Hydrothermal activity and Architecture of Slow-Spreading Ridge at TAG and Rainbow hydrothermal fields and Dante's Domes Megamullion in the Mid-Atlantic Ridge

-MODE'98 Leg2 MEGATRAIN cruise results summary-

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During MODE'98 Leg 2 cruise TAG and Rainbow hydrothermal fields and Dante's Domes megamullion were surveyed by submersible Shinkai 6500 and R/V *Yokosuka* in the Mid-Atlantic Ridge from 23 July to 23 August, 1998. The morphological change of the black smoker chimneys with normal fault reactivation at the TAG hydrothermal field and a low temperature emanation at the southern end of the Alvin zone were manifested. Comprehensive survey across the Dante's Domes megamullion was accomplished. The strong tectonic controlled chimneys were found at the Rainbow hydrothermal field.

In situ CTD with transmissionmeter, pH, Eh and gamma ray analyses as well as buoyant plume surveys were also carried out at TAG and Rainbow hydrothermal field. These results shed the light to hydrothermal activity and architecture of the slow spreading ridge studies.

Key words : Mid-Atlantic Ridge, Slow-spreading, Black smoker chimneys, Megamullion, Ultramafic hosted hydrothermal chimneys, Linear arrangement

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1. Introduction

A series of 15 dives designed to evaluate heat and material fluxes from active hydrothermal vents and architecture at the slow spreading ridge were successfully performed with the deep sea submersible *Shinkai 6500* at the TAG hydrothermal field, Dante's Domes megamullion and the Rainbow hydrothermal site on the Mid-Atlantic Ridge during a 32 day cruise started in Lisbon (Portugal) on 23 July, 1998) and ended in Lisbon, (Portugal) on 23 August, 1998. During this cruise detailed submersible observations were made at the following sites; (Fig.1 and Table 1). Hydrothermal fluid and buoyant plume samples, rocks, sediments, biological samples and geophysical data were obtained during MEGATRAIN cruise together with video and still photographic visual records along the submersible's track lines. Bathymetric and magnetic data along the R/V Yokosuka track lines were obtained at night.

2. The TAG hydrothermal field

2.1 Objectives:

Seven dives are planned on TAG mound and inactive relict mound. The objectives of these dives were as follows;

1) Construction of 3D architecture of the TAG hydrothermal mound after the 1994 ODP drilling to compare the differences in its whole edifice before and after drilling (Humphris et al., 1995; 1996; Fujioka et al., 1997, 1998).
2) Time series fluid and plume sampling of black and white smokers as well as diffuse flows to estimate the geochemical budget and the geochemical evolution of the TAG hydrothermal mound since the first report in 1986 (Edmons, 1996; Gamo et al., 1996; Rona et al., 1986.

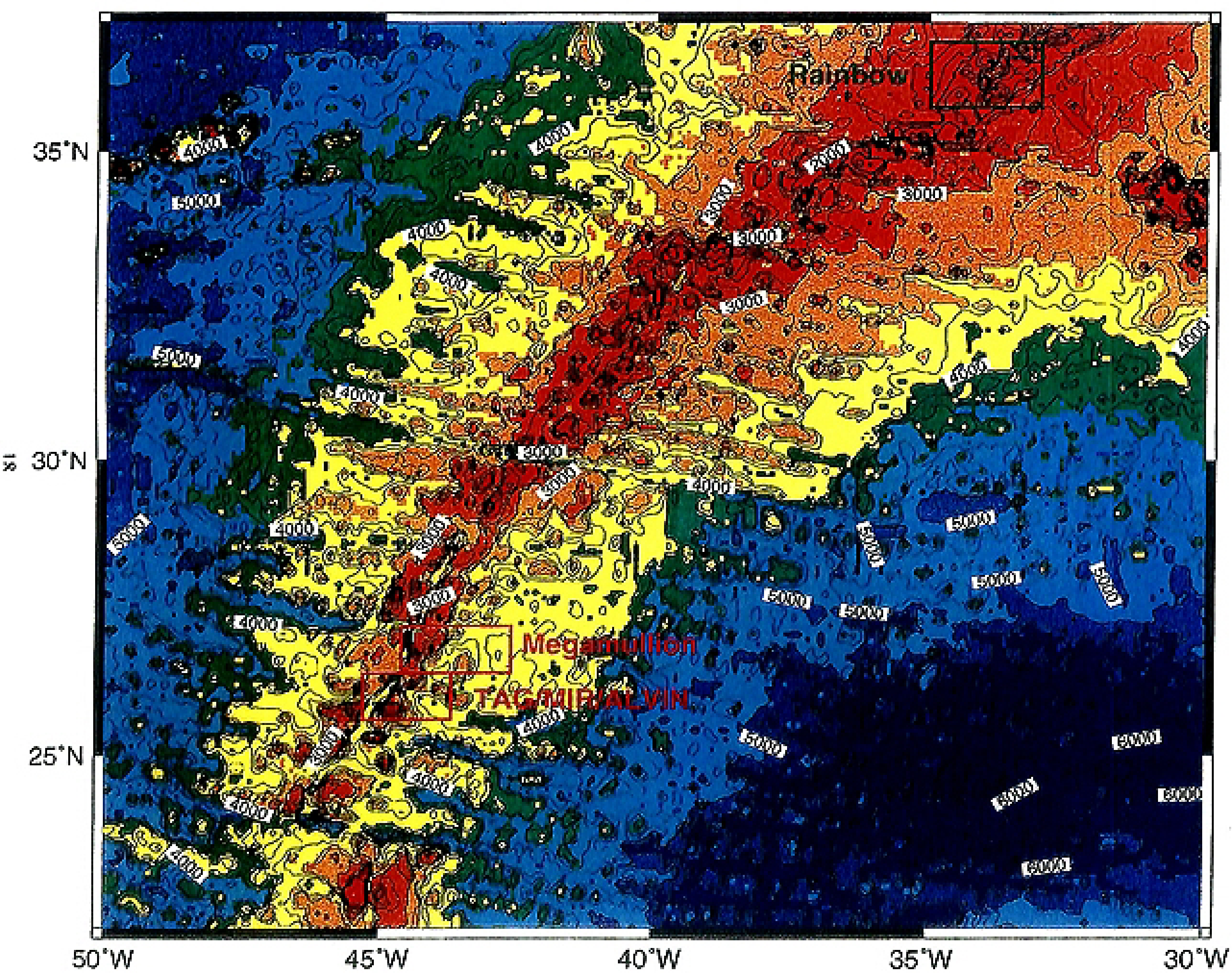

Figure 1 Index map of the survey areas

3) Heat flow measurements of both this active hydrothermal mound and dead mound (MIR and ALVIN zones) to estimate the heat budget and transfer (Becker et al., 1993, 1996; Kinoshita et al., 1996).
4) Collection of ore deposits from the active chimneys and debris flow samples from the northern wall, and from the Mir and Alvin zones which are fossil hydrothermal mounds, to date and analyze the chemical composition of the old ore deposits to estimate the chemical evolution of the hydrothermal activity in this hydrothermal field (Rona et al., 1993).
5) Sampling and observation of micro organisms in relation to the hydrothermal activity (Van Dover et al., 1988).
6) In-situ gamma ray analysis of an active hydrothermal mound to estimate the age of each chimney (Lalou et al., 1990, 1993).
7) In situ geochemical and geophysical measurements of hydrothermal fluids by CTDT, pH and Eh sensors, Gamma-ray detector and three-component magnetometer.

2.2 Major dive results.

We succeeded to have seven dives at TAG and adjacent area and the major results are as follows; Fig. 2 shows the topography of the TAG maound with submersible tracks and markers and Figs. 5a to 5c show the video images of the mound.

1) Changes of the active hydrothermal mound since 1994.

Changes of the active hydrothermal mound since 1994 were remarkable especially for the central black smoker complex (Laputa) which had shrunk and eroded, and for the #72 and #73 sites, (old markers 4 and 1 set up during the MODE '94 cruise) where chimneys were enlarged and growing. The Kremlin and Alvin marker E sites were also changed significantly; white smokers were active there during 1994, but now high-temperature clear water is discharging in their place. Two ODP re-entry cones were identified with hydrothermal precipitates on the surface.

2) Mass wasting on the southern margin of the mound.

Sink holes and slope failure apparently caused by dissolution of anhydrite and calcite had occurred on the southern margin. A anomalously high heat flow value was measured where southeast margin of the mound onlaps an adjacent volcanic dome.

Table 1 List of all dives during MEGATRAIN cruise

Dive No.	Date		Observer Institution	Major objectives	Survey Area	Sub. Nav.	Samples	Start End	Sub. position		Depth(m)
									Latitude(N)	Longitude(W)	
429	Wed	29-Jul.	Fujioka, K. JAMSTEC	A complete reconnaissance overview and update mapping of the TAG hydrothermal mound 4 years after the drilling	TAG active mound	LBL	1HF, 1C, P	11:41 15:31	26-08.203'N 26-08.232'N	44-49.213'W 44-49.526'W	3676 3554
430	Thu	30-Jul.	Chiba, H. Okayama univ.	Observation of stability and change in vent fluid chemistry at the TAG active mound and study of the formation mechanism of massive sulfide deposits	TAG active mound	LBL	5S, P, Or	11:45 15:34	26-08.201'N 26-08.194'N	44-49.514'W 44-49.610'W	3645 3530
431	Fri	31-Jul.	Masuda, H. Osaka city univ.	Observation of stability and change in vent fluid chemistry at the TAG active mound and study of the formation mechanism of massive sulfide deposits	TAG active mound	LBL	3S, 6R, 1HF, 3W, Or	11:39 15:42	26-08.158'N 26-08.221'N	44-49.580'W 44-49.628'W	3660 3591
432	Sun	2-Aug.	Rona, P. Rutgers Univ.	Location, mapping and sampling of possible new mound	New mound	LBL	5S, 1C, 1HF, 1G	11:35 15:44	26-09.628'N 26-09.556'N	44-49.262'W 44-49.157'W	3615 3571
433	Mon	3-Aug.	Naganuma, T. Hiroshima univ.	Isolation and characterization of microorganisms from the TAG hydrothermal vent field	TAG active mound	LBL	3S, 3W.	11:43 15:38	26-08.212'N 26-08.225'N	44-49.611'W 44-49.552'W	3653 3568
434	Tue	4-Aug.	Rona, P. Rutgers Univ.	Location, mapping and sampling of north hydrothermal zone (Alvin Zone), TAG hydrothermal field	TAG field, Alvin zone	LBL /SSBL	3S, 2R, 1HF	11:43 15:44	26-10.696'N 26-10.287'N	44-48.644'W 44-48.860'W	3458 3443
435	Thu	6-Aug.	Oomori, T. Univ. of Ryukyus	Geochemical studies on distribution and age of submarine hydrothermal ores: TAG active hydrothermal field	TAG active mound	LBL	13S, 1C, 5W, P	11:33 15:33	26-08.188'N 26-08.270'N	44-49.544'W 44-49.634'W	3650 3656
436	Fri	7-Aug.	Tucholke, B. WHOI	Structure and origin of oceanic metamorphic core complex in the slow spreading Ridge	Megamullion	SSBL	11R 1HF, 1G	11:17 16:09	26-36.471'N 26-36.765'N	44-19.422'W 44-21.163'W	2626 2357
437	Sat	8-Aug.	Fujioka, K. JAMSTEC	Stratigraphy and structure of the lower crust and upper mantle materials and origin of oceanic metamorphic core complex in the slow spreading oceanic lithosphere: The Dante's Dome Megamullion at 26°40'N on the Mid-Atlantic Ridge	Megamullion	SSBL	11R, 2C 1HF, 1G	11:30 15:51	26-34.412'N 26-34.396'N	44-14.357'W 44-15.639'W	3393 2814
438	Mon	10-Aug.	Tucholke, B. WHOI	Structure and origin of oceanic metamorphic core complex in the slow spreading Ridge	Megamullion	SSBL	R13, 1Or,	11:18 16:00	26-37.441'N 26-36.645'N	44-24.656'W 44-22.831'W	2720 2478
439	Tue	11-Aug.	Ishihara, T. GSJ	Structure and origin of oceanic metamorphic core complex in the slow spreading Ridge	Megamullion	SSBL	11R, 1C, 1FH, 1G, Or	11:30 15:55	26-34.966'N 26-35.366'N	44-16.062'W 44-18.560'W	3047 2727
440	Wed	12-Aug.	Fujioka, K. JAMSTEC	Stratigraphy and structure of the lower crust and upper mantle materials and origin of oceanic metamorphic core complex in the slow spreading oceanic lithosphere: The Dante's Dome Megamullion at 26°40'N on the Mid-Atlantic Ridge	Megamullion	SSBL	33R, 1C, 5W* 1HF, 1G	11:20 16:06	26-33.754'N 26-35.228'N	44-20.392'W 44-20.442'W	2902 2249
441	Fri	14-Aug.	Fujioka, K. JAMSTEC	A complete reconnaissance overview and updated mapping of ultramafic-housed hydrothermal activity of the Rainbow site at 36°14'N on the Mid-Atlantic Ridge	Rainbow site	LBL	3S, 1C, 3W, P, (3HF)	11:15 16:11	36-13.897'N 36-13.748'N	33-54.268'W 33-54.222'W	2395 2326
442	Sat	15-Aug.	Chiba, H. Okayama univ.	Geochemical study of fluid, Plume, and sulfide chimney of the Rainbow hydrothermal system at 36°14'N no the Mid-Atlantic Ridge	Rainbow site	LBL	3S, 2C, 6W, P	11:25 16:17	36-13.897'N 36-13.705'N	33-54.205'W 33-54.129'W	2331 2292
443	Sun	16-Aug.	Green, D. SOC	Geochemistry at the Rainbow Hydrothermal site: Fluxes and fate of major and minor trace elements	Rainbow site	LBL	5S, 3R, 3C, 4W, P, 1HF	11:28 16:15	36-13.884'N 36-13.764'N	33-53.937'W 36-54.051'W	2265 2225

Institutions
JAMSTEC : Japan Marine Science and Technology Center
WHOI : Woods Hole Oceanography Institute
GSJ : Geological Survey of Japan
SOC : Southampton Oceanography Center

Date and Time: Ship's time = UTC-3h
LBL = Long Base Line, SSBL = Super Short Base Line
Samples : S= Sulfide, R= Rock, C= Core sample, W= Fluid water, P= Plume sampling,
Or= Organisms, HF= Heat flow measurement, G= Gravity measurement
Navigation: D-GPS (WGS-84)
Depth measured by depth sensor on the submersible
* These water samples were for biological sample

3) Black and clear smoker fluids at the TAG active mound.

Black and clear smoker fluids were sampled at the active mound. The relationship among pH, alkalinity, and SiO_2 concentration suggests that the black smoker composition has not changed since the first sampling in 1986. (Conditions at the deep-rock/seawater reaction zone must have been stable for at least 12 years (Edmonds et al., 1996; Gamo et al., 1996). Despite drilling of a 125m ODP borehole, composition of clear smoker fluids sampled at the Kremlin site seems to be similar to that of white smoker fluids sampled at the upper terrace in 1994.

4) Huge, inactive mound north of TAG.

An old hydrothermal mound was located 2.5 km north of the TAG active mound and its height was measured at 68 m. Submersible survey showed that the mound was inactive, but. this mound is perhaps the highest hydrothermal mound yet known (Rona et al., 1993).

5) Low temperature system.

In the Alvin zone, an active low temperature system was found discharging 23°C clear water with a biota composed of sea anemones, bacterial mats etc. At least part of the Alvin zone is still active or is being reactivated.

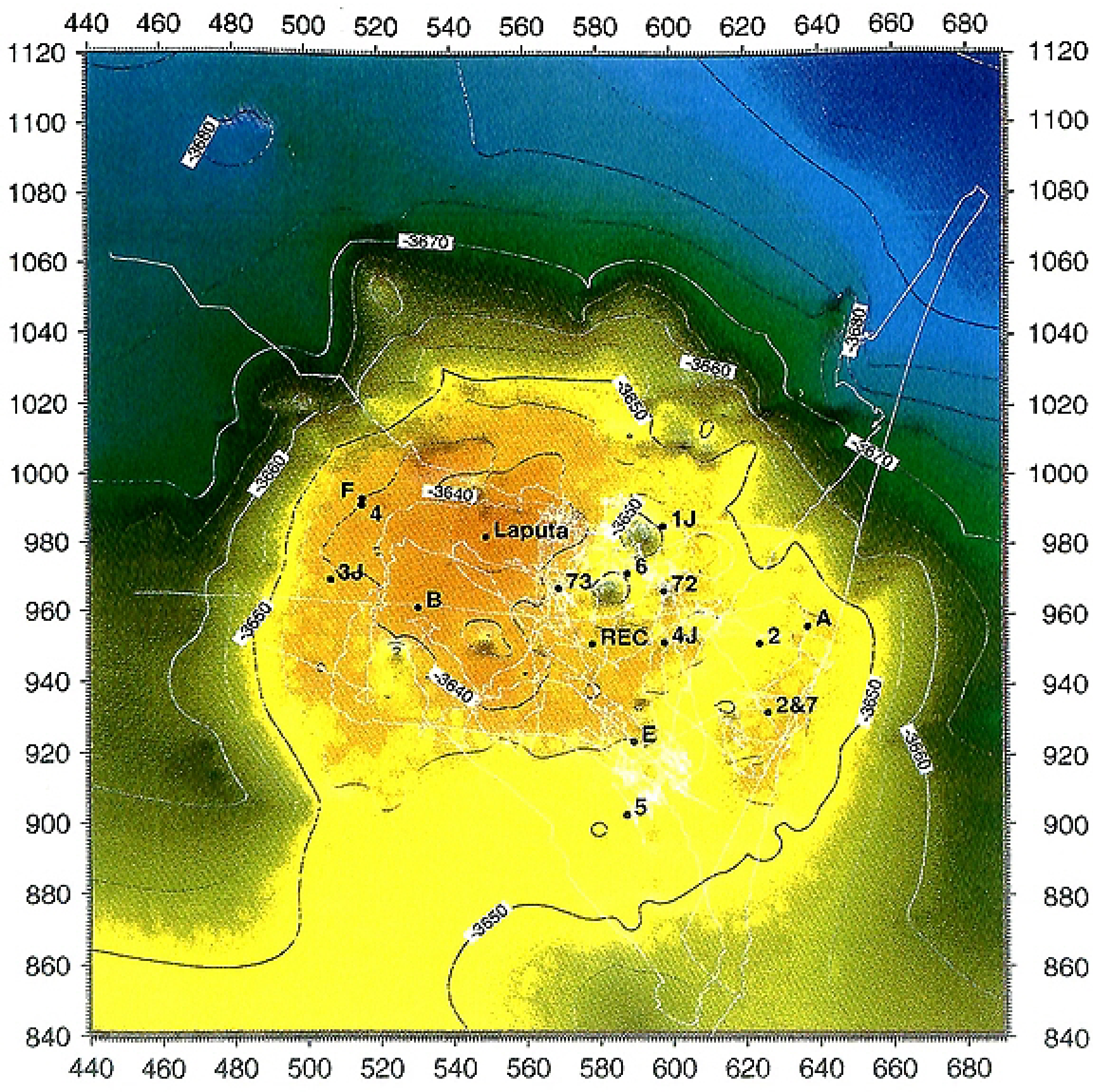

Figure 2 Bathymetric map of the TAG hydrothermal mound Markers from A to E were deployed by Alvin; Markers 1J to 4J and 72 to 73 were deployed by Shinkai 6500; Laputa is the central blacksmoker complex; REC is the ODP Re-entry cone.

3. Dante's Domes Megamullion site results.

Dante's Domes megamullion site was first identified by Tucholke and others (1998) by the topographic, gravity and magnetic anomalies (Cann et al., 1997; Cannat et al., 1995). The dive to the Dante's Domes was for the first time by the use of the manned submersible. Fig. 3 shows the topography of the Dante's Domes with submersible tracks and Figs. 6a to 6c show the video images of the Dome.

3.1 Objectives:

Five dives are planned on Dante's Domes, arrayed approximately along a dip transect that extends from breakaway to termination across the south of the two main domes. Observations and geological/geophysical sampling along this transect are intended to address the following objectives:

(1) To document whether the surface of the megamullion represents a fault surface.

(2) If the megamullion surface is a fault surface, to investigate the history of fault development and strain localization from recovered rock samples.

(3) To determine whether the surface of the megamullion exposes a cross section of the ocean crust and upper mantle, and to document in detail the composition and structure of this cross section.

(4) To analyze the structure of small isochron-parallel steps in the megamullion surface, determine if they are fault scarps, and evaluate them in the context of bending stresses in the rotating footwall.

(5) To obtain structural data on the mullions that will help to assess their origin.

(6) To analyze whether the sea-surface magnetic anomalies be explained by observed seafloor magnetization (as documented by on-bottom 3-component magnetometry and by laboratory measurements on recovered rock samples).

(7) To relate distribution of rock types and rock densities (e.g., gabbro, peridotite, serpentinite) to the observed sea-surface gravity field.

(8) To further constrain these relations by obtaining on-bottom gravity measurements along the transect.

(9) To determine whether the structure and inferred development of the megamullion is consistent with

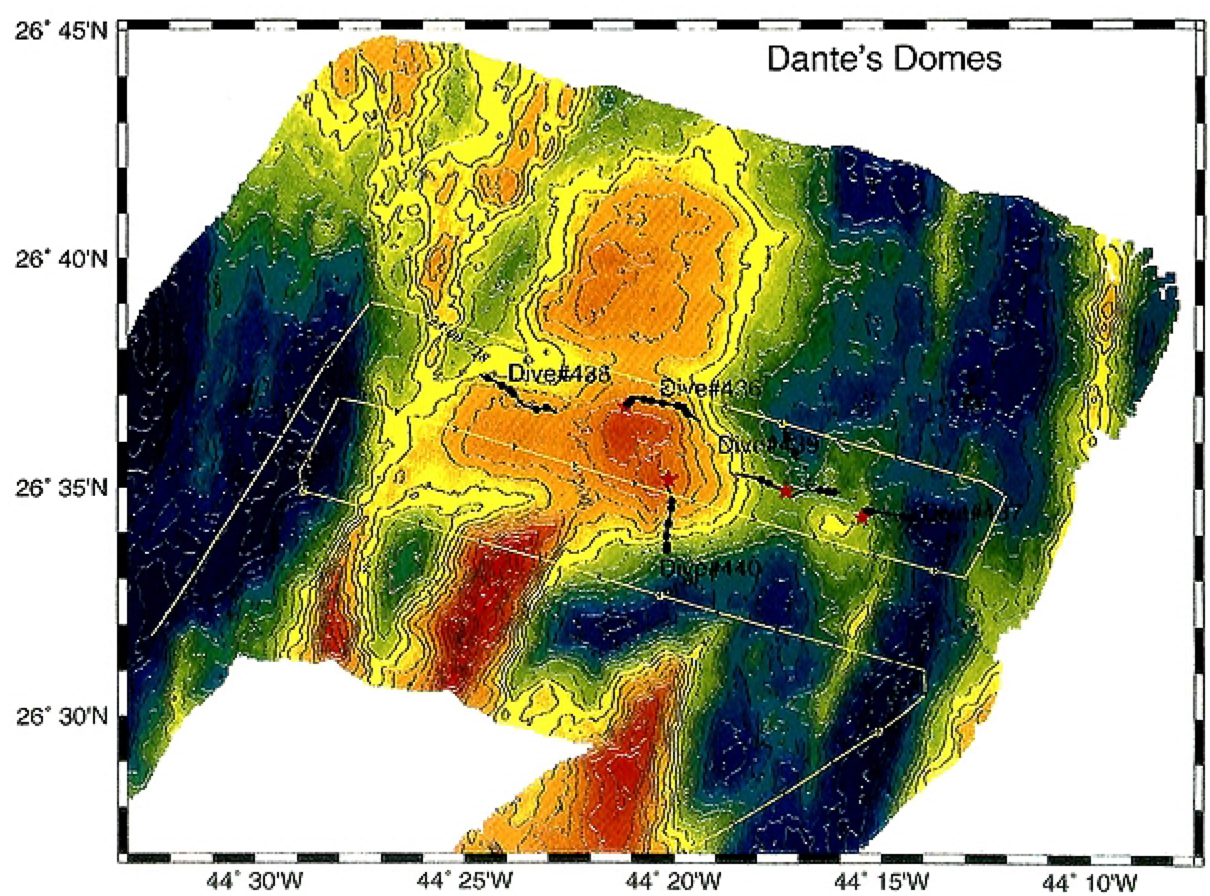

Figure 3 Bathymetric map of Dante's Domes

heat flow measured along the transect of dives.

(10) Incidentally, to determine whether venting of hydrothermal fluids may be occurring on the megamullion.

3.2 Major results:

Preliminary findings from the megamullion dives series are as follows.

(1) Where the detachment fault initially nucleated, a steep volcanic depositional slope on the east flank of the ridge at the previously identified breakaway indicates that this is not the true breakaway. Instead, this ridge and a set of smaller ridges to the west appear to constitute a set of "rider blocks" on top of the deeper detachment surface. The actual breakaway zone appears to be about 3 km farther east, located at a steep west-facing scarp near 44°13'W.

(2) The lithological section exposed by faulting near the breakaway zone is an upper- crustal section. With distance west from the breakaway zone, there is a small but probably significant increase in occurrence of deeper rocks, suggesting that lower crust and upper mantle may be exposed at least locally.

(3) The surface of the domes on the younger part of the megamullion is remarkably flat, and it slopes gently away from the crests of the domes. This unusually smooth surface most likely reflects very smooth basement buried beneath a few meters of sediment, and this basement is interpreted to be the detachment fault surface.

(4) Basaltic debris litters the eastern dome of the megamullion, but none of it appears to be in place. It is interpreted to be talus that was clipped from the overlying hanging wall and carried onto the megamullion footwall as the detachment fault slipped.

(5) Rocks recovered from the base of the eastern dome in the region of the highest residual mantle Bouguer gravity anomaly (RMBA) include a serpentinite and a gabbro. These are interpreted to represent samples of basement rock from beneath the detachment fault. Modeling of the on-bottom gravity data will help to test the validity of this interpretation.

(6) The youngest part of the megamullion contains in-place evidence of intrusive and extrusive magmatic activity. This may indicate that the rift valley was becoming more magmatically active late in the period of megamullion formation. This magmatism would have created a thicker crustal section, possibly explaining the decreasing RMBA over the young part of the megamullion.

(7) Igneous debris moving downslope on the gentle flanks of the megamullion domes is captured in unusual rock "fences" that meander for tens to probably hundreds of meters nearly parallel to bathymetric contours. The same debris moving downslope on steeper slopes near the breakaway zone forms chutes and creates significant debris flow deposits.

(8) Bottom currents are active in the study area, and they appear to circulate clockwise around the domes. They create extensive field of asymmetrical ripples both in calcareous ooze/marl and in overlying, coarse lag deposits of pteropod and iron-manganese debris. The lag deposits are transported both along-slope by the currents and downslope under the influence of gravity.

4. Rainbow hydrothermal site.

Recently found Rainbow hydrothermal site (Fouquet et al., 1998; German et al., 1996a, b; Parson et al., 1997; Barriga et al., 1997) has unique feature being composed of ultramafic-hosted low hydrogen sulphide system. Fig. 4 shows the topography around the Rainbow Ridge and Figs. 7a to 7c show the video images of the Rainbow hydrothermal field.

4.1 Objectives:

(1) To do topographic and geological mapping of the Rainbow hydrothermal site, in order to understand the tectonic control of the hydrothermal system,

(2) To locate active black smokers and diffuse flow if possible, and dead chimneys to know the distribution of the chimneys and to estimate the magnitude of the hydrothermal system,

(3) To sample sediments by push coring at off-mound locations, for the understanding of the distribution of the hydrothermal particles,

(4) To sample the plume of the black smoker fluids to characterize the geochemistry of the hydrothermal system,

(5) To sample sulfide and host rocks (maybe peridotite)

at the various locations, to understand the degree of reaction with hydrothermal solution,

(6) To measure heat flow values in an active vent site and off-active site, and

(7) To make an in situ measurements of pH, Eh, gamma-ray and CTDT continuously along the submersible track for the characterization of the hydrothermal vents.

4.2 Major results:

1) Location of black smoker vents.

At least 3 active black smoker vents were identified at JAMSTEC marker #79 (FLORES #9) of Dive #441, marker #81 of Dive #442, and marker #82 of Dive #443. Possibly seven black smoker vents were observed, including two near marker #79, and five near the marker #82 site.

2) Samples at the Rainbow site.

Hydrothermal fluids, plume, sulfide, hydrothermal precipitates, and host rocks were collected from the black smoker sites as well as from adjacent areas.

3) Linear distribution of dead chimneys.

Many dead chimneys were located during the submersible survey. They are slim and tall (max. 10m), but they remain standing, and they align in EW and NS directions. The hydrothermal system may be controlled by N-S and E-W trending fault systems. The top of the mound was like a long, narrow and steep ridge, and it was very difficult for the submersible to access because of strong currents and the steep, rugged topography.

4) Mass wasting and identification of markers.

Mass wasting, slope failure, and debris flow deposits were observed along the steep slopes of the hydrothermally altered zone. We located existing markers #10, 27, 35, 36, 41 and FLORES marker #9 during the dives.

5) Geochemical characteristics of the black smoker fluids of the Rainbow site

Three black smoker fluids were sampled at this site. The pH vs. SiO_2 concentration relationships suggest that the black smoker fluid at this site has low SiO_2 concentration, about 1/3 of quartz saturation at the measured temperature. This is probably because the host rock is peridotite, which was sampled in this area, and it may affect the concentrations of components other than aqueous SiO_2. High concentration of gaseous components was also found in these samples. These gaseous components most likely are H_2, CH_4, and H_2S, according to previous studies.

5. Other results

5.1 Detection of hydrothermal plumes using CTDT, Eh and pH sensors.

While the submersible was sinking to and rising from the seafloor, temperature, salinity, transmittance, Eh, and pH of the water mass were continuously monitored. Simultaneous anomalies in temperature, transmittance, and Eh were detected about 250m above the seafloor in all dives at the TAG hydrothermal area. They must correspond to a hydrothermal plume

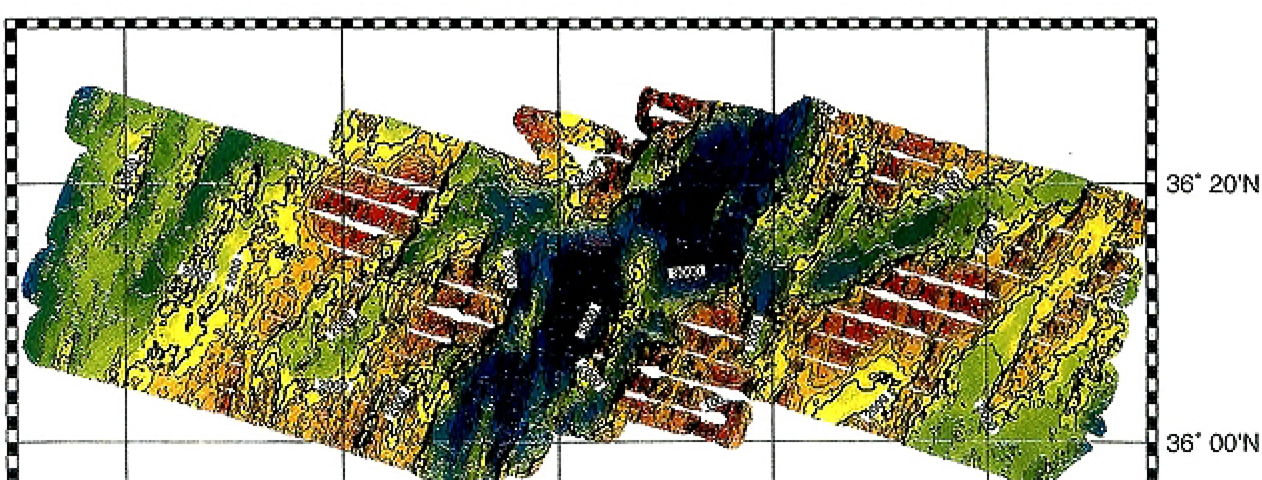

Figure 4 Bathymetric map of the Rainbow hydrothermal site

originating from the high-temperature venting. The intensity of the anomaly decreases with increasing distance from the active venting area. At the Rainbow site, temperature and transmittance anomalies were detected in all dives, but an Eh anomaly was found in only one dive (#443). This may reflect the difference in chemical nature of the hydrothermal plumes at two sites.

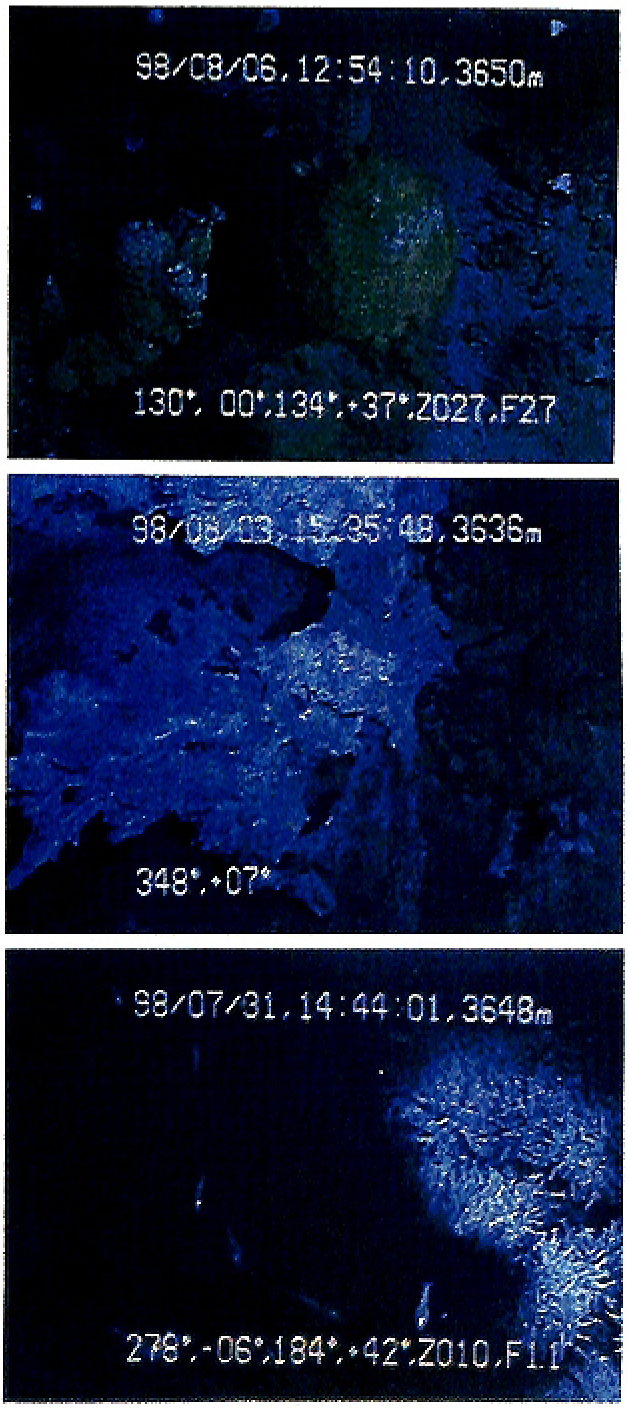

Figure 5 Instant photographs of the TAG hydrothermal mound during dive #435
a) White smoker dead chimney at the Kremlin site looking like a Arabic castle.
b) Angular, massive anhydrite aggregate at the foot of central blacksmoker complex.
c) Newly found black smoker with tremendous amount of Rimicaris shrimp.

Figure 6 Instant photographs of Dante's Domes during dive #438
a) Highly sheared part of intrusive body.
b) Scattered rubbles basaltic rocks on the pelagic clay.
c) Huge sponges on the rubbles.

5.2 In situ measurement using CTDT, and pH and Eh sensors at active hydrothermal areas.

Temperature, salinity, transmittance, pH, and Eh of water masses were successfully measured along the track lines of Shinkai 6500 at the TAG and Rainbow hydrothermal areas. Temperature, salinity, transmittance, Eh, and pH anomalies were detected simultaneously around venting sites. These anomalies were detected not only at chimneys venting hot fluid, but also at low temperature diffuse flow sites such as at the north-end of the Alvin zone. Anomalies in these factors should be used to locate venting phenomena at the seafloor.

Figure 7 Instant photographs of the Rainbow hydrothermal site during dive #443
a) Linear arrangement of many dead chimneys.
b) FLORES marker found at the westernmost blacksmoker chimney.
c) Active black smoker emanating black smoker fluid.

5.3 Geophysics.

1) We conducted swath surveys using the HS-10 multibeam system, a gravity meter, and a proton magnetometer and three-component magnetometer. The surveys covered 3500 miles of track in box surveys north of Dante's Domes and around the Rainbow site.
2) In situ three-component magnetic survey was conducted with Shinkai 6500 during all dives.
3) Sea floor gravity measurements were conducted across Dante's Domes at approximately equal intervals.
4) Heat flow measurements were conducted in 10 localities in the TAG area, at Dante's Domes and at the Rainbow hydrothermal site.

5.4 Biology and microbiology.

1) Dense swarms of shrimp, *Rimicaris exoculata* and to a lesser degree of *Chorocaris chacei*, were observed on active chimney walls at both the TAG hydrothermal mound and the Rainbow hydrothermal site.
2) The major food source for the shrimps is thought to be microorganisms associated with the chimneys, and the occurrence of sulfur-oxidizing bacteria was indicated by onboard preliminary cultivation.

6. Summary and future problems

We have collected samples and data from the Mid-Atlantic Ridge during the MODE'98 MEGATRAIN cruise. They are swath bathymetry, gravity and magnetic data and in situ pH, Eh, gamma-ray and CTD with transmission meter data during descent and ascent and along the ship's tracks of the submersible, visual still and video data and rocks, sediments, fluids and biology samples. We recognized significant change of the TAG hydrothermal mound and linear arrangement

of the chimneys of the Rainbow hydrothermal field and we collected basic data set across the megamullion site. These data and samples shed light on the origin and evolution of the Mid-Atlantic Ridge.
However, it seems to be difficult to detect a subtle change of the hydrothermal activity and to estimate the exact pass way of the hydrothermal fluid. It seems also difficult to have a perfect geologic and geophysical cross section of the megamullion site. Therefore we still need more cruise to have much more elaborated data and samples for the better understand the ridge processes.

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