dendrochronological calibration curve, and by the age plateau and rapid jumps that characterize the YD (see above). Extension of the calibration curve and the new data sets of INTCAL98 and INTCAL04 (Stuiver and Reimer 1998, Reimer et al., 2004) have enabled reconstruction of the fluctuations in atmospheric ^{14}C content during the YD, and provided the basis for wiggle-matching ^{14}C chronologies. The characteristic ^{14}C changes have themselves become time markers. For example, the chronology established for the Kråkenes Lake sequence (Norway) was the first to show the coincidence between a dramatic change in ^{14}C ages (11-10.6 kyr BP) and the onset of cooling at the beginning of the YD (Gulliksen et al., 1998). This coincidence has subsequently been observed in other records from European lakes, such as: Soppensee (Switzerland), Holzmaar (Germany), (Hajdas et al., 1993, 1995), Madtjärn (Sweden) and Gościąż (Poland) (Goslar et al., 1999). High-resolution ^{14}C dating of a deglacial cold event found on Kodiak Island also showed that Alaska experienced cooling which was synchronous with the YD in the North Atlantic region (Hajdas et. al. 1998).

Southern Hemisphere Records

The radiocarbon dating of the New Zealand Franz-Joseph Glacier re-advance at ca. 11 kyr BP (Denton and Hendy 1994) sparked debate on the global extent of YD cooling and drew attention to records from the Southern Hemisphere. A high-resolution ^{14}C chronology for the Kaipo Bog sequence from New Zealand provides further insight into a cold reversal that preceded early Holocene warming (Hajdas et al., 2006). In total,, 51 age points for Kaipo Bog were fitted to the INTCAL04 calibration curve (Reimer et al., 2004) via the OxCal (version 3.10) sequence calibration (Ramsey, 2001) (Fig. 1), which uses a Bayesian approach that incorporates known parameters into the fitting procedure. In this case, the known stratigraphy—age superposition with depth—defined the fitting procedure. This procedure resulted in reduced errors for calibrated ages and gave a continuous sequence of calendar ages independent of ^{14}C age plateaus or wiggles. Based on this chronology, cooling at Kaipo commenced between 13,820 and 13,590 cal yr BP (12,030 ± 90 ^{14}C yr BP) and ended ~1000 years later between 12,800 and 12,390 cal yr BP (10,790 ± 70 and 10,600 ± 90 ^{14}C yr BP). This improved chronology reveals that the cold event was not synchronous with the YD, an alternative scenario possible with the original chronology (Newnham & Lowe, 2000). High-resolution radiocarbon chronologies from two Patagonian sites, Huelmo (Chile) and Mascardi (Argentina) (Hajdas et. al. 2003) have also shown that the cold events observed in those two records preceded the YD chronozone by some 500 years but terminated close to the end of the YD.

In summary, these examples illustrate the potential of high-resolution radiocarbon dating for development of reliable timescales of Holocene and late-glacial records around the globe. Extension further back in time and refinement of the calibration curve will facilitate application of similar approaches to older time periods.

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Marine ^{14}C reservoir ages oscillate

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The current ^{14}C calibration scale, IntCal04, is tree-ring based up until 12.4 cal kyr BP but relies for the older part, up to 26 cal kyr BP, on surface-ocean data from planktic foraminifera and corals at a number of carefully selected locations (Reimer et al., 2004). In order to do so, it is assumed that a constant global marine reservoir age of 405 ± 22 yr, obtained by box modeling the period AD 1350-1850, and a constant local deviation from this global value, ΔR, can be applied beyond the range of tree-ring calibration. The (local) marine reservoir age under equilibrium conditions is determined by the balance between restricted ocean-atmosphere gas exchange and limited mixing between the mixed layer and the deep ocean. For the selected locations, reservoir ages close to 400 yr indicate that this limited exchange results in a ~5% ^{14}C deficit in the ocean mixed layer. The assumption that this reservoir age has remained constant in the past implies that (i) this mixing balance has been maintained, (ii) the general ocean circulation "pipeline" system, that is the system of thermohaline currents has not changed, and (iii) equilibrium has not been disturbed by changes in the production rate of cosmogenic isotopes, or (iv) in the size of the atmospheric carbon reservoir.

Dramatic climate changes occurred during the early stages of the last glacial to interglacial transition 19-14.5 kyr. They were accompanied by the most fundamental recent changes in ocean circulation, which also likely contributed to major shifts in CO_2 transfer from ocean to atmosphere, leading to the well-known deglacial rise in atmospheric pCO_2 from 190 to 240 ppmv at 14.5 kyr (Monnin et al., 2001; Köhler et al., 2005). For the preceding glacial period, back to the limit of radiocarbon dating around 50 kyr, ice core records provide further evidence for frequent large and rapid changes in climate and low atmospheric CO_2 concentrations in the range of 190 to 230 ppmv. Marine records now have confirmed these findings and shown that these events were in many cases coeval with large changes in the meridional overturning circulation of the oceans. During this period, global sea level also dropped, with stadial-interstadial related fluctuations, to a low of more than 120 m below present sea level at the last glacial maximum (23-19 kyr), before rising over the deglacial and early Holocene to present levels. Reconstructions of the paleointensity of the Earth's magnetic field from various ocean sediments (GLOPIS 75; Laj et al., 2004) give evidence of several episodes with a very weak earth magnetic field leading to increased production of cosmogenic isotopes, especially around 41 kyr BP; the Laschamp Event (Hughen et al., 2004a; Voelker et al., 2000). Thus, it seems that most of the conditions for constant marine reservoir ages—constant basin geometry, ocean circulation, ocean–atmosphere and surface–deep ocean mixing, ^{14}C production, and atmospheric reservoir size—have been violated. Although careful application of U/Th dating, supplemented by volcanic time markers—identified and dated in ice cores and/or terrestrial records—may supply absolute ages for the marine data set, the atmospheric ^{14}C content cannot be reconstructed as long as the local marine reservoir age at each particular point in time is not known.

Therefore, a secure correlation between single events in the ocean and on

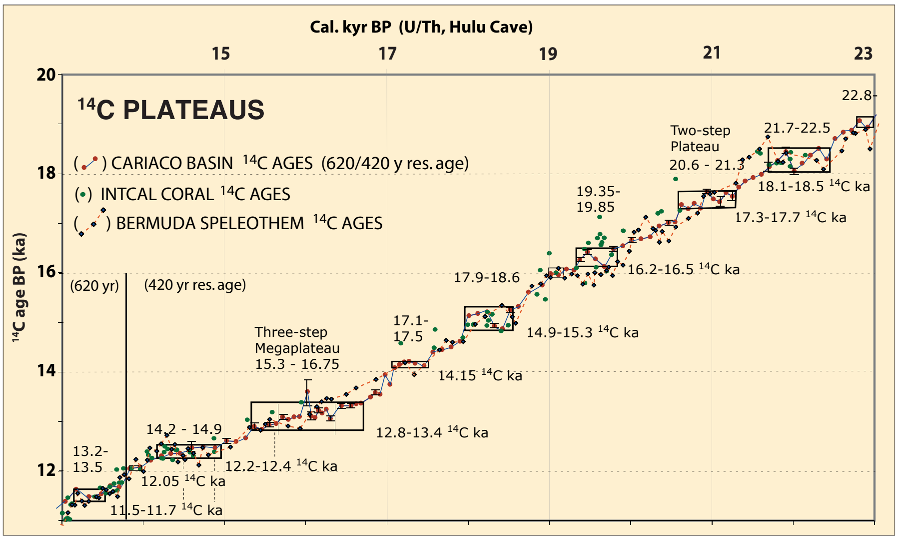

Figure 1: ^{14}C plateaus and their assigned boundary ages compiled by Sarnthein et al. (in press) from (1) the ^{14}C record of Cariaco Basin ODP Site 1002 for Termination Ia (Hughen et al., in press), (2) the combined set of Marine04 coral ages (Fairbanks et al., 2005; Reimer et al., 2004) (green dots), and (3) the Bermuda speleothem record (Beck et al., 2001, suppl.) (blue dots and dashed orange line). 1-σ bars are given for ^{14}C ages, where analytical error exceeds red-dot diameter. ^{14}C ages of <13.8 kyr are corrected for additional 200-yr reservoir effect (Kromer et al., 2004 and by comparison with Marine04 coral ages).

land based on ^{14}C dating cannot yet be established.

At near-shore sites, local reservoir ages are generally derived from paired dates of terrestrial material and marine shells. Reliable sample pairs are, however, hard to find and provide only one point in time. A new possibility to study varying reservoir ages is offered by apparent "plateaus" in the ^{14}C age depth relationship that turn up in densely dated, high-resolution sediment records, just as they do in the age-calibrated atmospheric ^{14}C record. This is to be expected and, under the ideal situation of constant marine reservoir, the ^{14}C age plateau of planktic foraminifera in the sediment should even be identical to that in the atmosphere. Yet, even under less than ideal conditions, atmospheric ^{14}C plateaus may still be recognized in sediment sections with high-resolution dating (spacing <200-400 yr) and, because the atmosphere is globally well mixed, provide a means of event correlation.

In a first application to an interval prior to tree-ring calibration, Sarnthein et al (in press) identified a reference suite of seven ^{14}C "plateaus" (i.e. intervals with low or reversed ^{14}C change vs calendar age) of variable length in the age-calibrated Cariaco ^{14}C record (Hughen et al., in press), and used this sequence for event correlation with four cores from key locations of the oceanic thermohaline circulation in the Pacific and Atlantic.

The suite of plateaus extends over the Last Glacial Maximum (LGM) and Termination-Ia intervals between 23 and 14 cal kyr in the partly varved marine sediment record at ODP Site 1002, Cariaco Basin (Hughen et al., in press; 2004a). The plateau-style structures defined in the Cariaco ^{14}C record largely match a number of coeval features in the 230Th-dated Bahama stalagmite record of atmospheric ^{14}C concentrations over the same deglacial interval (Beck et al., 2001) (Fig. 1), most conspicuously in the oldest (>21.7 cal kyr) and younger sections of the record (at <18 cal kyr), despite potential variations in reservoir age in Cariaco and dead carbon contribution in the speleothems. The cumulative IntCal04 set of coral-based paired 230Th and ^{14}C ages (Fairbanks et al., 2005; Hughen et al., 2004b) also confirms most plateau structures and their ages, e.g. at 23.0-21.5, 19.0-17.5, and in particular between 16 and 13 cal kyr. The Cariaco record, with its high-resolution timescale derived by correlation to the 230Th-dated timescale of the Hulu Cave stalagmite (Wang et al., 2001), provides the best available chronological standard sequence. Fluctuations in its reservoir age, assumed to be a constant 420-yr, will result in reservoir ages derived for other records that are off by the same amount, which makes their later correction easy.

Past ^{14}C marine reservoir ages of surface and bottom waters between 23 and 14 cal kyr were determined at one Atlantic (Iceland Sea) and three Pacific (South China Sea, Northwest Pacific, Santa Barbara Basin) locations. Sarnthein et al. (in press) identified a series of planktic ^{14}C plateaus in each record and tuned these to the Cariaco-based sequence of shorter and longer "atmospheric" reference plateaus. The calendar ages determined for the beginning and end of each of the seven reference ^{14}C plateaus provide the first accurate calendar age estimates for global deglacial marine records with an uncertainty determined by that of the correlation and the Cariaco age uncertainties (from ~270 yr beyond 20 kyr, and ~500 yr for 20-18.5 kyr, to 130-200 yr for 18.5-14.0 kyr; Hughen et al., in press). The ^{14}C age differences between the tuned and the reference plateaus represent the paleoreservoir ages of local surface water. Benthic apparent ventilation ages are the difference between coeval planktic and benthic ^{14}C ages plus the planktic reservoir age. Opposite trends in the reservoir ages obtained indicate major changes in deglacial meridional overturning circulation (MOC) during and after the late phase of Heinrich 1 (H1) stadial. In the subarctic northwest Pacific, these reservoir ages decreased in deep waters from 2800 to 1150 yr, in surface waters to 300 yr (vs >850 yr today), and in North Pacific upper intermediate waters from 4400/3800 to 2000 yr. By contrast, in the Icelandic Sea, source region of modern MOC, intermediate-water reservoir ages increased during LGM and H1 from 440 to >2000 yr, reflecting a brief northward reversal of Denmark Strait Overflow waters. The two best-established major atmospheric ^{14}C plateaus during late H1 and the early Bølling interstadial match the coeval two-step deglacial rise in atmospheric pCO_2 and appear to reflect major ocean CO_2 exhalation that resulted from MOC change and deep-ocean flushing.

The surprisingly large and diverse changes in reservoir ages obtained from the ^{14}C plateau tuning, and their apparent correlation with major changes both in oceanic circulation and in the carbon cycle, illustrate that deriving an atmospheric ^{14}C calibration from marine data and calibrating marine ^{14}C ages is not simple. On the other hand, the use of a suite of ^{14}C age plateaus in marine records for event tuning appears to offer the possibility both for global, reservoir-independent correlation between marine and terrestrial records and for the determination of local reservoir ages and oceanic mixing.

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