THE TIME-DEPENDENT PALEOCIRCULATION PROBLEM

A Project Supported by the *Ocean and Climate Change Institute* at WHOI

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Activity Report

We would like to thank the OCCI for this award. This award allowed us to make significant progress in the problem posed by the interpretation of paleoceanographic records from sediments, which is a larger research program of ours.

Goal The specific problem which we have addressed in the framework of this project was the development of a statistical method to extract oceanographic information from measurements of the ratio between two radioisotopes in Atlantic sediments: protactinium-231 (^{231}Pa) and thorium-230 (^{230}Th). Both radioisotopes are produced at about a constant rate in the ocean from the radioactive decay of uranium isotopes. Once they are produced, both ^{231}Pa and ^{230}Th are attached to particles sinking by gravity to the seafloor, where they become part of the sedimentary record. There is, however, an important difference between ^{231}Pa and ^{230}Th: whereas ^{230}Th is very quickly "scavenged" to the sediment, ^{231}Pa is less so and has therefore more time to be transported by the ocean circulation. This difference in particle reactivity has led paleoceanographers to suggest that measurements of the ratio between ^{231}Pa and ^{230}Th in marine sediments could be taken as an indicator of the strength of the ocean circulation in the geological past.

The goal of our project was to test the "null" hypothesis that ^{231}Pa/^{230}Th measurements in Atlantic sediments deposited during the last glacial and deglacial periods (roughly the period between 20,000 and 10,000 years ago) do not require a circulation different from the modern one, given the uncertainties in these measurements and our still incomplete understanding of the behavior of both radioisotopes in the ocean (in the statistical lingo a null hypothesis is a statement which in general one would like to reject). This project was a collaboration between Andrea Burke – a graduate student from the MIT/WHOI Joint Program in Oceanography – and myself. Interactions with Jerry McManus have also been very helpful.

Methods During a first phase of this project we have solved analytically a series of simple models of radioisotope transport and scavenging in order to develop intuition about the behavior of ^{231}Pa and ^{230}Th in the ocean. During a second phase, equipped with that intuition, a so-called inverse method has been applied to interpret $^{231}Pa/^{230}Th$ data from Atlantic sediments. I carried out the first phase and Andrea the second, for which I tried to provide her with useful guidance.

Inverse methods in general allow one to make inferences from “noisy” observations and imperfect theories – a problem common to almost all scientific disciplines. In our project, such a method was used to combine sediment $^{231}Pa/^{230}Th$ data with a model describing the transport of radioisotopes by the circulation and their scavenging by sinking particles. In order to make this combination possible the sediment $^{231}Pa/^{230}Th$ data were first converted into estimates of bottom water ^{231}Pa concentration with due regard for the uncertainties in the conversion. The inverse method allowed us to answer to the following question: by how much should the estimates of bottom water ^{231}Pa concentration which are derived from the sediment be changed or “adjusted” in order to render them compatible with the modern circulation? If the adjustment in the ^{231}Pa estimates is large compared to their uncertainties, then our null hypothesis should be rejected. If the adjustment is small, then it should be accepted.

Major Results We found that the estimates of bottom water ^{231}Pa concentration which are derived from Atlantic sediments need to be adjusted by only a small amount in order to make them compatible with the modern circulation: the adjustment is in general smaller than the uncertainties for the ^{231}Pa estimates for both the Last Glacial Maximum (LGM, a time interval near 20,000 years ago) and the Heinrich Event 1 (H1, another cold interval in the North Atlantic near 16,000 years ago). These results do not mean that there was no change in ocean circulation during the LGM and/or H1; they merely indicate that there is no evidence for such a change in the existing $^{231}Pa/^{230}Th$ data given the uncertainties.

On the other hand, we also found that the adjustment in the estimates of bottom water ^{231}Pa concentration for H1 is not random: the ^{231}Pa estimates for the deep sediment cores (3 cores raised from depths larger than 4000 m) must be decreased whereas the ^{231}Pa estimates for the shallower cores (3 other cores) must be increased in order to make them compatible with the modern circulation. Although this result is based on data from only 6 cores and the adjustment is in all cases smaller than the uncertainties, it does suggest the possibility that the vertical distribution of ^{231}Pa and hence perhaps also the circulation was different during H1 than today. Work is underway to assess the robustness of this result through additional inversions of ^{231}Pa/^{230}Th data.

Significance for the Scientific Community Earlier studies concluded from measurements of the ^{231}Pa/^{230}Th ratio in sediments that the ocean circulation in the North Atlantic basin was different from the modern one during cold time intervals of the geological past, such as the Heinrich Event 1. These measurements were then taken to support a popular theory in climate research, which postulates that the ocean circulation played a role in past climate change (via the heat that the ocean carries from the low latitudes to the high latitudes). From a new analysis of existing data we have shown that it is actually difficult to provide a quantitative basis, from the existing ^{231}Pa/^{230}Th data base, to the notion that the ocean circulation in the Atlantic basin was different from the modern during H1 as well as during the Last Glacial Maximum. Measurements of the ^{231}Pa/^{230}Th ratio in marine sediments are clearly useful, but we think that much more data are necessary and our understanding of the behavior of both radioisotopes in the ocean should be improved in order to draw solid, quantitative conclusions about the paleocirculation from ^{231}Pa/^{230}Th.

Presentation at Scientific Meetings The results from our project have so far been presented at two scientific meetings:

- Talk entitled "Testing paleoceanographic hypotheses using inverse methods: Application to ^{231}Pa/^{230}Th data for the Heinrich Event 1", presented at the General Assembly of the European Geosciences Union, April 2008, Vienna, Austria (speaker: O. Marchal). The abstract of this presentation has been published in *Geophysical Research Abstracts*, Volume 10, EGU2008-A-02654, 2008 (abstract available at http://www.cosis.net/abstracts/EGU2008/02654/EGU2008-A-02654.pdf)

- Talk entitled “Application of an inverse method to interpret $^{231}Pa/^{230}Th$ observations from marine sediments”, presented at the Goldschmidt Conference, July 2008, Vancouver, Canada (speaker: A. Burke). The abstract of this presentation has been published in a special edition of *Geochimica and Cosmochimica Acta*, Volume 72, Number 12S (abstract available at http://www.goldschmidt2008.org/abstracts/B.pdf)

A manuscript is in preparation which summarizes our major findings. Our objective is to produce a material of sufficient quality for submission to a peer-reviewed journal.

Next Steps Two possible perspectives are described below. First, an inverse method could be developed which is appropriate for combining sediment records with a *time-dependent* model. So far our work as well as earlier ones of a similar nature has neglected the information that is contained in the *rates* of change that are apparent in sediment records. For example, sediment data from two adjacent time intervals may well each be shown to be compatible with the modern circulation but the rate of change from one interval to the next documented in these data may not. Whereas the development of such a method for $^{231}Pa/^{230}Th$ was our initial intention for this project, it became quickly clear that other problems should be solved first before attempting such a development. In particular, the fact that the sediment data are in the form of a ratio ($^{231}Pa/^{230}Th$) whereas models of radioisotope transport and scavenging are framed in terms of concentration (i.e., either ^{231}Pa or ^{30}Th, but not in terms of $^{231}Pa/^{230}Th$) implies that the relation between the measurements and the model variables is a nonlinear one, which posed us with a major difficulty. In our project the problem was addressed by converting sediment $^{231}Pa/^{230}Th$ ratios into estimates of bottom water ^{231}Pa concentration by relying on the assumption that ^{230}Th is not sensitive to the circulation so that the flux of scavenged ^{230}Th to the local sediment can be approximated by the rate of ^{230}Th production in the overlying water column (this rate can be estimated with good accuracy). We have compiled ^{230}Th measurements in the Atlantic Ocean and found that the assumption is at least not incompatible with these measurements. From an estimate of the ^{230}Th flux to the sediment and the measurement of $^{231}Pa/^{230}Th$ in the sediment we were then able to estimate the concentration of ^{231}Pa in the bottom water for periods of the geological past.

Second, some inverse methods could be used to identify locations in the Atlantic where the provision of new sediment data (e.g., $^{231}Pa/^{230}Th$) would be particularly useful to infer information about the paleocirculation in this basin. The collection and analysis of paleoceanographic observations may be particularly expensive, and the problem of how to make the best use of the available resources has concerned paleoceanographers from the early days of the subject. Although the desirability of “optimal sampling strategies” has long been discussed among observers and modelers in both oceanography and paleoceanography, the actual conduct of such calculations has been few. Some inverse methods could contribute to such strategies in paleoceanography. For example, some allow one to estimate the sensitivity of a particular inference (e.g., the strength of the ocean circulation in a particular basin) to the observations that have been used to make that inference. In the future we would like to explore the extent to which inverse methods could contribute to optimal sampling strategies with the specific purpose of determining paleoceanographic circulations.