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Migration of the Kuroshio Extension in the Northwest Pacific since the Last Glacial Maximum

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ABSTRACT

The $\delta^{18}O$ values of planktic and benthic foraminifera and faunal assemblage of planktic foraminifera were investigated at a Northwest Pacific site (32°16′N, 158°13′E; 2514 m water depth) to understand the oceanographic changes in the Kuroshio Extension (KE) region over the past 23 kyr. The $\delta^{18}O$ differences between species and the relative abundances of the dominant planktic foraminiferal species have not changed greatly over the study period, suggesting that the subarctic boundary and the subarctic–subtropical transition zone have remained north of study site, while the study site itself has been under the influence of KE. Nevertheless, increased abundances of foraminiferal taxa that populated the subarctic–subtropical transition zone during the last glacial maximum (LGM) indicate the input of transition zone water through the KE, manifest as meandering cold-core ring eddies generated along the KE. Since this unstable surface environment is most pronounced along the main axis of the KE, it could have been induced by the southward displacement of the KE main axis to the vicinity of the study site, in tandem with the overall southward displacement of the Kuroshio–Oyashio Extension system during the LGM. The input of transition-zone water mass has also increased during the deglacial Northern Hemisphere cold intervals (i.e., Heinrich Stadial 1 and the Younger Dryas), suggesting that the strengthened surface wind system regulated the surface ocean condition. This demonstrates that the northern high latitudes are the dominant control on post-glacial oceanographic changes in the Northwest Pacific KE region.

1. Introduction

The Kuroshio Current (KC) is the western boundary current of the subtropical gyre in the North Pacific. The KC enters the open basin of the North Pacific Ocean off the east coast of Japan where it becomes the Kuroshio Extension (KE). The KE is an eastward-flowing inertial jet comprising the northern boundary of the North Pacific subtropical gyre accompanied by large-amplitude meanders and energetic pinched-off eddies (Fig. 1) (Qiu, 2001). The KE and the Oyashio Extension (OE), the eastward extension of the subarctic Oyashio Current (OC), converge off the east coast of Japan and form the subarctic boundary (SAB), defined as a boundary between subtropical and subarctic gyres (Itoh and Yasuda, 2010; Yasuda, 2003) (Fig. 1). The KE and adjacent boundary system have been extensively investigated and discussed for its significant impact on climate over adjacent continents.

The location of the KE changes meridionally on interannual to decadal time scales (Frankignoul et al., 2011; Qiu, 2000; Qiu and Chen, 2005; Seager et al., 2001). The KE system has also migrated southward or northward in the geologic past in response to global climate change over the millennial to glacial/interglacial cycles. For instance, Thompson (1981) and Thompson and Shackleton (1980) suggested that the boundary region of the subtropical-subarctic gyre migrated southward during the glacial periods of the late Pleistocene, as inferred from planktic foraminiferal assemblages in sediment cores from the western Pacific. Subsequent studies have sought to understand the paleo-position of the KE and SAB in the Northwest Pacific using proxy records of cores from topographic highs (e.g., Emperor Seamounts, Hess Rise, and Shatsky Rise) (Harada et al., 2004; Kawahata and Ohshima, 2002; Ohkushi et al., 2000; Ujiié, 2003; Yamane, 2003). These studies proposed that the SAB migrated southward relative to its present position during the LGM, based on abrupt down-core changes in sea surface temperature (SST) within sediment cores collected from the OE and SAB regions (Harada et al., 2004). However, the nature of past changes in the physical and biological properties, and paleo-location and spatial extent of the KE are not clearly understood. The eastward broadening of the KE due to bifurcation at ~159°E (Kuroshio Extension Bifurcation, KEB) and its strong meandering create a broad transition zone between the subarctic and subtropical gyres east of the Shatsky Rise (Fig. 1),

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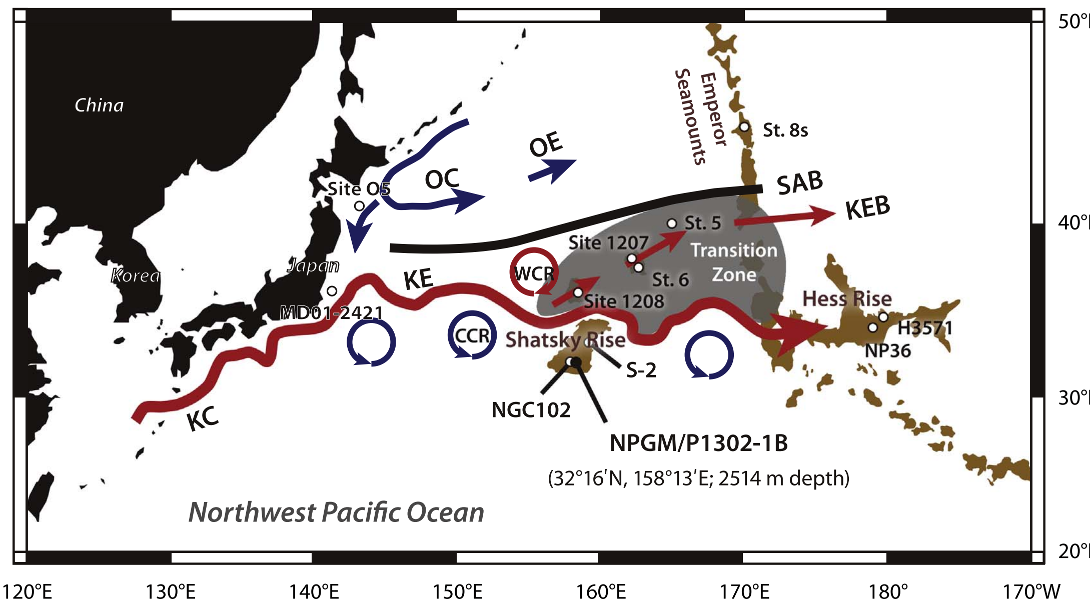

Fig. 1. Locations of sediment cores discussed in the text: NPGM/NPGP1302-1B (this study), MD01-2421 (36°01′N, 141°47′E), Site O5 (41°07′N, 143°31′E) (Oba and Murayama, 2004), NGC102 (32°20′N, 157°51′E) (Ohkushi et al., 2000), S-2 (33°22′N, 159°08′E) (Yamane, 2003), NP36 (34°12′N, 179°15′E) (Ujiié, 2003), H3571 (34°54′N, 179°42′E) (Kawahata and Ohshima, 2002), ODP sites 1208 (36°08′N, 158°12′E) and 1207 (37°47′N, 162°45′E) (Bralower et al., 2002), and Stations 5 (40°00′N, 165°04′E), 6 (37°45′N, 162°43′E), and 8 s (44°47′N, 170°10′E) (Harada et al., 2004). The brown-shaded area represents the oceanic rises and seamounts with water depths < 4000 m. Also shown is a schematic summary of the main hydrographic features of the Northwest Pacific. OC, OE, KC, KE, KEB, SAB, CCR, and WCR stand for the Oyashio Current, the Oyashio Extension, the Kuroshio Current, the Kuroshio Extension, the Kuroshio Extension Bifurcation, the subarctic boundary, a cold-core ring, and a warm-core ring, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where a weak meridional SST gradient makes it difficult to trace subtle movements of the frontal system (Qiu and Chen, 2005). These complex features have resulted in previous studies of the glacial–interglacial migration of the KE yielding conflicting results. For example, analyses of planktic foraminiferal assemblages and oxygen isotope compositions have suggested no distinct changes in water mass characteristics (Ujiié, 2003; Yamane, 2003), whereas benthic foraminiferal assemblages indicate the increased influence of the cold-component water during glacial periods (Ohkushi et al., 2000), despite the similar latitudes examined in these studies.

The present study aims to address the possible movement of the KE since the LGM, and its environmental consequences in the KE region. For this purpose, we collected piston and multiple cores at a site on the Southern High of Shatsky Rise (32°16′N, 158°13′E; 2514 m water depth), near the southern limit of the present-day KE path. We investigate the faunal assemblages of planktic foraminifera and the stable oxygen isotope compositions ($\delta^{18}O$) of three planktic foraminiferal species (*Globigerinoides ruber*, *Neogloboquadrina incompta*, and *Globorotalia inflata*) and a benthic species (*Uvigerina* spp.) since the LGM. This approach allows us to reconstruct the temporal evolution of the surface ocean environment associated with the movement of the KE at the study site, while also interpreting the maximum extent of southward displacement of the KE during the LGM. In addition, this study provides an opportunity to address the past movement of a frontal system during the deglacial Northern Hemisphere cold intervals such as the Heinrich Stadial 1 (HS1, 18–15 ka) and the Younger Dryas (YD, 12.8–11.5 ka).

2. Study sites and samples

Sediment cores NPGM 1302-1B (24 cm long) and NPGP 1302-1B (613 cm long) were recovered using a multiple corer and a piston corer, respectively, from the Southern High of Shatsky Rise in the Northwest Pacific (32°16′N, 158°13′E; 2514 m water depth) during the NPG 1302 cruise carried out by the Korea Institute of Ocean Science and Technology (KIOST) in 2013 (Fig. 1). Because some sediment disturbance during piston coring occurred at the sediment–water interface, the uppermost part of the piston core was substituted by the sampled multiple core (see Section 3).

The study site is located near the southern limit of the present-day KE, with its main axis centered at 34–35°N. Nevertheless, its path widens due to meandering to 32°N at ~165°E (Joyce, 1987; Qiu and Chen, 2010). Good preservation of calcareous microfossils in association with relatively high sediment accumulation rates is promoted by the elevated topography of the Shatsky Rise, which is ~3000 m shallower than the surrounding basin. The carbonate fraction makes up 65%–70% on the core top of NPGM/P 1302-1B, and it shows a gradually decrease down-core to a minimum of ~50% at the LGM. The contribution of inorganic silicate increases down-core to 27%, with a minor contribution of biogenic silica (< 4%).

3. Analytical methods

The study cores were subsampled in plastic bottles at an interval of 1 cm and freeze-dried for storage. Planktic foraminiferal assemblages were determined from at least 300 tests picked from the > 125 μm fraction of each sample. The foraminiferal species were identified based on Kennett and Srinivasan (1983), Saitō et al. (1981), and Ujiié and Ujiié (2000).

The $\delta^{18}O$ composition of planktic foraminifera records the physical and chemical conditions of the habitat depths at which they built their calcite tests. Based on the known habitat depths in the middle latitudes and the abundances of individual species in the studied core, three planktic foraminiferal species (*Globigerinoides ruber*, *Neogloboquadrina incompta*, and *Globorotalia inflata*) were chosen for analyses as the proxies of surface mixed layer, upper thermocline and the middle thermocline, respectively (Sagawa et al., 2011; Rebotim et al., 2017). These three planktic species and a benthic species (*Uvigerina* spp.) were picked from the > 250 μm fraction for $\delta^{18}O$ analysis. To avoid size-specific bias in isotopic composition (Ezard et al., 2015; Friedrich et al., 2012; and references therein), a single species was measured from a restricted size range (250–300 μm for *G. ruber* and *N. incompta*, and