Detection of hydrothermal plumes on the northern Mid-Atlantic Ridge: results from optical measurements

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Abstract

Several water column surveys conducted on the northern Mid-Atlantic Ridge have been instrumental in the discovery of three new hydrothermal venting sites, and seven other active segments. Hydrothermal sources have yet to be pinpointed in six of these segments. In this study, the observed frequency of high-temperature venting from 23°N to 41°N on the Mid-Atlantic Ridge (MAR), a distance of approximately 1900 km, is one venting system per 150 km of ridge. Combining these data with those of other investigators for the region from 12°N to 41°N leads to an approximate venting frequency of one site per 90 km of ridge, although venting frequencies on sections of the MAR within this region are as high as one site per 25 km. To support this frequency of venting, and considering the larger dimensions of the MAR rift valley, the ratio of axial to off-axis heat loss must be higher on the MAR than on faster spreading ridges. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Hydrothermal plumes from high-temperature vents are dynamic features produced by the venting of hot, chemically-rich, buoyant fluids. As these fluids cool, precipitates rapidly form. Plumes of dissolved and particulate material rise several hundred meters above the sea floor before reaching neutral buoyancy and spreading laterally, at which point they continue to display physical and chemical signatures distinctly different from background seawater. Opti-

cal instruments provide a rapid method for detecting these plumes in situ by measuring the concentrations of particles in the water column. Hydrothermal plumes also integrate the output from an entire vent field, including some output from diffuse venting which is entrained into plumes. Thus, the detection of hydrothermal plumes in the water column can be used to prospect for new sites of hydrothermal activity ([1], and references therein) as well as to predict characteristics of the venting site [2,3].

The first observations of high-temperature hydrothermal vents on the Mid-Atlantic Ridge (MAR) were made in 1985 at the TAG (Trans-Atlantic Geotraverse) hydrothermal field at 26°08′N [4,5] and the Snake Pit (MARK, Mid-Atlantic Ridge south of Kane) site at 23°22′N [6–8]. Water column obser-

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Table 1
Cruise chronology

Cruise	Ship	Dates	Active segments
FAZAR	*R/V Atlantis II*	Aug.–Oct. 1992	Lucky Strike
			AMAR
			AMAR Minor
			South AMAR
			FAMOUS
			North Oceanographer
			South Oceanographer
			Rifted Mountain
			South Kurchatov
KASP	*RRS Charles Darwin*	Feb.–Mar. 1993	Broken Spur
CD77	*RRS Charles Darwin*	Mar.–Apr. 1993	TAG
			Snakepit
			Broken Spur
HEAT	*RSS Charles Darwin*	Sept. 1994	Lucky Strike
			FAMOUS
			AMAR
Bridget	*RSS Charles Darwin*	Sept. 1994	AMAR (Rainbow)

vations since that time have indicated that there are other active hydrothermal areas; however, documentation of these sites has been difficult due in part to the large-scale dimensions of the MAR rift valley. Until 1992, TAG and Snake Pit remained the only known sites of hydrothermal activity on the MAR. It is still the common view that the MAR, with its slow spreading rates (average 1.3 cm y^{-1} half rate; [9]), is host to less hydrothermal activity than the faster spreading, more intensely studied ridges such as the East Pacific Rise (EPR) and Juan de Fuca Ridge (JdFR) [10]. These assumptions are based on the idea that slower spreading rates are indicative of lower magma supply rates (i.e., less magmatic activity), while frequent magmatic replenishments are required to support a high venting frequency [10]. Based on this scenario, the common view holds that the MAR should contribute less to the global oceanic heat and mass budgets, even though it makes up approximately one third of the 55 000 km long global mid-ocean ridge system. It is clear from data presented here and from the work of others [11–16] that the occurrence of high-temperature hydrothermal activity is not uncommon on the northern MAR, and possibly is as frequent as on faster spreading sections of the global ridge system. Therefore, it is likely that the northern MAR supplies a significant amount of heat and chemicals to the ocean, and

these fluxes should be accounted for in the global inventory.

Data presented here are from deployment of the Oregon State University ZAPS (Zero Angle Photon Spectrometer, [17]) instrument package during five cruises on the MAR: FAZAR (FARA program; Aug.–Oct. 1992; 33° to 41°N), KASP (BRIDGE program; Feb.–Mar. 1993), CD77 (BRIDGE program; Mar.–Apr. 1993), HEAT (MARFLUX/ATJ project; Sept. 1994) and Bridget (BRIDGE program; Sept. 1994). Three new hydrothermal sites were located during these cruises, and seven other ridge segments showed strong evidence of high-temperature hydrothermal activity (Table 1). This paper will treat only those data collected using the OSU instrument package, although complementary data in this region were collected by other investigators on these same cruises and others.

2. Data collection

The ZAPS instrument package used for this work was constructed at Oregon State University, and consisted of a SeaBird 9-11 *plus* CTD, a Chelsea Aquatracka Mk III nephelometer, a SeaTech transmissometer, a SIMRAD Mesotech Systems echo sounder/altimeter, a transponder, and the ZAPS

chemical sensor [17]. This instrument package was deployed both as a vertical profiling tool and as a towed sled. The same instruments were deployed at all sites discussed here, providing a unique comparison of these sites.

This paper focuses on data from the Chelsea nephelometer and the SeaTech transmissometer. The nephelometer measures light scattered at 90° to the incident light beam at a wavelength of 420 nm. Nephelometer data are reported in formazine turbidity units (FTU). Because its detector is positioned 90° to the light source, increases in particulate matter in the water column cause increases in amount of scattered light detected. Therefore, the nephelometer starts at a baseline of zero, and as the particle concentration increases more light reaches the detector. In contrast, the transmissometer measures the attenuation of 660 nm light as it travels through a straight 25 cm beam path. Therefore, the transmissometer starts with a baseline of 100% light transmission, and the signal decreases with increasing particle concentration. Transmissometer data are converted to light attenuation and are reported in units of inverse meters (m^{-1}).

Data were collected at either a 24 Hz or 12 Hz sampling rate. Designated ridge segments were surveyed with vertical profiles at key bathymetric features, or by tows along what was believed to be the neovolcanic zone, based on multibeam maps of the region (H.D. Needham, pers. commun., [18]). From tow-yo surveys conducted during five cruises and more than 85 vertical deployments it has been estimated that this instrument package is capable of detecting gradients in hydrothermal signals within an average of 12 km of their source. This distance is, however, dependent on current direction and the robustness of venting, as well as the geochemical characteristics of the vented fluids such as iron concentrations and the Fe/S ratio, since these are the major components for particle formation [19].

3. Hydrothermal sites on the northern MAR

3.1. Major hydrothermal sites

The seven confirmed sites of high-temperature hydrothermal venting on the northern MAR are la-

beled in black in Fig. 1. We define 'confirmed' here as those sites that have been visited and sampled by a submersible. These sites in chronological order of their discovery are: TAG (26°08'N), Snake Pit (23°22'N), Lucky Strike (37°15'N), Broken Spur (29°10'N), Menez–Gwen (37°52'N), Rainbow (36°14'N), and Logatchev (14°45'N). Investigators from IFREMER have recently located and conducted a dive series on hot springs at Menez–Gwen [20], which is within the segment referred to here as the Rifted Mountain segment. We conducted one lowering within the Rifted Mountain segment in 1992 where we detected a hydrothermal signal at approximately 750 m, consistent with a hydrothermal source on the seafloor at 1000 to 1050 m (Table 2). However, the Menez–Gwen site was not documented until 1994 [20]. Menez–Gwen does, in fact, lie within this depth range. We have, therefore, not visited the actual Menez–Gwen site with our instrument package and it will not be discussed in this paper. The Logatchev site was documented in 1993–1994 [21], and again will not be discussed in detail in this paper, as we did not collect data at this site. The number of confirmed sites should increase over the next decade as a result of further investigation.

In the fall of 1992, geochemistry groups from OSU and IFREMER conducted a water column survey of the northern MAR, between the Hayes Offset at 33°N and the Kurchatov Fracture Zone at 41°N, as part of the FARA (French–American Ridge Atlantic) Program. Eleven of the 19 segments within this region were sampled with the ZAPS instrument package deployed from the R/V Atlantis II (FAZAR cruise; C. Langmuir, chief scientist). Water column anomalies which were indicative of high-temperature hydrothermal activity (based on rise heights of the plumes) were detected in nine of these eleven segments (Fig. 1; Table 2), one of which was the Lucky Strike segment.

Small water column anomalies were observed throughout the Lucky Strike area. At the center of this segment is an axial seamount with three peaks surrounding a collapsed caldera; a portion of an obviously active chimney with attached mussels was recovered during dredging operations on the eastern side of eastern peak [22]. The Lucky Strike profile (Fig. 3) shows two distinct plume layers. These are most obvious in the nephelometry and manganese.
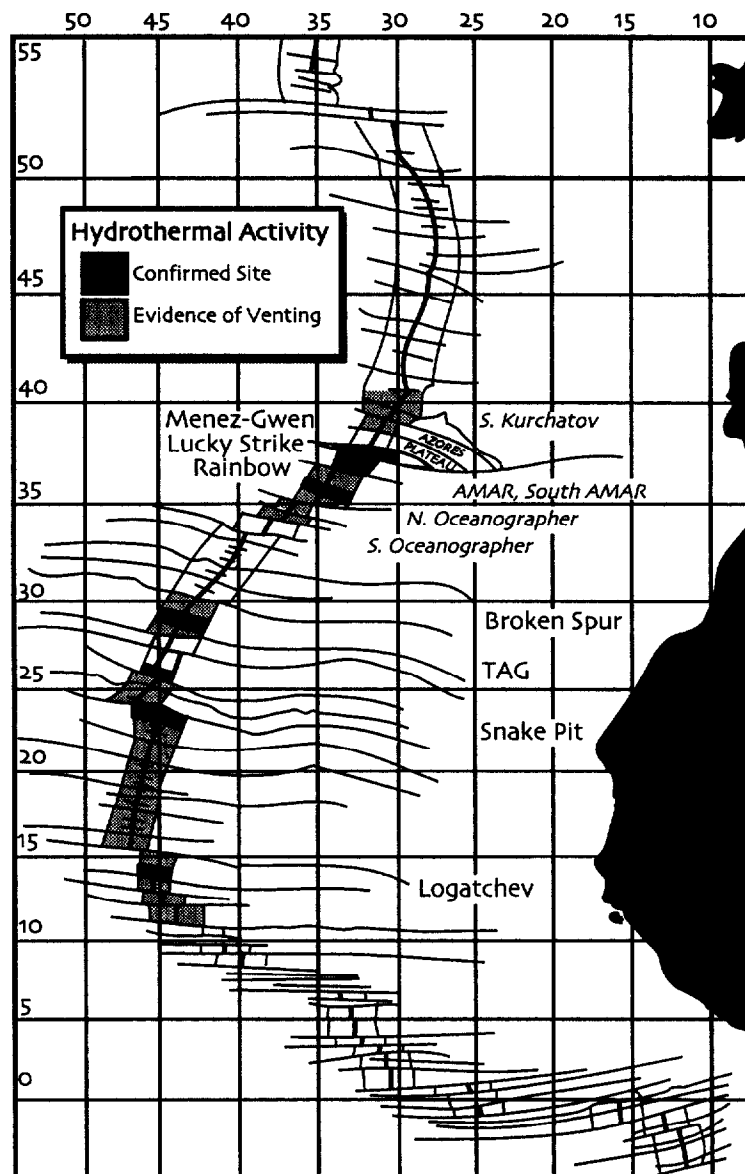
Fig. 1. Map showing the northern MAR hydrothermal sites. Black regions indicate sites where the exact location of hydrothermal activity has been observed using a submersible. Grey regions indicate segments where hydrothermal plumes have been observed. The FAZAR cruise covered the section from 33°N to 41°N, and for this region the names of the segments in which plumes were observed are labeled in italics. This map summarizes all evidence of hydrothermal activity on the northern MAR (see text), not just data collected as part of this study.

The upper maximum (1450 m) results from the vents discovered on the summit of the axial seamount [22]. A hydrographic survey was conducted within the Lucky Strike segment during FAZAR which produced evidence of additional vent sources north

of the axial seamount, shown in Fig. 3 as a lower maximum between 1750 and 1800 m. The source for this lower maximum has not yet been located [23]. Details of the hydrographic survey are discussed elsewhere [23,24].

Table 2
Largest nephelometer signals from each site

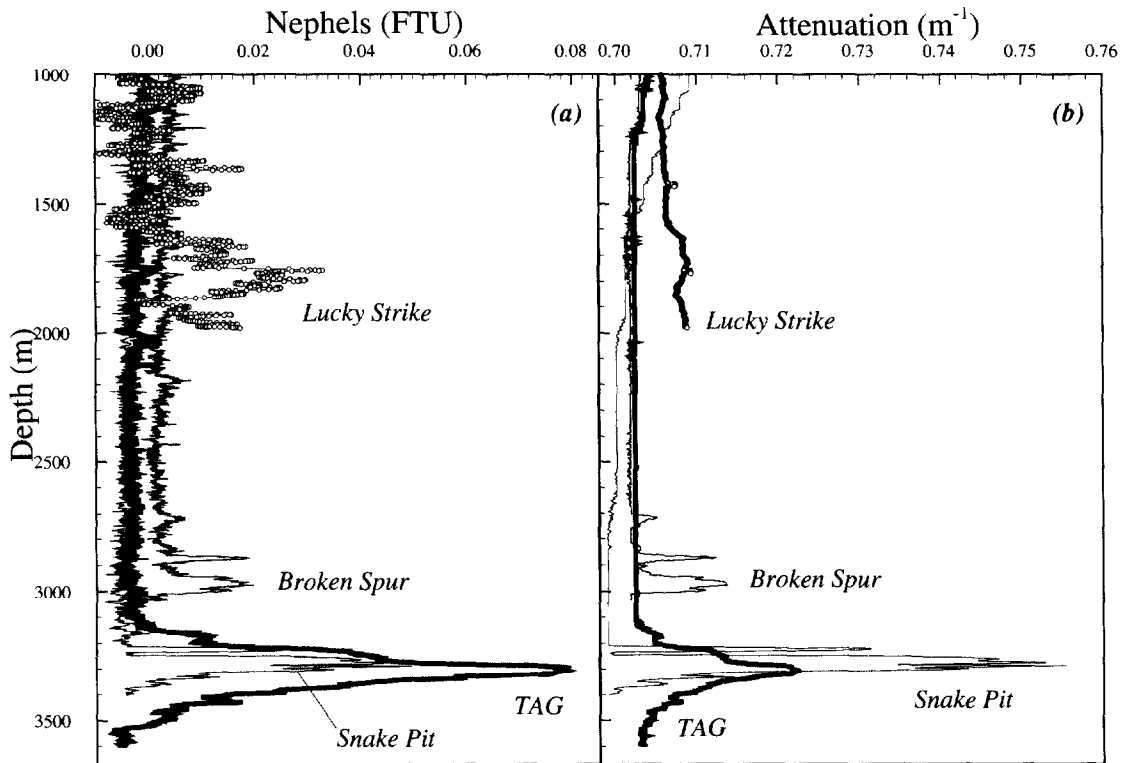| Site	Latitude, Longitude	Depth (m)		Magnitude (FTU)
		Plume	Bottom	
Rainbow	36°16′N, 33°53′W	2100	~2400	0.310
TAG	26°08′N, 44°49′W	3300	~3650	0.080
Snakepit	23°22′N, 44°57′W	3200	~3300	0.035
AMAR	36°23′N, 33°39′W	2100	2600	0.030
Lucky Strike	37°15′N, 32°20′W	1750	2120	0.028
		1650		0.020
South AMAR I	36°03′N, 34°08′W	1900	2630	0.021
		2250		0.008
Broken Spur	29°10′N, 43°10′W	2950	~3100	0.020
FAMOUS	36°34′N, 33°24′W	2400	~2650	0.018
South Kurchatov	40°28′N, 29°33′W	2150	2970	0.012
		2750		0.005
South AMAR II	36°02′N, 34°07′W	1600	2240	0.008
N. Oceanographer	35°17′N, 34°52′W	1700	2600	0.008
		2100		0.006
S. Oceanographer	34°52′N, 36°26′W	2200	3460	0.004
		3300		0.005
Rifted Mountain	37°50′N, 31°31′W	750	1016	0.003

Fig. 2. Vertical profiles from the confirmed venting sites. (a) Turbidity (FTU) from TAG (Trans-Atlantic Geotraverse), Snake Pit, Lucky Strike and Broken Spur, as measured by the Chelsea nephelometer. (b) The corresponding attenuation (m⁻¹) data measured by the SeaTech transmissometer. Measurements made at the Lucky Strike site are noisy (due to electronic interference in the instrument package on that cruise), yet show distinct maxima at the bottom of the profile, at 1750 m and at 1450 m.
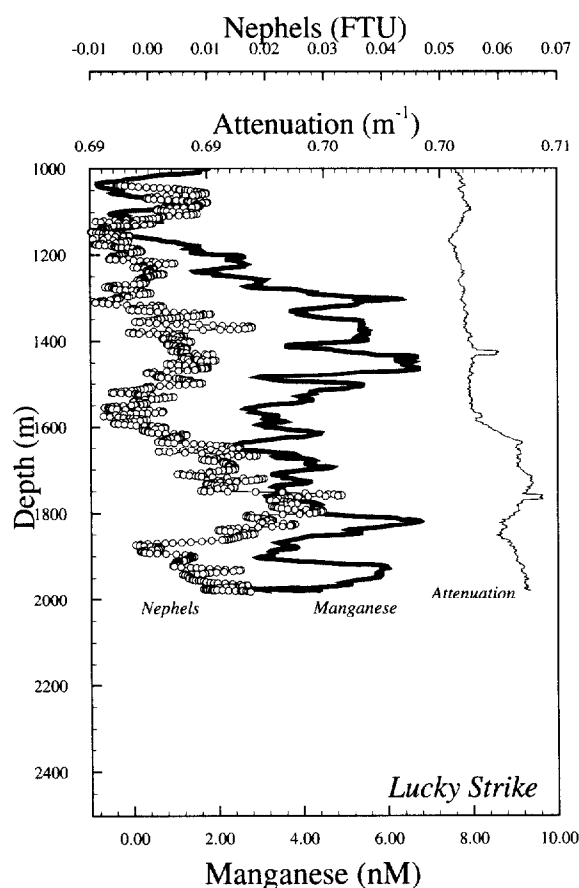
Fig. 3. The Lucky Strike plume shown at a larger scale. The thin line is the attenuation, the dotted line is nephels, and the heavy line is dissolved manganese as measured by the ZAPS instrument. The nephelometer (despite the noise in the signal) and the ZAPS instrument are much more sensitive to the Lucky Strike plume than is the transmissometer.

The Broken Spur venting site was discovered during the KASP cruise in 1993 aboard the *RRS Charles Darwin* cruise CD76 [14], which surveyed the Kane to Atlantis Supersegment between 27° and 30°N. This cruise employed a two part, telescoping survey technique. Long line surveys of the entire section were carried out by mounting optical instruments on the TOBI (Towed Ocean Bottom Instrument) deep-towed side-scan sonar platform (Southampton Oceanography Centre, UK). These devices detected hydrothermal anomalies in three segments: 27°, 29° and 30°N [14]. The area at 29°N (the Broken Spur segment) showed the largest anomaly, and this seg-

ment was selected for more detailed hydrothermal exploration. The detailed 'short-line' work was accomplished with the ZAPS package and the IOS 'WASP' camera sledge. Geochemical anomalies found during 12 vertical lowerings of the ZAPS instrument package within a 5 km by 5 km survey area were sufficient to pinpoint the hydrothermal field subsequently visited by *ALVIN* [14]. The position produced by the short baseline studies was so accurate that it was possible to place *ALVIN* within the hydrothermal field during the first descent. Sampling at Broken Spur during CD77 included one long tow from south to north along the ridge axis, as well as a number of vertical profiles. From this survey it appeared that the area of venting at Broken Spur was restricted to the one hydrothermally active ridge discovered on KASP. This conclusion was supported by a subsequent *Charles Darwin* cruise in 1995 that undertook a hydrothermal survey of the entire Broken Spur segment (C. German, pers. commun.).

Sampling at the TAG and Snake Pit sites was carried out on *Charles Darwin* cruise CD77 (H. Elderfield, principal scientific officer), and additional sampling was carried out at the Broken Spur site. Although the TAG and Snake Pit plumes have been well-characterized, the data are presented here for comparison, since we have deployed the same instrument package at all the sites listed in Table 2.

3.2. The AMAR area and the Rainbow site

One of the discoveries during the FAZAR cruise was a 550 m thick plume (1800 to 2350 m) detected at the southern end of the AMAR segment (Figs. 4 and 5b). This plume did not show the detailed structure and layering that some of the other plumes had displayed. This difference was interpreted as evidence that the AMAR nephel anomaly was in fact a well mixed distal plume resulting from a distant source of significant size [25,26]. Based on an analysis of water column data from the FAZAR cruise [25,26], sampling was conducted during the HEAT and Bridget cruises in 1994 [15] within this section of the AMAR area, in an attempt to pinpoint the source of the hydrothermal activity responsible for the AMAR anomaly detected during FAZAR. Investigations during the HEAT cruise [15] focused on the southern end of the AMAR segment where
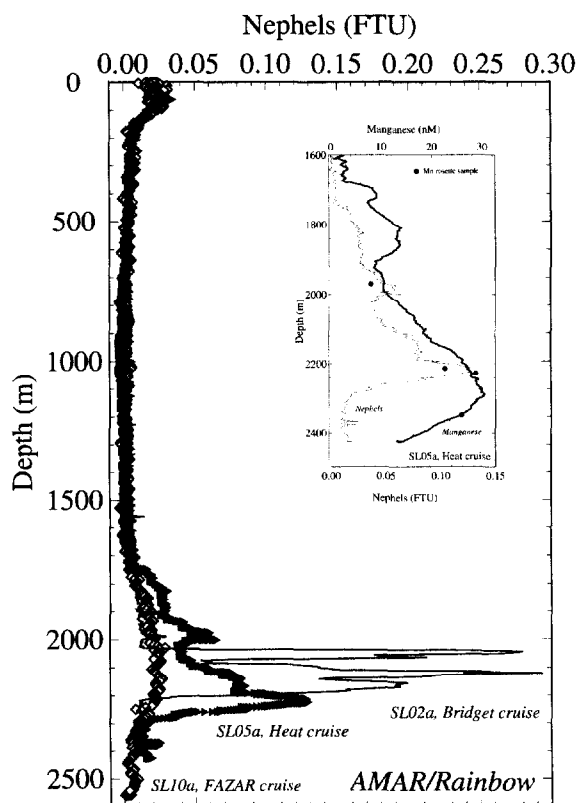
Nephels (FTU)

Fig. 4. Profiles of nephels showing an increase in the hydrothermal anomaly as the source of venting was pinpointed (FAZAR < HEAT < BRIDGET). The 550 m thick plume (1800 to 2350 m) observed during the FAZAR cruise (SL10a) was sampled at the southern end of the AMAR segment. A larger hydrothermal signal was measured during the HEAT cruise (SL05a), and then the largest plume was recorded during the BRIDGET cruise (SL02a) within the segment offset, just south of the AMAR segment. The FAZAR and HEAT profiles were taken approximately 24 and 4 km from the BRIDGET site, respectively. The inset is an expanded view of the plume seen during the HEAT cruise, showing nephels (thin line), dissolved manganese (thick line), and manganese as measured in rosette samples (circles) collected using the OSU instrument package and analyzed back on shore. (Rosette samples were not collected during either of the other profiles.)

even larger hydrothermal anomalies were detected with the ZAPS package (Fig. 4) and British rosette system. The inset on Fig. 4 shows the manganese anomaly associated with this plume, as measured by the ZAPS instrument as well as in discrete samples from the rosette. There is good agreement between the ZAPS manganese measurements made in situ and the discrete manganese samples, as well

as between these measurements and the concentration of hydrothermal pheral particles indicated by the nephelometry signal. It is not surprising that the dissolved plume (manganese) shows a different morphology than the particulate plume, since large particles are constantly lost from the plume. Finally, work during the Bridget cruise (immediately following HEAT) led to the discovery of a hydrothermal site at 36°14′N, 33°54′W, which was subsequently named Rainbow [27]. It seems clear that the Rainbow plume, sampled two years later, is the source of the AMAR anomaly as shown in Fig. 4. The AMAR and Rainbow plumes show similar features except that the distal part of the plume (AMAR) appears to have spread vertically as well as laterally resulting in a 550 m thick anomaly within the rift valley. Similar broad plume maxima were observed in other distal portions of this plume sampled during the Bridget cruise in 1994. This broadening with distance from the source also occurs in the South Pacific west of the EPR [28].

Particle plumes in the water column which display very sharp gradients are characteristic of near-field plumes. These sharp gradients, along with the magnitude of the particle anomaly observed at the Rainbow site, have been used to determine the location of a very strong vent source near the position of the profile shown in Fig. 4. This site produced the largest turbidity anomaly (0.31 FTU) thus far discovered on the MAR (Table 2). This site has just recently been documented by submersible [29] and was found to be one of the most active hydrothermal fields on the MAR.

3.3. Less well-characterized sites

There is water column evidence of hydrothermal activity in many other northern MAR segments. This study includes AMAR Minor, South AMAR, FAMOUS, South Kurchatov, Rifted Mountain (host to the Menez–Gwen site), North Oceanographer, and South Oceanographer segments which were sampled during the FAZAR cruise, however other studies of complementary sections of the northern MAR have shown hydrothermal activity in other segments [11–16]. The largest of the anomalies in this study (which were all smaller than those discussed in the previous section) are shown in Fig. 5.
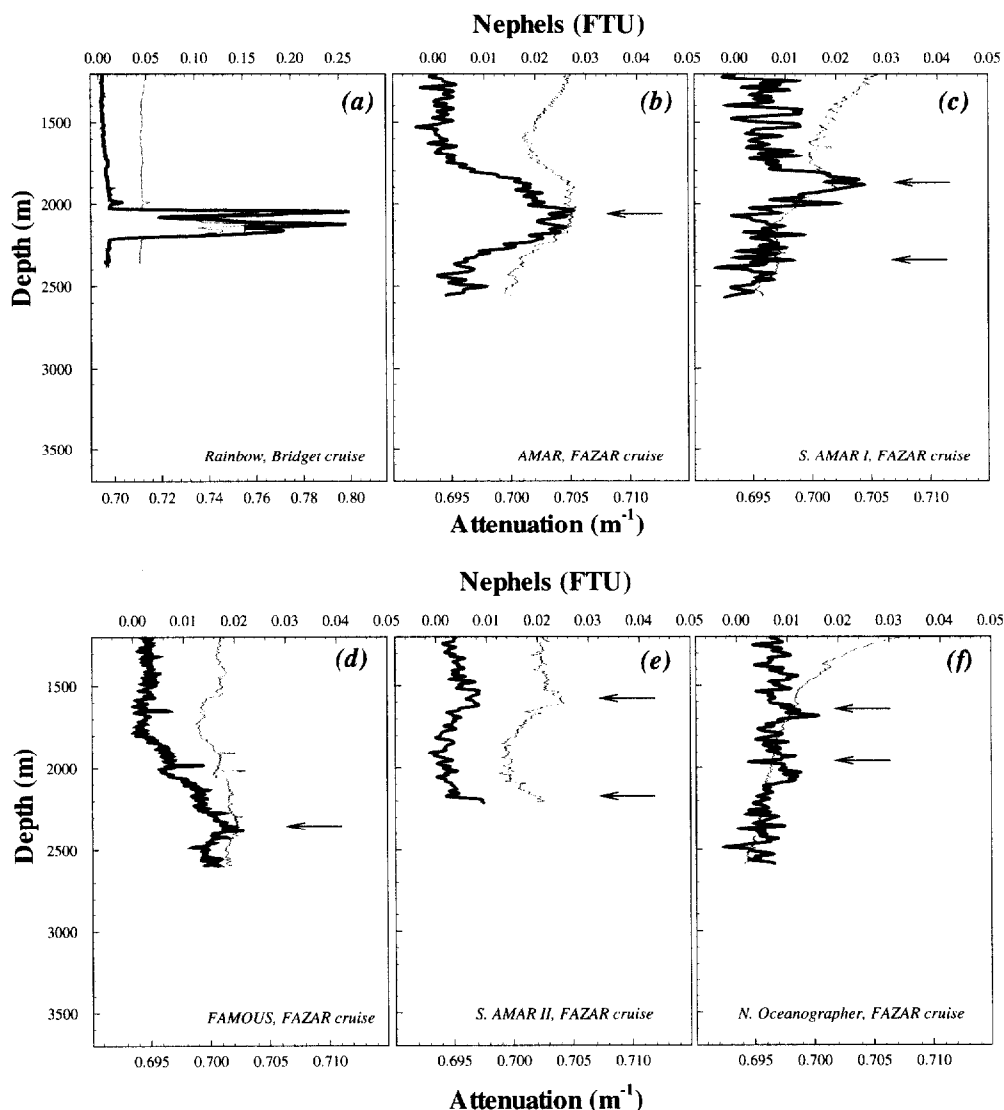
Fig. 5. Vertical profiles of nephels and attenuation observed within other segments on the northern MAR: (a) Rainbow, (b) AMAR, (c) South AMAR I, (d) FAMOUS, (e) South AMAR II, (f) North Oceanographer. The thick line is the nephelometer data, and the thin line is attenuation from the transmissometer. The nephelometer is generally a more sensitive indicator of hydrothermal particles in the water column. A different scale is used for the 'Rainbow' panel because of the size of the anomaly. (Note: data from the FAZAR cruise show a varying amount of electronic noise. This instrument package was assembled just before the FAZAR cruise, and the electronics configuration was modified for later cruises to help eliminate this problem.)

South AMAR is the next major segment south of the Rainbow offset. The first profile from this segment (Fig. 5c) shows a hydrothermal anomaly at 1900 m, distinguishing it from the very large Rainbow plume which has its maximum at 2100 m. A second profile in the South AMAR segment shows a plume maximum at yet a different depth (1600 m, Fig. 5e), indicating a source of venting distinct from both the Rainbow vent field as well as the other South AMAR plume in Fig. 5c. Furthermore, this profile was conducted approximately 25 km south of the Rainbow source. The lower anomaly below 2200 m (near the bottom), which probably corresponds with the lower plume in Fig. 5c, does

not show the same broadening that is observed in the Rainbow plume to the north in the AMAR segment. We, therefore, conclude that these plume maxima must originate from a source or sources other than Rainbow.

Also during the FAZAR cruise, a small plume was observed at 2400 m in the FAMOUS segment (Fig. 5d). Several more lowerings were conducted within the FAMOUS segment during the HEAT cruise. Very small plumes were also measured by the nephelometer at 2200 and 3300 m within the South Oceanographer segment (Table 2). Hydrothermal activity in this region is of particular interest because the mantle Bouguer anomaly low observed here is one of the most pronounced on the MAR [30]. In addition, the axial high is host to several large volcanic edifices. It should be noted that the anomaly listed in Table 2 was observed within the South Oceanographer segment, but not directly over the site of the mantle Bouguer anomaly, leaving the possibility that there may be a larger hydrothermal anomaly associated with the mantle Bouguer anomaly.

4. Analysis of results

4.1. Comparison of plumes

The hydrothermal plumes discussed here are the result of more than 85 deployments of the ZAPS instrument package on the MAR during five cruises. Fig. 2 shows representative nephelometry and attenuation profiles from all of the major venting sites sampled during these cruises. Since there were many profiles from each site, those chosen for this figure represent the maximum signal from each site, the assumption being that this profile would represent measurements made closest to the hydrothermal source.

The TAG site was sampled using the ZAPS instrument package during CD77 in 1993. At that time the TAG plume was the largest nephel anomaly detected on the MAR (the other confirmed sites at that time being Snake Pit, Lucky Strike and Broken Spur). The Snake Pit plume was approximately half the magnitude of TAG, while the Lucky Strike and Broken Spur plumes were much smaller in comparison. The

plume observed at South AMAR was comparable in size to the plume from the now well-characterized Broken Spur site (Fig. 2a).

The documented sites on the MAR occur in different venting environments. TAG is a large mound comprised of numerous individual vents [31]. This mound formed near the east wall of the valley, suggesting that faulting produced conduits which supply this venting site [32]. In contrast, the Lucky Strike site occurs within an axial seamount consisting of three summit cones near the center of the segment [22]. The Broken Spur site was so named because it occurs at the junction of two cross-cutting fissures that appear to join two spurs. Vents at Broken Spur are located on the walls and within an axial summit graben at the crest of the neovolcanic ridge [14], similar to the Snake Pit site which lies on a volcanic ridge within the neovolcanic zone of the MARK segment [6,8]. Snake Pit is the only site at which the light attenuation anomaly is stronger than the nephel anomaly (Fig. 2). At all other sites this relationship is reversed. Rainbow is distinguished from the other sites on the MAR by its location within an offset between the AMAR segment and the AMAR Minor segment [18], which raised the question of whether venting at this site was a result of the tectonic setting [15]. It now seems clear that this vent field, located at the intersection between the non-transform system faults and the ridge faults, is tectonically controlled [29]. In addition, the Rainbow site is hosted by ultramafic rocks [33], which suggests direct exchange between the ocean and the mantle and, therefore, may be important with respect to the heat budget of the MAR (H. Bougault, pers. commun.). The Logatchev site also occurs on ultramafic rocks [34] and, therefore, it is the site most similar to Rainbow, however, it is located approximately 60 km from the 15°20'N Fracture Zone, so it does not occur in the same tectonic setting.

Fig. 2a and b show nephelometry and attenuation profiles from TAG and Snake Pit. While the nephel anomaly for TAG appears larger than that for Snake Pit, the attenuation signal from Snake Pit is more than twice the size of the signal from TAG. This difference is an artifact of the measurement. Scattering (measured using the nephelometer) is more sensitive to a smaller class of particles. Therefore, differences in the ratio of scattering to attenuation must be re-

lated to differences in hydrothermal particle size, as determined by particle chemistry. The response of these two instruments to differences in particle shape have not been determined, but are also expected to be different and also dependent on particle chemistry. The larger attenuation signal, and accordingly the coarser particle population at Snake Pit, therefore, may be attributed to the four-fold lower iron : sulfide ratio [35]. Examination of Fig. 5 shows that for the most part the nephelometer is a more sensitive indicator of the particle anomaly than the transmissometer. Differences in the scattered/attenuated light ratios measured in the plume might, therefore, be useful as initial predictions of some of the chemical characteristics of the vent fluid.

4.2. Locations and apparent venting frequency on the MAR

From this study, average venting frequency on the northern MAR from 23°N to 41°N, calculated from the above observations, is approximately one active venting system per 150 km of ridge crest over a 1900 km section of the MAR. This should be considered a conservative estimate compared to those for the EPR or the JdFR, since the northern MAR has not been studied in the same detail as Pacific spreading ridges where photographic surveys of a narrow axial graben are often possible. Moreover, there are entire segments within this region of the MAR that have not yet been sampled. On a complementary section of the northern MAR, from 11°N to 26°N, Klinkhammer et al. [11] showed a frequency of at least one hydrothermal source per 340 km of ridge based on shipboard manganese (total dissolvable manganese, TDM) analyses of water column samples, predicting that the actual frequency would probably be much higher. It is interesting to note that as recently as 10 years ago it was widely believed that hydrothermal activity may be restricted to fast-spreading ridges.

In a recent MAR study between 36°N and 38°N German et al. [15] have shown evidence for seven hydrothermal sources within a distance of approximately 200 km, representing a venting frequency of one site every 25 to 30 km. Thus as exploration of the northern MAR continues, the estimates of venting frequency are beginning to compare closely to estimates for ridges spreading at faster rates [1,10].

It should also be noted that German et al. [36] surveyed 750 km of the Reykjanes Ridge and found that the Steinahöll vent field was the only hydrothermal source along that section of ridge. However, the Reykjanes Ridge is much different structurally than the portion of the MAR discussed here [15].

Baker and Massoth [37] have estimated the heat content of hydrothermal plumes on the intermediate-spreading JdFR at approximately 1000 MW. Heat loss from the TAG mound, in comparison, has been estimated to range between 225 and 1000 MW [4,38,39].

There are two reasons why vent frequency and heat loss from the MAR might be higher than initially thought. Stein and Stein [40] have predicted that the sealing age for hydrothermal circulation in both the Atlantic and Pacific oceans is 65 ± 10 Ma. The combination of similar heat outputs and comparable sealing ages for slower and faster spreading ridges would mean that a larger proportion of the heat flux on the MAR would occur closer to the ridge axis. In other words, because of the differences in structural characteristics between the MAR and faster spreading ridges, one would expect a higher proportion of the heat flux (from low-temperature diffuse flow as well as focussed, high-temperature venting) to occur within the MAR axial valley, which spans a width from 3 to 10 km [41–43], than within the axial graben of the typical intermediate- or fast-spreading ridge (approximately 300 m; [44]). In addition, this section of the MAR, near the Azores Platform, is characterized by significant tectonic extension and crustal fissuring [15], a setting which is expected to support vigorous convection [45]. In fact, helium data from the FAZAR study suggest that hydrothermal activity may increase toward the Azores Platform [46]. Other investigators have found that hydrothermal activity is present everywhere along a complementary section of the northern MAR (12° to 26°N, [47]) and a more recent study concluded that hydrothermal activity along the MAR is as common as that along the EPR, but that it develops in more diverse geological settings [48]. Therefore, one might predict that heat loss from high-temperature venting within the MAR rift valley would account for a greater proportion of the total heat loss from the MAR than the 10% average that has been estimated for global on-axis heat loss [40]. So, while the total

heat lost from the faster-spreading EPR and JdFR might be higher than the MAR, the heat loss from high-temperature venting in the axial region might be similar.

5. Conclusions

High-temperature hydrothermal venting on the slow-spreading northern MAR is more common than previously thought. Based on our observations, a conservative estimate of vent system frequency on the MAR between 23°N and 41°N averages one system per 150 km of ridge crest. Klinkhammer et al. [11] previously measured a frequency of one system per 340 km of ridge crest, while other recent studies have suggested that the venting frequency on the northern MAR may be even higher: one site per 25–30 km [15], and evidence of hydrothermal activity everywhere along the ridge from 12°N to 26°N [13]. Thus as exploration of the MAR continues, the frequency of venting becomes comparable to that found on faster spreading ridges such as the EPR. It appears that the previous assumption of lower venting frequency on the MAR was an artifact of the difficulties involved in surveying the vast MAR rift valley, and the resulting lack of detailed sampling. Variations in the ratio of high-temperature, axial to off-axis heat loss along the mid-ocean ridge system are required to maintain the vent frequency observed on the northern MAR and still remain within the magmatic supply constraints of slow-spreading ridges.

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