AN ABSTRACT OF THE THESIS OF

Carol S. Chin for the degree of Doctor of Philosophy in Oceanography presented on 10 August 1998. Title: Hydrothermal Activity Along the Northern Mid-Atlantic Ridge and in the Bransfield Strait Backarc Basin, Antarctica.

Redacted for privacy

Abstract approved: ______________________

Gary Klinkhammer

Seafloor hydrothermal circulation through young oceanic crust results in the expulsion of fluids as both diffuse and focused flow in the form of hydrothermal venting. High-temperature hydrothermal fluids are enriched in reduced chemical species that rapidly oxidize upon interaction with ambient, oxygen-rich bottom waters, resulting in plumes that are detectable in the water column both by their dissolved chemical composition as well as by their particle concentration. This study employed a novel instrument package which detected both dissolved manganese and particle concentration in situ. This package also included a standard CTD (conductivity, temperature, depth) and rosette for the collection of water samples. Because hydrothermal plumes integrate the output from an entire vent field, measurements in plumes can be used to estimate vent field fluxes. Some geochemical tracers from hydrothermal vents can also be detected thousands of kilometers from their sources. Thus, plumes provide the means to prospect for undiscovered hydrothermal sites, and can also predict characteristics of the venting site. This work includes studies of hydrothermal plumes along the northern Mid-Atlantic Ridge and in the Bransfield Strait backarc basin, Antarctica.

In recent years, the number of known hydrothermal sites on the Mid-Atlantic Ridge (MAR) has increased from two to seven, and most other segments between 12° and 41° N have shown evidence of high-temperature hydrothermal activity.

Furthermore, it appears that as one approaches the Azores Plateau, the concentration of dissolved δ^3He in the bottom water (originating from hydrothermal venting) increases, suggesting that hydrothermal activity increases toward the plateau. This is consistent with the significant tectonic extension and crustal fissuring observed near the Azores Platform, which is expected to support increased convection.

The Bransfield Strait is a backarc basin between the Antarctic Peninsula and the South Shetland Islands. Evidence of hydrothermal activity had been reported previously, but hydrothermal sources had not been pinpointed. In this study, surveys in the Central and Eastern Bransfield Basins revealed evidence of hydrothermal activity. A more detailed search in the Central Basin detected Mn, ^{3}He, temperature, and particle anomalies within confined regions on three of the volcanic edifices that lie along the Bransfield rift.

Hydrothermal Activity Along the Northern Mid-Atlantic Ridge and in the Bransfield Strait Backarc Basin, Antarctica

by

Carol S. Chin

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed 10 August 1998
Commencement June 1999

Doctor of Philosophy thesis of Carol S. Chin presented on 10 August 1998

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ACKNOWLEDGMENTS

I am very grateful to everyone who has served as a member of my committee over the years (Bob Collier, Jack Dymond, Bob Embley, Martin Fisk, Dave Graham and John Lupton), some of whom stepped in during last-minute scheduling. This work has benefitted greatly from their participation in discussions of the results presented here. Gary Klinkhammer has been a generous and supportive advisor, providing me with a wealth of sea-going experience and many opportunities to present this work at national and international meetings. This work has been supported by the Ocean Sciences Division of the NSF, and the Office of Polar Programs. I would also like to thank the U.S. RIDGE Office for their partial support of my participation in a number of RIDGE and InterRidge meetings and workshops where portions of this work have been presented.

The work presented here could not have been completed without the help and expertise of the following people: Kathryn Brooksforce, Paul Stoffregen, Andy Ungerer, Chi Meredith, Alex Faveluke, Chuck Sears, Tom Leach, Bruce Marler, Sue Pullen, Joe Bussell, Chris Moser, Bobbi Conard, Jay Simpkins and Chris Schneller.

One of the most valuable parts of the graduate school experience is the friendships that develop along the way. For their friendship and support, ski trips, hikes, T-shirt parties, mushroom hunts, petsitting, holiday dinners, Jello parties, and many other good times I'd like to thank Ann Morey, Babs Bruno and Johnnie Baker, Cara Wilson and Annie Connelly, Karen Thompson and Mark Stevensen, Rachel Sours-Page, Bob Peck, Chris Guay, Jim McManus, the Klinkhammer family and the Fisk family.

My parents and my grandmother have been a constant source of support and encouragement, and are always excited to hear about my work, despite the fact that it often takes me to far away places during times when they'd prefer to see me.

Most of all, I would like to thank my family, Randy Keller, who proved to me that Corvallis isn't such a bad place after all, and shared with me all the things he's found to be wonderful about Oregon; and Anthony, who is always a great source of entertainment and who had already seen me through one graduate program. They have graciously endured my experience as a graduate student, providing constant, loving support despite crazy, hectic times and my many months at sea. Randy has also spent many evenings sharing with me what he knows about the Bransfield Strait, and has helped me to understand a little about petrology.

CONTRIBUTIONS OF CO-AUTHORS

This thesis is a collection of manuscripts that include comments and contributions by co-authors. Chapters 1 (Introduction) and 5 (Summary and Conclusions) are my own work, but incorporate the comments of my Ph.D. committee (R. Collier, D. Graham, J. Lupton and G. Klinkhammer). Chapters 2 through 4, incorporated the comments and contributions from the co-authors, my Ph.D. committee members, and others who reviewed these manuscripts. Cara Wilson participated on the FAZAR and *N. B. Palmer* cruises and provided comments on Chapter 2 and two figures in Chapter 3. John Lupton provided all helium analyses, and contributed to the interpretation of the helium data. Gary Klinkhammer served as my advisor, provided funding for this research, and was in charge of the projects from which these manuscripts result.

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PREFACE

This thesis is written in manuscript format. It begins with a general introduction to hydrothermal activity and the study of hydrothermal plumes (Chapter 1), and finishes with a general conclusion (Chapter 5). Chapters 2 through 4 include contributions from co-authors (see Contributions of Co-authors section). Chapters 2 has been accepted for publication in *Earth and Planetary Science Letters* (Chin et al., in press). Chapters 3 and 4 are being prepared for submission to scientific journals. The results included in this thesis have been presented at a number of national and international meetings.

Hydrothermal Activity Along the Northern Mid-Atlantic Ridge and in the Bransfield Strait Backarc Basin, Antarctica

Chapter 1

Introduction

Hydrothermal activity is the seafloor expression of the dissipation of heat from newly formed oceanic crust. This cooling process drives hydrothermal circulation of seawater through the crust affecting not only the heat transport, but also the chemical composition of the crust through water-rock interactions, and ultimately the overlying seawater. Several different tectonic settings are host to hydrothermal activity: mid-ocean ridge spreading centers, backarc basins, submarine arc volcanoes, and submarine hotspot volcanoes. This thesis will discuss results from both a mid-ocean ridge (the Mid-Atlantic Ridge) and a backarc basin (the Bransfield Strait).

Mid-ocean ridges are, by far, the most studied setting for hydrothermal activity. Approximately 55,000 km of ridge crest girdles the Earth, making up the global mid-ocean ridge system. It is estimated that the global extent of backarc spreading centers is 10% that of mid-ocean ridges, or 5500 km. However, it is estimated that backarc regions may have a greater impact on the chemistry of the oceans because of a greater amount of hydrothermal circulation through these systems. Currently, there are 21 confirmed hydrothermal sites in mid-ocean ridge settings (Baker et al., 1995). Here we define "confirmed" as those sites that have been visited and vent fluids sampled using a submersible. In comparison, there are six confirmed hydrothermal sites in backarc settings (Baker et al., 1995). So, while mid-ocean ridges have been the focus of a greater number of studies, the proximity of many backarc regions to shore, and, in most cases, the relatively shallow water depth at which they occur has facilitated their study.

Submarine hydrothermal venting delivers an estimated 4.9×10^{19} calories of heat to the world's oceans annually (Jenkins et al., 1978), representing 30% of the heat lost from oceanic crust (Sclater et al., 1981; Stein and Stein, 1994). Of this, only 10% is estimated to result from on-axis heat loss. The remaining 90% presumably occurs as off-axis hydrothermal circulation.

The first hydrothermal vents were discovered almost 20 years ago (Corliss et al., 1979; Spiess et al., 1980). Since that time, hydrothermal venting has been documented along most of the world's mid-ocean ridges and in backarc basins to seafloor depths as great as 3600 m. However, before the documentation of hydrothermal vents on the seafloor, the existence of submarine hot springs was inferred from hydrothermal plume observations. Hydrothermal plumes are formed by the introduction of hot, chemically enriched fluids into the ocean at the seafloor. These fluids rise through the water column, entraining ambient seawater as they rise, until they reach buoyancy equilibrium, approximately 150 to 350 meters above the seafloor (Figure 1). With such rise heights,

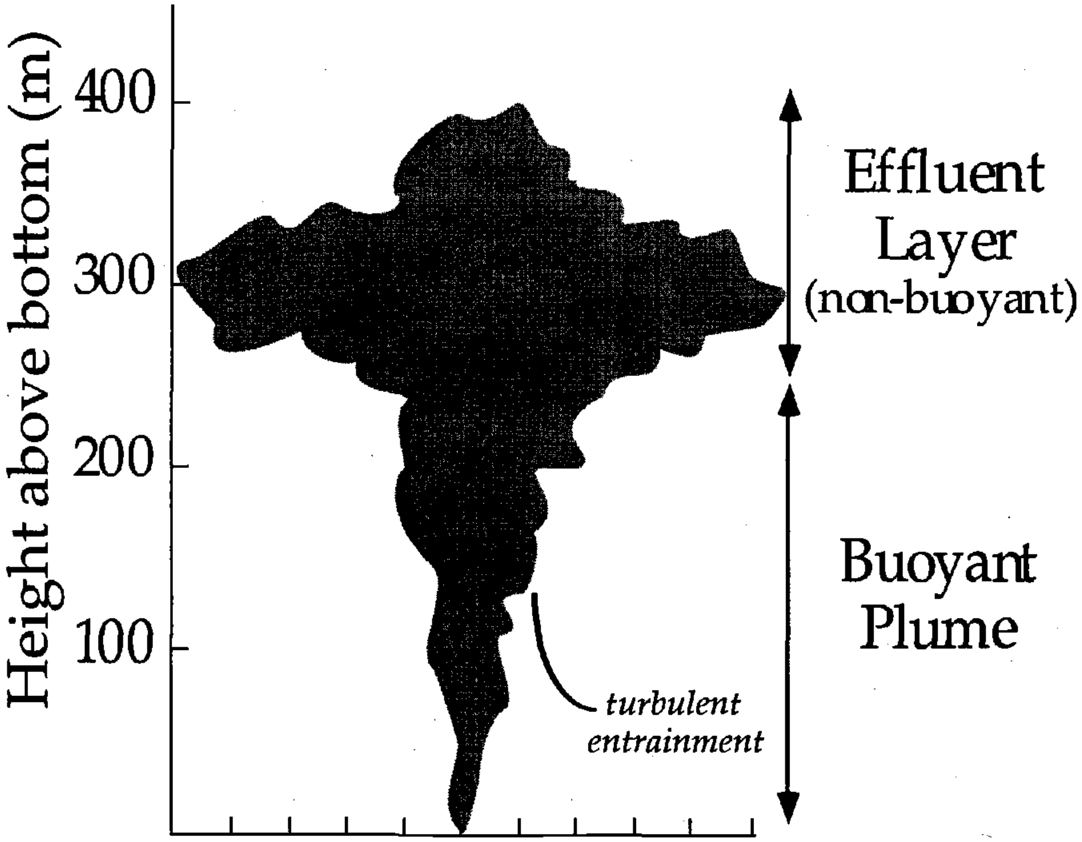

Figure I.1 Schematic diagram of a high-temperature hydrothermal plume. Typical rise height is approximately 300 meters above the seafloor. The x-axis scale has been left of, as the lateral dispersal of the effluent layer is highly dependent on the location of the plume, the local current regime, the background hydrography, and, in the case of the MAR, whether the observations are made along or across the ridge axis.

the thermal and chemical fluxes from plumes contribute significantly to the ocean's mid-depths. In addition, it is believed that plumes may provide the necessary mechanism for the dispersal of vent fauna.

Perhaps the first plume observation was that of Clarke et al. (1969) who detected excess ^{3}He in the deep Pacific Ocean. They noted that the helium maximum in their vertical profile corresponded with the approximate depth of the crest of the mid-ocean ridge system, and concluded that this excess ^{3}He must be terrestrial primordial helium entering the ocean from mid-ocean ridge spreading centers.

Hydrothermal effluents contribute a significant proportion of the global flux of iron and manganese to the oceans: 73% and 69%, respectively (Edmond et al., 1979; Von Damm et al., 1985; Chester and Murphy 1990). Thus, these two elements are readily detected in hydrothermal plumes; manganese primarily in the dissolved phase, and iron in the particulate phase because of its rapid oxidation from Fe^{+2} to Fe^{+3} in the form of iron oxides and oxyhydroxides. Our exploration of the Mid-Atlantic Ridge and the Bransfield Strait has taken advantage of these two plume tracers by measuring dissolved manganese in situ with the ZAPS probe, and particle concentration using both a nephelometer (detecting scattered light) and a transmissometer (detecting the attenuation of light by particles). In addition we collected samples for helium isotopic analyses. Helium is a particulartly valuable hydrothermal tracer because, next to temperature, it is the only truly conservative tracer for hydrothermal effluents. In addition, helium is a persistent tracer, and helium analyses can reveal hydrothermally derived anomalies thousands of kilometers from the venting source.

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Chapter 2

Detection of Hydrothermal Plumes on the Northern Mid-Atlantic Ridge: Results from Optical Measurements

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vol. 162, pp. 1-13, 1998.

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° 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 1 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.

Keywords: mid-ocean ridge; hydrothermal conditions; optical properties; scattering; attenuation

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. Optical 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 observations 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.

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.

Table II.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	*RRS Charles Darwin*	Sept. 1994	Lucky Strike FAMOUS AMAR
Bridget	*RRS Charles Darwin*	Sept. 1994	AMAR (Rainbow)

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 (Needham, pers. comm.; [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].

Hydrothermal Sites on the Northern MAR

Major hydrothermal sites

The seven confirmed sites of high-temperature hydrothermal venting on the northern MAR are labeled in black in Figure 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 ths 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

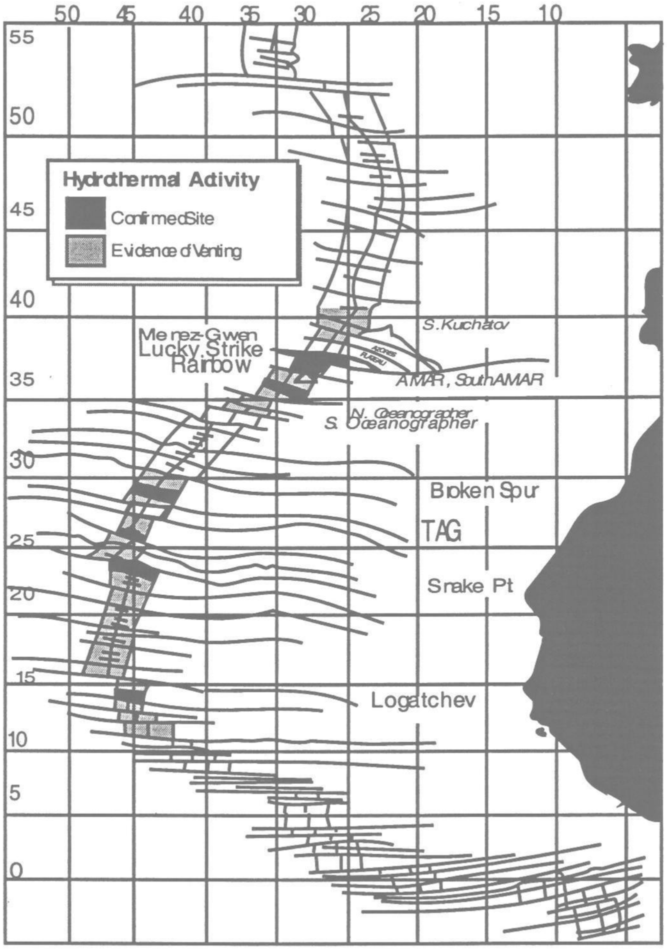

Figure II.1 Map showing the northern MAR hydrothermal sites. Black regions indicate sites where the exact location of hydrothermal activity has been observed using a submersible. Grey regions indicate segments where hydrothermal plumes have been observed. The FAZAR cruise covered the section from 33° to 41°N, and for this region the names of the segments in which plumes were observed are labeled in italicized font. This map summarizes all evidence of hydrothermal activity on the northern MAR (see text), not just data collected as part of this study.

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 (Figure 1; Table 2), one of which was the Lucky Strike segment.

Table II.2 Largest nephelometer signals from each site.

Site	**Lat, Lon**	**Depth (meters)**		**Magnitude**
		Plume	**Bottom**	**(FTU)**
Rainbow	36° 16' N, 33° 53' W	2100	~2400	.310
TAG	26° 08' N, 44° 49' W	3300	~3650	.080
Snakepit	23° 22' N, 44° 57' W	3200	~3300	.035
AMAR	36° 23' N, 33° 39' W	2100	2600	.030
Lucky Strike	37° 15' N, 32° 20' W	1750	2120	.028
		1650		.020
South AMAR I	36° 03' N, 34° 08' W	1900	2630	.021
		2250		.008
Broken Spur	29° 10' N, 43° 10' W	2950	~3100	.020
FAMOUS	36° 34' N, 33° 24' W	2400	~2650	.018
South Kurchatov	40° 28' N, 29° 33' W	2150	2970	.012
		2750		.005
South AMAR II	36° 02' N, 34° 07' W	1600	2240	.008
N. Oceanographer	35° 17' N, 34° 52' W	1700	2600	.008
		2100		.006
S. Oceanographer	34° 52' N, 36° 26' W	2200	3460	.004
		3300		.005
Rifted Mountain	37° 50' N, 31° 31' W	750	1016	.003

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 (Figure 2) shows two distinct plume layers. These are most obvious in the nephelometry and manganese. 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 Figure 2 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].

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

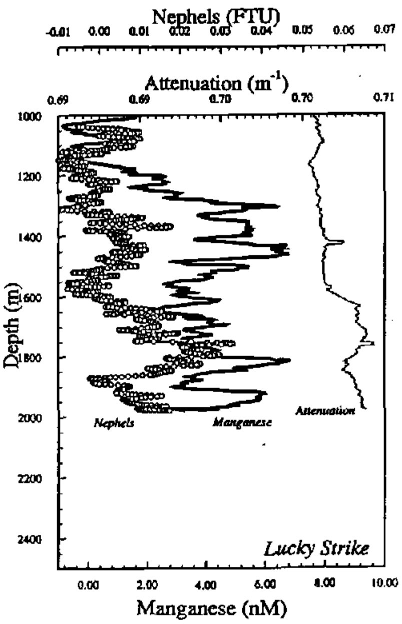

Figure II.2 The Lucky Strike plume shown at a larger scale. The thin line is the attenuation, the dotted line is nephels, and the heavy line is dissolved manganese as measured by the ZAPS instrument. The nephelometer (despite the noise in the signal) and the ZAPS instrument are much more sensitive to the Lucky Strike plume than is the transmissometer.

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 segment 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 (German, pers. comm.).

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 (Figure 3), since we have deployed the same instrument package at all the sites listed in Table 2.

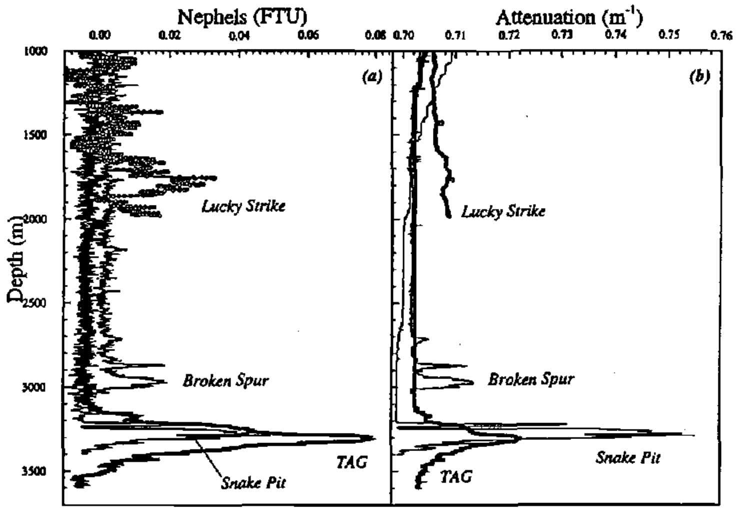

Figure II.3. Vertical profiles from the confirmed venting sites. (a) Turbidity (FTU) from TAG (Trans-Atlantic Geotraverse), Snake Pit, Lucky Strike, and Broken Spur, as measured by the Chelsea nephelometer. (b) The corresponding attenuation (m^{-1}) data measured by the SeaTech transmissometer. Measurements 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.

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 (Figure 4, Figure 5b). This plume did not show the detailed structure and layering that some of the other plumes

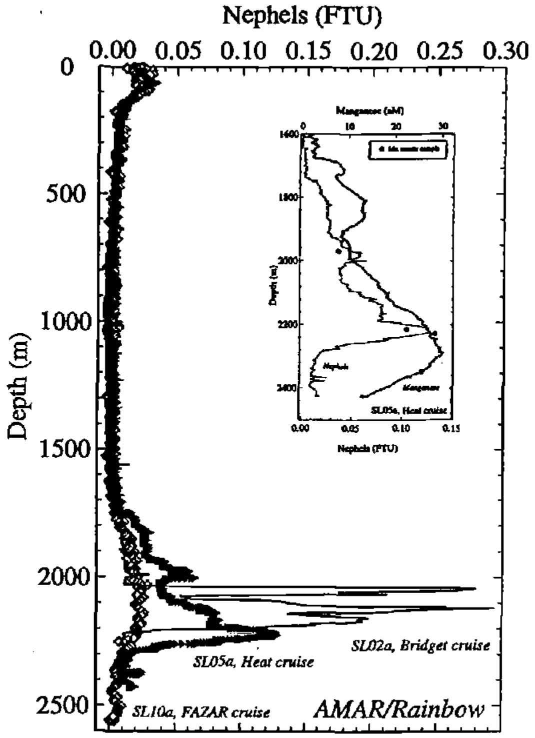

Figure II.4 Profiles of nephels showing an increase in the hydrothermal anomaly as the source of venting was pinpointed (FAZAR < HEAT < BRIDGET). The 550 m thick plume (1800 to 2350 m) observed during the FAZAR cruise (SL10a) was sampled at the southern end of the AMAR segment. A larger hydrothermal 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. *Inset.* 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.)

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.

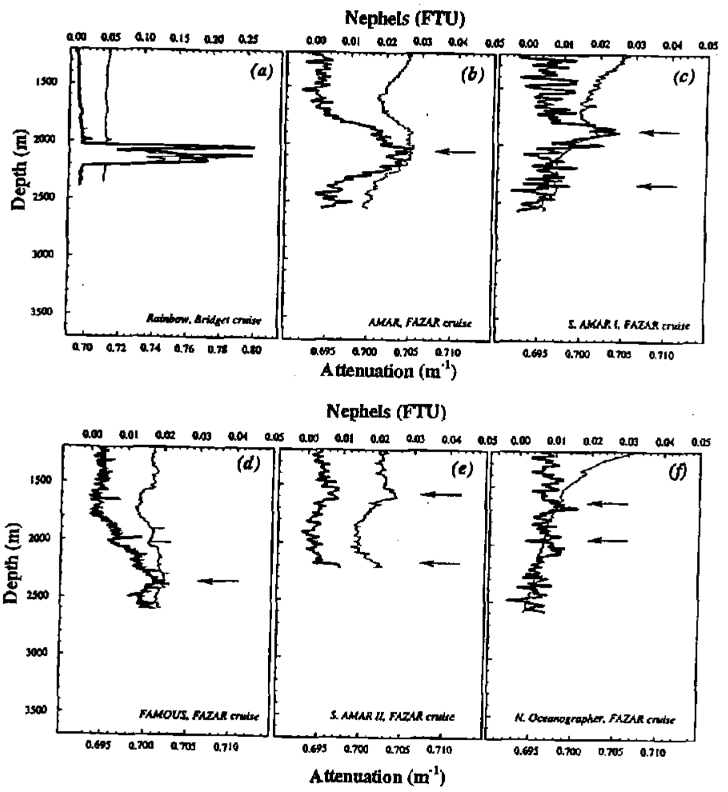

Figure II.5 Vertical profiles of nephels and attenuation observed within other segments on the northern MAR: (a) Rainbow, (b) AMAR, (c) South AMAR I, (d) FAMOUS, (e) South AMAR II, (f) North Oceanographer. The thick line is the nephelometer data, and the thin line is attenuation from the transmissometer. 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. Locations of these profiles are listed in Table 2. (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.)

Investigations during the HEAT cruise [15] focused on the southern end of the AMAR segment where even larger hydrothermal anomalies were detected with the ZAPS package (Figure 4) and British rosette system. The inset on Figure 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 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 Figure 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 Figure 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.

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 Figure 5.

South AMAR is the next major segment south of the Rainbow offset. The first profile from this segment (Figure 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, Figure 5e), indicating a source of venting distinct from both the

Rainbow vent field as well as the other South AMAR plume in Figure 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 Figure 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 (Figure 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.

Analysis of Results

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. Figure 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 (Figure 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 (Figure 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 (Bougault, pers. comm.). 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.

Figures 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 related 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 Figure 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.

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° 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° 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 that 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.

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° 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 the 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.

Acknowledgments

We wish to thank the principal scientific officers/chief scientists on our cruises: C. Langmuir, B. Murton, H. Elderfield and C. German. Multibeam maps for the FAZAR cruise were graciously provided by H. D. Needham. We would also like to acknowledge the support of the captains, officers, and crew of the *R/V Atlantis II* and the *RRS Charles Darwin.* Thanks are also due to H. Bougault, C. German and an anonymous reviewer whose careful reviews greatly improved this manuscript. We are also grateful to M. Palmer for his comments on an earlier version of this manuscript. This work was supported by National Science Foundation grant OCE-9105177 to GPK, and is a contribution to the FARA (French-American Ridge Atlantic) Program. Portions of this work were completed in collaboration with colleagues funded in the MARFLUX/ATJ and BRIDGE Programs.

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Chapter 3

Evidence of Hydrothermal Activity in the Central and Eastern Basins of the Bransfield Strait, Antarctica

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Abstract

The Bransfield Strait is a young, volcanically active backarc basin which separates the South Shetland Islands from the Antarctic Peninsula. It formed by rifting behind the South Shetland Island Arc, and now volcanism occurs both above and below sea level along the axis of this rift. It is now clear that hydrothermal activity also occurs along this rift.

The Strait consists of three subbasins: the Eastern, Central, and Western Bransfield Basins. In November 1995 we surveyed approximately 340 km of the Central and Eastern Basins for hydrothermal activity, with at least one profile every 20 km. The strongest hydrothermal signals were observed in the Central Basin along three of the major volcanic structures: Hook Ridge, the Three Sisters, and the Little Volcano. Anomalously high manganese concentrations (up to 11.9 nM) and δ^3He of 38% were observed over Hook Ridge (background values were 4 nM and 2%, respectively), where the ZAPS instrument package also detected strong particle anomalies. In addition, temperature anomalies between 0.010 and 0.025 °C were measured in these areas.

This hydrothermal activity occurs along a linear but discontinuous neovolcanic ridge that runs between Deception Island and Bridgeman Island in the Central Basin, and continues northeast of Bridgeman Island in the Eastern Basin. The rise heights of hydrothermal plumes, and the abundance of hydrothermally derived particles provide evidence for the occurrence of high-temperature, iron-rich hydrothermal sources on the volcanic ridges in the Central Basin. These plumes are comparable in size to some of the largest plumes observed on the Mid-Atlantic Ridge. We also found evidence of hydrothermal discharge from the flooded caldera at Deception Island. The injection of this plume of turbid and, possibly metal- and nutrient-rich water into the surface waters of the western Central Basin may have biogeochemical significance in this region of extremely high biological activity.

Introduction

The Bransfield Strait backarc basin formed by rifting behind the South Shetland Island Arc. Rifting has resulted in a 2-km-deep graben that extends over 400 km from Clarence Island to Low Island (Fig. 1). The graben is 30–40 km wide, with a southern margin that rises gently toward the pre-Tertiary Antarctic Peninsula continental magmatic arc through a series of widely spaced normal faults (Ashcroft, 1972). The northern edge of the graben (along the South Shetland Islands) is bounded by steep normal faults. Active rifting has caused recent earthquakes and volcanism along the northern margin of the strait and within the graben (Keller et al., 1992; Lawver et al., 1995).

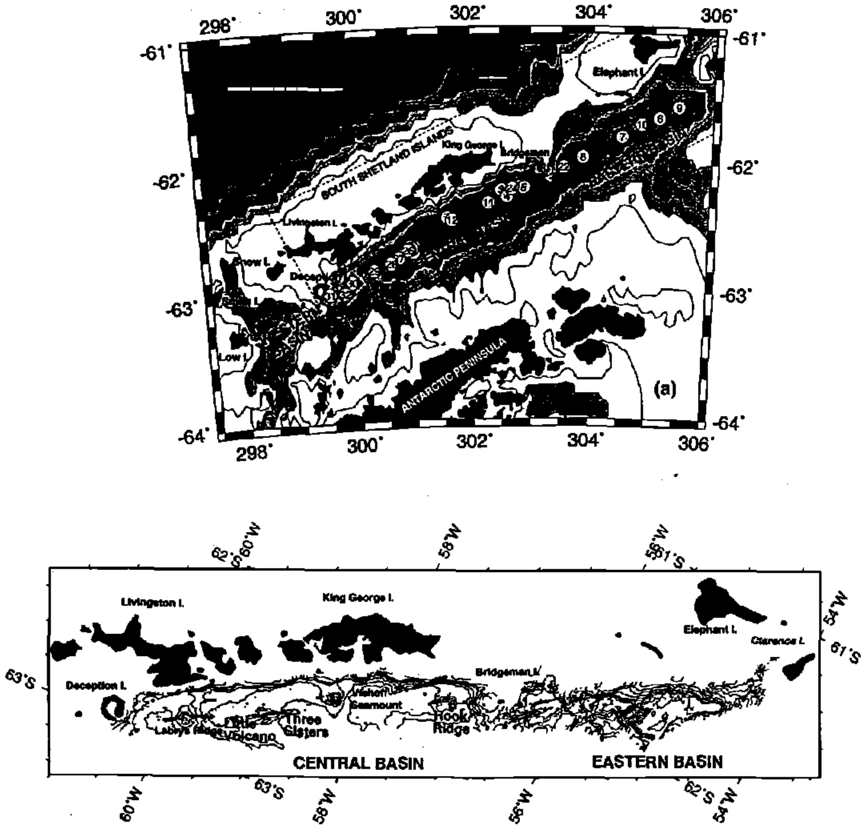

Figure III.1 Maps of the Bransfield Strait showing (a) the station locations and the surrounding bathymetry and geographic features and (b) the multibeam coverage of the NBP95-07 cruise. In (a) the shading changes at 500 m, 1000 m and 2000 m. The Bransfield Strait is isolated from outside waters below 500 m, except for in the eastern side of the Eastern Basin. The diamonds denote rosette casts, while circles are sled deployments. Numbered circles indicate the stations which compose the section plot shown in Figure 3.

Tectonics and Volcanism

The bulk of the Antarctic Peninsula and South Shetland Islands are composed of igneous rocks erupted in association with subduction of oceanic crust (Weaver et al., 1982; Hamer, 1983). Subduction along the length of the west coast of the peninsula was underway by Jurassic time and continued through the Mesozoic and Cenozoic, but ceased progressively northeastward up the peninsula as sections of the spreading ridge arrived at the trench (Barker and Dalziel, 1983; Mayes et al., 1990; Larter and Barker, 1991). Spreading on the last few ridge segments in western Drake Passage ceased at about 4 Ma, and subduction into the South Shetland Trench slowed dramatically or ceased at the same time (e.g., Barker, 1976; Barker and Dalziel, 1983).

The rifting that separated the South Shetland Islands from the Antarctic Peninsula and opened the Bransfield Strait began before 1.3 Ma and possibly as early as 4 Ma (Barker and Dalziel, 1983), and active volcanoes and earthquakes testify to its continuing activity (Pelayo and Wiens, 1989; Bush, 1992). The rift appears to extend 400 km from Low Island to Clarence Island (Fig. 1a), (Gonzalez-Ferran, 1985), with the ends of the rift terminating near the inferred extensions of the Hero and Shackleton Fracture Zones.

For the most part, subduction-related volcanism that formed much of the South Shetland Islands progressed from southwest to northeast, but appears to have stopped at about 20 Ma (Smellie et al., 1984; Birkenmajer et al., 1986). Isolated volcanism may have continued after this time, but only two localities with rocks older than 1 Ma and younger than 20 Ma are known (Birkenmajer et al., 1986; Rex and Baker, 1973).

Birkenmajer and Keller (1990) and Keller et al. (1992) established the presence of subaerial volcanism on King George Island and young (<30,000 to 300,000 years) submarine volcanism along the axis of the Strait. All these volcanoes fall between 57° W (Bridgeman Island) and 61° W (Deception Island) even though the rift appears to extend from 54° W to 62° W. This suggests either amagmatic rifting from 54° to 57° W and from 61° to 62° W, or the presence of additional, unsampled volcanic centers (Keller et al, 1996).

Deception Island Volcanism and Hydrothermal Activity

Deception Island is a flooded caldera breached at its southeastern corner. It is located at the southwest end of the Central Basin. It is the only subaerial feature in the Strait known to be volcanically active in the last 200 years and to be hydrothermally active at the present time (Elderfield, 1972; Orheim, 1992; Rey et al., 1995). The shores of the inner harbor, Port Foster, are host to hot springs which occur within the tidal zone. It is highly likely that other hydrothermal sources exist within the deeper portions of Port Foster (CH4, Tilbrook and Karl, 1993; Karl, unpublished data, pers. comm.; Mn and Rn, unpublished data of Suess, Fisk, Kadko and others). Rey et al. (1995)

have documented volcanic features on the seafloor in Port Foster, following an arcuate trend from Neptunes Bellows through the center of the caldera north toward Telefon Bay (the site of the most recent eruption). Tidal currents and the melting of snow and ice in the Austral spring/summer carry these enriched waters out through the breach in the caldera wall to the southeast and into the surface waters of the western Central Basin. A tidal model (Robertson et al., in press) shows tidal velocities are very high in the Bransfield Strait region, approaching 1 m s^{-1}. This suggests that Port Foster may be subject to significant tidal flushing, and that our observation of hydrothermal outflow from Deception Island may have been serendipitous because of its likely dependence on the tidal cycle.

Hydrothermal activity

Evidence for hydrothermal activity in the eastern Central Basin had been observed over the past ten years by a number of investigators. Manganese concentrations up to 7 nM, and corresponding δ^3He of >7% were measured in the water column at the eastern end of the Central Basin (Suess et al., 1988; Schlosser et al., 1988). Further evidence includes observations of hydrothermal alteration of sedimentary organic matter (Whiticar, 1985; Brault and Simoneit, 1990) similar to that associated with the Guaymas Basin hydrothermal site (Simoneit, 1983). In addition, qualitative analysis by electron microprobe of sediments recovered from a high heat flow area indicated the presence of Fe sulfide, Fe-Zn sulfide, Fe-Zn-Cu sulfide, Zn chloride, and Fe and Zn oxides (Lawver et al., 1995). Heat flow measurements at this site and another within this region of the Central Basin are high and variable (150-600 mW/m^2) and indicate the possibility of active hydrothermal circulation in this sedimented basin (Lawver et al., 1995). Despite this evidence suggesting the presence of hydrothermal activity in Bransfield Strait, neither the locations nor the magnitudes of the hydrothermal sources had been documented before our 1995 cruise (NBP9507).

The previous helium measurements in the Bransfield Strait have obtained anomously low ^{3}He/^{4}He ratios of 2.4-5.0 x 10^{-6} (Schlosser et al., 1988) compared to other volcanic areas (including hydrothermal sites) which typically exhibit the pure mantle ratio of 10 x 10^{-6} (Sano, 1986). This low ratio suggests a local source of radiogenic helium (^{4}He) within the Strait, either from decay in the sediments or from the rifting of continental crust within the basin (Schlosser et al., 1988). Similarly low values of ^{3}He/^{4}He have been reported for the Mariana backarc spreading center (Horibe et al., 1986) and in areas where continental crust is undergoing extension (Oxburgh and O'Nions, 1987).

In November 1995 we surveyed about 340 km of the Bransfield Strait for hydrothermal activity, with at least one profile every 20 km. We conducted thirty-two deployments of the ZAPS (Zero-Angle Photon Spectrometer, Klinkhammer, 1994) sled instrument package with water sampling, ten of which were tow-yo sections. We also carried out an additional 12 CTD/rosette casts to collect larger volumes of seawater. The Central Bransfield Basin (Fig. 1) was the focus of most of the detailed work, however, seven operations were also carried out in the Eastern Bransfield Basin. A survey conducted just outside the mouth of Deception Island detected a plume of warm, turbid water leaving Port Foster, the inner waters of the island.

Methods

Data Collection

The most cost-effective and efficient method of searching for hydrothermal sources on the seafloor is the detection of hydrothermal plumes in the water column. This approach not only identifies individual vent fields, but also places the hydrothermal activity in a regional hydrographic context. This characterization of the water column is important because knowledge of the background stratification is critical in the interpretation of the plume data.

The ZAPS instrument package consists of a SeaBird 9/11 *plus* CTD, a small rosette fitted with six 1.2-liter Niskins, a SeaTech transmissometer, a Chelsea nephelometer, a SeaTech light scattering sensor, a Sea Point turbidity sensor and the ZAPS probe which measures dissolved manganese *in situ*.. Water samples were collected using this instrument package as well as the ship's CTD/rosette for shore-based analyses of manganese. In addition, more than 100 water samples were collected for analyses of the helium isotopic composition.

During *NBP*95-07 we used a three-step approach in surveying the Bransfield Strait area, looking at increasingly smaller areas to pinpoint the sources of the observed hydrothermal plumes. This survey approach resulted in the location of three major venting areas in the Central Bransfield Basin. Because of time constraints, only the first phase of this survey strategy was completed in the Eastern Basin. Although hydrothermal activity was indicated by the signals we observed in this basin, the plume sources were not identified.

Laboratory Analyses

Manganese determinations with the ZAPS fiber optic spectrometer were calibrated by running standard solutions on shore before the field operations. These calibrations were adjusted after the cruise by comparing the field data with the manganese concentrations in samples collected with the rosette on the ZAPS package. These samples were analyzed for dissolved manganese and total dissolvable manganese (TDM, Klinkhammer et al., 1977) using a Fisons VG PlasmaQuad II Plus ICPMS interfaced to a Dionex Chelation Concentration Module.

Results and Discussion

In 1995 we found evidence of hydrothermal activity in both the Central and Eastern Basins of the Bransfield Strait (Klinkhammer et al., 1995; Chin et al., 1996). We located three major venting areas in the Central Basin, where the ZAPS instrument package detected the strongest signals: inside the Little Volcano (western end of Middle Sister), along the Three Sisters (a volcanic structure consisting of three parallel ridges), and near the top of Hook Ridge.

Little Volcano

The Little Volcano is a small, semi-circular seamount positioned at the southwest end of a volcanic edifice extending from the Middle Sister, as shown in Fig. 2. During operation SL27 we towed our package along the ridge and into this seamount. As seen in Fig. 3, only small nephel anomalies were observed over the ridge, but much larger anomalies were measured when the package entered the Little Volcano. A temperature anomaly of ~0.04 °C was associated with this turbidity anomaly. Results from rosette R10 conducted inside the caldera are shown in Fig. 4. The temperature anomaly is first apparent at 1085 m and then increases into the bottom, and TDM (total dissolvable manganese) shows a similar trend. The δ^3He results from this operation show a distinct gas plume with a maximum at 1085 m. The particle plume maximum at this site occurs almost 100 m deeper than the maxima for the dissolved species and temperature. This difference in plume height might result from rapid particle settling in a relatively quiescent caldera. The sinking of large particles and the separation of the particulate plume from the dissolved plume was previously observed on the Juan de Fuca Ridge within the "megaplume" (Baker et al., 1987; Baker et al., 1989). The relationship between attenuated and scattered light (measured by a transmissometer and a

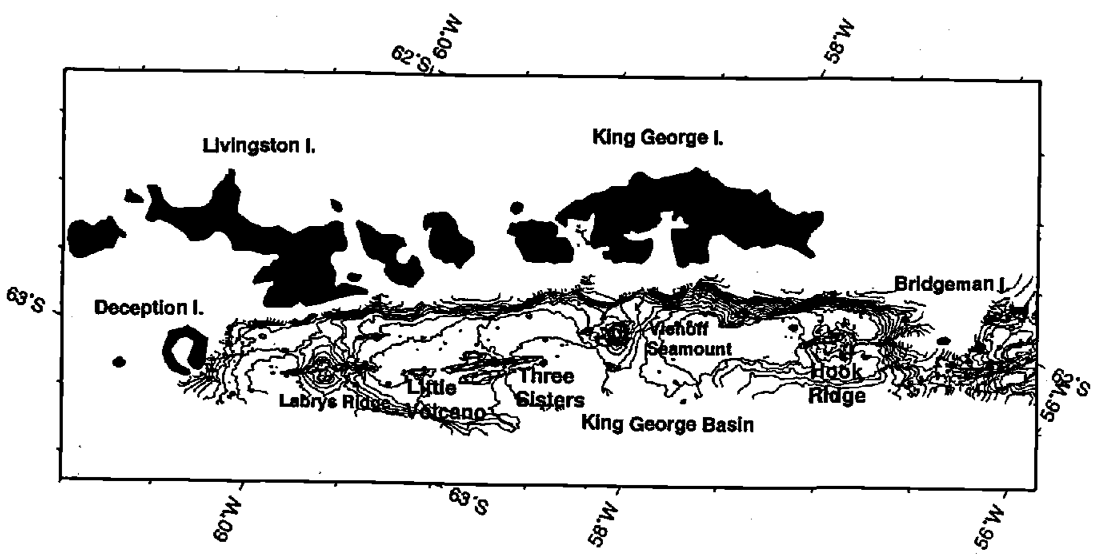

Figure III.2 Batymetric map of the Central Bransfield Basin, showing more detailed bathymetry which reveals the intermittent neovolcanic ridge through the Strait.

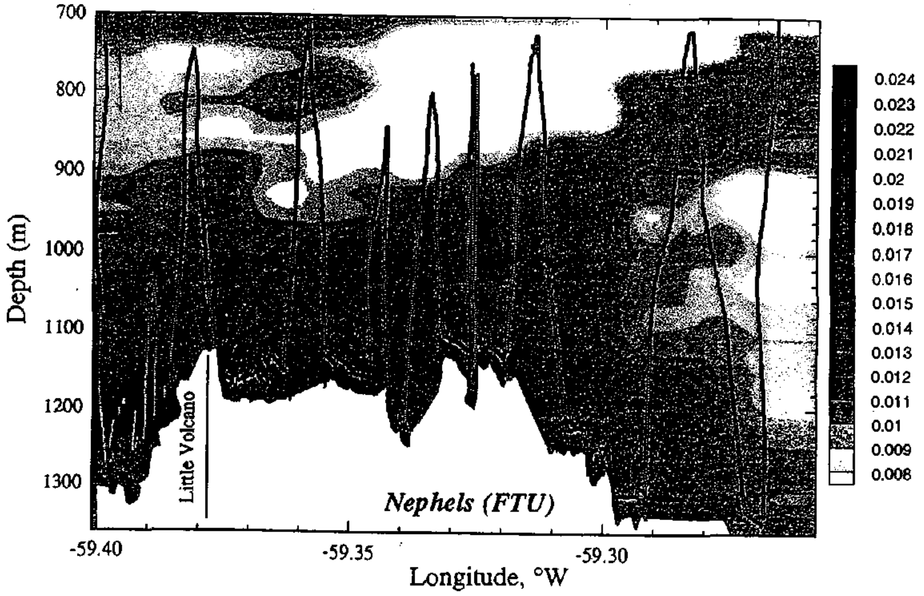

Figure III.3 Contour of nephels (FTU, formazine turbidity units), a measure of particles in the water, for sled tow 27 across a small ridge into the caldera of the Little Volcano. A particle-rich plume is evident within the caldera, about 60 m above the bottom. A smaller enrichment was seen above the ridge, rising through the water column to the east.

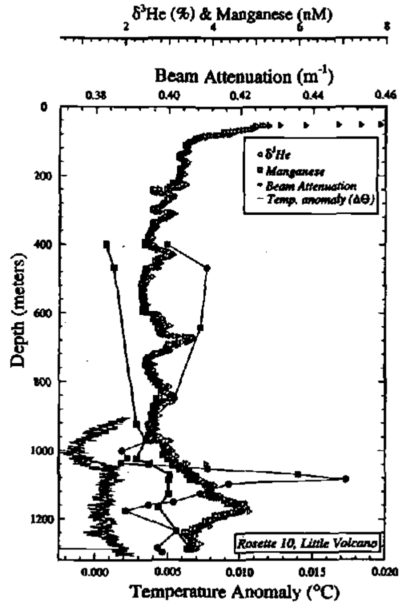

Figure III.4 Profiles of light attenuation (turbidity as measured by a transmissometer), temperature anomaly, δ^3He, and TDM (total dissolvable manganese) from rosette10 taken inside the Little Volcano caldera.

nephelometer, respectively) provides a qualitative estimate of the particle size distribution, since the transmissometer is more sensitive to larger particles, and the nephelometer to smaller particles (Zaneveld, pers. comm.). Throughout the Bransfield Strait the hydrothermal particles are relatively large compared to other hydrothermal sites that we have visited with the same equipment. We did not collect particle samples, so assuming that they are Fe oxyhydroxides, goethite (FeO•OH), chalcopyrite, and anhydrite (for the purpose of estimating density); and that they are relatively large, radius r=10 μm, the settling velocity can be estimated using Stoke's Law:

$$u = \frac{2gr^2\mathrm{Dr}}{9\mathrm{h}} \tag{1}$$

where g is gravitational acceleration, Dr is the density difference between the particle and seawater, and h is the dymanic viscosity. From these assumptions, the settling velocity is approximately 27 m/d. The actual rain rate of these particles is probably slower, because of tidal velocities and currents, however the Little Volcano site is within a caldera-topped seamount, so the influence of currents is probably lessened. With these relatively rapid settling rates, it is possible that large hydrothermal particles could settle, separating from a dissolved/temperature plume that is sustained by continuous venting.

Alternatively, the separation of the dissolved and particulate plumes may result from heterogeneous venting or venting of phase separated hydrothermal fluids. In this case, the upper plume would represent the vapor phase, enriched in gases such as ^{3}He, and the lower plume would be the metal-enriched phase, with the majority of those metals having precipitated. The two plumes could also have originated from separate vent orifices, one of which is more enriched in particle-forming iron and the other which is more enriched in the gas phase. Differences in the temperature at each orifice would result in differences in rise height.

Three Sisters

The Three Sisters are three parallel ridges as shown in Fig. 2. Initially five vertical lowerings of the OSU package were made on these ridges as a reconnaissance. Fig. 5 presents the turbidity profiles from these operations as recorded above North Sister (SL14 and SL15), Middle Sister (SL13 and SL17) and South Sister (SL16). Based on these results Sled tow 18 was carried out along Middle Sister. Particle anomalies were observed between 1050-1300 meters above the middle portion of the ridge (Fig. 6). Temperature anomalies were evident in several areas above Middle Sister, as shown in Fig. 7. These anomalies were seen between 970-1300 m depth, the largest anomaly being ~0.02°C at 1000 m depth in Sled tow 18. The patchiness of these anomalies and the fact that they are associated with turbidity maxima suggests a hydrothermal source.

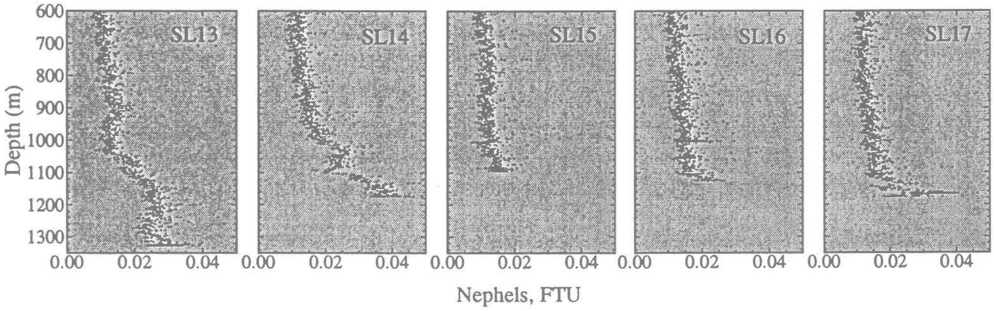

Figure III.5 Nephel profiles for sled verticals 13-17, taken at different locations along the Three Sisters. The strongest particle signals are seen in SL13 and SL14, taken above Middle Sister and North Sister, respectively (see Fig. 7). No hydrothermal activity was detected above South Sister, SL16.

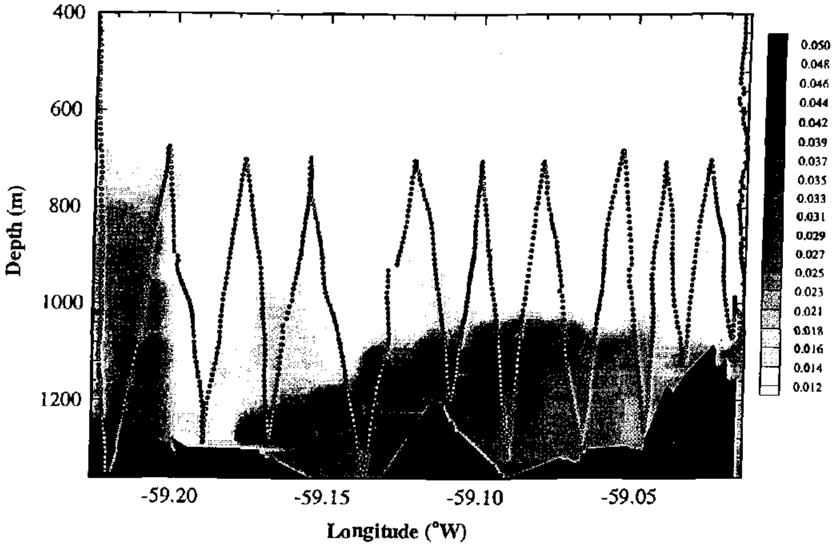

Figure III.6 Nephel contour plot for sled tow 18 along Middle Sister. Particle-rich plumes are evident above the ridge between 1050 to 1300 m depth.

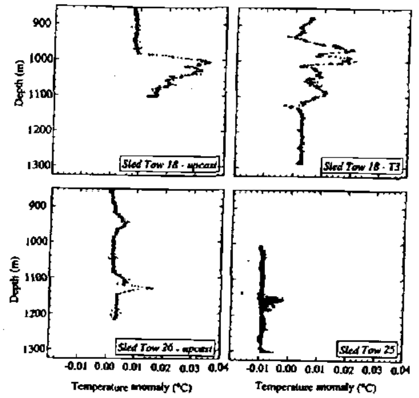

Figure III.7 Temperature anomalies measured in the Three Sisters area. The rise heights of these plumes indicate that they are the result of high-temperature venting.

Hook Ridge

Hook Ridge is the easternmost volcanic edifice in the Central Basin (Fig. 2), near the high heat flow site identified by previous studies (Lawver *et al.*, 1995), and is where previous investigators detected evidence of hydrothermal activity (Suess *et al.*, 1988;

Schlosser *et al.*, 1988). Particle anomalies were observed above the ridge during Sled tow 20, shown in Fig. 8. This site produced the most striking hydrothermal signals detected during the cruise. SL24 produced similar profiles of dissolved Mn and turbidity (Fig. 9). Note that the relative sizes of the dissolved (Mn) and particulate (attenuation and nephels) maxima are not the same. This result is consistent with venting from more than one source within the vent field, and because of differing source chemistry and temperature, the uppper and lower plumes show different dissolved:particulate ratios as well as different rise heights.

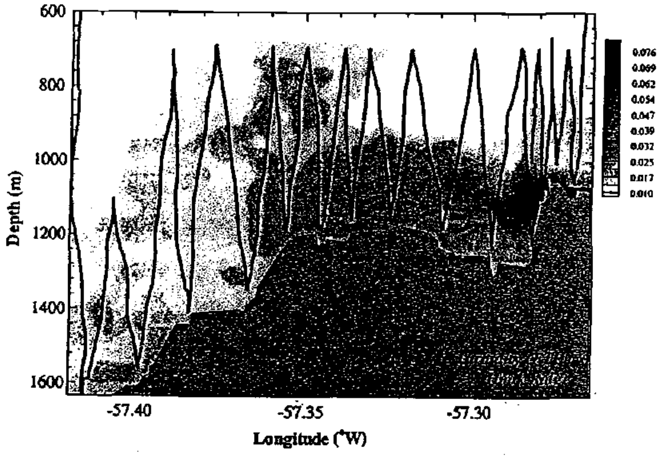

Figure III.8 Nephel contour plot for sled tow 20 along Hook Ridge. The large particle plume at ~57.28°W was observed while the package was on the flank of the ridge, rather than directly over ridge axis.

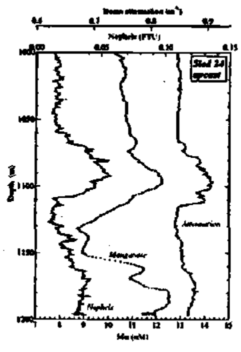

Figure III.9 Profiles of light attenuation, nephels, and dissolved manganese as measured by the ZAPS probe for sled upcast 24, near to where the large signal was seen during sled tow 20 on Hook Ridge. A large anomaly in all three measurements is evident between 1060-1110 m, with a smaller signal seen deeper at ~1175 m.

During the survey of the eastern summit at Hook Ridge it seemed that our instrument package passed very close to a vent site. This belief gained considerable support after the cruise when one of the water samples collected during rosette 10 was found to have a ∂^3He of 38% and a TDM concentration of 11.9 nM. Other operations at this site produced temperature anomalies (0.01 °C), constraining the venting site to within a 1-km^2 survey area. Given these results it seems certain that our package passed a few hundred meters or less from a vent site located near the eastern summit of Hook Ridge.

Deception Island

Deception Island is a flooded, breached caldera located at the southwestern end of the Central Basin. This island is the only subaerial feature in the Strait which is confirmed to be historically active (<200yrs.). The shores of the inner harbor, Port Foster, are host to hot springs which occur within the tidal zone. It is likely that other hydrothermal sources exist within Port Foster. Tidal currents and the melting of snow and ice in the Austral spring/summer carry these enriched waters out through the breach in the caldera wall to the southeast and into the surface waters of the western Central Basin. A survey conducted just outside Neptunes Bellows in 1995 indicated a plume of turbid and probably metal- and nutrient-enriched water flowing out from the island (Chin et al, 1996; Fig. 10). Previous investigators observed an abundance of cyanobacteria at Neptune's Bellows (Letelier, pers. comm.) This particle plume may therefore represent the presence of substantial bacterial populations within Port Foster, in addition to increased inorganic particulate material. Furthermore, primary productivity in the region of Deception Island is an order of magnitude higher than in the surrounding seas (Mandelli and Burkholder, 1966), presumably resulting from the significant hydrothermal input of reduced chemical species.

Eastern Bransfield Basin

We also observed hydrothermal signals in our initial survey of the Eastern Basin (Fig. 12), but time constraints prevented us from identifying the plume sources. Figure 12 is just one of seven vertical profiles that were conducted in the Eastern Basin. Five of these seven profiles showed turbidity anomalies. In addition, ∂^3He in the Eastern Basin shows a higher background than in the Central Basin, despite the fact that waters in the Eastern Basin have a shorter residence time because of the input of Weddell Sea water

(Wilson, 1997). This high background requires that there be a higher flux of He to the Eastern Basin.

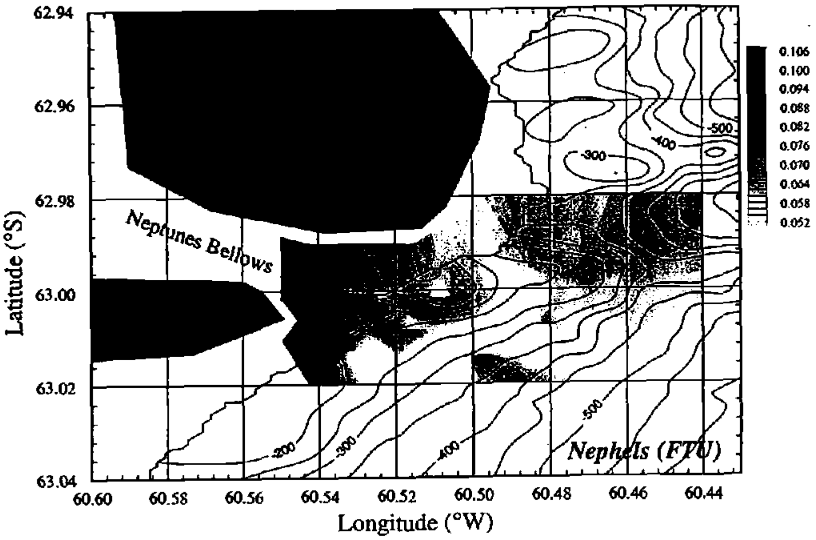

Figure III.10 Contoured nephels (FTU) overlain with the bathymetry (black contour lines) showing the hydrothermally derived plume of turbid and probably metal- and nutrient-rich water leaving Deception Island from Neptunes Bellows. Measurements were made using a Chelsea nephelometer mounted on the ZAPS sled.

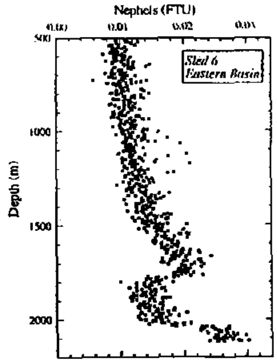

Figure III.11 One of seven vertical profiles of nephels (FTU) measured in the Eastern Basin using the Chelsea nephelometer.

Vent frequency and hydrothermal flux

A key question in any hydrothermal environment is how often vent fields occur along a ridge. This question is particularly interesting with respect to the Bransfield Strait, because it is uncertain whether true seafloor spreading has yet been established along the neovolcanic ridge (Lawver et al, 1997). Correlations have been drawn over the past few years between the occurrence of hydrothermal activity and other magmatic indices such as spreading rate, or rates of crustal production. From such assumptions, one might predict that hydrothermal venting would not be very common in a place such as the Bransfield Strait. However, plume measurements made in 1995 indicate that the hydrothermal systems in the Bransfield Strait are as robust as the largest plumes we have sampled on the Mid-Atlantic Ridge (Fig. 12). There are at least three such sites in the Central Basin, and evidence for additional sites in the Eastern Basin that we did not have enough time to pursue in 1995.

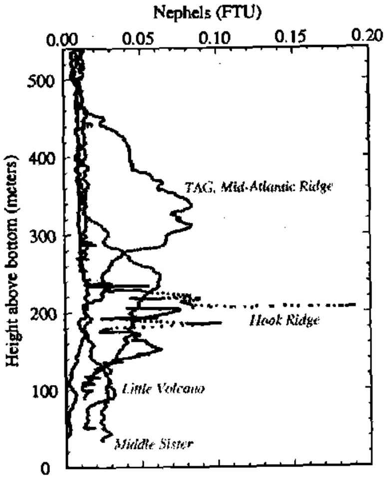

Figure III.12 The three hydrothermal signals seen within the Bransfield Strait compared with the plume measured the well-known TAG site on the northern Mid-Atlantic Ridge. Due to the differences in bottom depths between the Bransfield Strait and the TAG area, the profiles have been plotted versus height above the bottom. At the TAG site, this distance is equivalent to the rise height of the plume. However, in the Bransfield Strait the exact location of the hydrothermal sources, and therefore the depth of venting, is not known. The Bransfield Strait signals do not rise as high as the TAG plume, but are of comparable magnitude.

Estimates of heat flux from the two hydrothermal systems identified in the Central Basin are summarized in Table 1. These heat fluxes were calculated based on the Turner and Campbell (1987) model which uses the rise height (z_{max}) to estimate the buoyancy flux (B) as follows:

$$B=\left[\frac{z\ \max(N^2)^{3/8}}{3.8}\right]^4 \tag{2}$$

where $z_{\max}$ is the rise height of the plume and N is the buoyancy frequency in a stratified environment as defined by:

$$N=\left[\left(\frac{-g}{r_{\mathrm{ref}}}\right)\left(\frac{dr}{dz}\right)\right]^{1/2} \tag{3}$$

g is gravitational accelleration, r_{ref} is the reference density, and (dr/dz) is the density gradient (z = water depth). Heat flux is then calculated as:

$$H=\left[\frac{BrC_p}{g\ a}\right] \tag{4}$$

using values of heat capacity, C_p, thermal expansion coefficient, a, and density from tables in Bischoff and Rosenbauer (1985) that correspond to conditions at these two sites.

Table III.1 Heat fluxes calculated for two sites in the Central Basin, Bransfield Strait.

Location	Exit Temp. (°C)	Heat Flux (MW)	References
Hook Ridge	300 330 350	1050 1620 2460	(Chin et al., in prep.)
Little Volcano	300 330 350	150 220 340	(Chin et al., in prep.)
MAR, TAG*	360	500-940	Rudnicki & Elderfield (1992)
21°N, EPR*	350	144-311	Macdonald et al. (1980)
SJdFR, Cleft Segment* megaplume site		~350	Baker et al. (1989)
JdFR, Axial Seamount*		800	Baker et al. (1990)

*MAR = Mid-Atlantic Ridge, EPR = East Pacific Rise, JdFR = Juan de Fuca Ridge

Since we have not made measurements at the vent orifices, we do not know the exact exit temperatures of the vent fluids at these sites. Therefore, a range of exit temperatures is listed in Table 1. Heat fluxes at mid-ocean ridge hydrothermal sites are shown for comparison. The Little Volcano site shows a heat flux similar to that observed at 21°N on the East Pacific Rise, but heat fluxes measured at Hook Ridge are several times higher than those observed at TAG or Axial Seamount.

Ratios of ^{3}He/heat and Mn/^{3}He at Hook Ridge are compared with other mid-ocean ridge hydrothermal sites, and the Mid-Okinawa Trough backarc basin (Table 2). The ^{3}He/heat at Hook Ridge is comparable to those found in the deep event plume (at the meagaplume site) and at Axial Seamount while the R/R_A value is significantly lower.

Table III.2 Ratios of ^{3}He/heat and Mn/^{3}He.

Location	^{3}He/Heat (10^{-12} cm^3/cal)	Mn/^{3}He (g/cm^3)	R/R_A	References
Hook Ridge*	2.3	2.1×10^4	1.4	(Chin et al., in prep.)
EPR, 21°N†	0.4	7.2×10^4	7.8	Lupton et al.(1980)
MAR, TAG*		2.2×10^4	1.2	Rudnicki & Elderfield (1992)
Southern JdFR, Cleft Segment				
megaplume site*	0.14-0.3		7.9	Lupton et al. (1989)
deep plume*	2-4		7.9	
JdFR Axial Seamount†	2.2		8.1	Can.-Amer. Smt. Exped. (1985)
JdFR Endeavour Segment*	1-2		7.9	Lupton et al. (1985) Rosenberg et al. (1988)
Mid-Okinawa Trough† JADE site	0.29		6.3	Ishibashi et al. (1995)

*from plume samples †from vent samples

Plume Comparison

Particle profiles from each of the three hydrothermally active areas in the Central Basin are compared to the particle plume at the well-known TAG site on the Mid-Atlantic Ridge. From this comparison, it is clear that hydrothermal plumes in the Bransfield Strait are comparable to some of the largest plumes observed on the Mid-Atlantic Ridge with the same equipment (Klinkhammer et al., 1995; Chin et al., 1996; Fig. 12). The particle plume at Hook Ridge exceeds the levels at TAG while the plume at Middle Sister is comparable. The chemistry of the fluids from vents in the Bransfield Strait are undoubtedly capable of supporting abundant vent biota. One of the outstanding questions now is the effect of remoteness on biodiversity. Are vent biota established in the Bransfield Strait? If so what distinct characteristics do these animals possess? It is possible that vent biota in the Bransfield Strait may be an endmember in the chemotrophic kingdom.

Conclusions

As a result of this work, and consistent with findings in other backarc basins that have been explored, the Bransfield Strait was found to be hydrothermally active. Three distinct areas of activity were found in the Central Basin: the Little Volcano, the Three Sisters and Hook Ridge. The plume rise heights (150-300 m), and the abundance of particles at these sites are consistent with high-temperature, iron-rich hydrothermal venting. The magnitude of the particle enrichment at these sites is comparable to the plume at TAG on the Mid-Atlantic Ridge. These are the types of vent systems that are known to support abundant vent biota at mid-ocean ridge hydrothermal sites. Heat fluxes calculated for the Little Volcano site in the Central Basin are comparable to those reported for mid-ocean ridge hydrothermal sites, while those for Hook Ridge are several times higher than heat fluxes reported for either TAG or Axial Seamount. In addition to the discovery of these three high-temperature vent sites we also identified two other hydrothermal phenomena in the Bransfield Strait: a surface ocean plume associated with hydrothermal activity in the submerged caldera at Deception Island, and a possible site of sediment-hosted venting. Hydrothermal activity in the Central Basin of Bransfield Strait appears to occur along a linear neovolcanic ridge that runs between Deception and Bridgeman Islands, that pierces the sediment cover at several locations.

Acknowledgments

We wish to acknowledge the support of the captain and crew of the *Nathaniel B. Palmer*. Thanks to A. Ungerer for assistance with the ICP-MS analyses, and R. Greene for running the helium samples. In addition, this work benefitted from the assistance of the other scientists on NPB95-07. This research was funded by National Science Foundation grant OPP 93-17361 to G. P. Klinkhammer.

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Chapter 4

Water Column ^{3}He/^{4}He trends over the Azores Plateau, Northern Mid-Atlantic Ridge

Carol S. Chin, Gary P. Klinkhammer and John E. Lupton

Abstract

We collected water column samples over the MAR (Mid-Atlantic Ridge) from the Hayes fracture zone to the Kurchatov fracture zone (33° to 41° N) during a hydrothermal survey of the northern MAR, part of the French American Ridge Atlantic (FARA) Program. Measurements of δ^3He in these samples show a trend that increases over the Azores Plateau, consistent with progression toward a hotspot with an elevated ^{3}He signature. Because ^{3}He/^{4}He ratios in basalts from this same section of the MAR show a slightly decreasing trend toward the plateau (Kurz et al., 1982), changes in mantle source ^{3}He/^{4}He do not appear to account for the trend in water column ^{3}He/^{4}He. Elevated ^{3}He/^{4}He in the water column may therefore reflect an increase in hydrothermal activity northward along the ridge axis in this region, and thus a higher input of ^{3}He into the water column. Alternatively, this trend may indicate increased phase separation in hydrothermal fluids as the ridge shallows toward the Azores Plateau resulting in the more frequent occurrence of gas-enriched hydrothermal plumes. This section of the MAR includes three known hydrothermal sites: Rainbow, Lucky Strike, and Menez-Gwen. Our results would indicate that other, undiscovered hydrothermal sources must exist along this portion of the MAR to produce the observed water column ^{3}He/^{4}He trend.

Introduction

Significant quantities of primitive gases are trapped in the Earth's interior. The majority of mantle outgassing occurs through volcanism along mid-ocean ridges, and primordial helium is introduced into the oceans in this manner. The first evidence of this mechanism for the exhalation of primordial gases from the mantle was reported by Clarke et al. (1969) who measured elevated ^{3}He/^{4}He ratios in the deep Pacific. This excess ^{3}He in the water column attributed to the escape of primordial ^{3}He from mid-ocean ridge spreading centers, in this case from the East Pacific Rise. The conservative behavior of ^{3}He makes it an excellent tracer of hydrothermal activity. Because hydrothermal activity introduces ^{3}He at mid-depths in the ocean, it is also an important tracer of deep ocean circulation (Lupton and Craig, 1981).

We collected water column helium samples from the Mid-Atlantic Ridge (MAR) between the Hayes fracture zone and the Kurchatov fracture zone (33 to 41° N) during a hydrothermal survey of the northern MAR which was part of the French American

Ridge Atlantic (FARA) program. Nine of the eleven segments surveyed during this cruise showed hydrothermal anomalies in the water column (Klinkhammer et al., 1995; Chin et al., 1993; Chin et al., 1996, Chin et al., in press). The Lucky Strike vent site was discovered during this cruise (Langmuir et al., 1997), and was one of the sites sampled for helium. The FARA region of the MAR is also host to the Menez-Gwen and Rainbow hydrothermal sites (Fig. IV.1).

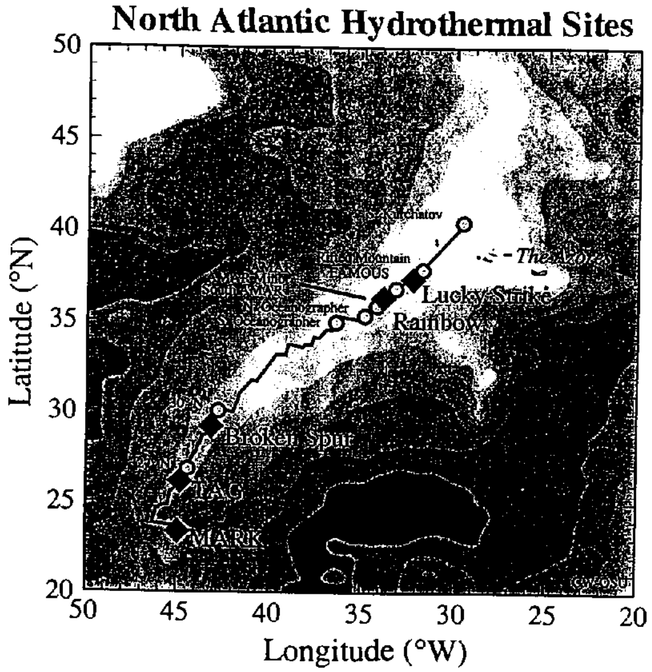

Figure IV.1 Locations of high temperature hydrothermal sites on the northern Mid-Atlantic Ridge. Those marked with diamonds have been explored with a submersible. Circles indicate sites where hydrothermal plumes have been observed in the water column.

Data Collection

The ZAPS instrument package used for this work was constructed at Oregon State University, and consisted of a SeaBird 9-11plus CTD, a Chelsea Aquatracka Mk III nephelometer, a SeaTech transmissometer, a SIMRAD Mesotech Systems echo sounder/altimeter, a transponder, a small rosette, and the ZAPS chemical sensor [17]. The shipboard data aquisition system included a Garmin MRN 100 Satellite Receiver that was interfaced to a computer. There the navigational information was merged with the incoming CTD data and stored on optical disk. The ZAPS instrument package was deployed both as a vertical profiling tool and as a towed sled. Water samples were collected using the rosette on the ZAPS instrument package as well as a CTD/rosette system fitted with 24 30-liter bottles.

Samples for helium isotopic analyses were transferred to copper tubing without exposure to air, as described by Lupton and Craig (1981).

Results and Discussion

The data reported here are from 27 vertical casts from which helium samples were taken. The station locations on the northern MAR are shown in Fig. IV.2. Plots of δ^3He show an increasing trend northward toward the Azores Plateau and then a decrease to the north as the plateau drops off (Figs. IV.3 and IV.4). The latitude of the 3 known hydrothermal sites within the FARA region of the MAR are shown on both

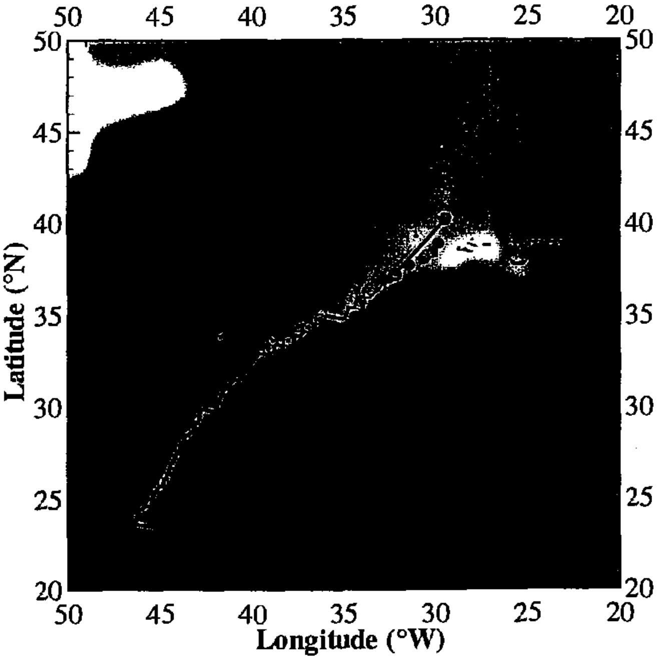

Figure IV.2 Helium sample locations on the northern Mid-Atlantic Ridge. Lighter greys indicate shallower bathymetry. Lightest shades indicate the location of the Azores Plateau.

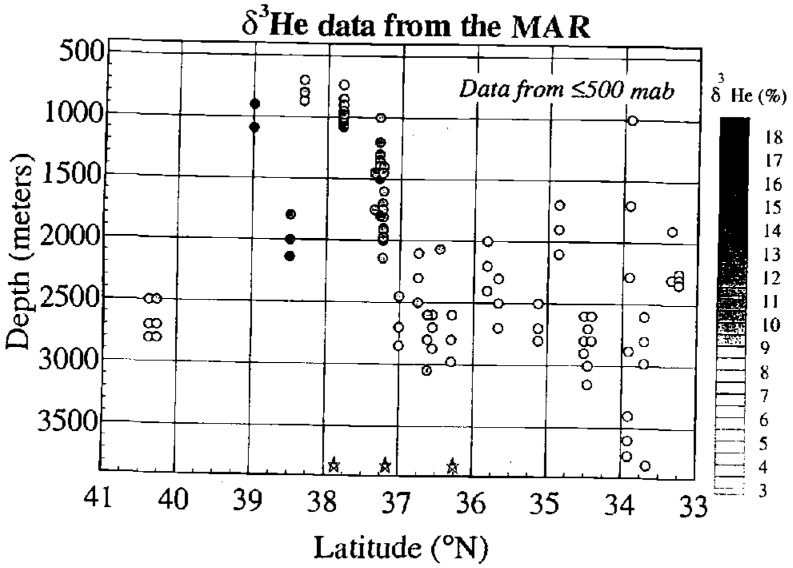

Figure IV.3 Sample depth vs. latitude from 33 to 41° N on the Mid-Atlantic Ridge, with darker shading indicating higher δ^3He. There is a distinct increase in the ratio toward the Azores Platform. All data are from ≤ 500 m above the bottom. The stars on the x-axis indicate the locations of (from north to south) the Menez-Gwen, Lucky Strike, and Rainbow hydrothermal sites.

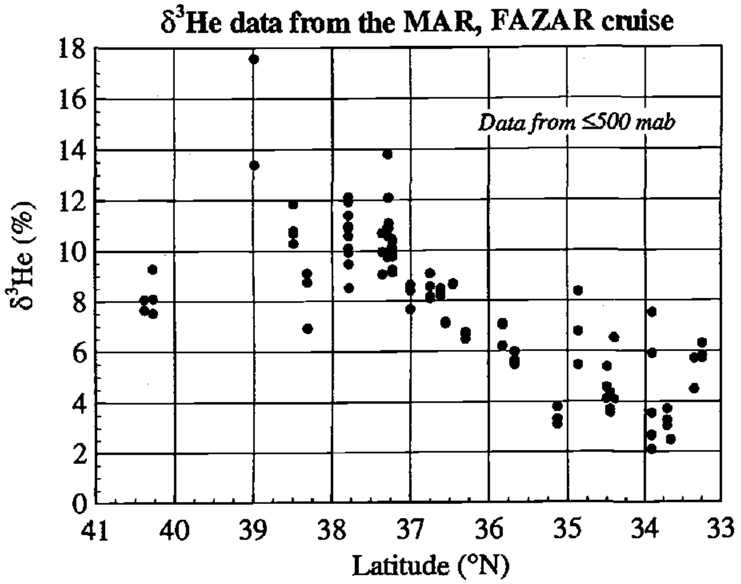

Figure IV.4 Helium vs. latitude from 33° to 39° N on the Mid-Atlantic Ridge. Note the increase in the He ratio toward the Azores Platform. All data are from ≤ 500 m above the bottom. Stars on the x-axis indicate the locations of (from north to south) Menez-Gwen, Lucky Strike, and Rainbow.

figures. The largest δ^3He values were not associated with any of these sites, but rather they were measured at the top of the Azores Plateau. Only those samples within 500 m of the seafloor are plotted because these samples are assumed to occur within the typical range of rise heights of a hydrothermal plume in this region. Changes in mantle source ^{3}He/^{4}He do not appear to account for the trend in the water column since ^{3}He/^{4}He ratios in basalts from this same section of the MAR show a slightly decreasing trend toward the Plateau (Kurz et al., 1982). In fact, because of dilution effects between hydrothermal fluids and seawater, it is unlikely that such a trend in the basalt chemistry would be detectable in water column samples.

determined by Wilson et al. (1995). Furthermore, helium data from Mediterranean brine basins (Winckler et al., 1997) indicate that the helium ratios in this region include a strong radiogenic component, lowering the ^{3}He/^{4}He ratio. The observed increase in dissolved δ^3He along the MAR is consisitent with gas data of Charlou et al. (1997) who reported increases in methane concentrations toward the Azores hot spot. Because of the oxidation rate of methane, it is unlikely that a methane signal in the MW would still be observable once it had reached the MAR, and the correlation between methane and δ^3He points to a hydrothermal origin for this feature.

Most likely, the trend toward higher ^{3}He/^{4}He ratios northward in the water column reflect the increased occurrence of hydrothermal activity toward the Azores Plateau. This would also account for the increase in methane concentrations toward the plateau observed by Charlou et al. (1997). In addition, this section of the MAR, near the Azores Platform, is characterized by significant tectonic extension and crustal fissuring (German et al., 1996), a setting which is expected to support vigorous convection (Wilcock and Delaney, 1996). This vigorous convection would be expected to support increased hydrothermal extraction of volatiles through water-rock interactions, transporting those volatiles to the ocean.

It is also possible that phase separation is more prevalent in hydrothermal systems as the ridge shallows toward the Azores Plateau, and that the increased occurrence of a gas-rich vapor phase leads to the increasing ^{3}He/^{4}He trend. However, it is not known, and is unlikely, that such differences in the ratio of vapor/fluid phases would be detectable in hydrothermal plumes.

To support the increasing ^{3}He/^{4}He trend in the water column, there must be additional undiscovered hydrothermal sites along this section of the northern MAR.

Based on their locations, it is not possible for the known hydrothermal sites to produce the observed trend.

Conclusions

Both helium and methane appear to increase toward the Azores Platform. Increasing $^3He/^4He$ in the water column may reflect an increase in hydrothermal activity northward along the ridge axis toward the Azores Plateau. This $^3He/^4He$ trend may indicate increased phase separation in hydrothermal fluids as the ridge shallows toward the Azores Plateau, resulting in gas-enriched plumes. It is more likely, however, that this trend represents increasing hydrothermal activity toward the Azores hot spot. Additional, undiscovered hydrothermal sources must exist along this portion of the MAR to produce the observed water column trend.

Acknowledgments

We are grateful to D. Graham for many thoughtful discussions of the data presented. We also wish to thank the chief scientist on the FAZAR cruise, C. Langmuir. Multibeam maps for the FAZAR cruise were graciously provided by H. D. Needham. We would also like to acknowledge the support of the captain and crew of the *R/V Atlantis II.* This work was supported by National Science Foundation grant OCE-9105177 to GPK, and is a contribution to the FARA (French-American Ridge Atlantic) Program.

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Chapter 5

Summary and 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. (1986) 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 (German et al., 1996), and evidence of hydrothermal activity everywhere along the ridge from 12° to 26°N (Charlou and Donval, 1993). 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 the lack of detailed sampling. Ratios of high-temperature, axial to off-axis heat loss along the mid-ocean ridge system must be higher on the northern MAR in order to maintain the vent frequency observed and still remain within the magmatic supply constraints of slow-spreading ridges.

Further evidence of more frequent hydrothermal venting on the northern MAR comes from observations of an increase in helium toward the Azores Plateau. Higher ^{3}He/^{4}He is measured in the water column as one approaches the Azores Plateau. This trend may indicate increased phase separation in the hydrothermal fluids as the ridge shallows toward the Azores Plateau, resulting in gas-enriched plumes. It is more likely, however, that this trend represents an increase in hydrothermal activity toward the Azores hot spot. Additional, undiscovered hydrothermal sources must exist along this portion of the MAR to produce the observed water column trend. If this trend does represent increased hyrothermal activity, it may provide a unique regional setting in which to examine other trends such as increases or decreases in biodiversity or faunal abundance at venting sties, and may therefore represent an important observation on which further studies may be based.

Consistent with findings in other backarc basins that have been explored, the Bransfield Strait was found to be hydrothermally active. Three distinct areas of activity were found in the Central Basin: the Little Volcano, the Three Sisters and Hook Ridge. The plume rise heights (150-300 m), and the abundance of particles at these sites are consistent with high-temperature, iron-rich hydrothermal venting. The magnitude of the particle enrichment at these sites is comparable to the plume at TAG on the Mid-Atlantic Ridge. These are the types of vent systems that are known to support abundant vent biota at mid-ocean ridge hydrothermal sites. Heat fluxes calculated for the Little Volcano site in the Central Basin are comparable to those reported for mid-ocean ridge hydrothermal sites, while those for Hook Ridge are several times higher than heat fluxes reported for either TAG or Axial Seamount. In addition to the discovery of these three high-temperature vent sites we also identified two other hydrothermal phenomena in the Bransfield Strait: a surface ocean plume associated with hydrothermal activity in the submerged caldera at Deception Island, and a possible site of sediment-hosted venting. Hydrothermal activity in the Central Basin of Bransfield Strait appears to occur along a linear neovolcanic ridge that runs between Deception and Bridgeman Islands, that pierces the sediment cover at several locations.

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Appendix

Water Column and Seafloor Hydrothermal Investigations of Two Volcanic Edifices in the Bransfield Strait: Results from *FS Polarstern* Cruise ANTXV/2

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Reprinted from *Antarctic Journal of the United States,* 1998 Review Issue,
In press, (not subject to copyright)

Introduction

The Bransfield Strait is a backarc basin between the South Shetland Islands and the Antarctic Peninsula that was formed by rifting behind the South Shetland Island Arc. This rifting has resulted in a 2-km-deep graben that extends over 400 km from Clarence Island to Low Island (Fig. 1). Active rifting has caused recent earthquakes and volcanism along the northern margin of the strait and within the graben (Keller et al., 1992; Lawver et al., 1995).

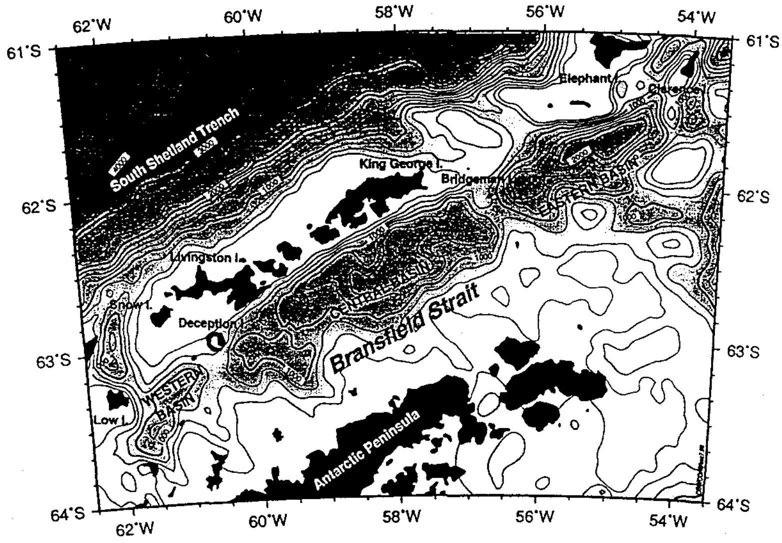

Figure A.1 Location map of the Bransfield Strait, between the Antarctic Peninsula and the South Shetland Islands.

Over the past twelve years, evidence of hydrothermal activity has been collected in the eastern Central Bransfield Basin. The 1995 *N. B. Palmer* cruise (NBP9507) documented water column evidence of hydrothermal activity at three locations in the Central Basin: Hook Ridge, the Three Sisters, and the Little Volcano (Klinkhammer et al., 1995). Anomalies in dissolved manganese, temperature, particle concentration, and δ^3He were measured in hydrothermal plumes at these sites (Chin et al., 1996, Klinkhammer et al., 1997). This study, conducted aboard the *FS Polarstern*, used water column and seafloor imaging and sampling techniques to search for the sources of the hydrothermal plumes sampled in 1995.

Hydrothermal Exploration

Measurement of light scattering

Hydrothermal precipitates form when hot, chemically rich hydrothermal fluids cool quickly due to mixing with cold, oxygen-rich ambient seawater. Very fine particles, <1μm, are carried upward with the buoyant fluids until the hydrothermal plume reaches buoyancy equilibrium with the surrounding water and begins to spread laterally.

A SeaBird 9/11*plus* CTD/rosette system was used for the water column work. A SeaTech Light Scattering Sensor (LSS) which measures backscattered light at 880 nm, was brought from Oregon State University and mounted on the CTD/rosette frame for the detection of turbidity anomalies associated with hydrothermal particles. This same instrument had been used on the 1995 cruise on the *N. B. Palmer.*

Water column temperature and particle anomalies

Particle anomalies measured *in situ* are often the first indication of hydrothermal activity in the water column. Hydrothermally derived particle anomalies were observed at stations CTD 57 and CTD 59 at Hook Ridge. Methane anomalies were also observed at Hook Ridge. The largest of these anomalies was measured at the station closest to the area of the largest hydrothermal anomalies observed in 1995 (Klinkhammer et al., 1995; Chin et al., 1996; Klinkhammer et al., 1997). A well-defined particle anomaly was also measured within the Little Volcano structure, however this anomaly seemed to be smaller than that detected in 1995 (*N. B. Palmer* cruise, NBP95-07).

Calculation of the temperature anomaly produced profiles showing a maximum of approximately 0.020 °C at 1100 m at stations PS47/057 and PS47/059 over Hook Ridge (Figure 2a and 2b). However, 9 days later this anomaly is completely absent from similar plots from nearby stations.

Water column studies in the vicinity of Little Volcano confirmed the presence of a hydrothermal plume which seemed to be confined to the caldera of this volcanic feature (Klinkhammer et al., 1995)

Collection of dissolved and particulate plume samples

The CTD/rosette system included 23 20-liter Niskin bottles which were used to collect discrete seawater samples. Since previous measurements showed strong hydrothermal particle anomalies in the Bransfield Strait, sampling of both the dissolved

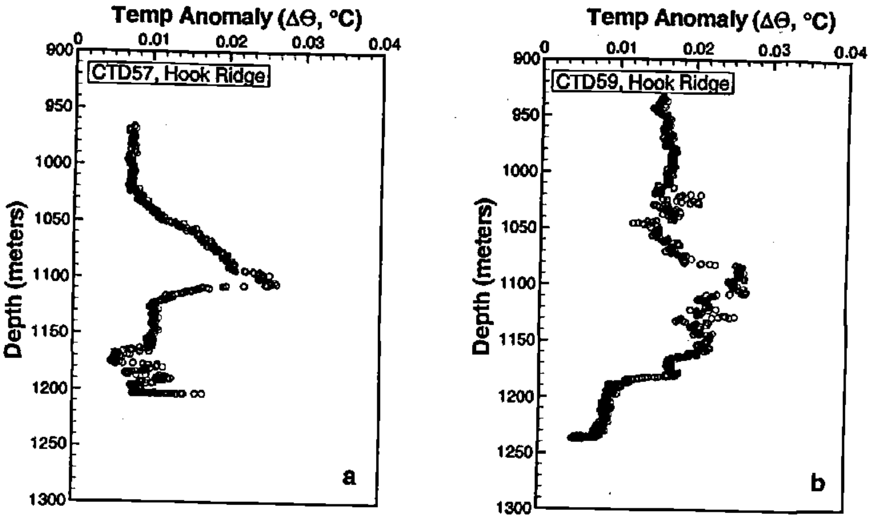

Figure A.2 Profiles of temperature anomaly from a) CTD 57 at Hook Ridge, near the site where the largest hydrothermal anomalies were observed on cruise NPB95-07, which shows an anomaly from approximately 1040m to 1120m, and b) CTD 59, also at Hook Ridge.

and particulate constituents was critical so that estimation of chemical fluxes could be made. Where particle anomalies were observed using the SeaTech LSS, 1 liter samples were drawn from the Niskin bottles and filtered onto pre-weighed 0.4µm Nuclepore membrane filters and stored in clean Analyslide containers. These particulate samples will be dried, reweighed, and analyzed in the lab at Oregon State University (OSU). Complementary dissolved seawater samples were collected during the filtrations (the filtrate), for analyses of dissolved metals. In addition, 250 ml samples were drawn from the rosette for the analysis of total dissolvable metals. These samples will be analyzed using a Fisons VG PlasmaQuad II Plus ICPMS interfaced to a Dionex Chelation Concentration Module.

Temperature anomalies on the seafloor from the OFOS-CTD

The temperature recorded by the "memory" CTD proved useful in defining, along with seafloor video observations, potential areas of hydrothermal venting. Two OFOS stations (PS47/065 and PS47/067) were carried out in the vicinity of and within the caldera of Little Volcano to document the seafloor geology of this volcanic feature, and to search for and map any hydrothermal precipitates or accompanying vent fauna on the seafloor. No temperature anomalies were recorded during either of these OFOS stations.

Extremely small anomalies in the temperature gradient were recorded during OFOS 67, however because of their size, and because of the rapid ascent and descent of the instrument as they were recorded, we attribute these features to water column heterogeneity.

Several temperature anomalies were observed during deployments of the OFOS camera system along the axis of Hook Ridge, near the site of the anomalies observed on cruise NBP95-07 in 1995 (Klinkhammer et al., 1995; Chin et al., 1996; Klinkhammer et al., 1997) During this first deployment, a pronounced temperature anomaly was recorded (>0.1°C in situ temperature) within a constrained area close to a small plateau at the ridge axis. This anomaly was confirmed by calculation of the temperature gradient, which showed up to 0.02°C temperature variations within the 2 second sampling rate of the instrument (Fig. 3). This temperature anomaly was accompanied by the occurrence of white crusts on the surface sediments at a water depth of approximately 1125 m.

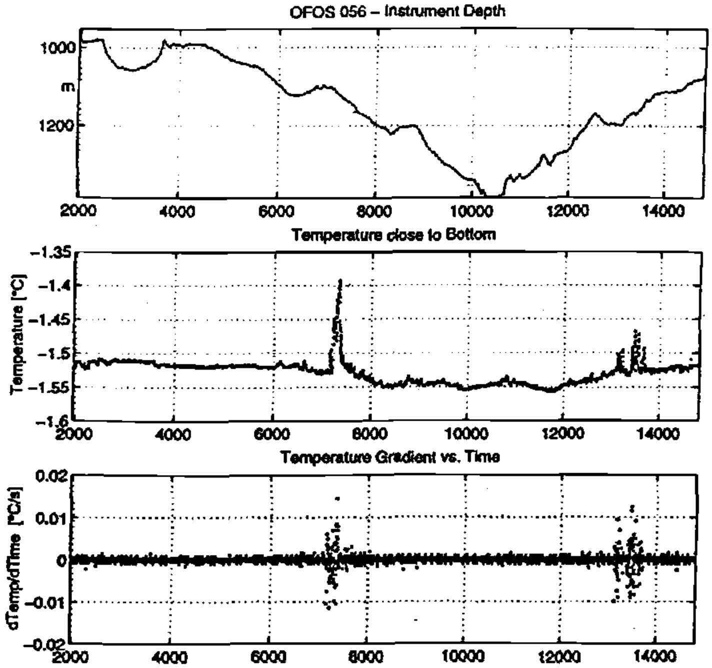

Figure A.3 Temperature anomalies recorded with the "memory" CTD that was mounted above the OFOS camera system, with (a) the seafloor depth for reference. Here the anomalies are represented as both temperature spikes (b) and temperature gradient (c). Rapid changes in the temperature gradient indicate instabilities in the water column, which are typical of buoyant hydrothermal plumes.

OFOS camera system and TV-grab

The OFOS camera system provides real-time, black and white video of the seafloor and is also used to take still color photos which can be more closely examined later onboard the ship. To monitor the exact depth of the instrument, a stand-alone or "memory" CTD was mounted on the wire above the instrument. This CTD allowed us to evaluate the temperature record for hydrothermal temperature anomalies encountered as the instrument was towed along the seafloor.

TV-grab documenting low-temp. hydrothermal activity at Hook Ridge

The TV-grab is a video-guided grab sampler. This instrument is towed along the seafloor and real-time video is used to evaluate sampling locations. Seafloor features that appeared to be hydrothermal in origin could be sampled upon command from a deckboard control unit, then brought back up to the ship for examination.

A haul of about 500 kg of sedimentary material and a few fragments of volcanic rocks and dropstones were sampled from a water depth of 1133 m. The foraminiferous sediment consisted of greyish-green, fine-grained, water suspended ooze covered by white to grey crusts, probably amorphous silica. Below the surface and intercalated within the sediment column, concretionary encrustations were precipitated conformable to the bedding surface of the sediments. Conformable precipitation obviously took place along worm burrows close to and parallel to the surface within the upper 5 cm. Disconformable mineralisation also occurs at depths up to 30 cm, clearly suggesting a hydrothermal origin. Immediately after recovery of the TV-grab, temperatures of approximately 24°C were measured in these sediements.

Conclusions

Low-temperature venting was found at Hook Ridge. It appears that high-temperature fluids are ascending through the sediment from depth and are cooled by mixing with seawater and by conductive cooling of fluids prior to venting. Evidence of high temperature venting was evident from water column measurements of temperature and particle anomalies. The occurrence of what appears to be inactive sulfide structures covered by iron oxyhydroxides indicated that high-temperature venting has occurred at Hook Ridge, though we were unable to pinpoint the current high-temperature site. This is most likely the result of the small field of view of a camera system in relation to the scale of the potential source region.

Acknowlegments

We wish to acknowledge the support of the captain, officers, and crew of the *FS Polarstern.* Thanks to C. Meredith for preparation of the filters and filtration equipment, and K. Brooksforce for gathering together all necessary cruise materials. This work benefitted from the assistance of the other scientists on expedition ANTXV/2. This research was funded by the Office of Polar Programs, NSF grant OPP 97-31695 to G. P. Klinkhammer. Financial support for the investigations using *FS Polarstern* was also provided by the Federal Ministry of Education, Research, and Technology, Bonn (grant 03G0531A).

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