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Variations in the radiolarian assemblages in the Bering Sea since Pliocene and their implications for paleoceanography

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ABSTRACT

Radiolarian assemblages were analyzed using samples from the IODP Site U1340 to reconstruct the paleoceanographic conditions in the Bering Sea. Based on the characteristic faunal changes, the radiolarian evolution at Site U1340 was divided into four major intervals from Stages I to IV, with Stage IV divided into Substages IVa and IVb. The radiolarians in each stage recorded significant paleoenvironmental conditions. In general, the Bering Sea was governed by an ocean ecological environment with stable warm and saline surface water during Stage I (4.15 Myr to 3.91 Myr). The environment in the Bering Sea fluctuated strongly during Stage II (3.91 Myr to 2.75 Myr) and was controlled by the cold-water masses and sea ices during Stage III (2.75 Myr to 1.07 Myr) with the gradual development of cold and well-ventilated intermediate water. Stage IVa (1.07 Myr to 0.47 Myr) was a transitional period characterized by the enhanced formation of cold subsurface and intermediate water as well as of the oxygen-rich deep water. During Stage IVb (after 0.47 Myr), the Bering Sea was mainly characterized by enhanced warmth during interglacial episodes and well-developed water layers that were generally comparable to those of the modern Bering Sea. These conditions indicated that the vertical water-mass structure of the modern Bering Sea began to form since 0.47 Ma. Every Stage boundary in the studied core was marked by notable changes in the radiolarian assemblages. These changes corresponded to the climatic cooling event at ~3.91 Ma, the intensification of Northern Hemisphere glaciation at ~2.75 Ma, the beginning of the middle Pleistocene transition at ~1.07 Ma, and the low-latitude radiolarian ecology event at ~0.47 Ma. In addition, the relative abundance pattern of *Cycladophora davisiana* indicates that the Bering Sea was the main source of the past North Pacific Intermediate Water at ca. 0.85 Ma (MIS22), ca. 0.63 Ma (MIS16), and ca. 0.18 Ma (MIS6), just as it was during the last glacial maximum.

1. Introduction

The Bering Sea, which is a marginal sea with high primary production, plays a significant role in modern and past global climatic systems (Takahashi, 1998, 1999b). As an outlet to both the North Pacific and the Arctic Oceans, the Bering Sea serves important functions in water mass exchange and heat equilibriums as well as in the chemical properties of different water types (Takahashi, 1998, 1999a). Given its pivotal role and unique location, the Bering Sea is a critical place for the reconstruction of subarctic climate variability on various time scales (Takahashi, 1999b, 2005). Therefore, a comprehensive knowledge of the paleoceanographic features of the Bering Sea can improve our understanding of the evolutionary history of the paleoenvironments related to the climate changes in the subarctic (Takahashi, 1998).

The Bering Sea's sedimentary sequence is relatively rich in siliceous plankton but has minimal calcareous microfossil content because of its high latitude location and special hydrological conditions. Thus, radiolarians with siliceous skeletons and various depth habitats are potentially effective proxies for paleoceanographic study in the Bering Sea. Several previous studies on paleoceanography have been conducted in the Bering Sea with radiolarians serving as proxy. Blueford (1983) and Wang et al. (2006) reported the depth distribution of the late quaternary radiolarians in the western and eastern parts of the Bering Sea, respectively. Morley and Robinson (1986) explain the stratigraphic significance of the radiolarian species *Cycladophora davisiana* (Ehrenberg) in the comparison of late Pleistocene/Holocene sequences with unusually high sedimentation rate in the Bering Sea. Wang and Chen (2005) developed the application of *C. davisiana* in stratigraphic correlations, and Itaki et al. (2009) discussed the change in intermediate water conditions based on the abundance profile of *C. davisiana*. Employing the characteristic radiolarian species, including *C. davisiana*,

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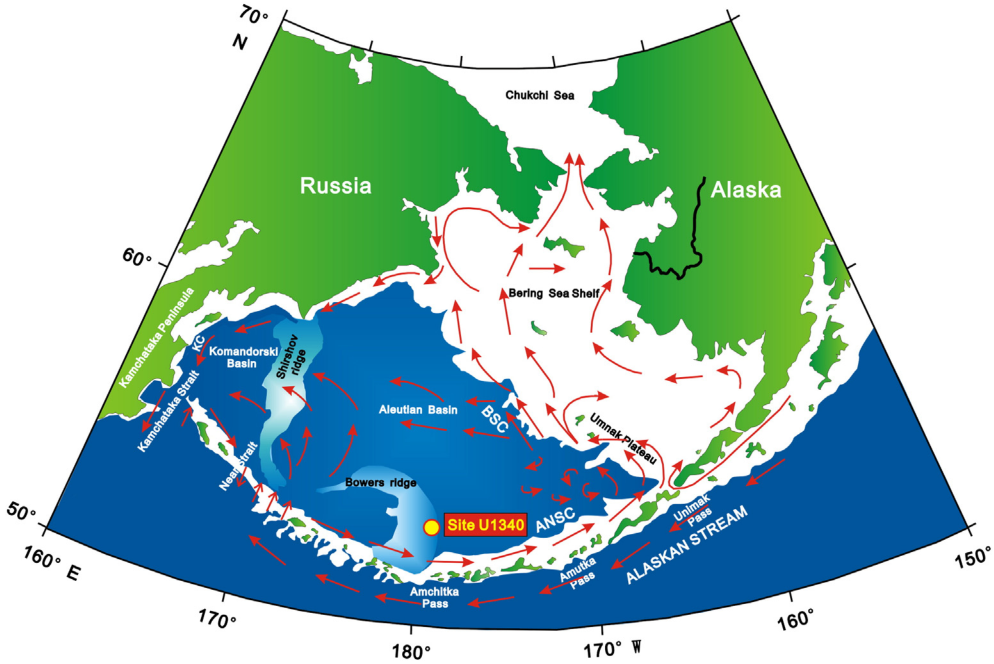

Fig. 1. The location of Site U1340, and surface water circulation in the Bering Sea (Revised after Takahashi et al., 2011). KC, Kamchatka Current; BSC, Bering Slope Current; ANSC, Aleutian North Slope Current.

Ceratospyris borealis (Bailey), and *Stylochlamydium venustum* (Bailey), Tanaka and Takahashi (2005) revealed the paleoenvironmental changes in the water-mass structures in the Bering Sea and determined the source regions of the past North Pacific Intermediate Water (NPIW) during the last 100 kyr. Itaki et al. (2012) reconstructed the millennial-scale variations in the vertical water column in the Bering Sea during the late Pleistocene with the combined data on radiolarians and geochemical components. In addition, various paleoceanographic studies have been conducted in the Bering Sea based on stable isotopes as well as on geochemical, lithological, and micropaleontological analyses (e.g., Sancetta, 1983; Sancetta and Robinson, 1983; Nakatsuka et al., 1995; Gorbarenko, 1996; Gorbarenko et al., 2005; Khusid et al., 2006; Gorbarenko et al., 2010; Zou et al., 2012). However, these studies only focused on the paleoenvironmental reconstruction of the late Pleistocene because of the limited length of the available sedimentary sequence. DSDP Leg 19 first drilled the long sediment cores covering the quaternary of the Bering Sea, but the recovery and quality of the core material was too poor to be used in paleoceanographic studies (Scholl and Creager, 1973). Thus, detailed paleoceanographic information on the Bering Sea that covers long time scales remained lacking until today.

In 2009, the Integrated Ocean Drilling Project (IODP) Expedition 323 retrieved high-quality sediment cores to investigate the Pliocene–Pleistocene paleoenvironmental conditions of the Bering Sea. Using the samples from Site U1340, IODP 323, Zhang et al. (2014) defined the Pliocene–Pleistocene radiolarian zones and updated the shipboard preliminary age model of Site 1340 (Takahashi et al., 2011). This model provided basic data for the paleoceanographic study in the Bering Sea. In the present work, we examine the variations in the radiolarian assemblages at Site U1340 to further reveal the paleoceanographic characteristics of the Pliocene–Pleistocene Bering Sea. This study aims to reconstruct radiolarian evolutions, paleoceanographic changes (including the oceanic conditions through the water column) and global climate changes.

2. Materials and methods

The samples used in the present study were obtained from the sedimentary sequence of Site U1340, IODP 323, which is located on the Bowers Ridge at 53°24.0008' N and 179°31.2973' W at a water depth of 1295 m (Fig. 1). The studied core with a maximum composite depth of 604 m was obtained by establishing the stratigraphic correlations among the three holes cored at Site U1340. The sediments in the studied core consisted mostly of dark green–gray diatom ooze or diatom silt, except for a few volcanic ash layers and siliciclastic sediments (Takahashi et al., 2011). Radiolarian preservation ranged from moderate to good. A total of 243 samples were taken with a sampling interval of 40 cm from the top 15 m and 3 m for the rest of the core.

During the sample processing, the samples were not washed to avoid the breakage and loss of radiolarian specimens. The detailed procedure for this process is as follows. (1) Approximately 1 g of the dried sample was weighed into a 50 ml beaker, which was then added with 25 ml of 10% H_2O_2 solution. (2) After approximately 30 min, the beaker was placed in a sonic oscillator for approximately 2 min to separate the clays that adhered to the radiolarian tests. The beaker

Plate I. All scale bars equal 100 μm. The meanings of the Sample ID are as follows, taking "U1340A-2H-3W, 52–54 cm; 7.42 m" for example, U1340: the number of the site providing the sample; A: the number of the Hole at Site U1340; 2: the second sediment core of the studied core in downward sequence; H: 'Hard Core', the type of the core; 3: the third section of the second sediment core; W: for working, the purpose of the sample; 52–54 cm: the distance from the sampling position to the top of the third section; 7.42 m: the depth of the sample. Figs. 1–2, *Spongotrochus glacialis* Popofsky: 1. (U1340B-1H-1W, 125–127 cm; 1.25 m), 2. (U1340A-70X-5 W, 2–4 cm; 591.42 m). Figs. 3–4, *Stylochlamydium venustum* (Bailey): 3. (U1340B-4H-4W, 2–4 cm; 29.92 m), 4. (U1340A-68X-1 W, 2–4 cm; 566.02 m). Figs. 5–6, *Spongopyle osculosa* Dreyer: 5. (U1340A-6H-4W, 2-4 cm; 46.44 m), 6. (U1340A-50X-1 W, 2-4 cm; 419.32 m). Figs. 7–8, *Stylodictya vilidispina* Jørgensen: 7. (U1340B-4H-4W, 2–4 cm; 29.92 m), 8. (U1340A-39H-1W, 2-4 cm; 333.72 m). Figs. 9–10, *Actinomma boreale* Cleve: 9. (U1340A-9H-1W, 2–4 cm; 70.42 m), 10. (U1340A-11H-5W, 2–4 cm; 95.42 m). Figs. 11–12, *Actinomma leptoderma* (Jørgensen): 11. (U1340B-1H-1W, 15–17 cm; 0.15 m), 12. (U1340A-9H-1 W, 2–4 cm; 70.42 m). Figs. 13–14, *Larcopyle buetschlii* Dreyer: 13. (U1340A-3H-6W, 72–74 cm; 21.62 m), 14. (U1340A-16H-7 W, 2–4 cm; 145.92 m). Figs. 15–16, *Lithomellisa setosa* Jørgensen: 15. (U1340A-11H-7 W, 2–4 cm; 98.42 m), 16. (U1340A-27H-7 W, 2–4 cm; 233.72 m). Figs. 17–18, *Cyrtopera laguncula* Haeckel: 17. (U1340A-2H-1 W, 14–16 cm; 4.04 m), 18. (U1340A-56X-7 W, 2–4 cm; 485.62 m). Figs. 19–20, *Antarctissa* (?) sp. 1: 19. (U1340B-1H-1 W, 15–17 cm; 0.15 m), 20. (U1340A-7H-2W, 2–4 cm; 52.92 m). Figs. 21–22, *Antarctissa* (?) sp. 2: 21. (U1340A-7H-2W, 2–4 cm; 52.92 m), 22. (U1340B-1H-1 W, 15–17 cm; 0.15 m).