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Reply to comment by S. Peacock on "Glacial-interglacial circulation changes inferred from $^{231}Pa/^{230}Th$ sedimentary record in the North Atlantic region"

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1. Introduction

[1] *Peacock* [2010, P10 hereafter] takes issue with several aspects of our recent article [*Gherardi et al.*, 2009, G09 hereafter]: (1) our description of the modern Atlantic meridional overturning circulation (AMOC), (2) apparent inconsistencies between modern circulation and our Holocene sedimentary $^{231}Pa/^{230}Th$ bathymetric profile, and (3) our use of cores for reconstructing AMOC from locations that do not lie beneath the Deep Western Boundary Current (DWBC). We welcome the comment as it affords us the opportunity to clarify important aspects of our approach to studying paleocirculation and to address any potential misunderstandings arising from the wording of our original text.

2. The ^{231}Pa and ^{230}Th Residence Times in the Water Column

[2] The use of sedimentary $^{231}Pa/^{230}Th$ to reconstruct past changes in the rate and geometry of the AMOC relies on the fact that ^{231}Pa has a longer residence time in the water column than ^{230}Th [*Anderson et al.*, 1983; *Nozaki and Nakanishi*, 1985]. The residence time of ^{230}Th is short enough to limit severely the extent to which it can be laterally transported after its production by the radioactive decay of uranium dissolved in seawater. By contrast, as a result of its longer residence time, ^{231}Pa is extensively redistributed by ocean circulation. Because the removal of the two radionuclides is controlled by reversible scavenging, their seawater concentrations in the absence of circulation and vertical mixing are very low at the sea surface and increase linearly with depth [*Bacon and Anderson*, 1982].

$$\partial^{ss}[X]_t/\partial t = \beta - S\,\partial\left(K^{ss}[X]_t\right)/\partial Z \qquad (1)$$

where $^{ss}[X]_t$ is the total activity of ^{230}Th or ^{231}Pa when the profile is at steady state with respect to scavenging, β is the production rate of the radioisotope (dpm m^{-3} yr^{-1}), S is the sinking rate of the scavenging particles, K is the fraction of total X associated with particles ($K = {}^{ss}[X]_p/{}^{ss}[X]_t$), and Z is the water depth.

[3] In deep water, K is nearly constant. Therefore, at steady state:

$$^{ss}[X]_t = \beta Z/S\,K \qquad (2)$$

[4] The lower $^{ss}[X]_t$ in the upper water column result in shorter "steady state residence times" (τ_{ss}):

$$\tau_{ss} = {}^{ss}[X]_t/\beta \qquad (3)$$

[5] Because of these shorter residence times, it takes a stronger circulation to produce the same ^{231}Pa deficit in shallower waters compared to deeper waters. This can be shown using the equation proposed by *Rutgers van der Loeff and Berger* [1993], which describes the lateral transport of ^{230}Th or ^{231}Pa.

$$\partial[X]_t/\partial t = \beta - S\,\partial\left(K[X]_t\right)/\partial Z - \left([X]_t - {}^{i}[X]_t\right)/\tau_w = 0 \qquad (4)$$

where $^{i}[X]_t$ and $[X]_t$ are total ^{230}Th (or ^{231}Pa) concentration measured at two locations on the same isopycnal with $^{i}[X]_t$ the concentration in the upstream source region and τ_w is the "transit time" of water between these two sites. In deep waters, K is nearly constant and to a first approximation can be removed from the derivative. Integrating this simplified equation thus gives

$$[X]_t{\cdot}\left(\beta\tau_w + {}^{i}[X]_t\right)\left(1 - e^{-Z/\tau wSK}\right) \qquad (5)$$

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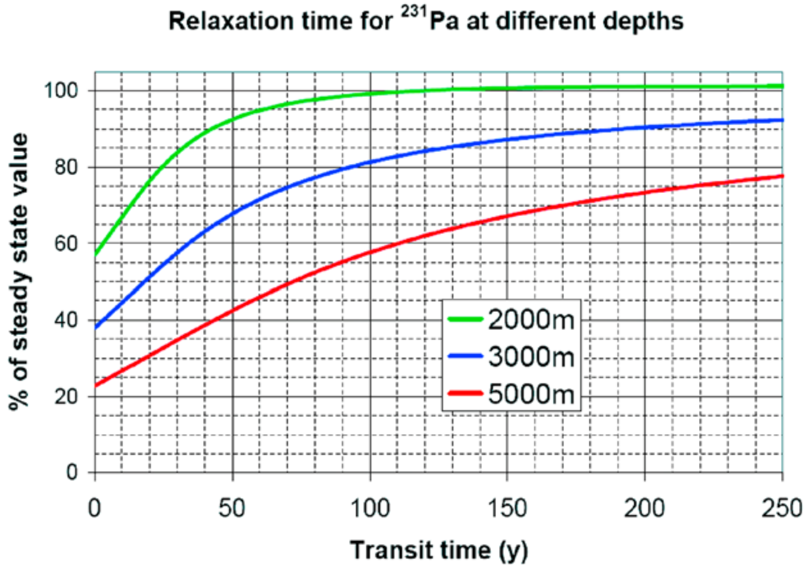

Figure 1. Relaxation of ^{231}Pa activity at different depths as described by equation (7) with $^{i}[X]_t$ = 0.14 dpm m^{-3}, S = 500 m, and K = 0.04. After 50 years of transit from the upstream source region, $[^{231}Pa]_t$ has reached 92.5% of its steady state value with respect to scavenging at 2000 m. It takes increasingly longer transit times to reach a similar level of concentration (relative to the steady state value) in deeper water (250 years at 3000 m and 850 years at 5000 m).

[6] This equation predicts that, as one moves downstream (increasing τ_w) the radioisotope profiles relax back to linearity slower as Z/SK increases. Since S and K change little with depth, the transit time required for relaxation of the profiles increases with depth; that is, linearity is regained closer to the source at shallower depth.

[7] From equations (2) and (3):

$$\tau_{ss} = Z/SK \qquad (6)$$

[8] Therefore:

$$[X]_t \cdot \left(\beta_{Th}\tau_w + {}^{i}[X]_t\right)\left(1 - e^{-\tau ss/\tau w}\right) \qquad (7)$$

[9] This equation predicts that the radioisotope profiles relax back to linearity more slowly with increasing τ_{ss}, which increases linearly with water depth (Figure 1). Profile linearity is thus regained closer to the source at shallower depths, and ^{230}Th regains linearity faster than ^{231}Pa because of its shorter steady state residence time in the water column.

[10] Therefore, even though there is a significant southward flow above 2500 m in the North Atlantic today [P10; *Lee et al.*, 1996; *Smethie and Fine*, 2001; *Schott et al.*, 2004], it is not fast enough to produce a significant ^{231}Pa export and, as a consequence, sediments deposited above that depth do not show a ^{231}Pa deficit relative to the overlying production. On the other hand, the same overturning rate at greater depth produces a measurable deficit in deep sediments because of the longer τ_{ss} of ^{231}Pa in deep water.

[11] In consideration of the above, what is most remarkable in our data, is the large deficit found in the shallow cores during the last glacial maximum (LGM), and to a lesser extent during the deglaciation. This requires that the rate of the shallow overturning at that time must have been much faster than observed in the modern ocean, while the smaller deficit in the deeper core must indicate that the deep overturning rate was slower than in the modern circulation. Clearly, we cannot conclude from our data that the renewal rate of water above 2500 m is slow today in any absolute sense, but the rate of shallow overturning (depth < 2500 m) must be significantly slower today than it was during the LGM, while the rate of deep overturning (depth > 2500 m) is relatively faster today than it was during the LGM.

[12] Sediment ^{231}Pa/^{230}Th integrates the meridional export of ^{231}Pa over the entire overlying water column in a way that is weighted by the depth-dependent τ_{ss} of ^{231}Pa [*Luo et al.*, 2009] and our Holocene sediment ^{231}Pa/^{230}Th bathymetric profile is entirely consistent with the present-day North Atlantic volume transport. The high sediment ^{231}Pa/^{230}Th measured above 2000 m reflects the shorter residence time of ^{231}Pa at these shallower depths. Although substantial meridional volume transport occurs today above 2000 m, it is too weak to export a large fraction of the ^{231}Pa from the upper overlying 2000 m of the water column. Between 2000 m and 3000 m, where we find the maximum lateral volume transport, we also find the sharpest decrease in sediment ^{231}Pa/^{230}Th (Δ^{231}Pa/^{230}Th$_{2000-3000}$ ~ 0.03). This is because the combined effect of increasing τ_{ss} and stronger lateral volume transport result in substantial lateral export of ^{231}Pa between 2000 and 3000 m. Sediments deposited at 3000 m therefore record evidence that a higher proportion of ^{231}Pa produced in the upper 3000 m is being laterally exported. Below 3000 m, lateral volume transport decreases but is still sufficient to effectively export a fraction of ^{231}Pa in

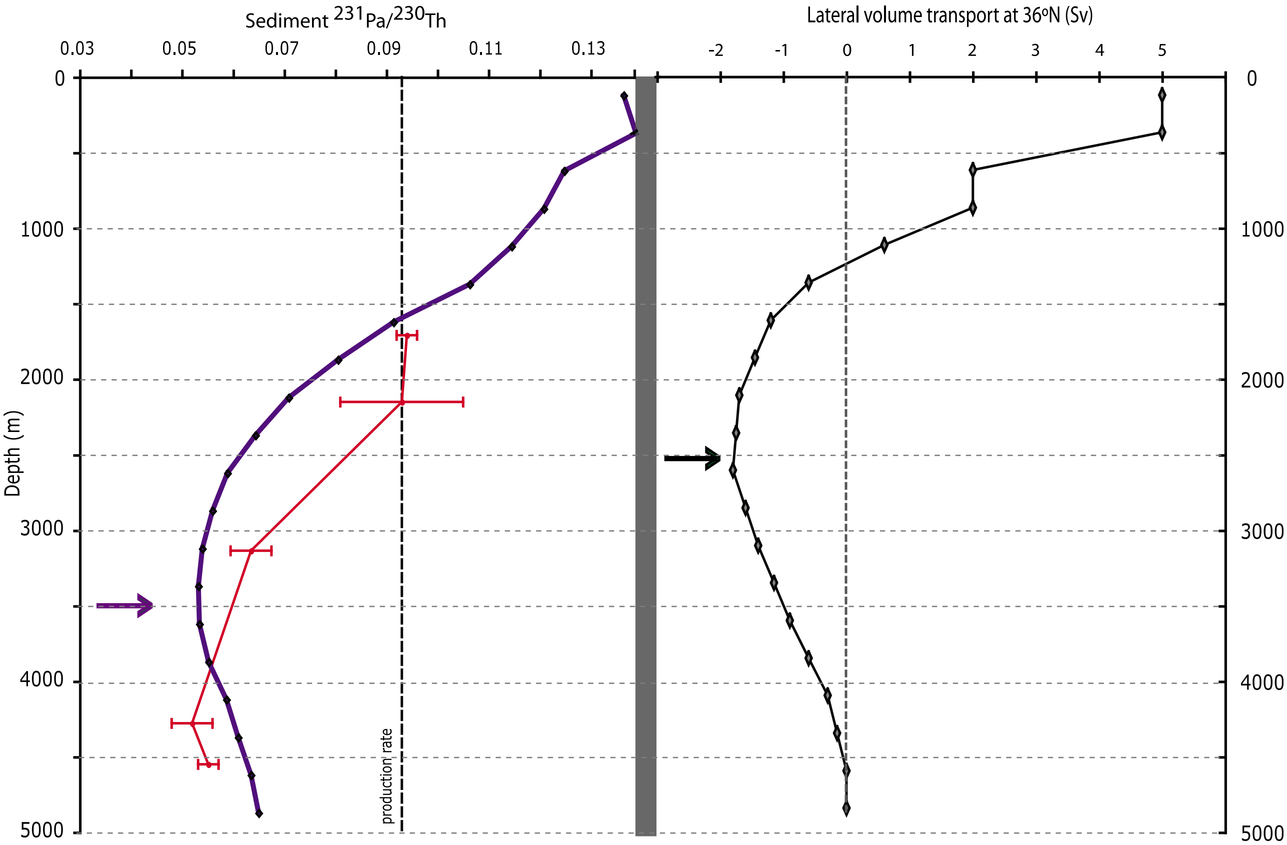

Figure 2. (left) Pa/Th depth profiles: sediment $^{231}Pa/^{230}Th$ generated at 36°N by imbedding the reversible scavenging model of *Bacon and Anderson* [1982] in a simple 2-D overturning circulation cell from *Luo et al.* [2009] that reproduces the volume transport estimated by *Wunsch and Heimbach* [2006] (purple line) compared to G09 Holocene depth profile (red line and dots). Black and purple arrows highlight maximum lateral transport and minimum $^{231}Pa/Th$, respectively (see discussion). (right) Lateral volume transport (Sv) estimated by *Wunsch and Heimbach* [2006] used in the model to generate the $^{231}Pa/^{230}Th$ bathymetric profile.

these deeper waters. The fraction of laterally exported ^{231}Pa integrated over the upper 4500 m therefore still increases (i.e., sediment $^{231}Pa/^{230}Th$ decreases). However, the decrease in sediment $^{231}Pa/^{230}Th$ between 3000 m and 4500 m is less ($\Delta^{231}Pa/^{230}Th_{\ 3000\text{–}4500} \sim 0.01$) than the decrease between 2000 m and 3000 m. In contrast, meridional volume transport in the upper 2000 m during the LGM was sufficiently vigorous to export a large fraction of the ^{231}Pa produced in the upper water column. Below 2000 m, sediment $^{231}Pa/^{230}Th$ gradually increases indicating that very little of the ^{231}Pa in deep water was exported.

[13] This intuitive understanding of the relation between sediment $^{231}Pa/^{230}Th$ and lateral volume transport can be corroborated by a simple two dimensional scavenging model (Figure 2) [*Luo et al.*, 2009]. When a circulation scheme is imposed to reproduce the volume transport estimated by *Wunsch and Heimbach* [2006], the model generates sediment $^{231}Pa/^{230}Th$ close to the production rate at 1500 m, even though lateral volume transport at this depth is relatively high and the minimum in sediment $^{231}Pa/^{230}Th$ is reached 1000 m below the depth of maximum lateral transport.

[14] P10 calculates ^{231}Pa residence time as the measured activity divided by the production rate using the water column data reported by *Luo et al.* [2009]. She concludes that these residence times do not increase between 1710 m and 4550 m and are inconsistent with our explanation. From equation (7), it is clear that P10 is using the wrong "residence time" to reach her conclusion. Instead, she should have used the "steady state residence time" (τ_{ss}) of ^{231}Pa, which is clearly a linear function of depth (equation (6)). In contrast to its linear increase with depth, we can expect to find relatively little geographic variations in τ_{ss} since it depends on the sinking rates of particles and K. This is consistent with the overlap for ^{230}Th profiles in the upper 1000 m (Figure 2 by P10). The relaxation time of ^{230}Th profiles in the upper 1000 m is fast enough that linearity is regained at all these stations. The similar slope for all the profiles indicates that SK must be similar at those different geographic locations. The wide divergence deeper in the profiles is clearly a reflection of circulation (why would scavenging affect deep water and not the upper 1000 m?), and may indeed help us better constrain abyssal circulation [*Marchal et al.*, 2007].

[15] P10 also uses a compilation of core top data (her Figure 3). She finds a general decrease in sedimentary $^{231}Pa/^{230}Th$ with increasing water depth, in general agreement with the G09 and the modeling results of *Luo et al.* [2009], but dismisses the significance of this finding because of the scatter in the data. It is clear that there is significant scatter in the compiled data, but sediment $^{231}Pa/^{230}Th$ does not just vary with depth but also with distance from the site of deep water formation [*Luo et al.*, 2009], which must account for part of the scatter. The color coding used by P10 roughly supports this. We must also realize that these data have been collected over several decades, using different analytical techniques and without cross calibration between laboratories. This will definitely add substantial noise to the data. Moreover, some of the core tops may not be modern sediments, in which case $^{231}Pa/^{230}Th$ would be low because of decay. It is also clear that when opal is present $^{231}Pa/^{230}Th$ will be higher. Such scatter is therefore not surprising.

3. Reconstructing AMOC Changes From $^{231}Pa/^{230}Th$ Records Over the North Atlantic

[16] The last point of contention is whether we must analyze cores taken directly under the DWBC to monitor past changes in the rate of AMOC. P10 argues that our cores are not taken from sites where the flow of water is representative of the zonally integrated circulation of the North Atlantic and therefore cannot monitor the strength of the AMOC. By her argument only cores taken from underneath the DWBC would have the potential to monitor the AMOC. In fact, sediment $^{231}Pa/^{230}Th$ just monitors a weighted integration of the residence time of water in the column overlying the coring sites and therefore average spatially (basin-wide) and temporally (centennial to millennial scale, depending on core resolution) all the complexities of ocean circulation geometry arising from the formation of recirculation gyres, eddies, etc. Just like deep water, ^{231}Pa is most likely to be exported from the North Atlantic through the DWBC. The strength of the DWBC largely dictates the residence time of deep water in the entire North Atlantic basin and a stronger DWBC result in shorter residence times and a more effective export of the ^{231}Pa produced in this basin. A key point here is that the strength of this export can therefore be monitored from anywhere in the basin. This spatial integration is not unique to $^{231}Pa/^{230}Th$ but is also clearly documented for all the other geochemical parameters that are sensitive to the residence time of water in ocean basins (e.g., O_2, nutrients, $\Delta^{14}C$, $\delta^{13}C$, etc. [*Broecker and Peng*, 1982; *Broecker et al.*, 1991; *Schlitzer*, 2000]). We can expect subtle spatial variations in the $^{231}Pa/^{230}Th$ signal within the North Atlantic (just as we find small variations in seawater nutrient concentrations, $\Delta^{14}C$, O_2 etc. between the eastern and western basins of the North Atlantic) and we have begun to document these in the work by *Gherardi et al.* [2005], but irrespective of the spatial distribution of our cores, the $^{231}Pa/^{230}Th$ signals retrieved from them monitor the broad features of the AMOC. This is not to say that we should not strive to increase our sediment $^{231}Pa/^{230}Th$ database. Contrasting sediment $^{231}Pa/^{230}Th$ within the North Atlantic may provide additional insights into past changes in the path of the DWBC and sites of deep water formation, but first-order qualitative conclusions on changes in the strength and geometry of the AMOC, as done by G09, can already be reached with some confidence. The goal of developing sediment $^{231}Pa/^{230}Th$ as a quantitative proxy for paleocirculation will require a partnership between data generation involving coring programs specifically targeting this problem, and modeling.

4. Conclusion

[17] Sedimentary $^{231}Pa/^{230}Th$ in the North Atlantic continues to be a promising tool to track past changes in the mean export rate of water masses, despite evident limitations related to particle flux and composition that must be evaluated carefully before interpretation of the records and any attempt to quantify the results. The temporal evolution and depth dependence of $^{231}Pa/^{230}Th$ as we present it in the work by G09 can best and most simply be explained by changes in the water depth distribution of integrated export of Pa, which must be related to the export of water masses.

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