, G. and Ostmo, S.-R. 1991 Initiation of Fennoscandian ice-sheet retreat during the last deglaciation. *Nature* 349: 513–516.

Lehman, S. J. and Keigwin, L. D. 1992 Sudden changes in North Atlantic circulation during the last deglaciation. *Nature* 356: 757–762.

Mangerud, J., Andersen, S. T., Berglund, B. E. and Donner, J. J. 1974 Quaternary stratigraphy of Norden, a proposal for terminology and classification. *Boreas* 3: 109–128.

Mangerud, J., Lie, S. E., Furnes, H., Kristiansen, I. L. and Lomo, L. 1984 A Younger Dryas ash bed in western Norway and its possible correlations with tephra in cores from the Norwegian sea and the north Atlantic. *Quaternary Research* 21: 85–104.

Moore, M. J., McCormac, F. G. and McCormick, F. (ms.) 1994 Investigation of changes in ocean circulation rate in the North Atlantic. Paper presented at the 15th International ^{14}C Conference, 15–19 August 1994, Glasgow, Scotland.

Nielsen, S. H., Heinemeier, J. and Rud, N. 1995 Comparative radiocarbon dating of shells and foraminifera: A systematic investigation. *In* Harkness, D. D., Miller, B. F. and Scott, E. M., eds., Proceedings of the 15th International ^{14}C Conference. *Radiocarbon* 37(3): in press.

Peacock, J. D. and Harkness, D. D. 1990 Radiocarbon ages and the full-glacial to Holocene transition in seas adjacent to Scotland and southern Scandinavia: A review. *Transactions of the Royal Society of Edinburgh, Earth Sciences* 81: 385–396.

Peacock, J. D., Austin, W. E. N., Selby, I., Graham, D. K., Harland, R. and Wilkinson, I. P. 1992 Late Devensian and Flandrian palaeoenvironmental changes on the Scottish continental shelf west of the Outer Hebrides. *Journal of Quaternary Science* 7: 145–161.

Ruddiman, W. F. and Glover, L. K. 1972 Vertical mixing of ice-rafted volcanic ash in North-Atlantic sediments. *Geological Society of America Bulletin* 83: 2817–2836.

Selby, I. (ms.) 1989 Quaternary geology of the Hebridean continental margin. Ph.D. dissertation, Nottingham University.

Southon, J. R., Nelson, D. E. and Vogel, J. S. 1990 A record of past ocean-atmosphere radiocarbon differences from the Northeast Pacific. *Paleoceanography* 5(2): 197–206.

Stuiver, M., Pearson, G. W. and Brazunias, T. 1986 Radiocarbon age calibration of marine shells back to 9000 cal yr BP. *In* Stuiver, M. and Kra, R., eds., Proceedings of the 12th International ^{14}C Conference. *Radiocarbon* 28(2A): 980–1021.

Stuiver, M. and Brazunias, T. 1994 Sun, ocean, climate and atmospheric $^{14}CO_2$: An evaluation of causal and spectral relationships. *The Holocene* 3, 4: 289–305.

Talma, A. S. 1990 Radiocarbon age calibration of marine shells. *Quarterly Report, Quaternary Dating Research Unit.* CSIR, Pretoria: 10 p.

Walker, G. P. L. 1971 Grain-size characteristics of pyroclastic deposits. *Journal of Geology* 79: 696–714.

Wohlfarth, B., Björck, S. and Possnert, G. 1995 The Swedish time scale: A potential calibration tool for the radiocarbon time scale during the Late Weichselian. *In* Harkness, D. D., Miller, B. F. and Scott, E. M., eds., Proceedings of the 15th International ^{14}C Conference. *Radiocarbon* 37(3): in press.

Yonge, C. M. and Thompson, T. E. 1976. *Living Marine Molluscs.* London, Collins: 288 p.