Chemical Characteristics of Hydrothermal Fluids from the Mariana Trough

T. Gamo
Ocean Research Institute, University of Tokyo, Tokyo, Japan

U. Tsunogai* and J. Ishibashi
Laboratory for Earthquake Chemistry, University of Tokyo, Tokyo, Japan

H. Masuda
Department of Geosciences, Osaka City University, Osaka, Japan

H. Chiba
Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan

Abstract Two hydrothermal active sites with hot fluid venting are known in the Mariana arc-backarc system: one is at the mid-Mariana Trough (18°13'N, 144°42'E; depth: 3,600 m) and the other at the southern Mariana Trough (13°24'N, 143°55'E; depth: 1470 m). Chemical characteristics (major element compositions, dissolved gas concentrations, isotope ratios etc.) of the hydrothermal fluids from the both sites have shown that the former activity is a sediment-starved backarc type, while the latter a sediment-starved arc type, although the data on fluid chemistry have not necessarily been accumulated enough so far. At the former site, clear hydrothermal fluids (maximum temperature: 287°C) from sulfate-sulfide chimneys were first taken during the DSRV *Alvin* dives in 1987. In 1992, the DSRV *Shinkai 6500* revisited the former site to find little temporal variation of fluid chemistry between 1987 and 1992. The latter site, which *Shinkai 6500* discovered in 1992 and surveyed in detail in 1993, has also clear fluid venting with the maximum temperature of >200°C. High CO_2 concentrations observed for the both sites suggest the effect of subducting slab materials below the Mariana Trough.

Introduction

Mariana Trough is a present-day spreading back arc basin behind the Mariana Trench, where the Pacific plate subducts under the Philippine Sea plate (Fig. 1). The spreading rate is thought to be ~3 cm y^{-1} as a full rate for these 3 m.y. (Hussong and Uyeda, 1981). Mariana Trough is characterized by active hydrothermal circulation with heat and material flux from seafloor (e.g. Ishibashi and Urabe, 1995). During the CEPHEUS Expedition of R/V *Hakuho Maru* (Ocean Research Institute, University of Tokyo, Japan) in 1982, water column CH_4 anomalies were found for the first time above the mid-Mariana Trough between 18°12'N and 18°15'N, possibly due to hydrothermal activity (Horibe et al., 1986). Five years later, detailed bottom surveys using DSRV *Alvin* (Woods Hole Oceanographic Institution, U.S.A.) in the mid-Mariana Trough revealed the existence of hydrothermal activity with high temperature vent fluids (up to 287°C) and biological communities along the axial region centered on 18°13'N (the filled square in Fig.1) (Craig et al., 1987; Campbell et al., 1987; Hessler et al., 1988).

It has been known that active submarine hydrothermal systems show not only spatial but also significant temporal variations (e.g. Baker et al., 1987; Lupton et al., 1989; Haymon et al, 1993). It is of much interest, therefore, to continue monitoring the fluid chemistry of the Mariana Trough hydrothermal activity in a wide area. This is the reason why the submersible *Shinkai 6500* of JAMSTEC

*present address: Institute of Hydrospheric-Atmospheric Sciences, Nagoya University, Nagoya, Japan

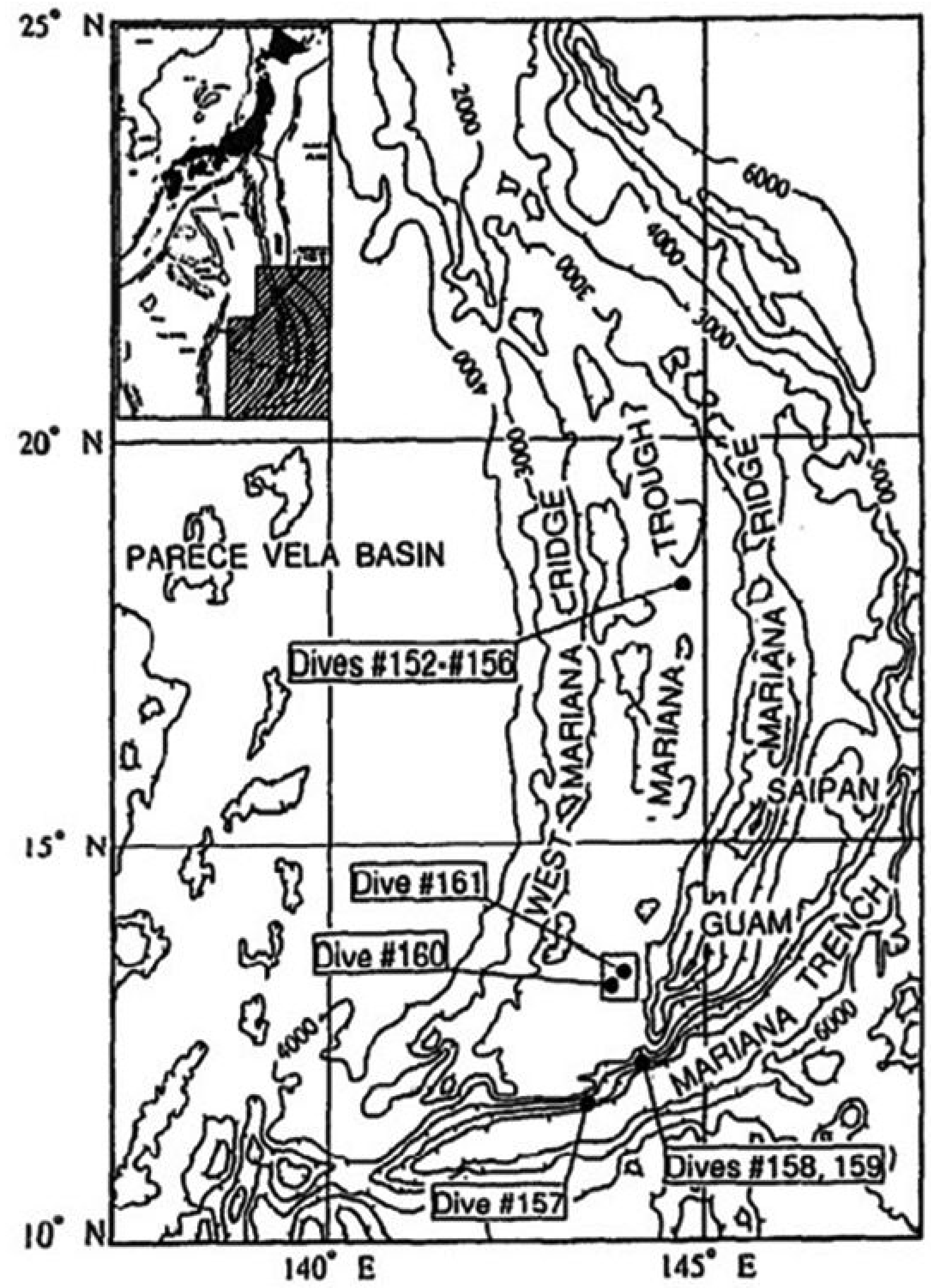

Figure 1. A topographic map of the Mariana area showing the locations of ten dives (#152-#161) of the submersible *Shinkai 6500* in 1992. Contours are every 1,000 meters.

visited the mid-Mariana Trough in 1992 and the southern Mariana Trough in 1992 and 1993. This paper reports the following two points: (i) little temporal variability of the mid-Mariana Trough hydrothermal activity between 1987 and 1992, (ii) discovery of a new venting site in the southern Mariana Trough and its chemical characterization.

Cruises

The Y9204 TRANSARC cruise of *Shinkai 6500* and her mother ship *Yokosuka* was dedicated to survey the Mariana area between November 5 and December 1, 1992, as a Japan-U.S. cooperative cruise (Gamo et al., 1993; 1994). The shipboard scientists from Japan were T. Gamo (chief scientist), H. Chiba, J. Ishibashi, T. Ishii, H. Masuda, S. Ohta, T. Shibata, J. Tamaoka, H. Tanaka, U. Tsunogai and T. Yamaguchi, and those from U.S.A. were P.A. Rona, P. Fryer, L.E. Johnson, K. Kelly, and A-L. Reysenbach.

Figure 1 shows the survey area, where ten dives were performed. Five dives (#152 to #156) were devoted for revisits to the mid-Mariana Trough hydrothermal site: Alice springs field (18°12'N, 143°30'E) to take hot fluid samples for geochemical studies, and two dives (#160 and #161) were performed in the southern (13°N) Mariana Trough to find a new hydrothermal active site (Forecast vent field). Results of the other three dives (#157 to #159) are not included in this paper, because they were devoted for trench studies.

Shinkai 6500 revisited the southern Mariana hydrothermal site (dive #161 site in Fig. 1) in 1993, during the SOUTHERN CROSS Cruise (chief scientists: K. Fujioka, S. Ohta). This cruise was also a Japan-U.S. collaborative one. H. Masuda and U. Tsunogai joined the cruise to continue the fluid chemical studies.

Observations

Mid-Mariana Trough (1992)

We could locate the Alice springs field very easily, because *Yokosuka*'s transponders had been already deployed there during the previous Y9203 Cruise of *Yokosuka* in September 1992 (chief scientists: K. Fujioka, H. Tokuyama). On the ocean floor of the #152 - #156 site (Fig. 1), we found a marker plate with white letters of "R1" and an old ballast block with letters of "No. 29", both of which had probably been released by *Alvin* in 1987.

Active hydrothermal chimneys (Fig.2) were erupting clear solutions, whose maximum temperature was 280°C, almost the same value as was observed by *Alvin* (287°C) in 1987. Biological communities around the hydrothermal vents were examined in detail by Prof. S. Ohta of Ocean Research Institute, University of Tokyo (deep-sea ecologist), who dived the same site by *Alvin* in 1987.

Figure 2. Hydrothermal chimneys observed at the Alice springs field during the dive #152 in 1992. The heights of the chimneys are between 50 and 100 cm. Enormous gastropods (*Alviniconcha Hessleri*) are seen at the foot of the chimneys.

Fluid samples were taken with an ORI manifold pump sampling system attached to the submersible. The sampling system consists of a deep sea impeller pump (Pelagic Electronics, model 5013A-P), an automatic rotating valve (Nichiyu Giken Kogyo, Co. Ltd.) to select one of the eight sampling bottles made of acrylic resin, and a Pt resistance thermometer at the fluid inlet tube for simultanesous temperature measurement during fluid sampling (Sakai et al., 1990; Ishibashi et al., 1995). The samples were analyzed for some chemical components (pH, alkalinity, Si, and H_2S) on board Yokosuka, and the rest samples were properly kept back to shorebased laboratories for additional chemical analyses.

The following experiments were also done during the #152 - #156 dives. Dr. P. Rona (NOAA) measured detailed bottom temperature distribution for heat flux estimation in a similar way to that of Rona and Trivett (1992). Dr. A-L. Reysenbach (Indiana University) deployed a "vent-cap" above a hydrothermal vent for in situ bacterial growth with successful retrieval. Many basaltic rocks, chimneys, sediments, particles and biological samples were taken as well as fluid samples. Mineralogy and ore texture of the chimney material were reported by Kase et al. (1994). Microbiological studies were done by Dr. J. Tamaoka (JAMTEC).

Southern Mariana Trough (1992 & 1993)

In 1992, we conducted detailed topographic surveys in the southern Mariana area from the trench to the backarc basin using *Yokosuka*'s multi narrow beam system, in collaboration with Dr. P. Fryer (University of Hawaii) (Fryer, 1993). Figure 3 is a simplified bathymetric map of the southern Mariana area obtained during the Y9204 cruise. The backarc spreading axis is recognized from (13°35'N, 143°48'E) to (13°03'N, 143°40'E) with an offset at around (13°30'N, 143°47'E). A significant transform fault (shown by a dashed

Figure 3. A topographic map of a part of the southern Mariana Trough area. The covered area of this map is indicated by the box in Fig. 1. Contours are every 250 meters. The two thick arrows and the broken line show *Shinkai 6500* dive transects in 1992 (dives #160 and #161) and a transform fault, respectively.

line in Fig.3) is evident from a lateral shift of the seamount at (13°09'N, 143°50'E).

Many seamounts in various sizes were found along the eastern side of the spreading axis, some of which may be a southern extension of the Mariana Island Arc. During the dive #161, we found a new hydrothermal active site (Forecast vent field) at the summit of a seamount (13°24'N, 143°55'E; depth: 1,470 m) located ~9 miles eastward from the spreading axis (Johnson et al., 1993). Clear solution (maximum temperature: 202°C) was emanating from white chimneys (Fig. 3), which mainly consist of anhydrite and barite, with much less abundance of sulfides than the chimneys from the dives #152-156 site. In 1992, we tried in vain to take fluid samples from the chimneys due to a trouble of the sampling system. Although no hydrothermal activity was observed on dive #160 seamount (13°14'N, 143°46'E, summit depth: 2760 m), there is a fissure parallel to the spreading axis at the western foot of the seamount, which implies tectonic activeness of the spreading axis.

Figure 4. A hydrothermal chimney observed at the summit of the dive #161 seamount (Forecast vent field). The height of the chimney is about 1 m.

During the cruise in 1993, we successfully took several hydrothermal fluid samples (maximum temperature: 197°C) from the Forecast vent site for chemical analyses in a similar way as that in 1992.

Results and discussion

Chemical characteristics of the hydrothermal fluid taken in 1992 from the mid-Mariana Trough (Alice springs field) and those taken in 1993 from the southern Mariana Trough (Forecast vent field) are summarized in Table 1, in comparison with those of the Alice springs field taken in 1987 (Craig et al., 1987; 1988; Campbell et al., 1987) and with those of other typical submarine hydrothermal sites.

The fluid chemistry as well as the maximum fluid temperature of the Alice springs field is similar between 1987 and 1992, suggesting little variation in hydrothermal activity during these five years. This is in harmony with the fact that the density and biomass of the vent communities (hairy gastropod, crab, galatheid, shrimp, actinian, etc.) observed in 1992 seemed to be similar to those in 1987, except for remarkable multiplication of a white whelk.

It should be noted that the Mariana Trough fluids, as well as the other back arc basin fluids (Table 1), show significantly high ΣCO_2 concentrations. The abundant CO_2 is likely to be derived from the subducting slab materials below the Mariana Trough. The effect of the slab materials was also pointed out from lower $\delta^{11}B$ value for the mid-Mariana Trough hydrothermal fluid (Table 1) than those of mid-oceanic ridges (Palmer, 1991).

Basalt samples recovered from the Forecast vent field was found to be classified as island-arc category (Fryer et al., submitted). As shown in Table 1, chemical characteristics of hydrothermal fluid of the Forecast vent field seem to be more similar to those of Suiyo Seamount, a typical island-arc hydrothermal

Table 1. Hot fluid characteristics of the mid-Mariana Trough (in 1987 and 1992) and those of the southern Mariana Trough in comparison with those of other submarine hydrothermal active sites (Data sources or references are summarized in Gamo (1995)).

Name of site	Okinawa Trough JADE	Okinawa Trough South Ensei	Izu-Bonin Suiyo Seamount	Mid-Mariana Trough Alice Springs 1987	Mid-Mariana Trough Alice Springs 1992	South Mariana Trough Forecast vent 1993	East Pacific Rise 21°N	Mid-Atlantic Ridge TAG	
Type Sediment-	Back-arc or Arc hosted	Back-arc hosted	Arc starved	Back-arc starved	Back-arc starved	Arc starved	MOR starved	MOR starved	(Seawater)
Depth (m)	1,340	710	1,380	3,600	3,600	1,490	2,600	3,700	
Smokers	Black	Clear	Clear	Clear	Clear	Clear	Black	Black and White	
Temp. (°C)	320	267-278	296-311	238-287	280	202	273-355	270-366	2-4
pH (25°C)	4.7	4.9-5.1	3.7	4.4	3.9		3.3-4.0	2.6-3.4	7.8
K (mM)	72	49-51	30	31	48	26	23-26	17-19	9.8
Rb (μM)	360			30			23-28	9-10	1.3
Mg (mM)	0	0	0	0	0	0	0	0	52.7
Ca (mM)	22	21-22	89		22	61	12-21	26-31	10.2
Mn (μM)	110	88-94	587		295	300	700-1020	670-1000	<0.001
Fe (μM)	2.8		435		6.4	11	650-2430	1640-5590	<0.001
B (mM)	3.4	3.7-4.0	1.4	0.83	0.71		0.50-0.55	0.36-0.41	0.43
SiO_2 (mM)	12.9	10.4-10.8	13.2	14	12.3	7.7	15.6-19.5	19-22	0.18
Cl (mM)	550	501-527	658	557	544	593	489-592	636-680	540
Alkalinity (mM)	1.9	3.0-3.5	-0.2	0.4	0.06	0.18	-0.2- -0.5	-3- -0.5	2.3
NH_4 (mM)	5.0	4.6-4.7	<0.1	~0		<0.1	<0.01		0.002
CH_4 (mM)	7.6	2.6-7.0	0.11			0.003	0.05-0.09		<0.000001
H_2S (mM)	12.4	1.6-2.4	1.6	<2.6	2.5	0.4	6.6-8.4	0.5-3.5	0
CO_2 (mM)	209	64-96	39.7	43.4		42.1	5.7-8.0		2.3
$\delta^{11}B$ (‰)	-1.0			20-30			29.0-33.0	29-35	39.5
$^3He/^4He$ (R/Ra)	6.1-6.9	7.0-7.5	8.1	8.5-8.6		8.1	7.8	7.5±0.9	1-1.2
$\delta^{13}C(CO_2)$ (‰)	-5.0- -4.7	-4- -5.3	-1.0	-4.3		-1	-7.0		-1- 0
$\delta^{13}C(CH_4)$ (‰)	-36- -41		-8.5			-11	-18- -15		
$^{87}Sr/^{86}Sr$	0.7089	0.71		0.7036	0.7038		0.7030-0.7036	0.7029-0.7046	0.7092

site, than those of the mid-Mariana Trough (backarc hydrothermal site). It is worth noting that the $\delta^{13}C(CO_2)$ and $\delta^{13}C(CH_4)$ values of the Forecast vent fluid (-1‰ and -11‰) are almost equal to those of the Suiyo Seamount fluid, significantly higher than those of the backarc and mid-oceanic ridge hydrothermal fluids (Tsunogai et al., 1994; Tsunogai, 1995).

Tsunogai (1995) stated that the high $\delta^{13}C(CO_2)$ and $\delta^{13}C(CH_4)$ values should be explained not by either sedimentary and crustal contribution or secondary fractionation processes, but by original characteristics of the source magma itself, several percent of which might be the subducting slab material. This explanation is consistent with the fact that the $^3He/^4He$ ratio of the Forecast vent field as well as that of the Suiyo seamount is almost the same as those observed at mid-oceanic ridges (Tsunogai, 1995).

Acknowledgements. We thank the shipboard scientific parties of the 1992 and 1993 cruises of *Yokosuka*, *Shinkai 6500* operation team, crew of *Yokosuka* for their invaluable collaboration. Useful advice and information from Drs. H. Hotta and K. Fujioka (JAMSTEC) are sincerely acknowledged. This study was financially supported by funds from Ministry of Education, Science, Sports and Culture of Japan, and from the Science and Technology Agency of Japan.

References

Baker, E.T., G.J. Massoth and R.A. Feely, Cataclysmic hydrothermal venting on the Juan de Fuca Ridge, *Nature, 329*, 149-151, 1987.

Campbell, A.C., J.M. Edmond, D. Colodner, M.R. Palmer and K.K. Falkner, 1987, Chemistry of hydrothermal fluids from the Mariana Trough back arc basin in comparison to mid-ocean ridge fluids. *EOS Trans. AGU, 68(44)*, 1531, 1987 (abstract).

Craig, H., Y. Horibe, K.A. Farley, J.A. Welhan, K-R. Kim and R.N. Hey, Hydrothermal vents in the Mariana Trough: Results of the first Alvin dives. *EOS Trans. AGU, 68(44)*, 1531, 1987 (abstract).

Craig, H., Y. Horibe, & K.A. Farley, Hydrothermal fluids from the Mariana Trough: results of the first Alvin dives, *Annual meeting of the Geochemical Society of Japan*, 2A11, 1988 (abstract).

Fryer, P., The relationship between tectonic deformation, volcanism, and fluid venting in the southwestern Mariana convergent plate margin, *Proc. JAMSTEC Symp. Deep Sea Res., 9*, 161-179, 1993.

Fryer, P., H. Fujimoto, M. Sekine, L. Johnson, J.

Kasahara, H. Masuda, T. Gamo, T. Ishii, M. Ariyoshi, & K. Fujioka, Lost volcanoes of the southwestern Mariana Island Arc: New swath-mapping and geochemical studies of the extension of the Mariana active island arc, *J. Geophys. Res.*, submitted.

Gamo, T. and the shipboard scientific party of the Y9204 cruise, Revisits to the mid-Mariana Trough hydrothermal site and discovery of new venting in the southern Mariana region by the Japanese submersible Shinkai 6500, *InterRidge News, 2*, 11-14, 1993.

Gamo, T., H. Chiba, P. Fryer, J. Ishibashi, T. Ishii, L.E. Johnson, K. Kelly, H. Masuda, S. Ohta, A-L. Reysenbach, P.A. Rona, T. Shibata, J. Tamaoka, H. Tanaka, U. Tsunogai, T. Yamaguchi, and K. Fujioka, Mariana 1992 diving survey by "Shinkai 6500" (Y9204 cruise): revisits to the mid-Mariana hydrothermal area and discovery of hydrothermal vents in the southern Mariana region, *JAMSTEC J. Deep Sea Res., 10*, 154-162, 1994 (in Japanese with English abstract).

Gamo, T., Wide variation of chemical characteristics of submarine hydrothermal fluids due to secondary modification processes after high temperature water-rock interaction: a review, in *Biogeochemical Processes and Ocean Flux in the Western Pacific* (H. Sakai & Y. Nozaki, eds.), TERRAPUB, Tokyo, pp. 425-451, 1995.

Haymon, R.M. D.J. Fornari, K.L. Von Damm, M.D. Lilley, M.R. Perfit, J.M. Edmond, W.C. Shanks,III, R.A. Lutz, J.M. Grebmeier, S. Carbotte, D. Wright, E. McLaughlin, M. Smith, N. Beedle, and E. Olson, Volcanic eruption of the mid-ocean ridge along the East Pacific Rise crest at 9°45-52'N: Direct submersible observations of seafloor phenomena associated with an eruption event in April, 1991, *Earth Planet. Sci. Lett., 119*, 85-101, 1993.

Hessler, R., P. Lonsdale and J. Hawkins, Patterns on the ocean floor, *New Scientist, 24(March)*, 47-51, 1988.

Horibe, Y., K.-R. Kim and H. Craig, Hydrothermal methane plumes in the Mariana back-arc spreading centre, *Nature, 324*, 131-133, 1986.

Hussong, D.M. & S. Uyeda, Tectonic processes and the history of the Mariana arc: A synthesis of the results of Deep Sea Drilling Project Leg 60, in *Init. Repts. DSDP, 60 (D.M. Hussong, S. Uyeda et al. eds.)*, Deep Sea Drilling Project , Washington D.C., pp. 909-929, 1981.

Ishibashi, J. and T. Urabe, Hydrothermal activity related to arc-backarc magmatism in the western Pacific, in *Backarc Basins: Tectonics and Magmatism*, ed by B. Taylor, Plenum Press, New York & London, pp. 451-495, 1995.

Ishibashi, J., Y. Sano, H. Wakita, T. Gamo, M. Tsutsumi, and H. Sakai, Helium and carbon geochemistry of hydrothermal fluids from the Mid-Okinawa Trough Back Arc Basin, southwest of Japan, *Chem. Geol., 123*, 1-15, 1995.

Johnson, L., P. Fryer, H. Masuda, T. Ishii & T. Gamo, Hydrothermal vent depossits and two magma sources for volcanoes near 13°20'N in the Mariana backarc: a view from Shinkai 6500, *EOS Trans. AGU, 74(43)*, Fall Meet. Suppl., 681, 1993 (abstract).

Kase, K., T. Shibata, & T. Gamo, Mineralogy and ore texture of the hydrothermal sulfide-sulfate chimney near 18oN, Mariana Trough, *JAMSTEC J. Deep Sea Res., 10*, 195-201, 1994 (in Japanese with English abstract).

Lupton, J.E., E.T. Baker and G.J. Massoth, Variable 3He/heat ratios in submarine hydrothermal systems: evidence from two plumes over the Juan de Fuca ridge, *Nature, 337*, 161-164, 1989.

Palmer, M.R., Boron isotope systematics of hydrothermal fluids and tourmalines: a synthesis, *Chem. Geol.(Isotope Geosci.), 94*, 111-121, 1991.

Rona, P.A. and D.A. Trivett, Discrete and diffuse heat transfer at ASHES vent field, Axial Volcano, Juan de Fuca Ridge, *Earth Planet. Sci. Lett., 109*, 57-71, 1992.

Sakai, H., M. Yamano, T. Tanaka, T. Gamo, E-S. Kim, J. Ishibashi, K. Shitashima, T. Matsumoto, T. Oomori, F. Yanagisawa and M. Tsutsumi, Geochemical studies of the hydrothermal system at the Izena Cauldron using "Shinkai 2000"---Reports on dive numbers 413 and 415, and on the liquid CO2 bubbles and hydrate collected during dive number 424, *JAMSTEC Tech. Rept. Deepsea Res., 6*, 69-85, 1990 (in Japanese, with English abstract).

Tsunogai, U., J. Ishibashi, H. Wakita, H. Masuda, T. Gamo, & K. Fujioka, Geochemical features of the southern Mariana Trough region as revealed by dissolved chemical composition of hydrothermal fluids, Japan Earth and Planetary Sciences Joint Meeting, H31-01, 1994 (abstract).

Tsunogai, Geochemical studies of migration process and source of fluids in the crust, Ph D. Thesis, University of Tokyo, 116pp., 1995.

T. Gamo, Ocean Research Institute,University of Tokyo, 1-15-1 Minamidai, Nakano-ku, Tokyo 164, Japan (e-mail: gamo@ori.u-tokyo.ac.jp)

U. Tsunogai, Institute for Hydrospheric-Atmospheric Sciences, Nagoya University, Furocho, Chikusa-ku, Nagoya 464-01, Japan (urumu@ihas.nagoya-u.ac.jp)

J. Ishibashi, Laboratory for Earthquake Chemistry, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan (ishi@eqchem.s.u-tokyo.ac.jp)

H. Masuda, Department of Geosciences, Osaka City University, 3-3-138, Sugimoto, Sumiyoshi-ku, Osaka 558, Japan (harue@sci.osaka-cu.ac.jp)

H. Chiba, Department of Earth and Planetary Sciences, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka 812, Japan (hchiba@geo.kyushu-u.ac.jp)