Discovery of abundant hydrothermal venting on the ultraslow-spreading Gakkel ridge in the Arctic Ocean

H. N. Edmonds[*], P. J. Michael[†], E. T. Baker[‡], D. P. Connelly[§], J. E. Snow[||], C. H. Langmuir[¶], H. J. B. Dick[#], R. Mühe[☆], C. R. German[§] & D. W. Graham[**]

[*] *The University of Texas at Austin, Marine Science Institute, 750 Channel View Drive, Port Aransas, Texas 78373-5015, USA*
[†] *The University of Tulsa, 600 College Avenue, Tulsa, Oklahoma 74104, USA*
[‡] *Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle, Washington 98115, USA*
[§] *Southampton Oceanography Centre, Southampton SO14 3ZH, UK*
[||] *Max-Planck Institut für Chemie, Postfach 3060, 55020 Mainz, Germany*
[¶] *Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138, USA*
[#] *Department of Marine Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA*
[☆] *University of Kiel, Institute of Geosciences, Olshausenstrasse 40, 24118 Kiel, Germany*
[**] *College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA*

Submarine hydrothermal venting along mid-ocean ridges is an important contributor to ridge thermal structure[1], and the global distribution of such vents has implications for heat and mass fluxes[2] from the Earth's crust and mantle and for the biogeography of vent-endemic organisms.[3] Previous studies have predicted that the incidence of hydrothermal venting would be extremely low on ultraslow-spreading ridges (ridges with full spreading rates <2 cm yr^{-1}—which make up 25 per cent of the global ridge length), and that such vent systems would be hosted in ultramafic in addition to volcanic rocks[4,5]. Here we present evidence for

© 2003 Nature Publishing Group

active hydrothermal venting on the Gakkel ridge, which is the slowest spreading (0.6–1.3 cm yr^{-1}) and least explored mid-ocean ridge. On the basis of water column profiles of light scattering, temperature and manganese concentration along 1,100 km of the rift valley, we identify hydrothermal plumes dispersing from at least nine to twelve discrete vent sites. Our discovery of such abundant venting, and its apparent localization near volcanic centres, requires a reassessment of the geologic conditions that control hydrothermal circulation on ultraslow-spreading ridges.

High-temperature venting on the sea floor gives rise to plumes which ascend through the oceanic water column, entraining sea water until they reach a level of neutral buoyancy some hundreds of metres above the seabed[6]. Subsequent lateral spreading of these plumes, with their associated signatures in temperature, chemical tracers and suspended particulate material, provides a means by which new hydrothermal vent sites can be located[2,7–9]. In 2001, the ice-breakers USCGC *Healy* and PFS *Polarstern* conducted petrological sampling and geophysical surveys along more than 1,100 km of the Gakkel ridge from 8° W to 85° E. In conjunction with this study, we conducted a reconnaissance for hydrothermal plumes using Miniature Autonomous Plume Recorders (MAPRs), which record temperature and light scattering (indicative of suspended particulate material) with depth[10]. Of 145 successful MAPR deployments, 119 (82%) showed layers of increased light scattering consistent with hydrothermal plumes, and 58 had discernible peaks in temperature correlated with the light-scattering signal (Fig. 1). This frequency of plume observations is higher than found in any previously surveyed area of the mid-ocean ridge. In three previous comparable surveys using MAPRs, the percentages of profiles showing plumes were 6–14% for the southeast Indian ridge (spreading rate 6.5–6.8 cm yr^{-1})[8], 20% for the southwest Indian ridge (0.84 cm yr^{-1})[11], and <50% for the East Pacific Rise (8–8.7 cm yr^{-1}, 15° 20′–18° 30′ N)[12].

The character of MAPR profiles can be used to infer proximity to the source of hydrothermal activity. Temperature anomalies associated with hydrothermal plumes are generally small (<0.01 °C) and only discernible close to the site of venting. Both the amplitude and shape of light-scattering peaks also provide information on location. Larger signals and profiles with multiple peaks indicate close proximity to the source. More than a few kilometres away from a vent site, light-scattering peaks will be smaller and smoother in shape, and temperature signals will be small if detectable. On the basis of these characteristics, we have identified nine vent sites on the Gakkel ridge to within a few kilometres (Fig. 1, Table 1). In addition to the water column data, at 6° 15′ W (site 1) *Healy* recovered fresh sulphide chimneys in a dredge. A subsequent camera tow from *Polarstern* revealed shimmering water and abundant biological activity in this area, which we have named ‘Aurora’. We also recovered hydrothermally altered rocks in several dredges,

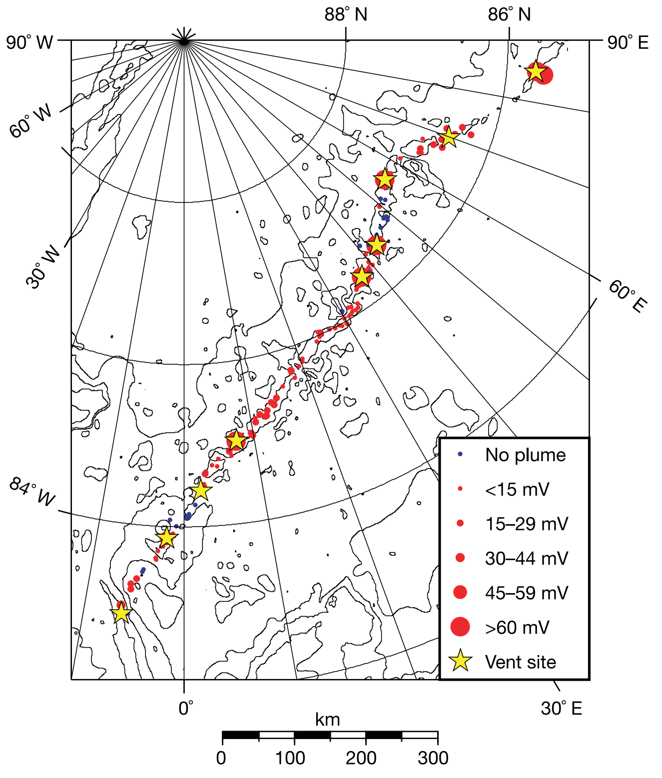

Figure 1 Map of survey area, indicating stations occupied by USCGC *Healy* and PFS *Polarstern* during the AMORE (Arctic Mid-Ocean Ridge Expedition) cruise at which MAPR profiles were obtained. (Also shown are 1,000-m depth contours from the International Bathymetric Chart of the Arctic Ocean.) MAPRs were deployed above 97 dredges, 19 wax cores, and 6 CTDs from *Healy*, and 28 TV-grabs, a heat-flow probe, and a camera tow from *Polarstern*. Symbols indicate the presence and amplitude of hydrothermal plume signals as recorded by the MAPR light scattering sensors. Optical backscatter is the primary tool by which hydrothermal plumes are detected, because temperature signals are generally extremely small and more rapidly dissipated. Increased optical backscatter results from the presence of suspended particles formed by the oxidation of hydrothermal iron and manganese on mixing with sea water. Blue circles show stations at which no plume signals were detected. Red circles are sized according to the amplitude of observed plume signals (in millivolts above background on the light-scattering sensor). Yellow stars indicate the locations of the nine hydrothermal vent sites described in Table 1.

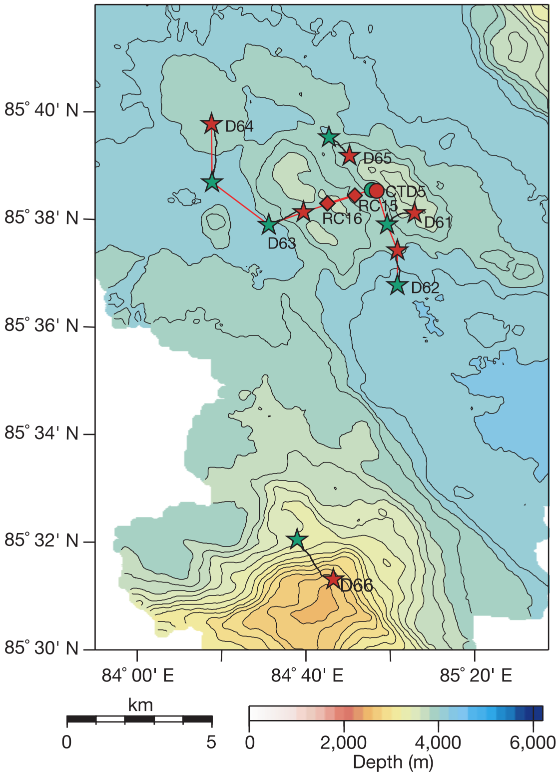

Figure 2 AMORE multibeam bathymetry of the volcanic area near 85° E, with AMORE station locations. Green and red symbols represent respectively the start and the end of a station. Stations are labelled according to the type of equipment deployed (D, dredge; RC, rock core; and CTD, conductivity–temperature–depth hydrocast). The red line indicates the path represented by the ‘sections’ in Fig. 3. Plumes were observed at all stations indicated on the map.

© 2003 Nature Publishing Group

including part of the subsurface plumbing system of a relict high-temperature hydrothermal field at 30° 05′ E.

The site at 85° N, 85° E (Table 1, Figs 2, 3 and 4a) is of particular interest because of its occurrence in an area of seismic[13,14] and probably volcanic[15] activity in 1999. Plumes observed in this area were extremely thick (up to 1,400 m, whereas most plumes we observed were <500 m thick), and are centred more than 1,000 m off the sea floor. Typical maximum rise height for hydrothermal plumes in the Pacific and Atlantic oceans is 200–400 m (refs 2, 6, 16). Indications from our Gakkel ridge survey suggest similar rise heights in most areas. The plumes at 85° E, in their thickness, height of rise and magnitude of signals, indicate the most vigorous hydrothermal venting seen anywhere in our survey.

Additional hydrothermal plumes were mapped that do not seem to originate from these nine vent sites (Supplementary Information). The MAPR data suggest at least three other sources: one near 2° 48′ E (between sites 3 and 4) seen as a small but sharp plume in both light scattering and temperature at 2,900 m, one between 8° E and 18° E identified as a widespread plume at 3,100 to 3,200 m, and one between 21° E and 31° E identified through multiple observations of small plumes at 3,400–3,500 m. Our observations thus imply at least nine, as many as twelve, and possibly additional undiscovered vent sites along this 1,100 km section of the Gakkel ridge. These results yield a frequency of at least one active vent site per 100 km along the ridge axis.

Our results not only document evidence of active hydrothermal venting on the Gakkel ridge, but also show an unusually high percentage of MAPR profiles that have signatures consistent with hydrothermal plumes. We collected water samples at six stations in order to check that the MAPR signals do indeed indicate hydrothermal plumes; several chemical tracers such as manganese are diagnostic of a hydrothermal origin. Total dissolvable manganese (TDMn) concentrations in the 85° E plume (Fig. 4a) exceed 10 nM, with background values <1 nM. Chemical confirmation, although important even for such large, unambiguous plumes, is most important for the many smaller MAPR signals observed on the Gakkel ridge (Fig. 1). Manganese concentrations in one such plume (Fig. 4b) clearly demonstrate the hydrothermal nature of the peak in light scattering, strengthening our interpretation of the remaining profiles. The apparent persistence of plumes on the Gakkel ridge may result from the nearly continuous nature of the axial rift valley compared with the segmentation observed on, for example, the Mid-Atlantic Ridge, which often limits the extent of an individual plume to a single ridge segment some tens of kilometres in length[17].

Understanding the frequency and geologic setting of hydrothermal venting along the mid-ocean ridge system is central to estimating the fluxes of heat and matter exchanged in these systems. The Gakkel ridge is particularly important, because 25% of the total length of mid-ocean ridges spreads at $<2\,\mathrm{cm\,yr^{-1}}$ (ref. 4). Early efforts at synthesizing the global distribution of hydrothermal vents[4] indicated a linear relationship between 'plume incidence' (defined as the percentage by length of ridge axis overlain by hydrothermal plumes) and ridge spreading rate and thus the magmatic heat input. To estimate the number of individual vent sites expected from this relationship, we assume that the plume overlying a single vent source will extend over 10 km of ridge axis[2]. On the basis of this relationship, the length of the Gakkel ridge that we surveyed would be predicted to have 4–5 vent sites, or less than half of what we observed.

Several recent studies[8,11,17–19] have found similar departures from the linear relationship between hydrothermal activity and spreading rate on intermediate- and slow-spreading ridges, and many have suggested that tectonic activity (faulting) is the mechanism that allows for prolonged focused venting where magmatic heat supply is low[5,20]. Most recently, on the ultraslow-spreading portion of the southwest Indian ridge between 10° and 16° E, where there is very

Table 1 **Primary vent sites identified during the AMORE cruise**

Site	Location	Geologic setting	Evidence for venting
1 'Aurora'	82° 53′ N, 6° 15′ W	Southern flank of saddle in centre of axial rift valley	Dredge recovery of sulphide chimneys, shimmering water and abundant macrofauna observed on camera tow, light scattering peaks in MAPR data.
2	83° 51′ N, 2° W	Southwestern face of volcanic edifice	MAPR: large-amplitude (50 mV) peak in light scattering with layered structure and corresponding peaks in temperature; two additional MAPR profiles in the same area showed smaller peaks at the same depth (2,400–2,600 m).
3	84° 26′ N, 2° 8′ E	Broad saddle in rift valley; depth of plume suggests that venting may originate on rift valley walls	Very sharp peak in MAPR light-scattering profile, 25 mV in amplitude over ~100 m depth interval (centred at 3,000 m) with corresponding temperature shift of ~0.006 °C.
4	85° 1′ N, 7° 27′ E	Elongate ridge on northwestern side of rift valley	MAPR profile with 86 mV light-scattering peak between 2,700 and 2,900 m, with an associated temperature peak of ~0.01 °C above background. Note dredging on this ridge recovered only peridotite.
5	86° 21′ N, 37° E	Volcanic ridge, slightly north of centre of rift valley	MAPR: multiple observations of light-scattering peaks at ~3,200 m, up to 70 mV in amplitude, with temperature peaks corresponding to the largest LSS peaks. A CTD cast provided confirming evidence through hydrography, transmissometry and manganese concentrations. Peaks in multiple profiles suggest at least two sources of venting on this ridge.
6	86° 32′ N, 43° E	Peak of volcanic mound on southern side of axial rift valley	Large, multilayered MAPR peaks in light scattering (up to 110 mV) and temperature (~0.015 °C); confirming hydrographic and manganese data from a CTD cast.
7	86° 59′ N, 55° 30′ E	Northwest side of axial volcanic ridge	MAPR: large multilayered peak in light scattering (maximum anomaly > 100 mV at ~2,600 m), with corresponding temperature peaks.
8	86° 32′ N, ~69° E	Axial volcanic mound	MAPR: multiple observations of light scattering (up to 30 mV) and temperature peaks at ~2,400 m.
9	85° 39′ N, 84° 50′ E	Axial volcanic mound	MAPR: multiple observations of large (60 mV LSS, 0.05 °C), extremely thick (up to 1,400 m) plumes centred at ~2,500 m; additional plume layers at ~3,300 m suggestive of second site; confirming hydrographic and manganese data from one CTD cast.

Supporting documentation for each site is available as Supplementary Information. LSS, light-scattering sensor; CTD, conductivity–temperature–depth profiler.

© 2003 Nature Publishing Group

little volcanic activity, several hydrothermal sites were discovered associated with large faults and hosted in ultramafic rocks[11]. Even the fast-spreading northern East Pacific Rise, where hydrothermal activity would be expected to be most closely tied to the magma budget, has been found to have a wide range of vent frequencies at similar spreading rates[12], indicating that on the scale of individual ridge segments the distribution of vents is controlled by the degree of faulting in the volcanic rocks. Extending these results to the Gakkel ridge, we expected to find most of our vent sites in highly faulted regions and predominantly associated with exposures of mantle rocks. Chemical differences between volcanic and ultramafic-hosted systems (and their effect on global ridge fluxes) have been highlighted in several studies of hydrothermal venting on slow-spreading ridges[11,21–23]. However, eight of the nine sites we have described are found in association with volcanic constructional features rather than with clearly tectonic features such as the rift valley walls. Only one (site 4) seems to be associated with ultramafic rocks. Our results indicate that this style of venting may not be as ubiquitous as recently presumed, and may require a new model for vent distribution at ultraslow spreading rates. Specifically, why are the vents on the Gakkel ridge localized at volcanoes, unlike on other slow-spreading ridges?

The basic requirements for hydrothermal circulation are a source of heat and a pathway for sea water to circulate within the rock. Slower spreading rates imply a weaker thermal gradient (less heat input at the ridge axis)[1], and thus deep-thrusting faults are required in order for circulating sea water to reach high temperatures on slow-spreading ridges. On the Mid-Atlantic Ridge and the southwest Indian ridge such faults enable the establishment of high-temperature vent systems, often in areas quite distant from ridge volcanoes[5,11]. We suggest that on the ultraslow-spreading Gakkel ridge, faulting cannot be the dominant control on the location of high-temperature venting, because of the overall thermally cool character of the crust[24,25]. Although faulting is still required, the implication is that the volcanic centres, which are both localized and widely spaced on the Gakkel ridge[26], are the only areas of the ridge with enough heat to drive high-temperature convection and give rise to the plumes we observed. Verification of this suggestion, and a fuller understanding of the distribution of volcanic[14,15] and hydrothermal activity on the Gakkel ridge, will require location and

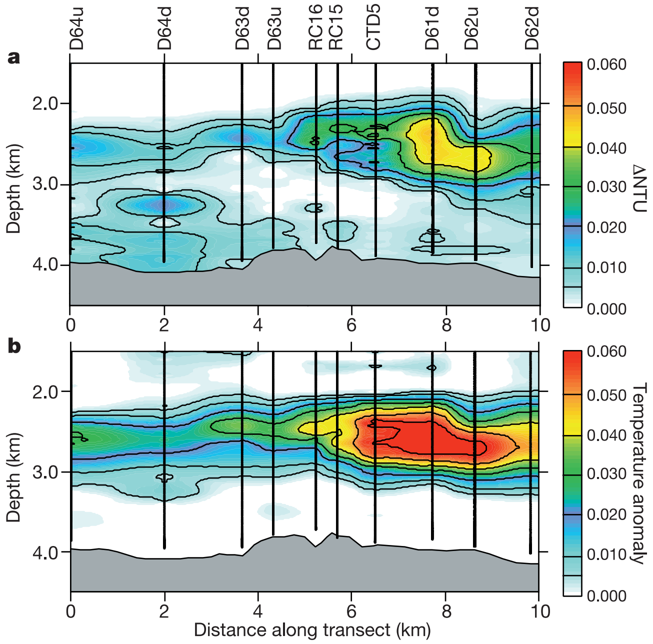

Figure 3 Light scattering and temperature data from the 85° E area, along the track indicated in Fig. 2. Vertical lines indicate the location of the profiles used for the section. **a**, Light scattering anomalies in NTU (nephelometric turbidity units, calculated from instrument voltage and defined in ref. 12). ΔNTU is the difference between the NTU value at a particular depth and that for the profile background. Yellows and reds thus indicate the strongest plume signals. Layering of the plume is most pronounced over the centre of the volcano near RC15 and CTD5, whereas the plume is thickest and the amplitude strongest near D61. **b**, Temperature anomalies (in °C) along the same section, defined as the difference in temperature between the measured profile and a polynomial fit to the background temperature profile.

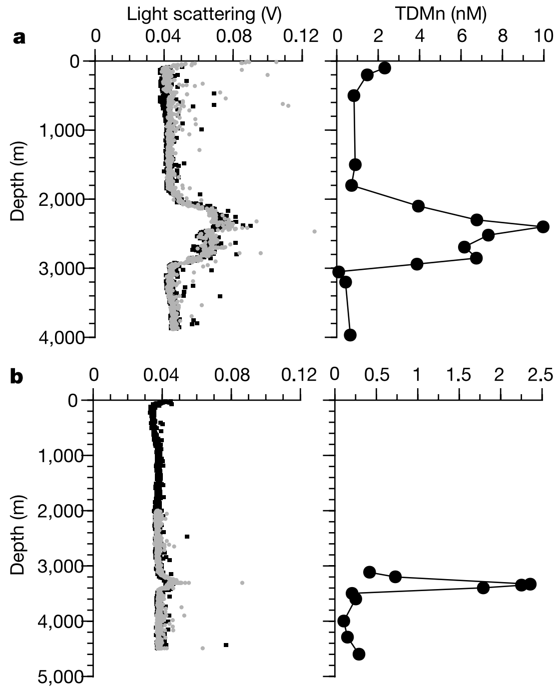

Figure 4 Light-scattering sensor and total dissolvable manganese (TDMn) data from AMORE CTD stations 5 and 9. The concentration of dissolved manganese is typically enriched by a factor of over a million in hydrothermal vent fluids compared to deep sea water, and is therefore still enriched even at the high dilution factors (~10,000:1) characteristic of hydrothermal plumes[7]. We measured TDMn instead of filtering the samples to determine solely dissolved Mn; therefore, some portion of the signal could result from leaching of manganese oxide coatings off suspended particles. Our TDMn concentrations, however, are comparable to those observed in other hydrothermal plumes, and higher than would be expected for acid-leachable Mn from the concentrations of suspended particulate material that are indicated by the light-scattering profiles[2,7,30], indicating along with the temperature data that the peaks in light scattering do not result from resuspension of bottom sediments off the rift valley walls and into the mid-water column of the axial valley. **a**, Light-scattering and manganese data for CTD 5 at 86° N, 85° E (Fig. 2). Similar results were obtained at sites 5 and 6 (Table 1 and Supplementary Information). Hydrocasts near sites 2 and 7 failed to intercept the plumes we had observed with the MAPRs, owing to difficulty positioning the ship in the ice. Note that for MAPR light-scattering profiles (including those found in the Supplementary Information), black symbols indicate the downcast profile of the station, and grey symbols are from the upcast. Higher values in volts from the light-scattering sensor indicate greater concentrations of suspended particulate matter in the water. Water samples for TDMn determination were collected on the upcast. **b**, Light-scattering and manganese data from CTD9 at 85° 59′ N, 24°42′ E. This station was designed to sample one of the ubiquitous smaller plumes observed with the MAPR light-scattering sensors (Fig. 1), in order to verify with chemical tracers that the physical signals observed were in fact hydrothermal in origin. The clear peak in manganese concentration coincident with the increase in suspended particulate matter provides confirmation of this and, by inference, the dozens of other MAPR light-scattering peaks observed.

© 2003 Nature Publishing Group