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Hydrothermal anomalies in the Lucky Strike segment on the Mid-Atlantic Ridge (37°17′N)

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Abstract

As part of the FARA (French–American Ridge Atlantic) project the northern Mid-Atlantic Ridge (MAR) was surveyed for hydrothermal activity between 33° and 40°N during the FAZAR cruise in August–October 1992. After detection of hydrothermal activity in the Lucky Strike segment (37°17′N) a detailed water column survey was undertaken in this region. During a follow-up cruise (with the DSRV ALVIN) several active high-temperature vents were found on the summit of an central seamount. Here we focus on the results of the water column survey undertaken during the FAZAR cruise. The influence of Mediterranean water and the site's shallow depth complicates the hydrography at Lucky Strike; background temperature and salinity gradients are usually too complex to indicate hydrothermal anomalies clearly. Light transmission anomalies within the Lucky Strike region were small, but were detected throughout the segment from mid-depth (~ 1500 m) all the way to the valley seafloor (~ 2300 m depth). The large depth range covered by these anomalies probably results from vertical mixing as well as the presence of multiple vent sources at various depths. Methane anomalies and a temperature anomaly observed deeper than the vents documented by ALVIN further support the idea of additional, deeper vents within this segment. Particle samples of the deep particle layer are enriched in Fe and trace metals.

Keywords: Mid-Atlantic Ridge; hydrothermal vents; thermal anomalies

1. Introduction

Since the discovery of hydrothermal venting systems in 1977 much research has been done on an individual vent area scale. For example, the Juan de Fuca Ridge, and parts of the East Pacific Rise have been studied extensively on this level. However, little is known about the frequency and distribution of hydrothermal venting along the remaining 55,000 km of the Mid-Ocean Ridge (MOR) system and slow-spreading ridges are particularly understudied. In order to understand hydrothermal activity on a global scale fully it is necessary to study hydrothermal activity in different tectonic settings along the

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MOR. Given the large expanse of the ridge system, it may never be practical, or feasible, to study with submersibles all of the vent sites that will be discovered in the future. Instead, it is important to develop surveying techniques that not only can efficiently detect signs of hydrothermal activity, but that can also characterize different venting systems on the basis of plume signatures.

The FARA (French–American Ridge Atlantic) project was established to study the northern Mid-Atlantic Ridge (between 15° and 40°N), a slow spreading end-member of the MOR. At that time there were only two known vent sites in the Atlantic, the TAG site at 26°N [1], and the Snakepit site at 23°N [2]. Both of these sites are outside the study area of the FAZAR cruise (French American ZAPS and Rocks; C. Langmuir, Chief Scientist), which in August–October 1992 conducted basalt sampling and water column surveys to examine the relationships between hydrothermal activity, bathymetry and petrology from 33° to 42°N. The objectives of the water program were to determine which segments were hydrothermally active, and to survey in detail the hydrothermal plume within an active segment. In this paper, light transmission, CH_4, CTD and particulate data from the Lucky Strike hydrothermal plume are examined in order to characterize the hydrothermal plume at this new site and comparisons are made between the observed plume signature and the preliminary vent fluid data.

2. Site description

The Lucky Strike segment is situated between 37°05–33′ N and 32°10–25′ W, just north of the FAMOUS segment and about 400 km southwest of the Azores Islands. The bathymetry of the central part of the segment is shown in Fig. 1. The rift valley is about 15 km wide with a sill depth of around 1300 m. The segment is not completely bound by the valley walls as the western sill drops down to 2000 m in the southern end of the segment. The valley depth varies from more than 2500 m, at the ends of the segment, to 1550 m, at the summit of a central seamount, the most dominant feature of the

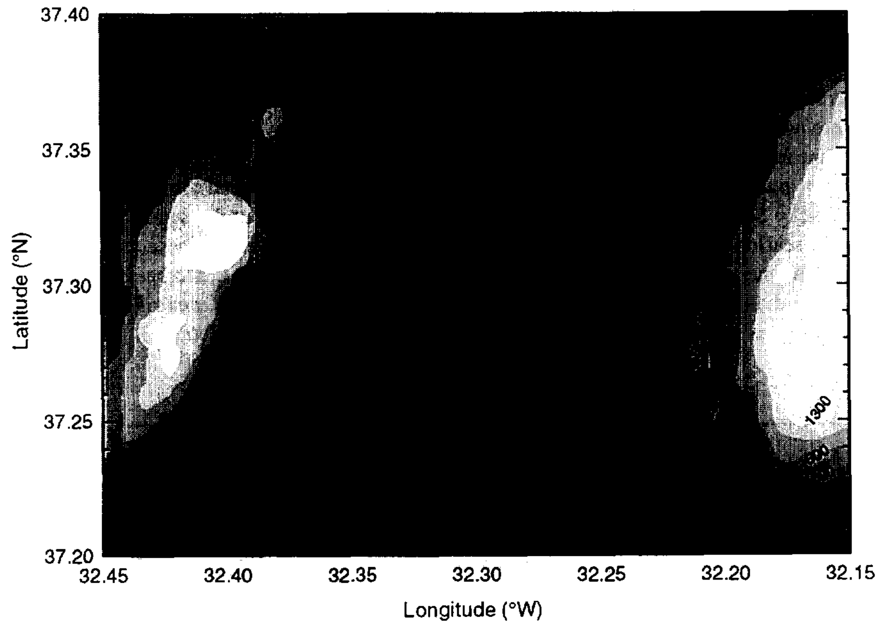

Fig. 1. Map of the Lucky Strike segment showing the position of OSU sled deployments (*SL*) and IFREMER hydrocasts (*HY*). Tows are indicated by solid lines, vertical casts by circles. The vent sites visited during the ALVIN cruise are marked on the Lucky Strike map with stars. The direction of the towed deployments discussed in the paper are marked by arrows. The bathymetry data for the Lucky Strike region was supplied by D. Needham and was collected as part of the SIGMA cruise. Contour interval is 100 m.

segment. During the FAZAR cruise an in situ chemical sensor (ZAPS [3]) detected Mn signals in the overlying water column [4], and a rock dredge between the three summits of the seamount recovered part of a sulfide chimney covered with live mussels. Based on these results, a short ALVIN cruise was undertaken in June, 1993, and several active vents were found in the depression between the east and south summits of the seamount. The vents were at depths between 1620 and 1710 m and were issuing fluids with maximum temperatures between 200° and 325°C. The cruise consisted of only six dives to the top of the seamount, which were insufficient to determine the boundaries of the vent field. Further exploration by the Nautile in 1994 discovered a lava lake surrounded with active vents between the summits of the seamount [5].

3. Data collection and processing

Water sampling during FAZAR was carried out with two systems; a CTD and rosette hydrocast unit from IFREMER, and a sled instrument package designed and constructed at Oregon State University (OSU). The hydrocast system (HY) was used primarily during the first leg of the cruise. During the second leg, the OSU sled system (SL) was used for more extensive investigations of selected areas where hydrothermal activity had been detected during the first leg. Within the Lucky Strike segment there were four vertical downcasts, and nine towed deployments (Fig. 1). In general, the sled was tow-yowed at a speed of about 1 knot, between 1000 m depth and the seafloor.

The OSU sled package consisted of a Sea-Bird CTD, a Sea Tech transmissometer, a Chelsea nephelometer, an instrument (ZAPS) to measure in situ levels of dissolved Mn [3], and a SIMRAD altimeter. The CTD data and GPS data from a Garmin GPS satellite receiver were interfaced to a computer to create a real-time display of the position and trackline of the ship and a calculated position for the sled. Navigation data files recording the ship position were merged with the sled CTD data. Loss of the sled-mounted transponder while at sea prevented a more accurate determination of the sled's position. Differences between the sled depth and wire-out readings indicate that the calculated position of the towed data can be off by as much as 1 km.

Water sampling on the sled was done with a General Oceanics Rosette with 6×5 l Niskin bottles. A Challenger Oceanics Stand Alone Pump (SAP), equipped with a 293 mm diameter, 1 μm Nucleopore® filter, was employed to collect particles in situ in the vicinity of the Lucky Strike vent site. Immediately upon recovery, the filter housings were transferred to a trace metal clean environment and the filters were rinsed with quartz-distilled (QD) water to remove sea salts. The filters were then sealed in plastic bags and frozen until transfer to the laboratory. The particles were leached from the filters by refluxing with concentrated QD HNO_3 for 48 h. The chemical composition of the resultant solutions was determined by atomic absorption spectroscopy and inductively coupled–atomic emission spectroscopy.

The IFREMER hydrocast unit had a Sea-Bird CTD, a Prieur type nephelometer, the ZAPS instrument, and a rosette fitted with 16×8 l Niskin bottles. Water samples were collected for CH_4 analysis. The samples were rapidly drawn by gravity into 125 ml glass bulbs fitted with teflon vacuum valves and poisoned with sodium azide. The samples were analyzed onshore at IFREMER in Brest within 2 months of sea operations. After trapping CH_4 on activated charcoal at -80°C, the analysis was performed by gas chromatography with a flame ionization detector [6]. For calibration, L'Air Liquide/Alphagaz CH_4 standards (2 ppm $\pm$ 2% and 10 ppm $\pm$ 2% in pure helium) were injected through calibrated loops into the detector at appropriate time intervals. Known amounts of CH_4 were injected into the stripping/trapping line, using the same procedure as for the water sample analysis. Blanks were measured between samples. A 3% standard deviation was obtained for 45 nl/l surface samples. The detection limit was 0.5 nl/l of seawater. Taking into account the precision of the calibration, blank correction, and reproducibility, the precision was $\pm$3% for CH_4 concentrations of 5–200 nl/l.

The CTDs were calibrated and had precisions of $\pm$0.002°C for temperature, $\pm$0.003 for salinity, $\pm$1 dbar for pressure, and the transmissometer had an apparent resolution of 0.02% in light transmission.

4. Results and discussion

4.1. Background hydrography

A good understanding of the background temperature and salinity structure is required in order to determine hydrographic anomalies resulting from hydrothermal activity. In Fig. 2 the variability of temperature and salinity within the Lucky Strike segment is compared with TAG data (Klinkhammer, unpublished data), which shows the more usual linear temperature and salinity background upon which hydrothermal anomalies can be easily identified. The TAG temperature anomaly (0.04°C) is four times smaller than the average temperature variation at a single salinity (0.16°C) within the Lucky Strike area. This large degree of inhomogeneity within Lucky Strike is due to two factors. One is that this segment lies within a front-like break of the Mediterranean Water (MW) tongue between 36.7° and 37.4°N, where the Azores platform is a physical barrier to the northward spread of the MW within the MAR rift valley [7]. Another factor is the relatively shallow depth of the Lucky Strike site, where venting occurs between 1620 and 1710 m, compared to the 3640 m depth of TAG. However, even at depths below 2000 m ($\sigma_\theta = 27.79$) there is considerable variation. Throughout most of the Lucky Strike segment it was impossible to identify hydrothermal temperature anomalies due to the non-linear background structure of temperature and salinity.

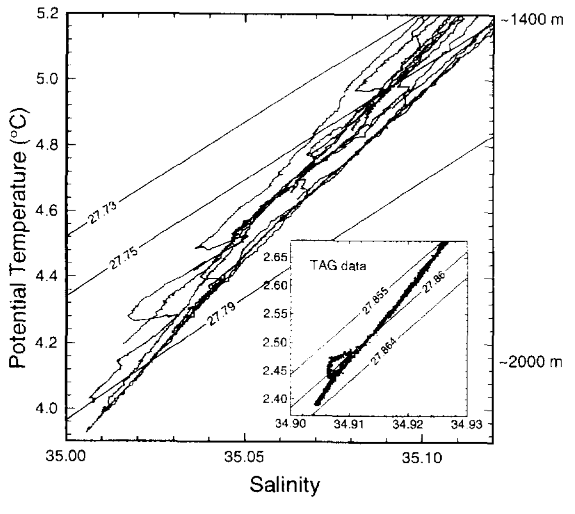

Fig. 2. Temperature–salinity diagram from casts throughout the Lucky Strike region (within a circle 12 km in radius) showing lines of constant σ_θ. The background variability in temperature and salinity is larger than typical hydrothermal anomalies. For comparison, the inset shows the same parameters from three casts taken in the TAG region (Klinkhammer, unpubl. data), which indicate the more usual linear temperature and salinity background upon which hydrothermal anomalies can easily be identified. Both sets of plotted data span a depth range of approximately 700 m.

4.2. Light transmission

The rapid cooling of hydrothermal vent fluids upon exiting the seafloor and mixing with ambient seawater leads to mineral precipitation [8–10]. The resulting particles can be detected in hydrothermal plumes as a decrease in light transmission or an increase in nephelometry signals [11,12]. Particle anomalies are often used to detect hydrothermal plumes as they are easily detectable with standard, real-time instrumentation [12–15].

Throughout the Lucky Strike segment there is a thick layer of particles which extends from mid-depths all the way to the seafloor (Fig. 3). These anomalies in light transmission are small (< 0.1%), especially in comparison to plumes from other MAR sites. The maximum height of this layer, indicated by values greater than the background value of 87.1%, was at about 1500 m. Higher penetration of this particle-enriched layer was seen in the northwest region, where it reached 1200 m, and above the seamount, where it reached 1350–1400 m depth. In some areas there is layering within the plume, suggesting that it is a composite of multiple plumes. For example, in the northwest region (Fig. 4a) in addition to the deep bottom layer anomalies, there is a higher plume centered at 1300 m. In the southwest there is an indication of two distinct plumes, one centered at 1700 m and the other at 1900 m (Fig. 4c). The deeper plumes are inconsistent with a vent source origin on the axial seamount, as they occur within or below the depth range of this venting (1620–1710 m), and they suggest that there are additional, deeper vents. This result is not too surprising as it was clear during the ALVIN cruise that the boundaries of the vent field were not found. Assuming a conservative 200 m rise height would place the vents producing the deepest plumes at 2100

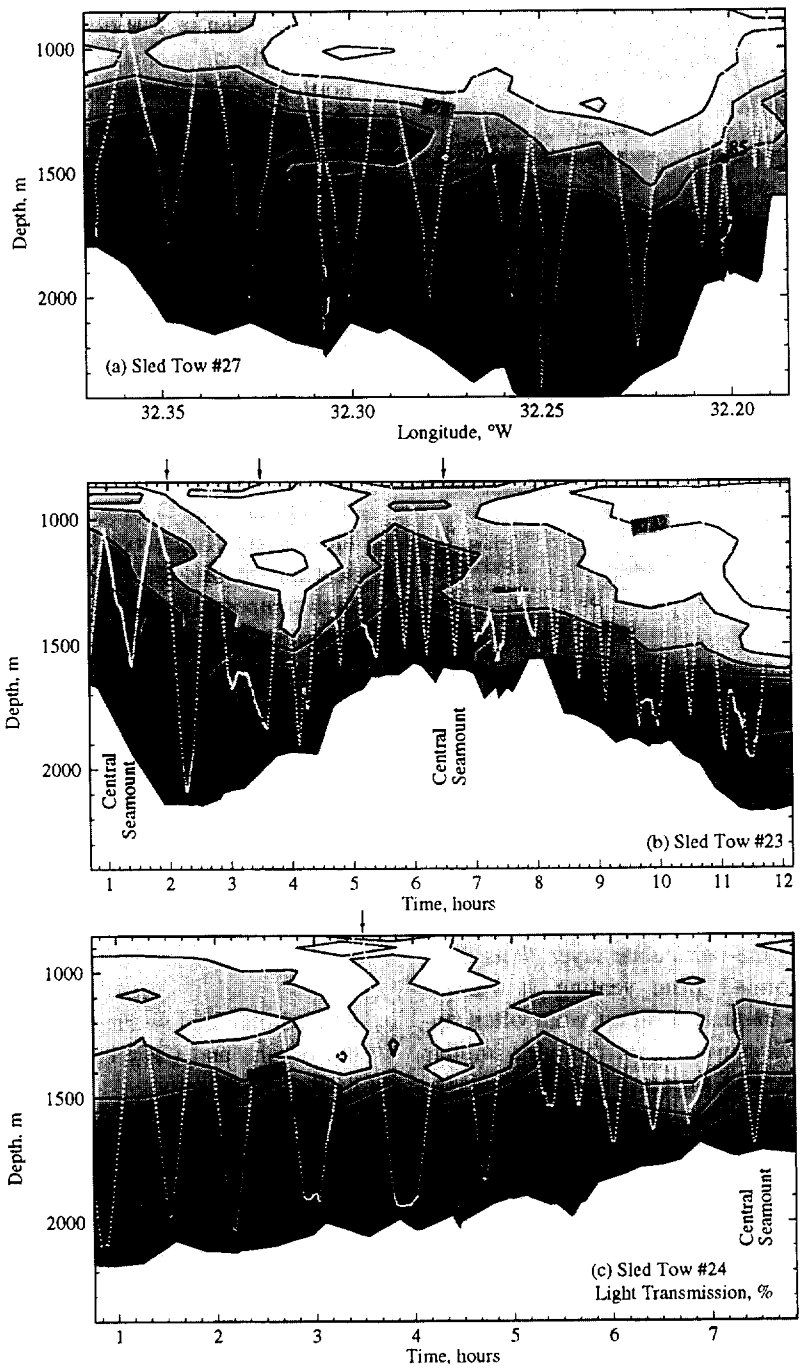

Fig. 3. Light transmission contour plots for (a) the North Section (SL27) (b) SL23 and (c) SL24. Only SL27 was a linear track, and is shown versus longitude. SL23 and SL24 are shown versus time, the arrows above these plots indicate a change in direction (tracklines are shown in Fig. 1). The dashed horizontal lines indicate the depth range of the venting observed by ALVIN. Contour interval is 0.01%. Also shown in (a) are the CH_4 values (in nl/l) from six water samples taken during SL27.

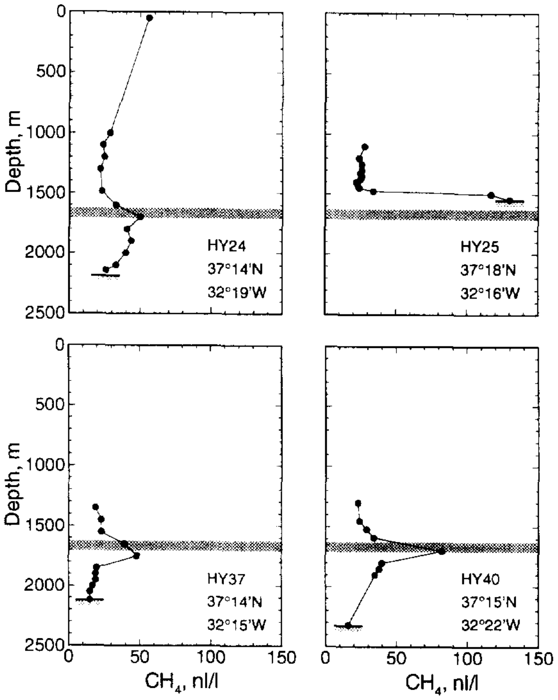

Fig. 4. CH_4 profiles vs. depth within the Lucky Strike region at HY24, HY37 and HY40 along the South section, and at HY25 over the eastern summit of the central seamount. The gray horizontal bands indicate the depth range of the venting observed by ALVIN.

m depth, giving a 500 m vertical range of active venting within this segment.

The light transmission signals within Lucky Strike are unusual in that there is no clear observation of a bottom boundary of the particulate layer. This deep plume could be formed from venting at various depths down the seamount, forming what often appears to be one thick plume. If so, this idea implies that venting is occurring over a considerably large area, in sharp contrast to the localized venting seen elsewhere on the MAR (TAG and Snakepit). In addition, enhanced mixing within this shallow segment probably contributes to the wide depth range of the hydrothermal signals, resulting in thick, homogeneous plumes with lower particle concentrations. It is also possible that this layer is caused from particle resuspension. However, no nephloid layers were observed within any of the other nearby segments sampled during the FAZAR cruise.

Parts of tow SL23 (Fig. 3b) and part of tow SL24 (Fig. 3c) went over the central seamount, and were very close to the active venting observed by ALVIN. The anomalies directly over the seamount are the smallest seen at Lucky Strike, being about half the magnitude of anomalies observed in the south and north parts of the segment. The maximum plume rise above the seamount is between 1350 and 1400 m depth. Away from the central seamount, the anomalies are considerably stronger below the depth of documented venting. Assuming that the particulate layer is hydrothermal in origin implies that either there is a much greater volume of fluid emitted at deeper depths (with similar particle concentrations) or that the fluids from the deeper, unsampled vents have a chemical composition different than those from the shallow vents on the seamount.

The generally small light particulate anomalies seen within the Lucky Strike area are consistent with the initial vent fluid chemistry which suggest that there is significant precipitation of metals below the seafloor at this site [4]. The seamount vents have high temperature fluids which are low in metals and enriched in gases, indicating a different style of hydrothermal activity than the high-temperature systems observed on the EPR and other MAR sites. The small particulate anomalies, as well as the geologic setting of Lucky Strike, is similar to the venting observed at the Axial Seamount on the Juan de Fuca ridge, where temperature and particulate anomalies are small and are not detectable further than a few kilometers from the vent field [16].

4.3. Methane

Hydrothermal venting is a major source of CH_4 to the oceans and CH_4 has been used as a tracer for hydrothermal activity [17–19]. The background CH_4 level within the Lucky Strike area is 15–20 nl/l, slightly higher than the background level of the Atlantic abyssal plain of 8–10 nl/l.

The CH_4 profiles from the Lucky Strike segment are shown in Fig. 4. The largest water column anomaly of CH_4 (130 nl/l) occurred just below 1500 m at HY25. This plume was 50 m above the eastern summit of the seamount, and slightly northeast of the area where vents were observed during the Lucky Strike ALVIN cruise. The other profiles were taken roughly 7 km south of the seamount. HY24 was taken at nearly the same location as the upcast of SL23 and the downcast of SL24. At this area the depth of the methane plume is virtually identical to that of the particle plume, suggesting that this deep particle layer is a consequence of hydrothermal venting rather than particle resuspension. Stations closer to the axial walls, HY37 and HY40, had larger CH_4 anomalies, but the plume was thinner and did not extend to the seafloor. It is possible that these differences in the magnitude and thickness of the CH_4 plume are time dependent because HY24 was taken 3 weeks before HY37 and HY40. All of the deep CH_4 profiles have anomalies within or below the depth range of documented venting, again suggesting that there are deeper vents within this segment.

Samples for methane were taken at three locations across the north section (SL27) at 1450 m and 1750 m depth (Fig. 3a). On average, these samples were more than 9 km away from the known venting site. Only one of these samples had a significantly elevated CH_4 concentration (85 nl/l). The samples from 1450 m depth are all at the upper boundary of the light transmission plume. Although the deeper samples at 1750 m are all clearly within the light transmission plume, their CH_4 values, 24–28 nl/l, are only slightly above the background value. The two highest CH_4 values within this section occur in the northeast, at depths (1450 m) consistent with a venting source on the central seamount.

While the maximum CH_4 plume values at Lucky Strike (48–130 nl/l) are comparable to other hydrothermally active areas on the MAR [6], the end-member vent fluids at Lucky Strike have higher CH_4 concentrations. Samples taken during the ALVIN cruise were 12–21 ml/kg, whereas the usual range of CH_4 concentrations from unsedimented ridges is less than 4 ml/kg [6,20–23]. This apparent contradiction can be explained by the fact that all of the methane samples except HY25 are at least 7 km away from the known venting. Methane is not conservative in plumes but is consumed by microbial oxidation [24].

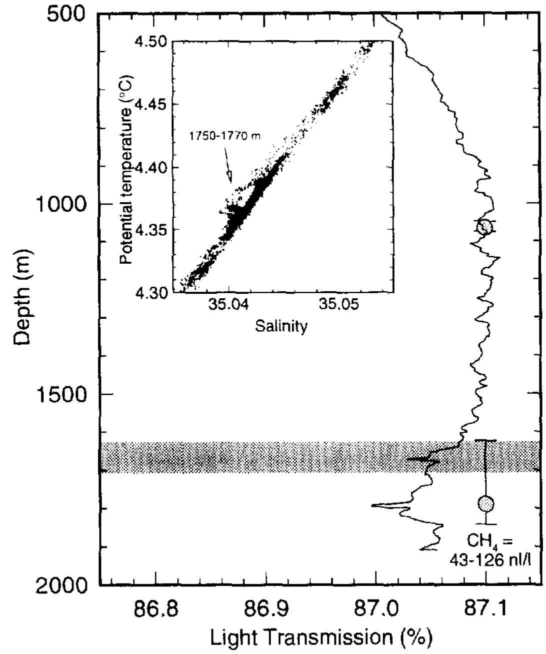

Fig. 5. Light transmission profile and temperature–salinity diagram for SL25. Two stand-alone pump samples were taken at this location. One was taken within the light transmission anomaly at ~1780 m (SL25), and one above the anomaly at ~1000 m (SL31); these are indicated by the gray dots. The vertical lines indicate the depth ranges of the package during the pumping. The gray horizontal band indicates the depth range of the venting observed by ALVIN. The CH_4 values from six water samples taken during the SL25 pump deployment varied between 43 and 127 nl/l. Temperature and salinity data taken during the deeper pump sample (SL25) is shown in the inset. A temperature anomaly of 0.02 is clearly evident between 1750 and 1770 m depth.

4.4. Particle data

Particle samples were collected during two deployments of the Challenger Oceanics Stand-Alone Pump System (SAPS), SL25 and SL31. The SAPS samples were taken at different depths at the same location (between the seamount and the eastern valley wall, see Fig. 1). The pump was positioned within a particle plume between 1650 and 1850 m depth during SL25, and was held in background water above the plume (1000 m depth) during SL31. The SAPS filtered 1,105 l of seawater in 110 min during SL25 and 630 l during SL31. Fig. 5 shows the light transmission profile and the temperature–salinity diagram from SL25. Water samples taken during the plume deployment (SL25) all had elevated CH_4 concentrations which ranged between 43 and 126 nl/l; the highest values being comparable to values observed directly over the active venting on the seamount. There was a small temperature anomaly of 0.02°C between 1750 and 1770 m.

The results of the particle analyses are shown in Table 1. Background particulate Fe concentrations in deep Atlantic water range from 1 to 4 nmol/l [25]. Fe concentrations above this range are often used to indicate the presence of particle-rich plumes generated by hydrothermal activity. The concentration of particulate Fe in sample SL25 is 10 nmol/l and indicates the presence of a small, but nevertheless distinct, hydrothermal input to this sample. Sample SL31 was collected around 780 m above SL25 and only contains 1.4 nmol/l, well within the background range. The particulate Al within the samples is presumed to be derived exclusively from aluminosilicates. Hence the Fe/Al ratio may be used as a measure of hydrothermal versus background signal within the samples. SL25 has a Fe/Al ratio of 12.7, compared to only 1.02 in SL31, again suggesting that there is a significant hydrothermal component within sample SL25.

In addition to elevated Fe levels, hydrothermal particles are enriched in other trace metals, such as V, Cr, Mn, Co, Ni and Cu, due to direct precipitation from vent fluids and/or from scavenging from seawater [15,25,26]. Although the observed enrichment is not very large, it can be seen in Table 1 that all of the transition elements in the SL25 sample are elevated relative to both SL31 (the non-plume sample) and to the background levels measured at TAG (except for Co, for which there is no available background measurement). The relatively small metal enrichment in the hydrothermal particles is consistent with analyses of end-member Lucky Strike hydrothermal fluids, which indicates that they are depleted in metals compared to other sites [4].

Overall, the data show that there is a small metal enrichment in the deep particle layer, which is consistent with a hydrothermal origin. In addition, the temperature–salinity anomaly and the high CH_4 concentrations at this depth provide a convincing argument for a hydrothermal source for this particle layer. Due to the fact that the anomalies observed at SL25 (1780 m depth) occur deeper than the observed vents, they add to the evidence for additional, deeper vent sites in this segment. Vents producing anomalies at this depth are most likely to be found near 2000 m depth, at the base of the seamount.

4.5. Flux estimates

Geophysical models of crust cooling indicate an average heat flow anomaly of 8.7×10^{12} W, which must be accounted for by hydrothermal circulation [27–30]. This estimate includes the diffuse, low-temperature, off-axial venting that is believed to account for as much as 70–90% of the hydrothermal heat loss [30] but, as yet, diffuse fluxes have been difficult to measure directly. It has been more straightforward to quantify heat flux from discrete black smokers. Various methods have been deployed to estimate the heat flux from high-temperature vent systems, over length scales ranging from the vent area [31–34] to hundreds of kilometers of ridge crest [35]. Because the initial buoyancy of the hydrothermal plume is linked to the vent heat flux, using plume observations is an attractive method of estimating heat flux on a vent field scale.

In a stratified background the terminal plume rise height, Z_{max}, is a function of the initial vent buoyancy flux, B, and the background density stratification, N, as first described by Morton [36]. As the heat flux is proportional to the buoyancy flux [37], the heat flux can be determined as:

$$H = \frac{\rho_o C_p}{\alpha g} \pi \left(\frac{Z_{max}}{5} \right)^4 N^3$$

Table 1
Results of chemical analyses of particulate samples SL25 and SL31

	Depth (m)	Fe (nmol/l)	Al (nmol/l)	V (nmol/l)	Cr (nmol/l)	Mn (nmol/l)	Co (nmol/l)	Ni (nmol/l)	Cu (nmol/l)	Sr (nmol/l)	Pb (nmol/l)	Na (nmol/l)	Mg (nmol/l)
SL25	1780	10	0.79	0.05	1.23	0.26	0.03	0.89	0.05	0.09	.007	51	1.2
SL31	1000	1.4	1.37	0.01	*	*	*	0.2	0.03	0.17	*	61	2.0
TAG [25]		2.8	2.8	0.016	0.006	0.13	–	0.003	0.026	–	0.007	–	2.6

* Concentration below detection limits. For comparison, average background values for the TAG region [25] are listed.

where: ρ_o is a reference density; C_p is the low temperature specific heat (4200 $Jkg^{-1}°C^{-1}$); α is the low-temperature coefficient of thermal expansion ($1.48 \times 10^{-4}°C^{-1}$); and g is the gravitational acceleration.

There are some potential difficulties with this equation. For one, it does not take into account other environmental parameters that can influence the rise height. Cross-currents reduce total rise height [38], resulting in an underestimation of the heat flux if they are not accounted for. On the other hand, plume confinement, which is likely with the deep axial valley of the MAR, and plume rotation will increase penetration height [39] and lead to potential overestimations of the heat flux. Furthermore, the large power dependencies of both Z_{max} and N in the equation can lead to considerable errors. Lastly, this calculation does not account for diffuse venting sources, although modeling work has suggested that low-temperature (40°C) diffuse venting will be entrained into nearby plumes and contribute to their rise height [34]. Despite these caveats, this equation remains a common method for calculating heat flux due to its simplicity.

The background density structure was extremely variable within the Lucky Strike segment. Values of N calculated from the data within Lucky Strike ranged between 8 and 12×10^{-4} s^{-1}. HY24 (Fig. 4) was about 500 m to the southwest of the Statue of Liberty vent field (Fig. 1) where fluids were issuing at a depth of 1635 m [40]. The CH_4 profile indicates a plume rise of 135 m if this vent field is the source of the CH_4 plume. Assuming an arbitrary error bar of 50 m on the plume rise yields a heat flux of 0.4–30 MW. Around 300 m to the south of the Statue of Liberty area there is a set of deeper vents (Eiffel Tower and three unnamed vents [40]) at depths between 1694–1710 m. Light transmission profiles near these vents show the maximum plume rise is at 1350 m depth, an average height of 350 m. Again, assuming a 50 m error bar on the plume rise yields a heat flux of 62–690 MW. The higher heat flux at this site is consistent with the ALVIN observations of more active venting, and higher temperatures, than at the Statue of Liberty vent area.

These calculations yield a total volume and heat flux for the Lucky Strike area of $8.6–29 \times 10^{-2}$ m^3 s^{-1} and 118–399 MW. In comparison, heat flux estimates for the TAG area range from 225 MW [41] to 500–940 MW [34]. An estimate for the newly discovered Broken Spur site [42] yielded 62 MW [43]. It is not possible to constrain the heat flux from the Lucky Strike area more closely without knowledge of the full extent of active venting on the central seamount.

5. Conclusions

Lucky Strike is an important new hydrothermal site for several reasons. Both the hydrothermal plume and the vent fluids exhibit styles not seen at any other site sampled. The light transmission anomalies are small but cover almost 800 m of the water column. Anomalous CH_4 concentrations and light transmission signals occur deeper than the known venting throughout the segment, suggesting that active hydrothermal venting is occurring from 1600 m down to 2100 m depth. Particles sampled from this deep layer are enriched in Fe, Mn and trace metals. The deep, unsampled vents produce a slightly more particle-rich plume, suggesting that either the deeper venting is more voluminous or has a chemical composition different than the shallow, sampled vents. The generally small particulate plumes within the segment are consistent with the end-member vent fluids, which have low metal and high gas concentrations [4].

This work has shown that high temperature venting is not always associated with strong particle plumes or detectable TS anomalies. The hydrothermal signals at Lucky Strike represent the lower limit of detectable hydrothermal venting from both hydrographic and particle anomalies. The plumes here illustrate the potential for missing hydrothermally active areas and thereby underestimating the occurrence of high-temperature hydrothermal activity. It is important to use a full water column program of chemical and optical measurements in surveying for hydrothermal activity. Studying hydrothermal systems which are in different geological settings or which have plume signatures different from known systems offers the greatest opportunity for expanding our understanding of hydrothermal activity on a global scale.

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