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The silica cycle in a Northeast Pacific fjord; the role of biological resuspension

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ABSTRACT

This study is a quantitative assessment of the role fish-induced bio-resuspension plays in the silica cycle of coastal waters. We used new, published and archived oceanographic data to construct a comprehensive silica budget for Saanich Inlet (Vancouver Island, Canada), a highly productive Northeast Pacific fjord, where siliceous diatoms dominate primary productivity. Anoxia in the deep water of the inlet persists during most of the year, precluding animal life, whereas abundant groundfish continuously rework and resuspend bottom sediments in the shallower, oxygenated margins. This resuspension transfers settled biogenic silica fragments from the sediment, where they are immersed in porewater that is rich with dissolved silica, to the overlying water, where the much lower concentrations accelerate their dissolution rate. The budget shows that Saanich Inlet sediments constitute a sink for approximately 250×10^6 mol Si y^{-1}. Most of this Si enters the inlet in advected, siliceous phytoplankton. Sediment resuspension by groundfish in the oxygenated margins of Saanich Inlet generates about 50% of the total flux of dissolved silica from the inlet seafloor. This resuspension also facilitates a massive transport of biogenic silica from the margins to the anoxic basin, where approximately 90% of all the biogenic silica is buried. The excess dissolution caused by fish activity reduces the burial efficiency of biogenic silica in the entire inlet sediments by about 20%. This case study emphasizes the link between the silica cycle and groundfish activity. Based on this study and because biological resuspension occurs in most regions of the ocean, we recommend that it will be taken into account when budgeting the silica cycle, and potentially other geochemical cycles, in marine environments.

1. Introduction

Diatoms that require dissolved silica (DSi) for the construction of their opaline (biogenic silica; BSi) skeletons dominate primary production in most coastal and upwelling zones around the world, accounting for about 40% of the ocean's productivity (Tréguer et al., 1995; Sarthou et al., 2005). The availability of dissolved silica (DSi) in surface water constitutes a major control in diatom production (Egge and Aksnes, 1992). Si inputs from terrestrial sources (river discharges), dissolution of BSi back to DSi in the water column and in the sediment, mixing processes that return DSi to the surface water and the accumulation of BSi in the seafloor (burial) collectively regulate DSi availability. The relative importance of settled BSi dissolution increases in shallow, coastal water bodies, where a larger fraction of the exported BSi from the surface water reaches the sediment (Ragueneau et al., 1994). Molecular diffusion and bioirrigation largely control DSi flux from the sediment, (Berner, 1980); other mechanisms that control DSi flux from marine sediments are generally considered minor (Buridige, 2006).

In a complementary study of Saanich Inlet, a highly productive fjord of Vancouver Island, British Columbia, Canada (Fig. 1), we demonstrated that sediment resuspension by groundfish activity enhances BSi dissolution in margin sediments by about 5.5 mmol m^{-2} d^{-1} (Katz et al., 2009). This enhancement is related to the fact that a decrease in saturation (i.e., an increase in the degree of undersaturation) in the surrounding water enhances BSi dissolution (Van Cappellen and Qiu, 1997). During biological

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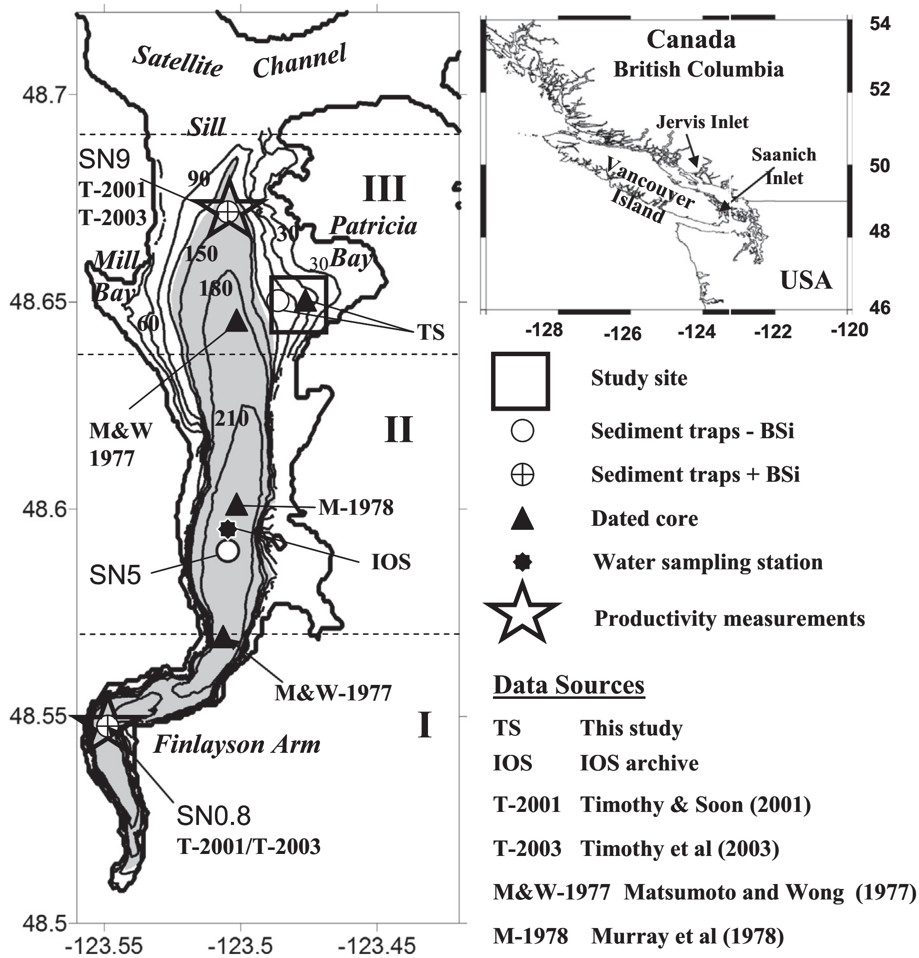

Fig. 1. A bathymetric map of Saanich Inlet. Gray shading marks the area of the basin that is deeper than 130 m and typically anoxic for most of the year. The white area between the 130 m depth contour and the shoreline denotes the oxygenated margins; the square frame in Patricia Bay defines the study site. The inset at the top right shows the locations of Saanich Inlet (on Vancouver Island) and Jervis Inlet in British Columbia. The legend defines the marked locations of deployed sediment traps (at 45–50 m depth), dated sediment cores, water sampling and productivity measurements, as well as of the referred data sources for these measurements. South to north subdivisions of the inlet are marked I, II and III. The map was produced using the Surfer-8 software, with bathymetric multi-beam data courtesy of the Canadian Hydrographic Service.

resuspension BSi particles are transferred from bottom sediments, where they are surrounded by porewater with high DSi concentrations, to the highly undersaturated bottom water. Modelers dealing with the silica cycle in marine and other aquatic ecosystems ignore DSi flux related to biological sediment resuspension (bioresuspension) by fish; most likely because inherently, fish (and other mobile fauna) are excluded from sediment incubation trials where nutrient fluxes are measured. In our current study, we construct a comprehensive silica budget for Saanich Inlet that is based on our own measurements as well as on earlier published and archived data. This silica budget adds to our understanding of the general oceanography of this much studied, North Pacific fjord and provides quantitative evidence of the important role of bioresuspension in the silica cycle in productive coastal ecosystems.

Saanich Inlet is a 23-km long and 225-m deep fjord (Fig. 1); no major rivers discharge directly into the inlet and most of the water exchange occurs over the shallow (~70 m) sill (Gargett et al., 2003). River discharge, mostly from the distant (~60 km) Fraser River (Fig. S1), results in exceptionally high DSi concentrations (exceeding 50 μM in winter) in the adjacent Strait of Georgia (Whitney et al., 2005). The Cowichan and Fraser Rivers (Fig. S1) indirectly supply much of the incoming surface water and nutrients into Saanich Inlet through its mouth. The inlet has exceptionally high phytoplankton productivity of 490–460 g C m^{-2} y^{-1} (Timothy and Soon, 2001; Grundle et al., 2009). This high productivity is dominated by diatoms (Sancetta, 1989) and driven by inverse estuarine circulation (incoming flows of fresher surface water and outflow of deep, inlet water). This circulation exports nutrient-depleted water and imports nutrient enriched water from tidally-mixed passes at the mouth of the inlet on a fortnightly tidal cycle (Gargett et al., 2003; Grundle et al., 2009); more detailed oceanographic settings of Saanich Inlet may be found in Appendix 1. The high productivity and limited water exchange at the sill contribute to the existence of anoxic or severely hypoxic waters deeper than ~130 m for most of the year (Anderson and Devol, 1973). The deep hypoxic/anoxic bottom lacks both groundfish (Yahel et al., 2008) and macrofauna (Tunnicliffe, 2000; Chu and Tunnicliffe, 2015) that could rework the sediment. Undisturbed, the anoxic basin sediments set in annual varves composed of light and dark laminas. The light laminas form during spring and summer, when the diatom to terrigenous sediment ratio is high, and the dark laminas form during winter, when riverine silt inputs dominate (Gross et al., 1963; Tunnicliffe, 2000).

The shallower, oxygenated margins support an abundant fish population (~0.5 fish m^2), particularly groundfish of the family Pleuronectidae (Yahel et al., 2008) and invertebrates such as squat lobsters (*Munida quadrispina*). Groundfish community composition varies at shallow depths; however, the small flatfish *Lyopsetta exilis* dominates between depths of 80 and 130 m (Yahel et al., 2008; Chu and Tunnicliffe, 2015). By emerging, resettling, and digging