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# Orbital obliquity cycles recorded in Kuroshio Current region, eastern Asia, around Plio–Pleistocene boundary

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ABSTRACT

Global climate underwent a period of significant cooling at the Plio–Pleistocene Transition (~2.6 Ma). The influence of this change on the Kuroshio Current region in the Pacific Ocean, off eastern Asia, is not well known. In this study, we clarify temporal changes in the paleoenvironment under the influence of the Kuroshio Current during the late Pliocene and early Pleistocene using high-resolution faunal proxy records of fossil Ostracoda (Crustacea). The study unit is the Ananai Formation in the southeastern region of Shikoku, southwest Japan. The modern analog technique (MAT) is employed for the quantitative estimation of paleo-bottom water temperatures (PBWTs) and paleo-water depth (PWD) during the deposition of the formation. Ostracode MAT results show PBWT fluctuations during warmest and coldest months, with values of 16°C–20 °C and 12°C–16 °C, respectively, and a PWD of 70–140 m, reflecting sea-level oscillations. Moreover, the PBWT in the coldest month is 3 °C–4 °C lower than present-day water temperatures at the same shallow water depths. Temporal changes in these paleoenvironmental variables based on MAT are in good agreement with global oxygen isotope records. Orbital obliquity cycles with 41-kyr periodicity are recorded for the first time in an onshore section in the Kuroshio Current region at the Plio–Pleistocene boundary interval.



## 1. Introduction

The Kuroshio Current is one of the strongest warm currents and flows in the northwest Pacific Ocean, off southwest Japan. The current is characterized by high temperature, high salinity (Barkley, 1970), and low biological productivity (Qiu, 2001). At the same time, it advects a large amount of heat from the tropics to northern mid-latitudes (Sawada and Handa, 1998) and has been significantly influencing the marine climate and organisms in eastern Asia for millions of years (Gallagher et al., 2015).

Despite the importance of determining the conditions of the paleo-Kuroshio Current, only a few studies have been conducted on Plio–Pleistocene formations deposited in the current's path (e.g., Iwatani et al., 2012). High-resolution quantitative proxy records from the Kuroshio Current region can provide essential insights for the synthetic understanding of western Pacific Plio–Pleistocene climates.

The modern global climate regime began to formulate around the Plio–Pleistocene boundary with the intensification of Northern Hemisphere glaciation (Pillans and Naish, 2004; Raymo et al., 2006) because of the restriction of low-latitude seaways and the influence of the seaways on oceanic heat transport (Ravelo et al., 2004). The climate was cooler compared with the present-day climate and characterized by a change in the large amplitude and short cycles of glacial–interglacial intervals, derived from 41-kyr orbital obliquity cycles (Sosdian and Rosenthal, 2009).

This changing climate from the late Pliocene to early Pleistocene was recorded in various studies. For example, the emergence of ice-rafted debris was observed at high latitudes (Maslin et al., 1995; Shackleton, 1997), and the presence of a cold-water calcareous nannofossil species drastically increased in North Pacific marginal seas in mid-to high-latitude regions (Sato et al., 2004). In the terrestrial sedimentary record, the deposition of desert loess in the Chinese Loess Plateau began from ~2.6 Ma, possibly connected with desert expansion resulting from the intensification of the East Asian winter monsoon (Ding et al., 2005). In seas adjacent to Japan, a

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branch of the Kuroshio Current repeatedly flowed into and intercepted the Japan Sea during the Plio–Pleistocene and rapid cooling apparently occurred at ~2.75 Ma in many areas around the Japan Sea (e.g., Yamada et al., 2005).

This study aims to reconstruct bottom water conditions around the Plio–Pleistocene boundary in the Kuroshio Current region, eastern Asia, from fossil ostracode assemblages, which are an effective environmental indicator. Ostracodes used here were obtained from the Ananai Formation, southwest Japan, which is typical of shallow marine deposits in Pacific coastal areas (Fig. 1).

## 2. Studied sections and materials

The Plio–Pleistocene Ananai Formation is sporadically distributed on the Muroto Peninsula, Shikoku, southwest Japan. The formation is mainly composed of poorly sorted siltstones and silty sandstones with intercalated conglomerate layers and shell beds (e.g., Iwai et al., 2006). According to Matsubara (2004), based on a compilation of biostratigraphic studies, the Ananai Formation is placed between calcareous nannofossil biozones CN12b and CN12d (Okada and Bukry, 1980) and assigned to planktic foraminifera zone N21 (Blow, 1969); the chronostratigraphic age is 2.78 or 2.73–1.97 Ma.

A drill core of ~70-m length (recovery rate 96%) was obtained in 2006 from the Ananai Formation (ANA-1, latitude 33° 26′ N, longitude 133° 57′ E) in the southern part of the Muroto Peninsula (Fig. 1). Iwai et al. (2009) determined that a reversed–normal polarity transition occurred at 28-m depth in the core, which can be assigned to the Gauss–Matuyama polarity boundary (2.608 Ma; Lisiecki and Raymo, 2005). In the present study, we focused on horizons in the middle to upper part of the core (~20-m thick), which exhibit especially clear sedimentary cycles, corresponding to the Plio–Pleistocene boundary. The study sequence is lithologically divided into five units (units 1–5 in the ascending order, Fig. 2). At the base of each unit, thin granule conglomerates that are rich in mollusks are intercalated with siltstones. According to Kondo et al. (2006), these lithological units can be correlated with transgressive–regressive cycles based on mollusk assemblages.

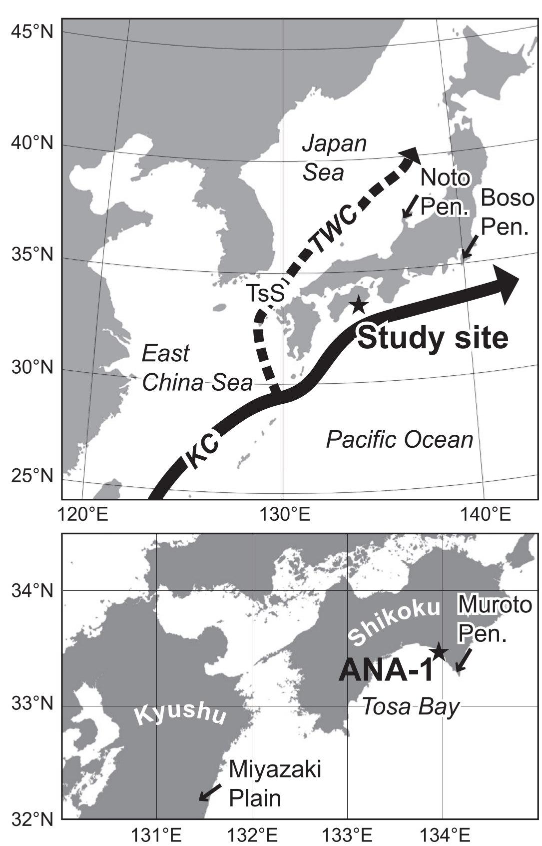


**Fig. 1.** Location of the study site, borehole ANA-1 in Ananai, southwest Japan. KC: Kuroshio Current, TWC: Tsushima Warm Current, and TsS: Tsushima Strait.

## 3. Ostracode analysis

More than 150 ostracode species were recorded in the study sequence. For fossil ostracode analyses, dried sediment samples (12–60 g) were weighed and disaggregated using sodium sulfate and naphtha methods (Maiya and Inoue, 1973). Residues were divided using a sample splitter, and 150–250 specimens were handpicked from residues coarser than 0.125 mm. Note that the number of specimens refers to the sum of left and right valves. One carapace was counted as two valves.

We plotted the total ostracode abundance in the studied sediments on the geologic column (Fig. 2), expressed as the number of ostracodes per gram of dried sediment.

### 3.1. Modern analog technique

To obtain firm estimates of paleo-bottom water environmental variables for the study site, we used the modern analog technique (MAT; Guiot, 1990). In previous studies, this method was successfully applied for the analysis of ostracode assemblages (Ikeya and Cronin, 1993; Cronin et al., 1994; Tanaka and Nomura, 2009; Iwatani et al., 2012). In this study, we employed the modern ostracode and modern climate datasets compiled by Iwatani et al. (2012). The ostracode dataset comprises 338 surface samples obtained from water depths of 0–986 m; the climate dataset was obtained from the Japan Oceanographic Data Center (J-DOSS, 2013), representing averages for 1874–2001. The climate dataset adopts three climate variables: bottom water temperature in the warmest month (BWTw), bottom water temperature in the coldest month (BWTc), and water depth.

We used a squared-chord distance (SCD) as a dissimilarity coefficient value (Prentice, 1980), which was calculated using the following equation:

$$d_{ij} = \Sigma(p_{ik}^{1/2} - p_{jk}^{1/2})^2$$

where $d_{ij}$ is the dissimilarity coefficient value between two samples $i$ and $j$ and $p_{ik}$ is the proportion of ostracode species $k$ in sample $i$. SCD values were calculated using Visual Basic for Applications in Microsoft Excel 2013. SCD values ranged from 0 to 2 for $0.0 < p_{ik} < 1.0$.

In the present study, climate variables reconstructed for eight best modern analogs were averaged by a weighting inverse to the SCD (Nakagawa et al., 2002). The weight function $w_1$ (x) is defined as follows:

$$w_1\,(\mathrm{x}) = |x|^{-1}$$

### 3.2. Q-mode factor analysis

We performed Q-mode factor analysis (CABFAC, Klovan and Imbrie, 1971) to reconstruct the evolution of the bottom water environment. Factor analysis is commonly used in micropaleontology to reveal and interpret common factors that affect assemblages. It was recently successfully applied in ostracode assemblage