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# Stable-isotope stratigraphy of the Pliocene–Pleistocene climate transition in the northwestern subtropical Pacific

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ABSTRACT

From Ocean Drilling Program (ODP) Site 1208 on Shatsky Rise below the Kuroshio Current Extension, we present the North Pacific's first orbital-scale benthic-foraminiferal $\delta^{18}O$ and $\delta^{13}C$ time series to span the Pliocene–Pleistocene climate transition. Excellent agreement between the Site 1208 $\delta^{18}O$ record and the global $\delta^{18}O$ stack of Lisiecki and Raymo (2005) provides orbital-scale age control and confirms continuous stratigraphy from 3.7 to 1.8 Ma at the single-hole site. Cross-spectral analysis of the $\delta^{18}O$ and $\delta^{13}C$ time series reveals that these are coherent to 80% confidence at the 41-kyr obliquity band prior to 3.3 Ma (glacial isotope stage M2) and increase to the 95% level thereafter. Throughout, $\delta^{18}O$ cycles consistently lead $\delta^{13}C$ cycles by ~3 kyr. This suggests that global-ocean $\delta^{13}C$ variations, as produced by terrestrial–marine $^{12}C$ transfers, were responsive to obliquity-induced climate changes before the Northern Hemisphere glaciations (NHG) reached mid latitudes at 2.7 Ma. In contrast, 41-kyr carbonate sedimentation (as derived from sediment reflectance) cycles, maxima tightly coupled to (>95% confidence) and in phase with minima in the $\delta^{18}O$ record, do not emerge until 2.7 Ma. Foraminiferal fragmentation counts indicate that carbonate preservation is not the primary process behind enhanced carbonate deposition during interglacials. Thus, we surmise that hydrography-related changes in biogenic opal and carbonate production in surface water best explain glacial–interglacial carbonate cycles beginning with significant NHG. Firm establishment of orbital-scale age control on the stratigraphically complete Site 1208 section now provides a platform for high-resolution paleoceanographic reconstruction of the relatively understudied North Pacific.



## 1. Introduction

The Pliocene–Pleistocene climate transition is characterized by the onset and intensification of extensive Northern Hemisphere glaciations (NHG) as evidenced by an increase in marine oxygen isotope ($\delta^{18}O$) values, beginning on average at 3.6 Ma (Mudelsee and Raymo, 2005), and a pronounced increase in ice-rafted debris in the North Atlantic (Jansen and Sjøholm, 1991) and North Pacific (Haug et al., 1995) at 2.7 Ma. Widespread Late Pliocene (3.3–3.0 Ma) warmth at middle and high latitudes relative to today (e.g. Chandler et al., 1994; Sloan et al., 1996; Lunt et al., 2010; Miller et al., 2010) is supported by records of marine microfossils and sediments, terrestrial vegetation, and sea-level reconstructions (Dowsett et al., 1996; Lisiecki and Raymo, 2005; Miller et al., 2005; Dowsett, 2007; Robinson, 2009; Sosdian and Rosenthal, 2009). Warm Pliocene climates with elevated $CO_2$ levels of 400 ppm (Pagani et al., 2010) have been receiving increased attention as possible analogues for future climate states. In recognition of global cooling with the onset of widespread NHG, the International Union of Geological Sciences recently (June 2009) redefined the Pliocene–Pleistocene boundary to include the Gelasian Age in the Pleistocene Epoch (Head et al., 2008; Ogg and Pillans, 2008).

Superimposed on the long-term trend toward cooler climates and more intense glaciations is strong 41-kyr variability in the marine $\delta^{18}O$ record (Lisiecki and Raymo, 2005, 2007) beginning at ~3 Ma (Raymo and Nisancioglu, 2003; Raymo et al., 2006). Because the marine $\delta^{18}O$ record incorporates high-latitude ice-volume and deep-ocean temperature changes (Shackleton, 1967; Shackleton and Opdyke, 1973; Sosdian and Rosenthal, 2009), this orbital-scale variability can be thought of as 41-kyr modulations in the mean climate state. Though some 30 $\delta^{18}O$ records from around the world ocean (the LR04 stack; Lisiecki and Raymo, 2005) establish this pattern of increasing 41-kyr variability, none is from the North Pacific. The deep North Pacific, as a "terminus" of the thermohaline circulation, a region of upward-directed overturn, may hold clues to important Pliocene–Pleistocene changes in deep ocean circulation (Kwiek and Ravelo, 1999; Ravelo and Andreasen, 2000) over the transition from small, ephemeral Northern Hemisphere glaciers of the Pliocene to the more glacially dominated Pleistocene climates. Additionally, detailed knowledge of this region's surface hydrography is critical for a more complete global perspective of climate change (Haug et al., 1995, 2005; Philander and Fedorov, 2003; Bralower et al., 2006).

At Ocean Drilling Program (ODP) Site 1208, located underneath the Kuroshio Current Extension, we present the North Pacific's first

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orbital-scale benthic-foraminifer $\delta^{18}O$ and $\delta^{13}C$ time series to span the Pliocene–Pleistocene climate transition. Excellent agreement between the Site 1208 $\delta^{18}O$ time series and the global $\delta^{18}O$ stack of Lisiecki and Raymo (2005) provides orbital–scale age control and confirms continuous sedimentation from 3.7 to 1.8 Ma. The evolution of spectral power in the $\delta^{18}O$ and $\delta^{13}C$ time series demonstrates response to obliquity forcing. Benthic-foraminifer $\delta^{13}C$ values, when compared against global-background $\delta^{13}C$ values as recorded at Site 849 (Mix et al., 1995), provide a means to assess basin-wide changes in carbon-isotope gradients during this climate transition. Together with shipboard measurements of changes in sediment lithology, the orbital-scale stable isotope records provide insights into the sensitivity of the subtropical northwestern Pacific Ocean to the expansion of Northern Hemisphere glaciers at 2.7 Ma.

## 2. Approach

### 2.1. Site location

At ODP Site 1208 on the central high of Shatsky Rise (36.1°N, 158.5°E, 3346 m water depth) core was recovered from a single hole (Fig. 1). The site samples a sediment drift composed of clay-rich nannofossil ooze (Bralower et al., 2002) beneath the modern-day Kuroshio Current Extension (Mizuno and White, 1983; Fig. 1). North Pacific Deep Water bathes the site, some 1000–2000 m below the core of the mid–depth southward return flow (Craig et al., 1981; Kroopnick, 1985; Reid, 1997; Schlosser et al., 2001). Shipboard magnetostratigraphy (Bralower et al., 2002) and calcareous nannofossil (Bown, 2005) and foraminiferal (Venti, 2006) biostratigraphies established robust age control for the upper Neogene section. The magnetostratigraphic (Bralower et al., 2002; Evans et al., 2005) age model indicated recovery of a complete Pliocene–Pleistocene section over which sedimentation rates increase from 35 m/my in the late Pliocene to 45 m/my in the early Pleistocene. Thus, the section is ideal for tuning to the standard $\delta^{18}O$ section of Lisiecki and Raymo (2005) (LR04), integrating the Site 1208 records into a global stratigraphic framework.

### 2.2. Sampling

We sampled 20 cc of sediment continuously every 10 cm from 86 m to 160 m below the sea floor, roughly one sample every 2500 years between 1.8 Ma and 3.7 Ma based on shipboard magnetostratigraphy (Bralower et al., 2002). Each sample was oven-dried, soaked in a hexametaphosphate solution buffered to a pH of 7.5, and washed over a 63-μm sieve using standard methodologies. From the sand-sized (>63 μm) fraction, between one and four tests (>212 μm) of the epifaunal benthic foraminifer *Planulina (Pl.) wuellerstorfi* were selected for isotope analysis. We chose *Pl. wuellerstorfi* for our time series for its predictable relationships to marine $\delta^{18}O$ and $\delta^{13}C$ (Belanger et al., 1981; Graham et al., 1981; Zahn et al., 1986; McCorkle and Keigwin, 1994) and its consistent presence in the Site 1208 Pliocene–Pleistocene section. The tests were sonicated in deionized water for 10 s to remove coccoliths and other clay-sized particles and then oven-dried for 12 h prior to stable-isotopic analysis.

### 2.3. Stable-isotope measurement

Stable-isotope analyses were conducted at the University of Delaware with the GV instruments IsoPrime dual-inlet mass spectrometer. The instrument is equipped with a Multiprep peripheral and used to perform automated reaction of up to 40 samples in individual vials with hot (90 °C) phosphoric acid. Oxygen and carbon isotopic values are corrected to the Peedee Belemnite standard using NBS-19 and Carrara Marble as in-house standards. For $\delta^{18}O$ values, analytical precision is better than 0.08‰; analytical precision for $\delta^{13}C$ is better than 0.05‰. To assess external reproducibility, we replicated measurements for some 100 sampling intervals. Duplicate (or triplicate for some intervals) values are on

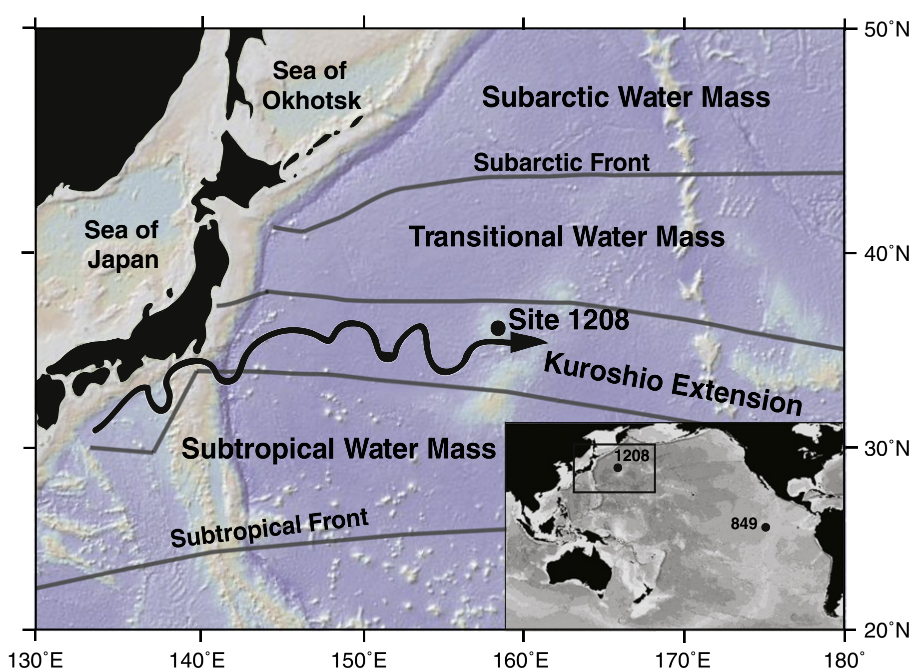


**Fig. 1.** Location of ODP Site 1208 in the northwest Pacific: surface water masses and bathymetry. The bathymetric basemap is generated using GeoMapApp (Haxby et al., 2006), a Java-based application available at www.geomapapp.org. The Kuroshio Current and extension is sketched to illustrate actual meander positions after daily Naval Research Laboratory forecasts. Its envelope is approximated from reconstructions of Mizuno and White (1983). Basin-wide bathymetry for the insert showing the location of the northwest Pacific region and eastern equatorial Pacific Site 849 is generated from the application at www.planiglobe.com.