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Revisit the K-segment of the Southeast Indian Ridge for new evidence of hydrothermal plumes

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During the first leg of a Chinese research cruise to the Southeast Indian Ridge (SEIR) in 2007, we revisited the K-segment of the SEIR and observed a water column turbidity anomaly at a CTD cast station. This station was located ~400 m from a dredge site on a plume anomaly detected in 1996 by US scientists. The characteristics of the turbidity anomaly detected in our survey are different from those observed 11 years previously, implying that either the detected anomalies have distinct and different plume sources or the robustness of the plume has changed in the intervening time. In addition, turbidity anomalies were observed at two localities on the K-segment in a deep tow-yo profile. If these two anomalies are not connected, the plume incidence calculated would be about 0.28, larger than the predicted value of 0.25 for a 65 mm/a spreading rate. This increase in plume incidence on the K-segment seems to be related to the influence of the St. Paul-Amsterdam hotspot, located about 300 km to the northwest.

Southeast Indian Ridge, hydrothermal plumes, turbidity anomalies, CTD cast, tow-yo profile

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Since the discovery of the first hydrothermal vent in the Pacific Ocean [1], our knowledge of the spatial distribution of hydrothermal vents at mid-ocean ridges around the world has been greatly increased [2]. Although evidence of hydrothermal activities has been reported in the Indian Ocean, the mid-ocean ridges there have still not been intensively investigated, partially because of their remoteness in the Southern Hemisphere. In 2007, the Chinese research cruise DY115-19 was conducted on board *R/V* Dayang Yihao to investigate the hydrothermal activities along the mid-ocean ridges in the Indian Ocean. During the first leg, the K-segment of the SEIR, located southeast of St. Paul Island (Figure 1), was investigated to search for evidence of hydrothermal activities. This paper reports on the hydrothermal plume anomalies detected during this short survey and provides guidance for future surveys of the hydrothermal activities of the region.

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1 Geological background

The Indian Ocean has three branching spreading ridges (Figure 1), the Central Indian Ridge (CIR), the Southwest Indian Ridge (SWIR) and the Southeast Indian Ridge (SEIR). Their spreading rates vary from ultra-slow spreading at the SWIR ($\leqslant$ 12 mm/a) to intermediate spreading at the SEIR. The SEIR extends southeastward from the Rodriguez Triple Junction (RTJ) and has a general NNW-SSE trend [3]. Across our study area (Figure 1), it has a spreading-rate of ~65 mm/a [4] and a spreading axis that is characterized by a small valley that deepens and widens toward the transform faults at the ends of the ridge segment [5]. The existence of an Indian Ocean isotope signature for the Indian Ocean mantle was confirmed by isotopic and trace element analyses of rock samples dredged from along the SEIR [6]; previous studies have provided clear geochemical evidence of the influence of the St. Paul-Amsterdam hotspot

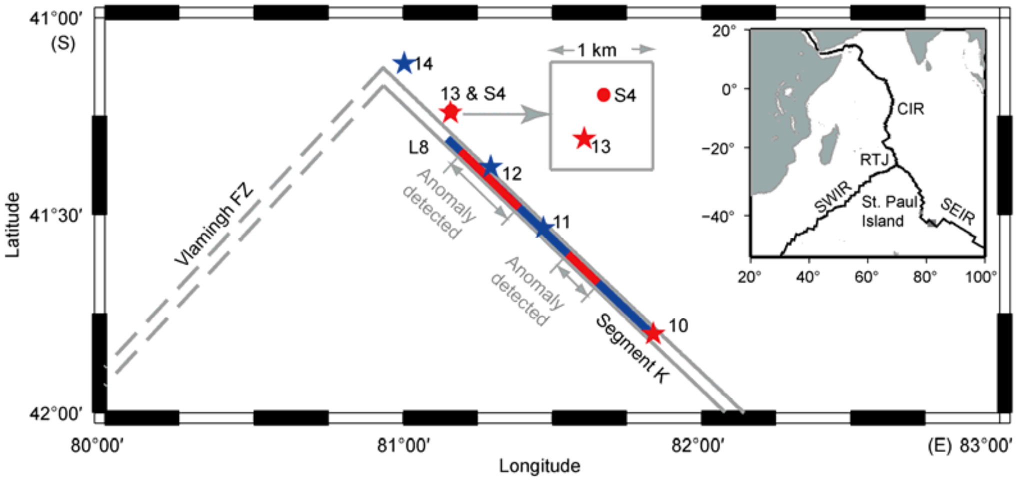

Figure 1 Study area. Our 2007 survey consisted of tow-yo profile L8 and an *in-situ* CTD station S4 (red filled circle). Stations (Sites 10, 11, 12, 13, and 14) from the 1996 survey [19] are also shown. Red colors indicate where water turbidity anomalies were observed and blue colors indicate where no anomalies were detected. Inserted panel is a sketch of the three branches of the Indian Ocean spreading ridges.

on the erupted basalts at the SEIR [7,8]. Unlike the CIR and the SWIR, where many previous investigations of the Indian Ocean ridges have been undertaken [9–17] including several that have included active hydrothermal sites [12,16,18], no active hydrothermal sites have been identified on the seafloor along the SEIR. The first and only report of hydrothermal plume activities on the SEIR was made by Scheirer et al. [19] from a sparse survey along a 1600 km-long section of the SEIR. Little progress has been made on plume investigations on the SEIR since then.

2 Method

To detect hydrothermal activity, we adapted the traditional but effective approach of measuring the water column turbidity using Miniature Autonomous Plume Recorders (MAPRs) [20], in this case provided by E. T. Baker of NOAA. Our rather short survey consisted of a CTD cast (S4) and a tow-yo profile (L8) along the K segment of the SEIR (Figure 1). During the CTD cast, one MAPR was attached to the CTD cable at a position 50 m above the CTD rosette. During the collection of the tow-yo profile, an array of five MAPRs was attached to the tow cable above the tow vehicle. The lowest MAPR was installed 20 m above the tow vehicle and four other MAPRs were distributed along the tow cable at a spacing of 100 m. Each light scattering sensor (nephelometer) on the MAPRs measures the water column turbidity as a voltage (expressed as Nephelometric Turbidity Units, NTU for short) [21], in this case at a sampling rate of 5 s. The presence of particles in the water causes an increase in light-scattering and thus leads to greater measured NTU values. These have been traditionally interpreted as the evidence for a plume emitted from a hydrothermal vent [22].

3 Results

At CTD cast station S4, a spike-shaped NTU anomaly was detected at a depth range of 2350–2400 m, with the anomaly centered at ~2380 m and an anomaly thickness of ~50 m (colorful lines in Figure 2). The seafloor depth at this site is about 2700 m, and therefore, the hydrothermal plume corresponding to this anomaly has risen to a height of at least 300–350 m above the seafloor. The average amplitude of the turbidity anomaly is about 0.02 V, with the anomaly of down-going profile (~0.02–0.03 V, shown as a blue line in Figure 2) having a slightly higher voltage than the anomaly of the up-going profile (~0.013 V, red line in Figure 2). Note that the water turbidity values have an increasing trend

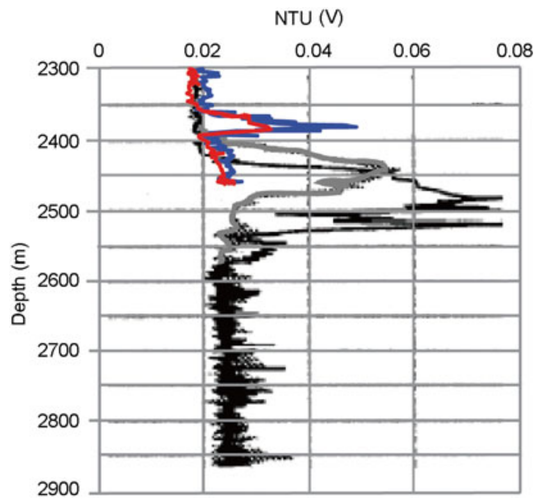

Figure 2 Comparison of water turbidity anomalies between measurements made in 2007 and 1996. The gray (downward) and black (upward) curves represent the measurements at Site 13 in 1996 (from Figure 3 of Scheirer et al. [19]). The blue (downward) and red (upward) lines represent our measurements during the S4 deployment in 2007.

from a depth of 2400 m to about 2450 m (the maximum depth that the MAPR was lowered to at this site), which possibly indicates the existence of hydrothermal plume in this layer.

The tow-yo profile L8 was conducted southeast of CTD station S4 along the same ridge (K-segment). The MAPR sensors were attached to the cable of the tow vehicle, which was towed behind the ship during the measurements. Because of the low weight of the tow vehicle and also the strong current, the *in-situ* locations of the tow vehicle and the MAPRs were different from the ship location, which was determined by ship-based GPS. The tow vehicle was mounted with a near-bottom altimeter and the vehicle was raised or lowered by winding in or reeling out the cable while underway to follow the seafloor topography. Owing to the lack of data detailing the precise length of cable extended at a particular point, it was impossible to calculate the exact location of the MAPR sensors. Thus the pressure measurements of each MAPR were used to shift the MAPR locations to match the topography.

Figure 3 shows the water turbidity measurements along the tow-yo profile. Turbidity anomalies were observed at two locations. The first section was between 41.35° and 41.5°S where turbidity anomalies (with a maximum of ~0.015 V) in this section were recorded at a depth range of 2400–2600 m. The second section was located between 41.6° and 41.7°S where turbidity anomalies detected below 2400 m also provided evidence for the existence of hydrothermal activities. Due to bad weather conditions during the survey, the tow vehicle was lifted above the seafloor for an extended distance between the two sections mentioned above, thereby resulting in the absence of valid data there. Because the observed anomalies at the two sections of the profile were observed at a similar depth, it is likely that they are connected and they may even originate from the same vent field. If so, the hydrothermal activity would extend over a length of more than 30 km along the ridge axis at the K-segment.

4 Discussion

Scheirer et al. [19] surveyed five sites (Figure 1) within our survey area along the K-segment. They detected definite water turbidity anomalies at Sites 13 and 10 and observed no turbidity anomalies at Sites 11, 12 and 14 (Figure 1). In this study, *in-situ* CTD station S4 (81°09.6′E, 41°14.3′S) was deployed about 400 m from the 1996 Site 13 (81°09.5′E, 41°14.5′S) [19] (location shown in Figure 1). Figure 2 compares the water turbidity profile from our CTD deployment with the measurements in 1996 [19]. The anomalies detected in 1996 rose to a height of about 350 m above the seafloor, with a plume thickness of 100–150 m at a depth range of 2400–2550 m [19].

The characteristics of the turbidity anomalies, especially the depth, thickness and amplitude, detected at the two closely located sites (S4 and Site 13) at two different times are very different from each other. The maximum anomaly detected in January 2007 was shallower and thinner than that measured in 1996, and also had a lower amplitude. Therefore, it is quite likely that the anomalies observed at S4 and Site 13 had distinct vent sources. Furthermore, very different turbidity anomalies were observed in down-going and up-going deployments at Site 13 in 1996. The up-going anomaly was 50 m deeper [19] and had a greater amplitude (0.05 V) than the down-going anomaly (0.03 V). Considering the upswing measurement at Site 13 was separated laterally from the downswing by ~500 m [19], it is possible

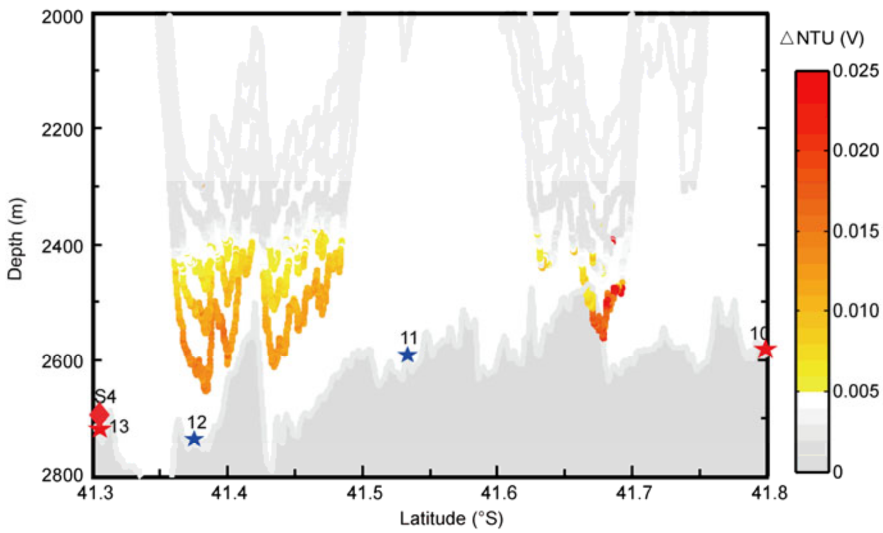

Figure 3 Near-seafloor track of tow-yo profile L8. Colors along the track reflect the measured water turbidity values. The gray shaded areas show the seafloor topography (data from the online open database Marine Geoscience Data System: http://www.marine-geo.org/). The red filled diamond indicates the projected location of the 2007 CTD cast S4. The filled stars (red stars: anomaly observed; blue stars: no anomaly observed) denote the projected location of the 1996 sites [19] within this section.

that these anomalies might also have arisen from different vents. The above conjectures would imply the existence of at least three hydrothermal plume sources within the area.

As noted in the previous section, the water turbidity profile observed at S4 exhibits increasing trend from a depth of 2400 m to about 2450 m. Because 2450 m is almost the maximum depth that MAPR was lowered to at S4, it is unknown at what depth the increasing trend would stop. However, the increasing water turbidity might be a sign of a candidate hydrothermal plume. We cannot exclude the possibility that this candidate plume is the same one as that detected in 1996, since they appeared at a similar depth range (starting from ~2400 m). If this is the case, because the amplitude of the anomaly seems to have been greatly reduced compared with that seen in 1996, it is highly likely that the robustness of this plume may have waned over the intervening years.

The 50-km-long tow-yo profile L8 runs northwest from the mid-point of the K-segment toward the Vlamingh FZ (Figure 1). Sites 11 and 12 in the 1996 survey [19], were also located along this profile (Figures 1 and 3). Site 11 was located in the intervening gap in L8 between the two anomalous sections and thus there is no valid data from the 2007 survey to compare with the 1996 measurements. At Site 12, no water turbidity anomaly was observed in 1996, but a turbidity anomaly at a depth of 2400–2600 m was detected at the same latitude in 2007. Thus the source of the plume for the 2007 anomaly seems to have been initiated after 1996.

From the 81 MAPR measurements in the 1996 survey, Scheirer et al. [19] did not find any clear correlation between the proximity to the St. Paul-Amsterdam hotspot and the abundance of hydrothermal activity from 76°E to 88°E along the SEIR. We therefore estimate the plume incidence, defined as the length of the ridge axis with plume anomalies over the total surveyed ridge length, to assess any hotspot influence on the hydrothermal activity of the K-segment.

It is unknown whether or not the two anomalous sections along L8 are connected. If they are connected, the hydrothermal activity would have a length of more than 30 km along the profile. If they are not connected, however, the plume incidence calculated within this section of the K-segment (between sites 10 and 14 [19]) would be about 0.28, which is still slightly larger than the predicted value of 0.25 for a 65 mm/a spreading rate [23]. We speculate that this increase in plume incidence at the K-segment could be related to the influence of the St. Paul-Amsterdam hotspot, located about 300 km to the northwest. The hotspot might have a positive influence on the thermal structure and therefore the magma budget of the K-segment. At the same time, tectonism is well developed in the surveyed region [5], which could lead to an increase in the permeability structure of the ridge, and subsequently enhance hydrothermal plume activities [2,24].

5 Conclusions

A water column turbidity anomaly of ~0.02 V at the depth of 2350–2400 m on the K-segment of SEIR was detected by a CTD cast deployment on *R/V Dayang Yihao* in 2007. The characteristics of this turbidity anomaly are different from those detected in approximately the same location in 1996 by US scientists on *R/V Melville*, implying that either the detected anomalies have distinct plume sources or the robustness of the plume changed over the intervening 11 years. Turbidity anomalies were also observed at two localities on the K-segment along a 50-km-long deep tow-yo profile. The estimated plume incidence from this single profile is greater than the predicted value of 0.25 for a 65 mm/a full-spreading rate based on global trends. This increase seems to be related to the influence of the St. Paul-Amsterdam hotspot, located about 300 km to the northwest.

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