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Horizontal and vertical distributions of planktic foraminifera in the subarctic Pacific

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ABSTRACT

Observations of the horizontal and vertical distributions of modern planktic foraminifera facilitate formation of ecological and geochemical inferences derived from the study of foraminiferal shells. In this study, we used plankton tows to collect planktic foraminifera at nine sites distributed longitudinally throughout the subarctic Pacific. A total of nine planktic foraminiferal species were identified. The horizontal distributions of the foraminiferal assemblages could be assigned to four regions. Characteristics of the foraminiferal assemblages and the horizontal distributions of their shell sizes appeared to be influenced by the sea-surface structure within each water mass. The vertical distributions of *Globigerina bulloides* and *Globigerina quinqueloba* were associated with the depth of the pycnocline; those of *Neogloboquadrina pachyderma* and *Neogloboquadrina incompta* were different and appeared to reflect a significant difference of optimum habitat temperatures. Based on the vertical distribution of shell sizes, we found evidence of vertical migrations during shell growth of *G. bulloides* and *N. incompta*. This information about the distribution of modern planktic foraminifera will facilitate reconstruction of past oceanographic conditions based on geochemical proxies in the subarctic Pacific.

1. Introduction

Planktic foraminifera are oceanic unicellular protozoa. All extant species of planktic foraminifera spend their lives floating freely between the surface and depths of 1000 m, and a number of species are associated with the oceanic environment or the water depth where they live (e.g., Hemleben et al., 1989). The chemical characteristics of planktic foraminiferal shells (e.g., $\delta^{18}O$ and Mg/Ca) provide records of oceanographic conditions where calcification occurred (e.g., temperature, salinity), records that are critical for resolving the actual mechanisms of climate change. Elucidation of the patterns of the horizontal and vertical distributions of foraminifera, the factors governing their distribution, and processes involved in their ontogenetic development are therefore essential for reconstructing oceanographic conditions with geochemical records from planktic foraminifera. Plankton tows are useful tools for identifying the horizontal and vertical distributions of planktic foraminifera and have been employed to investigate the ecology of these organisms.

The subarctic Pacific is located at the terminus of the thermohaline circulation of the ocean, where nutrient-rich deep water from lower latitudes is transported to mid-depths. As a result of the mixing of its surface waters to mid-depths, the subarctic Pacific is characterized by surface waters that contain high concentrations of nutrients, and biological production in the area is high (e.g., Takahashi et al., 2002), including the production of planktic foraminifera (Reynolds and Thunell, 1985; Eguchi et al., 1999). Several studies have investigated the ecology of planktic foraminifera at the margins of the subarctic Pacific. Sediment trap observations have revealed that the foraminiferal assemblage of the western margin of the subarctic Pacific Ocean (St. 50 N; 50°N, 165°E) is characterized by the dominance of *Globigerina quinqueloba*, *G. bulloides*, and *Neogloboquadrina pachyderma* during the summer (Kuroyanagi et al., 2002), and that of the eastern margin of the subarctic Pacific Ocean (St. PAPA; 50°N, 145°W) is characterized by the dominance of *G. quinqueloba*, *G. bulloides*, *Orbulina universa*, and *G. scitula* during the summer (Sautter and Thunell, 1989). Plankton tows in these regions, in contrast, have revealed that the vertical distributions of foraminiferal species are related to several attributes of the water, including temperature, chlorophyll-*a* (Chl *a*) concentrations, and light intensity (Kuroyanagi and Kawahata, 2004; Kahn and Williams, 1981; Field, 2004). However, the distributions of planktic foraminifera throughout the subarctic Pacific have not been well documented, and little is known about how foraminiferal assemblages at the western

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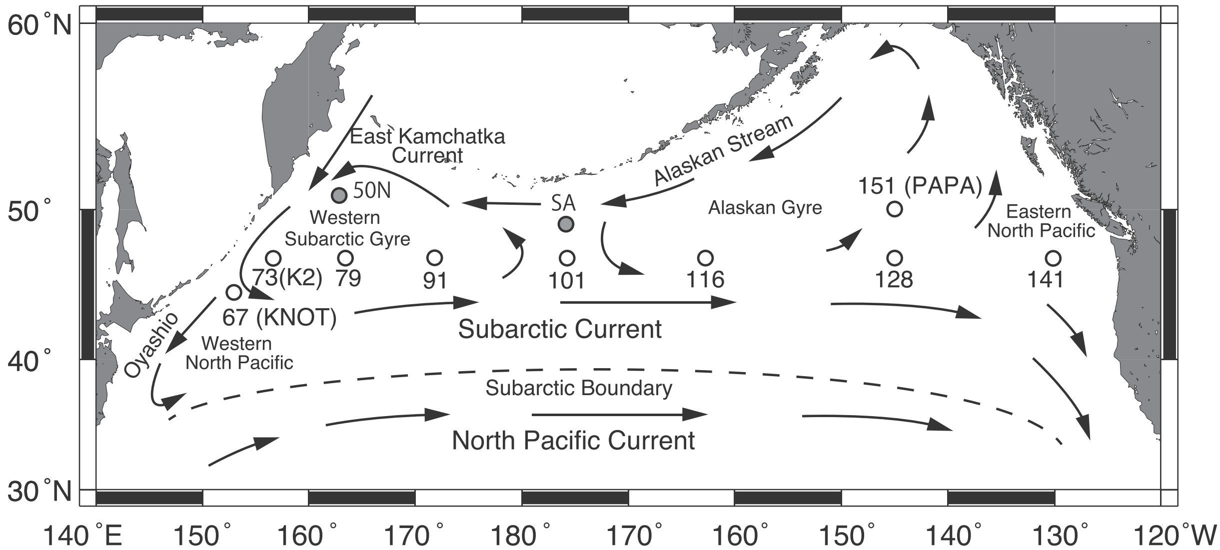

Fig. 1. Topographic map showing the location of sampling stations in the subarctic Pacific. White circles indicate stations where plankton tows were deployed during leg 2 of cruise MR14-04. Gray circles indicate sediment trap stations in the previous studies. Arrows shows the direction of the major surface currents. Map drawn by GMT Online Map Creation (http://sfb574.geomar.de/gmt-maps.html).

and eastern margins of the subarctic Pacific are related to each other. Furthermore, the relationships between the distribution of planktic foraminifera and seawater characteristics in this area are not very well understood.

Consideration of the fact that foraminifera migrate vertically through the water column during their life is also critical for reconstructing oceanic conditions from geochemical signals recorded in their shells as well as for understanding planktic foraminifera ontogeny. Some species of planktic foraminifera are known to migrate vertically during their life and release gametes at a depth that is species-specific (Schiebel and Hemleben, 2005). Measurements of single-chamber or single-specimen geochemical signals (e.g., Mg/Ca and $\delta^{18}O$) of foraminiferal shells from sediment trap samples have been employed to better understand the vertical migrations of planktic foraminifera during their life (e.g., Steinhardt et al., 2015). However, in-situ monitoring based on plankton tow sampling is required to demonstrate migration patterns. Field (2004) performed vertical plankton tows off southern California (USA) and identified growth stages of planktic foraminifera based on the sizes of their tests. Field (2004) has suggested that the habitats of *G. bulloides* and *N. pachyderma* become progressively deeper as they grow in this region. In-situ observations of vertical migrations are important when investigating planktic foraminiferal ontogeny under different seawater conditions in the subarctic Pacific.

In this study, we present snapshots of the horizontal and vertical distributions of planktic foraminifera collected by plankton tows deployed at nine sites distributed longitudinally throughout the subarctic Pacific to elucidate for the first time the relationships between foraminiferal assemblages and in-situ seawater conditions. We also measured the size of individual shells, and we examined the relationship between the vertical migration of the foraminifera and the growth of their shells.

2. Oceanographic setting

The subarctic Pacific has two prominent gyres: the Western Subarctic Gyre to the west and the Alaskan Gyre to the east (reviewed by Harrison et al., 2004). Both the Western Subarctic Gyre and the Alaskan Gyre are characterized by permanent haloclines (i.e., salinity-driven density gradients) in the upper 300 m (Gargett, 1991), and both are well known as regions of high-nutrient and low-chlorophyll (HNLC) concentrations in the water. However, several differences between the physical and chemical characteristics in these two gyres have been reported. First, because of advection of cool, nutrient-rich water from the Sea of Okhotsk and the East Kamchatka Current (Nakamura et al., 2000; Aramaki et al., 2001), the surface water of the Western Subarctic Gyre is generally cooler and has higher nutrient concentrations than the surface water of the Alaskan Gyre (Locarnini et al., 2013; Garcia et al., 2014. Phytoplankton blooms may occur in water with high concentrations of nutrients. The occurrence of such blooms is evidenced by the high Chl *a* concentrations in the Western Subarctic Gyre during the late spring to early summer (Obayashi et al., 2001; Imai et al., 2002), whereas Chl *a* concentrations remain low throughout the year in the Alaskan Gyre (Welschmeyer et al., 1993; Wong et al., 1995). Second, the mixed layer in summer is more stratified and generally shallower in the Western Subarctic Gyre (~10 m; Tsurushima et al., 2002) than

Table 1
Locations, dates, durations of plankton tow samples and lunar age of sampling date.

Station Number	Position		Date	Time (local)	Seafloor depth (m)	Lunar age	
67 (KNOT)	44°05′ N	154°59′ E	25 July 2015	10:25–12:25	5335	27	
73 (K2)	47°01′ N	160°01′ E	27 July 2015	00:21–02:15	5197	0	New moon
79	46°59′ N	166°44′ E	31 July 2015	00:51–02:19	5957	4	
91	47°00′ N	173°49′ E	03 August 2015	02:23–04:17	5813	7	
101	47°00′ N	174°57′ W	05 August 2015	12:25–14:12	5790	9	
116	46°59′ N	158°08′ W	11 August 2015	12:23–14:30	5230	15	Full moon
128	46°54′ N	144°26′ W	15 August 2015	13:35–14:05	4680	19	
151 (PAPA)	49°59′ N	144°58′ W	16 August 2015	12:15–14:15	4253	20	
141	46°58′ N	130°01′ W	20 August 2015	19:45–21:45	2632	24	