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Hydrothermal deposition on the Juan de Fuca Ridge over multiple glacial–interglacial cycles

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ABSTRACT

Hydrothermal systems play an important role in modern marine chemistry, but little is known about how they may have varied on 100,000 year timescales. Here we present high-resolution records of non-lithogenic metal fluxes within sediment cores covering the last 500,000 years of hydrothermal deposition on the flanks of the Juan de Fuca Ridge. Six adjacent, gridded cores were analyzed by x-ray fluorescence for Fe, Mn, and Cu concentrations, corrected for lithogenic inputs with Ti, and normalized to excess initial ^{230}Th to generate non-lithogenic metal flux records that provide the longest orbitally resolved reconstructions of hydrothermal activity currently available. Fe fluxes vary with global sea level over the last two glacial cycles, suggesting higher hydrothermal deposition during interglacial periods. The observed negative relationship between Fe and Mn indicates variable sediment redox conditions and diagenetic remobilization of sedimentary Mn over time. Thus, Mn fluxes may not be a reliable indicator for hydrothermal activity in the Juan de Fuca Ridge sediment cores. Cu fluxes show substantial high-frequency variability that may be linked to changes in vent temperature related to increased magmatic production during glacial periods. Deglacial hydrothermal peaks on the Juan de Fuca Ridge are consistent with previously published records from the Mid-Atlantic Ridge and the East Pacific Rise. Moreover, on the Juan de Fuca Ridge, the deglacial peaks in hydrothermal activity are followed by relatively high hydrothermal fluxes throughout the ensuing interglacial periods relative to the previous glacial period.
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1. Introduction

Hydrothermal vents are unique biogeochemical environments in the deep ocean. More than a hundred modern hydrothermal systems have been discovered, in every ocean, at both divergent and convergent tectonic margins (e.g., Beaulieu et al., 2013). Despite their importance to the marine environment, however, little is known about how hydrothermal systems and their chemical fluxes may fluctuate and evolve over long timescales. Long-term (million-year) studies (e.g., Kuhn et al., 2000; Lyle et al., 1986) have demonstrated that hydrothermal activity responds to major tectonic events, such as spreading jumps and ridge reorganization, but these records do not have the resolution to investigate hydrothermal variability on orbital (10s–100s kyr) timescales. Reconstructions at higher resolution are critical for investigating the nascent hypothesis that glacial–interglacial sea level variability may influence mid-ocean ridge (MOR) systems. Lowering of global sea level during glacial periods would reduce the hydrostatic pressure on mid-ocean ridge melt centers (Huybers and Langmuir, 2009; Lund and Asimow, 2011), inducing an increase in melt production that might also generate vigorous hydrothermal venting and thicker ocean crust. Milankovitch cycles in ocean ridge bathymetry have been observed at the Southern East Pacific Rise (Tolstoy, 2015) and in the Australian–Antarctica Ridge (Crowley et al., 2015), but their relationship to climate remains contentious (Huybers et al., 2016; Olive et al., 2016a, 2016b, 2015; Tolstoy, 2016). Reconstructions of hydrothermal activity on the Mid-Atlantic Ridge (Middleton et al., 2016) and the East Pacific Rise (Lund et al., 2016; Lund and Asimow, 2011) reveal pulses of hydrothermal activity, but whether this phenomenon is globally representative and consistent across longer glacial–interglacial timescales as well as prior deglaciations remains unknown.

Furthermore, the integrity of metal fluxes as a proxy for hydrothermal activity has yet to be scrutinized with regards to

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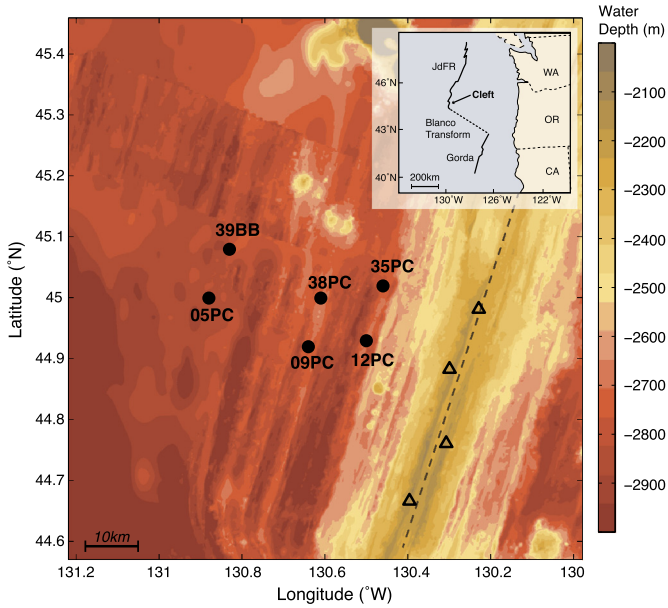

Fig. 1. Map of the study region. Bathymetric map of the Cleft Segment, with inset showing the geographic position of the Juan de Fuca Ridge in the Northeast Pacific Ocean. The ridge can be identified as the NE–SW trending bathymetric high (in yellow), and the axis is identified with a dashed line. AT26-19 core locations on the western flank of the ridge are shown with black dots. Triangles show the locations of known modern hydrothermal vents (Beaulieu et al., 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the elemental variability of hydrothermal chemistry at a mid-ocean ridge. Distinct chemical signatures in different hydrothermal sources can create ambiguity in interpreting trends in metal fluxes in ridge flank sediments. While modern vent systems appear to be relatively stable in terms of vent dynamics and plume chemistry over observational timescales (years to decades), these plume characteristics may not maintain stability over longer time periods (1,000s to 10,000s years). In this paper, we utilize a gridded suite of sediment cores on the Juan de Fuca Ridge to reconstruct elemental fluxes of Fe, Mn, and Cu in order to evaluate how hydrothermal activity has varied over multiple glacial cycles.

2. Materials & methods

2.1. Regional setting and core sites

The Juan de Fuca Ridge (JdFR) is located in the Northeast Pacific Ocean about 500 km off the coast of North America, and the Cleft Segment study area comprises the southern end of the JdFR system (Fig. 1). This intermediate spreading ridge (56 mm/yr; Wilson, 1993) is characterized by extensive hydrothermal activity and hot spot volcanism (Karsten and Delaney, 1989; Massoth et al., 1994; Normark et al., 1983). Modern hydrothermal activity on the Cleft Segment occurs within the axial cleft in hydrothermal fields at the north and south ends of the segment (Baker, 1994; Embley and Chadwick, 1994; Massoth et al., 1994). Typical plumes from these vents precipitate hydrothermal particles rich in Fe, Mn, and Cu (Feely et al., 1994), which have been observed as far as 100 km away from the ridge (Baker et al., 1985). Major eruptive events in the 1980s generated new pillow mounds and reinvigorated hydrothermal activity along the segment (Embley and Chadwick, 1994), and these observations are consistent with the expectation that hydrothermal activity may respond to increased magmatic activity (Baker and Hammond, 1992).

This study focuses on the long, stratigraphically intact records of six sediment cores (AT26-19-05PC, -09PC, -12PC, -35PC, -38PC, -39BB) collected on the SeaVOICE cruise of the R/V Atlantis in September 2014 to the JdFR (44.89–44.97°N, 130.50–130.88°W, 2678–2711 m). The cores form two transects extending west of the ridge, with 05PC and 39BB the farthest from the ridge (∼50 km), then 09PC and 38PC (28 km) and 12PC and 35PC as the closest to the ridge (18 km) (Fig. 1). Despite repeated attempts, cores were not recovered east of the ridge, possibly because the east side of the ridge is covered in a basalt flow that may be impenetrable to standard coring procedures. Age models for the sediment cores have been developed using benthic $\delta^{18}O$, coretop radiocarbon, and lithologic stratigraphy (Costa et al., 2016). The region exhibits highly variable sedimentation patterns, both spatially and temporally, with a large range of sedimentation rates (0.25–3.18 cm/kyr). Compositionally, the sediments show clear glacial–interglacial variations in dry bulk density (Costa et al., 2016) and mass flux (Costa and McManus, 2017) that largely reflect carbonate preservation cycles.

2.2. Analytical methodology for metal concentrations

Cu, Fe, Mn, and Ti intensities (count rates) were measured with an XRF core scanner (ITRAX, Cox Ltd., Sweden) at Lamont-Doherty Earth Observatory of Columbia University (LDEO). Split core surfaces were smoothed and covered with ChemPlex Proline transmission film to minimize desiccation during analysis. XRF was performed at 2 mm resolution, using an integration time of 2 s and a molybdenum x-ray source set to 30 kV and 45 mA. Several cores (05PC, 09PC, and 12PC) were measured with a similar XRF core scanner (ITRAX, Cox Ltd., Sweden) at Woods Hole Oceanographic Institution. Those analyses were performed at 4 mm resolution, using an integration time of 10 s and a molybdenum x-ray source set to 30 kV and 45 mA. Results are comparable between the two instruments and indicate high reproducibility in the XRF measurements (Supplementary Fig. 1). Data from the LDEO scans will be used throughout this paper to remain consistent between the six cores.

XRF intensities were calibrated using discrete measurements analyzed by flux fusion. Samples from 05PC, 09PC, and 12PC were selected to cover the full range of XRF intensities observed in each core, and Cu, Fe, Mn, and Ti concentrations were analyzed by flux fusion following the procedure of Murray et al. (2000). Dried, homogenized samples (100 ± 5 mg) were combined with lithium metaborate flux (400 ± 10 mg) in graphite crucibles and fused at 1050 °C for 8–10 min. The graphite crucibles were removed from the furnace and agitated to ensure aggregation of the fused material. After reheating to 1050 °C, the fused bead was dissolved in 10% HNO_3, agitated for approximately 10 min, and then filtered and diluted for analysis. Samples were analyzed on an Agilent 720 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) at LDEO, and ICP-OES intensity data were calibrated to concentrations with fluxed standard reference materials (JLS-1, JDO-1, SCO-1, AGV-2, DTS-2b, W-2a) (Supplementary Fig. 2). Relative standard deviations are based on ten total replicates of the VOICE internal megastandard (VIMS): ±6.2% for Cu, ±2.0% for Fe, ±3.6% for Mn, and ±1.8% for Ti. Flux fusion data are provided in Supplementary Table 1.

Empirical calibrations of the XRF data were generated by iterative reduced major axis (RMA) regression of the XRF intensities and discrete elemental data (Rousseau et al., 1996). The XRF records were smoothed at 1 cm scale and interpolated onto the depths of the discrete samples, and an initial RMA regression was performed. Outliers were identified as those data points greater than five standard deviations away from the initial regression. A second RMA regression was then recalculated on the dataset with the outliers removed. Overall the XRF and ICP data agree reasonably well ($r^2 = 0.88$ for Cu, $r^2 = 0.92$ for Fe, $r^2 = 0.87$ for Mn,

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