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Dissolved silicon and its isotopes in the water column of the Bay of Bengal: Internal cycling versus lateral transport

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Abstract

The concentration of dissolved Si and its isotope composition are measured in the Bay of Bengal (BoB) region of the northern Indian Ocean; the isotope data are the first data set from the northern Indian Ocean. The measurements are made in eight depth profiles closely along the 87°E transect (GIO1 section of the international GEOTRACES program) and in a few samples from the northern shelf of the bay. Dissolved Si in the water column varies from ~0.6 to ~152.5 μmol/kg, whereas the δ^{30}Si data cover a range +1.2‰ to +3.6‰. The depth profiles of dissolved Si show generally lower values in the surface increasing with depth, whereas the pattern reverses in the case of δ^{30}Si. These vertical distribution patterns of Si and δ^{30}Si are similar to those reported in other oceanic regions and suggestive of the significant role of biological processes in governing Si biogeochemistry in the upper layers (top ~1500 m). In contrast, dissolved Si in near surface waters of the northern shelf and the southernmost station is exceptionally high. These results indicate a continental supply of dissolved Si from the Ganga–Brahmaputra river system (G–B) and submarine groundwater discharge (SGD) to the shelf region, and an intrusion of high salinity waters from the Arabian Sea in the southern bay. The δ^{30}Si values of ~1.34 ± 0.10‰ for deep/bottom waters of the BoB (depth >1500 m) are similar to those reported for the deep Southern Ocean and indicate the dominant control of water mass mixing. The dissolved Si concentrations in the bottom waters of the BoB are generally higher than those of the water mass endmembers, which suggest the need for an additional source of Si; *in situ* particle dissolution and/or benthic release in the central bay seem to be the potential candidate.

The annual Si budget in the top ~100 m of the BoB seems to suggest that meso-scale eddies frequently occurring during non-monsoon periods can supply at the most ~2.6 g Si/m^2/year, which is about 33% of the Si requirement to support new production in the bay. The supply of dissolved Si (~1.3 ± 0.5 × 10^{11} mol/year) from the G–B river system and SGD has been calculated based on the distributions of dissolved Si concentration and δ^{30}Si in the northern shelf waters. A comparison of this supply with the reported Si flux upstream of the estuarine zone indicates about 40% removal of dissolved Si in the G–B estuary. The mass balance of Si isotopes in the deep waters indicates that the dissolution of diatoms is the main cause of excess Si in the bay.

1. INTRODUCTION

Studies on marine biogeochemistry of Si and its isotopes have attracted attention in recent years because of its role in regulating the export flux of carbon from surface to deeper reservoirs of the global oceans (De La Rocha, 2003;

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Tréguer and De La Rocha, 2013, and references therein). Earlier studies on this topic were focused on the marine budget of dissolved Si, its cycling, and application as a water mass tracer (DeMaster, 1981; Nelson et al., 1995; Tréguer et al., 1995; Dileep Kumar and Li, 1996; You, 2000). Investigations on the budget of Si require knowledge of its sources to, and sinks within the oceans; in this context there have been several studies on its behavior in estuaries and shelf regions (Borole et al., 1977; DeMaster et al., 1991, 1996; Eyre and Balls, 1999; Somayajulu et al., 2002; Michalopoulos and Aller, 2004). During the last decade, studies on Si marine biogeochemistry took a major leap with the advent of Si isotope measurements in conjunction with its dissolved concentrations; this provided better insights into its various sources, sinks and internal cycling in the open ocean environments (Varela et al., 2004; Cardinal et al., 2005; Reynolds et al., 2006; Beucher et al., 2011; Cavagna et al., 2011; De La Rocha et al., 2011; Fripiat et al., 2011; de Souza et al., 2012a,b; Grasse et al., 2013). Ocean margin basins, being very productive due to nutrients supply via coastal upwelling and continental alluvial/fluvial inputs, are known to play an important role in the marine budget of Si. However studies of the Si cycle in these margin basins are still limited (Brzezinski et al., 2003; Cao et al., 2012; Ehlert et al., 2012).

The goal of this work is to better understand and characterize the processes regulating the distribution of dissolved Si in the Bay of Bengal (BoB) through a systematic study on its concentration and stable isotope composition (δ^{30}Si). The BoB is characterized by moderately high primary productivity (~80 to 120 g C/m^2/year in open ocean waters) largely dominated by diatoms (Madhupratap et al., 2003; Madhu et al., 2006; Prasanna Kumar et al., 2010, and references therein), that consume dissolved Si to make their frustules and export dissolved Si from surface waters to ocean interior. The dominance of diatoms (>85%) in the phytoplankton community of the BoB requires adequate supply of dissolved Si to surface waters; in this context there have been enquiries about the sources of Si and their relative significance. The Ganga–Brahmaputra (G–B) river system is the dominant source of freshwater and other fluvial materials including dissolved Si to the BoB. The available limited data on dissolved Si in these rivers and ground waters of Bangladesh yield an annual flux of ~2.3×10^{11} mol/year (Georg et al., 2009a), which is ~4% of the global riverine Si supply (Laruelle et al., 2009; Dürr et al., 2011; Tréguer and De La Rocha, 2013). Earlier studies have suggested that much of the nutrients including Si supplied by various rivers to the BoB are consumed in estuaries and therefore do not reach the open bay (Qasim, 1977; Prasanna Kumar et al., 2002). Another important source of Si and nutrients to surface waters of the BoB is meso-scale eddies (Kumar et al., 2004; Prasanna Kumar et al., 2004, 2007; Nuncio and Prasanna Kumar, 2012; Chen et al., 2013; Vidya and Prasanna Kumar, 2013), the relative significance of these two modes of nutrient supply to support the biological production in the open BoB however, is a topic of debate.

The GEOSECS program provided high depth resolution data on dissolved Si in two profiles from the BoB (stations

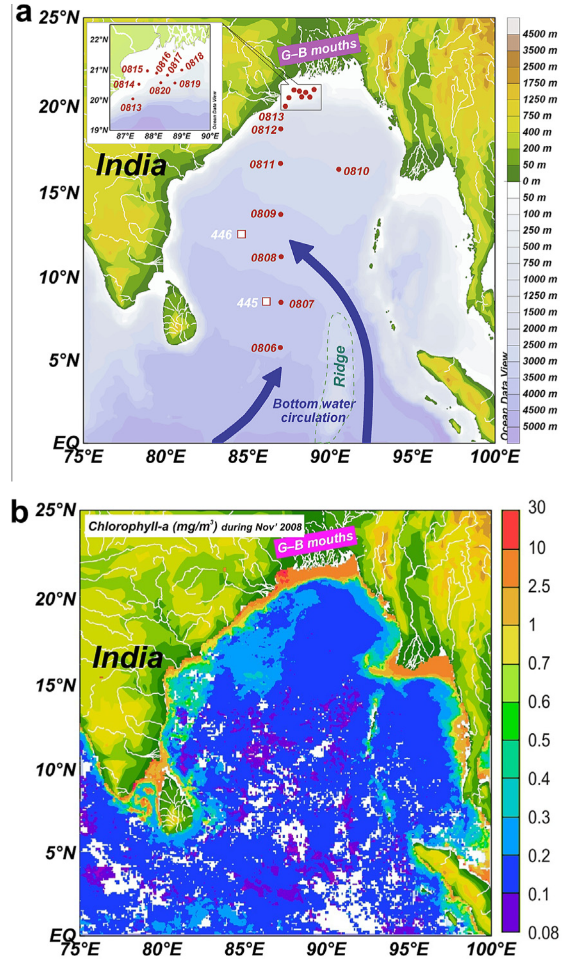

Fig. 1. (a) Locations of sampling stations (red circles represent stations occupied in this study and white squares during the GEOSECS program). The locations of shelf stations are enlarged in the inset. A schematic of bottom water circulation (Gordon et al., 2002) is also shown. (b) Chlorophyll-a (mg/m^3) distribution in BoB surface waters during November 2008 as superimposed over base map from ODV, is derived from satellite data (http://disc.sci.gsfc.nasa.gov/giovanni/). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

445 and 446, Fig. 1a). The data show that bottom waters of the BoB along with those of the Arabian Sea have higher dissolved Si concentrations compared to the rest of the Indian Ocean; this has been attributed to dissolution of biogenic silica at the sediment–water interface (Broecker et al., 1980; Dileep Kumar and Li, 1996; Gordon et al., 2002). More recently, some of the studies have underscored the importance of release of Si and other elements (e.g., REEs) from lithogenic detritus deposited on the ocean margins (Lacan and Jeandel, 2005; Arsouze et al., 2009; Jeandel et al., 2011; Singh et al., 2012). Thus, the distribution of dissolved Si in oceans is dictated by multiple processes; its supply from continents and hydrothermal sources, redistribution by mixing of water masses, particle–water interactions in the water column and pore waters, and export from the water column through biogenic debris. Si