## Report from Breakout Group: Radiocarbon and Pa/Th

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Radiocarbon in the modern deep ocean is one of our most important constraints on the overturning rate. It has been a long-standing goal of Paleoceanography to use this tracer in a similar way in the past ocean. However $^{14}C$ is usually employed as a chronometer and can not therefore also be a tracer. Several approaches have been proposed to independently constrain the calendar age of a sample such that its radiocarbon value can be used to estimate the $^{14}C$ content of the past. So far, benthic and planktonic foraminifera pairs and deep-sea corals have been the most widely utilized samples in this effort.

The ratio of unsupported, or excess, $^{231}Pa$ and $^{230}Th$ (Pa/Th) produced by the decay of uranium in seawater and deposited on the seafloor after adsorption on sinking particles is a promising dynamical proxy for the advection of subsurface waters. Although the residence time of each particle-reactive daughter nuclides is short relative to that of the parent uranium, the decadal residence timescale of Th ensures that its burial approximates production nearly everywhere in the ocean, while the centennial residence timescale of Pa allows it to be transported laterally along with deep and intermediate waters. The burial ratio thus varies inversely with the rate of advection. Despite the promise of this method, a number of questions remain regarding the spatial and temporal heterogeneity of the Pa/Th signal, the processes controlling the transfer of the signal from seawater to sediment, and differential scavenging over a range of particle compositions and fluxes.

### Radiocarbon Strawman A:

Overall the group felt that radiocarbon as a tracer of past circulation rate was ready for more measurements in the Atlantic over the last ~25 ka. The atmospheric record of $\Delta^{14}C$ and the ice core record of Be-10 are probably good enough for the last ~25ka to provide a basis for comparison with new deep ocean measurements. This is not to say that continued data collection is not important, just that the existing data set is much more complete than the deep ocean record and is detailed enough to calculate ocean-atmosphere differences. Both deep-sea corals and benthic-planktonic pairs are good prospects for generating precise data with good spatial coverage. These two methods clearly complement each other. Corals provide precise calendar ages and the chance to see rapid changes in the deep. Forams are more widely distributed than corals and may provide more continuous record at one location, though recent use of deep submergence tools to collect corals show great promise. The biggest drawback to using forams is the bioturbation-sedimentation rate couple. The shape of the benthic abundance curve will limit millennial scale records of benthic-planktonic pairs.

The single largest hole in our current understanding is the $\Delta^{14}C$ evolution of the Southern Source Water (SSW) end-member through time. If we can measure the mixing ratios between deep-water masses along with the $\Delta^{14}C$, this end-member record will allow us to calculate water mass ages from individual points in space and time. The presence of a 16ka deep-sea coral in the Drake Passage is a good reason to believe that there are many more samples there. In addition, the Bouvey Triple Junction seems like a promising location for more benthic-planktonic age pairs. Besides this concentration on the Southern Ocean, we feel that both depth and meridional gradients in $\Delta^{14}C$ are important to constrain with new measurements. An important open question is the degree to which zonal gradients could be important unknowns and biasing our "2-D" interpretation. This question seems to be best addressed with inverse models of modern and synthetic data sets before sample collection resources are devoted.

**Radiocarbon Strawman B:**

Both the Pacific and Indian Oceans are under explored for foraminifera pairs and deep-sea corals. Forams from the Equatorial and North Pacific regions may be exceptions to this rule and we are pursuing a summary of the existing data. To map the LGM distribution of $\Delta^{14}C$ globally may require only a small investment of effort as the $\Delta^{14}C$ gradients in these other ocean are likely to be much smaller than in the Atlantic. As with Strawman A, the key is to constrain the SSW end-member $\Delta^{14}C$ at the LGM. Both the production rate and atmospheric inventory of $^{14}C$ are fairly well known for this time period so we need only move ahead with more deep ocean measurements to make significant progress. For Strawman B the deep-sea coral record is clearly lagging behind the foraminifera data. The main difference for these samples is that a concerted effort has not been made to find samples in either the Indian or Pacific Oceans. Developing an algorithm for efficient coral collection searches based on multi-beam bathymetry is an important first step to matching the success had by several groups in the Atlantic.

Because of the dependence on collecting good SSW data, there is not a large difference in the effort needed to complete Strawman B as compared to Strawman A. However, there was a strong feeling in the group that an LGM map of radiocarbon in the deep ocean would not be as useful as it has been for the modern ocean. Based on the combined production rate (from Be-10) and atmospheric $\Delta^{14}C$ records over the last 40 ka there does not seem to be a time equivalent to the Holocene in the glacial data. Over the last 10,000 years the $^{14}C$ system is remarkable in its covariation with production rate, indicating that the $^{14}C$ cycle is largely in steady state. Given that the mean age of the ocean is not likely to be less than $10^3$ years, there is virtually no period during the last glacial and deglaciation where production rate and atmospheric $\Delta^{14}C$ covary for several thousand years. There may not be a steady state LGM circulation pattern in $\Delta^{14}C$. The group felt that transience in the system is more important to quantify than "snapshots" of a particular time period.

**Pa/Th Strawman:**

The simple application of Pa/Th may appear as a special case of the $^{230}$Th-normalization of sedimentary fluxes, with the normalized flux of $^{231}$Pa being compared to its production, yet many aspects of the system remain poorly understood. There are currently too few water column profiles and too sparse sedimentary data to provide a useful ground-truth for the proxy. Improving the spatial coverage in the Atlantic is a priority, with a longer-term goal of improving the coverage of key areas in the other oceans. In the Atlantic, meridional, zonal, and depth transects would all be valuable for sedimentary coverage. The handful of seawater profiles of dissolved and particulate radionuclides should be enhanced with additional profiles along the western margin, farther east but west of the mid-Atlantic ridge, and then in the eastern basin. These profiles should in all cases be tied to coretop sedimentary measurements. Sedimentary coverage can be done at much higher spatial resolution and meridional coretop transects should be completed both east and west of the mid-Atlantic ridge, with depth transects wherever possible. This coverage should also target the modern distribution of subsurface water masses, to allow comparison and modeling of the water mass and sedimentary signatures. This is particularly important to assess in cases where different water masses overlie one another, as the behavior of the Pa/Th system is not analogous to nutrient proxies, and is more likely to integrate the entire water column at a given location.

Similar spatial coverage is required to provide constraints on any given paleoceanographic circulation reconstruction. Although there may not be glacial or deglacial intervals that are truly ‘steady-state’, the time scale of response of Pa/Th is less than $10^3$years, and so millennial perturbations and longer interval should be readily recorded. The LGM reconstruction, and deglacial reconstructions of changes in the strength and depth of meridional circulation should therefore be explored. Depth transects that resolve vertical water mass boundaries are valuable, as they are for tracer proxies and radiocarbon. In addition, the integrative aspect of Pa/Th means that spatial depth maps and time series near the depths of the water mass boundaries may be more useful than for other proxies, since Pa/Th is more likely to reflect the overlying water mass and be less influenced by mixing and other small scale processes that may obscure the circulation signal near the boundary.