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Abstract

The high amplitude Mi-1 oxygen isotope excursion (23 Ma) represents a major short-lived glaciation and coincides with major biotic turnovers. The main hypotheses for driving this glaciation are: a confluence of "cold-orbit" Milankovitch parameters, and/or ocean gateway-driven increased biological productivity resulting in lowered pCO_2. We propose a comprehensive view of the coupled hydrosphere-atmosphere-biosphere-cryosphere during the glaciation and subsequent recovery to test these hypotheses. As a pilot study, a new high-resolution record will provide a detailed picture of changing sea surface temperatures (SSTs), biotic changes, upper water column structure, and productivity before, during, and after the Mi-1 event at a single key subtropical site located at the margin of eastern boundary current in the southeast Pacific.

1. Introduction

1.1 Background: The Mi-1 oxygen isotope excursion at 23 Ma (Fig. 1) is similar to the major glaciation at the Eocene/Oligocene boundary (Oi-1 event) in several respects. For one, both anomalies occur in two steps separated by several hundred thousand years [Miller *et al.*, 1991; Paul *et al.*, 2000; Zachos *et al.*, 2001; Lear *et al.*, 2004]. However, the Mi-1 event is fundamentally different because it represents a *transient event* rather than a *transition* from the 'greenhouse' climate state of the Late Cretaceous-Eocene to the 'icehouse' climate state of the Oligocene-Quaternary. Like the Oi-1 event, there is abundant evidence that the Mi-1 event is coincident with "cold-orbit" Milankovitch parameters [Zachos *et al.*, 2001; Billups *et al.*, 2004; Wade and Pälike, 2004; Pälike *et al.*, 2006; Wilson *et al.*, 2009], but this alone is not enough to cause the large-scale glaciation event (*e.g.*, [DeConto *et al.*, 2008]). Understanding the drivers of the Oi-1 event has progressed rapidly with the combined efforts of geochemistry, modeling, and micropaleontology [DeConto and Pollard, 2003; DeConto *et al.*, 2008; Liu *et al.*, 2009]. A similar approach seems prudent for approaching the Mi-1 event.

Mi-1 cooling is recognized across a range of terrestrial and marine climate indicators, and is a time of accelerated biotic turnover in the continental interiors [Strömberg, 2005], in maritime [Larsson *et al.*, 2010], shallow marine [Edinger and Risk, 1994], and pelagic environments [Kennett and Srinivasan, 1982; Kamikuri *et al.*, 2005]. At the peak of Mi-1, benthic oxygen isotope values shift more than 1‰, coeval with a ~2°C cooling of deep waters [Paul *et al.*, 2000] determined by Mg/Ca paleothermometry [Lear *et al.*, 2004] (fig. 2). Astronomical calibration of high-resolution records with orbital solutions [Laskar *et al.*, 2004] across the O-M boundary places the boundary at 23.0 Ma [Shackleton *et al.*, 2000], with the peak of the isotope excursion following by ~100 kyr [Billups *et al.*, 2004; Wilson *et al.*, 2009].

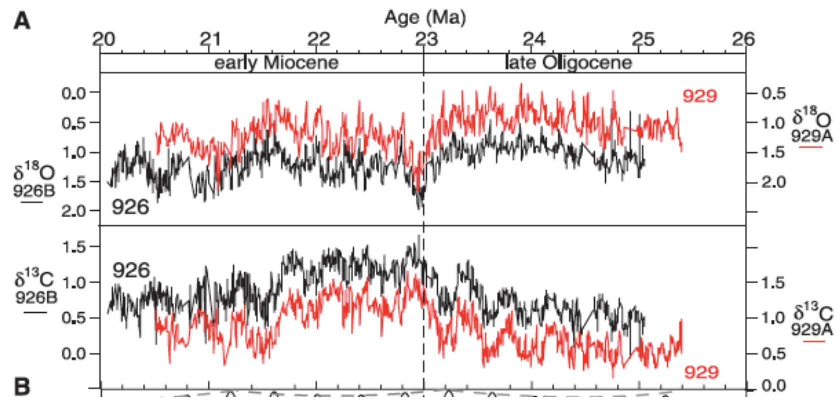

Fig. 1. Directly relevant to this proposal are tropical Atlantic Holes 926B (black) and 929A (red). Here benthic $\delta^{13}C$ and $\delta^{18}O$ records plotted

1.2 Hypothesis: We predict that productivity increased as a consequence of several factors including elevated weathering rates, perhaps associated with Himalaya-Tibetan Plateau uplift [Raymo, 1994], widening and deepening of Southern Ocean gateways and closure of Tethys (*e.g.*, [Lyle *et al.*, 2007]), and intensified trade winds and Southern Ocean divergence prior to the Mi-1 glaciation. We suspect that increased productivity, particularly in the tropics, was responsible for the major turnover of Caribbean corals [Edinger and Risk, 1994; Johnson *et al.*, 2008], tropical radiolarians [Kamikuri *et al.*, 2005], and other biota. Our sampling strategy will allow us to test whether changes in SSTs and/or productivity coincide with the Mi-1 event, and whether any of these parameters impacted the subtropical biosphere. Other hypotheses exist, such as changing flow direction through tectonic gateways [von der Heydt and Dijkstra, 2005; 2006], though these hypotheses only explain the tropical signal, not the global signal in the biota. Currently, the only high-resolution oceanic records of this event are in the tropical Atlantic and Southern Ocean [Zachos *et al.*, 2001; Billups *et al.*, 2002].

1.3 Proposal: In this study, we propose to generate a new high-resolution (3-kyr) record at ODP Site 1237 in the subtropical southeast Pacific in close collaboration with Yale (Pagani and Zhang). To resolve paleo sea-surface temperature (SST) estimates, a number of different proxies will be used: TEX_{86} and alkenones (to be performed at Yale), as well as Mg/Ca and $\delta^{18}O$ (UMass). These four methods of paleotemperature estimation each have their own strengths and weaknesses that we hope to address and avoid by using them in combination. As species-specific Mg/Ca calibration for extinct species is impossible, it might not be possible to resolve quantitative SSTs with confidence. However, we will still recover a ***qualitative*** temperature record, where we can examine the relative timing of changes as well as relative strength in the thermocline. As with all science, independent testing and corroboration of results is vital. The Yale team will also reconstruct $p\mathrm{CO}_2$ using ε_p.

To understand the changing biotic influence we will conduct planktic foram population analyses, allowing an investigation into the exact coeval nature of the biologic effects of the glaciation and, more importantly, the changing productivity signal. Multi-species $\delta^{13}C$ and $\delta^{18}O$ are vital to understanding water column structure and the carbon cycle. The location of Site 1237 at the edge of the eastern boundary current of the subtropical South Pacific gyre will tap into the influence of changing nutrient levels derived from the Southern Ocean as hypothesized here. Our multi-proxy paleotemperature collaboration with Yale will allow us to determine the magnitude of SST cooling, if any, concomitant with the purported drop in $p\mathrm{CO}_2$ levels associated with the Mi-1 glaciation. The multi-proxy approach also has the potential to deconvolve the ice volume and paleotemperature signals (the two main components of the measured $\delta^{18}O_{calcite}$) to determine the relative timing of glaciation versus any changes in SSTs in the subtropical southeast Pacific. Even without a robust quantitative temperature estimate, we will still be able to identify the growth of ice: an increase in $\delta^{18}O$ and no associated decrease in temperature is evidence for ice-sheet growth. Recovering the timing and sequence in paleotemperature and/or productivity events is a main thrust of this proposal.

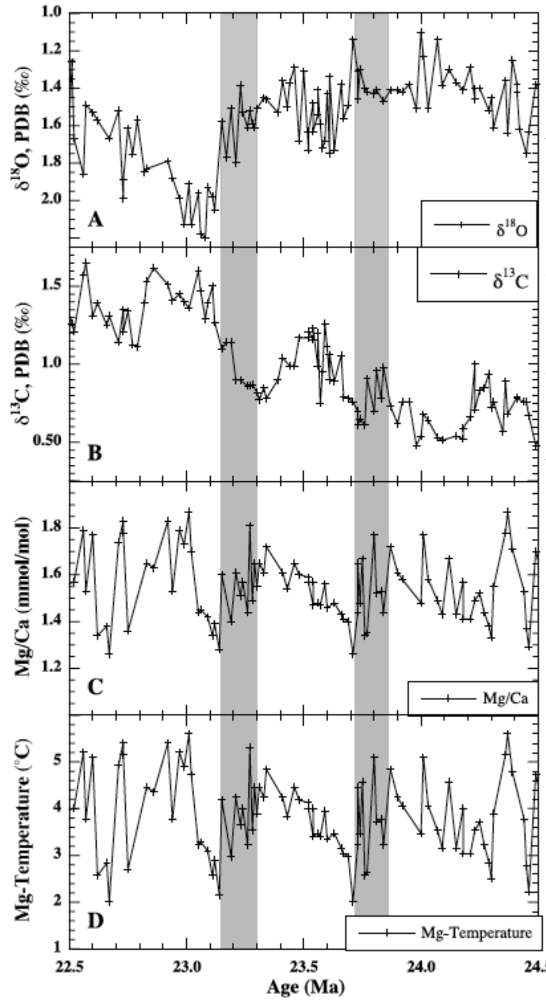

Fig. 2. Lower resolution study at tropical Pacific Site 1218 using benthic foraminiferal $\delta^{13}C$ and $\delta^{18}O$ and Mg/Ca data. Grey bars are intervals of Mg/Ca-derived temperature decrease. This record implies the cooling took place

2. Methods

2.1 Time slice target: We will target a 500-kyr window centered on Mi-1 (23.0 Ma). We plan to sample the body of the Mi-1 glaciation (~23.3-22.8 Ma) at higher resolution (up to ~3 kyr), with lower-resolution before and after Mi-1 (~25-21 Ma). This resolution is supportable based on the sedimentation rate of Site 1237 at this time [Shipboard Scientific Party, 2003].

2.2 Site Selection: We are focusing on a single site in the subtropical southeast Pacific. Modern location is the Peru Margin, however its paleo-position is under oligotrophic-mesotrophic conditions in the South Pacific gyre at the margin of the eastern boundary current. It has existing paleomagnetic and biostratigraphic control, which will be augmented by our own higher-resolution planktic foraminifera study. Initial IODP Reports [Shipboard Scientific Party, 2003] indicate moderate to good preservation of the forams, and preliminary investigation indicates the possibility of biomarker analysis [Pagani and Zhang, pers. comm.].

This site was also chosen to act as a 'bridge' site to two records of this event, examining their competing influences; Sites 926/929 and 1090 are from the Ceara Rise in the tropical Altlantic and Southern Atlantic, respectively (Fig. 1). These records from the Atlantic indicate a variety of climatic and biologic changes throughout the Mi-1 event, and by correlating a vastly different record, both in terms of oceanographic regime (oligotrophic-mesotrophic) and location (Pacific), we can expand our understanding of both the local and global extents of this event.

2.3 Biologic Data Gathering: Planktic foraminiferal population counts will be based on the >125 μm fraction; species depth ecologies have been established for the latest Oligocene-earliest Miocene interval [Pearson and Wade, 2009; Pearson *et al.*, 1997]. Mixed layer taxa dominate assemblages in low- to mid-latitude localities with a thick mixed layer, while thermocline taxa dominate assemblages in settings with a thinner mixed layer or seasonal shoaling of the thermocline and elevated productivity (*e.g.*, [Chaisson and Ravelo, 2000; Nathan and Leckie, 2009]). For the time series isotopic analyses, one benthic species, and three planktic species representing thermocline and mixed layer depth habitats will be picked. Time series analyses of select mixed layer and thermocline species allows us to determine relative changes in upper water column structure by measuring the changing oxygen isotope gradient between species.

2.4 Geochemical Proxies: A single species of epifaunal benthic foraminifera (*Cibicidoides* sp.) will be analyzed for $\delta^{13}C/\delta^{18}O$. Planktic foraminifera from restricted size ranges will be analyzed for their $\delta^{13}C/\delta^{18}O$ values. We recognize the potential for "vital effects" distorting the $\delta^{13}C$ and Mg/Ca proxies, but these effects, related to photosynthetic symbionts, are minimized by utilizing larger test sizes (e.g., 355-425 µm). A split of each crushed, homogenized sample will be used for $\delta^{13}C/\delta^{18}O$ analyses. Before analysis, a sample is ultrasonically cleaned and dried. Isotope analyses will be performed at UMass using a Finnigan Delta XL+ with a Kiel III automated carbonate preparation system, while trace-metal analyses on the mixed layer planktonic and epifaunal benthic foram will be performed at Yale's ICP-MS facility and clean lab.

An orbital analysis will be performed on the $\delta^{13}C_{benthic}$, $\delta^{18}O_{benthic}$, and Mg/Ca records at Site 1237. This will serve as a temporal foundation for all the geochemical data, as well as to permitting high fidelity correlation to existing records: Site 926/929 and 1090 [Billups *et al.*, 2002; Zachos *et al.*, 2001]. These correlations between sites are vital to test the synchronous nature of microfossil turnover and connections to temperature or productivity. Evidence for changing productivity in the oligotrophic-mesotrophic Site 1237 setting will be based on assemblage changes and carbon isotope gradients between mixed layer and thermocline planktic and benthic foraminiferal taxa, and carbonate mass accumulation rates (MAR).

3. Results and Further Significance

3.1 Expected Results: To simplify, we present our expected order of events in bullet form:

1. Pre-event productivity increase (evidence: $\delta^{13}C$ negative shift due to upwelling of nutrient-rich water, increase in % thermocline taxa in foram population counts, MAR)

2. Planktic foram evolutionary turnover (extinction plus originations) associated with productivity increase (evidence: changes in simple diversity)

3. SST cooling (evidence: Mg/Ca, $\delta^{18}O$, Yale paleotemperature estimates) and associated "cold-orbit" parameters (evidence: astronomically tuned $\delta^{13}C_{benthic}$ records)

4. Ice-sheet growth (*potentially recoverable* evidence: $\delta^{18}O_{sw}$ record)

5. Post-event SST warming (evidence: Mg/Ca, $\delta^{18}O$, Yale paleotemperature estimates)

3.2 Application and Significance: We propose to generate a high-resolution multi-species record of the Mi-1 event. This will be the first record of this interval to be able to examine water-column structure and productivity changes, and will be the first of South Pacific origin. It will allow us to demonstrate connections between the Southern Ocean and tropics, as well as the synchronicity/diachrony of many events throughout our study interval. With our fundamental chronology work, three proposed proxies, and our biological data we can understand many different aspects of the Mi-1. By combining our data with our collaborators SST and pCO2 estimates we can realize a relatively complete understanding of early Miocene climate near the Eastern Boundary Current of the South Pacific. This work would fit in a number of scientific journals, but some likely candidates include: *Palaeogeography, Palaeoclimatology, Palaeoecology (Paleo^3)*, *Paleoceanography*, and *Geology*.

This study is designed with a larger NSF proposal in mind, targeted to the Paleo Perspectives on Climate Change (P2C2) grant. The larger project ties together modelers (DeConto and Pollard), biogeochemists (Pagani and Zhang), and micropaleontologists (Fraass and Leckie) to address a single problem using different tools. This pilot proposal attempts to address the global impact of Mi-1. This fellowship would provide a young scientist with a portion of a fundamentally multi-disciplinary and highly collaborative experience. Because this research is a collaboration with biogeochemists at Yale as well as paleoclimate modelers at UMass, there is great potential for cross-pollination of ideas. The plan for the larger study will include data-driven modeling, as well as three additional sites (ODP 756, 926, and 1090) for multi-species foraminiferal work combined with other paleotemperature estimates, and up to 6 sites solely for TEX_{86} and alkenone paleotemperature estimates. By using a global distribution of ocean records, as well a multi-disciplinary approach, we hope to answer questions about the global carbon cycle, the extent of Mi-1 glaciation, feedback mechanisms, timing of biotic and surface ocean responses, and the ocean structure leading up to, during, and following this short-lived glaciation.

4.1 Summary Work Plan: Sampling (UMass & Yale), processing and extraction of biomarkers (Yale), census counts and picking of planktic foraminifera from Site 1237 (UMass)

- (First Semester) Sampling of Site 1237 at high resolution
- (First Semester) Foraminiferal population census counts and picking for multi-species stable isotopes and Mg/Ca at Site 1237 (UMass)
- (Second Semester) Analyses of foraminiferal calcite for $\delta^{13}C$, $\delta^{18}O$, and Mg/Ca (UMass), synthesis with Yale-generated paleotemperature data
- (Second Semester) Publication of results in scientific journal

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