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How many vent fields? New estimates of vent field populations on ocean ridges from precise mapping of hydrothermal discharge locations

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ABSTRACT

Decades of exploration for venting sites along spreading ridge crests have produced global datasets that yield estimated mean site spacings of ∼12–220 km. This conclusion demands that sites where hydrothermal fluid leaks from the seafloor are improbably rare along the 66 000 km global ridge system, despite the high bulk permeability of ridge crest axes. However, to date, exploration methods have neither reliably detected plumes from isolated low-temperature, particle-poor, diffuse sources, nor differentiated individual, closely spaced (clustered within a few kilometers) sites of any kind. Here we describe a much lower mean discharge spacing of 3–20 km, revealed by towing real-time oxidation–reduction–potential and optical sensors continuously along four fast- and intermediate-rate (>55 mm/yr) spreading ridge sections totaling 1470 km length. This closer spacing reflects both discovery of isolated sites discharging particle-poor plumes (25% of all sites) and improved discrimination (at a spatial resolution of ∼1 km) among clustered discrete and diffuse sources. Consequently, the number of active vent sites on fast- and intermediate-rate spreading ridges may be at least a factor of 3–6 higher than now presumed. This increase provides new quantitative constraints for models of seafloor processes such as dispersal of fauna among seafloor and crustal chemosynthetic habitats, biogeochemical impacts of diffuse venting, and spatial patterns of hydrothermal discharge.

1. Introduction

Hydrothermal circulation is the dominant global agent for the transfer of heat, chemicals, and microbial life from the upper lithosphere to the ocean. The global fluxes of hydrothermal heat, hydrothermal fluids, and some (mostly conservative) hydrothermal chemical species from the neovolcanic zone of ocean spreading ridges (OSRs) are reasonably well estimated (e.g., Elderfield and Schultz, 1996). However, for many biological, chemical, and physical processes at the crust-ocean interface, a key variable in assessing the role of hydrothermal discharge is the number and spacing of distinct discharge sites ("vent fields") along the 66,000 km of OSRs. The spacing of hydrothermal oases is critical to understanding the dispersal of chemosynthetic fauna (McGillicuddy et al., 2010; Vrijenhoek, 2010; Beaulieu et al., 2015) and recruitment success after ecosystem disruptions such as seabed mining (Hilário et al., 2015) and seafloor eruptions. Interest in the nature and number of low-temperature (<∼50 °C), diffuse venting sites, especially those isolated from sites of higher-temperature discrete

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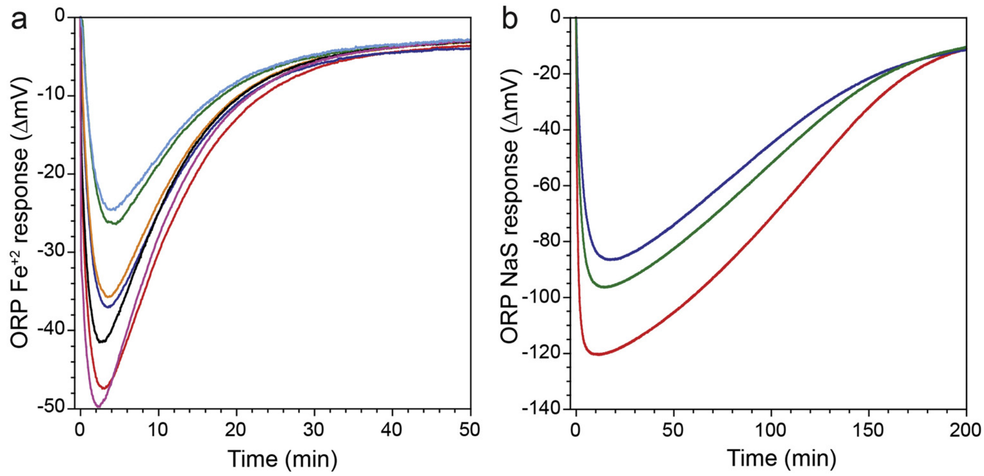

Fig. 1. Laboratory response of multiple ORP sensors in the same bath during a single exposure to (a) Fe^{+2} (dissolved ferrous ammonium sulphate) and (b) sulphide (dissolved NaS) (Walker et al., 2007). All ORP values are the raw (electric) potential reading of an inert Pt electrode against a KCl saturated Ag–AgCl reference electrode. Responses result in an immediate decline in voltage, followed by a lengthy recovery once the reduced chemicals are flushed from the bath; the sulphide cycle is longer than for Fe^{+2}. The recovery cycle does not affect the magnitude of subsequent responses. Values of individual sensors can vary by tens of millivolts, but absolute values are unimportant when using the sensor for only qualitative detection of hydrothermal plumes. Initial concentrations were ∼90 nM for Fe^{+2} and ∼800 nM for NaS. In-situ calibration is impossible because plumes contain varying mixtures of multiple reduced chemicals.

venting, is increasing because Fe may be preferentially supplied to the ocean interior by diffuse discharge (German et al., 2015; Larson et al., 2015). Furthermore, the location of seafloor discharge provides our only direct information on the distribution of hydrothermal upflow sites, and thus on the pattern of hydrothermal circulation in the shallow crust (Hasenclever et al., 2014).

Thirty-five years of exploration has yielded an inventory of >500 active discharge sites on OSRs (Beaulieu et al., 2013, 2015). These and other inventories rely on published descriptions of discharge sites, which commonly lump closely spaced sites (e.g., within 10 km; Hannington et al., 2011) into a single named site. Beaulieu et al. (2015) used these data to predict a total of ∼1300 ± 600 sites on OSRs. This prediction implies a mean site spacing ranging from 25 km at ultrafast spreading rates (150 mm/yr) to 90 km at ultraslow rates (10 mm/yr). Similarly, Hannington et al. (2011) calculated that the spacing between 70 massive sulfide deposits on OSRs ranges from 10–330 km over the entire spreading rate range, roughly increasing with decreasing spreading rate.

However, direct evidence from crustal measurements and seafloor observations challenges the perception that vent fields are widely separated. Borehole measurements imply that the uppermost layer of very young crust is fractured and open, with bulk permeability as high as 10^{-10} m^2 (Fisher and Becker, 2000). This permeability is seemingly inconsistent with spacings of tens of kilometers between discharge sites, especially along ridge sections underlain almost continuously with an axial melt lens. Visual surveys along ridge crests at length scales of 10–100 km are rare, but where available show that discharge sites are far more common than implied by the global statistics (Haymon et al., 1991; Auzende et al., 1996; O'Neill, 1998; Haymon and White, 2004).

We propose that the disagreement between these two views of hydrothermal site spacing is a product of sampling strategy and sensor capability. Mapping of discharge sites at the globally relevant 100–1000 km scale is based almost exclusively on the detection of dispersing, non-buoyant, hydrothermal discharge (e.g., German and Parson, 1998; Baker and German, 2004). Observations are occasionally continuous over several ridge segments (German and Parson, 1998; Baker et al., 2006) but more generally use discrete sampling at intervals of several to tens of kilometers (Son et al., 2014). In either case, mapping of discharge plumes predominantly relies on the detection of broadly dispersing, conservative (e.g., ^{3}He, temperature) or quasi-conservative (e.g., optical, particulate Fe, dissolved Mn, CH_4) tracers that can be detected many kilometers from their source. These tracers are highly sensitive to particle-rich, "black smoker" discharge, generally at temperatures >∼100 °C, but their broad dispersion makes it difficult to distinguish closely spaced sites with commingling plumes. Detecting isolated discharge with a negligible particle or dissolved metal signature (e.g., Lost City; Larson et al., 2015), or with disorganized flow that inhibits plume rise, is more problematical. Discrete sampling is apt to miss small sites, and temperature anomalies from such sites are commonly too weak to be reliably detected during a tow. In this paper, we use continuous tows of a sensor package sensitive to hydrothermal tracers both persistent and ephemeral, from sources both particle rich and particle poor, to show that the present vent field inventory along fast- to intermediate-rate spreading ridges may underestimate the true value by at least a factor of 3–6.

2. Methods and geological settings

2.1. Sensor characteristics

Our surveys employed sensors that respond to both broadly dispersing (light backscattering, measured as Nephelometric Turbidity Units (NTU)) and ephemeral (oxidation–reduction potential (ORP)) tracers. NTU detects particle-rich discharge, generally at temperatures >∼100 °C, with copious "black smoker" minerals that create plumes extending tens of kilometers from their source. ORP detects hydrothermal discharge of all temperatures, including low-temperature diffuse venting as well as higher-temperature but particle-poor sources. It responds immediately, with decreasing potential values (E(mV)), to the presence of nanomolar concentrations of reduced hydrothermal chemicals (e.g., Fe^{2+}, HS^-, H_2) that are out of equilibrium with the oxidizing ocean (Fig. 1) (Walker et al., 2007). These chemicals rapidly oxidize or metabolize in close proximity to their seafloor source. In this paper, an ORP anomaly is identified by dE/dt more negative than −0.04 mV/s for consecutive measurements with an overall decrease $(dE) > 2$ mV (e.g., Fig. 2b). This method differentiates anomalies from slowly changing ORP values caused by gradually drifting electrode potentials (either positive or negative) responding to changes in pressure, temperature, or electrode recovery following contact with reduced chemicals. The timescale for redox equilibration of plume fluids is