



Detection of an unusually large hydrothermal event plume above the slow-spreading Carlsberg Ridge: NW Indian Ocean

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[1] About 90% of Earth's volcanism occurs along the global mid-ocean ridge system. Here, sporadic volcanic and tectonic activity is thought to cause cataclysmic release of hydrothermal fluids, forming event plumes. Each plume often contains as much hydrothermal effluent and heat as chronic hydrothermal venting from a typical vent site discharges during a year. To date, only a few event plumes have been detected, and only above intermediate-rate spreading ridges in the Pacific. Here, we report the first evidence for an unusually large event plume that originated from the slow-spreading (3 cm/yr full-rate) Carlsberg Ridge in the NW Indian Ocean. At 70 km long, up to 4540 km³ in volume and with up to 24×10^{16} J of excess heat, this event plume was substantially larger than previous ones and demonstrates that dispersion of hydrothermal heat and biological products from slow spreading ridges may be more significant and effective than hitherto imagined. **Citation:** Murton, B. J., E. T. Baker, C. M. Sands, and C. R. German (2006), Detection of an unusually large hydrothermal event plume above the slow-spreading Carlsberg Ridge: NW Indian Ocean, *Geophys. Res. Lett.*, 33, L10608, doi:10.1029/2006GL026048.

1. Introduction

[2] Submarine hydrothermal activity is a major conduit for transferring heat from the Earth's interior, and thus plays an important role in global ocean heat and chemical budgets [Baker and German, 2004]. Some of the most spectacular features of this activity are event plumes (EP's): boluses of tens of cubic kilometers of warm and turbid water, apparently triggered by seafloor volcanic and tectonic activity [Baker *et al.*, 1987]. While individual EP's contain hundreds of times more heat than steady-state (i.e., chronic) hydrothermal plumes, they have been observed only rarely and exclusively above intermediate spreading-rate (5.5–8 cm/yr full-rate) mid-ocean ridges (MOR's) in the Pacific Ocean [Baker, 1998; Nojiri *et al.*, 1989]. Hence their global significance remains uncertain. While a transient thermal event on the Mid-Atlantic Ridge was inferred from temperature excursions [Murton and Redbourn, 2000], the question remains how EP's are manifest at other spreading rates and, specifically, at slow spreading ridges (that constitute more than half the global MOR system). The significance of

EP's goes beyond mere novelty. They dissipate a greater proportion of heat compared to their dissolved chemical content than chronic high-temperature hydrothermal venting. Thus their occurrence at slow spreading ridges would extend this mode of hydrothermal circulation to a significantly greater proportion of the global MOR system. EP's may also provide the essential mechanism whereby large numbers of larvae of hydrothermal vent fauna can simultaneously escape the confining topography of slow spreading ridges to colonize distant, alternative sites.

2. Results

[3] In July 2003, CTD (Conductivity Temperature Depth) and MAPR (Miniature Autonomous Plume Recorder) casts were made over the Carlsberg Ridge, NW Indian Ocean. The instruments were inter-calibrated by deployment at the same station. Both types of instruments measured optical backscatter (OBS) and temperature, while salinity and water samples were acquired exclusively by CTD. In total, 36 vertical casts (including up and down profiles of up to 4 km apart) were made at 18 separate stations along the ridge axis. Sea conditions allowed occupation of only one full ocean depth CTD-rosette station, from which sixteen water samples were collected.

[4] OBS anomalies from 12 vertical profiles (Figure 1a) defined an exceptionally large, particle-rich plume (termed here: CR2003) overlying at least 70 km of the ridge crest between 61°30'E, 5°41'N and 60°33'E, 6°20'N (Figure 1b). Where found (on 23–24th July, 2003) CR2003 appeared similar in all profiles: being 700–1000 m thick and with peaks in OBS at 2330 m, 2500 m, 2700 m and 2900 m. Its top reached 2200 m, some 1200–1400 m above the rift floor and well clear the axial walls. These observations indicated a continuous plume originating from a common source. Toward the northwest (profile WP6 at 60°56'E, 6°03'E) both OBS and temperature increased steadily downward to the seafloor, indicating the origin of CR2003 from the crest of a 40 km-long axial volcanic ridge (Figure 1c).

[5] Potential temperature (θ) and salinity (S) data revealed θ/S ratios within CR2003 that were distinctly different from the background water column (Figure 2). At a given potential density (σ_{2500}), referenced to a depth of 2500 m, CR2003 was both colder and less saline than background, a feature typical for neutrally buoyant hydrothermal plumes in the deep Atlantic and Indian oceans [Speer and Rona, 1989; Rudnicki and German, 2002]. Isohaline estimates of excess temperature ($\Delta\theta$), calculated by deviations from the linear θ/S of the background water column [McDougall, 1990; Thurnherr and Richards, 2001], correlated closely with increasing OBS and yielded a maximum excess temperature of +0.07°C (Figure 2b).

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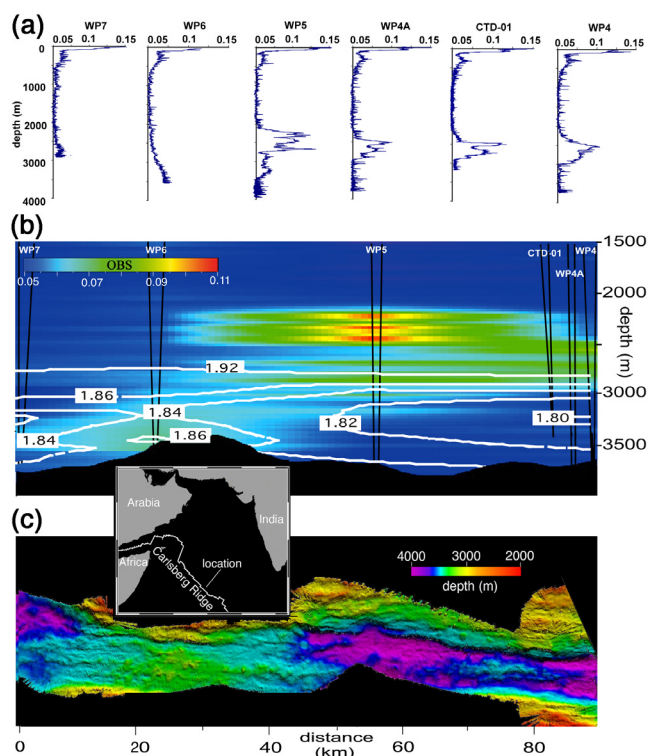


Figure 1. (a) Vertical profiles of optical backscatter (OBS) expressed as NTUs (nephelometric turbidity units) showing a common structure and depth for the particulate plume. (b) Colored 2D plot of OBS and in situ temperature (white contours annotated in °C), with locations of up and down casts (black lines) made at each station (annotated), along 90 km of the crest of the Carlsberg Ridge, over a period of 43 hours. The profiles were collected using CTD (Conductivity Temperature Depth) and MAPR (Miniature Autonomous Plume Recorder) instruments. These recorded temperature, depth and optical backscattering anomalies. The black silhouette indicates the sea floor topography. (c) Multibeam swath bathymetry showing second order ridge segments forming basins floored by axial volcanic ridges and flanked by 800–1000 m high axial walls.

Concentrations of manganese and iron also correlated with increases in both $\Delta\theta$ and OBS throughout the vertical profile occupied by the CTD rosette (Figure 2c).

[6] The only known mechanism for injecting a bolus of water with excess temperature, depleted salinity, and elevated manganese and iron concentrations high above an MOR is hydrothermal activity. The excess iron alone indicates local provenance (iron readily oxidizes and settles after flocculating). Alternative origins – such as Red Sea outfall advected for over 1000 km to the Carlsberg Ridge – would yield warm but salty water, without elevated concentrations of dissolved metals. Likewise resuspended pelagic sediment would lack both a salinity and temperature anomaly.

3. Interpretation

[7] While CR2003 had many characteristics typical of neutrally buoyant plumes from high-temperature hydrother-

mal discharge [Baker *et al.*, 1995], it also had some important differences, being: wider (e.g. ~ 70 km compared with 5–15 km), arose higher (1000–1400 m vs. 150–250 m), and thicker (700–1000 m vs. 100–250 m). In these respects it more closely resembled EP's of the type described from the Pacific Ocean [e.g., Baker *et al.*, 1989], although the latter were a third smaller (~ 20 km in diameter).

[8] Diagnostically, EP's are distinguished from chronic hydrothermal plumes by a TDMn/heat ratio of <0.15 nMol/J (compared with an average of 0.25), indicating higher rates of heat transfer for corresponding rates of chemical ex-

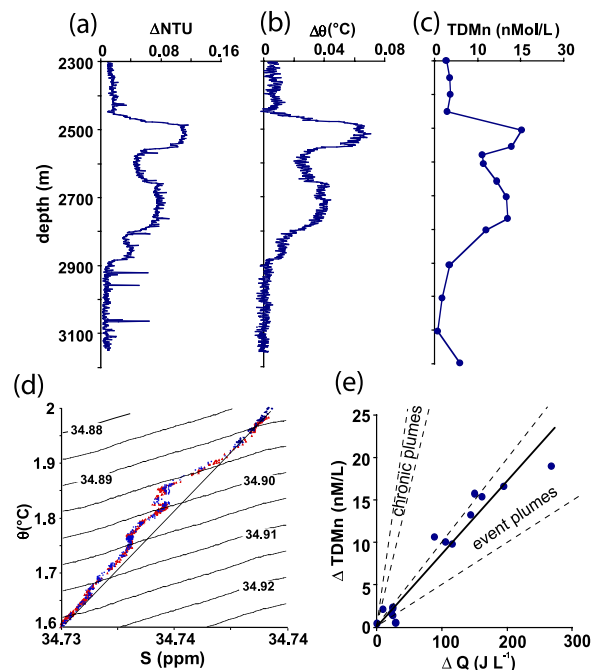


Figure 2. Vertical profiles determined at hydrographic station CTD-01 showing (a) the anomalies in optical backscatter (Δ NTU). (b) Excess temperature ($\Delta\theta$) calculated from the deviation of θ from its bi-linear mixing relationship with S (e.g., Figure 2d) as expressed immediately above and below plume depth [Thurnherr and Richards, 2001]. Such isohaline estimates of $\Delta\theta$ assume purely geothermal heating and are subject to $\sim 40\%$ error caused by uncertainties in the salinity of the discharged hydrothermal effluent and the variable entrainment of bottom water [Lavelle and Baker, 1994]. (c) Total dissolvable manganese (TDMn), analysed by graphite furnace atomic absorption spectroscopy following pre-concentration by complexation with dithiocarbamate and solvent extraction with chloroform [Bruland *et al.*, 1979; Statham, 1985]. (d) Isopycnal contours of potential density (labeled as g L⁻¹ m⁻¹ + 1000), mapped to a reference pressure of 250 bar, show water within CR2003 was less saline (S) and of lower potential temperature (θ) than background water of similar density. (e) Excess total dissolvable manganese (Δ TDMn) correlates with excess heat (Δ Q) indicating a high temperature, hydrothermal source. Δ TDMn/heat in CR2003 falls within the field of known EP's and well below the field for hydrothermal plumes emanating from chronic 'black smokers' [Massoth *et al.*, 1998].

Table 1. Comparison Between CR2003 and Other MOR Event Plumes^a

Event Plume	MOR Location	Heat, 10 ¹⁵ J	Mn/Heat, nMol J ⁻¹	Fe/Mn	Size, km	Riseheight, m	Thickness, m
EP86A ^b	SJdFR	89	0.11 ± 0.03	7.6 ± 2.1	20	1000	600
EP87A ^c	SJdFR	32	0.08 ± 0.01	1.8 ± 0.3	16	500	600
KAIYO87 ^d	NFB	ND	0.031	ND	ND	900	500
EP93A ^c	NJdFR	4.1	0.14 ± 0.08	6.9 ± 1.5	10	1100	400
EP93B ^f	NJdFR	10	0.16 ± 0.01	4.3 ± 0.8	5	1000	400
EP93C ^f	NJdFR	18	0.11 ± 0.03	4.5 ± 1.1	5	700	600
EP96A ^g	GR	21	0.11 ± 0.02	5.7 ± 1.2	12	700	600
EP96B ^g	GR	5.1	0.1 ± 0.02	7.4 ± 0.9	5	600	500
CR2003	CR	74–240	0.08 ± 0.02	5.1 ± 0.7	>70	1400	700–1000

^aSJdFR is the Southern Juan de Fuca Ridge; GR is the Gorda Ridge; NFB is North Fiji Basin, and CR is the Carlsberg Ridge.

^bBaker et al. [1987], ^cBaker et al. [1989], ^dNojiri et al. [1989], ^eMassoth et al. [1994], ^fMassoth et al. [1995], ^gMassoth et al. [1998].

change [Massoth et al., 1995, 1998]. The heat content per unit volume (Q) is calculated from $\Delta\theta$ by:

$$Q = \rho C_p \Delta\theta_i \quad (1)$$

Where: Q is in Joules, ρ is the density of seawater at an ambient pressure of 250 bars at 2°C (e.g. 1029 kg L⁻¹), C_p is the specific thermal capacity of seawater at 250bars (4100 J/Kg), and $\Delta\theta_i$ is the calculated excess temperature at depth interval i [Bischoff and Rosenbauer, 1985; Gill, 1982].

[9] Equation (1) yields a mean Q of 139 J/L for CR2003, between 2450 m and 2900 m, with a maximum of 284 J/L occurring at 2500 m, coincident with the largest OBS signal. Significantly, CR2003 had a TDMn/heat ratio of 0.08 ± 0.03 nMol/J, placing it well within the field of known EP's [Massoth et al., 1995, 1998] (Figure 2e).

[10] While CR2003 overlay at least 70 km of the Carlsberg Ridge crest, all previously observed EP's were axisymmetric and less than 20 km wide. Experimental and numerical simulations give an explanation for this limitation [Lavelle, 1995; Woods and Bush, 1999]: elongate EP's rapidly form a string of axisymmetric rotational eddies each with a radius, in deep-ocean conditions, of approximately 10 times the plume's rise-height. Assuming CR2003 comprised a series of quasi-merged eddies, with a length (L) greater than an individual eddy radius (R), its volume (V) can be approximated by:

$$V = \Sigma(\pi z R_i L_i / 2) \quad (2)$$

Where z is the thickness, R is the radius, L is the length of each layer between depth intervals (i), and the outer boundary of each layer is where $\Delta\theta_i > 0.001^\circ\text{C}$.

[11] And the volume for each depth interval (i) is approximated by:

$$V_i = \pi z R_i L_i / 2 \quad (3)$$

Equations (2) and (3) are used to derive a lower estimated volume for CR2003 of ~1,500 km³. Alternatively, an upper estimate follows if we assume CR2003 had a normal axisymmetric shape. This is calculated by substituting L/2 for R in equations (2) and (3) above and yields ~4,500 km³. From this, the total heat content (H) of the plume is approximated by:

$$H = \Sigma Q_i V_i \quad (4)$$

where Q_i is the average heat content for the plume volume (V_i) between each depth interval (i).

[12] In the absence of S and $\Delta\theta$, Q is inferred from its correlation with excess OBS (Δn):

$$Q = 200\Delta n, (r^2 = 0.88) \quad (5)$$

From equations (1) to (5), the heat content of CR2003 is estimated between 7.4×10^{16} J and 2.4×10^{17} J. The propagated error in both cases is ±40%, largely as a result of uncertainty in $\Delta\theta$.

[13] These heat contents allow calculation of the equivalent volume of basaltic magma (V_b) that has cooled from its liquid temperature to the ambient temperature of the bottom water:

$$V_b = H / [\rho_m(C_{p_m}\Delta T_m + L) + \rho_b(C_{p_b}\Delta T_b)] \quad (6)$$

where: H is the heat content of the plume, ρ_m , C_{p_m} and L are the density (2700kg m⁻³), specific heat (1000 J kg⁻¹ C⁻¹) and latent heat of crystallization (4×10^5 J kg⁻¹) of basaltic magma at 8 wt. % MgO respectively and (ΔT_m) is the temperature difference between eruption (1200°C) and solidification (1000°C); ρ_b is the density (3000kg m⁻³) and C_{p_b} the specific thermal capacity (1100 J kg⁻¹ C⁻¹) of the solid basalt and ΔT_b the temperature difference between solidification (1000°C) and the bottom water (2°C).

[14] Equation (6) yields an estimated volume of basaltic magma of between $1.7 \pm 0.7 \times 10^7$ m³ (i.e., 0.03 km³) and $5.5 \pm 2.2 \times 10^7$ m³ (i.e. 0.1 km³); equivalent to a 2m thick circular flow of between 1.7 and 3 km in radius, or a dike 1 m wide by 2 km high and between 9 and 27 km long.

4. Discussion

[15] While the chemical and thermal similarity of CR2003 to previous EP's formed above intermediate spreading MOR's (Table 1) implies a common mode of origin, CR2003's unusually large size suggests EP formation is sensitive to spreading rate.

[16] Brittle failure of the shallow crust causing a sudden release of warm hydrothermal fluid [e.g., Cann and Strens, 1989] is unlikely to have generated CR2003 or other EP's, which are chemically distinct from high-temperature hydrothermal effluent (having lower metal/heat [Massoth et al., 1995] and helium/heat ratios [Lupton et al., 1999]). Assuming a mean temperature in layer 2A of 50°C [Henstock et al., 1993] and a porosity of 15% [Jacobson, 1992], CR2003 would require between 3.5 and 13×10^8 m³ of warm (50°C) fluid, released from between 2.8 and 8.6 km³ of

rock. But it is unclear whether such a bolus of warm fluid would arise 1000 to 1400 m [Turner and Campbell, 1987; Lupton, 1995].

[17] Alternatively, Palmer and Ernst [1998] proposed a compelling model for EP formation by the eruption of pillow lavas, citing experiments that produced Mn/Heat ratios, from quenching basalt, within the known range for EP's [Seyfried and Mottl, 1982]. The model also predicts EP magnitude to vary proportionally with eruption volume. The latter is thought to scale inversely with spreading rate [Perfit and Chadwick, 1999], probably as a result of the coupled thermal and mechanical properties of spreading ridges, where strain is proportional to opening stress multiplied by the height of a dike [Jacoby and Higgs, 1995]. Because dike height is thought to relate to the thickness of the brittle lid [Smith and Cann, 1993], a thicker lid on slow spreading ridges results in greater magma overpressure and less frequent but wider dikes feeding larger eruptive volumes. Thus the unusually large size of CR2003 may be a common feature of slow spreading ridges.

[18] The relationship between spreading rate and the magnitude of an EP may also play an important role in the biogeography and diversity of hydrothermal vent invertebrates. Gene flow between slow spreading MOR hydrothermal sites is thought to depend particularly on the ability of larvae to escape topographic and hydrographic barriers, such as deep axial valleys and fracture zones [Mullineaux and France, 1995; Van Dover et al., 2002; Tyler and Young, 2003]. This has been shown for the Mid-Atlantic Ridge where larval dispersion is strongly restricted by the deep and enclosing rift walls [Murton et al., 1999]. Yet as MOR topography becomes more rugged with decreasing spreading rate, a corresponding increase in eruption volume can trigger larger magnitude EP's (like CR2003), which entrain greater numbers of larvae and rise higher above the rift walls where they can be steered by currents flowing parallel to the underlying topography [Thurnherr and Richards, 2001]. Thus EP's might provide the essential mechanism for vent fauna to escape *en mass*, migrate and ultimately colonize widely separated hydrothermal vent sites along slow-spreading MOR's.

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