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Late Quaternary climate changes around the Elephant Islands, Antarctic Peninsula

Young-Suk Bak* *The Earth and Environmental System Research Center, Chonbuk National University, Jeonju 561-856, Republic of Korea*
Kyu-Cheul Yoo
Ho Il Yoon } *Korea Polar Research Institute, Incheon 406-840, Republic of Korea*

ABSTRACT: Sixty-seven species of diatoms of 28 genera were identified in Core GC03-C2 acquired from the north slope of Elephant Island, Antarctic Peninsula. The number of diatom valves per gram of dry sediment ranged from 0.2~17.3 × 10^7g^{-1}, and these were dominated by *Fragilariopsis kerguelensis* (65.8%). Diatom assemblage analysis reconstructed the Quaternary paleoclimatic change the Elephant Islands. Four diatom assemblage zones were identified according to the frequency of critical taxa as follows: zone I, from 830 to 710 cm (Antarctic Cold Reversal); zone II, from 700 to 550 cm (Deglaciation zone); zone III, from 540 to 260 cm (warm period; Holocene); and zone IV, from 250 to 0 cm (cool period; Holocene). The high abundance of reworked species includes *Actinocyclus ingens, Denticulopsis hustedtii, D. praedimorpha,* and *D. dimorpha* appeared in Zone I by turbidity currents and ice rafting in the area during the glaciations-deglaciation event.

Key words: Antarctic Peninsula, Elephant Island, Quaternary, diatom assemblage, reworked species

1. INTRODUCTION

Diatom assemblage analysis provides one of the best sources of paleoenvironmental information and is widely used to determine biological productivity or sea ice during the late Quaternary in the high-latitude regions (Medlin and Priddle, 1990; Stoermer and Smol, 1999; Armand et al., 2005; Crosta et al., 2005; Gersonde et al., 2005; Stickley et al., 2005). Further, diatoms serve as one of the most sensitive proxies for oceanographic reconstructions of the Southern Ocean where they are extremely abundant and diverse, with many species restricted to particular environments. Their opaline silica skeletons, which are particularly well preserved in Antarctic sediments, provide a paleoenvironmental record. Diatom distribution is controlled by environmental conditions, including water temperature, salinity, and stability as well as light, nutrient availability, and sea-ice cover (Defelice and Wise, 1981; Dunbar et al., 1985; Leventer and Dunbar, 1996; Zielinski and Gersonde, 1997; Cunningham and Leventer, 1998). There are some areas for glacial-interglacial research in Antarctica (Hall, 2009; Allen et al., 2011). Recently, there have been a few studies about the climate change using diatom during the late Quaternary around the Elephant Islands (Bak et al., 2010, 2011). The objective of this paper is provide a new analysis of down-core change of diatom assemblages in core GC03-C2 from the northern region of Elephant Island, which was studied to reveal climate change during the Late Quaternary.

2. OCEANOGRAPHIC SETTING

Elephant Island is located northeast of the South Shetland Islands, and is adjacent to the Bransfield Strait and the Drake Passage. Elephant Island is situated close to the Shackleton Fracture Zone and the South Scotia Ridge, which are active transform plate boundaries (Klepeis and Lawver, 1996; Kim et al., 1997). Elephant Island is 90% ice-covered and was uplifted by approximately 100 m since 6.4 Ma (Rebesco et al., 1997; Trouw et al., 2000). Elephant Island is surrounded by complex ocean currents that traverse the Bellingshausen Sea, Bransfield Strait, Drake Passage, and the Weddell Sea. On the shelves of Elephant Island, the waters, which are referred to as Antarctic Peninsula shelf waters (Deacon and Foster, 1977; Patterson and Sievers, 1980; Amos, 2001; Priddle et al., 1994; Hofmann et al., 1996; Zhou et al., 2010), are strongly influenced by intrusions of the Antarctic Circumpolar Current (ACC), local runoff, and cooling. The northward and southward excursions of the ACC in the southern Drake Passage have been characterized (Orsi et al., 1993, 1995; Hofmann et al., 1996; Amos, 2001; Schodlok et al., 2002; Zhou et al., 2010).

The waters associated with the ACC are as follows: the warm Antarctic Surface Water (ASW), the cold Winter Water (WW) below the ASW, and the warm Circumpolar Deep Water (CDW) (Nowlin and Klinck, 1986; Orsi et al., 1995; Hoffmann et al., 1996; Schodlok et al., 2002; Sprintall, 2003). The temperature (<0.1 °C) and low salinity (<34.6‰) of the ASW extend to a depth of approximately 200 m (Carmack and Foster, 1975). The current of Wedell Sea Water are flowing in the Elephant Island region (Gordon and Nowlin, 1978; Whitworth et al., 1994), input from upstream regions along the western Antarctic Peinsula (Stein, 1986, 1988, 1989; Niiler

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*Corresponding author: sydin@jbnu.ac.kr

et al., 1991; Capella et al., 1992; Garcia et al., 1994; Hofmann et al., 1996). The CDW of the Bransfield Strait is the coldest, originating from the Weddell Sea and exerting a local cooling influence (Zhou et al., 2010). Further, depths greater than 800 m are referred to as the high-density Weddell Sea Deep Water (-0.7 °C $< T < 0$ °C) and the Weddell Sea Bottom Water (<0.7 °C) (Orsi et al., 1993; Matano et al., 2002).

3. MATERIALS AND METHODS

The gravity core GC03-C2 (830 cm long; 61°07.3′S, 61°01.2′W) was obtained at a depth of approximately 3200 m north of Elephant Island (Fig. 1).

Eighty-three samples were collected from the core at 10 cm intervals for diatom analysis (Fig. 1). The dry samples were placed in the beaker with 25 ml of 30% hydrogen peroxide (H_2O_2). 10% Hydrochloric acid (HCl) was then added to remove organic carbonate for another 24 h. They were then centrifuged three times at 1,700 rpm for 15 second; samples were washed with distilled water to remove chemical residue and salt crystals between centrifuging. Washed samples were prepared for quantitative diatom abundance analysis using conventional microscope slides according to the random settling method of Scherer (1994). All diatoms were counted in a minimum of 200 specimens, excluding resting spores of *Chaetoceros* spp. Diatoms were identified using a Nikon E400 microscope at magnifications of ×400 and ×1000. The number of microfossils per gram was calculated as follows: Abundance = $((A \times B)/(C \times D))/E$ (A = number of specimens counted; B = area of the settling chamber; C = number of fields of view; D = area of field of view; E = mass of sample). The age of the sediment, was determined by AMS (accelerator mass spectrometry) ^{14}C dates. Five radiocarbon accelerator ages were obtained from the core.

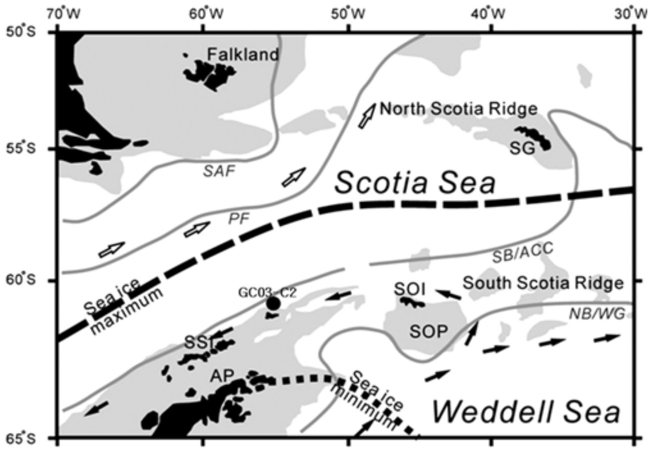

Fig. 1. Location of the GC03-C2 core. Gray lines indicate fronts and boundaries of the ocean current systems: SAF, Sub-Antarctic Front; PF, Polar Front; SB/ACC, southern boundary of the ACC; NB/WG, northern boundary of the Weddell Gyre (Orsi et al., 1993, 1995; Whitworth et al., 1994).

4. RESULTS AND DISCUSSION

Sixty-seven diatom species belonging to 28 genera were recognized, and the most abundant species was *Fragilariopsis kerguelensis* (65.8%) (Fig. 2). Also present were *Thalassiosira antarctica, Actinocyclus cuvatulus, Rhizosolenia styliformis, Eucampia antarctica* var. *recta*, and *E.*var. *antarctica*. Samples of bulk sediment were radiocarbon-dated using accelerator mass spectrometry and ages were corrected using a local reservoir age of 1160 years (Bjorck et al., 1991) (Table 1). In marine sediments, MS is in turn a function of terrigenous source composition and dilution by biogenic material. While the low magnetic susceptibility values may be ascribed to biogenic dilution of magnetic minerals, the high values are likely to reflect variations in mineralogy and grain size (Yoon et al., 2009).

4.1. Diatom Assemblages

Four assemblage zones are established from the entire core according to the abundance of diatom valves, the vertical distributions of major species and magnetic susceptibility (Fig. 2).

4.1.1. Diatom assemblage zone I: (830–710 cm)

The number of diatom valves per gram of dry sediment was very low, ranging from 0.2 to $1.5 \times 10^7 g^{-1}$. The high abundance of *Actinocyclus curvatulus* indicates neritic environment (Romero et al., 2002). *Eucampia antarctica* is reported to two varieties as *E. antarctica* var. *antarctica* and *Eucampia antarctica* var. *recta* (Fryxell and Prasad, 1990; Fryxell, 1991). The high abundance of the polar form of *Eucampia antarctica* (*Eucampia antarctica* var. *recta*) in assemblage zone I is consistent with the low abundance of the subpolar form of *E. antarctica* (*E. antarctica* var. *antarctica*) (Fig. 2). *Thalassiosira antarctica* is widespread in Antarctic waters and is generally associated with the relatively open-water primary production of marginal ice-edge environments (Leventer and Dunbar, 1987, 1988, 1996; Fryxell and Kendrick, 1988; Leventer, 1992; Leventer et al., 1993; Taylor et al., 1997; Zielinski and Gersonde, 1997). The GC03-C2 is located at a transitional zone between winter sea-ice zone and summer sea-ice zone. The vegetative valves of *T. antarctica* were not detected in diatom assemblage zone I, but *Eucampia antarctica* var. *recta* is abundant. Moreover, the lowest primary productivity and relatively high magnetic susceptibility values (132~342) are associated with glacial environment (Vanderaveroet et al., 1999). It was because the grain-size is better sorted than glacial ones during interglacial stages, and is silt-dominated. Contradistinctively, the glacial sediments are richer clay or sand size particles, poorly-sorted (Vanderaveroet et al., 1999). At the upper part of 780 cm horizon, MS value indicates a relatively high than the lower part. Conversely, there is a rapid decrease in *F. ker-*

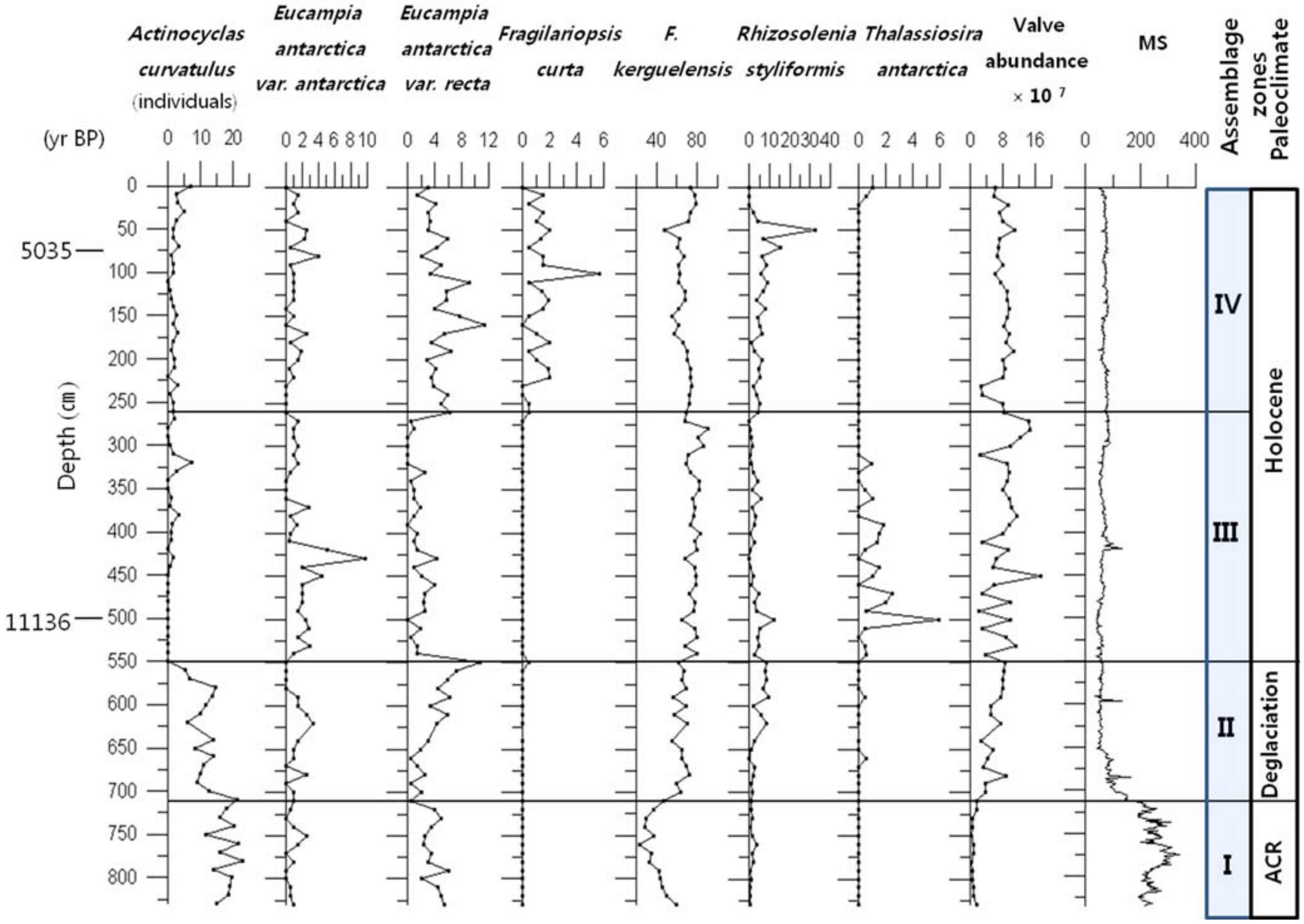

Fig. 2. Assemblage zones and vertical distribution of selected indicators from GC03-C2. ACR; Antarctic Cold Reversal (Stenni et al., 2010).

guensis (open water species) in the upper part of 780 cm horizon. This change in the diatom assemblage zone I indicates cooling condition, and correlates with the Antarctic Cold Reversal (ACR) following the end of AIM1 (Antarctic Isotopic Maximum) (Stenni et al., 2010). Also, this is consistent with the results of radiocarbon dating (700 cm: ca. 14,340 yr).

4.1.2. Diatom assemblage zone II: (710–550 cm)

The range of diatom valves per gram of dry sediment was 0.3–11.1 × $10^7 g^{-1}$, and is higher than that of assemblage zone I. The abundance of *A. curvatulus* gradually decreased, although that of *E. antarctica* var. *recta* increased from lower to upper levels. The relative abundances of open-water species such as *F. kerguelensis* and *R. styliformis* increased in assemblage zone II. *F. kerguelensis* is a valuable paleoindicator used to identify open marine environments. Today, it predominates between 52–63°S (Burckle et al., 1987) where summer surface water temperatures exceed 0 °C (Krebs et al., 1987). The abundance of *F. kerguelensis* is inversely correlated with sea-ice distribution (Burckle and Cirilli, 1987), and this species is present in the ACC and PF (Bathmann et al., 1997; Zielinski and Gersonde, 1997; Crosta et al., 2004). *Rhizosolenia styliformis* is most abundant in open-water environments where the sea ice does not freeze or forms for short durations during winter (Crosta et al., 2005). The magnetic susceptibility values drastically decreased while the number of open-water species increased. This zone corresponds to the deglaciation period of gradual warming beyond the end of the Antarctic cold Reversal.

4.1.3. Diatom assemblage zone III: (550–260 cm)

The number of diatom valves per gram of dry sediment ranged between 2 and 17.3 × $10^7 g^{-1}$ and was the highest of all zones. However, the abundances of *A. curvatulus* and *E. antarctica* var. *recta* were markedly reduced. The subpolar form of *E. antarctica* increased in the upper part of assemblage zone III compared with zone II, and the abundance of open-water species such as *F. kerguelensis* and *T. antarctica* increased. As mentioned before, *Fragilariopsis kerguelensis* is dominant between 52–63°S (Burckle et al., 1987), and a paleoindicator suggests open marine deposition. Therefore, this assemblage corresponds to the warm period of the mid-Holocene climatic optimum (Table 1) with low mag-

Table 1. Radiocarbon ages of the GC03-C2 core sediment

Depth (cm)	Lab code	^{14}C age^{uc} (yr BP)	^{14}C age^{c} (yr BP)	Materials
0	NZA21512	3573 ± 70	2413	Bulk sediment
70	NZA21513	6195 ± 85	5035	Bulk sediment
200	NZA21514	7227 ± 50	6067	Bulk sediment
320	NZA21515	9394 ± 40	8234	Bulk sediment
500	NZA21516	12296 ± 50	11136	Bulk sediment

^{uc}uncorrected for reservoir effect; ^{c}corrected for reservoir effect.

Table 2. Age of selected diatom species from GC 03-C2

Datum	species	Age (Ma)	Reference
LO	*Actinocyclus ingens*	0.62	Kellogg & Kellogg, 1986
LO	*Denticulopsis hustedtii*	4.5	Ciesieiski, 1983
LCO	*D.dimorpha*	10.1	Baldauf & Barron, 1991
LO	*D. praedimorpha*	10.5	Ciesieiski, 1983
FO	*D.dimorpha*	11.9 (12.2)	Baldauf & Barron, 1991
FO	*D. praedimorpha*	12.6	Gersonde & Burckle, 1990
FO	*D. hustedtii*	14.2	Gersonde & Burckle, 1990

FO: first occurrence, LO: last occurrence, LCO: last common occurrence.

netic susceptibility values and high diatom valve abundance (Fig. 2), and is accompanied by a marked increase in the abundance of *T. antarctica*.

4.1.4. Diatom assemblage zone IV: (260–0 cm)

The number of diatom valves per gram of dry sediment ranged between 2.5 and 14.4 × 10^7g^{-1}, representing a decrease compared with that of assemblage zone III and sea-ice species (*E. antarctica* var. *recta* and *F. curta*) shows a marked increase in abundance; however, *T. antarctica* was not detected. *F. curta* is highly abundance near the sea ice edge (Kang and Fryxell, 1992, 1993; Leventer and Dunbar, 1996). Therefore, this assemblage may have been present during a period of climatic cooling (Table 1) compared to the period of assemblage zone III.

Reworked diatom species such as *A. ingens, Denticulopsis hustedtii, D. dimorpha, and D. praedimorpha* were present in high abundance in assemblages I to II. These species correspond to Miocene–Pleistocene periods (Table 2), but increased from the last glacial to deglaciation periods (Fig. 3). Pudsey (2000) suggests a supply of old sediment by turbidity currents and ice rafting in the area during the glaciation-deglaciation event. The results of the study areas (GC03-C2) are not unlike the results from the surrounding sediment core GC03-C1, showing the palaeoclimatic change from the LGM (Last Glacial Maximum) to Neoglacial (Bak et al., 2010, 2011). There is no deposit of the LGM in the GC03-C2 core wherein, deglaciation appears from the lowest horizon, no evidence of neoglacial cooling event. However, diatom assemblages from GC03-C2 core show the cooling event (Antarctic Cold Reversal) in the periods of deglaciation.

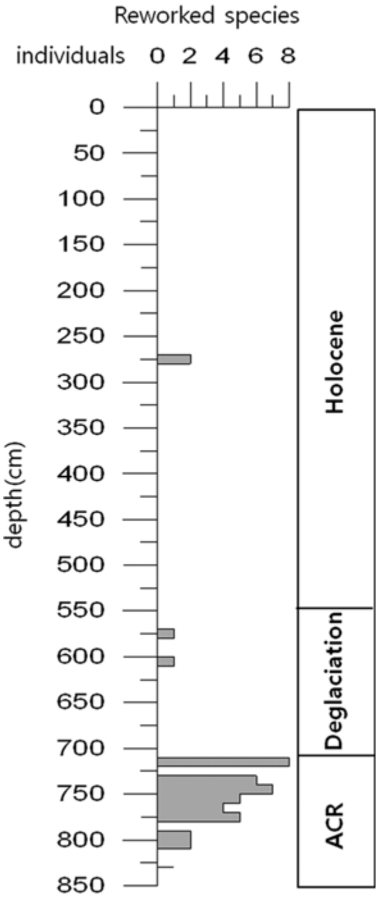

Fig. 3. Summary of reworked diatoms present in core GC03-C2.

The paleoclimatic changes between late glacial-deglacial periods can be reconstructed from the GC03-C2 core date. The magnetic susceptibility and the diatom faunal reveals that a marked cooling event in the area during the ACR. While following the deglaciation, *F. keruelensis* and valve abundance are characterized by consistently high values. The mid-Holocene climatic optimum, represented by the core interval between 550 and 260 cm, is expressed by a decrease in the *E. antarctica* var. *recta*. After a warming, the diatom data showing an increase of *E. antarctica* var. *recta* and *F. curta* suggest a colder interval between 260 and 0 cm.

5. CONCLUSION

We identified four distinct diatom assemblage zones in the GC03-C2 core sediment taken from the north slope of Elephant Island, Antarctic Peninsula based on the vertical distribution of diatom species and magnetic susceptibility values. These zones are defined as follows: zone I (830–710 cm, Antarctic Cold Reversal period); zone II (710–550 cm, Deglaciation period); zone III (550–260 cm, Holocene); and zone IV (260–0 cm, Holocene).

The Antarctic Cold Reversal period is characterized by the increase of sea-ice species in association with the lowest primary productivity and high magnetic susceptibility values. The Deglaciation period is characterized by a high abundance of open-water species. The Holocene of Zone III corresponds to the warm period characterized by a marked increase in the abundance of *T. antarctica*. The Holocene of Zone IV is characterized by a marked increase in sea-ice species (*E. antarctica* var. *recta* and *F. curta*) during the cooling events.

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