Deep-Sea Research II ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

Where are the undiscovered hydrothermal vents on oceanic spreading ridges?

Stace E. Beaulieu [a,*], Edward T. Baker [b], Christopher R. German [a]

[a] Woods Hole Oceanographic Institution, 266 Woods Hole Rd., Woods Hole, MA 02543, USA
[b] Joint Institution for the Study of the Atmosphere and Ocean—PMEL, University of Washington, Seattle, WA 98115, USA

ARTICLE INFO

Keywords:
Hydrothermal springs
Hydrothermal activity
Mid-ocean ridges
Spreading centers
Plate boundaries

ABSTRACT

In nearly four decades since the discovery of deep-sea vents, one-third of the length of global oceanic spreading ridges has been surveyed for hydrothermal activity. Active submarine vent fields are now known along the boundaries of 46 out of 52 recognized tectonic plates. Hydrothermal survey efforts over the most recent decade were sparked by national and commercial interests in the mineral resource potential of seafloor hydrothermal deposits, as well as by academic research. Here we incorporate recent data for back-arc spreading centers and ultraslow- and slow-spreading mid-ocean ridges (MORs) to revise a linear equation relating the frequency of vent fields along oceanic spreading ridges to spreading rate. We apply this equation globally to predict a total number of vent fields on spreading ridges, which suggests that ~900 vent fields remain to be discovered. Almost half of these undiscovered vent fields (comparable to the total of all vent fields discovered during 35 years of research) are likely to occur at MORs with full spreading rates less than 60 mm/yr. We then apply the equation regionally to predict where these hydrothermal vents may be discovered with respect to plate boundaries and national jurisdiction, with the majority expected to occur outside of states' exclusive economic zones. We hope that these predictions will prove useful to the community in the future, in helping to shape continuing ridge-crest exploration.

1. Introduction

Since the first observation of deep seafloor hot springs, or hydrothermal vents, at the Galápagos Rift in 1977, submarine hydrothermal activity has been studied in all ocean basins, over a wide range in depth, and in diverse volcanic and tectonic settings. Exploration was initially directed at fast-spreading mid-ocean ridges (MORs), focused by the presumption at that time that the comparatively weak magmatic budget of slow-spreading ridges would translate to negligible venting. Peter Rona offered a prominent and passionate dissent to this view, starting even before the Galápagos discoveries. In 1974, Peter and co-authors published the first paper hypothesizing the existence of a hydrothermal site on a slow-spreading ridge: TAG, near 26°N on the Mid-Atlantic Ridge (Scott et al., 1974). Over the next decade, Peter doggedly collected evidence that TAG not only provided a record of past hydrothermal discharge, but was presently active. His persistence was spectacularly rewarded in 1985 by the discovery of black smokers and a massive sulfide mound at TAG (Rona et al., 1986), a site “the size of the Houston Astrodome” in Peter's colorful language. This discovery opened the community's eyes to a wider geologic, chemical, and biological diversity than imagined along the global ridge crest. Fittingly, one of Peter's last publications was the landmark AGU Geophysical Monograph 188, which summarized decades of work on the diversity of hydrothermal systems on slow-spreading ridges (Rona et al., 2010). Our paper on the worldwide distribution of hydrothermal vents, written in the spirit of Peter's enthusiasm for exploration, is dedicated to his memory.

Motivations for the first hydrothermal discoveries were primarily in the geosciences and geared towards understanding seafloor spreading and the role of hydrothermal circulation in cooling of the ocean crust and as a source for heat and chemical fluxes to the ocean. The discovery of unique life endemic to deep-sea vents created an entirely new field of marine biology, expressed more recently in the efforts of the Census of Marine Life, to better understand the biogeography and connectivity between hydrothermal oases (Baker et al., 2010b; Moalic et al., 2012). These motivations continue, complemented by renewed commercial interest in the inventory and distribution of seafloor massive sulfide deposits (Hannington et al., 2011), and by advances in

* Corresponding author. Tel.: +1 508 289 3536.
E-mail address: stace@whoi.edu (S.E. Beaulieu).

http://dx.doi.org/10.1016/j.dsr2.2015.05.001
0967-0645/© 2015 Published by Elsevier Ltd.

quantifying vent discharge on chemical and biogeochemical cycling in the ocean (Amend et al., 2011; German and Seyfried, 2014).

Systematic surveys for hydrothermal activity, with a goal of locating active vent fields at the seafloor, have been reviewed at roughly decadal intervals, with previous compilations for the 1980's and 1990's (Baker et al., 1995; Baker and German, 2004). Here, we not only compile systematic hydrothermal surveys of mid-ocean ridges (MORs) and back-arc spreading centers (BASCs) during the 2000's, but also assign surveyed lengths to specific plate boundaries and national jurisdictions. In conjunction with the most recent data on locations of active vent fields (Beaulieu et al., 2013), we include new hydrothermal surveys along ultra-slow, slow, and BASC ridges to revise the equation for a linear relationship between vent field frequency and spreading rate. This linear relationship has been described as the magmatic budget hypothesis; i.e., variability in magma supply is the primary control on the large-scale hydrothermal distribution pattern along spreading ridges (Baker and German, 2004). Building on the assumptions of the magmatic budget hypothesis (Baker and German, 2004), we estimate the number of vent fields remaining to be discovered at spreading ridge axes. Further, and recognizing uncertainties in applying the global analysis to specific regions, we predict how many hydrothermal vents are likely to be discovered per MOR and BASC region and according to national jurisdiction within exclusive economic zones (EEZs). We provide these results in the context of national and commercial interests in seafloor hydrothermal deposits as potential mineral resources and also in the context of connectivity and biogeography of vent-endemic fauna.

2. A global inventory of surveyed spreading ridges

In this global compilation, we explicitly relate systematic hydrothermal surveys on MORs and BASCs to the submarine oceanic spreading ridge (OSR) "digitization steps" and a subset of continental rift boundary (CRB) steps in the PB2002 model of plate boundaries (Bird, 2003). We use 1968 digitization steps in our analysis, with a mean length of 36 km and length range from 1 km to 103 km (Supplementary information). For 46 of the 52 plates in the PB2002 model (Bird, 2003), active submarine vent fields are known from at least one boundary (Fig. 1, Supplemetary Table 1). A re-analysis of surveyed strike length using the PB2002 model (Bird, 2003) confirms that as of the previous review (Baker and German, 2004), ~20% of the global ridge crest had been at least sparsely surveyed for hydrothermal activity, including 22% of the ~60,000 km of MORs but only 11% of ~11,000 km of BASCs (Supplementary Table 1; see Supplementary information for categorization of survey density).

In the past decade, an additional 12% of the global ridge crest was systematically surveyed at least sparsely for hydrothermal activity, bringing the total surveyed to one-third of the global strike length (Supplementary Table 1). In this study, eight recently surveyed, non-hotspot portions of the global ridge crest, plus one earlier survey, have been added (and another was extended) to prior syntheses to revise the equation for a linear relationship between vent field frequency and spreading rate. Six of these newly surveyed regions reflect national and commercial interests in assessing the potential for seafloor mineral deposits (Table 1A). Much of the recent effort was directed toward BASCs, which are now 35% surveyed as compared to 32% of MORs (Table 1, Supplementary Table 1). Systematic hydrothermal surveys in the past

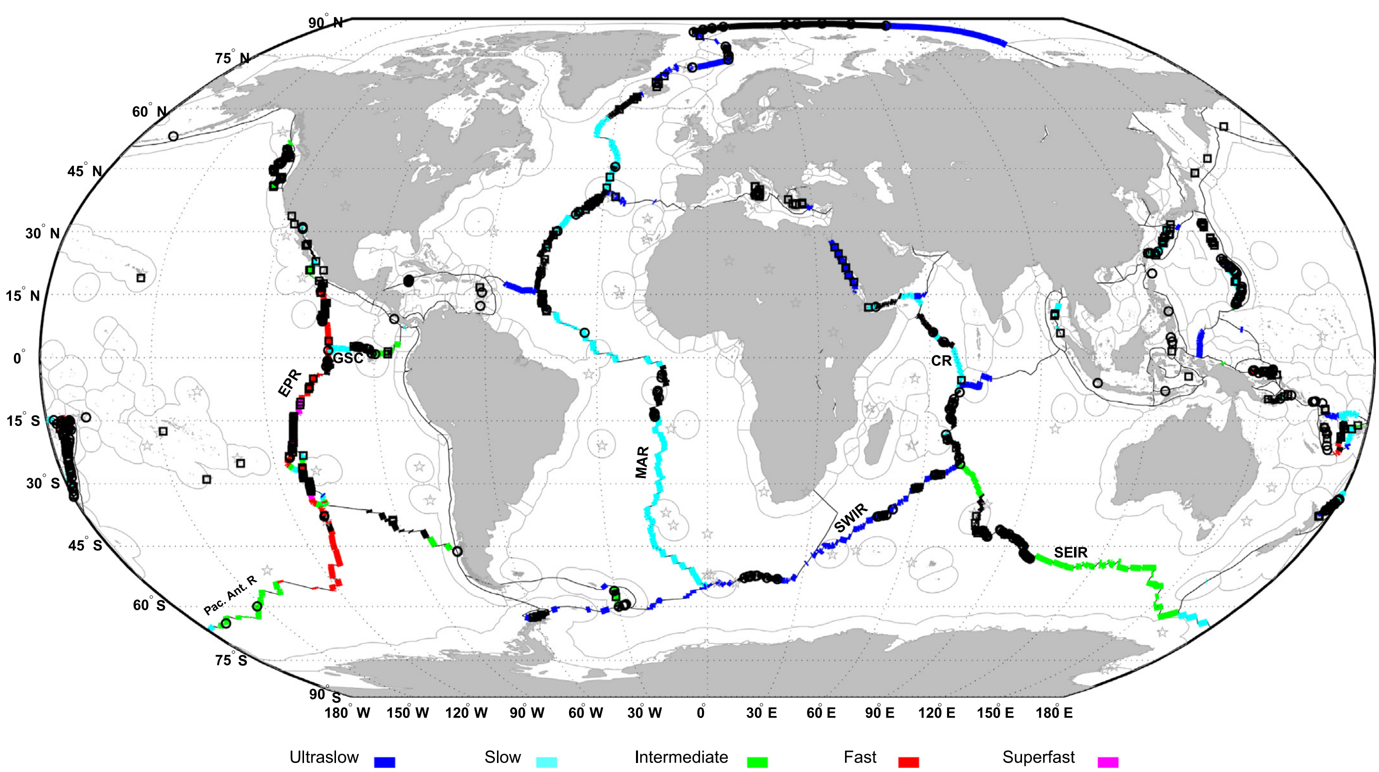

Fig. 1. Map depicting portions of the global ridge crest remaining to be systematically surveyed for hydrothermal activity. Global map with color indicating spreading rate categorized to ultraslow (<20 mm/yr), slow (20–55 mm/yr), intermediate (55–80 mm/yr), fast (80–140 mm/yr), or superfast (>140 mm/yr) for steps in the PB2002 model (Bird, 2003) that have *not* been surveyed for hydrothermal activity (surveyed steps are plotted black). Other plotted datasets include plate boundaries (Bird, 2003) (thin black line), EEZs (VLIZ, 2009) (thin gray line), confirmed and inferred active vent fields in all tectonic settings [black open: square=discovered prior to year 2000, circle=discovered during or after year 2000; note: this includes 48 more vent fields than in Beaulieu et al., (2013)], and hotspots (Husson and Conrad, 2012) (gray open star). Labels: CR, Carlsberg Ridge; EPR, East Pacific Rise; GSC, Galápagos Spreading Center; MAR, Mid-Atlantic Ridge; Pac. Ant. R, Pacific Antarctic Ridge; SEIR, Southeast Indian Ridge; SWIR, Southwest Indian Ridge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Please cite this article as: Beaulieu, S.E., et al., Where are the undiscovered hydrothermal vents on oceanic spreading ridges? Deep-Sea Res. II (2015), http://dx.doi.org/10.1016/j.dsr2.2015.05.001