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First Record of Massive Blooming of Benthic Diatoms and Their Association with Megabenthic Filter Feeders on the Shallow Seafloor of an Antarctic Fjord: Does Glacier Melting Fuel the Bloom?

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Abstract – We report a conspicuous benthic diatom bloom on an Antarctic fjord shallow seafloor, which has not been reported elsewhere in Antarctica. A thick and massive growth of benthic diatoms was covering or being entangled with a variety of common benthic megafauna such as stalked ascidians, sponges, tube-dwelling polychaetes, gastropods, bryozoans, and others. This finding is an outcome of recent investigations on benthic communities in Marian Cove, King George Island, where glacier retreat has been proceeding quickly for the past several decades. Dominance of benthic diatoms during the austral summer has been frequently reported in shallow Antarctic nearshore waters, which in turn indicates their potential as a primary food item for secondary producers living in this harsh environment. However, previous blooming records of the benthic diatoms were primarily based on data from water column samples. We are the first to report observational evidence of shallow seafloor substrates, including the massive blooming of benthic diatoms and their associations with common benthic megafauna in an Antarctic fjord.

Key words – Antarctic fjord, glacier melting, benthic diatom, *Paralia sulcata,* benthic megafauna, Marian Cove, King George Island

1. Introduction

Glacier retreat in the Antarctic fjords has had a pronounced effect on marine environments and biota because it introduces icebergs and meltwater loaded with terrestrial elements (Moon et al. 2015 and literature therein). This influence seems to be strongest in shallow nearshore waters, particularly those close to retreating marine-terminating glaciers and meltwater sources, where slow-moving and sedentary benthic inhabitants are likely most vulnerable (Barnes and Conlan 2007; Barnes and Souster 2011; Clarke et al. 2007; Cook et al. 2005; Moon et al. 2015; Siciński et al. 2011; Smale et al. 2008).

Marian Cove is a typical Antarctic fjord off King George Island, the largest of the South Shetland Islands. This area is one region where warming and glacier retreat are proceeding faster than anywhere else in the world (Clark et al. 2007; Rückamp 2011; Turner et al. 2014 and literature therein). Tidewater glaciers are well-developed at the end of the cove, and these glaciers have retreated approximately 1.7 km from 1956 to 2012 (Lee et al. 2008; Moon et al. 2015; Park et al. 1998). Glacial carving and snow melting begin in early summer and persist throughout the austral summer, introducing considerable amounts of floating ice and turbid meltwater that develop a very distinct environmental gradient in the seawater (Ahn et al. 2004; Moon et al. 2015; Yoo et al. 1999, 2002, 2015; Yoon et al. 1998). Even after the summer season, haphazard break-up of the glacier occurs continuously until June when the winter season begins (personal observation while wintering in 2015). Details of the hydrographic features in the cove have been described by Yoo et al. (2015).

During recent SCUBA diving investigations in Marian Cove, we found highly rich assemblages of benthic megafauna at shallow depths (15–35 m) (KOPRI 2012a, 2013, 2014; Moon et al. 2015). In addition to these faunal assemblages, we observed a widespread phenomenon in the cove: a conspicuous

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thick and massive growth of benthic diatoms on the seafloor and on a variety of benthic megafauna. This phenomenon was distinguishable from previously reported blooms of benthic diatoms on various biotic or abiotic substrates in intertidal and shallow subtidal Antarctic waters (Ahn et al. 1997; Al-Handal and Wulff 2008a, 2008b; Blazewicz-Paszkowyoz and Ligowski 2002; Krebs 1983; Lange et al. 2007; Totti et al. 2005) due to its large scale and tight association with benthic megafauna. The massive brownish matter, mostly comprised of benthic diatoms, was completely covering or entangling a variety of common benthic megafauna such as stalked ascidians, sponges, polychaetes, gastropods, bivalves, bryozoans, gorgonians, and many others.

In this study, we provide photographic images of the massive benthic diatom bloom on the shallow seafloor, including their megafaunal associations. No reasonable explanation for this phenomenon has been postulated in the current literature, and we provide several perspectives and some ideas for future studies.

2. Materials and Methods

Study area

Marian Cove (Fig. 1) is a small confined glacial fjord (~4.5 km long and ~1.5 km wide) with a maximum depth of ca. 120 m. It is one of the tributary embayments of the Maxwell Bay off King George Island. Sea ice often forms in the winter (Jul through Sep), and sea ice break-up usually occurs during spring or early summer (Oct–Nov). A variable cover of drifting ice occurs during much of the year. There is annual variation in the sea ice coverage and timing of sea ice break-up (KOPRI 2012a, 2012b, 2013, 2014). The cove has very distinct environmental gradients during austral summer due to glacial-melting processes (Yoo et al. 2015 and literature therein). One study demonstrated that nearshore benthic communities respond to this climate-induced process sensitively and measurably over a relatively short distance within the cove (Moon et al. 2015). Marked summer time bloom in water columns dominated by benthic diatom has been reported (Ahn et al. 1997; Kang et al. 2002).

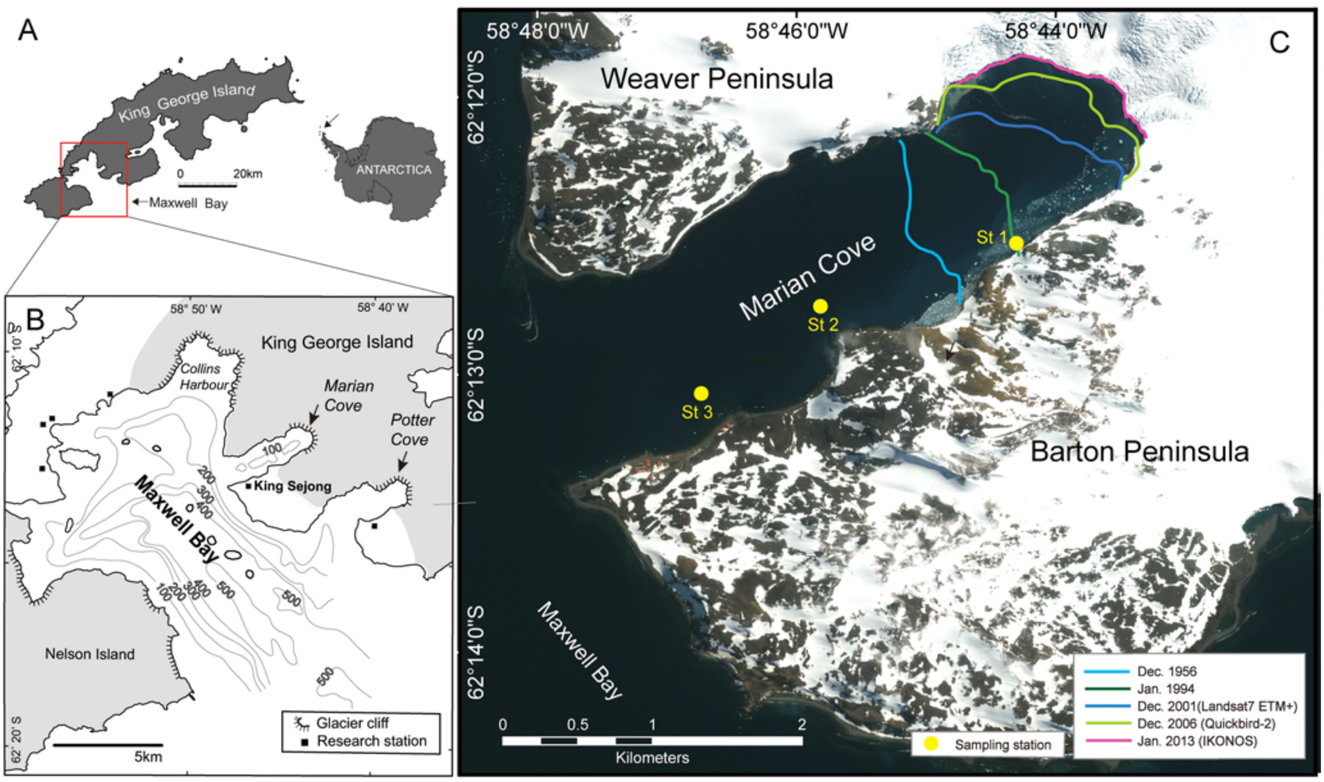

Fig. 1. Geographic location of the study area and sampling sites. (A) Location of King George Island and Maxwell Bay. (B) Bathymetry of Maxwell Bay and its tributary embayment. Bathymetric contours are drawn based on information from the Atlas Hidrografico Chileno Antarctico from the Instituto Hidrografico de la Armada, Chile (1982). The grey area denotes glacier cover. (C) Sampling stations are labeled St. 1, St. 2, and St. 3 in Marian Cove. Glacier lines are drawn based on information from satellite images and aerial photographs (Modified from Moon et al. 2015)

Further information on the environmental features of this area has been described by Moon et al. (2015) and Yoo et al. (2015).

Sample collection and photography

The conspicuous feature, i.e. *a thick and massive growth of diatoms on a variety of megabenthic fauna*, is seemingly widespread within the cove, but rarely observed at < 20 m depths (personal observations). Therefore, we sampled and took underwater photographic observations at depths of 30–35 m. We took underwater photographs at various distances (St. 1: inner, St. 2: intermediate and St. 3: outer coves, Fig 1C) from retreating glaciers during two austral summer seasons (2012/2013 and 2013/2014) by SCUBA diving. Diatom samples were obtained from St. 3, where we found more animals entangled with benthic diatoms. Several megabenthic epifaunal specimens with thick brownish matter, mostly ascidians and sponges, were collected randomly by SCUBA diving. Brownish matter was retrieved from each specimen and preserved in 5% seawater-buffered formalin. These preserved samples were transported to the Korea Polar Research Institute for microscopic analysis.

Microscopic analysis and species identification

Subsamples were taken from the 5% formalin-preserved specimens to identify the diatom species, and the subsamples were pooled. The pooled diatom sample was divided into ten aliquots, and one slide was prepared from each aliquot (a total of 10 slides). Diatoms were identified using a light microscope (LM; Axiophot, Zeiss, Germany). At least 10 fields or 300 cells were counted on each slide. Frequent taxa comprised > 5% of the specimens on a slide and > 20% was considered a common taxon. A scanning electron microscope (SEM; JSM-5600LV; JEOL, Tokyo, Japan) was used to identify species that could not be identified under a light microscope. The diatom samples were cleaned for SEM analysis following the method of Hasle and Fryxell (1970).

3. Results and Discussion

We found a variety of benthic fauna (> 50 taxa) that were completely covered or entangled with a thick growth of brownish matter at all three stations (Figs. 2 and 3). These animals were mostly filter feeders, such as ascidians, sponges, bryozoans, tube-dwelling polychates, and gorgonians (refer to Table 2 in Moon et al. 2015). Microscopic examination demonstrated

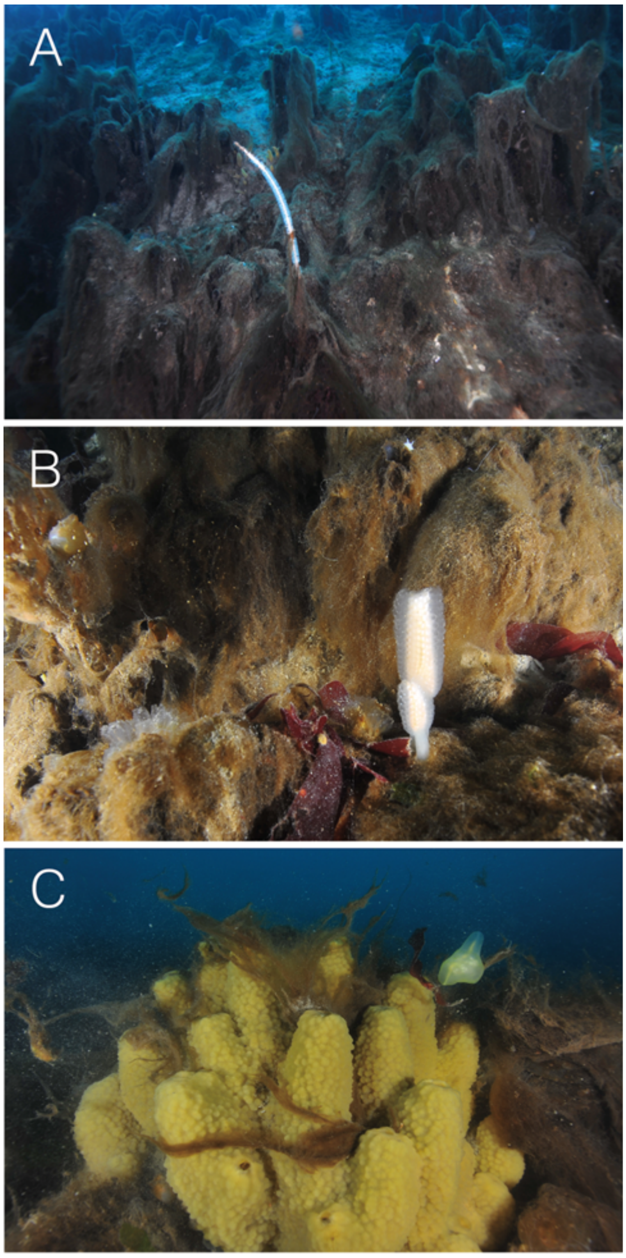

Fig. 2. Common filter-feeders overgrown with benthic diatoms in the outer cove (St. 3 in Fig. 1C). (A) A stalked ascidian *Molgula pedunculata* population (ca. 20 cm in height) completely covered with a thick growth of diatoms. The ascidian *M. pedunculata* is among the most prevalent species in this cove (Moon et al. 2015), occurring at a very high density in the outer cove (~148 individuals/m^2) (KOPRI 2014). The white long strand is the gorgonian *Arntzia gracilis* (50 cm in height), which was reported recently for the first time at < 40 m in this cove (Song et al. 2012). (B) The stalked ascidian *M. pedunculata* population covered with diatoms and colonial ascidians (white) (ca. 10 cm in height). (C) Sponge (ca. 1 m in height and 1.2 m in diameter) and the comb jelly (*Lyrocteis flavopallidus*) are on top. Photographs were taken at 30–35 m depths in late-December (A) and mid-January (B & C) 2013

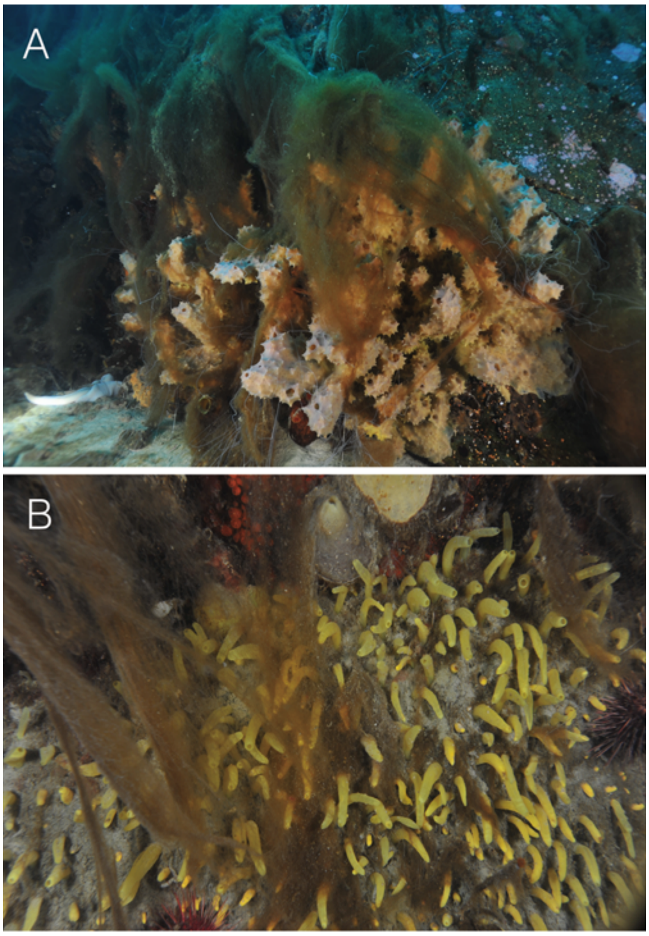

Fig. 3. Other common filter feeders entangled with a diatom bloom in the inner and intermediate coves (St. 1 and St. 2, respectively in Fig. 1C). (A) Sponge (ca. 60 cm in height) associated with other filter feeders, such as the tube-dwelling terebellid polychates and ascidians, in the inner cove. (B) Another sponge species with dense tube-like yellow papillae (each papilla 1–2 cm in length) also associated with other sponge species, ascidians, and sea urchins etc. Photographs were taken in mid- and early-January 2013 at 30–35 m depths

that the brownish matter consisted mostly of benthic diatoms.

Table 1 shows the list of diatom assemblages associated with several common megabenthic epifauna, mostly ascidians and sponges. Except for a few species in the brownish matter, most were benthic. The most common species (> 20% of specimens on a slide) were *Cocconeis* spp. and the chain-forming centric diatom *Paralia sulcata* (Fig. 4). The next most frequently occurring species (5- < 20%) included *Achnanthes* spp., *Amphora* sp., *Eucampia antarctica*, *Navicula* spp., *Odontella litigiosa*, *Pleurosigma* sp. Taxonomical composition and the relative abundance, however, should be further confirmed by quantitative sampling and refined taxonomical analysis in the future.

Table 1. List of diatom species associated with several megabenthic epifauna (mostly ascidians and sponges) commonly occurring at depths of 30–35 m in Marian Cove, a typical Antarctic fjord in Maxwell Bay, King George Island

Benthic
Achnanthes bongrainii
Achnanthes sp.
Amphora sp.
Cocconeis costata
Cocconeis fasciolata
Cocconeis schuettii
Eucampia antarctica
Fragilaria striatula
Licmophora spp.
Licmophora gracilis
Navicula glaciei
Navicula perminuta
Odontella litigiosa
Paralia sulcata
Pleurosigma directum
Pseudogomphonema sp.
Pelagic
Chaetoceros dichaeta
Fragilariopsis rhombica
Fragilariopsis spp.
Nitzschia lecointei
Nitzschia longissimi
Thalassiosira spp.

This phenomenon was found at most distances from the retreating glaciers except for the innermost ice-proximal zone, mostly at depths of 30–35 m (personal observations during underwater surveys in KOPRI 2012a, 2013, 2014; Moon et al. 2015). Blooms were rarely observed at shallower depths (< 20 m), indicating that the conspicuous blooming of benthic diatom tends to occur at places where seabed habitats are stabilized (i.e., the least affected by physical disturbance arising from ice scouring and sedimentation). Moon et al. (2015) demonstrated that glacier retreat and its consequent processes (ice scouring and sedimentation etc.) impact the structure and function of the megabenthic epifaunal communities at this cove. Similarly, the same process could be affecting the intensity of diatom blooms. Since we only dived down to ca. 35 m, we cannot report how deep this phenomenon may occur. Further investigation using a remotely operated vehicle (ROV) should assess how deep these blooms occur.

The benthic diatoms were closely associated with several

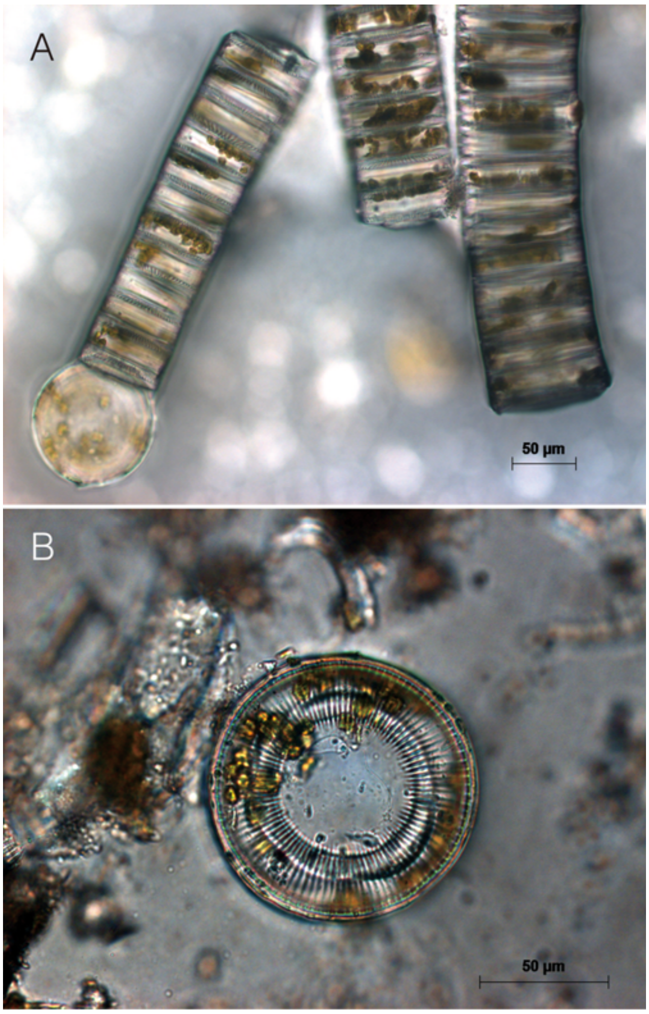

Fig. 4. The chain-forming centric diatom *Paralia sulcata*. (A) Girdle view of the colonies (LM X200). (B) Valve view (LM X400)

common megabenthic animals, mostly filter feeders, such as ascidians, sponges, bryozoans, tube-dwelling polychaetes, and gorgonians, strongly indicating that these benthic diatoms are a much more important primary food source than was previously thought. These megabenthic filter feeders, many of which are opportunistic, comprise the largest trophic group at all sampling stations in the cove (~60%) (Moon et al. 2015). These filter feeders may take advantage of their tight association with benthic diatoms by readily obtaining diatoms as a food item. Although we did not confirm that these benthic animals feed on the attached diatoms, previous studies showed that benthic diatoms constitute an important food item in the gut contents of various filter-feeding Antarctic macrobenthic fauna, such as bivalves (Ahn 1994), hydroids (Gili et al. 1996), ascidians (Tatián et al. 2004), and sponges (Totti et al. 2005). A significant portion of diatoms was observed in the gut contents of hydroids in neighboring Potter Cove (Gili et al. 1996) and ascidians (Tatián et al. 2004), The tight association between the benthic fauna and diatom blooms may benefit both parties, as the epibenthic megafauna seem to provide stable substrates for benthic diatoms to anchor at depths shallow enough to receive light for photosynthesis.

This striking benthic diatom bloom in association with a variety of benthic fauna raises questions, such as what drives benthic diatom blooming and whether this is a local or regional phenomenon in nearshore Antarctic fjords influenced by glacial melting. High abundances of benthic diatoms in the Antarctic nearshore water column has frequently been ascribed to increased light intensity following sea ice break-up (melting) in early summer or wind-driven resuspension of sediment deposited on the sea bottom (Ahn et al. 1997; Gilbert 1991a, 1991b; Kang et al. 2002; Krebs 1983; Lange et al. 2007). While these explanations may describe the increased occurrence of benthic diatom in water columns, these explanations cannot be used to explain the seafloor blooming in association with benthic animals, as found in this study.

Ongoing warming and consequent glacier melting are expected to proceed over the next decades or longer, particularly in the Antarctic Peninsula Region (Rückamp et al. 2011; Turner et al. 2014 and literature therein). Future studies are necessary to elucidate whether blooming of these benthic diatoms is attributable mainly to meltwater processes and if so, what the consequences of these blooms may be to the Antarctic fjord ecosystem. In addition, the tight association of the massive diatom bloom with the common megabenthic filter feeders warrants analytical studies with trophic tracer (e.g., carbon and nitrogen stable isotopes or fatty acids) techniques. These studies would substantiate the idea that benthic diatoms are of prime importance as the primary food source for the major constituent organisms in the Antarctic fjord benthic food web.

4. Conclusion

We report, for the first time, an unprecedented conspicuous feature in an Antarctic fjord, *massive blooming of benthic diatoms and their tight association with megabenthic filter feeders in the shallow seafloor*. Our findings raise questions about what drives the phenomenon and necessitates future studies to elucidate the underlying mechanisms or processes. The conspicuous association between benthic diatoms blooms and common megabenthic fauna, mostly filter feeders, warrants analytical studies using trophic tracer techniques to delineate the benthic food web structure in the nearshore Antarctic marine ecosystem. Knowledge on the diatom composition associated with benthic megafauna would also be improved with refined taxonomy and quantitative analysis.

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