Hot vents in an ice-cold ocean: Indications for phase separation at the southernmost area of hydrothermal activity, Bransfield Strait, Antarctica

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Abstract

During the expeditions ANT-XV/2 with R/V Polarstern in 1997/98 and NBP 99-04 with R/V IB N.B. Palmer in 1999, the first samples of hydrothermally influenced sediments of Bransfield Strait were obtained at Hook Ridge, a volcanic edifice in the Central Basin of the Strait. The vent sites are characterized by white siliceous crusts on top of the sediment layer and temperatures measured immediately on deck are up to 48.5°C. The shallow depth of these vent sites (1050 m) particularly controls the chemistry of the pore fluids that are enriched in silica and sulfide and show low pH values. Chloride is depleted up to 20% and the calculated hydrothermal endmember concentration is in the range of 1–84 mM. Since other mechanisms for Cl depletion can be ruled out clearly, the composition of this fluid is attributed to phase separation. While the Cl-depleted fluid is emanating at Hook Ridge, a Cl-enriched fluid can be identified in the adjacent King George Basin. Using a p,x diagram the two corresponding endmember concentrations reveal that the phase separation takes place at subcritical conditions (total depth: ~2500 m), probably along the whole volcanic edifice. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: liquid phase; separation; hydrothermal vents; Antarctica; Bransfield Strait

1. Introduction

Phase separation is a widely recognized phenomenon at mid-ocean ridges. The chemical composition of the fluids at hydrothermal vent sites critically depends on the depth at which phase separation occurs (e.g. [1–3]) and the timing of volcanic activity with respect to fluid venting (e.g. [4–9]). Vent sites of the East Pacific Rise (EPR) and the Mid-Atlantic Ridge (MAR) are
typically situated in water depths of 2300–3700 m. The shallowest hydrothermal system that has been intensively studied is located at Axial Seamount on the Juan de Fuca Ridge in a water depth of 1540 m. This system is especially known for its extreme fluid compositions that are attributed to phase separation at shallow depth although additional alteration reactions may also play a role [6,10]. Vents at even shallower depths have been explored on the MAR at 37°50′N (Menez Gwen, 840 m) and at 67°N (Kolbeinsey Ridge, 100 m), but only very few data exist on the chemical composition of their fluids so far. However, phase separation is suggested to occur at both sites [11–13].

In this paper we present investigations on a shallow vent site (1050 m) at Hook Ridge, one of the hydrothermally active areas of the Central Bransfield Strait that have been discovered earlier [14,15]. The reported site was first sampled in 1997 [16] and is the southernmost site of hydrothermal activity known to date. Its specific conditions are indeed unique, not only because of its high latitude but also due to its shallow depth and thin sediment cover.

Bransfield Strait is a marginal basin that is only just on the transition from intracontinental rifting to back-arc spreading and represents an early stage of the evolution of a hydrothermal system. Therefore, this area is of a wider interest to studies on the general development of ridge vent systems.

2. Geological and tectonic setting

Bransfield Strait is a marginal basin located between the Antarctic Peninsula and the South Shetland Islands (Fig. 1); it is about 400 km long and has a maximum width of 80 km. The basin is volcanically and tectonically active and several subaerial and submarine volcanic edifices are situated along and parallel to the major rifting axis. Subduction along the South Shetland trench ceased or at least drastically slowed down about 3–4 Ma BP [17,18], followed by the onset of extension in the back-arc region about 1–2 Ma BP [19], whereas the earliest known back-arc volcanism only began about 0.3 Ma BP and is still active [20]. Due to the lack of active arc volcanism and subduction Bransfield Strait is considered an extensional marginal basin with intracontinental rifting occurring along parallel axes rather than a back-arc basin with seafloor spreading on oceanic crust [16,17,19,21]. In contrast to this tectonic particularity, the geochemistry of dredged rocks of basaltic to basaltic–andesitic composition is similar to other back-arc basalts [19,21].

The investigated volcanic edifice, Hook Ridge, is situated on the central rifting axis of the Central Bransfield Basin at 62°12′S/57°17′W. It reaches a water depth of about 1050 m, whereas the adjacent, flat-bottomed King George Basin is approximately 2000 m deep. The hook-shaped structure is covered with a thin layer of soft diatomaceous mud; bare rocks appear only at steeper flanks.

3. Investigations of hydrothermal activity

Hydrothermal activity within the Bransfield Strait was first documented by thermogenic carbohydrates in the sediment [22–25] and 3He plumes in the water column [26]. Heat flow measurements [20] and further investigations of water column anomalies (temperature, Mn, particles) verified the existence of active hydrothermal activity in this area [14,15].

During the expeditions ANT-XV/2 with R/V Polarstern in 1997/98 (ANT) and NBP 99-04 with R/V IB N.B. Palmer in 1999 (NBP), we carried out detailed investigations of the seafloor and water column at Hook Ridge using a video-guided camera sled (OFOS), a video-guided grab sampler (TVG), and a towed instrument package (ZAPS). Details of the deployed instruments and water column anomalies (T, CH4, Mn, turbidity) are reported in [16] and [27].

All vent sites were situated on the ridge crest (Fig. 1, Table 1) and were characterized by white siliceous crusts on top of the sediment layer (see photograph in [16]). The memory CTD mounted on OFOS recorded elevated temperatures in the water column 2–4 m above the white patches. The highest T anomalies coincide with Fe, Mn, and turbidity plumes measured with the ZAPS system.
at the same location [27] and were detected within a crater-like structure with fairly steep inner walls. In the SW corner of this feature, we sampled the warmest sediments with temperatures of 48.5°C (NBP-TVG 68) and 42°C (NBP-TVG 69), respectively. The sediment underneath the silica cover of NBP-TVG 69 had a soupy consistency and also contained a ~25 cm thick ash layer. In contrast to other hydrothermal systems, vent fauna was not observed at this site.

Table 1
Synopsis of reported vent (vent) and reference (ref.) sites sampled by TV-grab at Hook Ridge during cruises ANT-XV/2 with R/V Polarstern (ANT) and NBP 99-04 with R/V IB N.B. Palmer (NBP) with maximum temperature, core location and water depth

<table>
<thead>
<tr>
<th>Cruise-station</th>
<th>Max. temperature (‡C)</th>
<th>Latitude (‡S)</th>
<th>Longitude (‡W)</th>
<th>Water depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANT-TVG 89 (ref.)</td>
<td>–</td>
<td>62° 11.64'</td>
<td>57° 17.67'</td>
<td>1134</td>
</tr>
<tr>
<td>ANT-TVG 91 (vent)</td>
<td>24</td>
<td>62° 11.80'</td>
<td>57° 17.67'</td>
<td>1133</td>
</tr>
<tr>
<td>NBP-TVG 27 (ref.)</td>
<td>–</td>
<td>62° 11.45'</td>
<td>57° 17.07'</td>
<td>1058</td>
</tr>
<tr>
<td>NBP-TVG 35 (vent)</td>
<td>11</td>
<td>62° 11.86'</td>
<td>57° 17.87'</td>
<td>1162</td>
</tr>
<tr>
<td>NBP-TVG 68 (vent)</td>
<td>48.5</td>
<td>62° 11.51'</td>
<td>57° 16.62'</td>
<td>1052</td>
</tr>
<tr>
<td>NBP-TVG 69 (vent)</td>
<td>42</td>
<td>62° 11.53'</td>
<td>57° 16.68'</td>
<td>1045</td>
</tr>
</tbody>
</table>
4. Sampling and analytical methods

The sediment temperature was measured with a conventional thermometer directly within the sediment immediately upon recovery of the TVG-grab sampler. Subsamples were taken with plastic tubes and the pore water was separated from the sediment using a Teflon squeezer under inert gas atmosphere. The pH of bulk sediment was measured with a glass electrode prior to squeezing, with buffers prepared in artificial seawater [28]. Analyses of dissolved silica and sulfide were carried out directly after pore water extraction by standard photometric methods [29], with some modifications for samples with high sulfide content. Mg and Ti were analyzed by inductively coupled plasma-atomic emission spectrometry (ICP-AES); Cl$^-$, Br$^-$, and SO$_4^{2-}$ by ion chromatography, both in the laboratories of GEOMAR. Selected solid phase samples of the ANT cruise were also analyzed for their Mg concentration using X-ray fluorescence analysis (XRF) at TU Freiberg. Isotopic analyses of pore waters ($\delta^{18}$O, $\delta$D) were carried out by mass spectrometry at an external laboratory (Geochemische Analysen, Sehnde).

5. Results and discussion

5.1. Pore water characteristics and calculation of the Cl endmember concentration

The substantial characteristics of hydrothermal influence are high silica concentrations (up to $\sim$2.4 mM), sulfide enrichments (up to $\sim$1 mM), Br$^-$ and Cl$^-$ depletions (Cl$^-$ down to 442 mM), and low pH values ($\sim$5) (Table 2, see also [27]). Both Mg and sulfate are depleted significantly in NBP-TVG 68 and 69 compared to the reference site.

In analogy to hydrothermal fluids, pore waters at sedimented hydrothermal sites are generally assumed to be a mixture of hydrothermal fluid and diagenetically altered pore water. As Mg has been shown to be totally removed from solution during basalt–seawater interaction [30,31], calculations of endmember concentrations are commonly done by extrapolation to zero Mg. However, these calculations can also be made assuming an endmember fluid of zero sulfate concentration, since sulfate is likewise quantitatively removed within the recharge zone of a hydrothermal circulation cell as has been shown for many sites [32]. In contrast to sediment-starved systems, both Mg$^{2+}$ and SO$_4^{2-}$ are subject to diagenetic reactions at sedimented sites, which requires particular consideration. During the degradation of organic matter sulfate is reduced to sulfide and Mg$^{2+}$ may be desorbed from the sediment by cation exchange [33] or leached from the matrix by the hot and acid fluids. XRF measurements of Hook Ridge sediments reveal that almost half of the Mg content has been leached by hydrothermal alteration; e.g. at vent site ANT-TVG 91 the Ti-normalized Mg content is 3.5 ± 0.2 (on a molar basis), compared to 6.5 ± 0.4 at reference site ANT-TVG 89. Under these circumstances, the working assumption of zero Mg in the endmember fluid is not applicable. We therefore assume an endmember fluid with zero sulfate. If sulfate reduction is a relevant process within the sediment column under consideration (50 cm), this procedure would result in an overestimation of the hydrothermal fluid component.

We apply two different approaches for calculation of the hydrothermal endmember concentration: simple two-component mixing and linear extrapolation. For mixing we chose the deepest pore water sample from NBP-TVG 68, which has the lowest concentrations of Mg (43.7 mM), SO$_4^{2-}$ (21.9 mM), and Cl$^-$ (442 mM) and, hence, is the sample with the highest content of hydrothermal component. The sulfate concentration of this pore water sample can be obtained by mixing seawater (28.9 mM SO$_4^{2-}$) with 24% of a hydrothermal endmember with zero SO$_4^{2-}$ concentration. From this mixture and a bottom water Cl$^-$ concentration of 555 mM, the calculated endmember concentration for Cl$^-$ is 84 mM. The second approach is illustrated in Fig. 2 and includes pore water samples from all NBP-TVG stations. Linear regression of Cl$^-$ versus SO$_4^{2-}$ of all stations but TVG 69 yields a Cl$^-$ endmember concentration of 1 ± 10 mM. With respect to the TVG 68 sample taken for the mixing approach, this result is
Table 2
Compilation of concentrations of pore water constituents and pH of the sediments

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

**ANT-TVG 89 (reference)**

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

**ANT-TVG 91 (vent, 24°C)**

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

Table 2 (continued)

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

**NBP-TVG 27 (reference)**

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

**NBP-TVG 35 (vent, 11°C)**

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

**NBP-TVG 68 (vent, 48.5°C)**

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

**NBP-TVG 69 (vent, 42°C)**

<table>
<thead>
<tr>
<th>Depth (cmbsf)</th>
<th>Si(OH)4 (µM)</th>
<th>ΣH2S (µM)</th>
<th>Br (µM)</th>
<th>SO4 (µM)</th>
<th>Mg (µM)</th>
<th>pH</th>
</tr>
</thead>
</table>

**cmbsf**: cm below seafloor; **na**: not analyzed; **bdl**: below detection limit.
equivalent to a mixture of 20% hydrothermal component (1 mM) with 80% bottom water (555 mM). The extremely low Cl\textsuperscript{3}\textsuperscript{−} endmember concentration clearly rules out a contribution of diagenetic sulfate reduction. If the measured sulfate concentration was the result of a sulfate reduction, the original SO\textsubscript{4}\textsuperscript{2−} concentration would be higher. Hence, with the chlorinities of the pore waters remaining unchanged the Cl\textsuperscript{3}\textsuperscript{−} endmember concentration inferred from the Cl\textsuperscript{3}\textsuperscript{−}/SO\textsubscript{4}\textsuperscript{2−} correlation would be even more depleted (indicated schematically by the arrow in Fig. 2). Ex situ oxidation of sulfide can alter the sulfate concentration as an artefact of pore water sampling. This is assumed to be the case for TVG 69, which is therefore excluded from the regression.

To summarize, the endmember calculation results in a percentage of 20–24% for the hydrothermal component and, accordingly, a Cl\textsuperscript{−} concentration of 1–84 mM. The range in endmember concentrations for Cl\textsuperscript{−} is due to the fact that these calculations are very sensitive to small changes in the endmember composition.

5.2. Phase separation

Phase separation takes place in the oceanic crust if a hydrothermal fluid (evolved seawater) encounters the two-phase boundary as illustrated in the phase diagram (Fig. 3). The common preceding process is entrainment of seawater into the crust where it is heated, eventually expands, and ascends to the seafloor due to buoyancy forces becoming predominant (adiabatic decompression). This process establishes a hydrothermal convection cell.

The two phases separated along the two-phase curve are often referred to as vapor and brine,
although their chemical composition and salt content vary greatly according to the $p,T$ conditions at which the phase boundary is encountered. While both phases have the same salinity at the critical point, the salinities of the separated phases vary significantly at higher and lower $p,T$ conditions [34,35]. At higher $p,T$ (supercritical conditions) small amounts of a very dense brine will condensate leaving the remaining vapor with a considerable salinity. With increasing depth/pressure of phase separation the segregated vapor phase reaches almost seawater salinity. On the other hand, at lower $p,T$ (subcritical conditions) the vapor generated due to boiling has very low salinity. The lower the depth/pressure of phase separation, the more depleted is the vapor in salt content. The resulting liquid phase (‘brine’) increases in salinity in proportion to the amount of vapor generated and removed. The $p,T$-salinity relationship is treated further below to estimate the depth of phase separation.

5.3. Evidence for phase separation

5.3.1. Cl depletion

The striking evidence for phase separation at Hook Ridge is the Cl-depleted pore waters with a deviation from seawater of up to 20% (NBP-TVG 68). Because laboratory experiments on basalt alteration have shown a maximum depletion of Cl in the fluid of 7% [36], Cl depletions greater than 10% are assumed to be due to phase separation (e.g. [2,7]). To fully ascribe the observed Cl depletion to phase separation, other mechanisms also causing decreases in Cl concentration have to be considered and eventually regarded as negligible.

*Influence of meteoric or magmatic waters:* As meteoric and magmatic waters have different deuterium and oxygen isotopic ratios compared to seawater, an input of one of these waters should result in a shift of the $\delta^{18}O$ and $\delta D$ values [37,38]. Isotopic analyses, however, reveal essentially equal signatures for $\delta D$ and only slightly elevated $\delta^{18}O$ for the vent compared to the reference site (Fig. 4). Due to the very low water content of basaltic rocks ($\sim 0.2\%$ to $> 1\%$ at subduction-related settings [39]), dehydration is not likely to release a sufficient amount of water. Additionally, magmatic waters have low Br/Cl ratios, which would decrease the ratio of the fluid [9,40,41] which is also not observed (Fig. 5). These findings clearly rule out the influence of magmatic or meteoric waters on Cl depletion.

*Precipitation of Cl-bearing minerals:* When Cl is taken up into secondary mineral phases, the Br/Cl ratio of the fluid is altered significantly (e.g. [9,42]). In most of the cases, Cl is preferentially partitioned into the mineral resulting in an increase of Br/Cl with decreasing Cl concentration. The average of Br/Cl data of both pore waters and local bottom water (Fig. 5), however, shows only a slight deviation from the global mean of seawater ($1.51 \pm 0.03 \times 10^{-3}$ compared to $1.55 \pm 0.04 \times 10^{-3}$ for the global mean [40]), considering the errors given. All samples scatter within a $\pm 3\%$ divergence around their mean (dashed lines). The measured values are in very good agreement with high temperature fluids from Axial Seamount ($1.50 \pm 0.05 \times 10^{-3}$ [10]) and North
5.3.2. Content of dissolved gases

If the emanating fluids are considered to be the vapor phase of a hydrothermal fluid separated at low pressures, they should contain significant amounts of dissolved gases (e.g. [6,7]). The measured concentrations of dissolved sulfide (at low pH mostly as H$_2$S) show large enrichments at the vent sites (Table 2). Taking the maximum value of $\sim$1 mM and assuming the percentage of end-member fluid is 22%, the endmember concentration of H$_2$S is calculated to be $\sim$4.5 mM. This is at the lower limit of what is usually observed for Cl-depleted endmember fluids [5,7,8], which is remarkable, because we are dealing with pore waters from sediment. During the pore water extraction, especially at low pH values, dissolved gases are partitioned into the gas phase and thus are irreversibly removed. All concentrations of pore water constituents that are in equilibrium with a gaseous species (HS$^-$/H$_2$S, HCO$_3^-$/CO$_2$) are therefore minimum values. Taking this artefact into account, the concentrations of gases in the pore water are easily imaged to be as high as any vent fluid with Cl depletion previously measured (e.g. up to 12 mM H$_2$S at EPR, 18 mM H$_2$S at the ASHES vent field [43]).

5.3.3. Corresponding ‘brine’ phase

While the low-chlorinity vapor phase ascends immediately, the corresponding liquid phase (‘brine’) may accumulate within the crust before being expelled [3,44,45]. To investigate Cl concentration at greater depth we deployed a gravity corer adjacent to Hook Ridge in the King George Basin (ANT-SL 63, cf. Fig. 1) where the sediment–basement interface is at about 50 mbsf [22]. This core shows strong hydrothermal influence inferred from petroleum accumulation and decreasing strontium isotopic ratios with depth (A. Dählmann, unpublished data). Cl concentrations of the pore waters increase with depth reaching a maximum of 579 mM at 6 m (Fig. 6). At this site, pore water concentrations of the upper sediment column are strongly influenced by diagenetic sulfate reduction, precluding extrapolation versus SO$_4$ for Cl endmember calculation, but Mg is not released from the sediment at this environment. Hence, the Cl endmember concentration, determined by extrapolation to zero Mg, is 703 $\pm$ 12 mM (Fig. 6).

5.4. Depth and temperature of phase separation

To estimate the depth of phase separation we use a p-x diagram (Fig. 7) drawn from the data given in [46]. The pressure–salinity relationship is characterized by a single salinity at the critical pressure (inflection of the curve) and diverging salinities for decreasing depths. Dashed lines indicate the correspondent pressure of the two-phase boundary curve and $x$ values at intersec-
tions of the two lines give the salinities of segregated phases.

The calculated endmember of about 1–84 mM for the vapor and 703 mM for the liquid phase fit best with the 390°C isotherm, with a vapor concentration of 65 mM and a liquid concentration of 653 mM at the boiling point. The isotherms for 380°C and 400°C reveal a liquid concentration too low (521 mM) and vapor concentration too high (197 mM), respectively. As the isotherms are only given in 10°C intervals in [46], the conditions at the reaction zone cannot be interpolated more closely and might deviate from the given results by some degrees and bars, because the \( x \) values are very sensitive to \( p, T \) changes.

The \( T, x \) data suggest that the phase separation takes place at subcritical conditions at a total depth of about 2500 m (250 bar), assuming hydrostatic pressure also within the crust [43]. Considering the different water depths (1050 m at Hook Ridge and 2000 m in the King George Basin) and the sediment layer in the basin (50 m), the total depth of 2500 m is achieved about 1450 m within the crust at Hook Ridge and 450 m in the basin. We therefore assume that phase separation occurs underneath Hook Ridge, extending along the strike of the whole volcanic edifice as far as to station SL 63 (Fig. 8). The vapor phase is advecting vertically and expelled at the top of Hook Ridge (TVG stations) whereas the ‘brine’ phase accumulates in the upper crust and Cl is transported diffusively through the sediment cover of the King George Basin. The very shallow depth of phase separation (500 mbsf in the basin) is a possible scenario because intracrustal diapirism is a typical feature in Bransfield Strait [17] and phase separation at depths as shallow as < 200 mbsf has been reported elsewhere [47]. Since the ‘brine’-revealing sediment core in the King George Basin is situated in the prolongation of

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**Fig. 6.** Correlation of Cl\(^-\) with Mg for endmember calculation of a deep-seated brine in King George Basin at the base of the hydrothermally influenced core ANT-SL 63. Calculated Cl\(^-\) endmember concentration is 703 ± 12 mM.

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**Fig. 7.** \( p, x \) Diagram for NaCl-H\(_2\)O solutions for six isotherms, data for the curves from [46]. Dashed lines indicate corresponding pressures of the two-phase boundary for seawater calculated from the \( p(T) \) equation given in [35]. \( x \) values at intersections with the isotherms give the salinities of segregated phases at the annotated \( p, T \) conditions (circles for vapor and squares for brine phase).
the volcanic structure at the base of Hook Ridge, the two locations are considered as parts of one large volcanic–hydrothermal system, with the vents at the top of Hook Ridge being the sites of active fluid emanation.

5.5. Temperature and manifestation of venting

The visible manifestations of the diffuse fluid venting at Hook Ridge are white silica crusts (opal-A) that precipitated directly above the sediment as well as within the pore space, especially within coarse-grained ash layers through which the fluids probably spread. Calculations on silica solubility (after [48]) reveal that the measured Si concentration in the pore water (NBP-TVG 69) is in approximate equilibrium with amorphous silica at the measured ex situ temperature of 42°C. From the analyses of δ¹⁸O of SiO₂ from this

Fig. 8. Schematic section along strike of the rift axis at Hook Ridge and the northern part of the adjacent King George Basin to illustrate phase separation processes. Proportions of the various features are not to scale.

grab an in situ temperature of about 38°C is calculated. Both methods demonstrate that heaving through the cold water column (≈−1.5°C) does not reduce the pore water temperature significantly, owing to the large volume of the retrieved sediment block (≈1 m³) and the compact shape of the grab sampler with a small surface/volume ratio. The measured ex situ temperatures are, therefore, likely very close to the in situ temperatures.

Apart from siliceous crusts and small Fe-oxide stubs, no other seafloor manifestations of fluid venting were observed during the video-sled surveys. The lack of further observations can be attributed to several reasons:

1. Subcritical phase separation at shallow depth produces a vapor phase with extremely low concentrations of sulfide-forming metals. This is due either to the high degree of boiling at these con-
ditions or to the low temperature itself. In the first case, the metals are effectively partitioned into the remaining liquid phase while the fluid is boiling. In the second case, they precipitate at greater depth while the fluid is cooled during adiabatic ascent. In either case, the vent fluids do not build visible edifices and diffuse low-temperature emanations dominate the hydrothermal flux even at bare rock sites [8, 43, 47].

2. At sedimented sites, the sediment layer inhibits a rapid ascent of the fluid and causes a more effective cooling by mixing with the ambient pore water. If the fluid still bears higher amounts of potential chimney-forming minerals when entering the sediment column, they will largely be precipitated within the sediments as has been shown for the Middle Valley site at the Juan de Fuca Ridge [49]. However, at other sedimented ridges such as Guaymas Basin and Escanaba Trough hydrothermal chimneys also occur [50, 51]. At Hook Ridge, the only surface expression of hydrothermal activity is concretionary encrustations of metal sulfides (marcasite and pyrite) within the sediment matrix, obviously precipitating along burrow traces that probably served as fluid conduits (ANT-TVG 91 [16]).

3. Talus pieces of former chimney fragments have been found buried within the sediment. Their mineralogy indicates fluid temperatures in excess of 250°C during the formation of the chimney [27]. Additionally, Mn and T/S water column anomalies detected during cruise NBP 99-04 clearly indicate the presence of high-temperature hydrothermal activity at this site [27]. Thus, besides geological reasons for the absence of active chimneys at Hook Ridge, the lack of finding active vents might simply be due to their scarcity and small spatial scale.

6. Conclusion

With the discovery of thinly sedimented vent sites at Hook Ridge and the investigations of the pore water chemistry we can unequivocally verify the existence of phase separation in Bransfield Strait. The calculated Cl concentrations are among the lowest measured at any MOR site (< 100 mM). To our knowledge there is no other location where phase separation has been invoked from pore water data at a sedimented site although fluid chemistry at Guaymas Basin and Escanaba Trough is consistent with phase separation [52].

Although chimney-like sulfides were found within the sediment column and evidence for active high-temperature venting is given by water column plumes [27], no active hot vent site has yet been directly observed. Cruises ANT-XV/2 and NBP 99-04 reported here are part of the ongoing research in Bransfield Strait and the first with video and camera systems. Our findings suggest that black-smoker-type vents remain to be discovered within Bransfield Strait.

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