Quaternary Science Reviews 192 (2018) 59–70

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Holocene paleoceanography of Bigo Bay, west Antarctic Peninsula: Connections between surface water productivity and nutrient utilization and its implication for surface-deep water mass exchange

Sunghan Kim [a], Kyu-Cheul Yoo [a, *], Jae Il Lee [a], Boo-Keun Khim [b], Young-Suk Bak [c], Min Kyung Lee [a], Jongmin Lee [b], Eugene W. Domack [d, 1], Andrew J. Christ [e], Ho Il Yoon [a]

[a] *Korea Polar Research Institute, Incheon, 21990, South Korea*
[b] *Department of Oceanography, Pusan National University, Busan, 46241, South Korea*
[c] *Department of Earth and Environmental Sciences, Chonbuk National University, Jeonju, 54896, South Korea*
[d] *College of Marine Science, University of South Florida, Tampa, FL, 33620, USA*
[e] *Department of Earth & Environment, Boston University, Boston, MA, 02115, USA*

ARTICLE INFO

Article history:
Received 27 December 2017
Received in revised form
23 April 2018
Accepted 20 May 2018

Keywords:
Holocene
Paleoceanography
West Antarctic Peninsula
Marine core
Geochemistry
Nutrient utilization

ABSTRACT

Paleoceanographic changes in response to Holocene climate variability in Bigo Bay, west Antarctic Peninsula (WAP) were reconstructed through geochemical, isotopic, sedimentological, and microfossil analysis. Core WAP13-GC47 is composed of 4 lithologic units. Unit 4 was deposited under ice shelf settings. Unit 3 represents the mid-Holocene open marine conditions. Unit 2 indicates lateral sediment transport by a glacier advance during the Neoglacial period. The chronological contrast between the timing of open marine conditions at core WAP13-GC47 (*ca.* 7060 cal. yr BP at 540 cm) and the ages of calcareous shell fragments (*ca.* 8500 cal. yr BP) in Unit 2b suggests sediment reworking during the Neoglacial period. Unit 1 was deposited during the Medieval Warm Period (MWP) and the Little Ice Age (LIA). Surface water productivity, represented by biogenic opal and total organic carbon (TOC) concentrations, increased and bulk $\delta^{15}N$ (nitrate utilization) decreased during the warmer early to middle Holocene and the MWP. In contrast, surface water productivity decreased with increased bulk $\delta^{15}N$ during the colder Neoglacial period and LIA in Bigo Bay. The nitrate utilization was enhanced during cold periods in association with strong surface water stratification resulting from increased sea ice meltwater discharge or proximity to an ice shelf calving front in Bigo Bay. Reduced nitrate utilization during warm periods is related to weak stratification induced by less sea ice meltwater input and stronger Circumpolar Deep Water influence.

1. Introduction

The west Antarctic Peninsula (WAP) is among the most rapidly warming areas in the world (e.g., King, 1994; Vaughan et al., 2003; Cook et al., 2016) where atmospheric mean air temperatures rose 2.5 °C in the Antarctic Peninsula from A.D. 1950 to 2000 (Turner et al., 2005). This warming has been accompanied by a general trend of ongoing glacial retreat in the WAP that initiated between A.D. 1955 and 1969 (Cook et al., 2005a, 2016; Rignot et al., 2014). Additionally, winter sea ice duration in the WAP is decreasing in response to recent warming (e.g., Smith and Stammerjohn, 2001; Vaughan et al., 2003; Stammerjohn et al., 2008). Dramatic, rapid increases in the near-surface temperature over the last few decades were observed along the WAP (Cape et al., 2015 and references therein). Accordingly, the transition from a polar to subpolar climate in the WAP has profound impacts upon surface water production, with phytoplankton biomass decreasing in the north and increasing further south since the late A.D. 1970s (Montes-Hugo et al., 2009). Given the host of recent, rapid, and interconnected climatological, biological, oceanographic, and glaciological changes across this region, studies of Holocene paleoceanographic changes associated with the AP ice sheet are paramount to understanding the region's future vulnerability to climate change.

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* Corresponding author.
E-mail address: kcyoo@kopri.re.kr (K.-C. Yoo).

[1] Deceased in November, 2017.

https://doi.org/10.1016/j.quascirev.2018.05.028

Decades of marine sediment core studies of the Antarctic continental shelf revealed a suite of marine sediment facies that correspond to past glacio-marine environments (Domack et al., 2003; Hillenbrand et al., 2010) and reconstruct the spatio-temporal variations of grounded ice in the WAP since the Last Glacial Maximum (LGM) (Larter et al., 2014; The RAISED Consortium et al., 2014). In the Amundsen Sea and Bellingshausen Sea sectors of the WAP, the LGM ice sheet remained in the outer to middle shelf area until 5 ka, but rapidly retreated toward the modern positions in the inner shelf (Larter et al., 2014). Given this apparent sensitivity of grounded ice on the inner shelf, a deglacial history of this region may provide important insights for future climatic change. The proximity of inner shelf sediment records to the grounded ice margin provides greater potential to detect past grounding line fluctuations. Despite dynamic – and often complex – deglaciation patterns of the inner shelf (Allen et al., 2010 and references therein), inner shelf records back to the earliest Holocene from WAP fjords remain to be studied in depth.

Upwelling and intrusion of relatively warm and saline Circumpolar Deep Water (CDW) onto the WAP shelf (Smith et al., 1999; Smith and Klinck, 2002; Klinck et al., 2004; Jenkins and Jacobs, 2008; Moffat et al., 2009) enhances basal melting in the sub-ice shelf cavity that accelerates grounding line retreat and ice shelf collapse (Klinck et al., 2004; Bentley et al., 2005; Rignot, 2006; Smith et al., 2007a). During the Little Ice Age (LIA) reduced upwelling and influence of the CDW onto the WAP shelf may have facilitated local ice shelf expansion (Ishman and Domack, 1994; Domack et al., 1995; Bentley et al., 2005; Christ et al., 2015). Surface water productivity also presumably changed in response to CDW upwelling variability due to its enriched nutrient content. Primary productivity increased under open ocean conditions during the warmer mid-Holocene, whereas primary productivity decreased synchronously with greater sea ice coverage during the colder Neoglacial period (e.g., Domack et al., 1995; Shevenell et al., 1996; Taylor et al., 2001; Brachfeld et al., 2003; Domack et al., 2003; Allen et al., 2010; Christ et al., 2015). Although the variability of the CDW intrusion onto the WAP shelf areas is demonstrably related to environmental changes in the WAP (Domack et al., 2003), the role of the CDW in nutrient utilization across the WAP has not been discussed, despite the water mass's enriched nutrient character (Ainley and Jacobs, 1981; Jacobs et al., 1985; Castagno et al., 2017). The nutrient cycle in the WAP shelf can, therefore, be related to and understood in the context of past changes in surface water productivity and degree of upwelling/stratification.

In this study, we compiled a multi-proxy record from sediment cores collected from outer and inner Bigo Bay, WAP that includes: magnetic susceptibility (MS), water content (WC), biogenic opal concentrations, total organic carbon (TOC), total nitrogen (TN), $CaCO_3$, diatom assemblage analysis, and bulk $\delta^{15}N$, a proxy for nitrate utilization (e.g., Francois et al., 1992; Altabet and Francois, 1994). Here, we reconstruct Holocene deglaciation patterns and paleoceanographic changes, including surface water productivity and nutrient utilization, in the WAP, and improve upon previously poorly reported proxies, such as bulk $\delta^{15}N$, biogenic opal, and $CaCO_3$ concentrations in relation to other sedimentological observations.

2. Study area

Bigo Bay (65°43′S, 64°30′W; Fig. 1) is a small (~15 km long by ~11 km wide), northwest-southeast-trending fjord in the west Graham Land coast along the Grandidier Channel bordered by Leroux Bay to the north and Barilari Bay to the south (Fig. 1). Bigo Bay is characterized by over-deepened basins that range in depth between 520 and 700 m, as well as several shallow areas (>50 m) and small glaciated islands. Comrie Glacier and several small unnamed marine-terminating glaciers drain into Bigo Bay (Fig. 1). Historic records of ice front positions document the decay of a small ice shelf pinned between Lizard Island and the northern wall of the fjord (Ferrigno et al., 2008).

The Antarctic Circumpolar Current (ACC) flows clockwise in a broad zone around Antarctica (Fig. 1). Strong surface circulation of the upper layer (50–100 m depth) near the shelf slope is associated with the eastward flow of the southernmost front of the ACC (Meredith et al., 2010). This flow can form semi-closed gyre-like circulations over the outer shelf and intrude onto the shelf in places, most notably toward the northern end of the WAP (Klinck et al., 2004). Spring and summer melt of sea ice and glacial ice decreases surface water density and forms Antarctic Surface Water (AASW), a water mass that is also important for upper layer circulation in the WAP (Meredith et al., 2010). A pycnocline separates AASW from deeper circulation dominated by the CDW derived from the ACC (Meredith et al., 2010). The CDW, an intermediate depth water mass, is relatively warm (>1.5 °C), salty (34.65–34.7‰), and nutrient rich (Ainley and Jacobs, 1981; Jacobs et al., 1985; Castagno et al., 2017). Although the CDW exists at depths below 200 m, this water mass can upwell onto and flow across the WAP shelf through over-deepened troughs carved by paleo-ice streams that extend from the continental shelf break to the inner shelf (e.g., Klinck, 1998; Smith et al., 1999; Smith and Klinck, 2002; Klinck et al., 2004; Martinson et al., 2008). Intrusions of warm, saline, and nutrient-rich CDW onto the shelf interact with and are modified by, overlying water masses (Hofmann et al., 1996; Klinck, 1998; Smith et al., 1999). The rugged, glacially sculpted bathymetry of the inner WAP shelf may contribute to and enhance water mass mixing (Bentley et al., 2009).

Sea ice may play an important role in environmental changes around the WAP (e.g., Shevenell et al., 1996; Vaughan et al., 2003; Allen et al., 2010). Freshwater input through sea ice melt enhances ocean surface water stratification; therefore, it is important to understand the changes in the freshwater budget of the WAP across a range of time-scales (Meredith et al., 2010). A thin layer of sea ice melt generated during the spring can greatly stabilize the surface ocean to create a favorable light environment that may encourage phytoplankton bloom development by retaining the biological cells (Mitchell and Holm-Hansen, 1991). Glacial meltwater can provide similar conditions (Dierssen et al., 2002), along with a potential supply of micronutrients (such as iron) sourced from glacial scouring of underlying bedrock and sediment to the surface ocean, as well as micro-nutrient accumulation via atmospheric deposition (Meredith et al., 2010).

This multi-proxy record from outer and inner Bigo Bay provides the opportunity to examine Holocene paleoclimate variability and its effect upon the dynamics of marine-terminating glaciers, sea ice, and water masses on the inner shelf of the WAP.

3. Material and methods

Three shallow sediment cores were collected from Bigo Bay by the R/V *Araon* during the ANA03C Cruise in 2013, including: a 5.63 m long gravity core WAP13-GC47 (65°36.7675′S, 64°45.5070′W, 673 m water depth) and a 0.42 m long box core WAP13-BC47 (65°36.7675′S, 64°45.5070′W, 673 m water depth) from the outer fjord, and a 6.79 m long gravity core WAP13-GC45 (65°45.1004′S, 64°31.4884′W, 516 m water depth) from the inner fjord (Fig. 1b).