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Selenium and trace element mobility affected by periodic displacement of stratification in the Great Salt Lake, Utah

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ABSTRACT

The Great Salt Lake (GSL) is a unique ecosystem in which trace element activity cannot be characterized by standard geochemical parameters due to the high salinity. Movement of selenium and other trace elements present in the lake bed sediments of GSL may occur due to periodic stratification displacement events or lake bed exposure. The water column of GSL is complicated by the presence of a chemocline persistent over annual to decadal time scales. The water below the chemocline is referred to as the deep brine layer (DBL), has a high salinity (16.5 to 22.9%) and is anoxic. The upper brine layer (UBL) resides above the chemocline, has lower salinity (12.6 to 14.7%) and is oxic. Displacement of the DBL may involve trace element movement within the water column due to changes in redox potential. Evidence of stratification displacement in the water column has been observed at two fixed stations on the lake by monitoring vertical water temperature profiles with horizontal and vertical velocity profiles. Stratification displacement events occur over periods of 12 to 24 h and are associated with strong wind events that can produce seiches within the water column. In addition to displacement events, the DBL shrinks and expands in response to changes in the lake surface area over a period of months. Laboratory tests simulating the observed sediment re-suspension were conducted over daily, weekly and monthly time scales to understand the effect of placing anoxic bottom sediments in contact with oxic water, and the associated effect of trace element desorption and (or) dissolution. Results from the laboratory simulations indicate that a small percentage (1%) of selenium associated with anoxic bottom sediments is periodically solubilized into the UBL where it potentially can be incorporated into the biota utilizing the oxic part of GSL.

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1. Introduction

The Great Salt Lake (GSL) is a terminal lake located next to a large developing urban area which includes over 1.7 million people. The lake is divided into two distinct regions (North Arm and South Arm) by a railroad causeway completed in 1959. Lake circulation is restricted by the causeway, and typically the South Arm of the lake is stratified and characterized by the presence of a dense deep brine layer (DBL) originating from the North Arm (Madison, 1970). The North Arm brine is denser than the overlying South Arm brine and flows underneath and to the bottom of the South Arm where it gathers decaying organic matter falling through the water column and becomes anoxic forming the DBL.

The condition of stratification (meromixis) in the South Arm of the lake is maintained for annual time periods, punctuated with intermittent periods during which the stratification is not detected due to changes in freshwater input (Loving et al., 2000; Gwynn, 2002). Thermal and chemical stratification was observed for the entire study period from May 2006 through October 2007. The prolonged periods of meromixis are in direct contrast to freshwater lakes which typically experience annual turnover and complete water column mixing resulting from seasonal changes in thermal stratification (Hutchinson, 1957).

The South Arm of the GSL receives input from industrial, urban, mining, and agricultural sources within the 37,500 km^2 watershed supplying the lake. Most of the trace element contribution to the lake is anthropogenic (Domagalski et al., 1988). Studies of trace element concentration in the lake have characterized the UBL and DBL since construction of the railroad causeway (Stephens and Gillespie, 1976; Tayler et al., 1980; Sturm, 1980). Previous studies have characterized the GSL as a self-cleaning system which removes metals through precipitation and sedimentation (Tayler et al., 1980). However, this characterization of the system as self-cleaning was based on a comparison of inflow concentration to lake concentration. A decrease in lake concentration compared to inflow concentration was demonstrated only for Cd, Cu and Zn, whereas other trace elements such as As and Se showed enhanced

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lake concentrations relative to inflow concentrations (Tayler et al., 1980). More information is needed related to the sediment–water interaction to determine whether trace elements are permanently lost from the system due to sedimentation and precipitation or whether they may be periodically released back into the water column.

Recent interest has been focused on establishing a numerical standard for Se for the open waters of the GSL to protect avian wildlife. High levels of Se in water have been shown to cause malformations in bird embryos and chicks and may even lead to death (Ohlendorf et al., 1986). Selenium (and other trace elements) in sediments of the GSL may enter the food chain via brine shrimp (*Artemia franciscana*), which are filter feeders, and bioaccumulate as some birds using the GSL ingest brine shrimp as their diet (Utah Department of Environmental Quality, 2008). The load of Se to the GSL from surface water inflow over a period of 12 months from May 2006 to April 2007 was 1560 kg (Naftz et al., 2009). Approximately 10 kg/year of the total Se load to the GSL may come from seasonal re-saturation of shoreline sediments based on collection of shoreline sediments and laboratory leachate tests to determine the amount of Se released (Naftz et al., 2009). Removal of Se from the GSL is primarily controlled by volatilization, 1455 kg/year (Diaz et al., 2009a), and sedimentation accounts for removal of 624 kg/year of Se (Oliver et al., 2009). Assuming that the Se load and removal mechanisms balance each other over an annual cycle, the residence time of Se in the GSL is on the order of about 3 to 5 years (Diaz et al., 2009b). However, although the removal values are within the range of error of the measured load, a slight statistical increase in Se over the period of study was observed indicating that there may be an unmeasured load of Se to the lake (Naftz et al., 2009).

Selenium is located directly below sulfur in group VI-A of the periodic table and therefore is chemically similar. Selenium can exist in four oxidation states: selenide [Se (−II)], elemental selenium [Se (0)], selenite [Se (IV)] and selenate [Se (VI)]. Under most natural, aqueous, aerobic environmental conditions, Se exists as an oxyanion selenite (SeO_3^{2-}) or selenate (SeO_4^{2-}) (Masscheleyn and Patrick, 1993). Under reducing conditions Se (−II) is the dominant species and is often associated with an insoluble iron phase (Masscheleyn et al., 1990).

At the Saanich Inlet along the southeastern portion of Vancouver Island, Canada, selenite and selenate were present in the upper oxic waters, and organic selenide species became dominant in the anoxic hydrogen sulfide deep waters (Cutter, 1982). The stratification in the GSL is similar with the DBL characterized as anoxic and containing hydrogen sulfide. Selenium is also of concern to the ecosystem of the Salton Sea, California, dissolved water concentrations are 0.5–2 µg/L and lake bed sediment concentrations are 0.58–11 mg/kg (Schroeder et al., 2002). The Se values in the GSL fall on the low end of the range of Salton Sea concentrations.

The South Arm of the GSL contains an upper brine layer (UBL) characterized by oxidizing conditions and is in direct contrast to the reducing DBL below. Mobility of Se in each layer as well as in the lake bed sediment is likely to be influenced by the dominant species. Selenium flux from the sediment may be influenced by the redox conditions of the overlying water (Byron and Ohlendorf, 2006). Anoxic conditions (DBL) would favor reducing conditions that would promote Se association with insoluble iron phases while oxygenated conditions (UBL) would promote the opposite effect and release Se from the sediment into the overlying water as selenite or selenate (Masscheleyn and Patrick, 1993). Selenium enters the lake from surface water sources primarily in the dissolved phase (defined as water passing through a 0.45 µm filter) as selenate (average of 21% of the dissolved Se as selenite) (Naftz et al., 2009).

In contrast, arsenic typically exhibits the opposite effect to redox conditions compared to Se. Arsenite [As(III)] and arsenate [As(V)] are the two primary oxidation states of As. Under oxidizing conditions arsenate is the dominant species while arsenite is dominant under

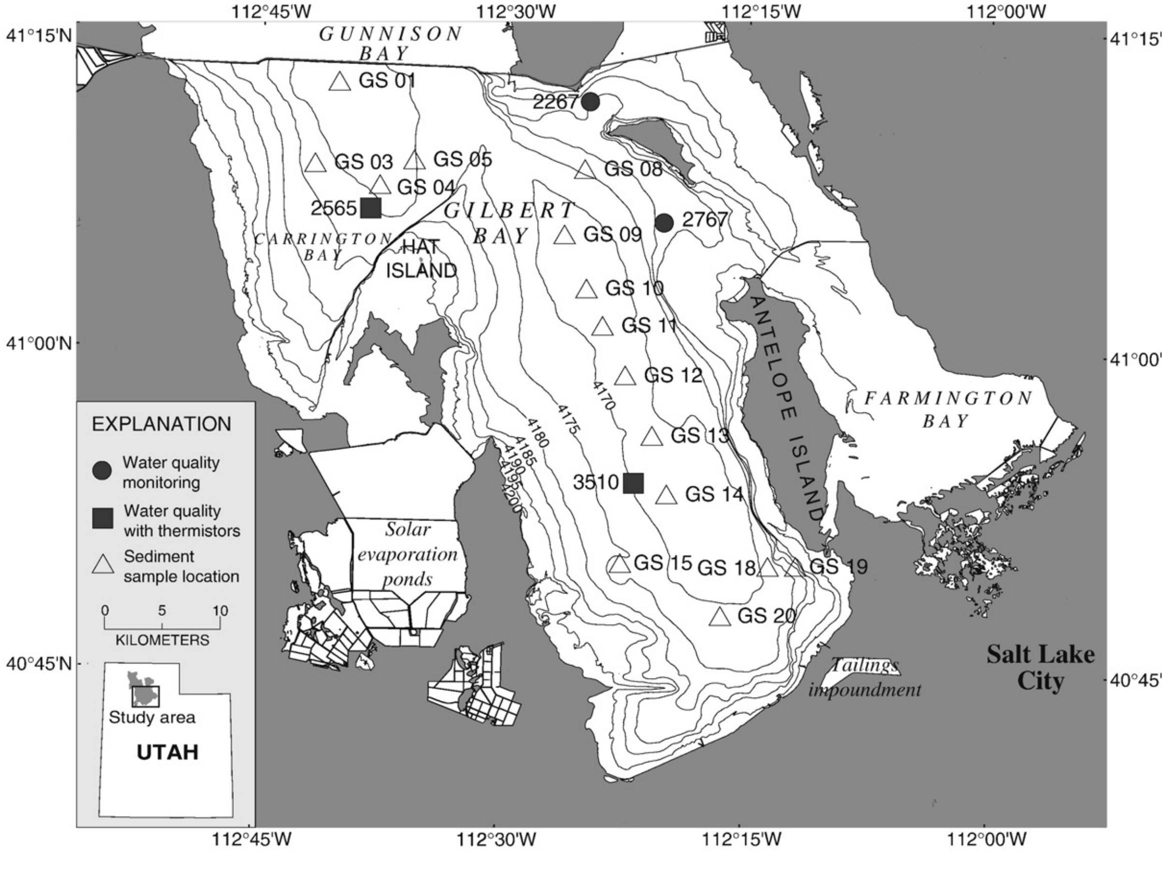

Fig. 1. Great Salt Lake sampling locations (modified from Baskin (2005)).