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PLANKTIC AND BENTHIC ^{14}C RESERVOIR AGES FOR THREE OCEAN BASINS, CALIBRATED BY A SUITE OF ^{14}C PLATEAUS IN THE GLACIAL-TO-DEGLACIAL SUIGETSU ATMOSPHERIC ^{14}C RECORD

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ABSTRACT. This article presents a compilation of planktic and benthic ^{14}C reservoir ages for the Last Glacial Maximum (LGM) and early deglacial from 11 key sites of global ocean circulation in the Atlantic and Indo-Pacific Ocean. The ages were obtained by ^{14}C plateau tuning, a robust technique to derive both an absolute chronology for marine sediment records and a high-resolution record of changing reservoir/ventilation ages ($\Delta^{14}C$ values) for surface and deep waters by comparing the suite of planktic ^{14}C plateaus of a sediment record with that of the atmospheric ^{14}C record. Results published thus far have used as atmospheric ^{14}C reference U/Th-dated corals, the Cariaco planktic record, and speleothems. We have now used the varve-counted atmospheric ^{14}C record of Lake Suigetsu terrestrial macrofossils to recalibrate the boundary ages and reservoir ages of the seven published records directly to an atmospheric ^{14}C record. In addition, the results for four new cores and further planktic results for four published records are given. Main conclusions from the new compilation are the following: (1) The Suigetsu atmospheric ^{14}C record on its varve-counted timescale reflects all ^{14}C plateaus, their internal structures, and relative length previously identified, but implies a rise in the average ^{14}C plateau age by 200–700 ^{14}C yr during the LGM and early deglacial times. (2) Based on different ^{14}C ages of coeval atmospheric and planktic ^{14}C plateaus, marine surface water $\Delta^{14}C$ may have temporarily dropped to an equivalent of ~0 yr in low-latitude lagoon waters, but reached >2500 ^{14}C yr both in stratified subpolar waters and in upwelled waters such as in the South China Sea. These values differ significantly from a widely assumed constant global planktic $\Delta^{14}C$ value of 400 yr. (3) Suites of deglacial planktic $\Delta^{14}C$ values are closely reproducible in ^{14}C records measured at neighboring core sites. (4) Apparent deep-water ^{14}C ventilation ages (equivalents of benthic $\Delta^{14}C$), deduced from the sum of planktic $\Delta^{14}C$ and coeval benthic-planktic ^{14}C differences, vary from 500 up to >5000 yr in LGM and deglacial ocean basins.

INTRODUCTION: OBJECTIVES

Over the last decades, radiocarbon dating of planktic foraminifera in marine sediments evolved as a standard stratigraphic tool. It proved crucial for correlating centennial- and millennial-scale climate signals in paleoceanographic and terrestrial sediment records on a global scale, and for estimating the rates of climate change over the last 40 kyr. However, various authors (Bard 1988; Broecker et al. 1984; Stuiver and Braziunas 1993; Fontugne et al. 2004; Grootes and Sarnthein 2006; Sarnthein et al. 2007) have become increasingly aware of a significant variability in the planktic ^{14}C signal that is linked to spatial and temporal changes in the local ^{14}C reservoir age of surface waters. The latter is the difference between coeval atmospheric and marine ^{14}C concentrations, which presents the ^{14}C fraction that has decayed over the reservoir age. The remaining marine ^{14}C concentration commonly is listed as $\Delta^{14}C$, but actually corresponds to $\Delta\Delta^{14}C$ in physical wording. ^{14}C ages need to be corrected for this local anomaly before any relevant age correlation can be established. Yet, estimates of ^{14}C reservoir ages of the modern—that is, pre-bomb, "undisturbed"—offshore ocean waters are very rare because of the atmospheric nuclear weapons testing (Stuiver and Braziunas 1993). Even rarer are independent estimates of past ^{14}C reservoir ages; thus, their temporal and spatial changes are widely unknown. A major additional problem concerns changes in the atmospheric ^{14}C content beyond ~14,000 calendar yr BP, the details of which remained poorly known until recently (Bronk Ramsey et al. 2012).

^{14}C plateau tuning of densely dated high-resolution marine sediment records to an atmospheric calibration record provides a robust technique to derive both an absolute chronology for the sediment records and a high-resolution local record of changing $\Delta^{14}C$ values for surface and deep waters (Sarnthein et al. 2007). We designate as a ^{14}C plateau, both in the Suigetsu profile and in marine age-depth profiles, a section where several planktic ^{14}C ages have almost constant values—that is,

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an overall gradient of <1 ^{14}C yr per cal yr and variations less than an equivalent of ±100 to ±300 yr. Hence, these ^{14}C dates form a plateau-shaped scatter band that extends over ~5 to 50 cm and up to 200 cm in sediment cores with sedimentation rates of >10 cm/kyr (the full data set is available at PANGEA, http://doi.pangaea.de/10.1594/PANGAEA.837511; the data is also posted as Tables S1, S2, and S3 online in the Supplemental files accompanying this article). For the chronological calibration of the plateaus, the correlative atmospheric ^{14}C record needs to be based on annually resolved, absolutely dated sediment and/or plant records that have incorporated atmospheric carbon at the time of formation (Reimer et al. 2013). Yet, lacking such a record beyond the 14-ka limit of tree-ring calibration, our reservoir age records reported thus far had been based on an atmospheric record reconstructed from marine carbonates formed in surface waters and on speleothems.

With the publication of the Suigetsu record (Bronk Ramsey et al. 2012), a fully atmospheric ^{14}C record is now available. This article presents 11 records of glacial-to-early-deglacial planktic and 8 records of benthic ^{14}C reservoir ages (23–13 cal ka) from the Atlantic, Indian, and North Pacific oceans (Figure 1). Four planktic records are new (GIK 23074, MD08-3180, ODP 1002, and MD02-2503) and four have been augmented with new planktic ^{14}C dates [(PS2644, GIK17940, and MD01-2416 (Sarnthein et al. 2007); MD02-2489 (Gebhardt et al. 2008)]. Absolute ages and ^{14}C reservoir ages for the records are derived using the Suigetsu atmospheric ^{14}C record on its varve-counted timescale instead of the earlier atmospheric proxy ^{14}C record based on corals, Cariaco planktic forams, and Bahama speleothems. The records enable us to establish accurate age control and to display centennial-scale changes in sedimentation rate at 11 deep-sea sites. Moreover, they serve as sensible tracers of the origin and structures of ocean surface waters to uncover ocean features such as stratification, vertical mixing, and the upwelling of subsurface waters over LGM and deglacial times. Finally, they form a robust basis to reconstruct apparent deep-water ventilation ages from paired ^{14}C dates of benthic foraminifera.

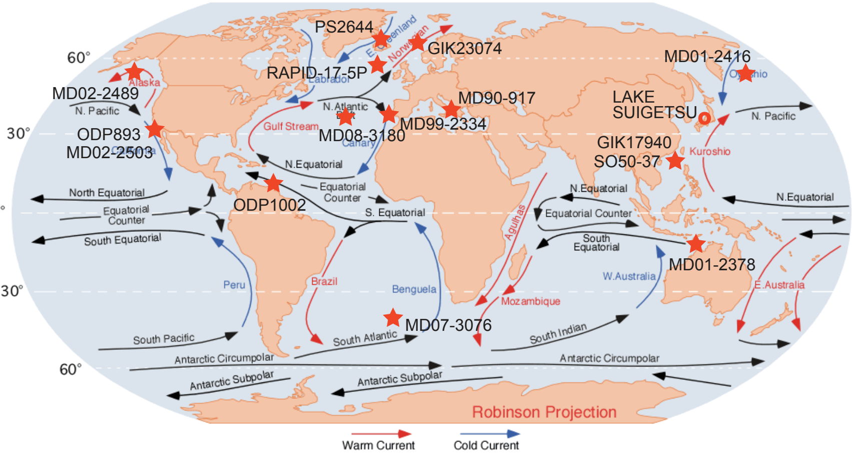

Figure 1 Core locations and ocean surface currents

METHODS

^{14}C Record of Lake Suigetsu as Basis for Age Calibration

Our plateau-tuning method (Sarnthein et al. 2007) is based on a suite of 11 glacial and deglacial atmospheric ^{14}C plateaus and subplateaus (Figure 2a) providing two lines of evidence: (1) the calendar age of the upper and lower boundaries of each plateau recorded and (2) the average ^{14}C age of each ^{14}C plateau. To improve the age calibration of these 11 (sub)plateaus and 19 plateau boundaries in our sediment records, we now abandon our previously used reference record that relied on the joint information of ^{14}C-dated Cariaco Basin sediments, ^{14}C- and U/Th-dated corals, and the ^{14}C- and U/Th-dated Bahama and Hulu Cave speleothems (Beck et al. 2001; Wang et al. 2001; Fairbanks et al. 2005; Hughen et al. 2006; summarized in Sarnthein et al. 2007), all linked to inorganic carbon dissolved in water. Instead, we now employ the varve-counted atmospheric ^{14}C record of Lake Suigetsu (Bronk Ramsey et al. 2012), a record that caused changes to our previous age assignments (Figures 2a,b), but appears superior to other records for the following reasons:

- The ^{14}C record of Lake Suigetsu sediments, which are continuously varved beyond ~10 cal ka, is the only decadal-to-centennial-scale resolution, purely atmospheric ^{14}C and Δ^{14}C record available beyond 13.9 cal ka (Reimer et al. 2013).

- The influence of reworking was constrained by selecting for dating fragile plant materials that cannot survive reworking (Bronk Ramsey et al. 2012).

- For peak glacial and deglacial times, we consider the varve-counted timescale superior to the modeled Suigetsu timescale (Supplemental Text #1) because varve counts avoid feedback from the carbonate-based atmospheric proxies. The modeled timescale is tuned to satisfy dead carbon fraction (DCF) restrictions in the U/Th-based Hulu H82 and the Bahama GB 89 25 3 timescale (Bronk Ramsey et al. 2012), which creates a dependence of the Suigetsu atmospheric calibration curve on the characteristics of the carbonate systems used for calibration. This leads to strong, unreasonable deviations from the varve counting by up to 650 yr and a significant offset from the NGRIP ice core timescale, especially around 18 cal ka. The offset may result from possibly significant but unknown variations in the "dead carbon" effects of the speleothem records, which over this period that is marked by severe changes from arid to humid conditions (Wang et al. 2001), exceed the limits set in the modeling.

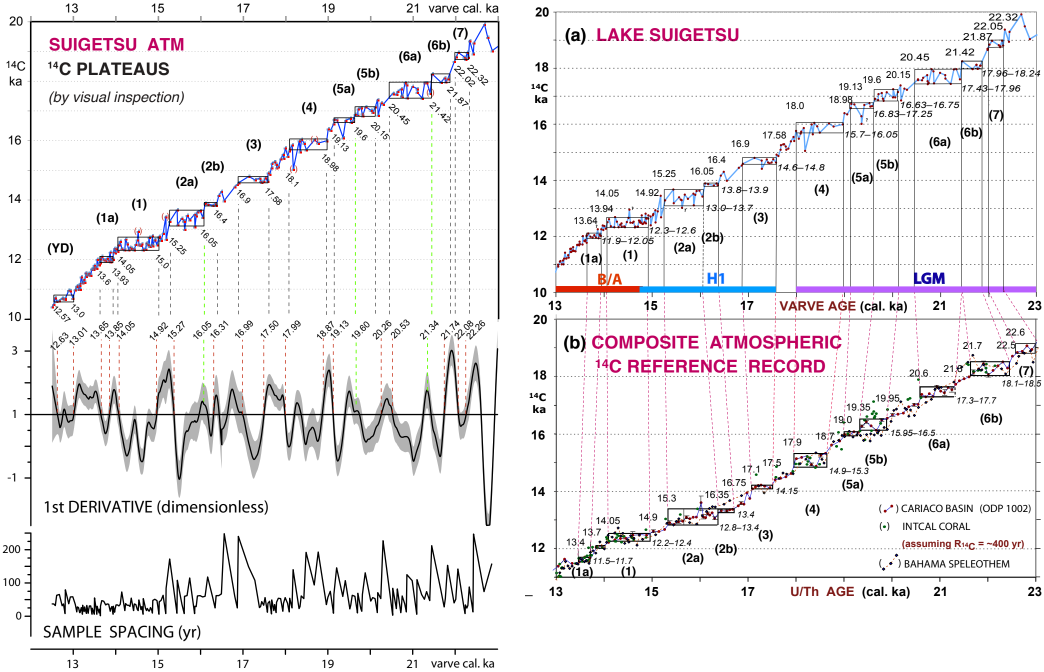

Figure 2 (a, left) Comparison of ages of atmospheric ^{14}C plateau suite in Lake Suigetsu section (Bronk Ramsey et al. 2012) with (b, right) the plateau suite of mixed ^{14}C records of Cariaco Basin, Bahama speleothem, and IntCal coral on U/Th age scale, with ^{14}C ages corrected for assumed 420-yr reservoir age (Sarnthein et al. 2007). Numbers of ^{14}C plateaus (horizontal boxes) in parentheses. Atmospheric ^{14}C ages are given to the right, calendar ages above. The middle panel in Figure 2a shows units of the 1st derivative (^{14}C yr per cal yr) and 1σ uncertainty range. 1st derivatives >1 indicate ^{14}C jumps. B/A = Bølling-Allerød; H1 = Heinrich 1; LGM = Last Glacial Maximum.

- The varve-counted Suigetsu record produces lower reservoir ages than IntCal09 or the age-modeled Suigetsu reference records, ages that are to be preferred following the definition of Sarnthein et al. (2007).

- The Suigetsu atmospheric ^{14}C record reproduces all ^{14}C plateaus, their internal structures, and relative length as previously identified in the composite ^{14}C record of Cariaco Basin sediments, IntCal corals, and Bahama speleothems. However, it implies a rise in the average ^{14}C plateau age by <200 ^{14}C yr during the LGM, >700 yr at its end, and <200 yr in the Bølling-Allerød.

Yet, the varve-counted timescale has a problem. When comparing the varve-counted Suigetsu record of pristine atmospheric ^{14}C with uncorrected ^{14}C concentrations of peak glacial to deglacial Barbados corals (Fairbanks et al. 2005), Cariaco planktic forams (Hughen et al. 2006), and the Hulu H82 speleothem (Southon et al. 2012), we find extended periods with little or no age difference between atmospheric Suigetsu and the carbonate records. For some corals, however, we even find negative, hence "illegitimate," ^{14}C reservoir age ranges near 18 to 18.5 cal ka (Fairbanks et al. 2005), for Cariaco planktic ^{14}C dates from 17–18.5 ka (on the basis of plateau tuning; at 16.4–17 ka, when tuned to the Hulu timescale). As compared to Hulu Cave ^{14}C dates, we find in Suigetsu short-term excursions at the top portion of all ^{14}C plateaus from 15.3 back to 23 ka, where ^{14}C ages are slightly higher than those at Hulu Cave. Although Suigetsu ^{14}C ages show scatter and have uncertainties in the range 100 to 300 yr at 1σ, these cannot explain the observed systematic offsets over a period of 8000 yr. This suggests the varve-counted timescale is too young in this period by 250–300 yr. Despite this problem, we chose the varve-counted timescale for the aforementioned reasons and because it is based on direct measurements, not on assumptions and correlation.

In Figures 3–13, stratigraphic units were defined following Mix et al. (2001) for the Last Glacial Maximum (LGM, 23–18 ka, instead of 23–19 ka), Denton et al. (2006) and Sarnthein (2011) for Heinrich Stadial 1 (HS-1, 17.5–14.7 ka), and the GICC05 age scale (Svensson et al. 2006) for the Bølling-Allerød (B/A, 14.7–13.0 cal ka). In each sediment core, these basic units were assigned by means of δ^{18}O records with bidecadal to centennial-scale sampling resolution (data sources are cited separately for each core).

Analysis of ^{14}C Ages Discussed Herein

^{14}C ages of most sediment cores were measured on monospecific samples of planktic (and/or benthic) foraminifera specimens at the Kiel Leibniz AMS Laboratory following standard procedures (Nadeau et al. 1997). Results were derived from the difference between the measured ^{14}C concentration and a ^{14}C carbonate background value and are expressed as conventional ^{14}C ages. Most background values were analyzed on the "dead carbon" of planktic foraminifera specimens of Marine Isotope Stage (MIS) 11 and/or of MIS 5.5, if pertinent ^{14}C data were available from the core site studied. In various cores, in particular at ODP 1002 and MD08-3180, ^{14}C ages were measured at the Center for AMS at Lawrence Livermore National Laboratory (CAMS-LLNL) and more recently, at the University of California Irvine (UCI), where they used samples of marble to determine the ^{14}C background (Hughen et al. 2004).

As compared to previously published ^{14}C data of cores GIK17940, MD01-2378, MD01-2416, MD02-2489, ODP893A, and PS2644 (Sarnthein et al. 2007, 2011; Gebhardt et al. 2008), the sampling density and reach of ^{14}C records was increased and the tuning of plateaus carefully reconsidered on the basis of the new atmospheric ^{14}C reference record of Lake Suigetsu (Bronk Ramsey et al. 2012).

Objective Derivation of ^{14}C Plateaus and Their Boundaries

If one takes an ample uncertainty of 250 ^{14}C yr, incorporating sampling effects and timescale uncertainty, the data in the Suigetsu ^{14}C age-age plot (Figure 2a) can be seen as scattering around a straight line, which reflects a ^{14}C timescale that indeed corresponds to real time. However, if one tries to extract more and new information from the record, one zooms in and tries to understand the fine structure of the record and the information it contains, that is, to find all ^{14}C plateaus and ^{14}C jumps in between. Jumps are indicated by data series, where the ^{14}C vs. calendar year slope exceeds 1, in general to a significant extent. Avoiding artifacts due to data noise can, however, be a problem in the visual definition of plateaus.

Here, we present a new mathematical method for an objective identification of ^{14}C plateaus and jumps by means of statistically estimating the 1st derivative of all downcore changes in the ^{14}C age–calendar age relationship. The derivative is estimated using a running kernel window to overcome the effect of individual outliers. As outlined above, values >1 are indicative of jumps separating plateaus. Uncertainty bands are constructed using bootstrap resampling (Mudelsee 2014). Technical details and the computational program kernel.f90 of this statistical approach are given in Supplementary Text no. 2.

This technique has been implemented for all ^{14}C records presented herein. In most cases, close agreement was obtained with the plateau boundaries simply selected by visual inspection (Figure 2a), despite the relatively low data density. Yet, to detect some of the visual plateaus at low data resolution we had to rely on the jumps between the ^{14}C plateaus as primary evidence for unambiguous mathematical detection. As shown in Tables S3a and S3b, about half of the computed plateau boundary ages of the Suigetsu record do not differ by more than 5–50 yr, the others by 80–110 yr. In many cases, the 1st derivative makes for a somewhat later start and earlier ending of the plateaus, as expected from smoothing by the window. This implies a slight reduction in the mathematically determined plateau length. For practical reasons (summing all ^{14}C dates to derive ^{14}C averages for each plateau, including those left out by the 1st derivative artificially shortening the plateaus), we continued to base our calculations of reservoir ages, our tuned calendar ages of plateau boundaries, and sedimentation rates on the boundary ages defined by visual inspection.

Derivation of Planktic ^{14}C Ventilation Ages

^{14}C ventilation ages present the difference in ^{14}C age between contemporaneous oceanic and atmospheric samples. Oceanic samples usually consist of corals and planktic or benthic foraminifera picked from a sediment core and are easily obtained. By contrast, securely correlated atmospheric ^{14}C samples (e.g. terrestrial plant remains) are rarely available in deep-sea sediments. Instead, we determine both the ^{14}C reservoir age and the absolute age of any layer sampled in a marine sediment section by means of the ^{14}C plateau-tuning technique (Sarnthein et al. 2007), which provides absolute and ^{14}C ages of the contemporaneous atmosphere by means of the Suigetsu ^{14}C calibration record (Bronk Ramsey et al. 2012). We follow the common assumption, supported by observations of the atomic bomb effect (Nydal et al. 1980; Druffel 1989), that ^{14}C concentrations in the surface ocean closely reflect within a decade those in the atmosphere. On this basis, the age-defined upper and lower boundaries of a suite of ^{14}C plateaus in a marine sediment core provide a series of absolute age control points via correlation to the upper and lower boundaries defined for plateaus in the varve-counted atmospheric ^{14}C reference record of Lake Suigetsu.

In addition, the tuning technique derives past reservoir ages of surface waters (and planktic ‰ Δ^{14}C; Table S1) from the difference between the uncorrected ^{14}C age of any particular planktic ^{14}C plateau measured in a sediment core and that of a well-constrained equivalent atmospheric ^{14}C plateau within a suite of plateaus numbered 1–7 in the Suigetsu reference record covering the LGM and Termination 1 (Table S3). Prerequisites, rules, and caveats of the plateau tuning technique were defined in Sarnthein et al. (2007, 2011; further details shown in Figures 3–13). This technique requires marine sediment cores with sedimentation rates exceeding 6–10 cm/kyr. Short-term changes in local sedimentation rates, resulting from planktic plateau tuning, should not exceed a factor of 1.5 to 2.0 between two successive plateaus, except for sediments in regions immediately offshore.

Caveats and Uncertainties

A frequently asked question concerns the large changes of reservoir age to be expected in surface waters, more specifically, how these changes might affect the structure of ^{14}C plateaus and how they might bias the plateau tuning technique. The answer relies on the particular structures that mark both the whole plateau suite 13–23 ka and single plateaus (e.g. long vs. short plateaus; two-step plateaus; etc.) in the varve-counted Suigetsu atmospheric ^{14}C record (Bronk Ramsey et al. 2012). On this basis, one can specify irregularities within a plateau suite and single plateaus such as a short-term drop in reservoir ages, which results in fragmented ^{14}C plateaus and enlarged ^{14}C jumps as found in various sediment cores near the end of HS-1. By contrast, a rise in reservoir ages leads to shortened ^{14}C jumps. In total, the approach of plateau tuning uses two general assumptions: (1) Reservoir age changes of surface waters take 10–100 yr (per analogy to shifts from DO stadials to interstadials), whereas ^{14}C plateaus under discussion often last 400–1000 yr. (2) Reservoir age regimes are conservative, lasting over several hundred to several thousand years per analogy to the duration of Dansgaard-Oeschger and Heinrich stadials and interstadials; thus, they will cover timespans extending over several successive ^{14}C plateaus.

To calculate past planktic reservoir ages and associated Δ^{14}C, we subtract the average ^{14}C ages of atmospheric ^{14}C plateaus 1–7 in the Lake Suigetsu record (Bronk Ramsey et al. 2012) from the average ages of the respective planktic ^{14}C plateaus measured in deep-sea cores, as shown in Figures 3–13 (data sources and analytical errors are listed in Table S2, plateau definitions and planktic ventilation ages in Table S3). Uncertainties of planktic ^{14}C age and Δ^{14}C are derived from the bandwidth of the respective plateaus enveloping the Suigetsu atmospheric and planktic ^{14}C ages each, assuming that half the plateau width includes the complete data scatter of ^{14}C ages, except for some extreme outliers. These are <10%, thus roughly correspond to a 0.9 uncertainty range of 1.68σ. ^{14}C analytical uncertainties are considerably smaller. Combining the 1.68σ uncertainties of the atmospheric and marine ^{14}C plateau records by the square root of the sum of the squares gives an estimate of the corresponding uncertainty in the planktic Δ^{14}C estimate. The resulting uncertainty of LGM age estimates amounts to ±250–450 yr.

Apparent Benthic ^{14}C Ventilation Ages

Finally, the planktic ^{14}C ventilation age can be summed with the difference between paired raw benthic and planktic ^{14}C ages to provide the apparent age of local deep-ocean ventilation and benthic Δ^{14}C values (Figures 3–13). Apparent benthic ^{14}C ventilation ages for ocean waters mean the time needed for a sample with pristine atmospheric ^{14}C concentration to decay to the ^{14}C concentration observed in shallow- and deep-ocean samples, finally depicted in ^{14}C values of foraminifera. The age is “apparent” because it is not a real age, since fluctuations in atmospheric ^{14}C concentration, CO_2 exchange between surface ocean and atmosphere, oceanic mixing, and carbonate dissolution co-determine the observed atmosphere-ocean ^{14}C concentration ratio. For mass and isotope balance calculations, ^{14}C concentrations are employed, expressed as fraction of modern carbon (FMC).

In our study, the “projection age” technique (Adkins et al. 1998), which considers a short-term ^{14}C heritage in the benthic ^{14}C signal, was not employed for deriving deep-ocean ventilation ages for two reasons: (1) Short-term changes in atmospheric ^{14}C introduce an uncertainty in the inherited-age calculation that clearly exceeds that of plateau tuning. (2) The varve-counted atmospheric ^{14}C record of Suigetsu (Bronk Ramsey et al. 2012) reveals for the LGM an older period of roughly constant $\Delta^{14}C$ around 24–21 ka, separated by a ~70‰ drop (600 yr) near 21 ka from a younger one extending from ~20.5–17.5 ka. We neglect these shifts for our LGM average estimates of benthic $\Delta^{14}C$ in view of the overall magnitude of the benthic $\Delta^{14}C$ shifts under discussion and further uncertainties that apply to the derivation of deep-water $\Delta^{14}C$ (e.g. centennial-to-millennial-scale variability).

For the subsequent HS-1, deep waters with apparent ^{14}C ages of 1000–5000 yr may contain a more significant $\Delta^{14}C$ heritage of LGM waters reaching up to 120‰ (equal to ~1000 ^{14}C yr) from an antecedent ^{14}C-enriched atmosphere, making them artificially "young." However, the magnitude of the short-lasting local ventilation pulses, displayed by "young" deep waters (e.g. in the northern Pacific; Figures 10, 11), by far exceeds what could be expected from an inherited $\Delta^{14}C$ signal during HS-1. The B/A provides a further potential example for a short-term ^{14}C heritage of "fossil" deep waters, which may reach up to 100–220‰ (equal to 850–2000 ^{14}C yr), when benthic ventilation age estimates were fairly low for all ocean basins (Sarnthein et al. 2013), in part possibly an artifact of inherited high $\Delta^{14}C$, a factor so far neglected because of reconstruction uncertainties.

RESULTS

Here, we present ^{14}C records of 11 sediment cores and their interpretation using plateau tuning to the varve-counted Suigetsu atmospheric ^{14}C reference. These records monitor the character of surface (and in part, also deep-) water masses and their ventilation ages in the northern and subtropical North Atlantic, in the subtropical eastern and western South Atlantic, the Timor and South China Seas, and the northern subpolar and eastern subtropical North Pacific (Figure 1, Table S1). All ^{14}C data have been deposited at the PANGAEA databank (http://doi.pangaea.de/10.1594/PANGAEA.837511).

Norwegian Sea

The planktic ^{14}C record of Core GIK 23074 is based on 56 dates of *Neogloboquadrina pachyderma* sin that cover the interval between 13.5 and 22 cal ka (Figure 3, Table S2a). In general, the suite of planktic ^{14}C plateaus closely follows that of the Lake Suigetsu record. Peak glacial planktic ^{14}C reservoir ages varied between ~500 and ~800 yr. Subsequent to plateau 5a (19 cal ka), planktic reservoir ages increased from ~600 to an extreme of ~2000 yr during HS-1, a rise that resulted in a reduction of ^{14}C jumps that separate plateaus 5a, 4, 3, and plateau 2b. Inversely, plateau 2a (~16 to ~15 cal ka) was completely distorted because of a steep drop in planktic reservoir age from ~2000 down to ~140 and ~300 ^{14}C yr, values that arise from ^{14}C plateaus 1 and 1a. This drop was linked to a major meltwater incursion that is documented by a prominent negative excursion of planktic $\delta^{18}O$ by more than 2‰ (Voelker 1999). The 1st derivative largely confirms the visually selected plateaus, but is ambiguous for the transition 2a/2b (meltwater incursion), possibly also for the transition 6a–6b at low data density. On the basis of plateau tuning, the sedimentation rates in Core 23074 varied on centennial timescales between 25 and 50 cm/kyr, except for the meltwater event, where the rates increased up to >60 cm/kyr.

Icelandic Sea – East Greenland Current

The planktic ^{14}C record of Core PS2644 consists of 32 dates measured on *N. pachyderma* (s) for a core section extending from ~21.5 to 15.0 cal ka. In addition, four ^{14}C ages were analyzed on top and below this core section (Figure 4, Table S2b). Pronounced ^{14}C jumps both at the base and top of this record (in addition to structural sediment unconformities) suggest short stratigraphic hiatuses that mark the ends of HS-1 and HS-2. The suite of peak glacial and deglacial ^{14}C plateaus 6a–2a follows

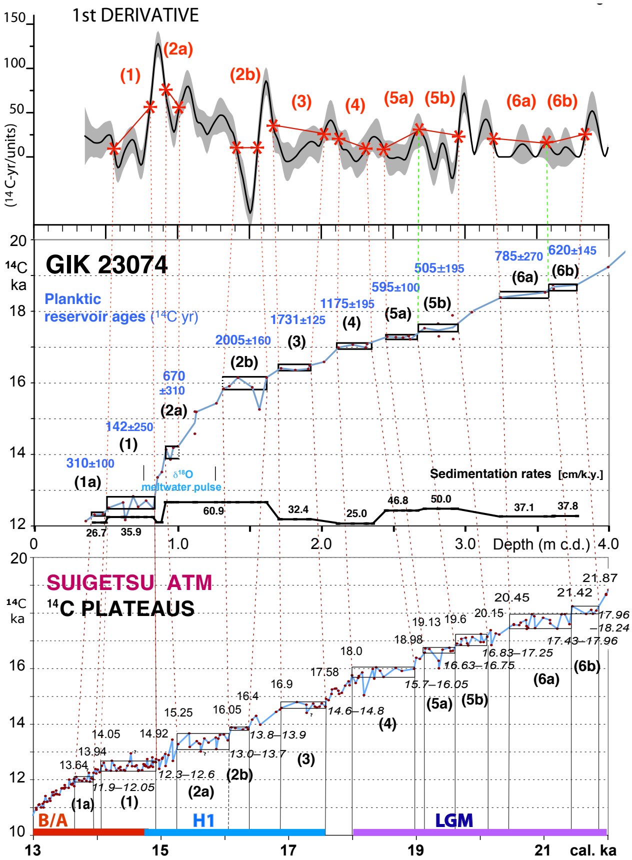

Figure 3 Planktic ¹⁴C record of Core GIK 23074 plotted vs. core depth (unpublished data). Planktic ¹⁴C plateaus (horizontal boxes) are compared to atmospheric (atm) ¹⁴C plateau suite of Lake Suigetsu (Bronk Ramsey et al. 2012), where atmospheric ¹⁴C ages are given to the right, calendar ages above. Local planktic reservoir ages (in blue) result from the difference between the average uncorrected ¹⁴C age of planktic ¹⁴C plateaus measured in the core and the ¹⁴C age of equivalent atmospheric ¹⁴C plateaus numbered 1–7 (numbers in parentheses). Top panel shows units of the 1st derivative (¹⁴C yr per m core depth) and 1σ uncertainty range, with high values indicating ¹⁴C jumps and ¹⁴C plateaus (numbered in red) constrained at "half-height" by asterisks. B/A = Bølling-Allerød, H1 = Heinrich Stadial 1, LGM = Last Glacial Maximum. Sedimentation rates are based on ages of plateau boundaries.

closely that of the Suigetsu record, thus revealing a fairly constant planktic reservoir age that gradually drops from ~2200 ¹⁴C yr during the LGM to ~1700–1900 ¹⁴C yr during HS-1. The subsequent plateau 1 is lost in the hiatus. Although the peaks and valleys of the 1st derivative allow a definition of plateaus and jumps in good agreement with the visual selection, the two extra peaks in plateau 2a and that in plateau 4 show the sensitivity of the technique to data scatter with low data density.

The unusually high planktic reservoir ages of subsurface waters (then probably covered by sea ice within the East Greenland Current) are strongly corroborated by a series of 21 benthic ventilation ages that strongly oscillate between 100 and 2600 yr. Except for a striking drop to 570/1740 ¹⁴C yr near 21 ka, the benthic ages (largely measured on *Cibicidoides* sp.) were similar or slightly higher than the paired planktic ages during the LGM, but much younger under the changed MOC regime of HS-1 (Sarnthein et al. 2013). Here, benthic ventilation ages decreased to 110–390 ¹⁴C yr near 18.5 cal ka and 770/850 ¹⁴C yr near 17 cal ka as compared to planktic reservoir ages of 1920 to ~1670 ¹⁴C yr. The low benthic age level implies that any major lowering of the planktic reservoir age estimates would necessarily lead to negative benthic ventilation ages, which is physically impossible.

The plateau tuning at Site PS2644 leads to sedimentation rates that were as low as ~3.8–6.5 cm/kyr during the LGM. After 19 cal ka, however, the rates rose to ~9–14.5, and finally, after 16.4 cal ka, up to ~21 cm/kyr during deglacial plateaus 2a and b, a timespan of massive meltwater input (van Kreveld et al. 2000).

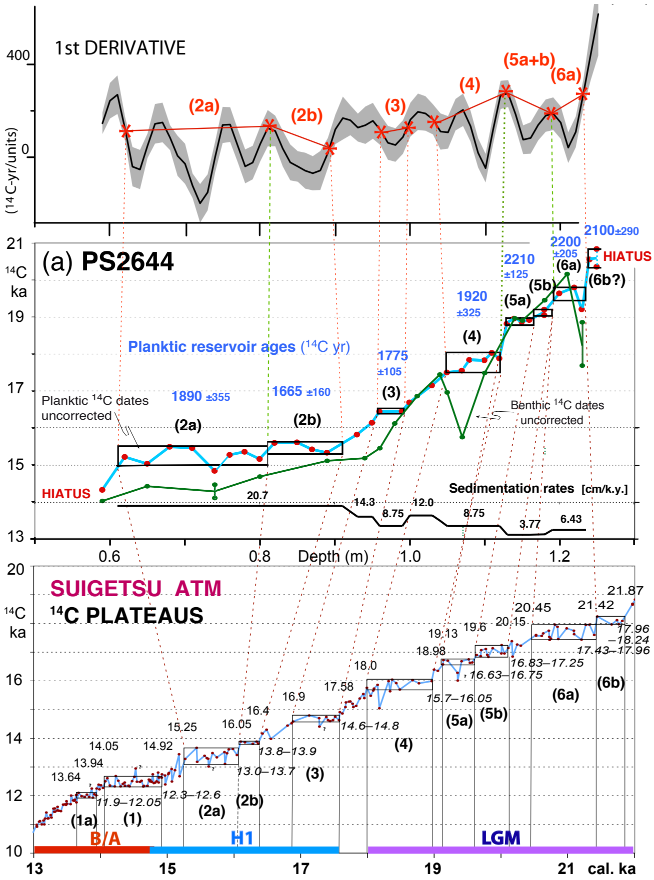

Figure 4 Planktic and benthic ^{14}C records and sedimentation rates of Core PS2644 (Sarnthein et al. 2007, suppl.). Details of figure caption see Figure 3. Green line connects uncorrected ^{14}C age data of paired benthic foraminifera samples.

Central Subtropical Atlantic – Azores Current

Unfortunately, the planktic ^{14}C record of Core MD08-3180 suffers from unusually large analytical age uncertainties between 270 and 500 cm core depth, which result from excessive CO_2 cleaning measures (Figure 5; Table S2c). Nevertheless, a total of 66 ^{14}C dates measured on samples of *Globigerina bulloides* still provide a suite of distinct ^{14}C plateaus that can be tuned smoothly to plateaus 5b to 2a in the Suigetsu record. The 1st derivative provides good agreement for the definition of plateaus 2a, 2b, 3, 5a, and 5b plateau 3 despite a high data point with large uncertainty. For plateau 4, the data scatter suggests a breakup in smaller plateaus that, however, have no atmospheric counterpart and fake a significant shortening of this plateau.

Plateaus 5b, 5a, and 4 result in LGM planktic reservoir ages of ~300–550 ^{14}C yr, a level common to most ages published for samples from elsewhere in the subtropical ocean (Stuiver and Braziunas 1993). Subsequent plateaus 3, 2b, and 2a suggest an abrupt rise in planktic reservoir ages up to 1300 and 1650 ^{14}C yr during HS-1. In part, these high ages are significantly higher than coeval apparent benthic ventilation ages (measured on mixed benthic species), e.g. at plateaus 3 and 2a. This excess in planktic ages necessarily corroborates the unexpected high level of planktic reservoir ages, per analogy to the reasoning discussed for Core PS2644 (Figures 4 and 5).

Plateau 1 is hardly preserved and almost lost within a steep ^{14}C slope at 330–260 cm core depth, where planktic ^{14}C ages drop by >3000 ^{14}C yr over a short time interval lasting from 15.25 to

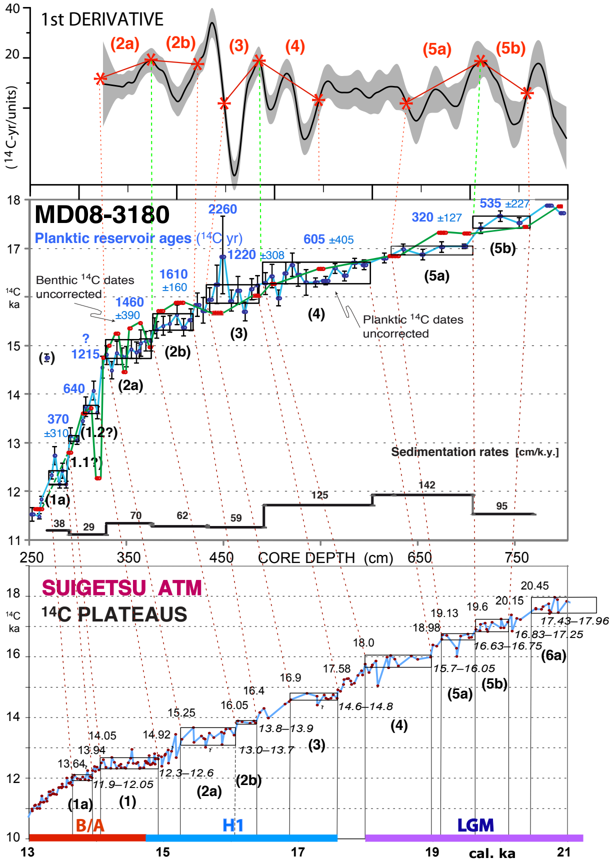

Figure 5 Planktic and benthic ^{14}C records and sedimentation rates of Core MD08-3180 (unpublished data). For details of figure caption, see Figure 3. Green line connects uncorrected ^{14}C age data of paired benthic foraminifera samples. Horizontal width of red dots reflects sample thickness.

<13.5 cal ka. On the basis of a planktic δ^{18}O record (unpublished data; sampling resolution better than 50 yr), this drop definitively does not result from a stratigraphic gap but documents a ~1400 ^{14}C yr decrease in planktic reservoir ages down to 370 ^{14}C yr at plateau 1a, an age shift that covers terminal HS-1 and early B/A (Figure 5). During that time, benthic ^{14}C ages likewise decrease by >3000 yr, thus recording a significant, almost abrupt drop in benthic ^{14}C ventilation age near ~3000 m water depth, though possibly somewhat enlarged by downcore bioturbational mixing. Plateau tuning in Core M08-3180 leads to average sedimentation rates of ~115–175 cm/kyr for the LGM, ~55 cm/kyr for HS-1, and 32 cm/kyr for the early B/A.

Western Tropical Atlantic – Cariaco Basin

The widely known planktic ^{14}C record of ODP Site 1002 (Figure 6; Table S2d) is in this time interval based on 115 ^{14}C dates (Hughen et al. 2006). They were averaged out of many duplicate and triplicate dates in a set of altogether 197 ^{14}C dates either analyzed on *Globigerinoides ruber* white or on *G. bulloides*, in rare cases also on mixed planktic foraminifera obtained from 4.8 to 10.5 m core depth. The ^{14}C record comprises a suite of ^{14}C plateaus 1a to 7 being tuned without problems to the Suigetsu reference record. The values of the 1st derivative show a good agreement with this visual tuning, except for the boundary lost between plateau 5a and 5b.

Different from common assumptions (Hughen et al. 2006), the planktic ^{14}C reservoir ages at ODP Site 1002 underwent major changes. LGM planktic reservoir ages (plateaus 7 and 6) decreased from

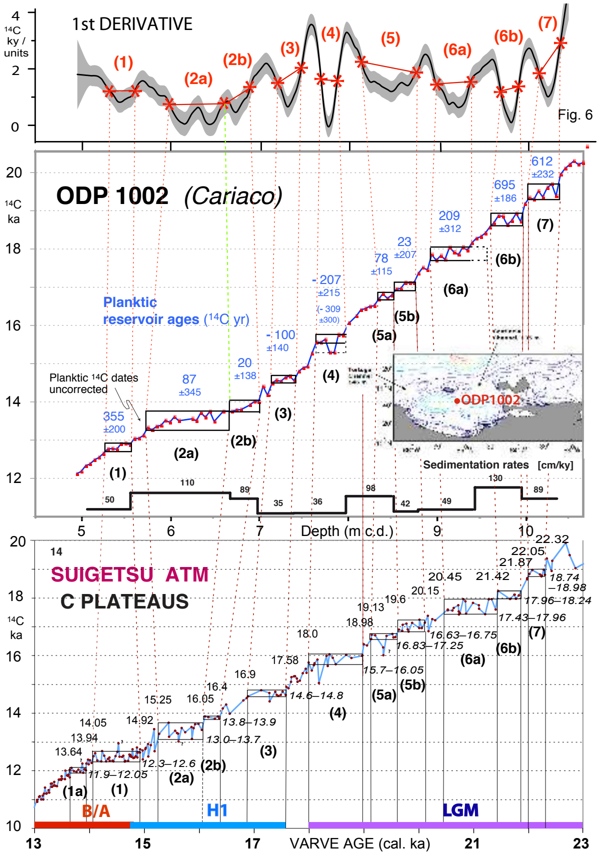

Figure 6 Planktic and benthic ^{14}C records and sedimentation rates of ODP Core 1002 (^{14}C dates of Hughen et al. 2006). For details of figure caption, see Figure 3. Insert map shows bathymetric setting of Cariaco Basin.

~700 to ~25 ^{14}C yr. We surmise that this drop led to an amputation of lower plateau 6a, thereby to an expanded transition from plateau 6b to 6a. After 20.5 cal ka, the planktic reservoir ages oscillated near 0 yr with one "illegitimate" value of –210 yr (though still within the uncertainty of ±215 yr) until the end HS-1, up to the top of plateau 2a, an age level hitherto unknown. It may be related to the glacial low sea level, which in part may have been enhanced by a slightly delayed isostatic uplift (Mitrovica 2013). Accordingly, the inflow of surface waters from the open Caribbean Sea into the lagoon-style Cariaco Basin was strongly constricted to two narrow and shallow channels (inset map in Figure 6), and thus dropped to a minimum. In turn, the immediate short-term exchange of atmospheric carbon became dominant on the carbon inventory and ^{14}C signal of surface waters in the Cariaco Basin. Finally, after 15 cal ka, the reservoir ages returned to a level of ~350 ^{14}C yr as characteristic of subtropical surface waters, when the deglacial sea-level rise had flooded all barriers that encompassed the Cariaco Basin.

The plateau-based age scale results in highly variable sedimentation rates as may be expected for sediment deposits immediately near shore. Peak glacial rates of 90–130 cm/kyr were followed by early deglacial rates of 35–50 cm/kyr and culminated at 90–110 cm/kyr near the end of HS-1; 50–70 cm/kyr were characteristic of B/A times.

Subtropical Eastern Indian Ocean – Timor Sea

The planktic ^{14}C record of Core MD01-2378 is based on 74 ^{14}C dates measured on *G. ruber* white

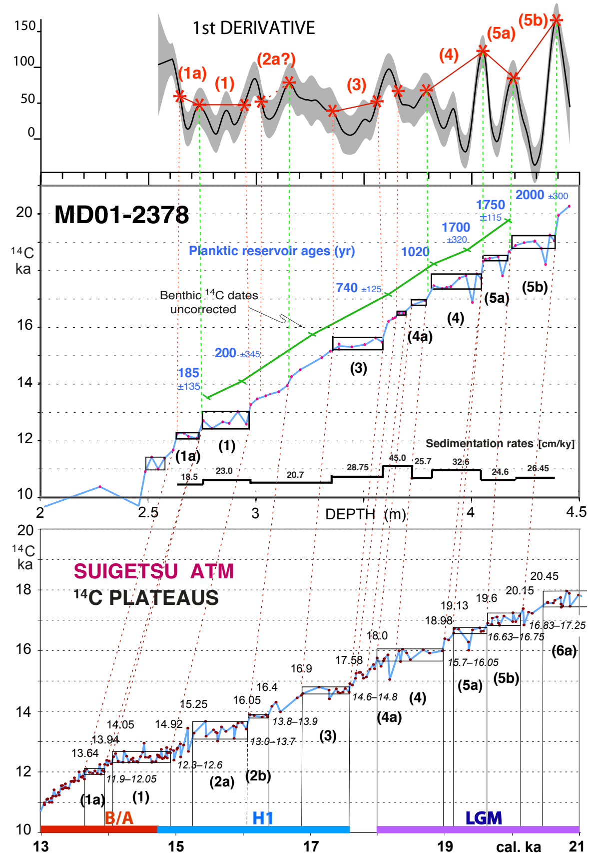

Figure 7 Planktic and benthic ¹⁴C records and sedimentation rates of Core MD01-2378 (Sarnthein et al. 2011). For details of figure caption, see Figure 3. Green line connects uncorrected ¹⁴C age data of paired benthic foraminifera samples.

(Figure 7, Table S2e; Sarnthein et al. 2011). It shows a suite of plateaus that can readily be tuned to the atmospheric Suigetsu record with only plateaus 2a and 2b missing. The 1st derivative confirms the visual plateau selection. During the LGM, planktic reservoir ages reached 2000 to 1700 yr, probably controlled by a coastal upwelling of old intermediate waters in front of the dried-up Australian shelf. Both the end of the LGM and late HS-1 were marked by a pronounced drop in reservoir age, first down to 700 yr and finally, to ~200 yr. The latter value was characteristic of B/A times. Benthic apparent ventilation ages near 1800 m water depth varied between >3000 yr during the LGM and less than 1500 yr during the B/A.

The ¹⁴C plateau stratigraphy results in fairly constant sedimentation rates that range between ~18.5 and 33 cm/kyr. A short-lasting maximum of 45 cm occurred just prior to the onset of HS-1, the minimum of 18.5 cm/kyr in the upper B/A (Figure 7).

Two Neighboring Sites in the Northern South China Sea

The planktic ¹⁴C record of Core 17940 (~1725 m water depth) consists of 50 ¹⁴C dates measured on *G. ruber*, rarely replaced by *Globigerinoides sacculifer* (Figure 8; Table S2f; data of Sarnthein et al. 2007). Planktic ¹⁴C plateaus 1a to 3 are readily tuned to those defined in the ¹⁴C record of Lake Suigetsu. Their selection is supported by the 1st derivative, provided a clear peak inside plateau 2b is attributed to data scatter.

Below plateau 3, a 3000-yr-wide jump in ¹⁴C ages occurs over two stratigraphic gaps lying about

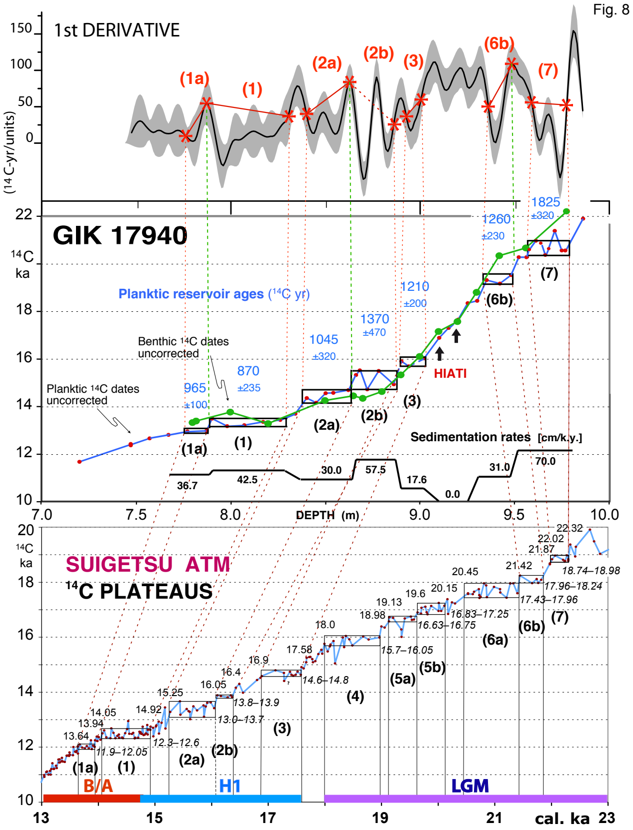

Figure 8 Planktic and benthic ^{14}C records and sedimentation rates of Core GIK17940 (Sarnthein et al. 2007, suppl.). For details of figure caption, see Figure 3. Green line connects uncorrected ^{14}C age data of paired benthic foraminifera samples.

8 cm apart. They are well documented by undulating shell layers of planktic gastropods in the sediment profile, each of them several mm thick and confined by sharp lower and upper sediment boundaries. If we follow the definitions of plateau tuning by Sarnthein et al. (2007) and only accept the lowest-possible reservoir ages, the ^{14}C plateaus right below the hiatuses need to be tuned to plateaus 6b and 7. This implies that a sediment section corresponding to almost 3000 yr of deposition was lost in the hiatuses. Yet, even this tuning leads to LGM reservoir ages of about 1800 and 1300 yr, an age level truly exceptional for subtropical seas. Its magnitude can only be explained by an upwelling of old deep waters, that is, by an estuarine circulation system in the largely land-locked South China Sea during peak glacial times. Subsequent to the outlined hiatuses the planktic reservoir ages dropped to ~850–1350 yr. The high level of reservoir ages in Core GIK17940 is supported by 17 benthic ^{14}C ages and (apparent) benthic ventilation ages at ~1700 m water depth that largely equate to the planktic values or get a little higher. In the sediment section of ^{14}C plateau 2a and 2b, the benthic ^{14}C ages even are lower than the paired planktic values. Thus, any theoretical lowering of planktic reservoir ages would imply unreasonably low benthic reservoir ages, which would suggest transient but totally unreasonable deep-water formation in the South China Sea during the B/A and Younger Dryas.

Apart from the hiatus, the plateau tuning resulted in sedimentation rates of 30–70 cm/kyr for the LGM and early HS-1 and 30–60 cm/kyr during the late HS-1 and B/A. A number of planktic and benthic ^{14}C dates were also measured at the neighboring Site SO50-37 (Broecker et al. 1988), located less than 100 nautical miles away from Site GIK17940 but almost 1000 m deeper, at 2695 m

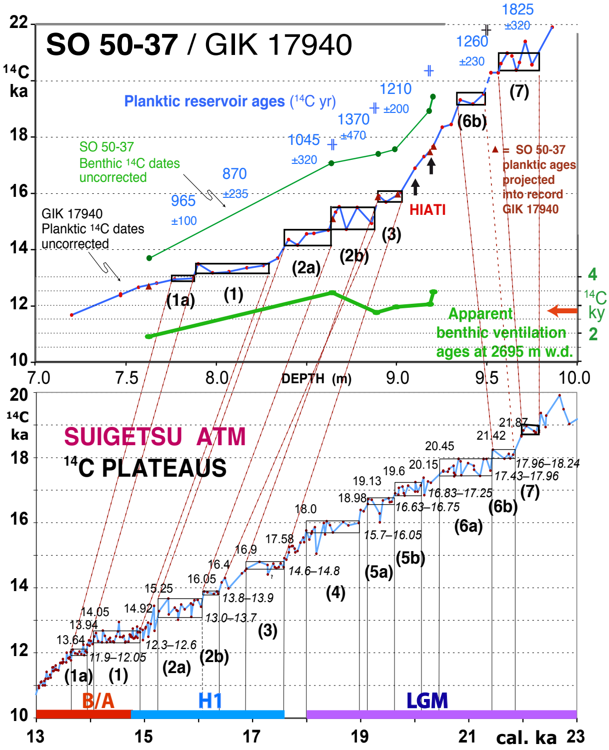

Figure 9 Planktic and benthic ^{14}C records and sedimentation rates of Core SO50-37 (^{14}C dates of Broecker et al. 1988). For details of figure caption, see Figure 3. Planktic ^{14}C ages of Core SO50-37 (red arrow heads) are projected onto the depth scale of the planktic ^{14}C record of neighbor core GIK17940 (Figure 8), assuming that planktic reservoir ages do not change over short distances near the northern South China Sea margin (Sarnthein et al. 2007, suppl.). Thin green line connects uncorrected ^{14}C age data of paired benthic foraminifera samples. Bold green line depicts temporal evolution of apparent benthic ventilation ages that sum up the planktic reservoir age and the coeval benthic-planktic age difference. Horizontal red arrow shows apparent modern ventilation age.

water depth. Assuming that planktic reservoir ages were not subject to any major change over short distances within the South China Sea, we projected the planktic ^{14}C ages of Core SO50-37 onto the depth scale of the planktic ^{14}C record of the neighbor core GIK17940 (red triangles in Figure 9; Table S2g) to obtain an age control based on plateau tuning and a corresponding set of local planktic and benthic reservoir ages. As a result, we find apparent benthic ages at ~2700 m depth that were 1000 to 2500 yr higher than the low benthic ventilation ages in Core GIK17940 at ~1700 m depth over HS-1 and B/A, which is a clear signal of stable deep-water stratification over deglacial times.

Subpolar Northwest Pacific – Detroit Seamount

The planktic ^{14}C record of Core MD01-2416 is based on 42 ^{14}C dates measured on *N. pachyderma* (s), which constitute ^{14}C plateaus 1a–4 at 80–225 cm core depth (Figure 10; Table S2h; Sarnthein et al. 2007) that can be correlated with plateaus 1a–4 of Suigetsu, both visually and via the 1st derivative. Plateau 2a is disrupted by several extremely young outlier ages at 151–163 cm core depth, to a lesser degree also plateau 4 by outliers at 208 and 230 cm depth. Core radiography suggests that the outliers may result from burrows of *Zoophycos* characteristic of episodes of low nutrient flux at the seafloor (Löwemark et al. 2005). These burrows likewise affected some 7 or 8 out of a total of 29 benthic ^{14}C ages at more than 130 cm core depth and imply a downhole transport of benthic specimens by ~30 to 40 cm, rarely up to ~70 cm below the past sediment surface.

Planktic reservoir ages decreased gradually from a late peak glacial maximum of ~1700 ^{14}C yr to ~430–700 yr during the late HS-1 and B/A. In parallel, apparent benthic ventilation ages (measured on mixed benthic species) dropped from peak glacial fluctuations between ~3700 and 5100 yr to ~3300–3100 during HS-1 and down to ~2600–2000 ^{14}C yr during the B/A. The benthic dates do not

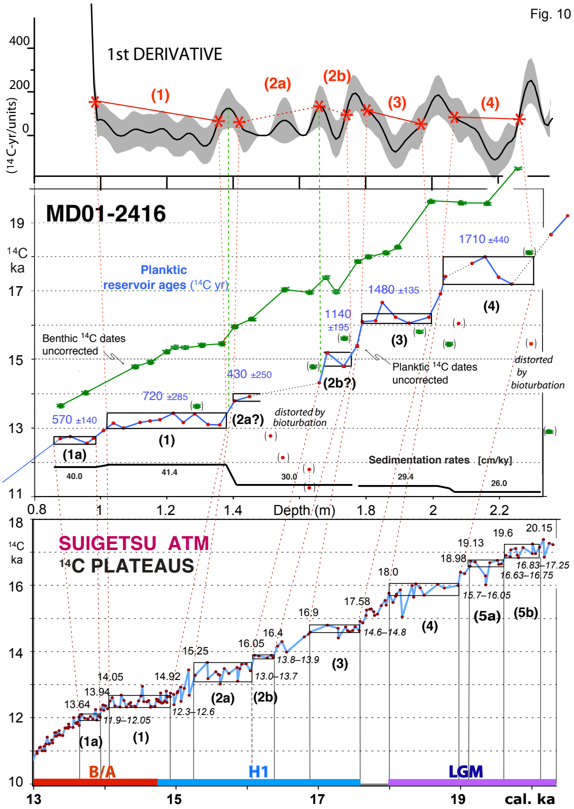

Figure 10 Planktic and benthic ^{14}C records and sedimentation rates of Core MD01-2416 (Sarnthein et al. 2007, suppl.). For details of figure caption, see Figure 3. Green line connects uncorrected ^{14}C age data of paired benthic foraminifera samples.

indicate any local deep-water formation in the northwestern North Pacific, in contrast to those at northeast Pacific Site MD02-2489 (Sarnthein et al. 2013; Rae et al. 2014). An isolated LGM minimum of ~3300 yr is regarded as spurious, possibly resulting from small-scale phase shifts between the paired planktic and benthic ^{14}C signals (Figure 10). Sedimentation rates of 26–30 cm/kyr stayed almost constant over the late LGM and HS-1, but increased significantly up to >40 cm/kyr during the B/A.

Subpolar Northeast Pacific – Patton Seamount

The planktic ^{14}C record of Core MD02-2489 (Figure 11; Table S2i) consists of 28 ^{14}C dates measured on *N. pachyderma* (s) (Gebhardt et al. 2008) that constitute an undisturbed record of ^{14}C, confirmed by 1st derivatives and correlated with Suigetsu plateaus 1–4. They imply sedimentation rates of 23 to ~32 cm/kyr for the LGM and HS-1 as compared to >42 cm/kyr for the B/A, trends that are similar to those at Site MD01-2416.

Planktic ^{14}C reservoir ages amounted to 1560 ^{14}C yr near the end of the LGM and to 1110–800 yr during the earliest deglacial from 19–17 cal ka, which was almost 50% less than at the northwest Pacific Site MD01-2416. After 16.5 cal ka, during HS-1 and B/A, reservoir ages were ~450–550 ^{14}C yr, almost identical with those at MD01-2416. Younger Dryas and Holocene reservoir ages may have closely resembled the range of 500–700 yr measured off Canada by Southon and Fedje (2003). Benthic ventilation ages estimated for MD02-2489 at ~3600 m water depth were significantly lower than those estimated at ~2300 m depth for the northwest Pacific Site MD01-2416

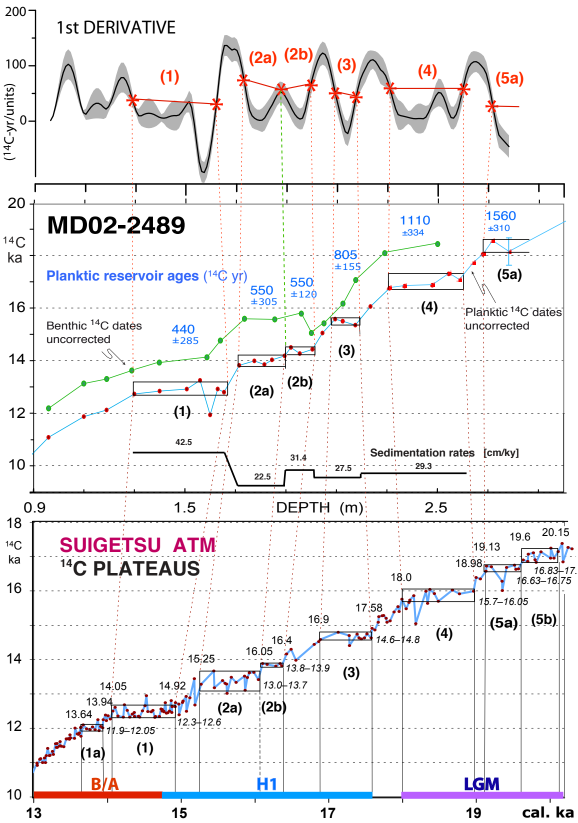

Figure 11 Planktic and benthic ^{14}C records and sedimentation rates of Core MD02-2489 (Gebhardt et al. 2008, suppl.). For details of figure caption, see Figure 3. Green line connects uncorrected ^{14}C age data of paired benthic foraminifera samples.

(Figures 10 and 11). This trend applied to the entire glacial-to-deglacial timespan and resembles the pattern of ventilation ages found today (Sarnthein et al. 2013). Of particular interest is a well-documented excursion of benthic ventilation ages down to 1050–1200 ^{14}C yr near 17.4–16.0 cal ka, since it records a rare but major event of deep-reaching North Pacific deep-water formation (Sarnthein et al. 2013; Rae et al. 2014).

Subtropical Northeast Pacific – Santa Barbara Basin

Planktic ^{14}C records were generated on *G. bulloides* from two closely neighboring core sites, ODP 893A (37 ^{14}C dates; Sarnthein et al. 2007) and MD02-2503 (33 ^{14}C dates), to investigate potential small-scale changes in ^{14}C plateau stratigraphy (Figures 12 and 13, Tables S1, S2j, and S2k). Each record shows a suite of ^{14}C plateaus, visual as well as in the 1st derivative, that can be correlated with Suigetsu 1a–3. Both cores reveal internal structures of the narrowly confined ^{14}C plateaus as well as trends and size of planktic ^{14}C reservoir ages that are almost identical. Hence, the reservoir ages of coeval intervals generally differ by much less than the analytical uncertainty, and thus can be closely reproduced over a lateral distance of ~30 nautical miles. These ages amount to 965–1060 ^{14}C yr for plateau 3, reach a maximum of 1365–1490 yr for plateau 2b and of 1215–1400 yr for plateau 2a, that is, for HS-1. Subsequently, they drop abruptly to ~400–535 yr over the timespan of B/A plateaus 1 and 1a and to ~300 yr near the end of B/A as compared to an age of ~600 yr today.

By contrast, sedimentation rates show significant differences among the two cores. This is possibly partly a result of different coring techniques and partly induced by the core break between cores 3 and 4 in ODP Hole 893A at 27.3 m. Rates of ~125–350 cm/kyr occur at the slightly deeper

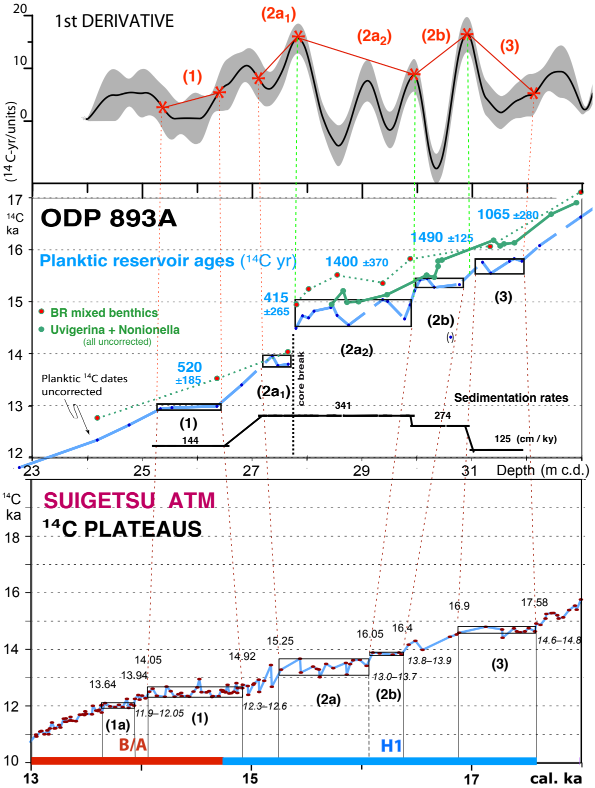

Figure 12 Planktic and benthic ^{14}C records and sedimentation rates of ODP Core 893A (Sarnthein et al. 2007, modified). For details of figure caption, see Figure 3. Bold green line connects uncorrected ^{14}C age data of paired benthic foraminifera samples (*Uvigerina* and *Nonionella*); green dotted line shows results of mixed benthic species of Brendan Roark (BR) (details in Magana et al. 2010).

Site ODP893, with more steady rates of ~200–290 cm/kyr at the shallower site MD02-2503, though the orders of magnitude are equal (Figures 12 and 13).

Magana et al. (2010) discussed in detail the difference in benthic ^{14}C ages, when analyzing different epi- and endofaunal species at ODP 893A (Figure 12). Using ages of *Uvigerina* sp. and *Nonionella* sp. only, two shallow infaunal species, (apparent) benthic ventilation ages ranged between ~1300/1500 and 2000 ^{14}C yr over HS-1 and dropped to ~1000 yr during B/A, as compared to ~1250 yr today. Counterintuitively, the deglacial changes in the apparent ventilation age of intermediate waters entering the Santa Barbara Basin behaved directly opposite to the changes expected on the basis of sediment structure, which was nonlaminated during HS-1 and laminated during B/A (Behl 1995).

DISCUSSION

Sediment Features Possibly Affecting ^{14}C Plateaus

The reach of single ^{14}C plateaus may be modified by bioturbational homogenous mixing across short-term changes in the abundance of a foraminifera species used for ^{14}C dating (mixing depth of 2 cm in low-productivity regions such as the Nordic Seas, up to more than 10 cm in high carbon flux regions; Trauth et al. 1997). This mixing may produce small-scale "artificial" ^{14}C plateaus by broadening the age range of relative abundance maxima farther upcore and downcore. However, species counts so far available for our cores under discussion do not reveal any significant affinity of frequency spikes to the plateaus defined. Moreover, complete suites of up to 11 plateaus with lengths of >10 to 100 cm each by far exceed the impact of bioturbational mixing depth in most cases under discussion.

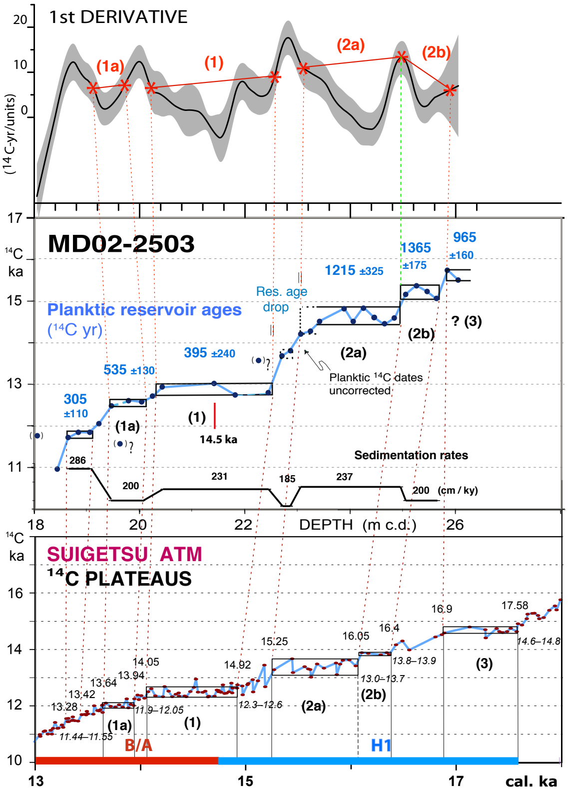

Figure 13 Planktic ¹⁴C record and sedimentation rates of Core MD02-2503 (unpublished data). For details of figure caption, see Figure 3.

In contrast, burrows of *Zoophycos* (Löwemark et al. 2005) may distort significantly the general structure of ¹⁴C plateau suites, forming small nodules of foraminifera with aberrant ¹⁴C ages up to 2500 yr younger than immediately above and below. These age outliers spread up to 100 cm downcore from their coeval source sediment, as documented in Core MD01-2416 (Figure 10). Zoophycos burrows appear particularly common for intervals marked by major oscillations between high and extremely low nutrient fluxes.

Finally, aberrant structures in ¹⁴C plateau suites may serve to trace short-lasting events of sediment erosion and/or coring gaps at core breaks common in ODP holes (e.g. at ODP Site 893A in Figure 12). In particular, an unusually large ¹⁴C jump exceeding 2500 yr served as fingerprint of hiatuses in Core 17940 (Figure 8), gaps that indeed were confirmed by two ~5- to 10-mm-thick, slightly graded layers of planktic pteropod shells, each on top of a wavy unconformity.

Global Distribution Patterns of Planktic Reservoir Ages

The reservoir ages of the 11 globally distributed ocean sediment cores, presented in Figures 3–13 and Table S1, display an unexpectedly large, yet often coherent, variability over the LGM-deglacial period connected with ocean mixing and ocean-atmosphere gas exchange. Various ocean features may induce this variability much in excess of the widely accepted global average of ~400 ± 100 yr (Stuiver and Braziunas 1993). Extreme age values of up to 2500 yr are frequent in glacial and deglacial high-latitude seas, where the subsurface habitat of planktic foraminifers may have been sealed from an ongoing CO_2 exchange with the atmosphere by a fresh- and meltwater lid and, in particular, by sea ice. These features probably caused the extremes in planktic reservoir ages recorded at sites 23074 and PS2644 in the Nordic Seas and at Site MD01-2416 and MD02-2489 in the subpolar

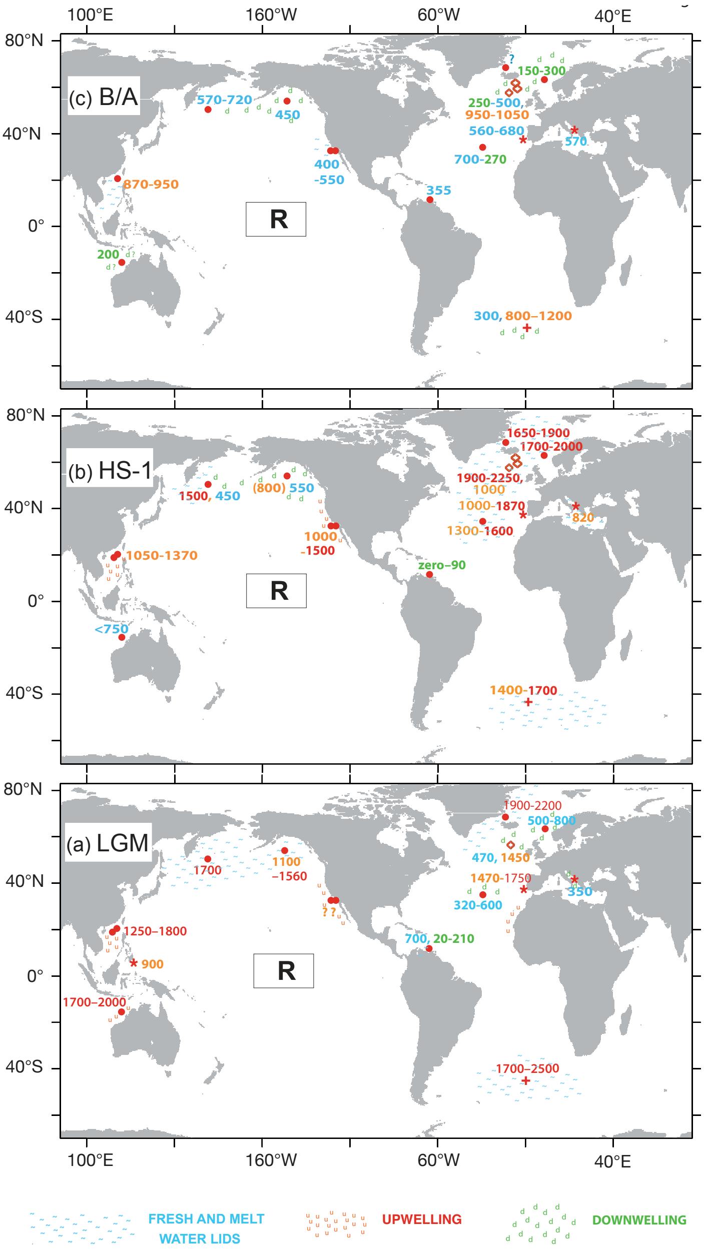

Figure 14 Global distribution of planktic ^{14}C reservoir ages (R) during the LGM, HS-1, and the B/A. Data and data sources are given in Table S1: LGM reservoir age off southern Philippines from Sarnthein et al. (2013). Green numbers: negative $\Delta R = -400$ to -100 yr; blue: ΔR of -100 to $+{\sim}400$ yr; orange: ΔR of 400 to 1100 yr; red: ΔR of 1100 to 2100 ΔR yr. Note strong zonal age anomalies in North Atlantic during LGM. (a) Absolute planktic ^{14}C reservoir ages.

NW Pacific (Figure 14a). Moreover, they will apply to Site MD08-3180 west of the Azores, where a planktic $\delta^{18}O$ record documents the short-lasting advection of meltwaters during HS-1 and HS-2 (unpublished data). Finally, they may have also induced the maxima in reservoir age reported for Core MD07-3076 in the (northernmost) Southern Ocean (Skinner et al. 2010).

Likewise, extremely high reservoir ages are common in surface waters of low- and mid-latitude seas, more specifically, in zones of coastal and/or equatorial upwelling, where old, poorly ventilated intermediate waters are admixed to the surface ocean (e.g. at Timor Sea Site MD01-2378 during

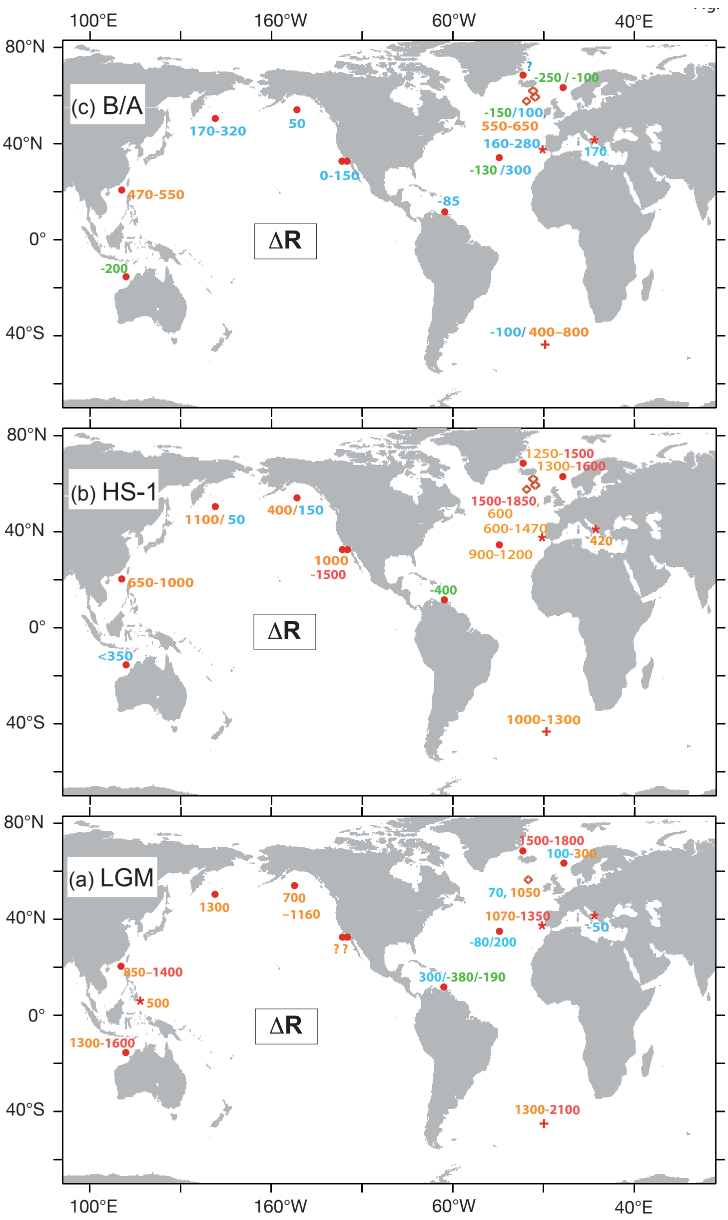

Figure 14b ΔR values (deviations from 400 yr).

peak glacial times; at East Pacific sites ODP 893 and MD02-2503 during HS-1; Figures 7, 12, and 13). Necessarily, any rise in the ages of upwelling-affected surface waters may depend on both a rise in upwelling intensity, on bathymetry- and morphology-controlled lateral shifts of coastal upwelling cells, and on the age inherited from upwelled source water, as displayed by Fontugne et al. (2004) for Holocene surface waters off south Peru.

Upwelled old deep waters also mark the surface waters of adjacent seas located in belts of humid climate, such as the South China Sea characterized by an estuarine pattern of overturning circulation.

This means upwelled deep waters at Site GIK17940 largely originate from the inflow of Pacific deep waters and are most common along the innermost basin margin. Upwelling was particularly intensive during the LGM, as recorded by extreme planktic ^{14}C reservoir ages reaching 1250–1800 yr (Site GIK17940; Figure 8). During that time, the lowered global sea-level induced a closure of all (shallow) seaways of the South China Sea toward the southwest and left open only a connection toward the northwest, to the West Pacific, thus forming a basin particularly prone to estuary-style circulation.

Our high estimates of planktic reservoir ages that exceed 2000 ^{14}C yr are confirmed by independent evidence based on a tuning of planktic foraminifera ages to U/Th-dated ash layers (Northeast Atlantic, Waelbroeck et al. 2001), to age control points in paleoclimatic records derived from ice cores (South and North Atlantic; Skinner et al. 2010, 2014; Thornalley et al. 2011), and on ^{14}C ages of paired wood chunks (northeastern and western North Pacific; Southon and Fedje 2003; Sarnthein et al. 2013).

On the other hand, ^{14}C reservoir ages may on rare occasions drop over short timespans down to 0–300 yr in sea regions (Figure 14a) that are marked by an extreme exchange of atmospheric CO_2. This either concerns regions of intensive deep-water formation such as in the Nordic Seas, in parts of the subtropical gyre, and in small lagoon-style basins in the subtropics that are almost closed off from the open sea and obtain little freshwater discharge such as the Cariaco Basin during times of extreme glacial and deglacial sea-level lowering (Figure 6).

Figure 14b depicts the distribution pattern of ΔR, which reflects the bias in age control, when assuming a constant ^{14}C reservoir age of 400–500 yr for the LGM, HS-1, and B/A. In many sea regions and all time slices, these ΔR values deviate, often strongly, from modern values and may range between –400 and 1000 to 2000 yr. These data imply that age correlations that ignore these spatial and temporal variations in ^{14}C reservoir age will lead to age errors that exceed the duration of a complete Dansgaard-Oeschger cycle (1460 yr; Grootes and Stuiver 1996).

CONCLUSIONS

The varve-counted atmospheric ^{14}C record of Lake Suigetsu, currently the best basis for ^{14}C ages, was used to define a suite of 11 atmospheric ^{14}C plateaus and subplateaus and the calendar ages of 19 plateau boundaries for the timespan 23–13 cal ka. We used this reference record to (re-)calibrate previously published and four new planktic ^{14}C plateau records of 11 deep-sea cores with sedimentation rates exceeding 10 cm/kyr and to derive planktic ^{14}C reservoir ages from various regions in the North Atlantic, North Pacific, the Timor Sea, and South China Sea, with an uncertainty range of 100–350 yr, rarely up to 450 yr.

For an objective identification of ^{14}C plateaus, we here present a new mathematical method. It defines the "^{14}C plateau" as a period or sediment section in which a suite of ^{14}C ages changes downcore by <1 ^{14}C yr per cal yr, which mathematically means the 1st derivative of the ^{14}C age–cal age or the ^{14}C age-depth curve has low values, ideally around zero. The technique provides objective support for the plateaus defined by visual inspection and thus for the database of absolute ages and reservoir ages compiled in this paper.

The resulting planktic reservoir ages vary between zero and 2500 yr and provide a database of local reservoir ages at key sites in the global ocean reflecting a strong spatial and temporal variability. If ignored, the absolute age control of deep-sea sediment records may be biased by up to 2000 yr, a timespan exceeding that of a Dansgaard-Oeschger cycle. Variations in reservoir age like the peak glacial values between 900 and 2550 yr in the North Pacific, Southern Ocean, and Icelandic Sea, in contrast to low ages of 300–800 yr found in parts of the North Atlantic, and Norwegian and Mediterranean Seas, indicate their link with ocean circulation. During Heinrich Stadial 1, North Atlantic reservoir ages widely increased to 1000–2250 yr in contrast to ages of ~500 yr found in the subpolar North Pacific. Temporarily ^{14}C reservoir ages dropped to 0 to ~200 yr in sea regions, where the exchange with atmospheric CO_2 has dominated the surface water composition such as in the Cariaco Basin during low sea-level stands and in regions with extensive deep-water formation.

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