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Changes in Pacific Ocean circulation following the Miocene onset of permanent Antarctic ice cover

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ABSTRACT

We integrate micropaleontological and geochemical records (benthic stable isotopes, neodymium isotopes, benthic foraminiferal abundances and XRF-scanner derived elemental data) from well-dated Pacific Ocean successions (15–12.7 Ma) to monitor circulation changes during the middle Miocene transition into a colder climate mode with permanent Antarctic ice cover. Together with previously published records, our results show improvement in deep water ventilation and strengthening of the meridional overturning circulation following major ice expansion at ~13.9 Ma. Neodymium isotope data reveal, however, that the provenance of intermediate and deep water masses did not change markedly between 15 and 12.7 Ma. We attribute the increased $\delta^{13}C$ gradient between Pacific deep and intermediate water masses between ~13.6 and 12.7 Ma to more vigorous entrainment of Pacific Central Water into the wind-driven ocean circulation due to enhanced production of intermediate and deep waters in the Southern Ocean. Prominent 100 kyr ventilation cycles after 13.9 Ma reveal that the deep Pacific remained poorly ventilated during warmer intervals at high eccentricity, whereas colder periods (low eccentricity) were characterized by a more vigorous meridional overturning circulation with enhanced carbonate preservation. The long-term $\delta^{13}C$ decline in Pacific intermediate and deep water sites between 13.5 and 12.7 Ma reflects a global trend, probably related to a re-adjustment response of the global carbon cycle following the last 400 kyr carbon maximum (CM6) of the "Monterey Excursion".

1. Introduction

The meridional overturning circulation (MOC) plays a key role in regulating global climate, as it strongly influences CO_2 storage in the deep ocean, latitudinal heat transport and gas exchange with the atmosphere. The ocean's density structure and the strength of the MOC are largely controlled by the source and rate of deep and intermediate water production. Thus, reconstructing past water mass distribution and changes in ocean circulation is critical for understanding long-term climate development and the processes driving climate change, as well as for predicting future trends. Comparatively little is known about the evolution of intermediate and deep water masses and the development of ocean circulation during the middle Miocene, when Earth's climate transitioned from relatively warm conditions ("Miocene Climatic Optimum") into a colder mode, characterized by permanent polar ice cover following Antarctic ice-sheet expansion.

Changes in the configuration of low latitude inter-oceanic passages altering water exchange and heat fluxes between the Pacific and Atlantic Oceans (Central American Seaway) and between the Tethys, Indian and Southern Oceans (eastern portal of Tethys Ocean) have been conjectured as the main drivers of long-term Miocene climate and oceanographic evolution (Woodruff and Savin, 1989; Wright et al., 1992; Heinze and Crowley, 1997; Nisancioglu et al., 2003; Motoi et al., 2005; von der Heydt and Dijkstra, 2006; Butzin et al., 2011). However, results from modeling experiments appear somewhat contradictory, and paleoceanographic reconstructions, based on paleontological and geochemical proxy data, are often poorly constrained, thus providing limited insights into the main processes controlling ocean circulation during middle Miocene warmer and cooler phases. In particular, the source of deep water formation and changing rates of the MOC on a warmer Earth without a fully developed Antarctic ice sheet remain matters of intense debate. These issues are specifically relevant to constrain contrasting scenarios of future climate evolution. Thus, the warmer middle Miocene period potentially provides a useful analog to test predicted changes in ocean circulation associated with global warming and melting of polar ice.

A major challenge for paleoceanographic and paleoclimate reconstructions that extend beyond the Pleistocene and Pliocene is that continuous, well-preserved marine sedimentary records are sparse and age models have large uncertainties. Here, we

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compare ventilation and water mass proxy data (benthic $\delta^{18}O$ and $\delta^{13}C$, radiogenic Nd isotopes, benthic foraminiferal distribution and XRF scanning Mn/Ca data) in well-dated, expanded sedimentary sequences from Pacific sites sampling different intermediate to deep water masses. We focus on the middle Miocene interval from 15 to 12.7 Ma, which includes the major Antarctic ice sheet expansion and global cooling step at ~13.9 Ma (Shackleton and Kennett, 1975; Savin et al., 1975; Woodruff and Savin, 1991; Wright et al., 1992; Flower and Kennett, 1993, 1995; Abels et al., 2005; Holbourn et al., 2005, 2007; Shevenell et al., 2004, 2008). Integration of new and published data sets from Southeast Pacific Ocean Drilling Program (ODP) Sites 1236 and 1237, western Equatorial Pacific ODP Site 806, central Equatorial Pacific Deep Sea Drilling Program (DSDP) Site 574, Southwest Pacific DSDP Sites 588 and 590, and Southern Ocean ODP Site 1171 allows to closely monitor water mass evolution and changes in the strength of the Pacific MOC following the major Antarctic ice sheet expansion marking the end of the middle Miocene warm period.

2. Pacific Ocean circulation

2.1. Modern oceanography

Today, the deep Pacific basin is mainly fed by Circumpolar Deep Water (CPDW), a mixture of Antarctic Bottom Water (AABW) and North Atlantic Deep Water (NADW) that originates from the Antarctic Circumpolar Current (Reid, 1986, 1997; Talley, 1993; Tsuchiya and Talley, 1996; Sigman et al., 2010). This deep water accumulates nutrients and loses oxygen as it transits northwards into the North Pacific before returning as a nutrient enriched, oxygen depleted southward flow (Pacific Central Water, PCW) at 1–3 km depth (Fig. 1). Deep water is not formed in the open North Pacific Ocean presently due to low salinity surface waters inhibiting convection (Warren, 1983; Emile-Geay et al., 2003; Kiefer, 2010). Pacific intermediate waters, which have their sources in the Southern as well as the Northern Hemispheres, exhibit highly contrasting properties (Fig. 1). The Antarctic Intermediate Water (AAIW) is a nutrient depleted water mass with high oxygen content and a high $\delta^{13}C$ signature that extends to ~15–20°S in the South Pacific Ocean and is centered at water depths of 800–1000 m (Kroopnick, 1985; Tsuchiya and Talley, 1996; Talley, 1999). The North Pacific Intermediate Water (NPIW), which originates in the northwest Pacific Ocean, spreads south to latitudes of 15–20°N in water depths of 400–700 m (Talley, 1993, 1997; You, 2003). In contrast to the AAIW, the NPIW forms with relatively little contact to the atmosphere and is thus characterized by abundant nutrients, low oxygen content and low $\delta^{13}C$ values. Radiocarbon ages from the North Pacific, Atlantic and Southern Oceans revealed that deep water ventilation changed markedly over the last glacial cycle (Sikes et al., 2000; Robinson et al., 2005; Galbraith et al., 2007; Marchitto et al., 2007), although patterns are more equivocal in other regions of the Pacific Ocean (Broecker et al., 2004, 2008). In the North Pacific and Atlantic Oceans, there is evidence that the abyssal ocean remained poorly ventilated during the Last Glacial Maximum and early deglaciation until vigorous NADW formation resumed at ~14.6 ka (Galbraith et al., 2007). This led to the suggestion that enhanced NADW formation near the start of the Bølling promoted an increased

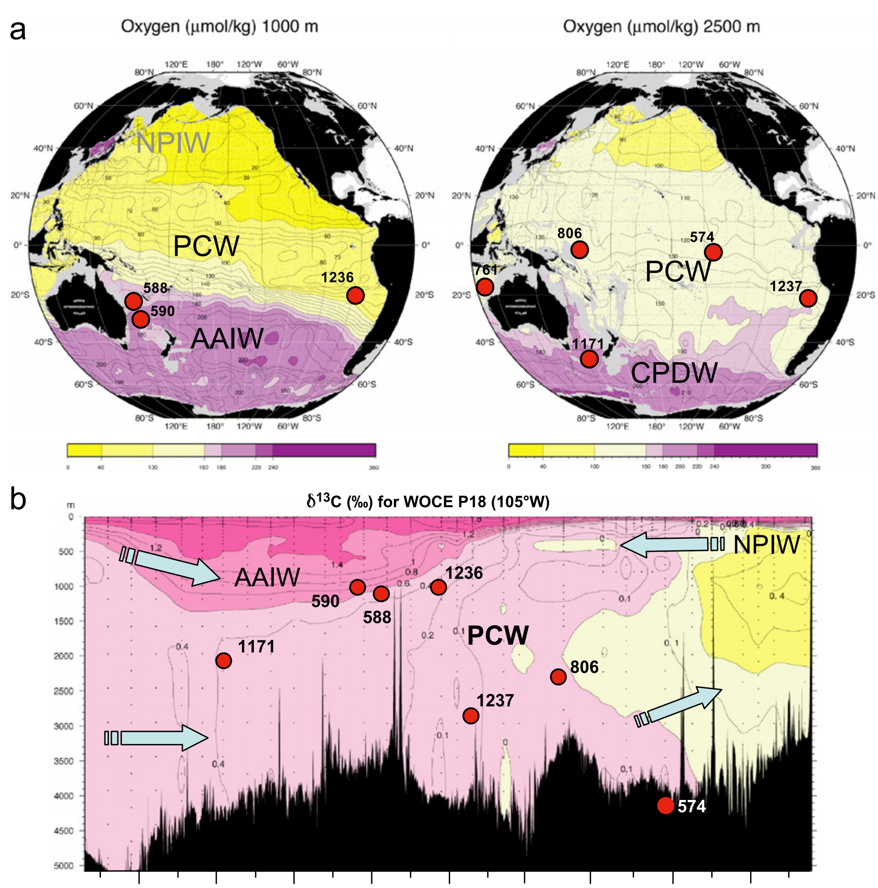

Fig. 1. (a) Modern O_2 distribution at 1000 m and 2500 m water depth in Pacific Ocean (Talley, 2007) and (b) vertical profile showing present day distribution of water masses in Pacific Ocean with locations of ODP Sites 1236 and 1237 and $\delta^{13}C$ (WOCE, Talley, 2007). NPIW: North Pacific Intermediate Water, PCW: Pacific Central Water, AAIW: Antarctic Intermediate Water, CPDW: Circumpolar Deep Water. Locations of sites discussed in text are shown.