Water temperature variation and thermal conductivity in the Kuroshima Knoll area, southwestern part of the Ryukyu Arc

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Abstract The Kuroshima Knoll, located in the southwestern part of the Ryukyu Arc, is one of the best fields for the study of gas hydrate dissociation, because the Pressure-Temperature condition at the top of the knoll is close to the phase boundary between gas and hydrate. In order to understand the geothermal structure around the Kuroshima Knoll, heat flow and thermal conductivity measurements were carried out around the knoll during the R/V "Kaiyo" KY03-09 Cruise. During heat flow measurements we found that the vertical variation of water temperature was as large as 1.2 degC just above the seafloor at Sites A and B on top of the knoll. This can either be temporal or spatial variation, and it disturbs the subbottom temperature field significantly, possibly affecting the state of hydrate. The heat flow value is 42 mW/m^2 and thermal conductivity is 1.0 W/m/K at the Site 2 in the Yaeyama Basin. The thermal conductivity value in the Yaeyama Basin istypical for the ordinary marine sediment. On the other hand, the thermal conductivity is much higher (1.8 Wm^{-1}K^{-1}) at the *Calyptogena* colony site (Site A) on top of the knoll.

Keywords: Kuroshima Knoll, heat flow, thermal conductivity, water temperature, Ryukyu Arc

1. Introduction

Cold seep is one of major phenomena on the seafloor and occurs not only along submarine active faults in accretionary prism but also in shelf-slope area. They are important to evaluate the total flux of methane through the sediment/water interface and to elucidate sub-seafloor fluid circulation. However, the origin of seep fluid, especially in relation to the dissociation of gas hydrate, is still unclear.

The chemosynthetic communities and carbonates at cold seep sites were found on top of the Kuroshima Knoll, which is located about 26 km south of the Ishigaki Island, the southwestern part of the Ryukyu Arc (Fig. 1; Matsumoto et al., 1997, 1999). Previous surveys using HOV "Shinkai 2000" and the ROV "Dolphin-3K" show the detailed distribution of chemosynthetic communities and carbonates on top of the knoll (Fig. 2B; Machiyama et al., 2001a, 2001b, 2003; Shinjo et al., 2001). Furthermore, more than 15 methane gas vents accompanied with *Bathymodiolus* colony were found at this site (Fig. 2B; Machiyama et al., 2001b). The carbon and oxygen isotopic study of these carbonates suggests that the methane dissociated from gas hydrates is involved in the formation of cold seep (Takeuchi et al., 2001, 2003).

Gas hydrate is one of the clathlates, and naturally exists as a solid comprised of water molecules forming a rigid lattice of cages, containing a molecule of natural gas, mainly methane (e.g., Kvenvolden, 1988, 1993, 2000). The oceanic gas hydrate is estimated to occupy more than one quarter amount of the dissolved carbon in the ocean (e.g., Matsumoto, 1995). One volume of methane hydrate has about 175 volumes of methane gas under a standard condition, and methane hydrate is easily dissociated by a pressure reduction or a temperature rise. Gas hydrate, therefore, impacts on the earth system such as a global environmental change and carbon cycle, as an unstable carbon reservoir (e.g., Matsumoto, 1995; Kennet et al., 2000, 2003).

The Kuroshima Knoll is one of the best fields for the study of gas hydrate dissociation, because the P-T condition on top of the knoll is close to the phase boundary between gas and hydrate. This data report provides the results of water temperature and thermal conductivity measurements around the Kuroshima Knoll (Fig. 2; Table 1). The heat flow measurement has never been carried out in the Ryukyu Arc, except in the hydrothermal area of the Okinawa Trough (e.g., Yamano et al., 1988). Piston coring and heat flow surveys were carried out as a part of R/V "Kaiyo" KY03-09 Cruise. The objectives of this cruise are; 1) acquisition of geochemical data in the cold seep area, 2) acquisition of heat flow data for understanding the geothermal structure around the knoll, and 3) paleoenvironmental reconstruction around the knoll. The outline of this cruise was presented by Machiyama et al. (2004).

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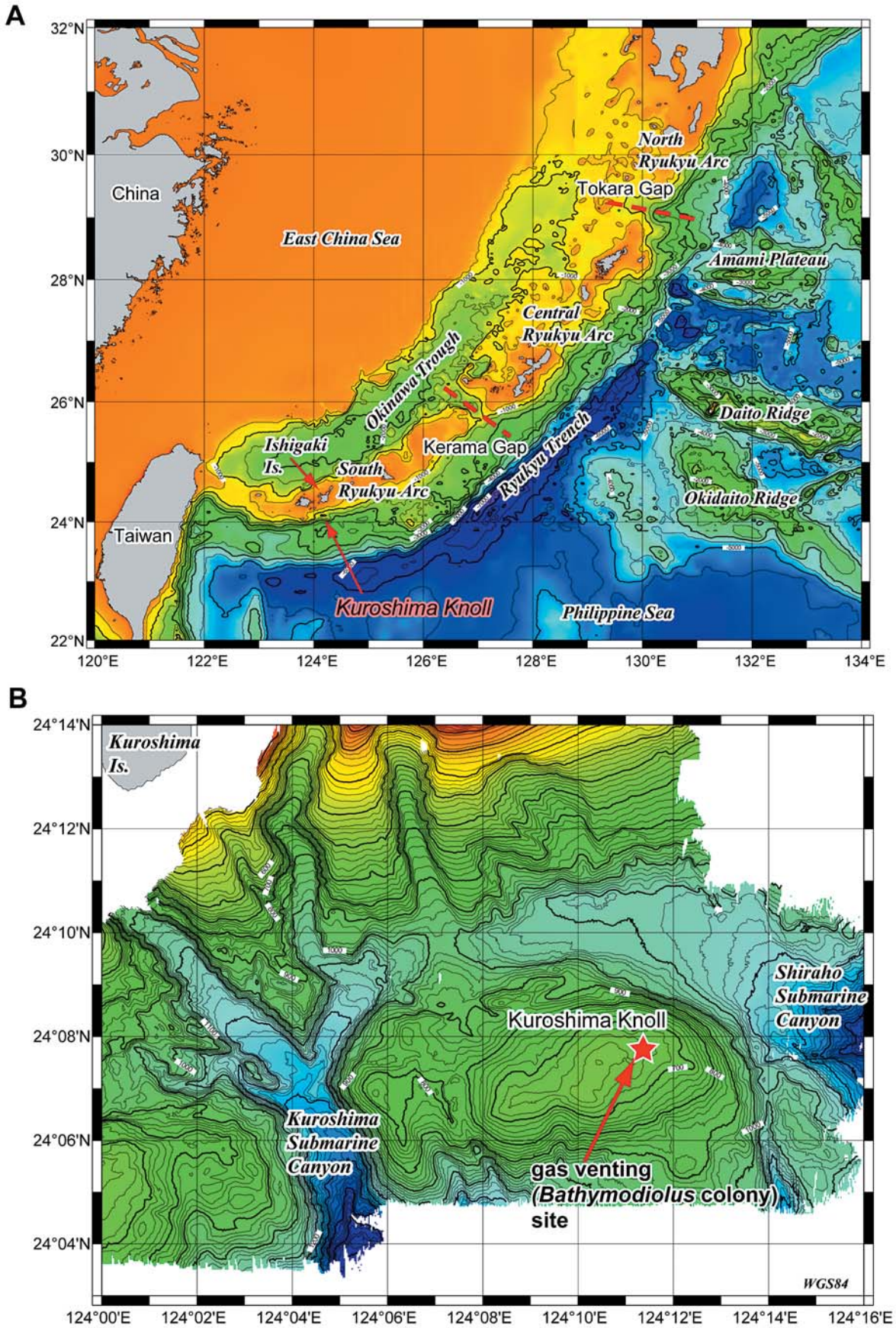

Figure 1: Location map of the Kuroshima Knoll. **A**. Geologic setting of the Ryukyu Arc. The Ryukyu Arc is divided into three segments by two tectonic lines, called the Tokara Gap and the Kerama Gap, respectively. **B**. Locality of the gas venting site on the top of the knoll. Bathymetric data taken from the NT04-03 Cruise.

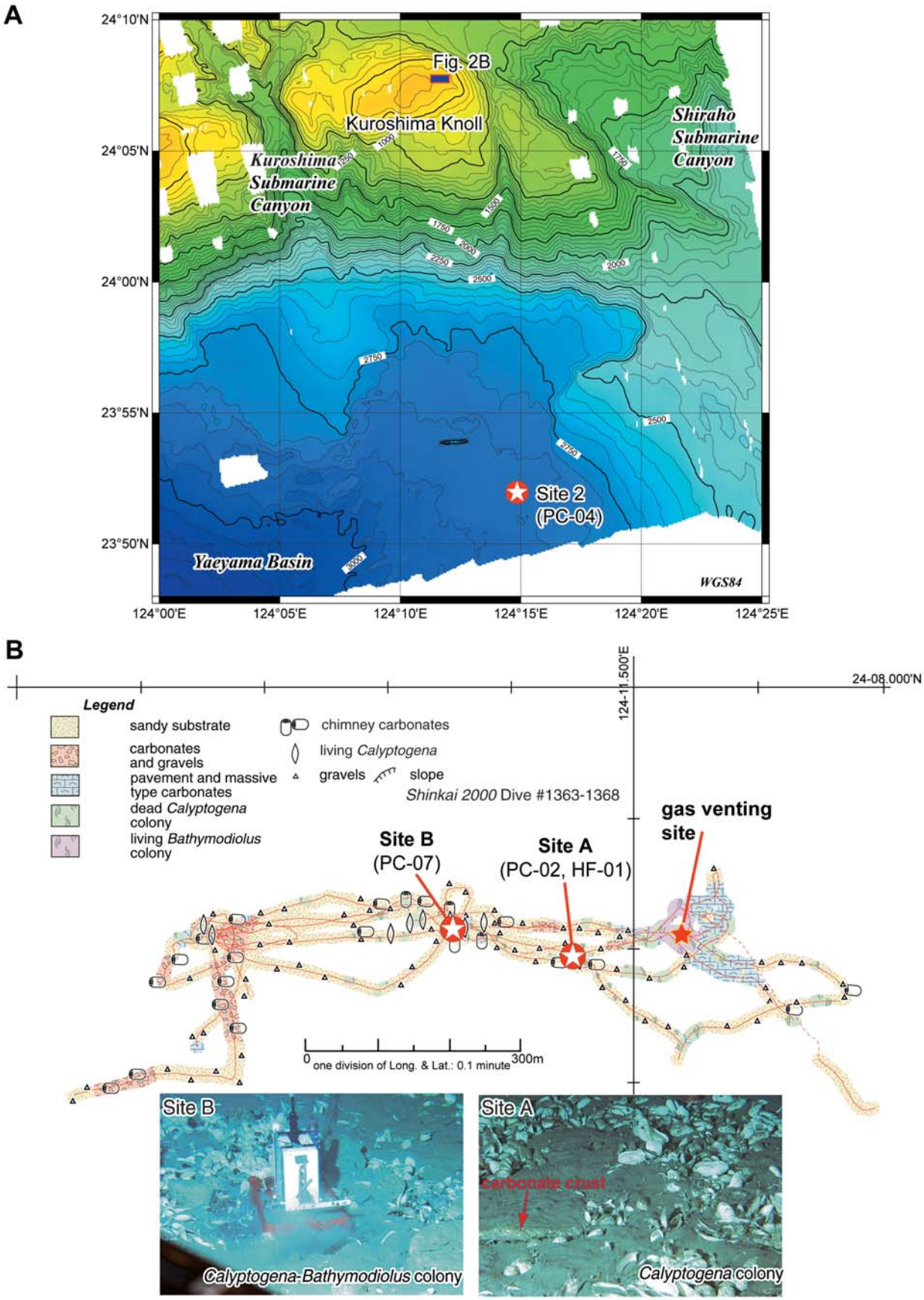

Figure 2: Location map of the piston coring and heat flow measurement sites around the Kuroshima Knoll. **A**. Site 2 (PC-04) is in the northeastern part of the Yaeyama Basin. Bathymetric data taken from the KY02-01 Cruise. **B**. Geologic route map around the cold seep sites on the top of the knoll. Sites A (PC-02) and B (PC-07) are in the westward of the gas venting site. Modified from Machiyama et al. (2003).

Table 1: Operation summary of piston coring/heat flow measurement.

No.	Date/Time	Location		Depth (m)	Recovery		Operation
		Latitude	Longitude		Location	(cm)	
HF-01	Aug. 24, 09:43	24° 07.80 N	124° 11.45 E	645	Site A	unknown	Heat flow measurement
PC-02	Aug. 24, 15:05	24° 07.81 N	124° 11.45 E	645	Site A	222.5	Piston coring
PC-04	Aug. 25, 08:15	23° 51.98 N	124° 14.96 E	2,857	Site 2	325.5	Piston coring with heat flow measurement
PC-07	Aug. 25, 17:41	24° 07.82 N	124° 11.36 E	649	Site B	379.9	Piston coring

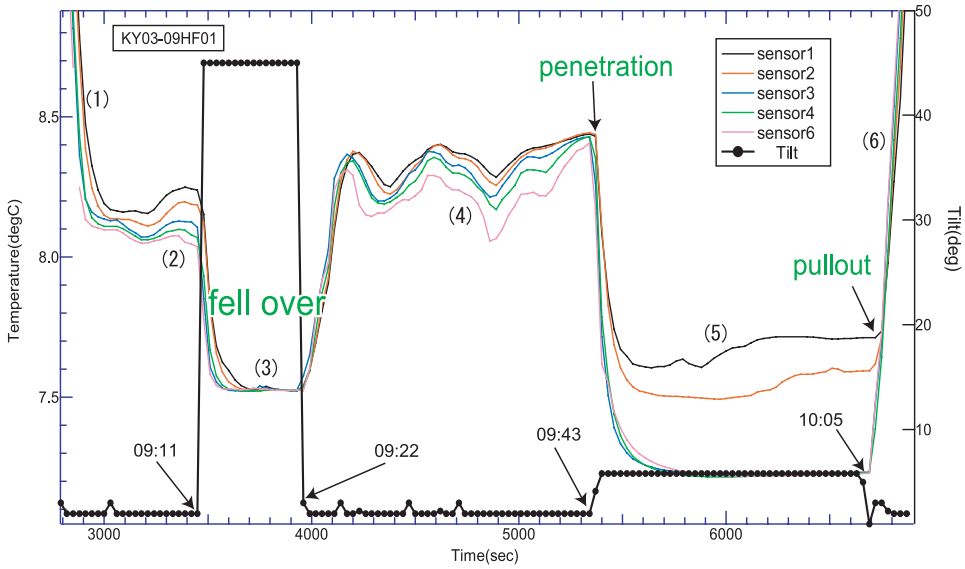

Figure 3: The temperature and tilt profile of HF-01 (Site A). Tilt data shows the inclination of data logger of the heat flow meter from vertical position.

2. Geologic setting of the Kuroshima Knoll

The Kuroshima Knoll is a small isolated knoll, which is separated by the Kuroshima Submarine Canyon to the west and the Shiraho Submarine Canyon to the east and to the north (Fig. 1B). The southern slope of the knoll continues into the Yaeyama Basin, which reaches the water depth of more than 3000 m (Fig. 2A). The flat top of the knoll ranges from 630 to 800 m in depth.

The lithified to semi-lithified sandstone and mudstone of the Shimajiri Group are exposed on top of the knoll. Calcareous nannofossils from these strata show 1.0 to 1.5 million years (Ma) in age (Matsumoto et al., 1999), and can chronologically correlate to the Chinen Formation in the Okinawa Island (Nakagawa et al., 2001; Sato et al., 2004). The Shimajiri Group is overlain by younger calcareous sediments, such as muddy sand (unlithified foraminiferal packstone) and gravels (e.g., Matsumoto et al., 1999; Machiyama et al., 2001a; 2004).

The chemosynthetic communities, including *Calyptogena*, *Bathymodiolus*, and bacterial mats, and cold seep carbonates has been discovered in the north-eastern part of the knoll (e.g., Matsumoto et al., 1999; Machiyama et al., 2001a; Okutani et al., 2004). Small *Calyptogena* colonies, vast numbers of dead *Calyptogena* shells, and a large *Bathymodiolus* colony accompanied with methane gas venting, extend in the eastern to the western direction. Carbonates of cold-seep

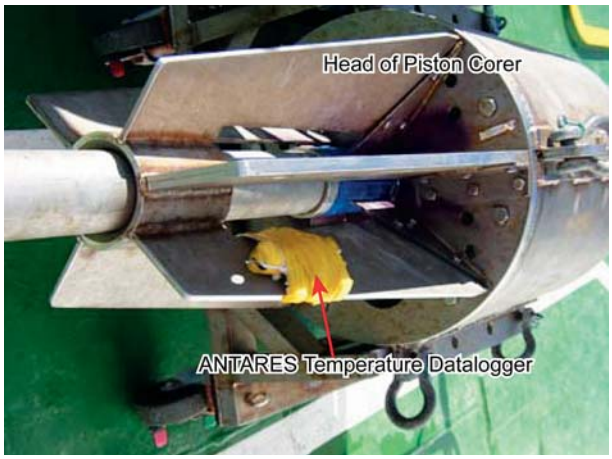

Figure 4: ANTARES Temperature Datalogger and head of Piston Corer.

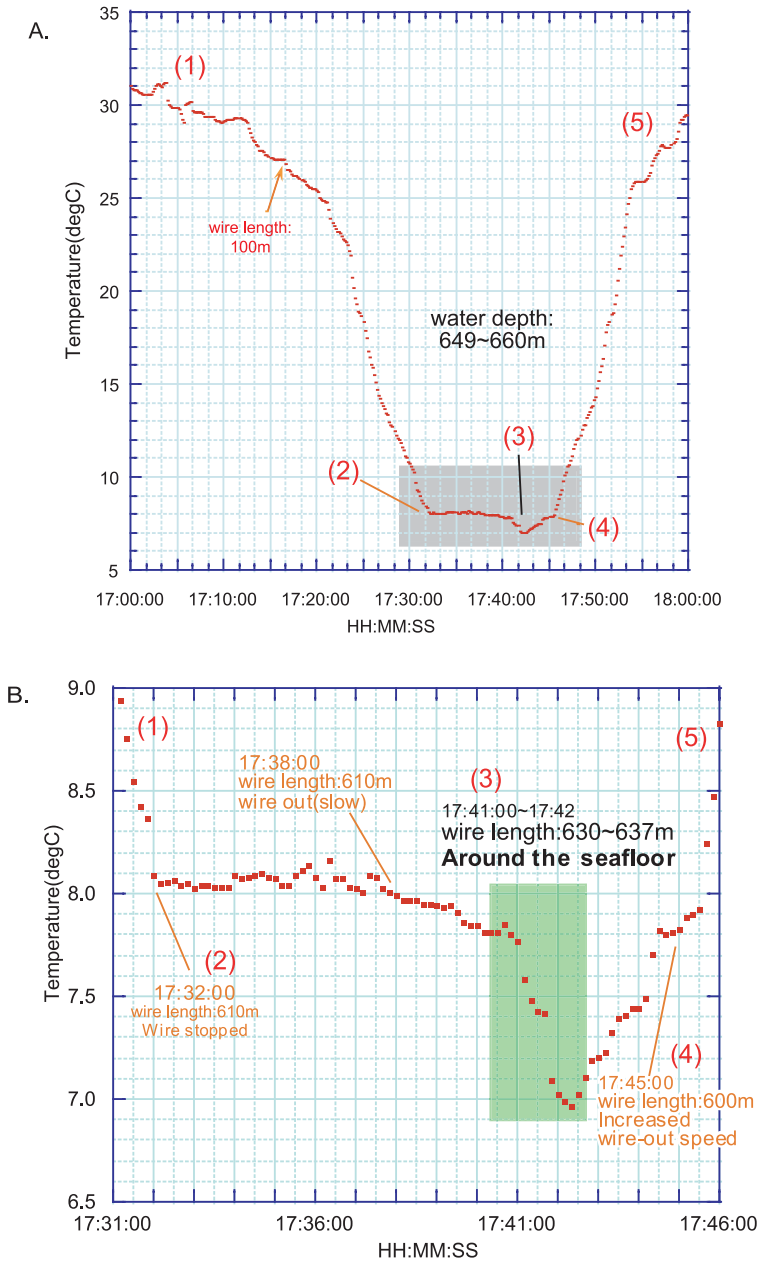

Figure 5: The temperature profile of PC-07 (Site B). **A**. All record of the water temperature. The area of gray-colored square is expanded in Fig. 5B. **B**. Water temperature profile around the penetration of the piston corer.

origin, such as chimneys, nodules, and pavements, are also distributed in E-W direction. Furthermore, distribution of the cracks, brecciated basement rocks, pockmark-like hollows, and undulating seafloor is consistent with the distribution of seeps and carbonates (e.g., Machiyama et al., 2001b). The single-channel seismic profiles show that many fractures and probable small gas reservoir are present just beneath the methane gas venting site (Machiyama et al., unpub. data). Thus, the venting methane gas is interpreted to migrate upward along the fractures from the gas reservoir.

3. Water temperature on top of the Kuroshima Knoll

In order to understand the geothermal structure of the Kuroshima Knoll, heat flow measurement (HF-01) was carried out at Site A (*Calyptogena* colony site) on top of the knoll during the KY03-09 Cruise (Fig. 2B). However, we could not get reliable heat flow value due to the vertical water temperature difference of 1.2 degC within ~30 m just above Site A ("Penetration" in Fig. 3; Machiyama et al., 2004). In order to verify the temperature variation just above the seafloor, water temperature measurement was carried out at Site B during the PC-07

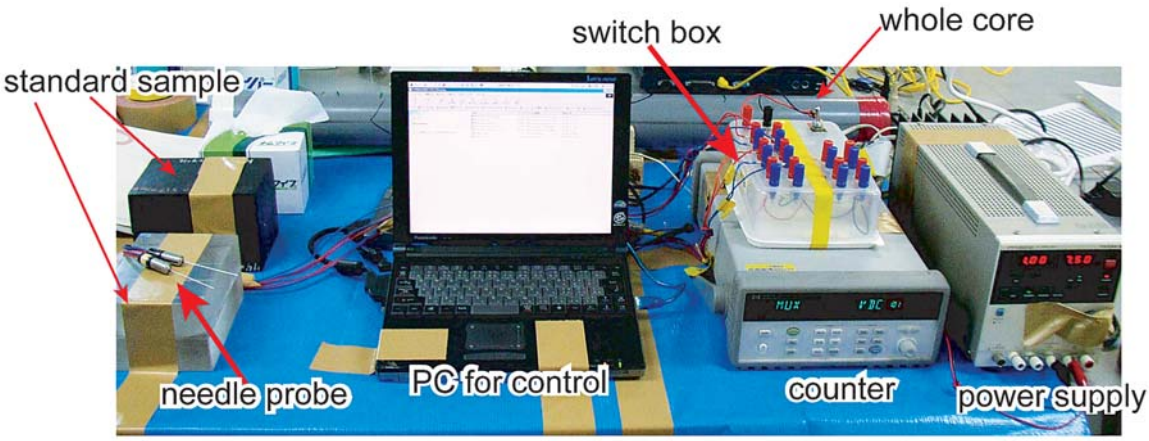

Figure 6: Instruments for needle probe method.

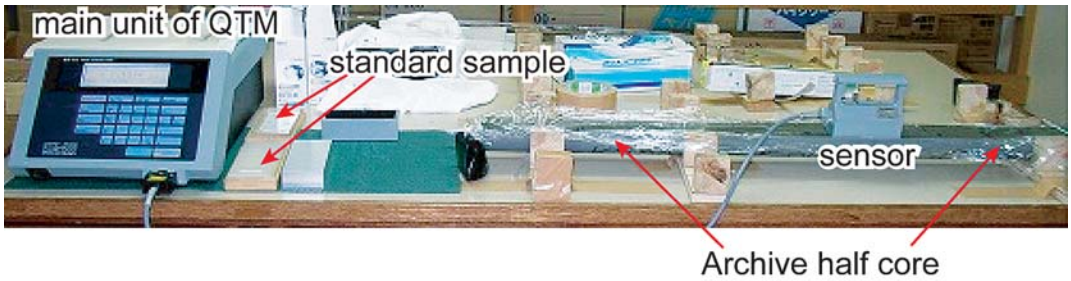

Figure 7: Instruments for QTM method.

operation. We used ANTARES Temperature Datalogger (manufactured by ANTARES Datensysteme GmbH), which was attached at the head of the piton corer (Fig. 4).

The operation of PC-07 was as follows. The water temperature record is shown in Figs. 5A and 5B.

1) 17:06: Piston corer landed on water: (1) of Fig. 5A
2) 17:32: Wire was stopped: (2) of Figs. 5A and 5B
3) 17:41: Landed on the seafloor and got coring sample: (3) of Figs. 5A and 5B
   17:42: Left the seafloor: (3) of Fig. 5A
4) 17:42: Take up the piston corer slowly: (4) of Fig. 5A
5) 17:45: Wind the wire speedily: (5) of Fig. 5A

Temperature decrease by 0.2-0.3 K is recognized between (2) and (3) in Fig. 5B. The temperature decreases by 1K at (3) (Fig. 5B The temperature increases 1K during (4). Then depth variation is 6m at (3) and 30m at (4). Maximum temperature difference reaches 1.2K for 30 m from (2) to (3) (Fig. 5B).

Temperature records from both HF01 and PC07 sites show a sudden temperature decrease of ~1degC within 10-30m above seafloor. However, we cannot define clearly the temperature profile or temporal variation above seafloor, either because there is a difference in the operation method between heat flow and piston coring, or because the time stamp for wire length log may be shifted from that of temperature data logger. More measurements with detailed observation logs are needed to clarify the geothermal structure around the Kuroshima Knoll in the future.

4. Measurement of thermal conductivity and heat flow

4.1 Measurement of thermal conductivity

During the KY03-09 cruise, we measured thermal conductivity for PC-02 (Site A) and PC-04 (Site 2) cores in the laboratory onboard. The coring sites are shown in Fig. 2. The PC-02 and PC-04 cores were measured by the Quick Thermal Conductivity Meter (QTM), and the PC-04 core was also measured by the needle probe method (Von Herzen and Meazwell, 1959).

The needle probe method is best used for saturated sediment samples (Fig. 6). The needle probe is made from a thermister and heater in metal pipe that has enough length for external diameter (more than 50 times). It is inserted into sediment core sample after its temperature is equilibrated to the surrounding environment. We applied the needle probe method for whole-

Table 2: Thermal conductivity of PC-02 core. The effects of 'flow in' (core disturbance) are shown in the pale green area. Each average is calculated for normal and 'flow-in' data and all data, respectively.

Depth(cm)	TC(W/m/K)		
12.4	1.416		
22.4	1.871		
42.4	1.508		
52.4	1.869		
62.4	1.732		
72.4	1.710		
82.4	1.853		
92.4	2.109		
102.4	2.123		
112.4	2.040	average	1.823
122.4	2.930		
143.2	2.166		
153.2	1.782		
163.2	1.896		
173.2	1.930		
183.2	2.234		
193.2	2.726		
203.2	2.588		
213.2	2.338		
223.2	2.412	average	2.300
		all data average	2.062

Flow in

round core samples whose outer pipe was drilled for probe insertion.

The QTM method is used for archive half core samples (Fig. 7). The flat face of the QTM sensor, on which a thermister and a heater is attached, is brought in tight contact on the cross section of core samples. In both methods, thermal conductivity is determined from the the temperature increase curve while the core sample is continuously heated.

Quartz glass and silicone rubber are used as standard samples for calibration. Then the conductivity is corrected for *in-situ* temperature and pressure is corrected by the formula (Ratcliffe, 1960):

4.2 The results and discussion of thermal conductivity measurement

The results of thermal conductivity measurement are shown in Table 2, Table 3, Fig. 8, and Fig. 9. The average of PC-02 core is 1.82 W/m/K, and the average of PC-04 core is 1.05 W/m/K.

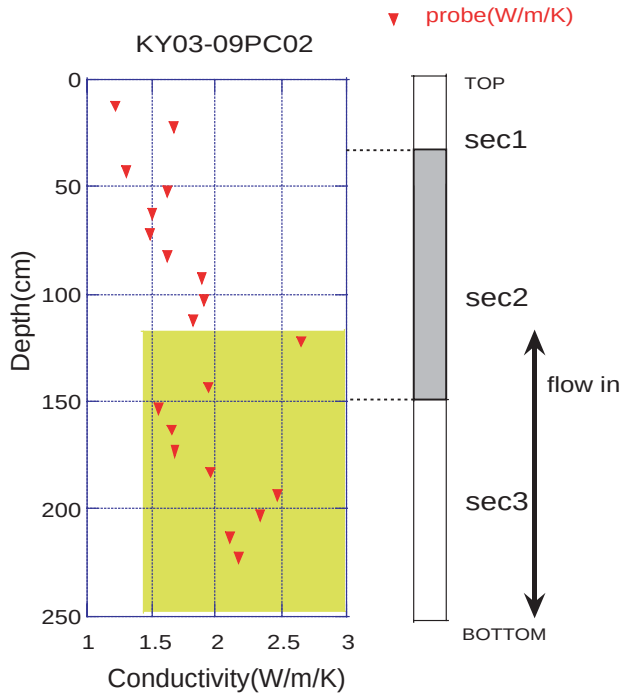

Figure 8: Thermal conductivity of PC-02 core. The effects of 'flow in' (core disturbance) are found in the yellowish green area.

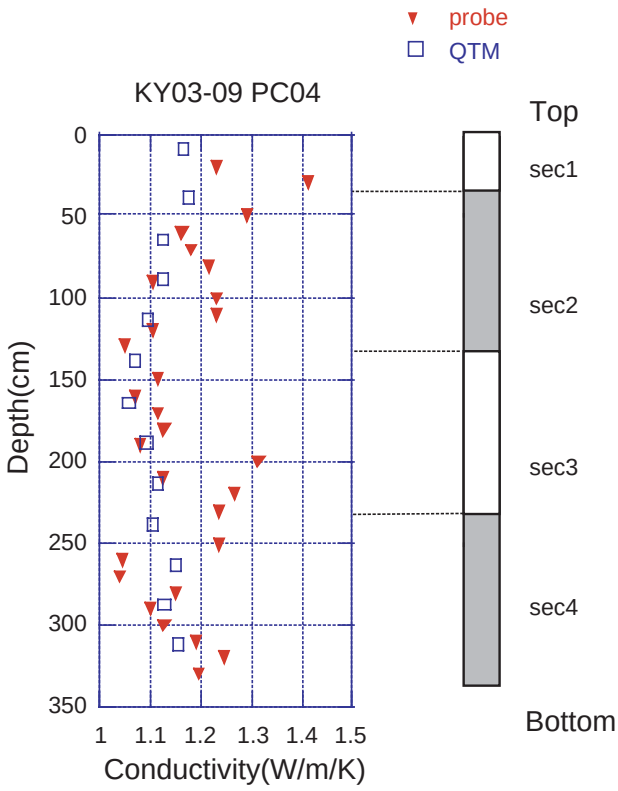

Figure 9: Thermal conductivity of PC-04 core.

Table 3: Thermal conductivity of PC-04 core. Each average is calculated for the QTM method (pale blue area), the needle probe method (pink area), and all data, respectively.

Depth(cm)	probe(W/m/K)	QTM(W/m/K)
330.5	1.0514	
320.5	1.1011	
313.4		1.1101
310.5	1.0521	
300.5	0.99475	
290.5	0.9606	
288.4		1.0816
280.5	1.0084	
270.5	0.91154	
263.4		1.1022
260.5	0.91709	
250.5	1.0925	
238.4		1.0597
230.7	1.0916	
220.7	1.1183	
213.9		1.062
210.7	0.98261	
200.7	1.1661	
190.7	0.94945	
188.9		1.043
180.7	0.99475	
170.7	0.98181	
163.9		1.009
160.7	0.93928	
149.7	0.98458	
138.9		1.0223

Depth(cm)	probe(W/m/K)	QTM(W/m/K)
130	0.91379	
120	0.96732	
113.9		1.0483
110	1.0897	
100	1.0858	
90	0.96979	
88.9		1.0779
80	1.0752	
70	1.041	
63.9		1.0769
60	1.0262	
49	1.1464	
38.9		1.1288
29.5	1.2608	
19.5	1.09	
8.9		1.1174

average	1.025113	1.072246
all data average		1.04868

Thermal conductivity of PC-02 core shows very high value as muddy sediments (Table 2 and Fig. 8). The total average value is 2.06 W/m/K. This value is not true because PC-02 core was disturbed by a ‘flow-in’ in the lower part of the core (Fig. 8). Thus, the thermal conductivity value in the ‘flow-in’ part of the PC-02 core is not used for consideration. On the other hand, the value of PC-04 core in the Yaeyama Basin (Table 3 and Fig. 9) is similar to that of the Nankai Trough sediments (Yamano et al, 1992). It is considered that the high value in the PC-02 core is probably due to diagenesis of the sediment, because the PC-02 core sample is older than that of PC-04. Furthermore, the value of the thermal conductivity tends to concentrate on the each stratigraphic horizon (see Figs. 8 and 9). This is interpreted as a sedimentological effect, such as the difference of lithology and physical properties.

The thermal conductivity data varies between the needle probe and QTM method (Fig. 9). This is possibly caused by the difference of analytical method. The heat source in the needle probe method conducts the surrounding sample of the needle, but the heat source of QTM method conducts only the face of the sample. In the measurement of needle probe method, for example, a void of sediment in the core cannot be recognized before the measurement, because of whole core samples. On the other hand, the QTM method can check the condition of split core face. From the above point of view, the disturbed core never been measured by the QTM method. This is possibly the cause of the different thermal conductivity value at the same depth (Fig. 9).

4.3 Heat flow value in the Yaeyama Basin

During the KY03-09 cruise, we measured thermal gradient in the Yaeyama Basin (Machiyama et al, 2004). Therefore, we estimate that the heat flow value in the basin is about 42 mW/m^2, from the thermal gradient and the thermal conductivity data. This low heat flow value may result from the age of the Philippine Sea Plate, though we could not get another heat flow data in this area. Many data are needed to reveal the thermal structure around this area.

5. Summary

Heat flow and thermal conductivity measurements were carried out around the knoll during the R/V "Kaiyo" KY03-09 Cruise on the Kuroshima Knoll. We found that the vertical variation of water temperature was as large as 1.2 degC just above the seafloor at Sites A and B on top of the knoll. This can either be temporal or spatial variation, and it disturbs the subbottom temperature field significantly. The thermal conductivity is anomalously high (1.8 Wm^{-1}K^{-1}) at the *Calyptogena* colony site (Site A) on top of the knoll.

More geothermal measurements are needed to clarify the geothermal structure around the Kuroshima Knoll in the future.

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