Marine Chemistry 176 (2015) 21–33

Contents lists available at ScienceDirect

Marine Chemistry

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

Comparative roles of upwelling and glacial iron sources in Ryder Bay, coastal western Antarctic Peninsula

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ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 15 June 2015
Accepted 20 June 2015
Available online 27 June 2015

Keywords:
Iron
Aluminium
Iron budget
Glacial input
Upwelling
Ryder Bay

ABSTRACT

Iron (Fe) is an essential micronutrient for phytoplankton, and is scarce in many regions including the open Southern Ocean. The western Antarctic Peninsula (WAP), an important source region of Fe to the wider Southern Ocean, is also the fastest warming region of the Southern Hemisphere. The relative importance of glacial versus marine Fe sources is currently poorly constrained, hindering projections of how changing oceanic circulation, productivity, and glacial dynamics may affect the balance of Fe sources in this region.

Dissolved and total dissolvable Fe concentrations were measured throughout the summer bloom period at a coastal site on the WAP. Iron inputs to the surface mixed layer in early summer were strongly correlated with meteoric meltwater from glaciers and precipitation. A significant source of Fe from underlying waters was also identified, with dissolved Fe concentrations of up to 9.5 nM at 200 m depth. These two primary Fe sources act on different timescales, with glacial sources supplying Fe during the warm summer growing period, and deep water replenishing Fe over annual periods via deep winter mixing.

Iron supply from deep water is sufficient to meet biological demand relative to macronutrient supply, making Fe limitation unlikely in this area even without additional summer Fe inputs from glacial sources. Both glacial and deep-water Fe sources may increase with continued climate warming, potentially enhancing the role of the WAP as an Fe source to offshore waters.

1. Introduction

The Southern Ocean is the largest high-nutrient, low-chlorophyll (HNLC) region in the world, and holds the greatest inventory of unused nutrients in surface waters. Iron (Fe) is the primary factor limiting productivity in this region, as determined by several mesoscale, in-situ Fe-enrichment experiments (Boyd et al., 2007). In contrast, the sea–ice margins are not Fe-limited, as is evident from higher biological productivity, greater macronutrient utilisation and biological carbon dioxide (CO_2) drawdown (Carillo et al., 2004).

Several pathways supply Fe to the ocean, including estuarine and groundwater inputs, shelf/slope sediment resuspension, hydrothermal vent activity, glacial runoff, iceberg melt and atmospheric deposition (Boyd et al., 2012). In particular, the relative importance of glacial Fe sources remains poorly constrained (de Jong et al., 2012), with recent work indicating glacial Fe inputs are much greater than previously thought (Shaw et al., 2011; Hawkings et al., 2014). One of the most productive regions of the Southern Ocean, the western Antarctic Peninsula (WAP) shelf has been identified as a source region of Fe to the Atlantic sector (de Baar et al., 1995; Holeton et al., 2005; de Jong et al., 2012; Hatta et al., 2013). High Fe concentrations near shore result in a horizontal Fe gradient observed at distances up to 3500 km (de Jong et al., 2012).

Importantly, the WAP is undergoing dramatic changes in regional climate. It is currently the fastest warming region in the Southern Hemisphere (King, 1994; Vaughan et al., 2003). Changes have already been documented in ocean temperature and density structure (Meredith and King, 2005; Martinson et al., 2008), retreat of glaciers (Cook et al., 2005) and sea ice dynamics (Stammerjohn et al., 2008). All of these factors can potentially influence Fe inputs and cycling, raising questions concerning the consistency of the WAP as a source region for Fe inputs to the broader ocean. Recent studies (Boyd et al., 2012) suggest that the balance of Fe supply and use may change with global warming; in this context, the future evolution of the carbon pump in this setting is uncertain. Additionally, inputs from incursions of Circumpolar Deep Water (CDW; Moffat et al., 2009) and meltwater (Meredith et al., 2013) are balanced by export of shelf waters, some of which feed back into the Antarctic Circumpolar Current (ACC) in the

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http://dx.doi.org/10.1016/j.marchem.2015.06.017
0304-4203/© 2015 Published by Elsevier B.V.

north via Bransfield and Gerlache Straits (Hofmann et al., 1996; Zhou et al., 2002), and where topography or cyclonic gyres direct the flow offshore (e.g., Beardsley et al., 2004; Klinck et al., 2004). Thus, changes in margin Fe sources have the potential to affect offshore waters.

In this study, we investigate sources of Fe by making measurements of dissolved Fe (dFe) concentrations and total dissolvable Fe (TDFe) concentrations during the austral summer of 2009–10 at a coastal site in Marguerite Bay on the WAP. Despite the importance of this region as a source of Fe, relatively few studies have measured Fe in the WAP region, and ship-based studies provide spatial coverage but limited temporal resolution. This is the first to monitor both dFe and TDFe throughout a bloom in the Antarctic sea-ice zone. Time-series and depth profile data are used to identify changes in Fe through time during a growing season, which we relate to inputs, water mass changes, and biological productivity. We also construct a detailed Fe budget for this site.

2. Methods

2.1. Study site and oceanographic setting

Ryder Bay is a shallow (maximum ~500 m) coastal embayment of Adelaide Island, open to Marguerite Bay to the south and bounded by the retreating Sheldon Glacier to the north (Fig. 1). Largely representative of Marguerite Bay (Clarke et al., 2008), Ryder Bay is subject to processes that influence physical and biogeochemical conditions throughout the coastal WAP region (e.g.: seasonal ice cover, glacial inputs). Further, it is the site of the Rothera Oceanographic and Biological Time Series (RaTS) programme conducted by the British Antarctic Survey at the nearby Rothera Research Station. Through this programme, water column conditions and biological activity have been monitored year-round in Ryder Bay since 1997 (Clarke et al., 2008). The accessibility of the RaTS site, long-term environmental dataset and proximity to a retreating glacier make Ryder Bay an ideal location for investigating the relative importance of glacial- and marine sediment-derived trace metal supply.

The Marguerite Bay region, along with the WAP, differs from many other Antarctic shelf regions in its proximity to the ACC, and the accelerating inputs of glacial meltwater from land. The oceanic source for WAP shelf waters is CDW, the warm, mid-level water mass of the ACC that arrives on the shelf in a less modified form than in other areas due to the absence of an Antarctic Slope Front (Klinck, 1998; Clarke et al., 2008; Meredith et al., 2008). CDW incursions are most pronounced near deep, glacially-carved canyons such as Marguerite Trough underlying Marguerite Bay (Moffat et al., 2008). Shelf circulation inshore of the ACC includes a southwestward flowing Antarctic Peninsula Coastal Current that is thought to enter Marguerite Bay at the northern end and exit near Alexander Island, although the detailed circulation within the bay remains uncertain (Moffat et al., 2009).

Water masses along the WAP shelf, including Marguerite Bay and Ryder Bay, have been described in detail (e.g., Clarke et al., 2008; Meredith et al., 2010). Briefly, warm (>1.0 °C), nutrient-rich CDW intrudes in relatively unmodified form onto the shelf (Martinson et al., 2008; Moffat et al., 2009), forming the dominant water mass at depth. Vertical mixing of CDW provides heat and macronutrients to the near-surface layers, with enhanced mixing occurring in coastal and shallow regions (Wallace et al., 2008). Above the CDW, heat loss and sea-ice

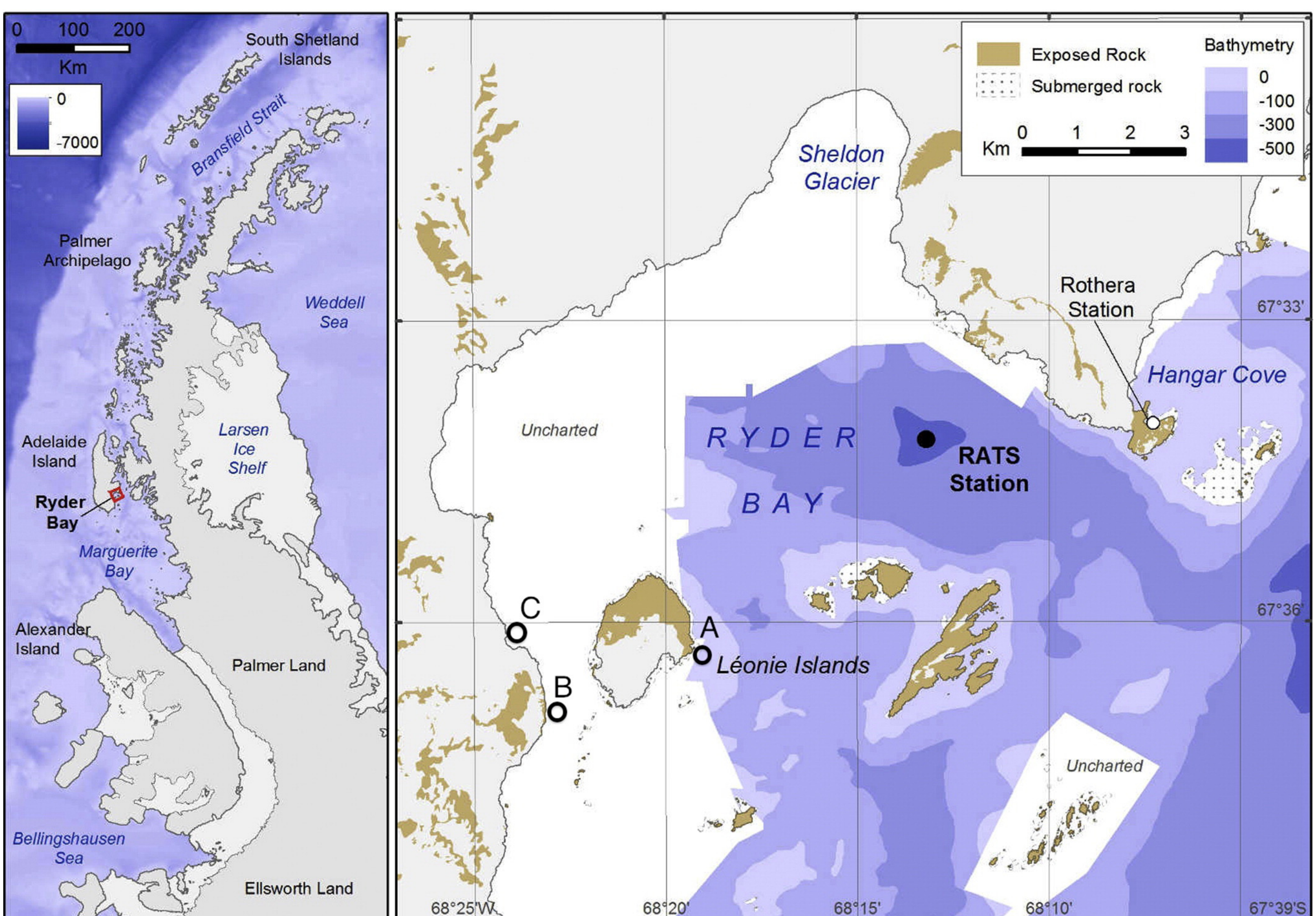

Fig. 1. Map of the western Antarctic Peninsula (left) and Ryder Bay (right), showing the RaTS sampling site and local bathymetry. Also shown are three additional sampling sites, two near exposed land (A, B) and one near the edge of a glacier (C).