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3. PRE-DRILLING OBSERVATIONS OF CONDUCTIVE HEAT FLOW AT THE TAG ACTIVE MOUND USING *ALVIN*[1]

Keir Becker[2] and Richard P. Von Herzen[3]

ABSTRACT

During the 1993 *Alvin* dive series to the TAG hydrothermal field, 50 measurements of conductive heat flow were attempted at the 50-m-high, 200-m-diameter TAG active mound. The 43 successful stations included gradient and thermal conductivity measurements made with the 5-thermistor, 0.6- or 1-m-long *Alvin* heat flow probes, which with a few exceptions could be pushed into most locations on and off the sulfide mound. The stations were made in a variety of characteristic environments on and off the mound, and were transponder-navigated to an estimated accuracy of ±5 m relative to the 10-m-diameter central complex of black smokers. The distribution of these stations allows a reasonable mapping of coherent patterns in the conductive heat flux from the mound. As might be expected, conductive heat flow values are extremely variable (0.1–86 W/m^2) within a few meters of the black smokers, where the station environments were generally pockets of sulfide debris amid larger sulfide rocks with widespread shimmering water indicative of diffuse hydrothermal flow. On the west side of the sulfide rubble plateau that surrounds the central black smoker peak, a coherent belt of very low heat flow (<20 mW/m^2) is present 20–50 m west of the smokers, suggestive of local, shallow recharge of bottom water. On the south and southeast side of the mound, very high heat flow exists (>5 W/m^2) on the sedimented terraces that form the slope down from the "Kremlin" area of white smokers, suggesting an extension of the fluid flow processes responsible for the white smokers. Heat flow is also high (0.3–3 W/m^2) in the pelagic carbonate sediments on the surrounding seafloor within a few tens of meters of the southwest, northwest, and northeast sides of the mound. The distribution of these areas of high and low heat flow in general supports a possible schematic model of subsurface patterns of heat and fluid flow within the active mound (Tivey et al., 1995), and was used to guide placement of several of the holes drilled during Leg 158.

INTRODUCTION

The deep submergence vehicle *Alvin* was used to survey the TAG active hydrothermal mound both before and after drilling by the Ocean Drilling Program (ODP) during Leg 158. Before drilling, a 20-dive program was conducted in April 1993 to study the active and relict hydrothermal features in the TAG area (Becker et al., 1993; Evans et al., 1993; Rona et al., 1993b; Von Herzen et al., 1993). Among the several objectives of this program, one primary aim was to map the distribution of conductive surface heat flow over the active mound, to study heat and fluid transfer processes within the mound, and to aid in the planning of the Leg 158 drilling targets and in the interpretation of drilling results.

Within the 2 months immediately before Leg 158, two additional multi-objective submersible surveys of the TAG active mound were conducted, the first using *Shinkai* 6500 and the second using the *MIR* submersibles. Ten additional heat flow stations were occupied during the *Shinkai* 6500 operations, using a clone of the *Alvin* heat flow probe described herein. Four months after Leg 158, a follow-up 12-dive program was conducted using *Alvin* in February–March 1995. This program also had multiple purposes, including collecting 16 additional heat flow stations and mapping the locations of the many holes drilled into the TAG mound during Leg 158.

The primary purpose of this report is to present the basic results of the pre-drilling *Alvin* heat flow survey, insofar as these data suggest hypotheses about fluid flow processes that were considered in planning site locations. Other observations made during both the 1993 and 1995 *Alvin* programs will be reported elsewhere. In particular, this paper will not present the heat flow stations collected during the 1994 *Shinkai* 6500 operations nor the 1995 *Alvin* operations; these additional heat flow data will be integrated with the 1993 data in a detailed study of both spatial and temporal variability in heat flow at the TAG mound for a more complete report elsewhere.

SITE SUMMARY

The TAG active hydrothermal mound on the Mid-Atlantic Ridge at 26°N is one of the largest known massive sulfide deposits on the seafloor, and is also the site of vigorous present-day hydrothermal venting. It was first reported by Rona et al. (1986), and is described in detail elsewhere in the literature (e.g., Rona et al., 1993a; Tivey et al., 1995) and in this volume (see Chapters 7–11 and Kleinrock et al.). The TAG mound rises about 50 m above the surrounding seafloor, which consists of pillow lavas draped with roughly a meter of pelagic carbonate sediments. Located on crust about 100,000 yr old, the TAG mound has apparently been produced by several phases of intermittent hydrothermal activity over the past 50,000 yr (Lalou et al., 1993); these include a present-day phase with vigorous venting by both hot (≈360°–365°C) black smokers and cooler (≈220°–300°C) white smokers.

Recent detailed survey work by Kleinrock et al. (this volume) confirms that the TAG active mound is nearly circular in plan, about 200 m in diameter, with a bi-level platform about 20–30 m higher than the surrounding seafloor, topped by a pinnacle of hot black smokers about 10 m in diameter. This pinnacle of black smokers is offset slightly to the northwest of the center of the mound, and a region of lower temperature white smoker venting (the "Kremlin" area) occurs southeast of center. In addition, warm fluids vent diffusely from large areas of the surface of the mound. Thus, the present-day patterns of fluid flow and heat transfer within the mound are complex and poorly understood, although surface observations and samples

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[2] Division of Marine Geology and Geophysics, Rosenstiel School of Marine and Atmospheric Science, 4600 Rickenbacker Causeway, University of Miami, Miami, FL 33149, U.S.A. kbecker@rsmas@miami.edu

[3] Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, U.S.A. rvonh@cliff@whoi.edu

have allowed a schematic model to be constructed (Fig. 1; from Tivey et al., 1995).

A key to understanding the subsurface flow processes lies in adequately mapping the surface distribution of conductive and convective heat fluxes, which was a primary purpose of the heat flow surveys from *Alvin* and *Shinkai* 6500. As the planned drill holes were chosen partly to constrain the subsurface flow patterns, a secondary purpose of the 1993 heat flow survey was to fine-tune the positions of the possible drill holes. Although many more holes were actually drilled during Leg 158 than originally planned, the heat flow data were indeed used in siting several of these holes, as described in the following text and in Chapters 7–11 (this volume).

METHODS

Heat Flow Measurements from *Alvin*

Two titanium-alloy probes are available for measuring heat flow from *Alvin* (Fig. 2). These are identical in all respects except for probe length and spacing among the thermistors. Each probe contains five thermistors plus a heater wire to enable measurement of thermal gradient and thermal conductivity in situ. A small pressure case at the top of each probe houses the control electronics and interface to the in-board computer, as described by Bradley (1991). The thermistors and control electronics are calibrated for readings of in situ temperatures up to 40°C. The probes can be deployed either manually using the *Alvin* arm or hydraulically on a frame that assures penetration normal to a base set on the seafloor. The former method was used on the TAG mound, as it gives the pilots much better feel when an obstruction is encountered, but it required visual or video determination of the angle of penetration. For all the stations reported here, the tilt of the probe was judged to be <15°, and no tilt corrections were applied to the gradients and heat flow values.

The original plan for the 1993 dive series was based on the expectation that the sulfide mound would be too hard to penetrate directly with the *Alvin* probe. In this context, we planned to drill short (≈1 m) vertical holes, using the diamond drill developed by Stakes et al. (1993), seal the holes with simple glands in small funnels, and then reenter the holes later with a heat flow probe for an assessment of the gradient as manifested in the fluids in the hole. This plan was abandoned when (1) the drill developed problems, and (2) we quickly found that we could penetrate the mound with the shorter *Alvin* heat flow probe in most places. Thus, we were able to use the *Alvin* probe in its full capability (including in situ conductivity measurements) for high-quality stations, and we could deploy it in the normal, more time-efficient station procedure. As a result, we collected a more complete heat flow data set (attempting 50 measurements) than initially expected.

With the *Alvin* resting on the seafloor at a station site, the normal station procedure consisted of four successive operations, as follows: First and last were 2- to 3-min periods of recording bottom-water temperatures, to allow minor corrections to the thermistor readings such that they all read identical bottom water values. The uncorrected bottom-water temperature readings from the five thermistors typically ranged over about 0.1°C, and the reference bottom-water value (2.65° ± 0.05°C) to which they were corrected was generally chosen as the mean of these readings. The thermal gradient was assessed during the second segment, which included probe insertion and about 10 min of recording thermistor temperatures as the probe equilibrated toward the in situ gradient. For most stations, thermal conductivities were then measured during the third segment, which included application of a calibrated heat pulse for 10 s, and recording of the probe temperatures for an additional 10 min as the heat pulse decayed into the formation (Lister, 1979). Thus, a typical heat flow station required roughly one half hour of dive time, with the probe left in the seafloor for at least 20 min to measure both thermal gradient and thermal conductivity.

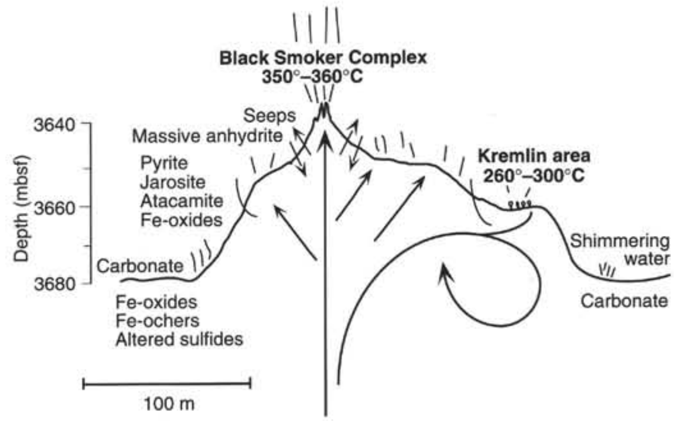

Figure 1. Schematic cross-section of the active TAG mound from northwest to southeast. Flow patterns within the mound are hypothesized from the mineralogy and chemistry of deposits and fluids sampled at the surface of the mound (from Tivey et al., 1995).

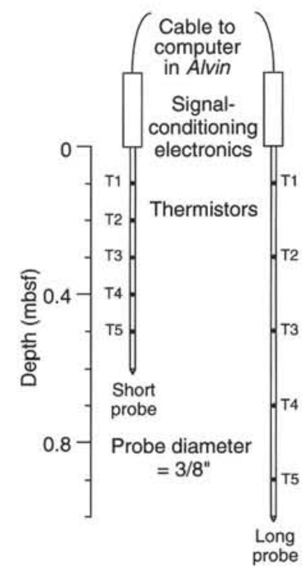

Figure 2. Sketch of the two *Alvin* heat flow probes used during the 1993 dive program to the TAG mound.

After correction of probe temperatures to read uniform bottom water values, the station data were processed to determine in situ temperature and thermal conductivity at each thermistor position, after which the gradient and conductive heat flow were calculated by linear regression of temperatures vs. depth and integrated thermal resistance (or Bullard depth), respectively. The processing procedure used the full Bullard (1954) F-function, and was very similar to the iterative method of Villinger and Davis (1987) for standard oceanographic heat flow probes using a heat pulse for thermal conductivity. Our method differed from that of Villinger and Davis in two respects: First, the code was written to account for the fact that the *Alvin* computer samples the temperatures of all of the probe thermistors at 2-s intervals, a much higher data rate than is typical for most oceanographic heat flow probes. Second, slightly different acceptance criteria were programmed to assess convergence of the iterative procedure to stable values of the in situ temperatures, thermal conductivities, and final reported heat flow values.

Alvin Station Navigation

All submersible operations at the TAG active mound were navigated with bottom transponders. For the 1993 survey, four transponders were deployed roughly in a box pattern 3–4 km on each side and centered on the mound. This resulted in four transponder pairs against which to determine sub position without any ambiguities about baselines. It also ensured that at all times at least one of the four pairs would yield a valid position, even when the sub was masked from the remaining transponders by the topography of the mound. However, we experienced difficulties with the transponder navigation during the cruise, as follows: The *Alvin* navigation programs use the traveltimes to only a single, arbitrarily selected pair of transponders at any given time, rather than calculating a true least-squares position based on all valid traveltimes. In contrast to the nominal accuracy expected of transponder navigation (5–10 m, Beogeman et al., 1972), we experienced offsets on the order of 50 m among apparent positions calculated with each of the four useful transponder pairs. This probably arose from inaccuracies in initially determining the positions and/or depths of one or more of the four transponders, and led to some navigational confusion during the survey when we switched from one transponder pair to another.

After the cruise, the sub navigation was corrected for this effect as follows: The algorithms used in the *Alvin* navigation program were modified to calculate and tabulate separate apparent positions based on each of the four useful transponder pairs, whenever valid traveltimes were recorded. This allowed the construction of four separate incomplete dive tracks based on each of the useful transponder pairs. When overlaid, these dive tracks clearly showed that virtually all of the differences in apparent positions could be accommodated by simple offsets with a small amount of rotation. Many common features were present among the separate dive tracks, which allowed them to be assembled into a single master dive track along which relative positions were indeed accurate to the degree expected of bottom transponder navigation. Finally, the master dive tracks were fixed in a geographic frame of reference making use of the fact that every dive visited the well-defined central Black Smoker Complex roughly 10 m in diameter. Thus, the station positions reported herein are all corrected to a positional accuracy of ±5–10 m relative to the central Black Smoker Complex.

Construction of Base Map and Deployment of Seafloor Markers

The depth contours on the maps shown herein were determined from the *Alvin* pressure gauge from all times when the sub was stationary on bottom. Unfortunately, the *Alvin* altimeter was not working during the 1993 dive program, so we could not survey the bathymetry of the mound. Also, the data from previous *Alvin* work at the mound cannot be integrated with our data in that the past data also show positional offsets when switching among transponder pairs; however, traveltimes between sub and transponders were not directly recorded for this past work, so the past data cannot be recalculated as the 1993 positions were. As a result, we had fewer than 100 depth-position data points to use in compiling the base map used here. Considering the relative paucity of depth-position data, this base map is reasonably consistent with a map of much higher quality compiled by Kleinrock et al. (this volume) based on the AMS-120 survey conducted in 1994. The hole locations, heat flow data, and other survey data will be integrated with the Kleinrock et al. (this volume) base map following the 1995 *Alvin* dive program.

A key to this integration will be the six markers (A–F) deployed with transponder navigation during the 1993 program, which were later revisited or imaged during subsequent dive programs, the AMS-120 survey, and the drilling leg. These markers were constructed of white polyethylene discs, configured to be readable either from directly above, as with the AMS-120 or the reentry video system used on the drillship, or from the side, as from a submersible. They were deployed mostly near the end of the 1993 dive program, in positions chosen partly because of patterns emerging in the heat flow data set (described in the following text).

HEAT FLOW OBSERVATIONS

A total of 50 heat flow stations were attempted during the 1993 dive series, of which 43 yielded useful heat flow data (Table 1, Fig. 3). The quality ratings of the stations in Table 1 are compiled on a subjective scale based primarily on the number of thermistors yielding good data and the consistency of the gradient and heat flow profiles. Examples of four stations with poor, fair, good, and excellent quality ratings are shown in Figure 4; the results of processing the good and excellent examples are shown in Figure 5. Ratings of "good" or better were reserved for stations for which at least four of the five thermistor readings were valid; an "OK" rating was used for a station with three valid, consistent readings. For those stations that were rated only poor or fair in quality, typical problems included insufficient penetration, failure of the conductivity measurement, or clear evidence of warm-water flow past the probe. To a large degree, the relative rating of a given station varied with the local sedimentary environment, which ranged from continuous sediment cover off the mound and on the southeastern slope of the mound, to rugged blocky sulfides with small pockets of sediment near the active black and white smokers.

The map of heat flow values is shown on Figure 6. The heat flow profiles recorded for all of the 37 stations rated "OK" or better (i.e., all of the stations with three or more valid thermistor readings) were essentially linear. These stations were theoretically capable of resolving consistent curvature in the profiles caused by pore-fluid convection, but such curvature was not observed in any station. In other words, the heat flow data show evidence only for conductive heat transfer, with the exception of four stations rated "poor" because of the unmistakable signature of warm water flowing past the probe in the holes made by the penetration of the probe (Figs. 4A, 6). The lack of evidence in the heat flow profiles for advection may be somewhat surprising, given the vigor of the high-temperature venting at the TAG mound, as well as the widespread but patchy occurrence of diffuse flow of warm fluids from the surface of the mound. However, in many cases the lack of advective signature may simply reflect the fact that the successful heat flow measurements were constrained to sites with at least some minimal thickness (»0.5 m) of relatively impermeable sediments or soft sulfides, with advection locally focused toward more permeable exposures.

Figure 7 shows the cumulative distribution of heat flow values for the 1993 survey. Immediately apparent is the preponderance of low values, resulting in relatively low mean and median values despite the proximity of all the stations to such vigorous hydrothermal venting of various styles on the mound. Given the variability in the local environments of the heat flow stations, as well as the possible complexities in the sub-surface fluid flow patterns, it was conceivable that the heat flow data would show no regular variations (i.e., that heat flow would be locally variable on a scale of only meters). However, several important patterns were indeed apparent in the heat flow data, reflecting coherent distributions of both low and high heat flow values except in the immediate vicinity of vigorous venting. These patterns have important implications for heat and fluid flow processes within the TAG mound, and they were also used in site selection, as described in the following. Note that the heat flow data set is probably not complete enough to justify constructing a contour map, giv-

Table 1. Results of processing heat flow stations from 1993 *Alvin* operations at the TAG active mound.

DIVE HF#	PROBE #TH	Processing results: Quality	Grad (K/m)	HF (W/m^2)	K (W/[m·K])	Comments
2582-1	L-3	OK	0.015	0.013	0.87	T2 registered higher than T3 and was ignored
2582-2	L-4	Good	3.259	2.530	0.78	Nonlinear gradient straightened by K variations
2582-3	L-0	Poor	?	?	?	Big data gap (logger off)—possibly unprocessable
2582-4	L-4	Good	0.684	0.582	0.85	Irregular profile
2582-5	L-4	?	0.382	(0.376)	?	Two K pulses, first one of unknown power
2583-1	L-?	Poor	?	?	?	Insufficient penetration
2583-2	L-3	OK	0.013	0.011	0.85	Very low gradient
2583-3	L-3	OK	0.004	0.003	0.86	Very low gradient
2583-4	L-4	Poor	(11.22)	?	?	Problem with warm water flow past probe
2583-5	L-3	OK	0.228	0.31	(1.35)	HF calculated using K from adjacent 2583-6
2583-6	L-3	OK	0.100	0.135	1.35	High K's at bottom three thermistors
2583-7	L-3	OK	1.178	1.504	1.28	High K's at bottom three thermistors
2587-1	S-4	Good	0.019	0.013	0.71	Penetration not logged, penetration time assumed
2587-2	S-4	Very good	0.027	0.021	0.78	Very good quality for such low HF
2587-3	S-5	Good	0.010	0.009	0.83	Low gradient → error in calculated penetration
2587-4	S-5	Excellent	0.161	0.114	0.71	Excellent station quality
2587-5	S-4	Very good	89.8!	86.2!	0.96	T1 K processing failed, perhaps because of extreme HF
2588-1	S-2	Fair	10.39	(14.0)	(1.35)	Poor penetration, no K measurement; K assumed from nearest station (2583-6) in similar environment
2588-2	S-4	OK	0.004	0.003	0.74	Low gradient → error in calculated penetration
2588-3	S-3/4	Good	0.969	0.827	0.85	K bad for T2, but using T2 in gradient → 0.955 K/m
2588-4	S-4	Good	2.004	1.477	0.74	
2588-5	S-3	Fair	4.262	(3.15)	(0.74)	K pulse did not activate; K assumed from 2588-4
2590-1	S-4	Very good	0.433	0.363	0.84	
2590-2	S-5	Very good	0.620	0.476	0.77	
2593-1	S-3	Good	1.065	0.812	0.76	
2593-2	S-4	Very good	0.101	0.078	0.77	
2593-3	S-2	Fair	5.877	10.578	1.80	T3 T-time looks odd, perhaps in warm water
2593-4	S-2/3	OK	1.544	2.934	1.90	K bad for T3, but using T3 in gradient → 1.464 K/m
2593-5	S-?	Poor	?	?	?	Warm water flow past probe
2593-6	S-3	Fair	37.757	47.370	1.25	Irregular gradient in very high HF; flowing water?
2593-7	S-?	Poor	?	?	?	Slightly negative gradient and penetration
2594-1	S-3/4	Good	6.959	5.035	0.72	T5 failed; T1 K bad, but using T1 temp → 6.329 K/m
2594-2	S-4	Very good	0.379	0.283	0.75	T5 dead
2594-3	S-?	Poor	≈0	≈0	?	T1 in warm water; T2–T4 virtually isothermal
2594-4	S-4	Good?	0.062	0.154	2.48	Very high K's
2596-1	S-5	Good	12.113	9.184	0.76	Nonlinear gradient; linear model → T1 too shallow
2596-2	S-3	OK	7.792	6.368	0.82	T3 showed odd behavior, ignored in processing
2596-3	S-3	OK	0.043	0.043	0.99	
2598-1	S-4	Good	0.723	0.700	0.97	
2598-2	S-3/5	Good?	26.855	16.740	0.62	K's very low; K's unprocessable for T1 and T2; using T1 and T2 in gradient → 24.977 K/m
2598-3	S-5	Very good	16.202	12.003	0.74	
2598-4	S-5	Very good	16.540	11.509	0.70	K's low, but processable
2598-5	S-?	Poor	?	?	?	40°–50° water flowing past probe
2598-6	S-5	Very good	8.538	5.630	0.66	K's low, but processable
2598-7	S-5	Excellent	4.509	3.112	0.69	K's low, but processable
2600-1	S-5	Very good	2.809	2.035	0.72	Calculated penetration slightly deep?
2600-2	S-5	Excellent	0.886	0.714	0.81	
2600-3	S-5	Excellent	0.672	0.513	0.76	
2600-4	S-5	Excellent	0.023	0.018	0.79	Calculated penetration slightly deep?
2600-5	S-4	OK	0.441	0.457	1.04	T3 and T4 virtually isothermal

Notes: HF# = heat flow solution. #TH = number of thermistors registering valid sediment reading (L = long probe, S = short probe). Grad = gradient. K = mean station conductivity.

en the local variability, so the patterns as described below have been illustrated by simply highlighting the relevant stations on Figure 8:

1. The 12 stations collected within about 20 m of the base of the black smoker edifice exhibited extreme local variability, with conductive heat flow values ranging from 0.1 to 86 W/m^2. These 12 stations include 3 of the 4 examples for which no value could be calculated because of the effects of warm water flowing past the probe during the measurement period. The extreme variability is interpreted to be a result of the rugged terrain near the black smoker edifice plus small-scale local variability in secondary fluid flow in the immediate vicinity of the vigorous Black Smoker Complex. Markers "B" and "C" were respectively deployed about 20 m southwest and northwest of the Black Smoker Complex, within this zone of rugged terrain and highly variable heat flow.

2. Only one station was possible in the white smoker "Kremlin" area, where penetration was more difficult to achieve than elsewhere on the mound. This station yielded a very high value of 9.2 W/m^2, as might be expected, although it is entirely possible that there is a similar degree of local variability as in the immediate vicinity of the Black Smoker Complex. Marker "E" was deployed in the Kremlin area at the site of the hottest white smoker vent sampled during the 1993 dive program, and several holes at TAG-2 were drilled within 10–20 m of this marker during Leg 158 (Chapter 8, this volume).

3. The south and southeast edge of the mound is characterized by a terraced slope evenly covered by roughly a meter of sediment that appears to be a mixture of fine sulfide debris and the local carbonate ooze. Only about 20 m south of the southern edge of the Kremlin area, the first such terrace down the slope is notable for very high heat flow, with six values ranging from 5.0 to 16.7 W/m^2. One of these stations was taken in a small area (about 1 × 2 m) of surficial hydrothermal deposits, and indicated flow past the probe of water as warm as 50°C (Fig. 4A). Marker "D" was deployed at the location of this station. It is conceivable that this zone of high heat flow is related to the presence of a large volcanic dome to the south-southeast of the mound. However, the proximity to the Kremlin area suggests instead that the high heat flow and warm pore fluids may be related to the white smoker fluids venting at Kremlin, by means of an extension of the schematic fluid flow path underlying the Kremlin area shown in Figure 1. This sedimented terrace was suggested as an alternate drill

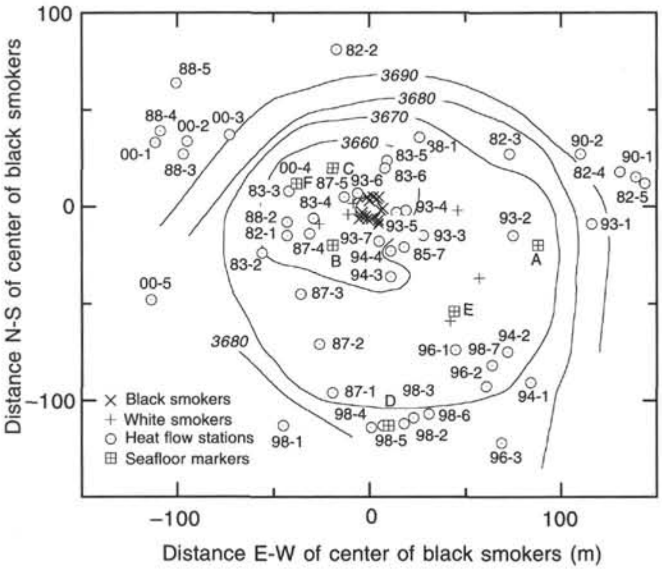

Figure 3. Locations of heat flow stations and seafloor markers deployed during the 1993 *Alvin* dive program at the TAG mound. Stations are identified by the last two digits of the four-digit dive number, plus the heat flow station number. For example, Station 98-1 is the first heat flow measurement on Dive 2598, and 00-5 is the fifth heat flow station on Dive 2600. Bathymetric contours are in meters as determined with the *Alvin* pressure-depth gauge.

site, where APC coring might be feasible, but drilling was not attempted here during Leg 158.

4. To the southwest, northwest, and northeast of the mound, heat flow values in the carbonate-draped seafloor surrounding the mound were surprisingly high, with ten values ranging from 0.5 to 3.5 W/m^2. These data confirm an earlier indication of high heat flow off the mound from two heat flow measurements made in a similar setting southwest of the mound during the 1990 *Alvin* dive program (Rona et al., 1993a). The high heat flow off-mound suggests that mound-related heat and fluid flow processes actually extend in the subsurface beyond the seafloor bounds of the sulfide deposit itself. The set of data to the northwest of the mound shows heat flow increasing with distance away from the mound. Therefore, an objective of the 1995 dive program was to extend this data set farther off-mound in order to document the extent off-mound to which heat flow is elevated. The off-mound areas of high heat flow were not planned as possible alternate drilling targets, as it is known that the sediment cover is thin and underlain by pillow lavas that are probably very difficult to drill.

5. The western section of the main platform of the mound is remarkable for the presence of a consistent belt of very low heat flow. All nine stations taken in a north-south belt about 20–50 m west of the Black Smoker Complex registered <20 mW/m^2. These nine stations are, in fact, the lowest nine values shown on the cumulative distribution of heat flow values from the TAG mound (Fig. 7). Although other effects could contribute to the depressed values in this belt, the consistency and very low magnitude of the conductive heat flow values argue for an area of local recharge of ocean bottom water. Such recharge probably does not extend to great depths but instead is probably entrained into the dominantly buoyancy-driven circulation within the mound itself. Marker "F" was deployed at the northern edge of the low heat flow zone during the last dive of the 1993 series. The belt of low heat flow was scheduled as an alternate drill site for Leg 158, (TAG-4), and four holes were actually drilled here during Leg 158, although drilling conditions were very difficult (Chapter 10, this volume).

SUMMARY AND CONCLUSIONS

An extensive set of heat flow measurements was collected on the TAG active mound during a 1993 pre-drilling survey cruise with *Alvin*—perhaps more extensive than expected given that the *Alvin* heat flow probes were surprisingly effective in penetrating most areas of the mound. The set of 43 successful measurements yields a fairly complete map of the distribution of conductive heat flow at the mound and in the surrounding seafloor, except within the Kremlin area on the mound southeast of the Black Smoker Complex, where penetration was more difficult.

The mean and median values for the full data set are quite low, reflecting an unexpected preponderance of low values. As might be expected, heat flow values within about 20 m of the Black Smoker Complex showed extreme variability, probably as a result of small-scale secondary fluid flow associated with the vigorous main vent system. Away from the immediate vicinity of the black smokers and the white smokers in the Kremlin area, the distribution of high and low heat flow values is fairly coherent, supporting the schematic model of subsurface fluid flow presented by Tivey et al. (1995). In particular, three main features of the distribution of heat flow have important implications for models of fluid flow associated with the mound, as follows:

First, very high heat flow and evidence of pore fluid advection were documented on the terraced southern and southeastern slope of the mound. This is interpreted here as the effects of an extension of the subsurface fluid flow pattern modeled by Tivey et al. (1995) beneath the Kremlin area, but this hypothesis was not tested during Leg 158 drilling. Second, high heat flow was observed in the sedimented seafloor surrounding the southwest, northwest, and northeast sides of the mound, suggesting an extension of the mound-related subsurface flow processes beyond the seafloor expression of the sulfide deposit. Third, the western section of the main plateau of the mound is remarkable for a north-south belt of very low heat flow only 20–50 m west of the Black Smoker Complex. This suggests local recharge of bottom water, not necessarily to great depths, but certainly significant enough to affect the compositions of circulating fluids and precipitates within the mound, as invoked by Tivey et al. (1995).

The 1993 heat flow data set at the TAG active mound is by no means complete, considering the local variability likely on a small spatial scale and the possibility of temporal variability over periods on the order of 1 yr. The 1993 data set has already been supplemented by ten additional measurements taken from the Japanese *Shinkai* 6500 in August 1994 and by 16 additional measurements from *Alvin* in February 1995. These additional measurements were largely directed toward more fully documenting the coherent patterns in heat flow already apparent in the 1993 data set, as well as assessing the possibility of temporal variability in the conductive heat transfer at the mound. Resolving whether any variability is due either to natural processes or to the effects of ODP drilling during Leg 158 will require very careful analysis and further modeling based on the integrated data sets from the TAG active mound.

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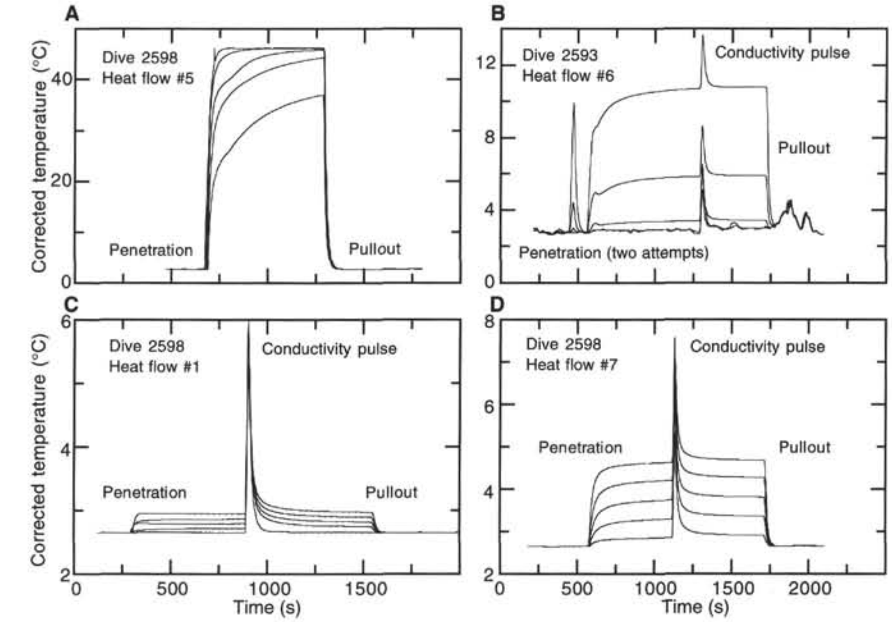

Figure 4. Examples of heat flow station temperature-time records illustrating four different relative quality ratings. **A.** Example of poor quality, from Station 2598-5. Although this record clearly indicates a high convective flux of water as warm as 50°C past the probe, it is unprocessable for any quantitative estimate of the conductive or convective flux. **B.** Example of fair quality, from Station 2593-6. Only the bottom three thermistors penetrated below seafloor, yielding a high but nonlinear gradient and heat flow with large error bounds. **C.** Example of good quality, from Station 2588-3. This station would have been rated very good if the uppermost thermistor had been fully penetrated or if the temperature-Bullard plot had been more perfectly regular. **D.** Example of excellent quality with all five thermistors fully penetrated and very high heat flow, Station 2598-7. The last two examples yielded processable data, and the results are illustrated in Figure 5.

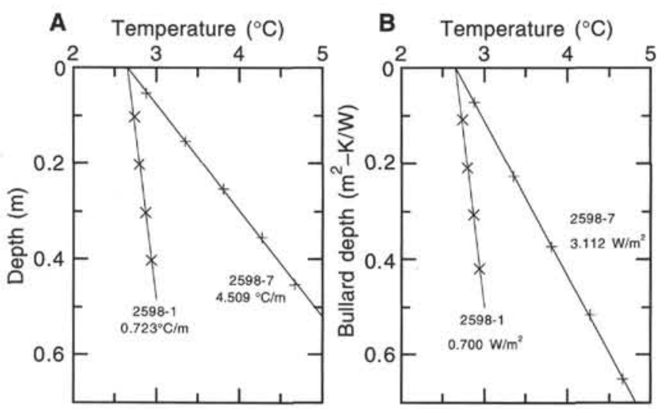

Figure 5. Results of processing the temperature-time data shown in Figures 4C and 4D. **A.** Temperature-depth data and least squares fits for the best estimates of linear gradient. **B.** Temperature-Bullard depth data and least-squares fits for the best estimates of conductive heat flow.

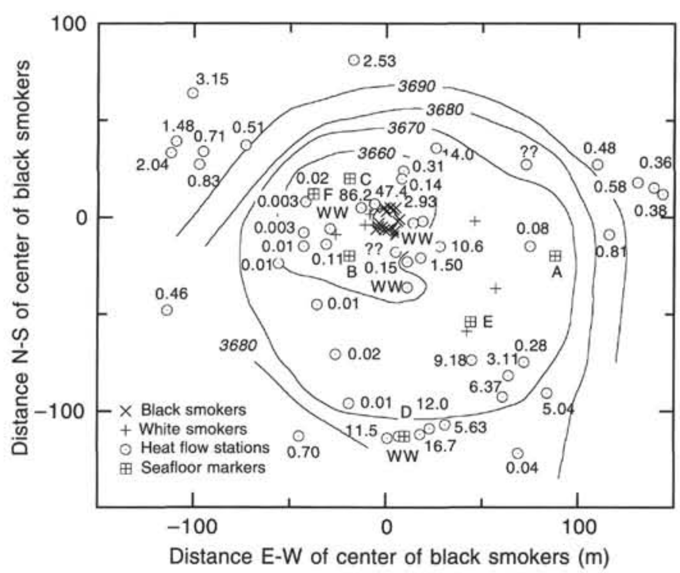

Figure 6. Map of 1993 heat flow values at the TAG mound. Heat flow values given in W/m^2. Stations made unprocessable because of flow of warm water past the probe are indicated by "WW" and stations made unprocessable for other reasons are indicated by "??".

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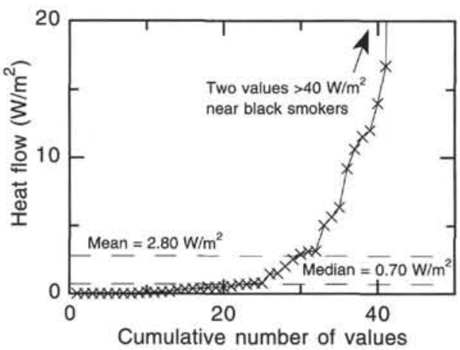

Figure 7. Cumulative distribution of 1993 heat flow values at TAG mound.

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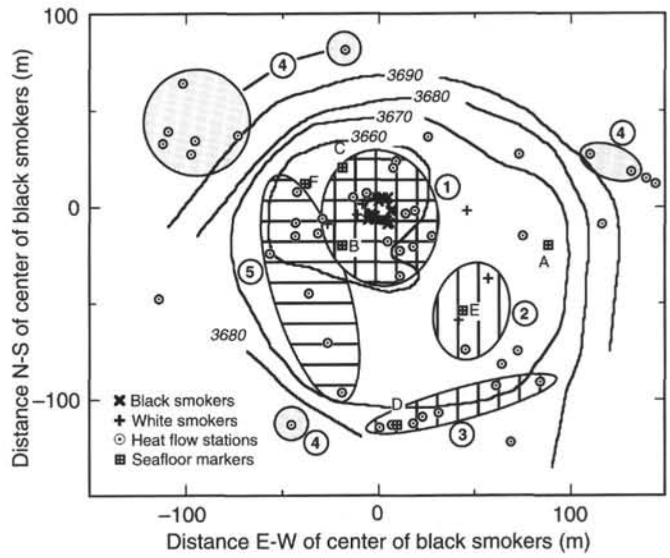

Figure 8. Coherent patterns in the heat flow data at the TAG mound, with vertical fill lines denoting very high heat flow, horizontal fill lines denoting very low heat flow, and stippling denoting moderately high heat flow. The highlighted zones are numbered in accord with the detailed descriptions in the text. Five patterns are apparent, as follows: (1) highly variable (0–86 W/m^2) heat flow within 20 m of the Black Smoker Complex; (2) a single very high value plus white smokers in the Kremlin area; (3) very high heat flow on the sedimented, terraced south and southeastern slope of the mound; (4) high heat flow in the seafloor adjacent to the southwest, northwest, northeast edges of the mound; and (5) the north-south zone of very low heat flow (<20 mW/m^2) on the main plateau of the mound about 20–50 m west of the Black Smoker Complex.