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Reconstruction of oceanic circulation patterns in the tropical Pacific across the early/middle Miocene boundary as inferred from radiolarian assemblages

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ABSTRACT

Although there have been attempts to infer Neogene oceanic circulation patterns in the tropical Pacific on the basis of multiple marine proxies, oceanic circulation patterns across the early/middle Miocene boundary are still poorly understood despite paleoclimate having significantly changed during this interval. In this study, we reconstruct the changes in tropical oceanic circulation patterns in the Pacific across the early/middle Miocene boundary based on radiolarian assemblages obtained at Integrated Ocean Drilling Program Site U1335 in the eastern tropical Pacific.

The radiolarian upwelling taxa increased during four intervals (18.4–18.1 Ma, 16.9–15.7 Ma, 15.2–14.6 Ma, 14.2–13.4 Ma). Radiolarian temperature index (RTI) was calculated using the relative abundances of the warm water (cluster B1) and cool water taxa (cluster B2) in order to evaluate relative temperature fluctuations of the surface water. The sea surface temperature index was relatively high from 16.8 to 16.0 Ma and gradually decreased from 16.0 to 14.6 Ma. Subsequently, the temperature index decreased stepwise at 13.9 and 13.4 Ma and became relatively low from 13.4 to 12.7 Ma. Comparison of the RTI record in the eastern tropical Pacific to the climatic index based on the benthic foraminiferal $\delta^{18}O$ record shows that variability in the two records follows a roughly similar trend from the early to the middle Miocene. However, the sea surface temperature record does not indicate a sharp increase in warmth in the eastern tropical Pacific during the mid-Miocene climatic Optimum-1 (MMCO-1), as suggested by the benthic isotopic record. This is likely because of increased upwelling of cool, nutrient-rich water at this time.

Beginning in the latest early Miocene (~17 Ma) radiolarian assemblages were dominated by different taxa in the eastern and western tropical Pacific. This pattern is interpreted as indicating a shallower thermocline in the east and a deeper thermocline in the west, based on the relative abundance of the upwelling taxa. There is an overall increasing trend in this difference since the latest early Miocene. We tie these events to the effective closure of the Indo-Pacific seaway and the development of a substantial western Pacific warm pool along with the development of a strong Equatorial Undercurrent.

1. Introduction

Oceanic circulation patterns in the tropical Pacific changed significantly throughout the Neogene (Kennett et al., 1985; Moore et al., 2004; Kamikuri et al., 2009a; Nathan and Leckie, 2009; Rousselle et al., 2013). Kennett et al. (1985) reconstructed surface water circulation patterns in the tropical Pacific Ocean based on biogeographic patterns of planktonic foraminifera for three time periods: the early Miocene (22 and 16 Ma) and the late Miocene (8 Ma). In the early Miocene (22 and 16 Ma), distinct faunal assemblages were present in the western and eastern areas, and an east-west thermocline depth gradient was suggested to occur throughout the tropical Pacific Ocean, with a relatively shallower thermocline in the eastern tropical Pacific and a deeper thermocline in the west. The relatively sluggish equatorial circulation, the absence of the Equatorial Undercurrent (EUC), and a weak North Equatorial Countercurrent (NECC) allowed distinct paleoceanographic (biogeographic) differences to develop between the east and west (Kennett et al., 1985). By the late Miocene, the east-west differences in foraminiferal assemblages had largely disappeared across the entire tropical Pacific, and these changes were interpreted as reflecting the development of the EUC and ECC systems due to the effective closure of the Indonesian Seaway (Kennett et al., 1985). The closure of the

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Indonesian Seaway created a pile-up of surface waters in the western tropical Pacific and hence the development of the easterly flowing EUC, along with a deeper thermocline depth in the western tropical Pacific. The barriers also induced a strengthened ECC between the early Miocene (16 Ma) and the late Miocene (8 Ma) (Kennett et al., 1985). Subsequent studies with more precise age control suggested that major oceanic circulation changes in the tropical Pacific occurred in the earliest late Miocene (ca. 11.5–10.0 Ma) (Chaisson and Leckie, 1993; Jian et al., 2006; Li et al., 2006; Kamikuri et al., 2009a; Nathan and Leckie, 2009). The circulation patterns changed significantly from a state resembling El Niño (warm eastern tropical Pacific) in the late Miocene and early Pliocene to a state resembling La Niña (cool eastern tropical Pacific) starting in the late Pliocene. The deepening of the thermocline depth in the western tropical Pacific and the reduction of Eastern Pacific Warm Pool occurred at about 4.2 Ma (Cannariato and Ravelo, 1997; Jian et al., 2006; Li et al., 2006; Sato et al., 2008; Kamikuri et al., 2009a). However, changes in oceanic conditions from the early to middle Miocene are still poorly understood even though this is an important interval during which paleoclimate changed significantly. The lack of information about this period is attributable to the increased carbonate dissolution in the tropical Pacific obscuring the assemblage changes in carbonate microfossils, which were traditionally used as proxies to reconstruct oceanic circulation patterns (Keller, 1981; Barron et al., 1985; Lyle, 2003; Mitchell et al., 2003; Pälike et al., 2012).

The purpose of this study is to reconstruct the changes in oceanic circulation patterns from 20 to 12.5 Ma across the early/middle Miocene boundary based on well-preserved radiolarian assemblages, using data from Integrated Ocean Drilling Program (IODP) Site U1335.

2. Paleoclimatic history through the early to middle Miocene interval

The early/middle Miocene boundary represents a time of major climatic change during the Neogene (Woodruff and Savin, 1989; Wright et al., 1992; Flower and Kennett, 1994; Zachos et al., 2008). The early Miocene was characterized by a significantly warmer climate than at present, particularly at high latitudes. Based on benthic foraminiferal oxygen isotope data, a peak in deepwater temperatures was recorded at 17–15 Ma, at what is called the Mid-Miocene Climatic Optimum (MMCO) (Flower and Kennett, 1994; Zachos et al., 2008). During the MMCO, tropical/subtropical organisms extended their ranges to the mid-to-high latitudes (Wolfe, 1985; Yamanoi, 1992; Ogasawara et al., 2008; Yabe, 2008), and the sea surface temperatures (SSTs) based on oxygen isotope records, TEX86 and Uk'37, were 27–30 °C in the tropical Indian Ocean (Stewart et al., 2004), 28–30 °C in the tropical Atlantic (Zhang et al., 2013), and 27–29 °C in the eastern tropical Pacific (Rousselle et al., 2013). The MMCO corresponds with the mid-Neogene climatic optimum of Tsuchi (1987) and the climatic optimum 1 of Barron and Baldauf (1990). The mid-Neogene climatic optimum was subdivided into two intervals (lower and upper) by the Miocene isotope (Mi) 2 event (Irizuki et al., 1998).

After the MMCO, a significant positive shift was recorded in benthic foraminiferal oxygen isotopes, which was called the Middle Miocene Climatic Transition (MMCT). This significant shift was associated with the growth of the East Antarctic Ice Sheet (Flower and Kennett, 1994; Zachos et al., 2008), abrupt major global cooling (Zhao et al., 2001; Billups and Schrag, 2002; Shevenell et al., 2004; Lear et al., 2010), global hiatuses (Keller and Barron, 1983; Woodruff and Savin, 1989; Kamikuri et al., 2004) and major turnovers in faunal and floral assemblages (Wei and Kennett, 1986; Barron, 2003; Thomas, 2007; Kamikuri et al., 2007, 2009b; Pound et al., 2012). These oceanographic/climatic changes were accompanied by the Monterey Carbon Excursion from the late early Miocene to middle Miocene, which is characterized by several distinct $\delta^{13}C$ maxima related to large-scale organic carbon-rich sedimentation in upwelling areas (Vincent and Berger, 1985; Woodruff and Savin, 1991; Flower and Kennett, 1994).

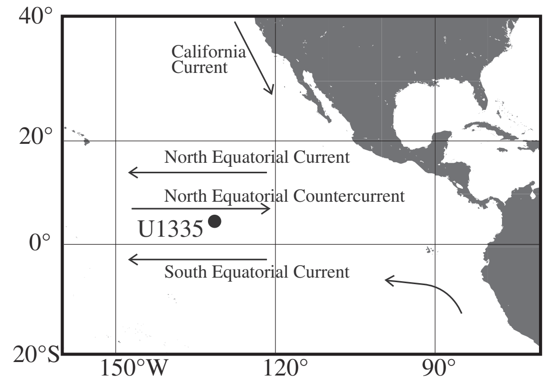

Fig. 1. Location of IODP Leg 320 Site U1335 and modern oceanographic currents in the eastern tropical Pacific.

3. Oceanographic setting of the tropical Pacific

In the modern ocean, the eastern tropical Pacific is one of the major upwelling areas and supports a significant proportion (18–56%) of the new biological production globally (Chavez and Barber, 1987). This high productivity not only raises the sedimentation rates of calcareous and siliceous ooze but also increases the amount of organic matter on the seafloor. Consequently, biological production in the eastern tropical Pacific plays a significant role in the global carbon cycle.

The eastern tropical Pacific Ocean is situated between the subtropical gyres of the North and South Pacific. In this region, the eastern boundary currents (the California and Peru Currents) turn west and run parallel to the equator until they merge with the North and South Equatorial Currents (NEC and SEC, respectively) (Wyrtki, 1966, 1967; Fiedler and Talley, 2006; Kessler, 2006; Pennington et al., 2006) (Fig. 1).

The NEC is formed by water from the California Current and flows from east to west roughly centered on 15°N in the tropical Pacific (Wyrtki, 1966; Kessler, 2006). The westward NEC bifurcates with part of the flow returning poleward at the start of the western boundary currents (the Kuroshio Current) and part turning equatorward to eventually feed the North Equatorial Countercurrent (NECC). The NECC flows eastward across the tropical Pacific roughly centered on 7°N between the NEC and SEC.

The SEC is driven by the southeast trade winds in the South Pacific Ocean and flows westward roughly centered on 2°S (Kessler, 2006; Pennington et al., 2006). The southeasterly trade winds cross the equator, and with the change in sign of the Coriolis effect, they induce an Ekman divergence that transports surface waters away from the equator in both hemispheres and consequently produces strong equatorial upwelling (Kessler, 2006).

The band of cool surface water, which occurs from about 3°S to 3°N and across the eastern and central tropical Pacific is called the equatorial "cold tongue" (Fiedler and Talley, 2006; Kessler, 2006; Pennington et al., 2006). In the equatorial cold tongue, surface nitrate and phosphate concentrations are generally high relative to those to the south and north of the equator. This upwelling also induces a shallower thermocline depth in the eastern Pacific than in the western Pacific (Jin, 1998).

The Equatorial Undercurrent (EUC), which flows eastward under the SEC, is centered on the equator. The EUC rises along the sloping thermocline from west to east, bringing an admixture of cool water close to the surface, which adds to the biologically important mechanism of nutrient upwelling along the equator (Wijffels, 1993; Kessler, 2006; Pennington et al., 2006) and feeds into the upwelling off Peru (Toggweiler et al., 1991).