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Time-series measurement of hydrothermal heat flux at the Grotto mound, Endeavour Segment, Juan de Fuca Ridge

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ABSTRACT

Continuous time-series observations are key to understanding the temporal evolution of a seafloor hydrothermal system and its interplay with thermal and chemical processes in the ocean and Earth interior. In this paper, we present a 26-month time series of the heat flux driving a hydrothermal plume on the Endeavour Segment of the Juan de Fuca Ridge obtained using the Cabled Observatory Vent Imaging Sonar (COVIS). Since 2010, COVIS has been connected to the North East Pacific Time-series Underwater Networked Experiment (NEPTUNE) observatory that provides power and real-time data transmission. The heat flux time series has a mean value of 18.10 MW and a standard deviation of 6.44 MW. The time series has no significant global trend, suggesting the hydrothermal heat source remained steady during the observation period. The steadiness of the hydrothermal heat source coincides with reduced seismic activity at Endeavour observed in the seismic data recorded by an ocean bottom seismometer from 2011 to 2013. Furthermore, first-order estimation of heat flux based on the temperature measurements made by the Benthic and Resistivity Sensors (BARS) at a neighboring vent also supports the steadiness of the hydrothermal heat source.

1. Introduction

The discovery of mid-ocean ridge hydrothermal systems in the 1970s and 1980s (e.g., Rona et al., 1975; Corliss et al., 1979; Spiess et al., 1980) has revolutionized our knowledge of the Earth's energy and geochemical cycles and their interconnections with biological processes. On a global scale, approximately 33% of the Earth's heat loss through the seafloor is transferred by hydrothermal circulation (e.g., German and Damm, 2006), which is an important source and sink for many geochemical species (e.g., Bickle and Elderfield, 2004). The reduced gases carried by hydrothermal outflows fuel chemosynthetic microbes that form the base of lush benthic fauna. The chemosynthetic microbes in turn alter the geochemical features of hydrothermal outflows and their impact on the global ocean (e.g., Govenar, 2012).

The coupling of submarine magmatic, tectonic, and hydrothermal processes has been a subject of intense study over the past several decades. A key research question under this theme is: how does the temporal evolution of a mid-ocean ridge hydrothermal system correlate with subseafloor magmatic heat supply and geological events? Long-term contemporaneous monitoring of seismic activity and venting intensity are two major observations needed to address this question. Heat flux, as a fundamental property of a hydrothermal system that relates to the magnitude of sub-seafloor heat sources, chemical flux, and biosphere conditions, is a benchmark variable for quantifying venting intensity.

Despite their importance, direct measurements of hydrothermal heat flux are scarce and characterized by large uncertainties (e.g. the heat flux of a vent field measured using different techniques can differ by up to an order of magnitude Ramondenc et al., 2006; Baker, 2007). Moreover, almost all the heat flux measurements made to date are either snapshots or repeated samples taken at year-long intervals. A rare exception is found in Goto et al. (2003), which presents a 7-month time series sampled every two days of the heat flux driving the hydrothermal plume above the central black smoker complex on the TAG mound, Mid-Atlantic Ridge. With this exception, most measurements provide little information on the temporal, especially short-term, variability of a hydrothermal heat source and its immediate response to geological events. Previous observations of hydrothermal effluent temperatures and chemical concentrations registered

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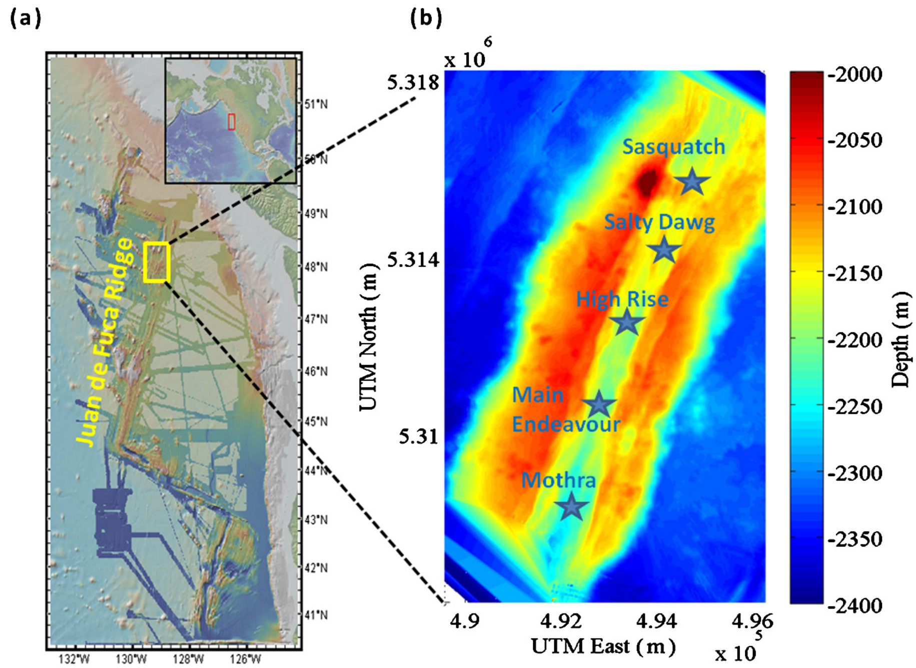

Fig. 1. (a) Bathymetric map created using GeoMapApp (http://www.geomapapp.org, Ryan et al., 2009) of the Juan de Fuca Ridge, an intermediate spreading center between the Juan de Fuca Plate on the right and the Pacific Plate on the left. The yellow block highlights the location of the Endeavour Segment. (b) Bathymetric map of the axial valley along the central Endeavour Segment with a resolution of 10 m. The blue stars mark the locations of 5 major vent fields. The bathymetric dataset was collected in 2012 using a ship-based multi-beam sonar (data courtesy of Karen Douglass from Ocean Networks Canada). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

profound perturbations caused by magmatic and tectonic events (e.g., Vondamm et al., 1995; Sohn et al., 1998; Baker et al., 1999; Johnson et al., 2000; Hooft et al., 2010). These perturbations in hydrothermal discharge had dramatic impact on vent macrofauna and subseafloor microorganisms (e.g., Johnson et al., 2000). However, the corresponding changes in hydrothermal heat sources or circulation patterns during an event remain unclear due to the lack of contemporaneous heat flux measurements.

The North East Pacific Time-series Underwater Networked Experiment (NEPTUNE) observatory is the world's first high-power (10 kW), high-bandwidth (10 Gbs) cabled observatory. Its installation at the Endeavour Segment of the Juan de Fuca Ridge via Ocean Networks Canada (http://www.oceannetworks.ca/installations/observatories/neptune-ne-pacific) enables scientists to study the temporal evolution of a hydrothermal system and its correlation with geological events through continuous long-term, high temporal resolution observations. In particular, by treating geological events as natural perturbation experiments, researchers can gain valuable insights into the subsurface hydrological structure and mechanisms underlying a hydrothermal system.

Underwater acoustics has been employed to acquire time-series measurements of the physical properties (e.g. flow rate, volume flux) of hydrothermal plumes in previous studies (e.g., DiIorio et al., 2005; Xu and DiIorio, 2012; Xu et al., 2013). In this paper, we report on a time-series measurement of hydrothermal heat flux acquired with the Cabled Observatory Vent Imaging Sonar (COVIS, Rona and Light, 2011; Xu et al., 2013), which is currently connected to the Endeavour node of the NEPTUNE observatory. Since its deployment in Sept. 2010, COVIS has been monitoring the hydrothermal plumes discharging from the Grotto mound, a hydrothermal vent cluster in the Main Endeavour Field (MEF) on the Endeavour Segment. By processing the acoustic data recorded by COVIS, we estimate the source heat flux driving the major plume above Grotto based on the classic plume model developed by Morton et al. (1956). The resultant 26-month, high-resolution (sampling rate ∼1 per day) heat flux time series is an unprecedented look at the temporal variability of a hydrothermal system.

2. Geological setting

The Endeavour Segment is located in the northern half of the Juan de Fuca Ridge, an intermediate spreading center between the Pacific Plate and the Juan de Fuca Plate (Fig. 1(a)). A ridge-parallel axial valley cleaves the central ridge crest and hosts five major hydrothermal vent fields (Fig. 1(b)). Multi-beam mapping of Endeavour at 1 m resolution by an autonomous underwater vehicle (AUV) discovered >800 active and inactive chimneys, some of which reach 50 m across and 50 m tall (Clague et al., 2008). Such intense hydrothermal venting is thought to be fueled by mining heat from the magma chambers beneath the vent fields (Wilcock et al., 2009). Besides robust venting activity, Endeavour is characterized by abundant seismic activity with hundreds of small earthquakes (<4 magnitude) detected annually (Weekly et al., 2013). The microearthquake patterns detected by a local ocean bottom seismometer (OBS) network showed a positive correlation between the rate of seismicity beneath the vent fields and their heat fluxes (Wilcock et al., 2009).

Among the five major vent fields at Endeavour, the Main Endeavour Field (MEF) has been a focus of extensive studies since its discovery in 1982 (Tivey and Delaney, 1986). Located near the western boundary wall of the axial valley at depths between 2000 and 2200 m, the MEF hosts a total of 21 venting sulfide edifices with the highest venting temperature between 370 and 390 °C (e.g., Clague et al., 2008; Delaney et al., 1992). The geographical distributions of these sulfide edifices form two clusters in the north and south. Besides the active sulfide structures, the vent field is flanked to the east by a 500-m long band of extinct sulfide deposit (Fig. 2). By dating the sulfide samples collected from the MEF using $^{226}Ra/Ba$ ratio, Jamieson et al. (2013) suggests hydrothermal venting at MEF has continued for at least 2400 years. The venting temperature, salinity, and chemistry at