^{14}C plateau tuning – A misleading approach for marine paleoclimate studies

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We have already published, in 2021, a paper in CP (Bard & Heaton, 2021) which identified and evaluated the pitfalls of the Plateau Tuning (PT) method. In this previous paper, we expressed significant doubts regarding the ability of PT to simultaneously **1/** construct the chronologies of deep-sea sediment cores; and **2/** obtain marine reservoir ages (MRA) in a robust or precise manner.

Unfortunately, in their new paper, Sarnthein & Grootes do not address our criticisms with any substantial new work, i.e., by provision of new data, independent verification of the results they infer using PT, or statistical calculation. We therefore refer the reader to our original 2021 paper for a detailed point-by-point discussion of PT's issues (see also our responses to Sarnthein & Grootes and Grootes & Sarnthein' ≈ 50 pages of Community Comments which accompany this 2021 paper). Readers can also consult a recent review paper about radiocarbon in paleoceanography by Skinner & Bard (2022) which provides examples of PT results that lead to large and unexplained discrepancies with other records from the same areas. We feel it is not helpful to repeat all the same arguments here.

In this new submission, Sarnthein & Grootes only consider one narrow aspect of PT – whether long atmospheric ^{14}C-age plateaus exist and can be reliably identified. We are unfortunately still unconvinced that such an extreme atmospheric ^{14}C-age step-ladder is physically plausible or supported by observational data. The authors do not consider concerns regarding other key PT requirements: whether these atmospheric ^{14}C-age plateaus transfer to the marine environment; and, even if they do, whether they can be reliably identified in extremely sparse ^{14}C samples from sediment cores for which no independent timescale is available and for which the MRA correction is a priori variable.

We are therefore afraid that we remain of the view that PT cannot be seen as a reliable approach to the building of chronologies for marine sediment cores, and the results presented here on the changes in MRA of their plateau-tuned cores must be viewed with caution.

What Sarnthein and Grootes claim in their new work

Sarnthein & Grootes argue that they have proved the authenticity of their hypothesized atmospheric ^{14}C-age plateaus based on eyeballed comparisons with ^{14}C measurements from tree-rings and Hulu Cave. However, as we explain below, these comparisons involve considerable circularity (and we remain unclear how a reader can be confident that the hypothetical ^{14}C-age plateaus have been identified objectively). We therefore strongly believe that no objective statement can be made about the authenticity of the hypothesized atmospheric ^{14}C-age plateaus.

In the new submission, Sarnthein & Grootes have revised their 2020 suite of atmospheric ^{14}C-age plateaus – removing/merging some, while editing the starts and ends of others. These updated, hypothesized, atmospheric ^{14}C-age plateaus remain based upon the ^{14}C record of Lake Suigetsu, but with its revised calendar age chronology that was published by Bronk Ramsey et al. (2020).

Based upon the new hypothesized atmospheric ^{14}C-age plateaus, Sarnthein & Grootes revise the chronologies and MRA records of 19 deep-sea cores which they have published over the last decade. Having used the same 19 core datasets, and the same PT method, it is no surprise that the new results are very similar to what they had before. This new paper therefore provides limited new insight over their review published in 2020 in CP (Sarnthein et al. 2020).

Lack of independence between Lake Suigetsu and Hulu Cave Chronologies

Critically, readers need to be aware that the updated Suigetsu calendar age chronology (on which the new hypothesized ^{14}C-age plateaus are based) is not independent of the Hulu Cave ^{14}C record. Indeed, to create the updated Lake Suigetsu calendar age chronology, the (independent) varve-ages were adjusted/tuned so that the overall Suigetsu ^{14}C vs cal age record better matched the ^{14}C vs cal age record from the U-Th dated Hulu Cave stalagmites that constitute the backbone of the IntCal20 calibration curve (Reimer et al., 2020; Heaton et al., 2020a, 2021). See Cheng et al. (2018) for details of the Hulu ^{14}C vs U-Th record; and Bronk Ramsey et al. (2020) for a description of the Lake Suigetsu tuning that adjusts the varve counts of Schlolaut et al. (2018).

The (Hulu-tuned) Lake Suigetsu calendar age timescale differs by up to 3 cal kyrs from the original varved timescale. In addition to adjusting the long-term trend, the tuning also concerns the millennial-scale structures (see Figs. 1 and 5 by Bronk Ramsey et al. (2020); this Fig. 5 being reprinted as Fig. 3 by Sarnthein & Grootes). Due to this tuning, it is to be expected that the Hulu and Lake Suigetsu ^{14}C records show similar features at similar times – however, due to the lack of independence between the timescales of the records, and that ^{14}C features are themselves used in the tuning, one must be extremely careful not to overstate one's confidence that similarities in the two records after tuning provide robust and repeated evidence for the simultaneous presence of ^{14}C-age plateaus.

Until we can find an alternative chronology, then inference from Lake Suigetsu which uses its (Hulu ^{14}C-informed) calendar age information is not *solely* atmospheric. The tying to Hulu ^{14}C transfers many of the complexities of Hulu Cave to Lake Suigetsu - in particular, the assumption that the ^{14}C depletion in Hulu is equivalent to a constant dead carbon fraction.

Any ^{14}C-age plateaus identified using the Lake Suigetsu ^{14}C record are not therefore atmospheric-only. Furthermore, at least part of the agreement with Hulu Cave is due to (or at least reinforced by) the tuning which creates the Suigetsu timescale.

Variation in Atmospheric ^{14}C levels

Sarnthein & Grootes continue to confuse the question of whether there is evidence for a long staircase of ^{14}C-age plateaus that can be identified based upon Lake Suigetsu; with the question of whether there is high-frequency variation in atmospheric ^{14}C levels from 30 – 15 cal kyr BP.

As explained in Reimer et al. (2020), Heaton et al. (2020a) and Bard & Heaton (2021), it is highly likely that there is currently unknown variation in atmospheric ^{14}C levels from 30 – 15 cal kyr BP. Variation in atmospheric ^{14}C levels is seen from 15 – 0 cal kyr where we have directly-atmospheric tree rings and we would expect similar variations (at least) to have occurred beforehand. However, this does not mean either that:

- the structure from 30 – 15 cal kyr BP takes the form of long ^{14}C-age plateaus separated by huge jumps in atmospheric ^{14}C levels (i.e., implying that ^{14}C ages stay constant through time during 80% of the 30 – 14 cal kyr BP interval); or
- we can reliably and precisely separate genuine atmospheric ^{14}C variation from random fluctuations using the Lake Suigetsu ^{14}C record.

and it is misleading to conflate these issues.

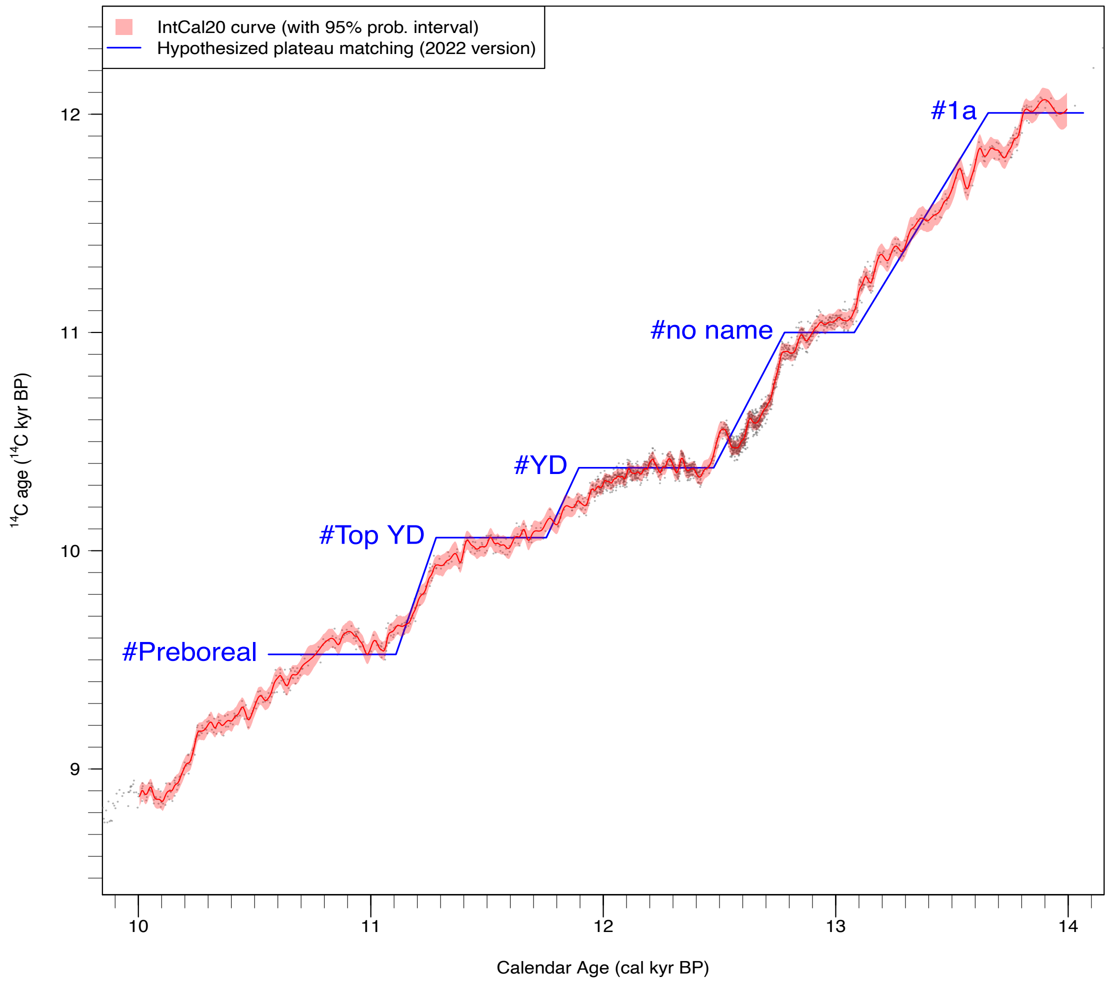

Figure 1: *Plot of the IntCal20 curve (during the time period where it is based upon gold-standard tree-ring ^{14}C determinations) against the hypothesized (2022) ^{14}C-age plateaus of Sarnthein & Grootes. Shown as small, light grey, dots are the underlying tree ring determinations. Evidence for the hypothesized plateaus amongst the tree ring determinations is unclear – arguments of equal strength could potentially be made that several other time periods exhibit similar tree-ring behavior as those identified as plateau periods by Sarnthein & Grootes. Equally, questions could be raised as to the length of the plateaus that have been identified.*

For the period covered by ^{14}C data on tree-rings, there are no ^{14}C-age plateaus that extend over 1000 cal yrs (or longer) as hypothesized by Sarnthein & Grootes for the older part of the record. Further, Sarnthein & Grootes hypothesize a set of ^{14}C-age plateaus from 14 – 10 cal kyr BP based upon Lake Suigetsu. These are shown in Figure 1 alongside the IntCal20 curve, and its constituent *gold-standard* tree-ring measurements. Sarnthein & Grootes argue that the ^{14}C-age plateaus they identify in this period agree with *gold-standard* tree-ring ^{14}C determinations. However, as can be seen in Figure 1, there is considerable variation in the ^{14}C-ages of tree-rings throughout this entire 4 cal kyr period with a range of inversions and wiggles and no objective definition of what should be considered to constitute a tree-ring plateau is given. To our eyes, the tree-rings present no obvious evidence for the ^{14}C-age plateaus they propose for tuning from 11.1 – 10.6 cal kyr BP; 11.8 – 11.3 cal kyr BP; and from 13.1 – 12.8 cal kyr BP; or at least no stronger plateau behavior than other directly neighboring time periods. This shows the difficulty of relying upon Lake Suigetsu alone to identify atmospheric variation. Further, without strong plateau behavior, the question of how to reliably identify matching ^{14}C features in sparse marine records remains.

The only ^{14}C-age plateau proposed in their suite which does appear to be seen in the tree rings might be from 12.5 – 11.9 cal kyr BP, however even this appears to be shorter in length, perhaps lasting only 300 cal yrs in the tree ring records. Even plateau 1A (Bölling-Alleröd) is not really a plateau when one incorporates the recent floating tree-ring sequences by Adolphi et al. (2017) – see Heaton et al. (2020a) and Muscheler et al. (2020).

Updating of hypothesized ^{14}C-age plateaus

The Figure 1 by Sarnthein & Grootes shows the resulting $\Delta^{14}C$ for the 30 – 14 cal kyr BP in which ^{14}C-age plateaus appear as decreasing trends equivalent to the radioactive decay (1‰ over 8 years). This graph is an update of Fig. 3a in our 2021 paper in CP. On this Figure, Sarnthein & Grootes compare their new plateau record (in bright purple) with the records we calculated with their previous definitions of plateaus.

The main changes in Fig. 1 by Sarnthein & Grootes are that former ^{14}C-age plateaus 6a and 6b have been merged and that plateau 7 has disappeared. In our Figure 2 below, we have remade Sarnthein & Grootes' submitted figure since the lines shown in their original do not appear to correspond to the calendar ages of the plateaus as given in their paper, notably for plateau 7 and the end of plateau 10a. Our Figure 2 is based on Table 1 of Sarnthein & Grootes (2022) which seems incompatible with their Figure 1. In blue, we show the implied $\Delta^{14}C$ record based on the 2022 hypothesized ^{14}C-age plateaus using the updated Lake Suigetsu record, in green the implied $\Delta^{14}C$ using the ^{14}C-age plateaus proposed in 2020.

Our 2021 CP paper was actually the first to provide a $\Delta^{14}C$ plot illustrating the implications of the atmospheric ^{14}C-age plateaus hypothesized by Sarnthein & Grootes. Our original intention was to show how physically unreasonable the atmospheric $\Delta^{14}C$ record must be in order to allow for such ^{14}C-age plateaus (a succession of very abrupt jumps followed by ramps cancelling the radioactive decay).

It remains the case that no mechanism is proposed to explain these massive and instantaneous $\Delta^{14}C$ increases (ca. 100 to 200 ‰) that occur without any relationship with ^{10}Be maxima in ice cores. It is thus surprising that in the summary of their new paper Sarnthein & Grootes claim the discovery of *"fine structure of jumps and plateaus in atmospheric and planktic radiocarbon (^{14}C) concentration that reflect authentic changes in atmospheric ^{14}C production."*

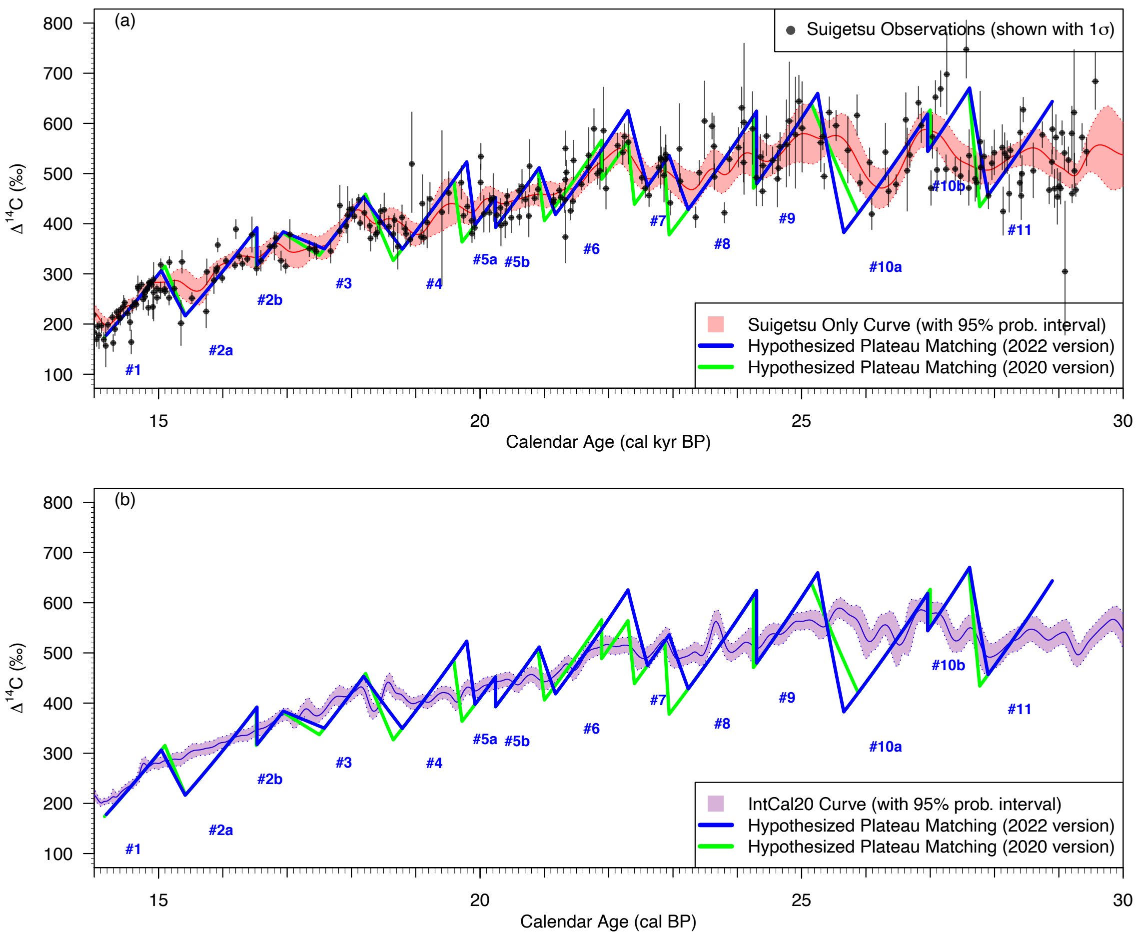

Figure 2: *Inferred $\Delta^{14}C$ reconstructions based upon the hypothesized ^{14}C-age plateaus proposed by Sarnthein & Grootes in 2020 (green) and here in 2022 (blue). Panel (a) shows the plateau-based $\Delta^{14}C$ reconstructions plotted against the Lake Suigetsu ^{14}C-determinations and a Suigetsu-only calibration curve. Panel (b) shows the plateau-based reconstructions against the IntCal20 $\Delta^{14}C$ estimate. Note: These plots are somewhat different from Figure 1 by Sarnthein & Grootes since their plot is not consistent with the calendar dates they provide (in their Table 1) for the hypothesized ^{14}C-age plateaus.*

Transferal of atmospheric ^{14}C variations to the ocean

Besides redoing PT tuning on their 19 ocean sediment records, Sarnthein & Grootes have not provided any new data or calculations to answer criticisms expressed in our 2021 paper.

In particular, none of our statistical concerns have been taken into account. The level of objectivity in the identification of plateaus in marine sediments remains unclear, and we have doubts as to how reproducible this identification process is when performed by others. Further, the authors provide very little discussion regarding the sparsity of most marine ^{14}C records, and how this likely prevents identification of any short-term and fine scale structure – especially when such sediment records do not have a timescale of their own and structure is only seen against depth (which, with PT, has a highly non-linear relationship with calendar age). In addition, the MRA is also variable through time which further complicates the tuning.

No independent evidence is provided to verify the inferred extreme changes of sedimentation rate, including hiatuses. Ground-truthing of PT should come from an independent comparison between PT and a detailed core chronology (based on other independent techniques) to derive sedimentation rates and reservoir age changes. This is a prerequisite to demonstrate the merit and added-value of PT. Such ground-truthing would also likely require objective criteria to identify the plateaus.

As shown by Fig. S1 to S19 by Sarnthein & Grootes, the variations in the sedimentation rate inferred by PT show very large downcore changes – ranging from several-fold to an order of magnitude (and infinity for hiatuses). These downcore changes (specifically the minimum sedimentation rate within any core) is what matters for signal alteration by bioturbation and other sediment mixing processes (i.e., not the mean sedimentation rate over the full core). Foraminifera counts are still not provided for the 19 cores and no effort has been made to model the effect of sediment mixing.

Sarnthein & Grootes still cite the results on four South Pacific cores with a reference to a paper by Küssner et al. (2020), which we understand has been rejected for publication in *Paleoceanography & Paleoclimatology* (cited as submitted to this journal in Sarnthein et al. 2020). These are the records which were significantly changed between the submitted and published versions of Sarnthein et al. (2020) without explanation (see the submitted version available publicly from the CP web site). Furthermore, two independent Community Comments accompanied our 2021 paper (Lamy & Arz 2021, Michel & Siani 2021), confirming our initial doubts about PT applied to those cores (Drs. E. Michel and G. Siani are listed as coauthors of the paper by Küssner et al., Dr. F. Lamy was listed as a coauthor of Küssner et al. in the submitted version by Sarnthein et al. 2020). In the new paper by Sarnthein & Grootes, the PT results on those South Pacific cores are now cited as a PANGAEA database by Küssner et al. (2020). This is clearly not satisfactory as PT relies heavily on subjective interpretations, which should be described and provided in a peer-reviewed paper.

Sarnthein & Grootes still think that the marine ^{14}C records can be matched directly to the atmospheric record, without taking into account the smoothing and lagging effects of carbon uptake and mixing in the surface ocean. The level of such oceanic smoothing is directly related to the value of the surface reservoir age. This adds inextricable complexity to PT supposed to provide both the chronology of the core and the local MRA record at the core site (with MRAs that are often up to several millennia inferred by PT). Our carbon cycle modeling results clearly illustrated this point (Bard & Heaton 2021). They were obtained with a rather generic 12-box model which had been compared with other models and with the more realistic 2D Bern model (Delaygue & Bard 2011). Such simple box models have been used in the frame of the IntCal group for decades (e.g., Stuiver & Braziunas 1993, Reimer et al. 2013, Heaton et al. 2020b).

Besides the multiple anomalies already mentioned in previous papers (Bard & Heaton 2021, Skinner & Bard 2022), the new submission by Sarnthein & Grootes led us to think about the pair of cores located in the South China Sea (GIK17940 and SO50-37, Figs. S6 and S7, respectively). The PT chronologies based on planktic ^{14}C ages lead to large MRA values in both cores ranging between 900 and 1900 ^{14}C yr. Surprisingly, the benthic ^{14}C ages in GIK17940 are about the same as planktic ^{14}C ages (Fig. S6), which leads to the conclusion that the water column was old, but completely mixed down to 2 km (the depth of the core is 1721 m). By contrast, the nearby core SO50-37, collected somewhat deeper (2655 m), exhibits ^{14}C ages on benthic foraminifera that are about 2-3 kyr older than planktics for the same time periods (Fig. S7). Given the deep homogenization invoked by Sarnthein & Grootes for that site (down to 2km), the benthic ^{14}C record of GIK17940 should also show the hypothesized age plateaus, which is obviously not the case (Fig. S6). This puzzling example is probably spurious and is not reassuring for the reliability of PT.

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