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Tracing submarine hydrothermal inputs into a coastal bay in Baja California using radon

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ABSTRACT

Hydrothermal fluid fluxes into deep ocean environments can be obtained from heat balance approaches. However, in shallow systems, hydrothermal heat fluxes can be masked by solar heating. In this paper, we use radon (^{222}Rn) as a naturally occurring geochemical tracer to map the location of hydrothermal fluid inputs, as well as low-temperature groundwater discharges, and quantify fluxes into Concepcion Bay, Baja California, Mexico. This fault-bound bay contains intertidal seeps with salinities ranging from 5.3 to 25.6, temperatures reaching 64 °C, and nitrate reaching 900 μM. The bay is subject to natural eutrophication and frequent red tide events. A detailed ^{222}Rn survey around the 100-km perimeter of Concepcion Bay allowed us to map the location of enhanced submarine groundwater inputs. Moorings at three contrasting coastal sites indicated that radon concentrations were higher at low tide and during the winter. Modeled hydrothermal fluid inputs ranged between 0.4 cm/day in the middle of the bay and 43.9 cm/day at the largest hydrothermal coastal seep site. Apparently, faults allow meteoric water to be heated and serve as conduits for its subsequent discharge through permeable marine sediments. When conservatively extrapolated to the entire bay using weighted distributions, these fluxes are estimated at 17.5 m^3/s, a flow much higher than local ephemeral rivers. About 42% of the fluxes described consisted of fresh groundwater with the remaining made up of recirculated seawater. New nitrogen inputs associated with groundwater pathways are estimated to directly account for at least 15% of the local primary productivity. Our combined spatial survey/time series strategy can be very useful to quantify hydrothermal fluid inputs in particular at vent sites where a temperature signal in shallow surface waters is difficult to be observed.

1. Introduction

High-temperature submarine hydrothermal activity is usually associated with active plate boundaries such as back-arcs in subduction zones and spreading centers. However, hot springs may also occur in regions that are not as tectonically active (Vidal et al., 1981). Areas of relatively low temperature hydrothermal fluid release are generally associated with faults and fissures due to conduit formation providing a pathway for groundwater transport. Since groundwater in fault zones is warmer and thus more buoyant, hydrothermal fluid upwelling may occur from host rocks through the faults to the surface (Forrest et al., 2005 and references therein).

The geochemical and physical properties of hydrothermal fluids can be quite variable. Gases such as CO_2 and CH_4 are often highly enriched at vent sites (Chen et al., 2005; Svensen et al., 2007). Hydrothermal fluids may have lower concentrations of Cl, SO_4, Na, Mg and Br than seawater and higher concentrations of Si, Fe, Mn, Ba, Ca, and As due to water-rock interactions (Vidal et al., 1981; Pichler et al., 1999; Wheat and Mottl, 2000; Dias et al., 2010). When discharging to seawater, hydrothermal fluids typically precipitate large amounts of Fe and Mn oxide and sulphide minerals that are enriched in several heavy metals (Canet et al., 2005a). The high fluid temperatures, low pH, and distinct geochemical composition can create a biologically-stressful environment (Melwani and Kim, 2008) or, alternatively, serve as a source of nutrients that fuel phytoplankton productivity near shallow vent sites (Estradas-Romero et al., 2009).

Several studies have explored the geochemistry and biology around hydrothermal vent sites (Tarasov et al., 2005) following the discovery of hydrothermal activity along mid-ocean ridges in the 1970s. Quantifying fluid fluxes has remained problematic as inputs are often patchy, diffuse, and highly dynamic (Canet et al., 2005a). In deep ocean environments, heat balance approaches often provide insights into fluid flow (Stein and Stein, 1994; Wheat et al., 2004). However, in

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lower-temperature shallow systems, hydrothermal heat fluxes can be masked by solar heating. A promising approach for estimating hydrothermal fluid inputs is the utilization of natural geochemical tracers such as radon and radium isotopes. Natural tracers integrate a signal associated with various pathways and are a good approach to characterize spatially heterogeneous systems (Burnett et al., 2006). Radium and radon isotopes are often highly enriched in groundwaters (or porewaters) relative to surface seawater.

In the previous decade or so, radon and radium isotope techniques have been developed to quantify submarine groundwater discharge (SGD) into the coastal ocean (Moore, 1996; Burnett et al., 2006; Swarzenski, 2007; Charette et al., 2008). In addition, advances in technology have allowed us to make continuous, automated radon-in-water measurements (Burnett and Dulaiova, 2003). SGD is defined as "any and all flow of water on continental margins from the seabed to the coastal ocean, with scale lengths of meters to kilometres, regardless of fluid composition or driving force" (Burnett et al., 2003a; Moore, 2010). This definition does not include deep-sea hydrothermal flows, but does include hydrothermal fluid inputs into shallow coastal environments.

To our knowledge, natural geochemical tracers have not been used to study shallow water submarine hydrothermal vents despite their accessibility for sampling and occurrence at several worldwide sites. Previous studies using tracers to gain insights into hydrothermal fluid inputs focused on deep ocean sites. For example, Moore et al. (2008) found high ^{223}Ra concentrations in deep waters near the Puna Ridge (Hawaii) and suggested that radium isotopes could be used to quantify fluid flows through the ocean crust. Radon enrichments in deep ocean waters were also used to gain insights into hydrothermal fluid inputs at the Juan de Fuca Ridge (Rosenberg et al., 1988; Wheat et al., 2004) and Galapagos Rift (Dymond et al., 1983).

Here, we use radon (^{222}Rn) as a naturally-occurring geochemical tracer to map the location of low temperature SGD as well as hydrothermal inputs and quantify their fluxes into Concepcion Bay, Baja California, Mexico. As radon variability in coastal waters over tidal time scales can be higher than seasonal changes (Santos et al., 2009a), we performed high temporal resolution sampling at selected sites during both the winter and the summer. Since the bay is located in an arid region, hydrothermal inputs may represent a major source of new chemical additions. The bay is known to be subjected to seasonal eutrophication even though there are no local anthropogenic nutrient sources (Morquecho and Lechuga-Deveze, 2004). Hence, we also assessed whether hydrothermal inputs are a major source of new nutrients fueling local primary productivity.

2. Materials and methods

2.1. Study site

Concepcion Bay (Fig. 1) is one of the deepest (25 to 35 m) and largest (282 km^2; 40 km long) coastal bays on the western shore of the Gulf of California. The bay is located in an arid region with summer temperatures ranging from 36 to 40 °C. Concepcion Bay is characterized by high evaporation rates, little or no river input, and high salinities. Average annual precipitation is only 200 mm; 80–90% of that occurs during the summer (Mendoza-Salgado et al., 2006).

Concepcion Bay is a large fault-bounded bay associated with a subduction setting (Forrest et al., 2005). A metamorphic complex of Paleozoic andesites contains the oldest rocks of Baja California. Outcrops of volcanic and sedimentary units were affected by regional faulting, and have been intruded by granitoids, creating steep topographic gradients along the coast. Submarine fluid venting has been observed at depths from the intertidal zone down to 15 m. Hydrothermal fluid temperatures may reach 88 °C at a depth of 10 cm within the sediments (Prol-Ledesma et al., 2004; Canet et al., 2005a). The geochemistry of hydrothermal waters, gases, and associated minerals in Conception Bay has been studied from several perspectives (Prol-Ledesma, 2003; Prol-Ledesma et al., 2004; Canet et al., 2005a, 2005b; Forrest et al., 2005) and found to be similar to deep submarine vents. However, the rates of hydrothermal fluid inputs into the bay have not yet been quantified.

While the bay is well mixed in the winter, thermal stratification develops in the summer as a result of low wind speeds and high surface water temperatures. A decrease of dissolved oxygen in waters below the thermocline ultimately leads to an anoxic environment and the formation of hydrogen sulphide. A sill at the mouth of the bay prevents bottom waters from mixing with Gulf of California waters. Upwelling of these anoxic bottom waters may cause massive shellfish mortality (Lechuga-Deveze et al., 2001). Harmful algal blooms (red tides) also occur in the bay late in the summer (Morquecho and Lechuga-Deveze, 2004). These blooms are likely driven by natural processes since the only local urban development is the village of Mulege (about 4,000 inhabitants) located about 3 km to the north of the Bay (Lechuga-Deveze et al., 2001).

2.2. Approach and methods

We performed field investigations in January, May, and September 2008. Our general strategy consisted of: (1) mapping dissolved radon distributions in near-surface waters along the bay shoreline to qualitatively identify possible submarine inputs into the bay; (2) performing moored time-series measurements at selected near shore sites to quantify SGD rates; (3) sampling groundwaters to characterize the endmember concentrations of the discharging fluids; and (4) deep water sampling in the middle of the bay to assess whether groundwater was entering the waters below the thermocline.

A high spatial resolution radon survey was performed according to procedures outlined by Dulaiova et al. (2005). The west coast of the bay was surveyed in January 2008, while the east coast was surveyed in May 2008. Briefly, surface water was continuously pumped to an air–water equilibrium chamber that degassed radon. The air space from this chamber was circulated to three radon-in-air monitors (RAD7; Durridge Co.) arranged in parallel. Radon-222 activities were integrated over 10 minutes while water temperature, salinity and GPS coordinates were continuously recorded. The spatial resolution for each ^{222}Rn value was controlled by the speed of the boat. As the boat velocity was about 5 km/h, each radon point represented an integration over about 500 m.

The survey results allowed us to select three representative sites to perform intensive (hourly) time series radon measurements during summer and winter conditions. A single RAD7 was deployed for about 24 h to assess whether tidal fluctuations influence groundwater inputs into Concepcion Bay. Water levels, temperatures, and salinities were monitored with a Van Essen CTD diver, while wind speeds were obtained from a weather station located in Mulege.

Surface and near-bottom samples were collected from two sites in the middle of the bay in September when a strong thermocline isolated bottom waters. Samples were collected from about 1-m below the water surface and about 2 m above the sediments using a peristaltic pump. We attempted to use Mn-fiber to sample radium isotopes (see below), but the reducing bottom water dissolved the Mn oxide coating from the fiber as discussed elsewhere (Todd et al., 1988). Station 1 was 30 m deep (26° 42.678−; −111° 50.295′) and Station 2 (26° 39.929′′ −111° 48.189) was 35 m deep.

We relied on three types of samples to characterize the radon concentrations in groundwaters entering the bay: (1) existing wells on local ranches, (2) intertidal seeps, and (3) beach groundwater. The local wells were easily sampled using each owner's pump. The intertidal seeps were sampled at low tide using a peristaltic pump from small collection pools. Shallow beach groundwater was sampled using a stainless-steel drive point piezometer system (Charette and Allen, 2006). Samples for ^{222}Rn analysis were collected in special 8-L