

models is to embed coastal models with finer resolutions (temporal and spatial) into the larger-scale models.

We know that many biogeochemical aspects of the coastal zones are globally significant and directly relevant to human activity, but there is much more to be learned. We need to understand the influence of the coastal zone on the global carbon cycle. We need to better constrain the physical and biological processes that control trace gas exchange. The role of anthropogenic nutrient inputs in trace gas emissions is particularly important. There are also regions in the coastal zones, such as salt marshes and mangrove swamps, that are still relatively understudied with respect to these

processes. Remote sensing is also showing us that major rivers have a strong influence on biological processes far into the ocean basins.

There is clearly a strong need to better constrain the role of the coastal zones in biogeochemical cycles and feedbacks. Observations and models both will contribute to improving our understanding of the coastal zone with respect to the carbon budget, trace gas emissions, and influence on atmospheric chemistry and aerosols. New observation systems with better spatial and temporal resolution will help us to understand the heterogeneity of the coastal zone, define their various types, and parameterize their functions in global models. With improved prognostic modeling,

we can explore mechanisms of current variability and predict future change.

The University Corporation for Atmospheric Research (UCAR)/NCAR Junior Faculty Forum on Future Scientific Directions was held 23–25 June 2004, at NCAR in Boulder, Colorado.

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Future Applications of Thorium-234 in Aquatic Ecosystems

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A fundamental and outstanding issue in marine biogeochemistry is understanding the mechanisms that control and enhance the flux of material from the surface ocean to depth. "Sinking particles" are the ultimate removal mechanism of many biologically and particle reactive elements from the ocean. This includes atmospheric carbon, which is converted from CO₂ to particulate phases during biological production and sequestered to deep waters via particle sinking. Unfortunately, the temporal and spatial magnitude of the sinking particle flux remains an elusive and difficult process to study.

Over the past decade, thorium-234 has increasingly been used to quantify particle fluxes from surface waters in both open-ocean and coastal environments. Thorium-234 ($t_{1/2} = 24.1$ days) is a particle reactive radionuclide that is produced in seawater by radioactive decay of its dissolved conservative parent, ²³⁸U. In principle, the disequilibrium between ²³⁸U and the measured total ²³⁴Th activity reflects the net rate of particle export from the surface ocean on timescales of days to weeks. Thus, ²³⁴Th should serve as an integrative tracer that is relatively forgiving in terms of biological patchiness and temporal heterogeneity. Furthermore, it enables multiple sample collection at a suite of depths throughout the water column, enabling a closer examination of particle flux and remineralization patterns.

In spite of advances in sample collection, analytical methods, and technology, there remain a number of important questions concerning ²³⁴Th speciation, reactivity, sample collection and analysis, and modeling strategies that affect our interpretation of ²³⁴Th disequilibrium. The uncertainties and debate regarding these issues need to be resolved if ²³⁴Th is going to continue to be successfully applied as an in situ tracer for the export of particulate organic carbon (POC) and associated biogenic and other particle reactive elements.

In August 2004, over 40 researchers from the United States, Europe, India, Australia, and China met at the Woods Hole Oceanographic Institu-

tion in Woods Hole, Massachusetts, for a workshop on the Future Applications of ²³⁴Th in Aquatic Ecosystems (FATE). The purpose of the workshop was to bring together a number of international experts in the collection, analysis, and interpretation of ²³⁴Th in aquatic ecosystems with diverse opinions and backgrounds. Geochemists not directly involved in ²³⁴Th measurements were also present to provide outside perspective into the current status and future directions of ²³⁴Th research. A number of students also attended the meeting and acted as scribes to record comments and ideas put forward during the working group sessions.

The participants were asked to discuss and define current issues in the use of ²³⁴Th as well as a coherent strategy for future endeavors. Invited talks (available at <http://www.geol.sc.edu/cbnelson/Thmeeting/Index.htm>) focused on four main areas (see below) and set the stage for in-depth discussions. A brief overview of the working group discussions is presented here.

Methodologies and Techniques

There are currently a number of techniques available for the measurement of ²³⁴Th. These techniques have inherent strengths and weaknesses that are not necessarily clear to those outside the ²³⁴Th community. Guidance and a consensus on where and when each method should or should not be used is needed, including specific recommendations regarding sample size and collection methods, preconcentration techniques, the use of yield monitors, counting procedures, and error analysis.

In addition, there are currently no specific ²³⁴Th standards available for intermethod and interlaboratory comparisons. This is due in part to the fact that ²³⁴Th has a very short half-life and is therefore not amenable to being distributed as a standard reference material. Many laboratories calibrate ²³⁴Th to deep-water samples and assume equilibrium with ²³⁸U (which is in turn derived from salinity).

However, sediment resuspension, deep-sea migrating zooplankton, and even the abundance

of deep particle layers, such as those produced from hydrothermal systems, may cause ²³⁴Th:²³⁸U disequilibria in some instances. Small disequilibria in surface waters are common, and uncertainties in calibration assumptions can result in large errors in the ²³⁴Th flux.

Given the wide range of procedures currently in use for the measurement of ²³⁴Th activity, the community should strive to rigorously define analytical procedures that can be compared using standardized materials, such as aged seawater rather than deep seawaters. This includes the calibration of equipment for specific sample types, i.e., particles, and geometries being measured.

Collection and Application of Particulate Organic Carbon/²³⁴Th Ratios

In order to convert ²³⁴Th fluxes into export of a particular element of interest, it is necessary to quantify the elemental to ²³⁴Th ratios of sinking particles at a given reference depth. The most common application is in determining the export of POC. POC/²³⁴Th ratios may vary widely depending on the geographical location, bloom versus nonbloom conditions, and collection technique (i.e., in situ pumps versus sediment traps).

While POC/²³⁴Th ratios may vary greatly within the upper 100 m and within coastal areas, evidence presented at the meeting provided convincing arguments that there is much less variability in open-ocean settings at depths just below the euphotic zone. The group agreed that at these depths POC/²³⁴Th ratios are often within a factor of 2–3. At least some of this range in the ratio of POC/²³⁴Th at depth is due to natural variability, but there are also differences in the POC/²³⁴Th ratio depending on the method of collection that needs to be further evaluated.

In essence, the thorium community has inherited the same issues encountered by the sediment trap community; there is no unbiased mechanism for collecting a representative "sinking particle." The group suggested that following specific protocols in the collection of particulate ²³⁴Th will reduce the range and uncertainty of POC/²³⁴Th measurements and allow for better intercomparisons between data sets. Further characterization of samples using simultaneous particle collection by

various techniques is needed to clarify why methodological differences occur, such as differences in POC concentrations from bottles versus pumps. Many examples were given where such studies are already under way. As better collection techniques are developed, natural variability in POC/ ^{234}Th ratios versus methodological differences will become more apparent.

Modeling and Synthesis

Historically, measurements of ^{234}Th have most often been treated with a simple one-dimensional, one-box model of ^{234}Th : ^{238}U disequilibrium for the determination of particle flux. Multiple particle box models for elucidating particle residence times, and particle aggregation/dissaggregation dynamics have also been applied. The advent of new analytical techniques, however, has enabled the collection of multiple profiles of ^{234}Th : ^{238}U disequilibrium with depth. In principle, data can be acquired that can address steady state versus non-steady-state assumptions and include the role of physical mixing processes. It appears that physical transport processes may influence the budget of ^{234}Th , particularly in coastal and upwelling areas, and hence the measured ^{234}Th : ^{238}U disequilibrium from which fluxes are derived.

Non-steady-state processes, such as bloom events in open-ocean oligotrophic settings, can also be important.

The group suggested that simple guidelines be developed that detail the complexity, uncertainty, and assumptions inherent in ^{234}Th -derived particle fluxes. For example, errors associated with non-steady-state models become increasingly large when ^{234}Th : ^{238}U disequilibrium is small due to propagation of analytical uncertainties. Such guidelines would help focus current sampling efforts and in the derivation of more accurate ^{234}Th particle export estimates.

Thorium 234 Speciation

To date, the application of ^{234}Th for deriving particle export has involved a measure of

^{234}Th : ^{238}U disequilibrium and the ratio of a specific element to ^{234}Th on sinking particles without any inherent understanding of the relationships between them, i.e., an empirical approach. While it may not be requisite to understand the speciation of ^{234}Th to constrain particle flux, the group concluded that a mechanistic understanding of particle interactions of Th is highly desirable. It was argued that at least some of the variability associated with changes in POC/ ^{234}Th ratios is related to ^{234}Th speciation within different regimes. Understanding why the POC/ ^{234}Th ratio varies should clarify the sample collection issues discussed here.

However, dissolved organic matter and organic ligand speciation in natural waters is a complex issue unto itself. Combined laboratory, mesocosm, and field-based studies that characterize the speciation of the dissolved, colloidal, and particulate ^{234}Th pool are recommended. These studies must examine the relationships between particulate ^{234}Th , number, and type of surface sites, biophysical ligand properties, and chemical composition as well as how these interactions are modified by biological activity over time. This undertaking will require a paradigm shift in the quest for a better understanding of a family of highly surface reactive macromolecular Th binding ligands that necessitates a larger investment in marine biophysical and analytical chemical research.

Conclusions and Future Work

The meeting was successful in delineating the community's current knowledge and use of ^{234}Th as a tracer of POC export, and in identifying issues that need to be resolved for future work. Throughout the course of discussions, however, it became apparent that ^{234}Th may be underutilized for examining particle-related processes beyond POC export. Advances in technology have now made it possible for ^{234}Th to be used as a tracer of particle formation and remineralization well below the depth of the euphotic zone. Thorium-234 may also be applied to help quantify particle scavenging

in coastal areas, estuaries, ice-covered regions, and even freshwater ecosystems. Furthermore, there may be specific scavenging processes, such as those involving marine snow and other constituents, such as iron, other radionuclides ($^{210}\text{Po}/^{210}\text{Pb}$), and metal and organic contaminants, that may be better used in combination with ^{234}Th for understanding surface export.

A series of five papers in a special volume of *Marine Chemistry* regarding ^{234}Th are scheduled to appear in summer 2005. An important objective of these papers is to help clarify the "mystique" of the ^{234}Th technique to the larger aquatic community, provide a summary of our current understanding of ^{234}Th applications, and set the stage for future endeavors of ^{234}Th in aquatic ecosystems.

Future Applications of Thorium-234 in Aquatic Ecosystems (FATE) was held 16–19 August 2004 at the Woods Hole Oceanographic Institution, in Woods Hole, Massachusetts.

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The ^{234}Th -Group: David Amiel, Bob Anderson, Robert Armstrong, Mike Bacon, Mark Baskaran, Ken Buesseler, Adrian Burd, Matt Charette, Kirk Cochran, Laurent Coppola, Minhan Dai, Timothy Eglinton, Kelly Falkner, Nicholas Fisher, Scott Fowler, Wilford Gardner, Laodong Guo, Orjan Gustafsson, Kate Hagstrom, Chin-Chang Hung, George Jackson, Carl Lamborg, Kanchan Maiti, Pere Masque, Juan Carlos Miquel, Bradley Moran, Paul Morris, James W. Murray, Kent Orlandini, Uta Passow, Kim Roberts, Alessia Rodriguez y Baena, Matthieu Roy-Barman, Michiel Rutgers van der Loeff, Peter Santschi, Manmohan Sarin, Nicolas Savoye, Sabine Schmidt, Jennifer Szlosek, Gillian Stewart, Tom Trull, James Waples, Sarah Weinstein, and Jianhong Xue.

—CLAUDIA BENITEZ-NELSON, University of South Carolina, Columbia; and THE ^{234}Th -GROUP

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In Memoriam

William Bandeen, 77, 2004, AGU Fellow, Atmospheric Sciences, 1961.

Raymond A. Lewandowski, 82, September 2004, Volcanology, Geochemistry, and Petrology, 1965.

Tsuneji Rikitake, 83, August 2004, AGU Fellow, Retired Life Member, Geomagnetism and Paleomagnetism, 1964.

Honors

Patricia Manley has received the 2004 Association for Women Geoscientists Foundation Outstanding Educator Award, which is presented to "well-established college or university teachers who have played a significant role in the education and support of women geoscientists both within and outside the classroom." During her 15-year stint at Middlebury College in Vermont, Manley has supervised numerous senior theses, with many of these students presenting their work at regional and national scientific meetings.

Saied Mostaghimi has received the 2004 Alumni Award for Excellence in Undergraduate Advising, which is presented annually by the Virginia Polytechnic Institute and State University to a faculty member "who has demonstrated outstanding advisement of graduate students."

Veerabhadran Ramanathan has been appointed by Pope John Paul II to be an academician of the Pontifical Academy of Sciences. He will contribute by attending scientific meetings, including the academy's plenary sessions, proposing subjects for scientific meetings, and nominating outstanding scientists for membership as well as young scientists of international reputation for the Pius XI Medal.