ies are beginning to address aspects of this. For example, there is intriguing evidence based on historical aerial photography from the 20th century, in addition to dating of lateral moraines and trimlines, that the Jakobshavn Isbrae catchment (Fig. 3) has fluctuated in volume several times since the Little Ice Age (Csatho et al., 2008). Yet we do not know whether, or what, contemporaneous external forcing was responsible for these changes. Nonetheless, this study does suggest that the contemporary observations, for this basin at least, are not atypical. The work has also shown that it is possible to produce (some of) the data we need to help place the modern observations in a longer-term context. There are currently no equivalent studies for WAIS catchments or on a larger scale in Greenland. In fact, even the gross deglacial evolution of the WAIS is poorly known (Ackert et al., 2007). Let's hope this changes soon!

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U-series dating of fossil coral reefs: Consensus and controversy

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New developments in U-series coral dating are sparking a healthy debate over how best to interpret coral ages from older fossil coral reefs, reinvigorating research in sea level changes during previous interglacial periods, and fostering a new appreciation of the challenges ahead.

Understanding potential magnitudes and rates of future sea level change is an urgent societal and scientific problem. The history of sea level change provides crucial information about the links between climate forcing, response, and sea level change; as well as critical constraints on future sea level rise. The most direct method for reconstructing sea level history is uranium/thorium (U/Th) dating of fossil corals that once grew near the sea surface. This method has the potential to provide a detailed and well-dated record of sea level change for the last 700 ka. Given the relatively continuous growth of coral reefs in tropical seas and the precision of U-Th dating, the construction of a detailed and accurate sea level history should be a straightforward task. Despite decades of effort, this crucial goal remains elusive because many U/Th ages are unreliable due to mobility of the relevant isotopes, a problem that worsens with increasing coral age. Recently, sea level research has been reinvigorated by new insight into the mechanisms of U-series isotope mobility in fossil corals and by significant improvements in analytical techniques.

Identifying reliable coral ages

Recent advances in analytical techniques have improved the precision of U/Th dating, extending the dating range to at least 700 ka (see Stirling and Andersen, this issue). Unfortunately, analytical challenges are not the only hurdle to be overcome in the pursuit of accurate U/Th coral ages. Isotope mobility often invalidates the "closed-system" assumption that is fundamental to radiometric dating techniques. Corals can either gain or lose uranium and thorium, changing the apparent age. Furthermore, many corals seem to be subject to a coupled loss or gain of ^{234}U and ^{230}Th isotopes (Fig. 1). The best explanation for this systematic addition appears to be the coupled addition of ^{234}Th (which rapidly decays to ^{234}U) and ^{230}Th that is produced by the decay of ^{238}U and ^{234}U in the surrounding carbonate matrix. This effect results in a bias toward erroneously older apparent ages. These "open-system" artifacts represent a key challenge in translating U/Th isotope ratio measurements into reliable coral ages. Two general strategies are employed to reduce the impact of these artifacts. The "screening" approach focuses on identifying closed-system corals using criteria such as initial $^{234}U/^{238}U$ and the $^{231}Pa/^{235}U$ chronometer (e.g., Gallup et al., 1994), while the "correction" approach attempts to correct ages for open-system effects (e.g., Thompson et al., 2003; Villemant and Feuillet, 2003; Potter et al., 2004; Scholz et al., 2004).

Seawater $^{234}U/^{238}U$

Both screening and correction approaches in U-series coral dating make an assumption about the initial $^{234}U/^{238}U$ of the coral, which is most often assumed to be similar to that of modern seawater. The validity of this assumption has some support from modeling of ocean ^{234}U residence times (Richter and Turekian, 1993), and data from aragonitic sediments suggest little evidence of a large long-term change over the last 800 ka (Henderson, 2002). In contrast, there is convincing evidence from initial $^{234}U/^{238}U$ in corals that ocean $^{234}U/^{238}U$ was as much as 7‰ lower during the last glacial period (e.g., Hughen et al., 2004). Although corals are not ideal archives of ocean $^{234}U/^{238}U$ because of open-system effects, information about past seawater $^{234}U/^{238}U$ may be gleaned from an isotope ratio diagram. The dominant trend, lying for the most part above the closed-system curve (Fig. 1), suggests that most corals appear to have gained both ^{234}U and ^{230}Th, although the possibility of ^{234}U and ^{230}Th loss cannot be rigorously ruled out. Thus, the lower bounds of the data array may indicate the unaltered compositions defining seawater $^{234}U/^{238}U$ for a specific time period (e.g., Andersen et al., 2008), regardless of the specific alteration mechanism. For coral dating, any difference between the assumed and actual initial $^{234}U/^{238}U$ will produce a systematic offset from the true age for corals selected as "reliable" using screening criteria, and a similar offset for ages calculated using a correction approach. The sensitivity of ages to assumptions about initial $^{234}U/^{238}U$ can be directly assessed. For example, for an age of 125 ka the sensitivity is about 400 years/‰ so that a difference of 5‰ between assumed and initial $^{234}U/^{238}U$ would produce an offset of approx. 2 ka (e.g., Thompson et al., 2003).

Error estimation and model-dependent sensitivities

Best practices for propagating measurement uncertainty are fairly well established, so that this source of age error is generally well quantified. However, all approaches to coral dating have inherent assumptions that, if violated, result in an erroneous age. Screened ages are only valid if the system has indeed remained closed. Corrected ages are accurate if, and only if, the processes producing the anomalies are those assumed by the applied model. If these sources of uncertainty are not addressed, errors will be generally underestimated. For example, the screening approach has traditionally used a range of initial $^{234}U/^{238}U$ around the modern seawater value to define "acceptable" ages. The range of acceptable values chosen is a source of error for the selected ages (Gallup et al., 1994). This uncertainty has an identical scaling to that introduced by the uncertainty in initial seawater $^{234}U/^{238}U$ (e.g., approx. 0.4 ka/‰ at 125 ka) but is an additional and independent source of error, even if the initial seawater value were perfectly known. This source of error is never included in formal error estimates and sometimes not mentioned at all in the reporting of screened ages. Another source of potential error for both screened and corrected ages is U or Th gain or loss. For example, an approx. 4% loss of uranium from a 125-ka-old coral may produce an age that is 9.5 ka too old, with an acceptable initial $^{234}U/^{238}U$ of 151‰. Such an extreme example would be readily detected by sample replication and stratigraphic constraints. For screened ages, the potential error is limited by the range of acceptable initial $^{234}U/^{238}U$ values. The potential error for corrected ages in this scenario is essentially limitless. The impact of open-system effects can be assessed from the age reproducibility of discrete pieces from the same coral, which all must be the same true age (Scholz and Mangini, 2007). While replicate measurements cannot directly address age accuracy, they at least provide a statistical assessment of the best-case uncertainties that are attainable.

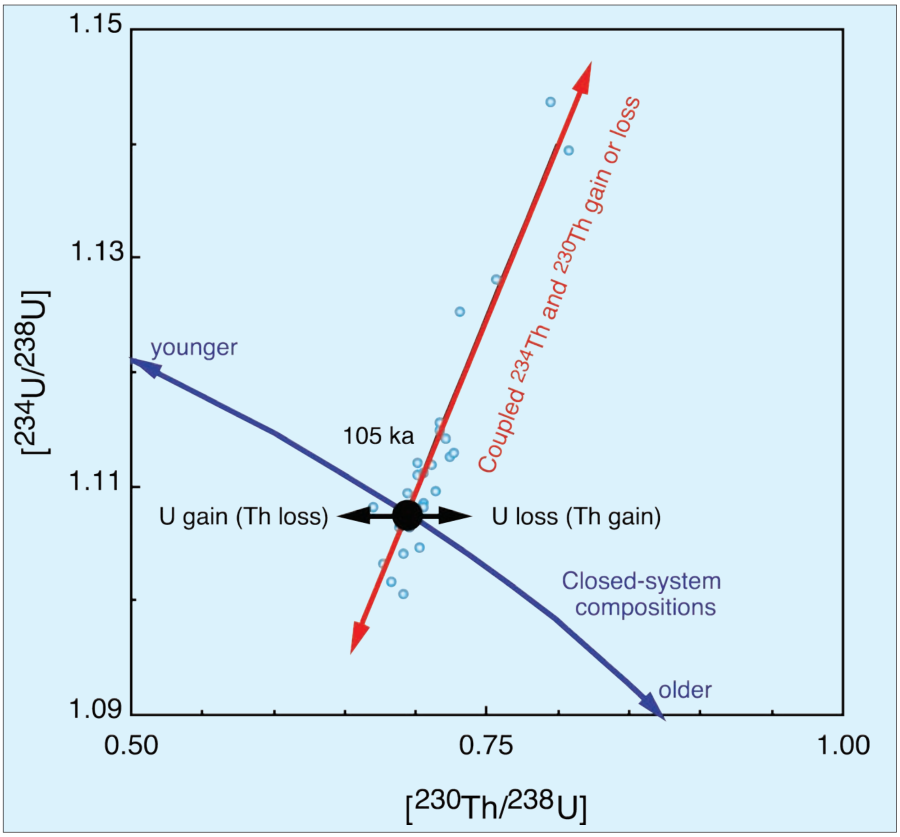

Figure 1: U/Th activity ratio diagram illustrating the major processes affecting U-series dating of older corals. The blue arc represents the range of closed-system isotopic compositions expected for corals that are approx. 65 to 165 ka and have evolved from a modern seawater uranium isotope composition. Each point along this arc corresponds to a unique U/Th age. The large black circle is the expected isotopic composition of a coral that is 105 ka old. The adsorption/loss of decay-produced ^{234}Th and ^{230}Th from/to the surrounding carbonate matrix will produce a range of compositions in the direction of the red arrows. U or Th gain or loss will produce a range of compositions in the direction of the black arrows. The open blue circles are isotopic compositions of a suite of corals collected from the MIS 5c terrace on Barbados, West Indies, which should all be near 105 ka in age. The changes in isotopic composition due to these processes are a significant source of age error.

Stratigraphic context

Given the high potential for age artifacts imposed by open-system effects, any independent constraints on true age are very helpful. Fundamental stratigraphic constraints are currently underutilized in coral dating. Although coral reefs are not simple layer-cake constructs, and models of reef development can be quite complex, the fundamental laws of stratigraphy are not suspended. Any given coral cannot be older than the substrate on which it grows. Detailed transects of vertical sections with large numbers of dated corals afford the opportunity to test the ages obtained against stratigraphic context. Age population statistics of corals that are closely associated within a discrete and well-defined stratigraphic unit provide useful information. The scatter in such ages is the sum of differences in true age, the scatter due to open-system effects, and measurement uncertainty. Analytical uncertainties are known, and scatter due to open-system effects can be estimated with replicate measurements of individual corals, yielding a first-order estimate of differences in true age.

Standardizing age and error conventions

Although screening criteria and correction approaches improve age accuracy, neither provides a guarantee of accuracy. The potential for significant artifacts in older coral ages due to the failure of underlying assumptions remains a major area of controversy in the U-series dating community. The challenge going forward is to establish uniform practices for the reporting of coral age results, so that reported ages and uncertainties are directly comparable. It would be very helpful to establish agreed upon values for initial $^{234}U/^{238}U$ and estimates of the associated uncertainty, taking into account evidence for changes through time. The uncertainty in initial $^{234}U/^{238}U$ could be formally included in the age error, making the reported ages and their errors more readily comparable. In addition, all reporting of U/Th coral ages should include a statement about the sensitivity of the ages to open-system behavior, indicating worst-case scenarios calculated for the specific set of screening criteria and age model assumptions used. Replicate ages from discrete pieces of individual corals and stratigraphic constraints are very useful for objective assessment of the maximum obtainable age accuracy. Although dating older corals remains a significant challenge, improved analytical precision and better understanding of open-system effects promise renewed progress in our effort to document sea level changes during earlier glacial cycles.

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Using models to inform the field community: Far-field sea level data applications

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Far-field sea level data contain information on past global ice volume and the source distribution of meltwater pulses. To extract this information in an accurate and effective manner requires site selection that is informed by model output.

When ice sheets and glaciers exchange mass with the oceans, the resulting sea level response is spatially variable due to the influence of the mass redistribution on the solid Earth and the gravity field (Farrell and Clark, 1976). The spatial and temporal variability in the sea level response reflect the evolution of grounded ice, as well as the physical structure and properties of the Earth's interior. Observations of this response can therefore be inverted to infer information on past ice sheet evolution and solid Earth structure. This inversion procedure generally requires the use of a model that relates the relevant model parameters (ice evolution and solid Earth properties) to the observable quantity (sea level). In this short paper, the process of using far-field sea level observations (i.e., those distant from major glaciation centers) to constrain the past evolution of ice sheets is reviewed. Emphasis is placed on two recent papers that use model predictions to determine optimal locations to solve a particular problem (Clark et al., 2002; Milne and Mitrovica, 2008). In doing so, these studies promote a two-way dialog between the observational and modeling communities that is necessary for efficient progress in solving outstanding problems.

Inferring past global ice volume

A classic application of far-field sea level data is the inference of past global ice volume through estimates of eustatic sea level (e.g., Fleming et al., 1998). This is the component of sea level change associated with a raising or lowering of ocean surface height through mass exchange with the cryosphere, and is calculated by simply dividing the volume of grounded ice gain/loss by the area of the ocean (and multiplying by the density ratio of ice to water to account for the volume change in the phase transition). This procedure has been applied to infer past global ice volume at different times. For example, measurements of the sea level lowstand during the Last Glacial Maximum (LGM) have been used to infer the magnitude of grounded ice volume at that time (e.g., Yokoyama et al., 2000). Another important application is the use of sea level observations in the mid- to late-Holocene to infer ice volume changes prior to the industrial era (e.g., Nakada and Lambeck, 1989), as a reference of natural variability in the system.

Accurate application of this procedure is complicated by the fact that, even in far-field locations, the actual (observable) sea level change deviates significantly from the eustatic component of the change due to isostatic and tectonic processes (e.g., Clark et al., 1978). For this reason, even observations from tectonically stable areas must be corrected for isostatic effects before being used to infer a paleo ice volume (e.g., Milne et al., 2002). This correction procedure is based on a model and so is subject to some degree of error that depends on the accuracy of the model prediction at a given locality. The error can be minimized by choosing locations where: (1) sea level is close to the eustatic value, so as to limit the magnitude of the correction, and/or (2) the correction to be applied is relatively insensitive to uncertainties in ice/Earth model parameters. Milne and Mitrovica (2008) carried out a model sensitivity study to map

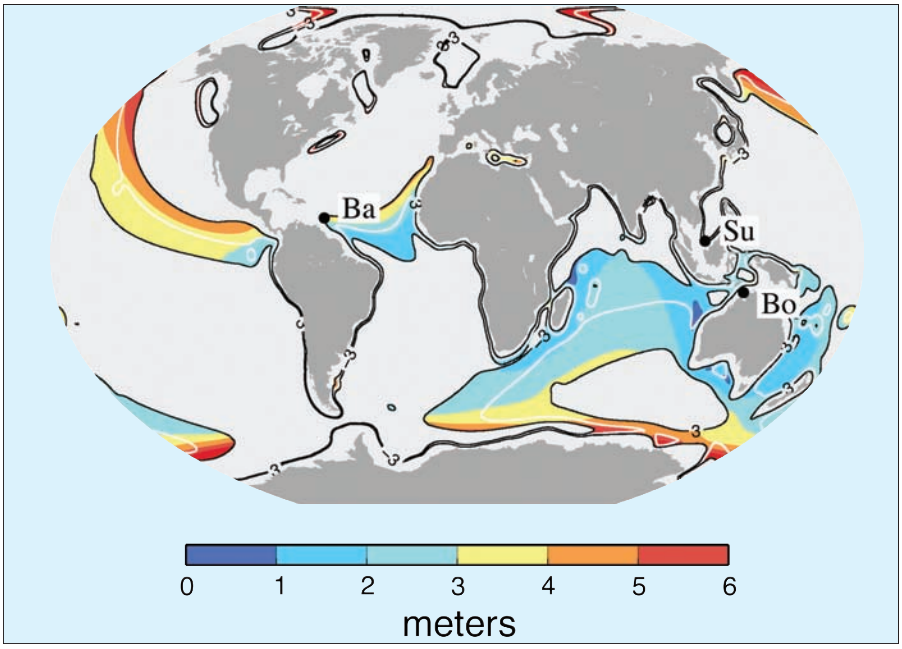

*Figure 1: Output for a large suite of model runs based on a single ice model and 162 Earth viscosity models. Results are shown for the Last Glacial Maximum (LGM; 21 cal ka BP). **White** contours indicate where the (mean) predicted sea level is equal to (mean) eustatic sea level. **Black** contours indicate where these values deviate by ±3 m (deviations > 3 m are masked by the light-gray shading). **Colored** contours show standard deviation of the predictions due to changes in Earth viscosity structure. Values of low standard deviation (blue colors) indicate where model predictions are insensitive to variations in Earth viscosity structure. Optimal localities for measuring sea level to estimate past ice volume are where the predicted sea level is close to the eustatic value (i.e., near the white contour) and the standard deviation is low (i.e., blue colors). Three locations where LGM sea levels have been measured are shown: Barbados (Ba), Bonaparte Gulf (Bo) and Sunda Shelf (Su). See Milne and Mitrovica (2008) for more details.*