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Helium, heat, and the generation of hydrothermal event plumes at mid-ocean ridges

John E. Lupton [a,*], Edward T. Baker [b], Gary J. Massoth [b,1]

[a] *NOAA Pacific Marine Environmental Laboratory, Hatfield Marine Science Center, Newport, OR 97365, USA*
[b] *NOAA Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115, USA*

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Abstract

Hydrothermal event plumes are unique water-column features observed over mid-ocean ridges, presumably generated by the sudden release of large volumes of hot, buoyant fluid. Although the specifics of event plume generation are unknown, event plumes have been attributed to the rapid emptying of a hydrothermal reservoir or to rapid heat extraction from a recently emplaced dike or seafloor lava flows. The chemical and thermal signatures of event plumes as compared to the underlying steady-state plumes offer important clues to the generation of event plumes. Event plumes have low ^{3}He/heat ratios of $\sim 0.4 \times 10^{-17}$ mol J^{-1}, similar to vent fluids from mature hydrothermal systems. In contrast, the steady-state plumes found beneath the event plumes have elevated and variable ^{3}He/heat ratios of 2 to 5×10^{-17} mol J^{-1}. Fluids collected directly over fresh lava flows have even higher ^{3}He/heat ratios of 2 to 8×10^{-17} mol J^{-1}, up to 30 times the event plume values. These disparate ^{3}He/heat ratios place strong constraints on models of event plume generation, especially models which rely on heat extraction from seafloor eruptions. Published by Elsevier Science B.V.

Keywords: geothermal systems; plumes; mid-ocean ridges; He-3; heat flow; Juan de Fuca Ridge

1. Introduction

The discovery of a large event plume over the southern Juan de Fuca Ridge (JdFR) in 1986 was the first indication that a portion of the convective heat flux from mid-ocean ridges is released episodically rather than by continuous steady-state venting [1]. This 1986 event plume, or megaplume, (originally designated MPI, now EP86A) was some 20 km in diameter, 600 m thick, centered about 800 m above the seafloor, and contained about 10^{17} J of excess heat, equivalent to the annual thermal output of a typical ridge-crest hydrothermal system. The unusual features of this plume, especially its high heat content, exceptional rise height, and three-dimensional symmetry led Baker et al. [1] to conclude that EP86A was generated by a sudden, brief, and massive release of hot, buoyant fluid rather than by the continuous venting that produces conventional hydrothermal plumes. In fact, Baker et al. [1] found such a conventional plume beneath EP86A. Since the discovery of EP86A, other event plumes of similar size, rise height, and symmetry have been observed over the Juan de Fuca Ridge in 1987 and

* Corresponding author. E-mail: lupton@pmel.noaa.gov
1 Present address: Institute of Geological and Nuclear Sciences, 30 Gracefield Road, Lower Hutt, New Zealand.

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1993 [2,3], in the North Fiji Basin in 1987 [4], and over the northern Gorda Ridge in 1996 [5]. Several models have been proposed for the generation of event plumes, including the rapid emptying of a hydrothermal reservoir [1,6–8], and rapid heat extraction from a recently emplaced dike [9] or seafloor lava flows [10]. Recently, Palmer and Ernst [11] have proposed a physical model of how an event plume could be generated directly by the cooling of pillow basalts erupted on the seafloor. In this paper we discuss several observational constraints on any models describing event plume generation, with particular emphasis on the unique signatures of helium and heat in event plumes as compared with steady-state plumes, especially those found immediately above the fresh lava flows that typically accompany dike intrusions.

2. Helium and heat signatures in event plumes

Lupton et al. [12] measured the concentrations of ^{3}He and ^{4}He in EP86A as well as in the underlying steady-state plume. Both plumes contained excess helium and heat, and the end-member helium isotope ratio, determined as the slope of a linear fit to ^{3}He concentration versus ^{4}He concentration, was identical in the two plumes. As expected, this end-member ^{3}He/^{4}He ratio was 1.10×10^{-5}, the same as found in pillow basalts from the southern JdFR [13]. This indicates that the helium in both plumes and in the basalts had a common origin in the local magma supply. In contrast to the uniform helium isotope ratio, the apparent ratio of ^{3}He to hydrothermal heat [2] in the underlying steady-state plume was $^3\mathrm{He}/\Delta T = 4.7 \times 10^{-17}$ mol J^{-1}, 14 times higher than the value of $^3\mathrm{He}/\Delta T = 0.3 \times 10^{-17}$ mol J^{-1} recorded in the event plume. This was a surprising result, since both helium and heat are conservative tracers presumably originating in the mantle, and therefore these tracers are expected to occur in constant proportions in mid-ocean ridge volcanic/hydrothermal systems. Furthermore, once a fluid mixture is vented into the deep ocean, the $^3\mathrm{He}/\Delta T$ ratio in the plume remains more or less constant, since turbulent mixing dilutes the concentrations of conservative tracers in proportion (see footnote 2). Thus it is implausible that the differing $^3\mathrm{He}/\Delta T$ ratios in the two plumes were produced by some mechanism in the ocean water column. Consequently, Lupton et al. [12] interpreted the widely different ^{3}He/heat ratios as evidence that the event plume and the underlying steady-state plume were generated by completely different mechanisms in the ocean crust. They proposed that the variation in ^{3}He/heat ratios was produced by a combination of differing water/rock ratios and differential extraction rates for helium and heat during the interaction between water and hot crustal rocks. Alternatively, it is possible that two different thermal regimes regulate the release of magmatic ^{3}He and heat: one associated with freely degassing surfaces of liquid magma at temperatures >1000ºC, the other with brittle fracturing in solidifying rock at temperatures <800ºC [15].

Since 1986, the bimodal ^{3}He/heat ratios observed on the southern JdFR have been found at several other sites (Table 1). In every case where helium data are available, the event plumes had $^3\mathrm{He}/\Delta T$ ratios falling in a narrow range of 0.3 to 0.4×10^{-17} mol J^{-1}, while the underlying steady-state plumes had elevated and variable $^3\mathrm{He}/\Delta T$ ratios of 2 to 7×10^{-17} mol J^{-1}. Surprisingly, an inventory of mature, quiescent-phase hydrothermal systems from various mid-ocean ridge systems shows that fluids from most have ^{3}He/heat $\sim 0.5 \times 10^{-17}$ mol J^{-1}, slightly higher but very similar to an event plume ^{3}He/heat signature [12]. Thus it is the elevated ^{3}He/heat ratio in the steady-state plumes which is anomalous, while the event plumes have a 'normal' ^{3}He/heat signature (see Fig. 3). Furthermore, these anomalously high values have been found to decline as a vent field ages. Baker and Lupton [19] for example, found that the $^3\mathrm{He}/\Delta T$ ratio in the steady-state plume at the EP86A site decreased from 4.7×10^{-17} mol J^{-1} to

[2] It is not possible to directly measure the excess heat ΔQ introduced into the water-column by hydrothermal venting. However, ΔQ can be estimated by calculating the temperature anomaly ΔT, which is the deviation of potential temperature θ from the linear mixing relationship between θ and potential density σ_θ. In the deep waters of the northeast Pacific, ΔT underestimates ΔQ by about 30 to 40% because of the entrainment of cold deep water that occurs during the ascent of buoyant hydrothermal plumes. We have not made any explicit correction for this entrainment effect in this paper. Therefore, uncorrected water-column measurements are reported as $^3\mathrm{He}/\Delta T$ rather than ^{3}He/heat ratios to avoid confusion. See Lavelle et al. [14] for a detailed discussion of these entrainment effects.

Table 1
Helium and heat in plumes and hydrothermal vent fluids

Feature	Location	Date	ΔT_{max} (ºC)	$^3He/\Delta T$ (10^{-17} mol J^{-1})	References
Event plumes					
EP86A	Cleft Segment, SJdFR	8/86	0.25	0.32	[1,12]
EP87A	Cleft Segment, SJdFR	9/87	0.20	0.32	[2]
EP93A	CoAxial Segment, NJdFR	7/93	0.14	0.32	
EP93B	CoAxial Segment, NJdFR	7/93	0.17	0.33	[3,16]
EP93C	CoAxial Segment, NJdFR	7/93	0.20	0.34	
EP96A	Northern Gorda Ridge	4/96	0.12	0.40	
EP96B1 [a]	Northern Gorda Ridge	6/96	0.035	0.43	[5,17,18]
EP96B2 [a]	Northern Gorda Ridge	8/96	0.07	0.43	
Steady-state plumes (associated with megaplume events)					
Under EP86A	Cleft Segment, SJdFR	8/86	0.06	4.7	
	Cleft Segment, SJdFR	9/87	0.04	2.6	[12,19]
	Cleft Segment, SJdFR	9/88	0.07	1.4	
Under EP93A/B	CoAxial Segment, NJdFR	7/93	0.06	1.7	[3,16]
Under EP93C	CoAxial Segment, NJdFR	7/93	0.08	1.8	
Under EP96A	Northern Gorda Ridge	4/96	0.06	3.4	[5,18]
Under EP96B	Northern Gorda Ridge	6/96	0.04	2.0	
Samples over fresh lava flows					
Tow T93B09	CoAxial Segment, NJdFR	7/93	0.27	2.2	[3,16]
Cast V96B12	Northern Gorda Ridge	6/96	0.02	6.1	[5,18]
Cast V98W01	Axial Seamount	7/98	0.12	7.5	[20,21]
Hydrothermal vent fluids (from mature sites) [b]					
Galapagos Site	Galapagos Rift	1977	20	0.52	[22]
21ºN Site	East Pacific Rise	1979	350	0.43–0.61	[23,24]
13ºN Site	East Pacific Rise	1982, 1984	>300	0.71–1.47	[25]
Cleft Segment	S. Juan de Fuca Ridge	1984	285	0.53	[26,27]
TAG 26ºN	Mid-Atlantic Ridge	1993, 1995	360	0.5 –1.3	[28,29]
Snake Pit 23ºN	Mid-Atlantic Ridge	1986	350	0.57–1.3	[29]
Lucky Strike 37ºN	Mid-Atlantic Ridge	1993	325	0.51–0.77	[30]

[a] EP96B1 and EP96B2 are thought to be the same event plume observed 60 days apart [5,17].
[b] For vent fluids, the ^3He/heat ratios have been corrected for the specific heat of 3.2 wt% NaCl solution using the data of Bischoff and Rosenbauer [31]. At 350ºC, 260 bar, $C_p = 6.41$ J g^{-1} K^{-1} compared with 4.19 J g^{-1} K^{-1} for water at 25ºC.

1.3×10^{-17} mol J^{-1} between 1986 and 1988, appearing to reset toward values typical of mature vent fields.

Phase separation is known to play a major role in defining the gas contents and chemical composition of hydrothermal fluids [10], and it is likely that at least part of the observed variations in $^3He/\Delta T$ in the water-column plumes is caused by boiling. Based on theoretical calculations and on actual measurements of vent fluids, the condensed vapor phase of a phase-separated fluid is enriched in volatiles and has elevated ^3He/heat. Thus the fluids which are most likely to have been affected by boiling are those which produce the steady-state plumes observed beneath the event plumes.

Lupton et al. [12] derived a theoretical ^3He/heat ratio for the upper mantle by assuming that >90% of the ^4He is produced by radioactive decay of U and Th, and that ^4He and heat are generated in the ratio of 1.7×10^{-12} mol J^{-1} by the α-decay series. Using a $^3He/^4He$ ratio of 1.1×10^{-5}, which is the average value observed in mid-ocean ridge basalts, they calculated an average upper mantle ^3He/heat ratio of $\sim 2 \times 10^{-17}$ mol J^{-1} [12]. In order to apply this estimate to mid-ocean ridges, one must assume that helium and heat are not fractionated during transport in the upper mantle. Although this theoretical value is higher than the ^{3}He/heat ratio in mature hydrothermal systems, it falls in the middle of the overall range observed at mid-ocean ridges (Table 1). Thus, if one averages over the life cycle of mid-ocean ridge hydrothermal systems, ^{3}He and heat may be supplied at the theoretical ratio of 2×10^{-17} mol J^{-1}.

3. Discussion

The unfailing association between event plumes, dike injections, and lava eruptions [32–39] makes it clear that the generation of event plumes is somehow connected to seafloor spreading events. In the case of EP86A, a fresh lava flow was discovered using bathymetric differencing techniques [32,33] and later confirmed with submersible observations on the seafloor [34]. Beginning in 1993, acoustic monitoring of the northeast Pacific using the US Navy hydrophone array provided real-time detection of magma injection events on the Juan de Fuca–Gorda Ridge system [35,36]. Dike injections on the CoAxial segment of the northern JdFR in 1993 and on the northern Gorda Ridge in 1996 were detected from the pattern of seismic T-wave source locations migrating along the ridge axis [35–37]. Rapid response cruises within 10 days to both areas discovered water-column event plumes and seafloor lava flows [3,5,35,38]. A similar pattern of migrating T-wave signals indicated a dike injection event on Axial Volcano on the central JdFR during January, 1998 [40]. Although no event plumes were observed, fresh lava flows and increased intensity of hydrothermal venting were detected within the Axial Volcano caldera [20,41]. The fact that the response cruise to Axial Volcano occurred 18 days after the T-wave event may explain the absence of a clearly defined event plume.

The apparent connection between the eruption of fresh magma and event plumes makes it tempting to attribute their genesis to heat extraction either from the injected dike [9] or the erupted pillow basalts [10,11]. However, the ^{3}He/heat results make it difficult to explain event plume generation simply by heat extraction from seafloor lava flows or dikes. As shown in Table 1, water samples collected immediately above fresh lava flows have the highest ^{3}He/ΔT ratios of any samples collected thus far, just the opposite of the 'normal' ^{3}He/ΔT ratios in the event plumes. For example, about 5 weeks after the onset of the 1996 Gorda Ridge event, hydrographic cast V96B12 collected water directly over the new lava flow found underneath event plume EP96A. The bottom bottles in this cast sampled a warm water layer highly enriched in ^{3}He (see Fig. 1). This layer, apparently originating from seawater interacting with the lava flow, had $^3\text{He}/\Delta T = 6.1 \times 10^{-17}$ mol J^{-1}, the highest ^{3}He/heat ratio observed for any sample collected after the 1996 Gorda Ridge event. Similarly high ^{3}He/heat ratios have been found in two other instances in which water samples were collected directly over recent lava flows associated

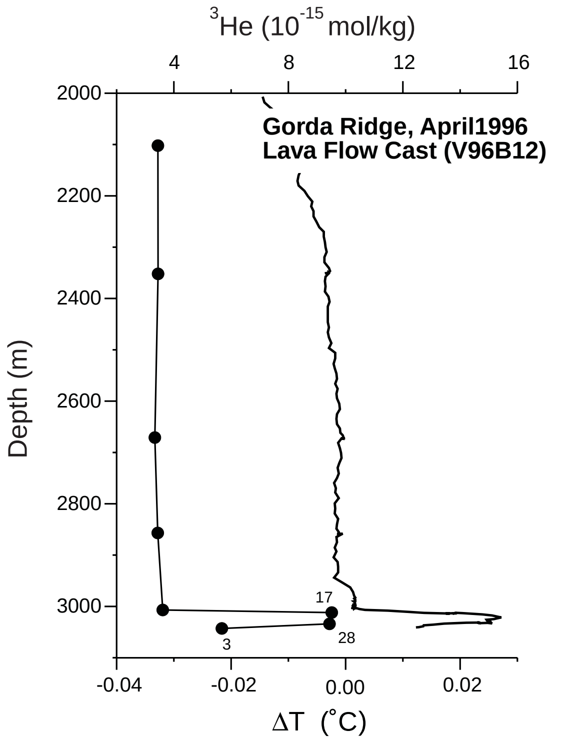

Fig. 1. Vertical profile of ^{3}He concentration (dots) and temperature anomaly ΔT (see footnote 2) (solid line) from hydrocast V96B12 directly over the recent lava flow on the northern Gorda Ridge. This cast was collected about 5 weeks after the onset of the Gorda Ridge event. The bottom ~40 m of the cast penetrated a warm water layer which is also highly enriched in ^{3}He. The small numbers, which also appear on Fig. 2a, refer to the individual sampling bottles closed within the bottom layer.

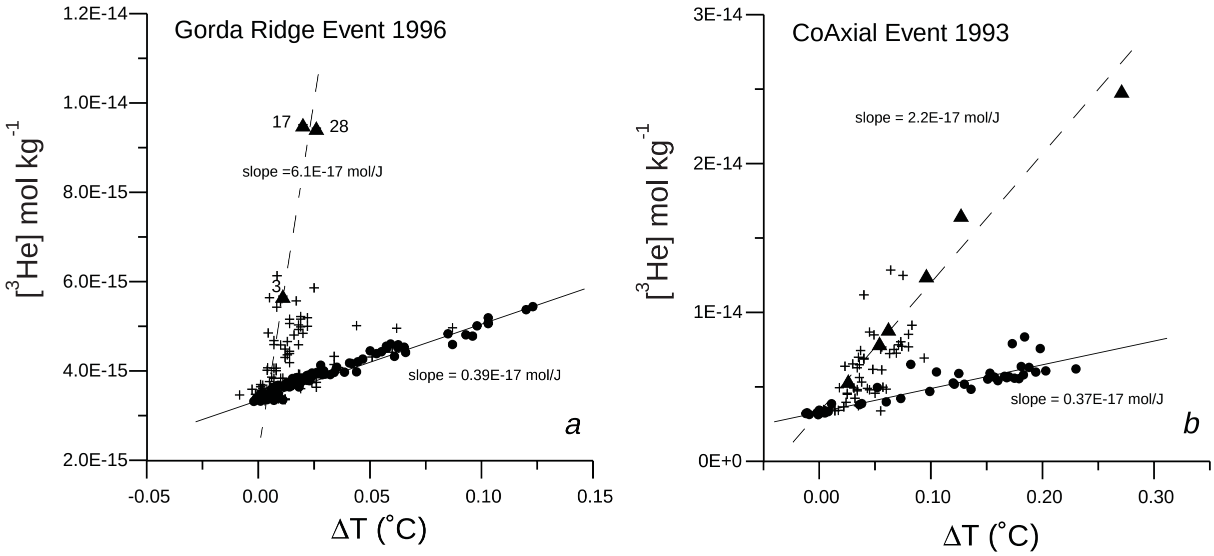

Fig. 2. (a) ^{3}He concentration versus temperature anomaly ΔT for samples collected in February through June 1996 during the Gorda Ridge event. Dots denote megaplume samples; plus signs denote samples from steady-state plumes; and triangles denote samples collected directly over the recent lava flow. Solid and dashed lines are separate linear least-squares fits to the megaplume and lava flow sample sets, respectively. The fitted slopes correspond to the ^{3}He/ΔT in the end-member hydrothermal fluid. Small numbers refer to the bottle numbers from the lava flow cast (see Fig. 1). Data from Lupton et al. [17], Kelley et al. [18] and J.E. Lupton [unpubl. data]. (b) Similar plot of ^{3}He concentration versus ΔT for samples collected in June through August 1993 during the event on CoAxial Segment, northern Juan de Fuca Ridge. Symbol designations are the same as for (a). Data from Lupton et al. [16].

with volcanic/hydrothermal events (see Table 1 and Figs. 2 and 3).

While it may be energetically feasible to create event plumes by heat extraction from seafloor pillow basalts over a ~10-day cooling period [11], any successful model of event plume generation must also explain many unique physical and chemical characteristics of event plume formation. If lava flows generate event plumes, then the fluids created by seawater cooling of the lava pillows must transform in a matter of days from low ^{3}He/ΔT ratios that supply event plumes to very elevated ^{3}He/ΔT ratios. Other chemical transitions must also occur. In addition to uniform ^{3}He/heat ratios, event plumes also have a uniform Mn/heat ratio of ~0.1 nM/J [42], roughly an order of magnitude lower than typical for steady-state plumes and for samples collected immediately over fresh lava flows [42,43]. While most of the heat available in the mapped lava flows at Cleft, CoAxial, and Gorda Ridge would be needed to produce the event plumes at those sites [5], the associated Mn requires only a few percent alteration of the pillows, depending on the efficiency of the seawater leaching [11]. The sensitive dependence of Mn/heat ratios on water/rock ratio and leaching temperature [44,45] thus demands that these conditions be perhaps unrealistically consistent within each lava flow during the short formation period in order to produce the uniform Mn/heat ratios observed among event plumes. A similar argument applies to the very uniform ^{3}He/heat ratios observed in event plumes, since ^{3}He/heat would be expected to be similarly sensitive to water/rock ratios.

An additional complication is the possible interaction between steady-state and event plumes. Palmer and Ernst [11] suggest that entrainment of steady-state plumes could contribute significantly to the Mn and Fe inventory of event plumes. Entrainment of the intense steady-state plumes found at each eruption site [1,3,5,41] would be extensive over a many-day period of event plume formation. Large-scale entrainment produces the same difficulty as pillow alteration: the entrained plumes at each site must be nearly identical in both composition and volume (rel-

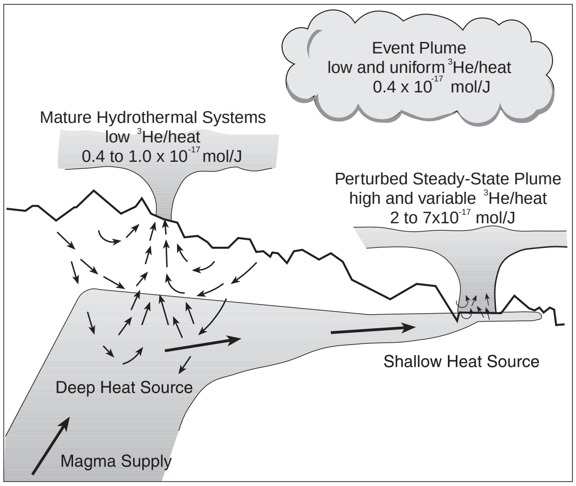

Fig. 3. Cartoon summarizing the ^{3}He/heat signatures which have been repeatedly observed in mature hydrothermal systems, in event plumes, and in the 'perturbed' steady-state plumes associated with event plumes. Figure derived from a similar figure in Butterfield et al. [10].

ative to the event plume) to produce uniform event plumes. This requirement is not so difficult for Fe, as Fe/heat ratios vary little between plumes at eruption sites, but substantial for the order-of-magnitude variations common for Mn/heat [42,43].

Additional data bearing on this problem have come from microbiological analysis of event plume samples. Summit and Baross [46] detected thermophilic organisms in samples from event plumes EP96A and EP96B from the 1996 Gorda Ridge event. Since these are anaerobic organisms which grow at temperatures of 50–90ºC, they concluded that these microbes could not have grown in the event plume after formation. This implies that these thermophiles and some portion of the event plume fluids themselves were derived from a pre-existing subseafloor reservoir [46].

4. Conclusions

These arguments indicate to us that the simplest model for event plume generation remains one in which the entry of magma into the crust causes a sudden increase in permeability, allowing hydrothermal fluid already resident in the crust to escape [1,6–8,19]. In this scenario, the escaping mature hydrothermal fluid creates the event plume, and the interaction between circulating seawater and the newly created dike or lava flow produces the anomalous steady-state plumes.

One way to solve the mystery of event plume generation would be to directly observe and sample event plume fluids as they escape from the seafloor. This observation is difficult to make, since most plume models indicate that event plume fluids are released within a period of hours to days [47]. If event plumes are observed in the absence of recent seafloor eruptions, this would eliminate lava flows as the source of water-column event plumes. Eventually, the construction of more robust models incorporating the effects of time-dependent extraction of heat and chemicals from hot rock will help to resolve the problem of event plume genesis.

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References

[1] E.T. Baker, G.J. Massoth, R.A. Feely, Cataclysmic hydrothermal venting on the Juan de Fuca Ridge, Nature 329 (1987) 149–151.
[2] E.T. Baker et al., Episodic venting of hydrothermal fluids from the Juan de Fuca Ridge, J. Geophys. Res. 94 (1989) 9237–9250.
[3] E.T. Baker et al., Hydrothermal event plumes from the CoAxial seafloor eruption site, Juan de Fuca Ridge, Geophys. Res. Lett. 22 (1995) 147–150.
[4] Y. Nojiri, J. Ishibashi, T. Kawai, A. Otsuki, H. Sakai, Hydrothermal plumes along the North Fiji Basin spreading axis, Nature 342 (1989) 667–670.
[5] E.T. Baker, Patterns of event and chronic hydrothermal

venting following a magmatic intrusion: new perspectives from the 1996 Gorda Ridge eruption, Deep-Sea Res. II 45 (1998) 2599–2618.
[6] J.R. Cann, M.R. Strens, Modeling periodic megaplume emission by black smoker systems, J. Geophys. Res. 94 (1989) 12227–12237.
[7] L.M. Cathles, A capless 350ºC flow zone model to explain megaplumes, salinity variations, and high-temperature veins in ridge axis hydrothermal systems, Econ. Geol. 88 (1993) 1977–1988.
[8] W.S.D. Wilcock, A model for the formation of transient event plumes above mid-ocean ridge hydrothermal systems, J. Geophys. Res. 102 (1997) 12109–12121.
[9] R.P. Lowell, L.N. Germanovich, Dike injection and the formation of megaplumes at ocean ridges, Science 267 (1995) 1804–1807.
[10] D.A. Butterfield et al., Seafloor eruptions and evolution of hydrothermal fluid chemistry, Philos. Trans. R. Soc. London A 355 (1997) 369–386.
[11] M.R. Palmer, G.G.J. Ernst, Generation of hydrothermal megaplumes by cooling of pillow basalts at mid-ocean ridges, Nature 393 (1998) 643–647.
[12] J.E. Lupton, E.T. Baker, G.J. Massoth, Variable ^{3}He/heat ratios in submarine hydrothermal systems: evidence from two plumes over the Juan de Fuca Ridge, Nature 337 (1989) 161–164.
[13] J.E. Lupton et al., Helium isotope variations in Juan de Fuca Ridge basalts, Geophys. Res. Lett. 20 (1993) 1851–1854.
[14] J.W. Lavelle, E.T. Baker, G.J. Massoth, On the calculation of total heat, salt, and tracer fluxes from ocean hydrothermal vents, Deep-Sea Res. II 45 (1998) 2619–2636.
[15] W.F. Giggenbach, Magma degassing and mineral deposition in hydrothermal systems along convergent plate boundaries, Econ. Geol 87 (1992) 1927–1944.
[16] J.E. Lupton et al., Variations in water-column ^{3}He/heat ratios associated with the 1993 CoAxial event, Juan de Fuca Ridge, Geophys. Res. Lett. 22 (1995) 155–158.
[17] J.E. Lupton et al., Tracking the evolution of a hydrothermal event plume with a RAFOS neutrally-buoyant drifter, Science 280 (1998) 1052–1055.
[18] D.S. Kelley, M.D. Lilley, J.E. Lupton, E.J. Olson, Enriched H_2, CH_4, and ^{3}He concentrations in hydrothermal plumes associated with the 1996 Gorda Ridge eruptive event, Deep-Sea Res. II 45 (1998) 2665–2682.
[19] E.T. Baker, J.E. Lupton, Changes in submarine hydrothermal ^{3}He/heat ratios as an indicator of magmatic/tectonic activity, Nature 346 (1990) 556–558.
[20] R.W. Embley et al., Time series investigations of an active volcano: the NeMO Project, EOS 79 (Suppl.) (1998) F921.
[21] J.E. Lupton et al., Anomalous helium and heat signatures associated with the 1998 Axial volcano event, Juan de Fuca Ridge, EOS 79 (Suppl.) (1998) F922.
[22] W.J. Jenkins et al., Excess ^{3}He and ^{4}He in Galapagos submarine hydrothermal waters, Nature 272 (1978) 156–159.
[23] J.E. Lupton, Helium-3 and manganese at the 21ºN East Pacific Rise hydrothermal site, Earth Planet. Sci. Lett. 50 (1980) 115–127.
[24] J.A. Welhan, H. Craig, Methane, hydrogen and helium in hydrothermal fluids, in: K. Bostrom, L. Laubier, P. Rona, K. Smith (Eds.), Hydrothermal Processes at Seafloor Spreading Centers, Plenum, New York, 1983, pp. 391–409.
[25] L. Merlivat et al., Hydrothermal vent waters at 13ºN on the East Pacific Rise: isotopic composition and gas concentration, Earth Planet. Sci. Lett. 84 (1987) 100–108.
[26] W.C. Evans et al., Geochemistry of some gases in hydrothermal fluids from the southern Juan de Fuca Ridge, J. Geophys. Res. 93 (1988) 15305–15313.
[27] B.M. Kennedy, Noble gases in vent water from the Juan de Fuca Ridge, Geochim. Cosmochim. Acta 52 (1988) 1929–1935.
[28] J.L. Charlou et al., Gases and helium isotopes in high-temperature solutions sampled before and after ODP Leg 158 drilling at TAG hydrothermal field (26ºN, MAR), Geophys. Res. Lett. 23 (1996) 3491–3494.
[29] M.D. Rudnicki, H. Elderfield, Helium and radon at the TAG and Snakepit hydrothermal vent fields, 26º and 23ºN, Mid-Atlantic Ridge, Earth Planet. Sci. Lett. 133 (1992) 307–321.
[30] P. Jean-Baptiste et al., Mantle ^{3}He in hydrothermal vents and plume of the Lucky Strike site (MAR 37º17′N) and associated geothermal heat flux, Earth Planet. Sci. Lett. 157 (1998) 69–77.
[31] J.L. Bischoff, R.J. Rosenbauer, An empirical equation of state for hydrothermal seawater (3.2 percent NaCl), Am. J. Sci. 285 (1985) 257–263.
[32] W.W. Chadwick Jr., R.W. Embley, C.G. Fox, Evidence for volcanic eruptions on the southern Juan de Fuca Ridge between 1981 and 1993, Nature 350 (1991) 416–418.
[33] W.W. Chadwick Jr., R.W. Embley, Lava flows from a mid-1980s submarine eruption on the Cleft segment, Juan de Fuca Ridge, J. Geophys. Res. 99 (1994) 4761–4776.
[34] R.W. Embley, W.W. Chadwick Jr., Volcanic and hydrothermal processes associated with a recent phase of seafloor spreading at the northern Cleft segment, Juan de Fuca Ridge, J. Geophys. Res. 99 (1994) 4741–4760.
[35] C.G. Fox et al., Acoustic detection of a seafloor spreading episode on the Juan de Fuca Ridge using military hydrophone arrays, Geophys. Res. Lett. 22 (1995) 131–134.
[36] R.P. Dziak, C.G. Fox, A.E. Schreiner, The June–July 1993 seismo-acoustic event at CoAxial segment, Juan de Fuca Ridge: evidence for a lateral dike injection, Geophys. Res. Lett. 22 (1995) 135–138.
[37] C.G. Fox, R.P. Dziak, Hydroacoustic detection of volcanic activity on the Gorda Ridge, February–March 1996, Deep-Sea Res. II 45 (1998) 2513–2530.
[38] R.W. Embley et al., Initial results of the rapid response to the 1993 CoAxial event: relationships between hydrothermal and volcanic processes, Geophys. Res. Lett. 22 (1995) 143–146.
[39] W.W. Chadwick Jr., R.W. Embley, T.M. Shank, The 1996 Gorda Ridge eruption: geologic mapping, sidescan sonar,

and SeaBeam comparison results, Deep-Sea Res. II 45 (1998) 2547–2570.
[40] R.P. Dziak, C.G. Fox, Hydroacoustic detection of submarine volcanic activity at Axial Volcano, Juan de Fuca Ridge, January 1998, EOS 79 (Suppl.) (1998) F921.
[41] E.T. Baker et al., The 1998 volcanic eruption at Axial volcano: hydrothermal plumes monitoring from moored instruments and shipborne response cruises, EOS 79 (Suppl.) (1998) F922.
[42] G.J. Massoth et al., Manganese and iron in hydrothermal plumes resulting from the 1996 Gorda Ridge event, Deep-Sea Res. II 45 (1998) 2683–2712.
[43] G.J. Massoth et al., Observations of manganese and iron at the CoAxial seafloor eruption site, Juan de Fuca Ridge, Geophys. Res. Lett. 22 (1995) 151–154.
[44] W.E. Seyfried, M.J. Mottl, Hydrothermal alteration of basalt by seawater under seawater-dominated conditions, Geochim. Cosmochim. Acta 46 (1982) 985–1002.
[45] W.E. Seyfried Jr., D.R. Janecky, Heavy metal and sulfur transport during subcritical and supercritical hydrothermal alteration of basalt: influence of fluid pressure and basalt composition and crystallinity, Geochim. Cosmochim. Acta 49 (1985) 2545–2560.
[46] M. Summit, J.A. Baross, Thermophilic subseafloor microorganisms from the 1996 north Gorda Ridge eruption, Deep-Sea Res. II 45 (1998) 2751–2766.
[47] J.W. Lavelle, The initial rise of a hydrothermal plume from a line segment source: results from a three-dimensional numerical model, Geophys. Res. Lett. 22 (1995) 159–162.