RESPONSE to the PREPRINT of E. Bard and T.J. HEATON (B&H)

"On the tuning of plateaus in atmospheric and oceanic ^{14}C records to derive calendar chronologies of deep-sea cores and records of ^{14}C marine reservoir age changes"

CLIMATE OF THE PAST, DISCUSSIONS

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Abstract

In response to an extended comment of Bard and Heaton (2021) (B&H) on the synthesis paper of Sarnthein et al. (2020) we counter their reservations both in the field of statistics and about the technique of ^{14}C plateau-tuning (PT), like in a manual, one-by-one, by means of telling lines of evidence. In particular, we single out the following points of view:

-- We show proof that results of PT of marine sediment records are hardly affected by bioturbational mixing and changes in foraminifera abundance, given the limitation of PT to cores with sedimentation rates >10 cm/kyr;

-- We illustrate the importance of initial guidelines of conventional stratigraphy to confine overall sedimentation rates as boundary condition and to derive alternative modes of PT for a whole suite of ^{14}C jumps and plateaus in a sediment record, ^{14}C structures to be compared to those of the paired atmospheric reference record of Lake Suigetsu.

-- Extended tests (Balmer & Sarnthein, 2016) revealed that changes in sedimentation rate *per se* are unable to generate a complete suite of ^{14}C plateaus by now already defined in some 20 sediment cores and independently corroborated by various lines of local evidence.

-- Over the interval 10 - 15 cal. ka, the plateau structures of the Suigetsu atmospheric (atm) ^{14}C record are clearly paired with well-defined tree ring- and floating tree ring-based ^{14}C structures (IntCal13; Adolphi et al., 2017). By comparison, we suggest that prior to 15 cal. ka the continuing ^{14}C fine structure of noisy Suigetsu with ^{14}C jumps and plateaus is by far more realistic than the admittedly smoothed ^{14}C trend of the Hulu speleothem and IntCal20, records that may also suffer from unknown but likely changes in the Hulu Dead Carbon Fraction (DCF).

-- By comparison to Holocene and late deglacial times, where PT may be constrained by tree ring records, glacial-to-early deglacial marine reservoir ages (MRA) can indeed be regarded as largely constant over time spans as long as ^{14}C plateaus about 500-1000 yr. In turn, major MRA changes are confined to more extended intervals of climate, sea ice cover, and ocean circulation similar to those of Heinrich events, Dansgaard Oeschger cycles, and their multiples.

-- Per analogy to the record of 10-15 cal. ka, overall ^{14}C changes and shifts in the radiocarbon clock at 15-29 cal. ka are necessarily focused to inter-plateau times, just 18 % of the total time span as estimated by B&H. This concept indeed was first documented by means of PT.

-- We show that minor intra-plateau changes in MRA indeed exist, although they cannot be specified by our limited sampling resolution of ~50-150 yr. Careful inspection of the complete suite of plateaus in each core enabled us occasionally to identify distinct intra-plateau changes.

-- Concerns about low sampling density are unfounded. ^{14}C structures in pelagic sediment records like boundaries of ^{14}C plateaus, were not "under-constrained" by ^{14}C ages but systematically documented by iterative sampling.

-- The box model discussion is scientifically correct. However, it only deals with *Pla,* the planktic ^{14}C concentration of ocean surface waters, and not with MRA = (*Pla-Atm*).

In view of these findings the technique of PT cannot be regarded as 'result of inherent pitfalls'. Rather PT is emerging as great opportunity to generate both a suite of narrow-standing and robust age tie points for marine sediment records and a record of short-term changes in MRA and paleoceanography for last glacial-to-deglacial times in ocean sediment cores where independent high-resolution calendar age information is usually rare.

1/ Introduction

In the fall 2019, Edouard Bard and Tim Heaton (B&H) got access to the discussion version (opened in CPD at 25-10-2019) of our paper “Plateaus and jumps in the atmospheric radiocarbon record – Potential origin and value as global age markers for glacial-to-deglacial paleoceanography, a synthesis” (Sarnthein et al., 2020). A letter to the Editor of CPD on 31-01-2020 stated they had written an extended comment to the paper but had submitted it as a research paper since it “includes substantial material of broad interest to the community using radiocarbon in marine sediments for geochronology and paleoceanography”. This preprint is now subject to our discussion.

We thank B&H for their time and the efforts they spent for a synthesis to fight the 'misery' of ^{14}C plateau tuning (PT) that we, in turn, regard as accomplishment and 'blessing'. Their detailed arguments and reasoning nicely extend far down to basic processes that may control an atmospheric and sedimentary ^{14}C record and are important when trying to specify a great number of major-to-minor potential pitfalls in our approach. Our response may help to clear various misconceptions and clarify crucial aspects of PT method, since all of us aim to find the best-possible technique to generate proper age control of ocean sediment records as now achieved by PT. In the following text-sections we try to summarize -- one by one -- the main concerns raised by B&H about PT in a brief initial statement. Subsequently, we give a detailed discussion and/or rebuttal of these concerns on the basis of our scientific reasoning and practice in PT.

2/ Paleoclimatic and paleoceanographic perspective

2.1/ *No independent constraint on sedimentation rate changes possibly creating ^{14}C plateaus*

-- For each marine sediment core PT is constrained on the basis of stratigraphic guidelines derived from widely accepted marine stratigraphic techniques such as δ^{18}O stratigraphy and/or sea surface temperature and climate records tuned to polar ice core stratigraphy (e.g., Voelker et al., 1988; Gebhardt et al., 2008; de la Fuente et al. 2015; Skinner et al., 2010; Waelbroeck et al., 2019; Wang et al., 1999). PT does not abolish but refine conventional age control. It is a wiggle matching technique that compensates for the lack of lamination in most sediment cores by matching a suite of plateaus covering thousands of years.

-- PT requires permanent monitoring of changes in short-term sedimentation rate at plateau boundaries. As a rule, rates of change between one plateau and the next are low. If they exceed a factor of 1.5 the guideline for PT suggests detailed inspection of sediment parameters to trace the origin of the changing sedimentation regime.

-- Model tests of Balmer & Sarnthein (2016) show that sections with enhanced sedimentation rates *per se* are virtually unable to explain a long suite of ^{14}C plateaus extending over sediment sections of up to tens of cm each.

Examples of independent PT confirmation are:

-- PS97-137 off Southern Chile (Küssner et al., 2020): A rough count of sediment laminations has fairly well confirmed the length of a PT-derived paired ^{14}C plateau for the LGM.

-- MD07-3088 off Central Chile (Küssner et al., 2020): Sedimentation rates and ages are confirmed by succession of four independent age values of ash layers.

-- MD07-3076, mid-ocean ridge South Atlantic (Balmer et al., 2016): Perfect match of PT-based MRA with MRA deduced by correlation to Antarctic ice cores.

2.2/ *Questionable claim for PT that Marine Reservoir Ages (MRA) have to be 'strictly constant' over single plateaus*

This statement presents a misinterpretation. ^{14}C structures in pelagic sediment records were not "under-constrained" by ^{14}C ages but systematically documented by iterative sampling, in particular close to plateau boundaries.

-- As nicely shown by B&H in Fig. 3, the ^{14}C concentrations in the atmosphere have been, and still are, varying irregularly on centennial time scales. PT is based on a close comparison of the *full suite* of planktic ^{14}C concentrations in a sediment core - averaged into one ^{14}C value for each low-slope section called 'plateau' - with their contemporaneous counterparts in the Suigetsu record of past atmospheric ^{14}C concentration.

-- PT gives (1) a suite of age tie points derived from translating U/Th-age based atmospheric plateau boundaries to the plankton-based ^{14}C record on a depth scale and (2) a record of average ^{14}C age differences between sedimented plankton and atmosphere, that is, of varying local Marine Reservoir Age (MRA). On the basis of conventional age control and internal ^{14}C plateau structures PT, of course, needs to ponder the best-possible match between the full two curves for the glacial-to-deglacial period considered. Plotting the derived atmospheric age tie points against core depth allows for variable sedimentation rates. No further assumptions are needed!

-- Most ^{14}C plateaus cover time spans of 300-700 yr each, rarely reaching up to 1100 yr, in agreement with Fig. 3 of B&H. We see no problem in accepting that the ocean carbon cycle and MRA have in most cases not been subject to major changes over these time spans and that changes were confined to short intervals in between. Major changes in MRA generally occur more rarely, at times of documented major change in ocean circulation such as in the context of Dansgaard-Oeschger (DO) and Heinrich events.

-- Centennial-scale scatter of ^{14}C values occurs *within* each single plateau defined as a ^{14}C scatter band with low or no slope with time/sediment depth. This scatter may indeed reflect real small-scale limited changes on decadal-centennial time scales besides sampling and measurement uncertainty. These minor variations have consciously been averaged for each plateau, since they can't be properly resolved by our sampling density and their small size makes them difficult to identify and separate from noise in the sediment and in the Suigetsu atmospheric ^{14}C record. The offset between the averaged planktic and atmospheric plateau bands defines the MRA averaged over single plateaus as an approximation of the more complex and variable system.

-- In about a quarter of all cores one or more plateaus of the suite were distorted, in particular near DO event 1. Here major changes in MRA were indeed uncovered within the time span of a plateau by means of systematically testing (and rejecting) of various alternative models used to tune a complete suite of plateaus and careful comparison of the complete suite and internal structure of plateaus registered in the ^{14}C record. In this way also "false" plateaus that B&H warn against in line 105-114 were unmasked. In a number of cases (as listed in section 2.1) PT-based MRA values were confirmed by independent tephra-based ages and further lines of age control based on conventional correlation of paleoceanographic tracers that likewise are subject to multiple uncertainties.

-- Careful PT develops high-resolution age control and provides MRA as input to document sequential short-lived changes in the carbon cycle, often related to short-term ocean circulation changes as 'real' events more rarely occurring at millennial scales. Prior to 15 cal. ka such information was largely missing on the basis of conventional age control that assumes long-term MRA means. New developments in reservoir age modeling are also improving this situation (Heaton et al., 2020; Butzin et al., 2020), but generally lack the spatial resolution to match specific sediment cores.

2.3/ *'Rung ladder' versus 'staircase' of age tie points - workable approximation vs. claim for reality?*

-- In part, the different wording simply results from using more or less stretched Y-scales and differential intra-plateau slopes in a ^{14}C age vs cal. age plot (B&H, Fig. 1). Different from this Fig. 1, the slope of ^{14}C scatter bands is not necessarily perfectly zero, as shown by tree ring-based records, e.g., near 10 cal. ka, and in 1st-derivative plots.

-- Figs. 1-3 of B&H form a useful base for discussion, although Fig. 1 unfortunately lacks a reconstruction of the crucial time section 10 to 14 ka. Here Suigetsu and tree ring data overlap giving the great opportunity to weigh Suigetsu ^{14}C plateaus against a truly atmospheric and better-defined plateau record based on tree rings of IntCal13 (Sarnthein et al., 2020, Fig 2; IntCal20 then not available yet; Reimer et al., 2020). The six plateaus defined for Suigetsu indeed match the seven of IntCal13, where Plateau 1a of Suigetsu may in reality depict two smaller ones in IntCal13. Vice versa, ^{14}C structures based on Hulu Cave ages are matched by significantly more scatter. Accordingly, we trust the Suigetsu record more than IntCal20 dominated by Hulu as best possible indicator of atmospheric ^{14}C beyond 14 cal. ka. This is corroborated by a comparison of Figs. 1, 2, and 3a and b of B&H that show the smoothed character of non-tree-ring IntCal20 relative to that of Suigetsu, thus a loss of fine structure needed for PT, as implied from the 10-to-14 ka intercomparison.

-- IntCal20 is the most reliable ^{14}C calibration presently available, but integrates ^{14}C ages from various carbon archives that in part filter the atmospheric ^{14}C signal through surface water and groundwater reservoirs, hence dampen ^{14}C fluctuations. In addition, local effects on the dead-carbon fraction by changes in rain fall, vegetation, soil cover, and $\delta^{13}C$ that occur on millennial-scales may influence the Hulu cave ^{14}C record (Kong et al., 2015). Also, coral- and foraminifera-based marine ^{14}C records are subject to variable MRA assumptions. Prior to 15 cal. ka, floating tree ring sequences are rare. Following the principle "absence of evidence is no evidence of absence" the lack of structures in the IntCal20 curve is far more speculative and dubious than the suite of structures recorded in the only direct atmospheric ^{14}C record of Suigetsu.

-- Since short-term plateau structures are distinct and common in the tree ring-based deglacial record 10-15 cal. ka (including plateau #1), moreover, all over the Holocene ^{14}C record, though much shorter, any lack of pertinent atmospheric ^{14}C structures over the preceding deglacial and peak glacial period would imply an assumption highly inconsistent, even if hypothesized by B&H in section 3.1.

-- B&H are concerned about the large portion of atmospheric ^{14}C drops at ^{14}C jumps that encompass only 18% of the total time span studied. Thus, radiocarbon would have never behaved as a 'normal' geochronometer merely driven by regular radioactive decay, a claim our results of PT indeed confirm. (i) This concern overlooks considerable internal secondary ^{14}C variations within most plateaus, including possibly spurious drops and ^{14}C reversals, that we necessarily eliminated by averaging the ^{14}C age over a plateau.

-- (ii) Indeed, we may get accustomed to accept that centennial-scale jumps of atmospheric ^{14}C age, similar to those found in the tree ring record for the last 15 cal. ka, paired with deep ocean circulation changes are real and form the rule rather than the exception. Plateaus during times of glacial-to-deglacial climate change appear far longer than most plateaus of the climatically 'quiet' Holocene, the last 8500 yr, which may reflect a different cause. We welcome B&Hs' notice of numerous, though unlikely abrupt rises in atmospheric ^{14}C. Also, we ourselves have discussed them internally already over years and regard them as valuable novel signals of short-term variations in ocean-atmospheric carbon exchange. As B&H say, processes controlling these partly fairly instantaneous processes are complex and difficult to model but highly challenging and worth to be traced by future studies.

2.4/ *B&H complain about a lack of a single figure illustrating all twenty marine ^{14}C records as compared to their atmospheric ^{14}C curve used for calibration – Justification of hiatuses.*
In Sarnthein et al. (2020) we decided to avoid a repetition of basic data sets already published and documented elsewhere. Also, we were advised to reduce the length of our synthesis paper. Thus Figs. S2 did not intend to display the qualities of MRA derivation but the global spatio-temporal distribution of MRA results. Further below, Fig. 1 may serve as example to illustrate the technique of PT.

-- In most sediment cores the published lineups of records show that the alignment of the suite of planktic ^{14}C plateaus to the paired atmospheric ^{14}C calibration curve is fairly robust. In contrast to claims of B&H, most short-term changes in sedimentation rate between consecutive plateaus are low, hardly exceeding a factor of 1.5-2.0. Sporadic major shifts indeed mark climate tipping points (such as depicted in laminated sediments of SW Pacific core MD08-3180 near to Heinrich Event 2 and/or by reversals of the Denmark Street Overflow during early HS-1 in core PS2644).

-- Different from the claim of B&H, careful visual inspection of pertinent sediment sections and local proxy records have proven that the hiatuses contested by B&H also form distinct sediment unconformities, hence must not be discarded as artifact of PT. Several stratigraphic gaps are simply reflected by "mega-jumps" in the high-resolution ^{14}C record (e.g., cores PS75/104-1, PS97/137-1, SO213-76, 17940 from South Pacific and South China Sea; synthesis Figs. S2c, d). These lines of evidence were discussed at length in various source papers summarized in our synthesis paper. Though widely not appreciated by paleoceanographers, hiatuses appear to be a feature actually widespread at high-sedimentation rate sites in the deep sea – One may assume: The higher the rates the more extreme they may be subject to changes in depositional regime.

-- B&H are concerned about recent changes in our plateau assignment for two South Pacific cores. These changes are the result of a valuable discussion on alternative tuning modes ongoing after a first public display of data in CPD. Finally, we choose the mode better supported by various lines of sediment-based evidence.

2.5/ B&H regret that *the focus of PT on ^{14}C plateaus may leave large parts of ^{14}C record unused in the process of matching a marine ^{14}C record to the atm. ^{14}C record of Suigetsu*. Conversely, Svetlik et al. (2019) just regard the high-slope parts of the ^{14}C record as crucial for defining the absolute chronology. Under this topic B&H introduce to a discussion of basic objectives.

-- The concern of B&H is opposed to that discussed in TOPIC 2.2, where they calculated (and are concerned) that Suigetsu-based plateaus cover 82% of the total time. The remaining 18%, that are the ^{14}C jumps in our Suigetsu record, may indeed confirm the conceptual model of Svetnik et al., hence form the crucial tie points for correlation to radioactive age control and to constrain past changes in MRA. Here it may be remembered that the distribution 82%/18% in part results from our choice of the length of the strictly horizontal plateaus and simplifies reality. Hence, we basically follow B&H in claiming that (most) "changes to MRA could only occur at plateau boundaries". Elsewhere changes may exist but cannot be resolved by the PT method. In summary, MRA derived from PT do form the best possible reconstruction available.

-- By now, the "special significance" required by B&H was only found for few plateaus of our ^{14}C calibration curve (e.g., Plateau YD, 1, and lower 2a; see our synthesis Fig. 6). Here we propose a potential link to rare deglacial events of major ocean degassing similar to that on top of the YD and HE-1.

-- We agree with B&H that aligning the entire ^{14}C record of a marine sediment core with that of the Suigetsu target curve, analogous to the wiggle matching technique for tree ring sequences, is the approach of our PT technique. Since our first paper of 2007 we stress the need that ^{14}C records should be aligned as a whole with their shape, not just with piecewise constant or slightly different offsets within and between the plateaus, the key to our MRA estimates.

2.6/ *Potential role of bioturbational mixing for ^{14}C plateaus.*

^{14}C plateaus in marine sediments of course were checked for potential 'natural' changes in sedimentation rates by means of conventional stratigraphic markers (SST, $\delta^{18}O$, etc.; see discussion on Topic 2.1) always employed as initial stratigraphic guideline. Also, the impact of bioturbational mixing was not overlooked as potential factor influencing ^{14}C plateaus (e.g., Küssner et al., 2018). Based on various lines of evidence and in view of the rule that PT is only applied to a complete suite of ^{14}C plateaus each, that is >80% of a ^{14}C record, bioturbation now was somewhat downgraded as potential factor for the origin of plateaus:

-- For PT, ^{14}C ages were only measured on monospecific plankton samples, on species that continued in the region studied over glacial to interglacial times (except for mixed samples from ODP Site 1002D; Hughen et al., 2006). This is in contrast to troubling pioneer records of Duplessy et al. (1986) and Bard et al. (1987), who compared stable-isotope and ^{14}C records of different species either characteristic of interglacial or of glacial times. Accordingly, bioturbational mixing resulted in a divergence of signals reaching up to 30 cm (i.e., ±15 cm) at deglacial times of abrupt climate change.

-- Trauth et al. (1997) gave first precise estimates of bioturbational mixing depth being clearly related to the local flux of nutrients / organic carbon. Low flux rates lead to mixing depths of 2-4 cm depth, high flux rates up to 8-12 cm. Thus, the position of plateau boundaries derived for a suite of plateaus in high-sedimentation rate cores may hardly present an artifact of differential bioturbational mixing, except for times of abrupt major change in nutrient flux.

-- We only applied PT to cores with average sedimentation rates of >10 cm/kyr. In many cores the rates exceed 20-40 cm/kyr and go up to >200 cm/kyr. The high rates contrast with most records ^{14}C-dated in early days, where bioturbational mixing was particularly relevant at pelagic sedimentation rates of 2-5 cm/kyr.

-- In some cores crucial for paleoceanography (e.g., MD08-3180; PS97-137-1) sediment lamination is definitely precluding any role of bioturbational mixing for ^{14}C plateaus.

-- PT of Core SHAK6K-05 provides a nice test case (Fig. 1) to compare short-term changes in the abundance of the planktic foraminifer *Globigerina bulloides* with the position and length of paired ^{14}C plateaus (Ausin et al., 2019 and 2021). In contrast to conjectures of B&H, none of the twelve plateaus up to >15 cm long is linked to any abrupt change in species abundance. The plateaus just display, one-by-one, the reference suite of paired Suigetsu atmospheric plateaus. Local high sedimentation rates of 10-30 cm/kyr probably exceed by far the depth of ongoing bioturbational mixing (up to ±7 cm; Ausin et al., 2019).

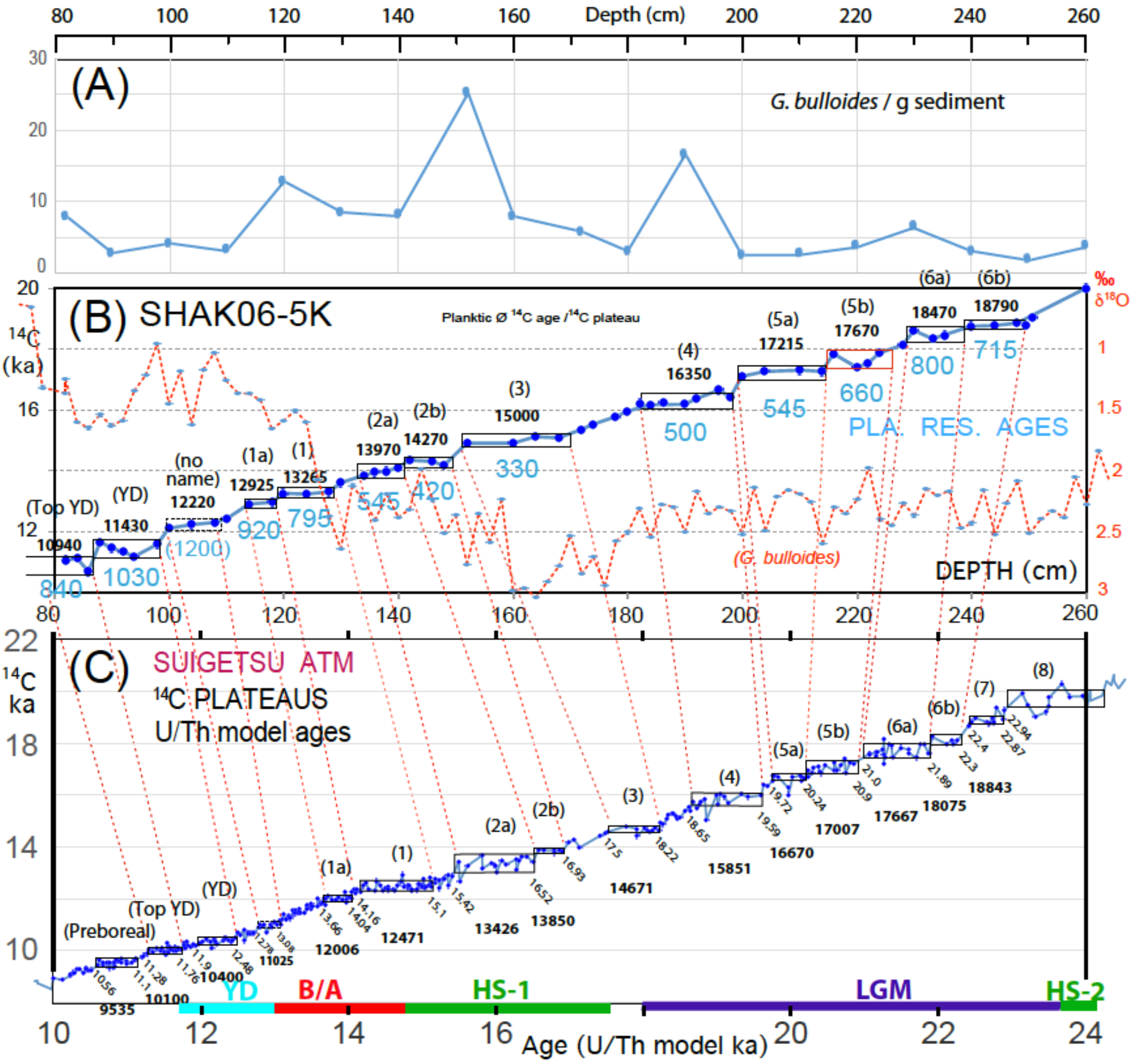

Figure 1. PT of planktic ^{14}C record from core SHAK06-5K with atmospheric (atm) ^{14}C record from SUIGETSU. A) Abundance of planktic foraminifera *Globigerinoides bulloides*. B) Planktic ^{14}C ages (blue dots) and oxygen isotope record (δ^{18}O, red dotted line) measured on *G. bulloides*, ^{14}C plateaus (black boxes), mean planktic ^{14}C age of each plateau (black numbers), and MRA (blue numbers) (Ausín et al. [2019] and [2021] modified). ^{14}C plateau numbers in B are deduced by visual correlation with C) atm. ^{14}C ages from Lake Suigetsu (blue dots), corresponding atm. ^{14}C plateaus (black boxes), and age control points (cal. ka) plotted versus U/Th-based model ages of Bronk Ramsey et al. [2012]. YD = Younger Dryas, B/A = Bølling-Allerød, HS1 and HS2 = Heinrich Stadial 1 and 2, LGM = Last Glacial Maximum.

2.7/ *Potential conflict of a sharp match of marine ^{14}C-age plateaus with atmospheric plateaus with the general understanding of the carbon cycle* (see B&H lines 318 ff).

-- B&H employ numerical (box) model experiments showing that both damping and phasing effects in marine surface waters may be in conflict with the main assumption of synchroneity of atmospheric and ocean signals of ^{14}C production. To meet this concern, we refer, like B&H, to the effect ^{14}C bomb spike of the early 1960s. The discussion of B&H focuses on changes in the surface ocean and correctly describes the limitations of ^{14}C variability in this reservoir. Yet they forget that MRA = (Pla - Atm) and that the large variability of atmospheric ^{14}C, as seen in Miyake events and the bomb spike, means that also MRA can show variations much larger and more rapid than displayed by the box model.

2.8/ *Plateaus were possibly linked to carbon cycle changes due to abrupt changes in meridional overturning circulation (MOC) like that at the end of the YD and HS1 events.*

-- As already outlined under Topic 2.5, we indeed found clues for the required "special significance" of few plateaus of our ^{14}C calibration curve, that is, for Plateau YD, 1, and lower 2a, as was discussed in the context of our synthesis Fig. 6.

-- Ocean-induced changes of the atmospheric carbon inventory may indeed result in 'very minor' (in the context of paleoceanographers), up to decade-long regional delays of the ^{14}C signal between different ocean regions with and without outgassing of deep-water CO_2. For outgassing regions B&H mention potential large effects with no delay. Elsewhere we have the same situation as discussed in 2.7. In view of the general broad uncertainty of conventional age estimates for marine sediment records (except for rare ages of marine ash layers; see the introduction of our synthesis) we agree with B&H that also an age control based on PT, though in our view far superior to conventional techniques, may hardly succeed to further constrain these regional age shifts covering less than 100 years.

2.9/ We missed to give in our synthesis paper (not intended to serve as textbook) a reference to early reconstructions of MRA on the basis of marine volcanic ash layers by Bard (1988) and Bard et al. (1994), a lack revealed by B&H. In turn, we tried to stress that several PT-based age estimates are clearly reproduced by those ages of specific ash layers in the meantime widely-established (here by Siani et al. (2013).

3.1 - 3.8/ Statistical perspective

3.1/ *Identification and correct match of 'true ^{14}C age plateaus' in sparsely sampled and noisy marine records despite potential influence of MRA changes and bioturbation* (also see 2.3)

-- PT tuning is blamed for a lack of proof by any independent age control. This concern can be clearly rejected: In each marine sediment core PT has been constrained on the basis of initial stratigraphic guidelines derived from various conventional marine stratigraphic techniques such as $\delta^{18}O$ stratigraphy and/or sea surface temperature records tuned to polar ice core stratigraphy (Rae et al., 2014; Sarnthein & Grootes, 2007; Sarnthein et al., 2015).

-- In contrast to suggestions of B&H, the correct pairing of plateaus identified both in marine and atmospheric ^{14}C records formed a central topic of discussion for each basic description of ^{14}C plateaus in a marine sediment core published so far (e.g., Sarnthein et al., 2015; Balmer et al., 2016). Again, we should emphasize that the full suite of plateau was considered instead of individual plateaus, as regularly suggested by B&H. In part, we handled the problem by frankly discussing alternative tuning modes (e.g., Küssner et al., 2020). In part, we admitted minor refinements in the mode of tuning of a suite of plateaus in papers published later-on, that is, as soon as additional lines of independent evidence were available.

3.2/ *Assignment of plateaus in marine ^{14}C records may be biased by too noisy data sets of marine sediment cores to a likewise noisy atmospheric record of Lake Suigetsu.*

-- B&H argue that the dead carbon fraction (DCF) of the Hulu Cave speleothem record has been stable around a low value of 480 ±55 ^{14}C yr and has not masked potential atmospheric plateaus in the Hulu ^{14}C record. Their conclusion is based on model tests and on a comparison of Hulu data for individual speleothems with tree-ring ^{14}C ages for the Allerød–Younger Dryas and Younger Dryas–Holocene transitions (Southon et al., 2012). Unfortunately, B&H ignore significant centennial-to-millennial-scale variations in a paired $\delta^{13}C$ record (by up to 7 per mil) over the period 23-10 cal. ka. In part these changes result from changes in climate-controlled soil-organic matter either derived from C3 (more negative $\delta^{13}C$) or from C4 (more positive $\delta^{13}C$) biomes prevailing in the formation of soil overlying the Hulu speleothem (Dorale & Liu, 2009; Reimer et al., 2020). In part, however, the change is controlled by the intensity and thickness of differential soil formation that definitely is far more advanced at humid C3 than for semiarid C4 biomes. Hence $\delta^{13}C$ changes in part form a rough proxy for the role of changing DCF for ^{14}C records in response to ($\delta^{18}O$-derived) climate change (Kong et al., 2005), variations not satisfyingly calibrated yet by Southon et al. (2012). Consequently, we do not see any need either "to smooth Suigetsu-based records" and/or to adjust the marine MRA to a marine average MRA of 480 yr used by the authors.

-- As pondered by B&H, a potential time-directional filtering of atmospheric ^{14}C signals by the Hulu speleothem may indeed be revealed by detailed analysis of the outlined $\delta^{13}C$ record. It shows major shifts that lag paired $\delta^{18}O$ shifts by ~650 to 700 yr (Kong et al., 2005).

-- Prior to 21 cal. ka, some ^{14}C plateaus of Suigetsu (e.g., Plateau #8, though also reflected in the Hulu record; and #10b) indeed are more difficult to define than other plateaus due to analytical uncertainties amongst three different ^{14}C laboratories.

-- B&H used the Bayesian spline statistical method for Suigetsu-based ^{14}C ages for Figs. 1 and 3a. Fig. 1 expands the scale of the Y-axis by more than a factor 2 relative to the X-axis, which necessarily subdues the optical effect of ^{14}C 'plateaus', but stresses the analytical uncertainties as compared to the 'green line' indicating the 15 plateaus listed in Table 1 of Sarnthein et al. (2020). Nevertheless, Fig. 1 shows a decent general agreement between the green PT curve and the pink 95% Bayesian spline range. Prior to 20 cal. ka, minor differences may be due to slight revisions of calendar ages listed by Bronk Ramsey et al. (2020) as compared to the ages Bronk Ramsey et al. published 2012, minor age shifts not properly assessed yet in the definitions given by Sarnthein et al. (2020).

-- In Fig. 2 B&H compare our record of ^{14}C plateaus with the IntCal20 curve. The smoothed character of IntCal20 beyond 13.9 cal. ka has been generally acknowledged. As explained by B&H in 3.8, this results from the IntCal aim to provide point wise summaries of the average of data from many different data sets, including carbonate-based marine data and speleothems, for the most reliable calibration of single radiocarbon results. This makes IntCal20 less suitable for exploring the fine structure of the atmospheric ^{14}C record than the purely atmospheric Suigetsu record.

3.3/ *Low ^{14}C sampling resolution for Lake Suigetsu and, even more so, for marine sediment records as compared to annually resolved the tree ring record may lead to a misalignment of marine records*.

-- The Suigetsu record shows an average sampling resolution of 20 yr at a highly resolved section near 14 cal. ka and one of 40-100 yr between 18 and 29 cal. ka. In turn, PT has been restricted by definition to plateaus longer than 300 yr, hence requires a minimum overall sampling resolution of marine sections better than 100-200 yr and one of 70-100 yr for sediment sections near plateau boundaries achieved by iterative sampling. Enhanced sampling resolution *within* a ^{14}C plateau has turned out as redundant and waste of effort.

-- In harmony with δ^{18}O and various other high-resolution stratigraphic records that are used as initial stratigraphic guideline, *PT only identifies the whole suites of ^{14}C age plateaus*. On their basis single plateaus are specified. Also, different modes of PT are tested and discussed for each sediment core on the basis of age records and correlations used by conventional age control widely accepted by paleoceanographers. PT, however, is leading to a much higher resolution of age tie points, in part to minor modifications of conventional age assignments, and most important, to a suite of reasonable estimates of local MRA.

-- After all, the suite of glacial-to-deglacial Suigetsu plateaus can now be successfully reproduced in more than 20 sediment sections from all sectors of the ocean where sufficiently high sedimentation rates occur (some records are still in process of publication). A marked plateau of an Early Holocene tree ring record was reproduced in three neighboring cores from the northern Norwegian Sea.

3.4/ *How to identify marine ^{14}C-age plateaus within single cores in the context of a changing and unknown sedimentation rate/ calendar age scale*.

This question has already been answered at length in preceding sections 3.3 and 2.2: PT identifies suites of plateaus strictly on the basis of initial stratigraphic guidelines based on conventional chronostratigraphic records widely accepted amongst paleoceanographers. PT has led to major refinements, in part also to modifications of conventional age control due to ^{14}C records with centennial-scale resolution.

3.5/ *Definition of ^{14}C plateau boundaries: Results of visual inspection versus estimates based on calculation of the 1st derivative of ^{14}C-age vs depth curve*

Comparative tests (Sarnthein et al., 2015; Fig. 2a) revealed good agreement of plateau boundaries deduced by visual inspection and by calculating the 1st derivative, though differential analytical errors have not been considered in these tests. Optimizing the kernel to the data set of the specific record requires a continued use of visual inspection. Evidence accumulated over the years suggests that ^{14}C jumps reflected by maximums in the 1st derivative present the best-reproducible evidence to calculate the position of plateau boundaries in a marine sediment record (Ausin et al., 2021). To some degree this finding that forms a backbone of the novel age control induced by PT may indeed support the 'staircase' model of B&H as compared to our 'rung ladder' model, an item discussed in Section 2.3.

3.6/ *Simulation tests to assess the ability to identify and tune ^{14}C-age plateaus in the context of 'noisy and sparse' ^{14}C data. To find the underlying calendar age scale in marine sediments B&H compare a tree ring-based IntCal20 record vs a 'pseudo-Suigetsu' atmospheric record and a pseudo-Cariaco marine record for the period 12-13.9 cal ka.*

3.7/ *Second series of simulation tests to assess the ability to identify and tune ^{14}C-age plateaus in pseudo-marine sediment records (similar to that of Cariaco) by tuning to a pseudo-atmospheric record.*

3.8/ *Differences in the precision of reconstructing past atmospheric ^{14}C levels -- A basic discussion of Lake Suigetsu and tree ring vs. IntCal20 records.*

A detailed answer to B&H discussion sections **3.6 - 3.8** is found in a companion contribution to this discussion, given by P.M. Grootes and M. Sarnthein, this volume of CPD.

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