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Description and environmental monitoring of Hokkai Cave in northern Japan.

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Abstract: Hokkai Cave was discovered in 2006 in southwestern Hokkaido, northern Japan, and has been conserved in its natural condition. This paper reports the results of a basic speleological study of the cave's environment conducted during 2006–2009, including a geomorphological survey, monitoring of cave air temperature, airflow and groundwater currents, and an initial interpretation of the cave's speleogenesis. These basic cave data are important to help improve palaeoclimatic speleothem sample selection, because speleothem geochemistry is also controlled by cave geometry and micro-meteorology. Hokkai Cave is a 479.8m-long, zigzag, horizontal system, with two entrances. The cave floor is mainly covered with clay, gravels and breakdown blocks. An underground river flows in the centre of the cave and a dry riverbed, and many springs and dolines are present around the cave. Pure white stalagmites in the cave are possibly suitable for use in Asian Summer Monsoon reconstruction studies. Air temperature in the inner cave (>15m from entrances) was stable throughout the year (7.5–7.7°C); in contrast, air temperature near the entrance was variable because of the influence of the outside air temperature. Inversion of airflow direction is driven by the air temperature gradient between the inside and the outside of the cave. When air temperature inside is warmer than outside, air flows from Ent.U (upper) to Ent. L (lower) and from Ent.U to the inside. When air temperature outside is warmer than inside, air flows from Ent. L to Ent.U and from the inner cave to Ent.U. These results agree with findings from previous studies. Inversion of airflow direction also affects the variation pattern of air temperature near the entrances. Monitoring also indicates that the underground river is usually dry except after heavy rainfall or snow melting.

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Hokkai Cave is a limestone cave that was discovered in June 2006 in southwestern Hokkaido, northern Japan. About 20% of the planet's dry ice-free area is occupied by karst landscapes (Ford and Williams, 2007), whereas only 0.44% of the volcanic islands of Japan are karstic rocks. Well-developed karst landforms include the Akiyosi-dai and Hirao-dai plateaus in western Japan, and caves up to 20km long occur in northern Japan (Akka Cave) and in the Southwestern Islands (Oyama-Suikyo Cave) (Mizusima and Kamiya, 1987; Sato *et al.,* 2004). Although Hokkai Cave is smaller than those caves, its discovery is important because few limestone caves have been discovered on Hokkaido Island (Kusaka *et al.,* 1996; Tajika, 1989, 2000).

Some caves that have a stable temperature and high humidity are noted for their peculiar ecosystems (Moore and Sullivan, 1978), other caves provide a regional water resource (Ford and Williams, 2007) or are important tourist attractions with beautiful speleothems (Cigna, 2005). Chemical analyses of speleothems are increasingly used in producing palaeoclimate reconstructions (McDermott *et al.,* 2004; Fleitmann *et al.,* 2006; Zhang *et al.,* 2008; Lachniet *et al.,* 2009; Jex *et al.,* 2010; Watanabe *et al.,* 2010; McDermott *et al.,* 2011; Fairchild and Baker, 2012). Therefore, caves should be protected as a valuable part of the natural heritage, and this necessitates comprehending individual cave conditions (e.g. geomorphology, meteorology and hydrology). In this study of Hokkai Cave, we report the results of a geomorphological survey and environmental monitoring of the cave's micro-meteorology and underground river water levels.

Setting of Hokkai Cave

Geology and geomorphology

Hokkai Cave is a limestone cave located about 20km northwest of Hakodate City, close to the Hekirichi River, which flows through the western end of the Hakodate Plain (40° 53′ N, 140° 33′ E) (Fig.1). The limestone outcrop around Hokkai Cave, which is known as the Kamiiso Limestone Bed, has width, length and thickness estimated at about 4km, 6km and 400m respectively, and is the largest limestone area in Hokkaido (Limestone Association of Japan, 1990).

Gorge-like valleys formed by river erosion occur around the cave's location, and several springs emerge from the limestone walls (Fig.2a). Small dolines up to several metres in diameter are observed on the mountain slope above the cave (Fig.2b). Having previously flowed into the Hekirichi River downstream of the cave entrance, the Kamanosenkyo River now sinks, leaving a dry riverbed starting at about 200m a.s.l. (Fig.2.c). A large meander of the Hekirichi River passes close to the cave and the Flat Plain "f", which is considered to be part of an old riverbed of the Hekirichi River, is preserved in the core of this major meander (Fig.1b).

The age of the Kamiiso Limestone was estimated to be late Jurassic by Mitani *et al.* (1966) on the basis of the presence of calcareous algae fossils *Mesophyllum* sp. However, Sakagami *et al.* (1969) analyzed conodont fossils from the Kamiiso Limestone and estimated its age as being late Triassic.

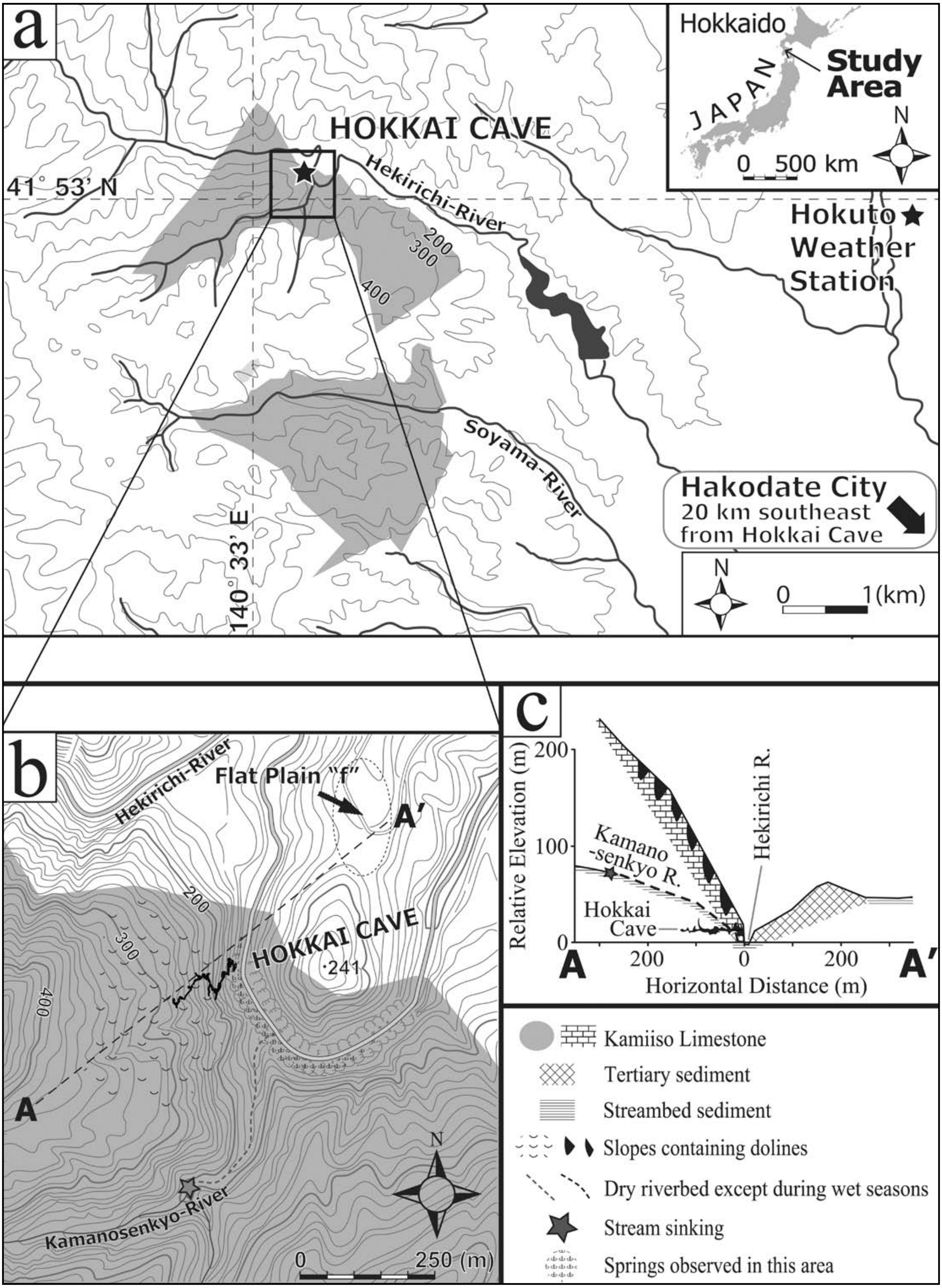

Figure 1: *(a) Regional topographical map of the setting of Hokkai Cave. (b) An enlarged view of the area around Hokkai Cave. The Kamanosenkyo River sinks where shown and the riverbed is dry downstream. Small dolines, springs and Flat Plain "f" which is considered as an ancient riverbed are located around the cave. (c) A cross-section around Hokkai Cave (along the line A–A'). Small dolines and the dry riverbed are located above the cave.*

Figure 2a: *Hekirichi river and springs around the cave.*

Climate

Southwestern Hokkaido lies in the subpolar zone. According to the Japan Meteorological Agency (http://www.data.jma.go.jp/obd/stats/etrn/index.php), at Hakodate city the average temperatures are: annual: 8.8°C; coldest month (January): −2.9°C; warmest month (August) 21.7°C. Average annual precipitation is 1160mm (from 1979 to 2000), with a season of heavy rainfall from July to November, with its peak in September because of the effect of the East Asian Summer Monsoon. Precipitation from December to June is relatively low, with about 60mm of rain or snow per month. In a typical year snowfalls occur between December and March.

Methods and Results

Cave surveying method and results

Hokkai Cave was surveyed, using a clinometer-compass and a fabric tape measure, to BCRA survey grade IV and the resultant survey is shown in Figure 3; passage length is 479.8m and the maximum difference of elevation is 9.8m. The cave is close to horizontal and is separated into a Lower Floor (LF) and an Upper Floor (UF). Relative elevations of the LF lie between 0.0 – 7.0m above the Hekirichi River, whereas the UF has developed between 4.0 – 10.0m above the river, especially between 7.0 – 8.0m, and the two are connected by a single shaft (Fig.3). The cave has two entrances, a the lower one leading into the LF (Ent. L on Figure 3) and an upper one into the UF (Ent. U on Figure 3), which is too small for explorers to enter. Developed mainly along a generally westsouthwesterly trend, in detail the cave displays a zigzag alternation of passages oriented southwest–northeast and southeast–northwest. The total length of the passages for each direction, and the dominant corridor directions, are NE–SW (30–50°), NNW–SSE (320–340°) and N–S (350–20°) as shown in Figure 4.

The cave walls are generally smooth, although they are rough and fragmented within Section Z (Fig.3), possibly as a result of frost action. Scallops are developed in sections B and G. Sections B and H to J are bore passages with circular cross-sections. Sections B, C and G have high ceilings because corrosion is well advanced along bedding planes in the limestone. Bed rock is only locally exposed in the cave floor, which is generally covered with clay or gravel. Coarse gravels, all composed of limestone fragments, cover the floors of sections Z, A, C, D, E and G; clasts are relatively small (averaging 20−50cm) in sections Z and A, whereas many blocks (> 1.0m) exist in sections C, D, F and G. Clay deposits are present throughout the cave and the floors of sections H, I and J are entirely clay covered. Allochthonous rounded gravels (< 3cm) are observed beneath the clay layer in sections B and I (Fig.2d). A layer of alternating sand and clay is observed in the walls of Section G. Bat guano deposits occur in sections A to F, and are especially thick in Section A.

Figure 2b: *A small doline above the cave.*

Figure 2c: *Dry riverbed in the Kamanosenkyo river.*

An underground river flows from northwest to southeast in Section G (Figs 2e and 3). The water level of the river was logged by an S&DL-mini 4800 (OYO Corporation) water-level logger. Seasonal variation of water level of the underground river is shown in Figure 5; the riverbed is commonly dry and only ten discharge events are recorded. Water levels were relatively high during two periods, from April to May and from August to September. An underground pond forms by dripwater accumulation at the boundary between sections I and J.

Figure 2d: *Cross-section of cave sediment in Section I.*

Figure 2e: *An underground river is present around Station 8 (see Figure 3).*

Dripwaters occur throughout the cave except in sections A and Z; drip rates vary from site to site. Speleothems are widespread within the UF in the form of flowstones, soda straws, curtains, stalactites and stalagmites. Generally the soda straws, curtains and stalagmites are shorter than 10cm but some stalactites exceed 30cm. Speleothems are common in sections A, C, D, E and J, and especially where many soda straws, curtains, stalagmites and flowstones occur in part of Section J (Fig.3). Most of the speleothems are active and wet, but many in Section A near the upper entrance are dry. All speleothems in Section A are pale brown and soiled by clay or guano, and considered as no longer growing, whereas those in the deepest Section J (Figure 2f) are pure white. A cross-section of a stalagmite sampled in Section J is shown in Figure 2g). Thin muddy layers are visible in the outer layers, whereas the inner layers are clean.

Cave monitoring method

HIOKI3641 temperature and humidity loggers and HIOKI3640 temperature loggers (HIOKI E. E. Corporation) were used for monitoring. Air temperature at Station 8 was logged by a temperature logger attached within an S&DL-mini 4800 (OYO Corporation) water level logger. Air temperature was monitored every 30 minutes between 28 September 2007 and 03 May 2009.

Air temperature was monitored at 9 stations (Fig.3). Station 0 was outside the cave, at a height of 1.5m on the left bank of the Hekirichi River, 10m upstream from Hokkai Cave. Stations 1, 2, 3, 5, 6, 7, 8 and 9 (note that there was no Station 4) were in the cave, installed at half the ceiling height where the ceiling height is ≤1.5m, or at 1.0m above the floor where the ceiling height is >1.5m. Because of the local geomorphology, however, Station 6 was installed at 2.0m above the floor.

Airflow was measured twice using the smoke from burning incense sticks, once during the day (11:00) on 02 September 2008 and once at night (24:00) on 29 September 2008. Incense sticks were ignited and the recorded angle (generalized into four angular intervals: 0–30°, 30–60°, 60–90° and 90°) traced by the smoke was taken as an indicator of airflow strength. Airflow current was monitored at narrow points where airflow was relatively strong (Fig.6).

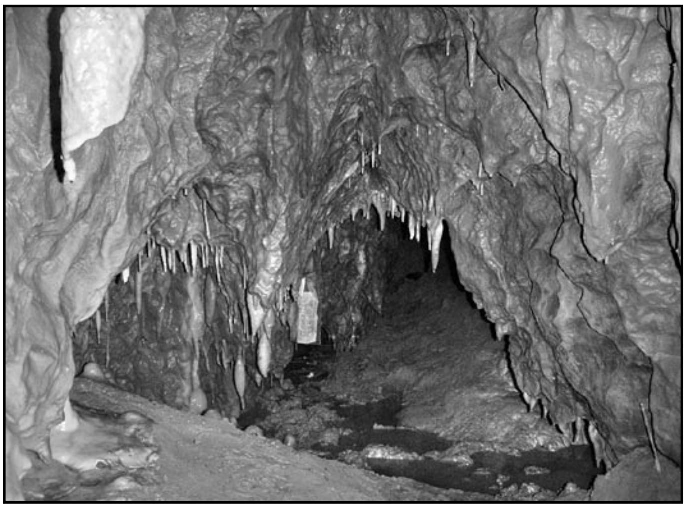

Figure 2f: *Pure white speleothems around Station 9 (see Figure 3).*

Figure 2g: *Cross-section of a stalagmite from close to Station 9 (see Figure 3).*

Result of air temperature monitoring

Seasonal variation of average air temperature (SVAT) and diurnal variation of air temperature (DVT) in the cave are shown in Figure 5. Following sensor breakdown some stations did not record data during specific periods: from 09 December 2007 to 20 March 2008 at stations 0, 1, 2, 3 and 5; from 22 September 2007 to 17 November 2007 at Station 6; after 08 April 2008 at Station 0; after 16 May 2008 at Station 3 and after 10 August 2008 at Station 1. Air temperatures at stations 1, 2 and 3 were re-monitored from 23 November 2008 to 28 May 2009.

Air temperature variation characteristics are summarized as:

(1) At stations 6, 7, 8 and 9, air temperatures were stable; consequently SVAT was very small through the year. The temperature was between 7.5 and 7.7°C at stations 6, 7 and 8, and 7.7 to 7.9°C at Station 9. DVT ranges were also stable (variability <0.1°C) throughout the year.

(2) At stations 1, 2, 3 and 5, air temperatures tended to be higher in summer and lower in winter, and SVAT ranges were variable depending upon the location: 5.8 to 10.5°C at Station 5; −4.6 to 19.0°C at Station 3; −1.6 to 10.8°C at Station 2 and −4.9 to 13.4°C at Station 1. DVT ranges are as follows. At Station 5: within 0.2 to 1.1°C in summer (July to September), and within 0.1°C in other seasons. At Station 3: ranges within 0.2 to 4.8°C, particularly large from September to October and from January to May. Station 2: ranges within 0.5 to 1.5°C, particularly large from late July to September and from November to April, with air temperature dropping to below freezing from late January to early March. Station 1: ranges within 0.2 and 6.1°C, particularly large from October to early November and from late March to May, with air temperature dropping to below freezing from late November to early April.

(3) At Station 0, the DVT was the largest among all the monitoring stations and often exceeded 10°C. Air temperature was lower than that recorded at the HWS, located 25m a.s.l., because Station 0 was located at 120m a.s.l. However, variation trends were similar between the two stations. The SVAT range at the HWS was −9.7 to 24.3°C and the DVT ranges were within 1.6 to 18.6°C.

Figure 2h: *Icicles and ice stalagmites around Station 2 (see Figure 3).*

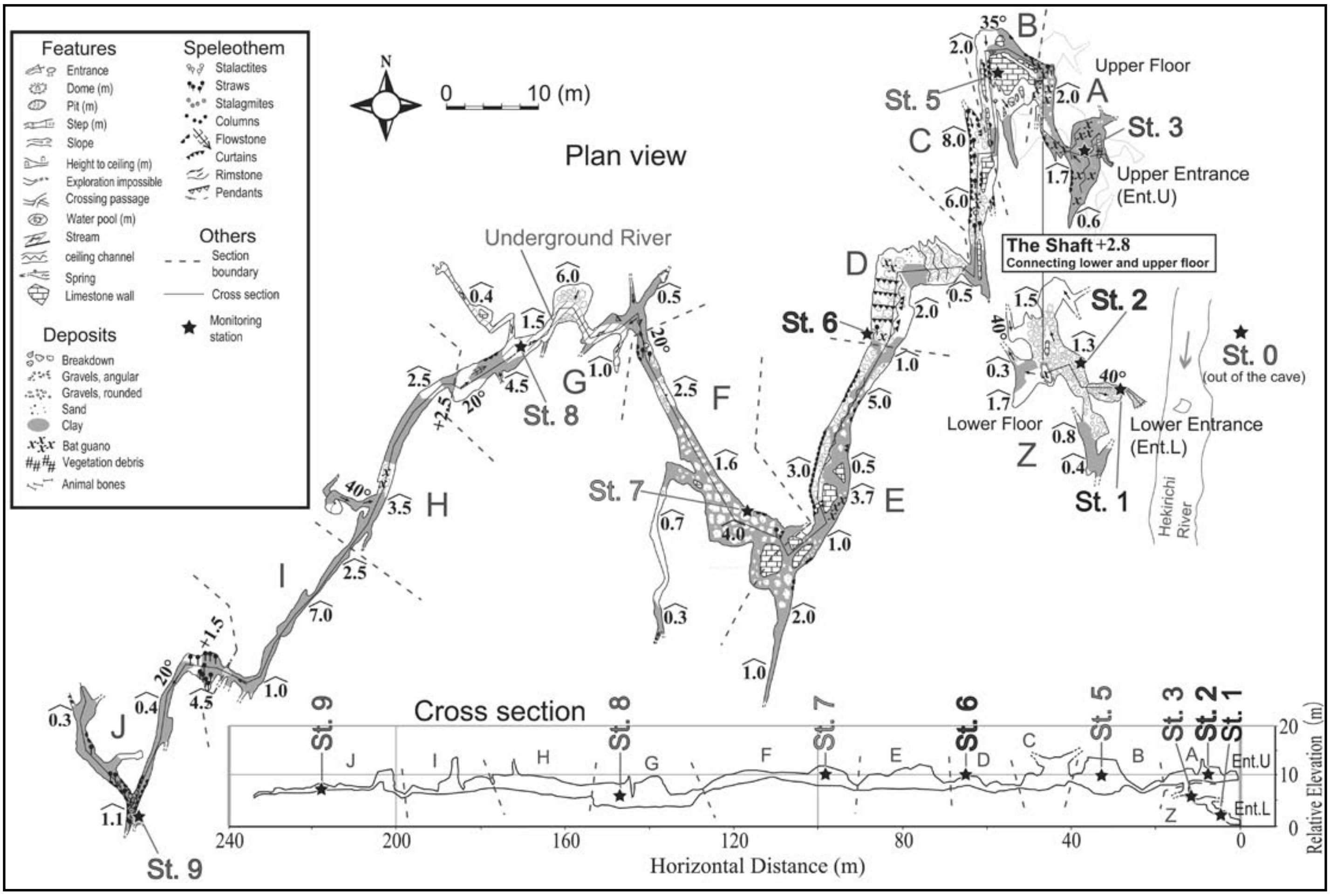

Figure 3: Plan and elevation of the Hokkai Cave showing the location of monitoring stations. The cave has two entrances; upper and lower floor are connected by a shaft. The cave is mostly horizontal, and the cave floor is covered with clay and gravels. An underground river flows in Section G. See text for discussion.

Results of airflow monitoring

Airflow was observed twice (02 and 29 September 2008; Fig.6). During the daytime monitoring (11:00 on 02 September) outside air temperature was 24.5°C. Airflow was observed from the inner cave to Ent. L and from Ent. U to Ent. L. Very strong airflow ($\theta = 90°$, where θ is the angle between the incense smoke and the vertical, which indicates airflow strength) was observed from Ent. U to the lower floor through Station 3 and from Station 2 to Station 1. Overall, airflow was strong ($60° < \theta < 90°$) near the entrances and weak ($0° < \theta < 30°$) in the inner cave. However, strong airflow ($60° < \theta < 90°$) was observed in narrow passages, for instance at the boundaries between sections F and G or sections G and H.

During the night-time monitoring (24:00 on 29 September 2008) outside air temperature was 5.8°C. Air flowed from Ent. L to the inner cave and from Ent. L to Ent. U. Very strong airflow ($\theta = 90°$) was observed around Ent. L, Station 1 and Ent. U, and from the lower floor to the deeper cave. Overall, airflow was strong ($60° < \theta < 90°$) near the entrances and weak ($0° < \theta < 30°$) in inner cave. However, strong airflow ($60° < \theta < 90°$) was observed in narrow corridors at the boundary between sections F and G. The night-time airflow was in the opposite direction to that during the daytime monitoring, except around Section B. Throughout the cave the airflow was stronger on 02 September than on 29 September.

Relationship between precipitation and river flow

Seasonal variation of water level in the underground river is shown by Figure 5b. The riverbed is normally dry but ten discharge events were recorded. Discharge amounts were relatively large during two periods, from April to May and August to September.

Discussion

The most important derivative products of systematic cave exploration are maps (surveys), which illustrate the extent and layout of the cave, shapes of passages, and (if a profile is included) the three-dimensional relationships of the passages (Kambesis, 2007). As mentioned by Fairchild *et al.,* (2006), the spatial setting of a speleothem (i.e. its distance from the entrance, depth below the surface, distance below the ceiling, etc) affects its growth. Such locational data are revealed only after detailed mapping. In addition, cave micro-meteorology, which includes air temperature, airflow and more, is influenced by cave geometry. Therefore, understanding cave geometry by way of the mapping is of fundamental important for those pursuing scientific studies in caves.

Speleogenesis

Various estimates related to the speleogenesis of Hokkai Cave can be derived from the following observations:

a) The Flat Plain "f" (Fig.1b) is considered as being an old riverbed of the Hekirichi River, although its age of formation is not yet determined;
b) Blocks (> 1.0m) observed in sections C, D, F and G (Fig.3) imply that those openings have been formed by collapse because the blocks are not rounded;
c) Some flowstone deposits in sections B, G and J have grown on top of clay sediments, suggesting that the period of clay inflow was followed by a period of stable speleothem growth. Landscape evolution or climate changes might have contributed to the change of sedimentary facies;

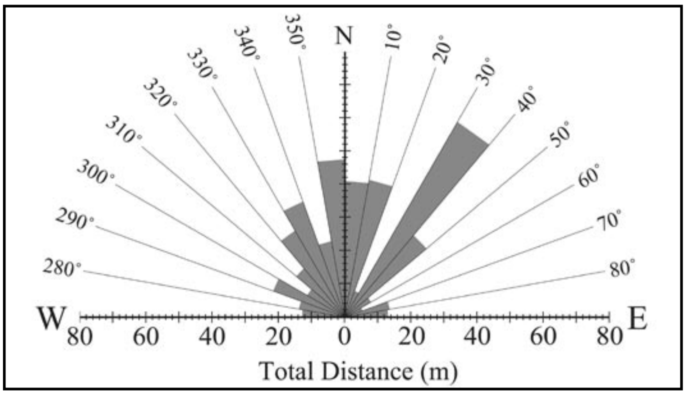

Figure 4: Passage direction variation in Hokkai Cave. The dominant directions are NE–SW (30–50°), NNW–SSE (320–340°) and N–S (350–20°).

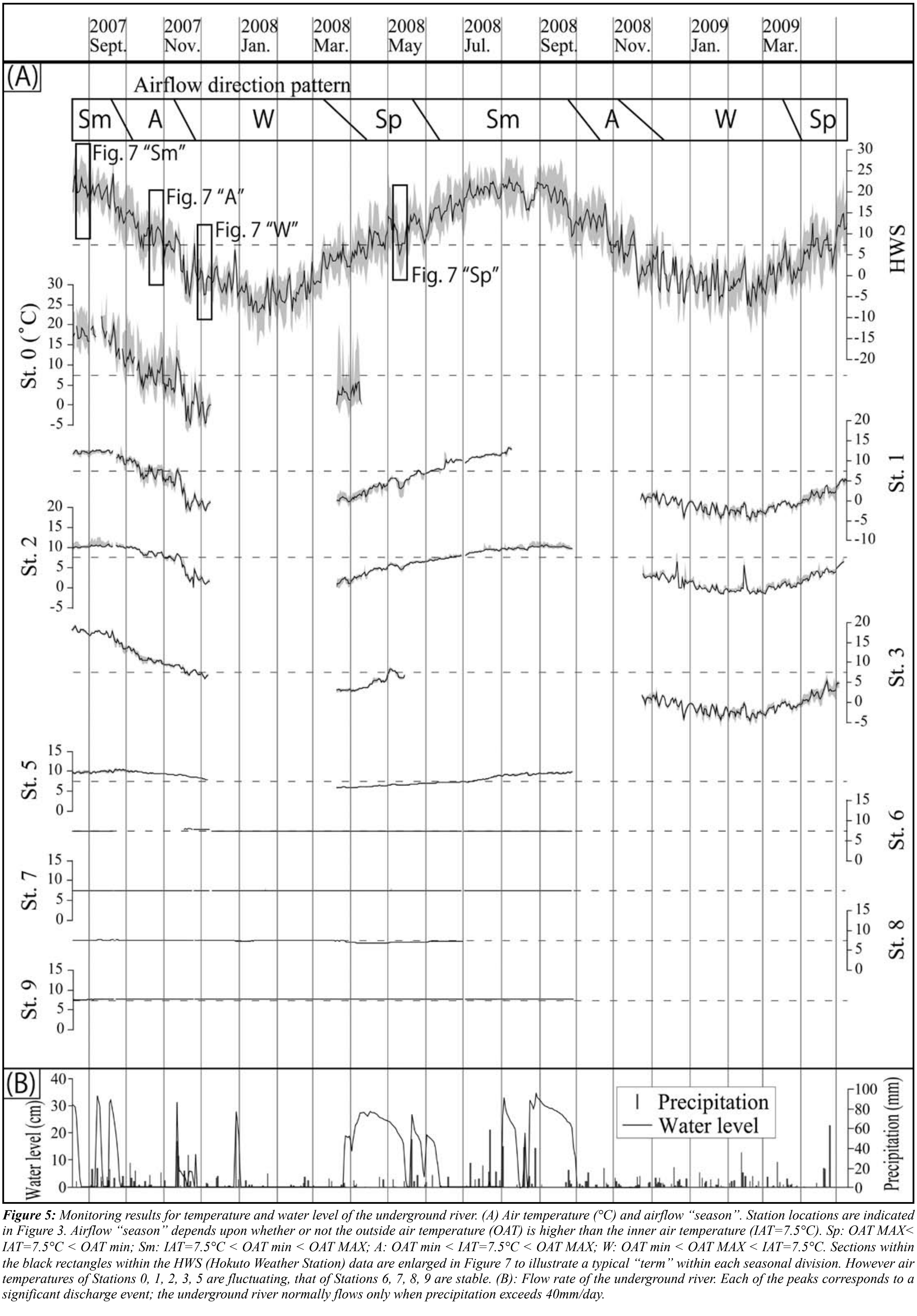

Figure 5: *Monitoring results for temperature and water level of the underground river. (A) Air temperature (°C) and airflow "season". Station locations are indicated in Figure 3. Airflow "season" depends upon whether or not the outside air temperature (OAT) is higher than the inner air temperature (IAT=7.5°C). Sp: OAT MAX< IAT=7.5°C < OAT min; Sm: IAT=7.5°C < OAT min < OAT MAX; A: OAT min < IAT=7.5°C < OAT MAX; W: OAT min < OAT MAX < IAT=7.5°C. Sections within the black rectangles within the HWS (Hokuto Weather Station) data are enlarged in Figure 7 to illustrate a typical "term" within each seasonal division. However air temperatures of Stations 0, 1, 2, 3, 5 are fluctuating, that of Stations 6, 7, 8, 9 are stable. (B): Flow rate of the underground river. Each of the peaks corresponds to a significant discharge event; the underground river normally flows only when precipitation exceeds 40mm/day.*

d) An allochthonous rounded gravel (< 3cm) layer (<30cm) exists below a clay layer in sections B and I (Fig.2d), probably as a result of flooding of the Hekirichi River;
e) A layer of alternating sand and clay is observed in the wall of Section H, where this layer is cut by the underground river. It suggests that the present underground river did not form this part of the cave but is an underfit stream that entered this passage after it had been filled with sandy and clayey sediments under an earlier flow regime;
f) Winter air temperature dropped below 0°C in Section Z (Fig.5), where the walls and ceiling are rough and fragmented, probably as a result of frost-shattering;
g) Bore passages observed in the cave suggest that parts of the cave developed within a karst aquifer, because their circular cross-sections are indicative of development under gravity-free conditions;
h) Speleothems in Hokkai Cave are deduced as being actively growing, because their surfaces are generally wet; only those in part of Section A, close to the entrance, are inactive.

These observations suggest that the speleogenesis of Hokkai Cave could have proceeded as follows:

Stage I

The Hekirichi River flowed through the area of Flat Plain "f" without significant meandering and with its riverbed about 60m higher than its present level.

Stage II

The Hekirichi River began to develop major meanders while ordinary underground openings were forming by dissolution below the contemporary water table.

Stage III

The water table dropped as the Hekirichi River began to cut down and the major part of the cave was formed above the water table and speleothems started growing; collapses occurred in unstable sections and passages enlarged. Passages were also widened around the entrance by the effects of frost-shattering. In sections H, I and J, sand and clay flowed into the cave filling it with clastic sediment. Later, the underground river took on its present form and part of the clay and sand fill was washed out. Subsequently, inflow of clastic debris diminished and flowstones began to grow on a layer of alternating sand and clay. At present, active speleothem growth continues and Hokkai Cave is still developing.

Air temperature and airflow

Introduction of cave air temperature and air circulation

Underground air temperature is known to be rather stable during the year below several metres depth and equivalent to mean annual surface air temperature (Moore and Sullivan, 1978). However, many exceptions are reported, e.g. Castleguard Cave, Canada (Atkinson *et al.,* 1983), Obir Cave, Austria (Spötl *et al.,* 2005) and St Michaels Cave, Gibraltar (Mattey *et al.,* 2008, 2010, 2013). These anomalies are caused by dynamic ventilation, or by geothermal flux, or by heat transfer from water (Baker and Fairchild, 2012). In cases of caves with stable air temperature, however, seasonal variations of air temperature (SVT) and diurnal variations of air temperature (DVT) generally occur in or near the entrance zone due to the effects of advection. Magnitude of the influence differs depending upon cave geometry and air circulation. The range influenced by external air temperature is from just a few metres to several kilometres. For example, in Kartchner Caverns, Arizona (Buecher, 1999), air temperature at a point 15m below the entrance fluctuated seasonally; air temperature near entrance was higher than deep inside during June and lower in November, whereas the air temperature deep inside was stable. In Heshang Cave, China (Hu *et al.,* 2008), air temperature fluctuated in line with outside air temperatures at a point 200m below the entrance, probably because the cave has a tube-like form and air circulation is easy.

Cave air circulation can be classified into 5 types: cave breathing; wind-induced flow; convection; water-induced flow and chimney circulation (Fairchild and Baker, 2012). Cave breathing is observed in caves where entrance passages are relatively narrow compared to total cave volume. Wind-induced flow is dependent on external airflow direction, the surface landscape and the geometry of the cave. Convection occurs in descending or ascending caves and in wide and high cave chambers. Water-induced flow involves air circulation forced by cave streams. Chimney circulation occurs in multi-entrance caves and depends upon air density differences (Wigley and Brown, 1976), with temperature being the main factor influencing air density. In cases where inner cave air temperature (IAT) is higher than outside air temperature (OAT), airflow enters into caves from the lower entrance and discharge from upper entrances (the chimney effect), whereas in cases where the IAT is lower than the OAT, the reverse occurs (the reverse-chimney effect). Generally the chimney effect occurs in winter and the reverse-chimney effect occurs in summer because the IAT is equal to the surface annual average air temperature. The cave "entrance" need not be large (i.e. Spötl *et al.,* 2005) and many caves connect to the surface via voids that are too small for access by speleologists. Airflow velocity is proportional to the altitude difference between lower and upper entrances.

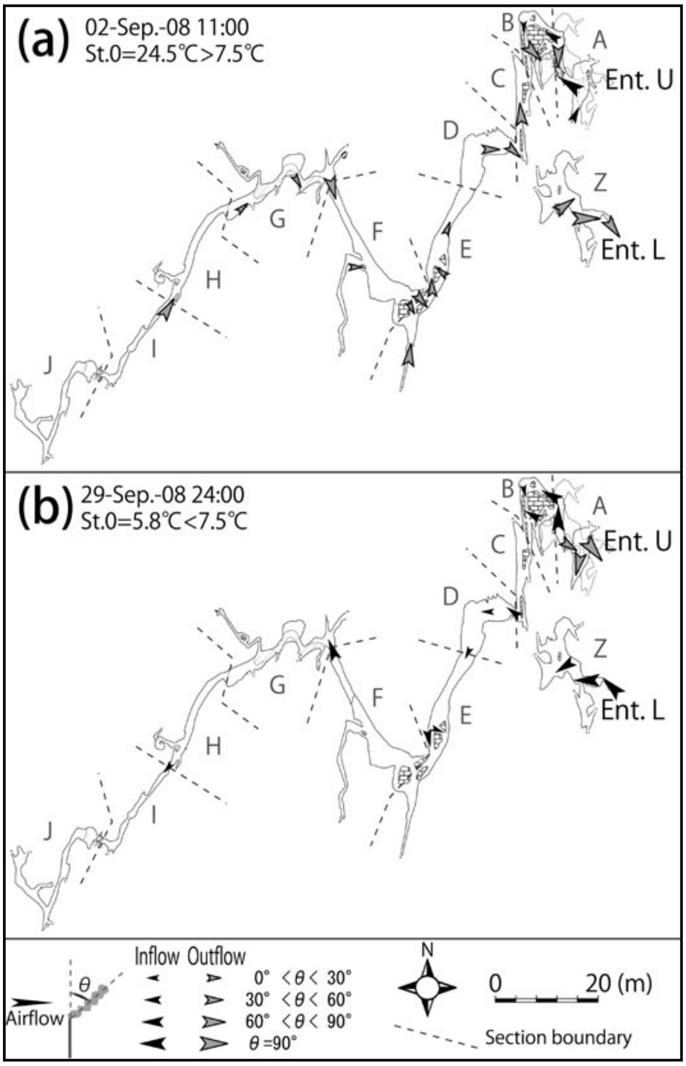

Figure 6: *Airflow direction and intensity in Hokkai Cave. Airflow direction depends on whether the outside air temperature (OAT) is higher than the inner air temperature (IAT) (about 7.5°C = annual mean air temperature) or not. (a) When the OAT is higher than the IAT, air flows from upper to lower and from inner to outer. (b) When the OAT is lower than the IAT, air flows from lower to upper and from outer to inner.*

There are some previous studies related to cave airflow. By monitoring air CO_2 concentration in Austria's Obir Cave, Spötl *et al.* (2005) estimated that air flowed from deep inside to the entrance in summer and from the entrance to deep inside during the winter. Monitoring annual air temperature variations and distribution throughout Kartchner Caverns alongside the outside air pressure, Buecher (1999) revealed that airflow direction inversion was ascribable to air density difference between the deeper cave and the surface. At Canada's Castleguard Cave, which has an 8km-long series of lateral passages and 350m of vertical extent, Atkinson *et al.* (1983) measured cave airflow velocity at 1 to 2 m/s. Airflow measured using an anemometer allowed Ohsawa (2009) to demonstrate seasonal inversion of flow direction in Inazumi Cave, southwestern Japan. In addition, Ohsawa (2009) pointed out that measurements taken near the cave ceiling confirmed air flow from the entrance to deep parts of the cave in winter.

Although cave air temperatures have been monitored at many sites worldwide, only a few studies have been conducted to include continuous monitoring for at least a full year, using several observation stations in caves that are not accessible to tourists. Monitoring in show caves is relatively easy, for logistical reasons (accessibility, availability of electricity, etc.), but the air condition can be much affected by human impact, as reported by Urusibara *et al.* (1998) and Cigna (2002). In the past, simultaneous monitoring at several observation stations has also been difficult because suitable monitoring machines were expensive. However, continuous air temperature monitoring is now more easily achievable because suitable monitoring machines are available at reasonable cost (Cigna, 2002).

Seasonal classification based on airflow direction fluctuation

In this consideration, the year is divided into four airflow seasons based on the diurnal variation of cave airflow.

Cave airflow direction depends mainly on the difference in air temperature inside and outside the cave (Moore and Sullivan, 1978). Because the air temperature of the inner cave (IAT) in Hokkai Cave is approximately constant at 7.5°C, the airflow direction depends primarily upon whether the outside air temperature (OAT) is higher or lower than 7.5°C. In fact, the OAT was higher than 7.5°C during the day (11:00) on 02 September 2008, when the air flowed from the inner cave to Ent. L, and the OAT was lower at night (24:00) on 29 September, when the air flowed from Ent. L into the inner cave (Fig.6).

Based on this model, diurnal variation of air temperature (DVT) of the OAT can be classified into the following three types: (a) OAT is higher than 7.5°C throughout the day; (b) OAT is lower than 7.5°C throughout the day; (c) the DVT of the OAT crosses the 7.5°C baseline.

Hence it is suggested that through a typical year, the three types shift as (b) (c) (a) (c) (b), as the seasons change. Therefore a year can be divided into four "seasons" based on the characteristics (Table 1).

If the classification is applied to the observed temperature variations, spring (Sp) is correlated to a period from late March to early June, summer (Sm): from late May to mid-October, autumn (A): from late September to early December, and winter (W): from early November to early April (Fig.5A).

Airflow and air temperature characteristics in each "season"

Diurnal variation of air temperature (DVT) at stations 0, 1, 2, 3 and 5 is shown in Figure 7 for a typical "term" (Sp, Sm, A and W) of each airflow season.

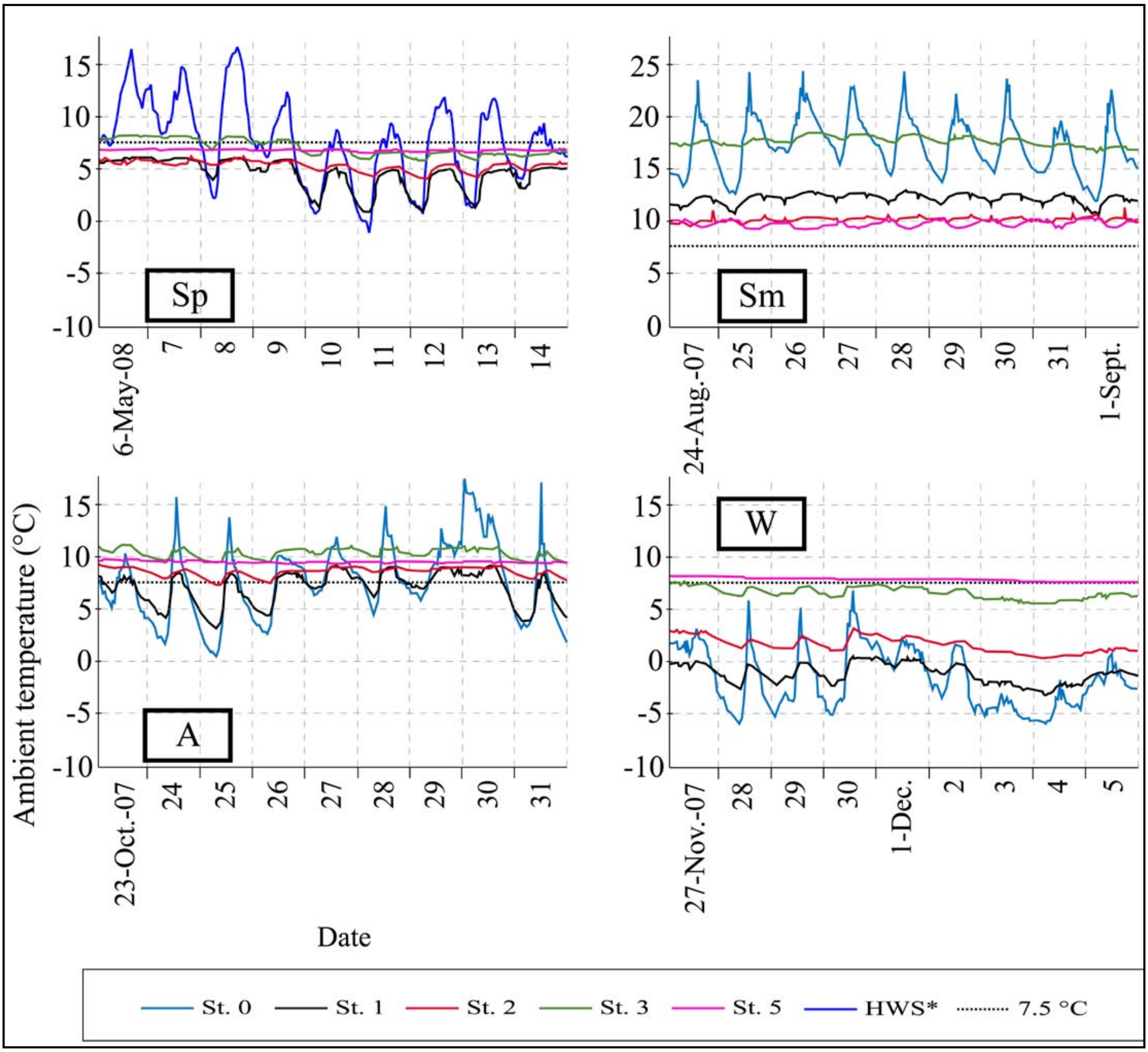

Figure 7: *Typical diurnal variability of air temperature at stations 0, 1, 2, 3 and 5 for a typical "term" of each airflow "season" (see Figure 5 and Table 1). Station locations are indicated in Figure 3. Dotted line (= 7.5°C) shows mean air temperature in the deeper zone (i.e. stations 6, 7 and 8), which approximates to the region's annual mean temperature. Air temperatures at stations 1, 2, 3 and 5 are synchronized with the outside air temperature, but the synchronizing pattern is different, depending upon the airflow direction; e.g. during the Sp season, air temperature at Station 1 was synchronized with Station 0 only during the night because cooler air flowed in from outside.* ***Note****: HWS*: allowing for the altitude difference between Hokuto Weather Station (about 20m above the sea) and Hokkai Cave (about 120m above the sea), HWS temperature values minus 0.6°C are plotted in Sp in place of Station 0 data, which could not be collected for logistical reasons.*

During the Sp season, in the daytime, air is expected to flow from Ent. U to Ent. L through stations 3, 2, and 1, and from the inner cave to Ent. L through stations 5, 2 and 1, whereas at night flow from Ent. L to Ent. U through stations 1, 2 and 3, and from Ent. L to the inner cave through stations 1, 2 and 5 is expected. Air temperature at Station 1 shows relatively large fluctuations and is synchronized with the OAT (i. e. Station 0). Air temperatures of stations 2 and 3 do not fluctuate as such, but they are also synchronized with the OAT. There is little fluctuation at Station 5.

Looked at in detail, the night-time air temperature at Station 1 is well synchronized with the OAT at a magnitude comparable to that during the day. This is because air flows from Ent. L to Ent. U through stations 3, 2 and 1 at night. Because Station 1 is located in a chimney-like shaft, it is most directly affected by variations of the OAT. In contrast, during the day, air temperature at Station 1 is not well synchronized with the OAT because air flows from Ent. U to Ent. L through stations 3, 2 and 1. The air temperature at Station 3, located near Ent. U, is not well synchronized with the OAT, possibly because Station 3 is located within a large chamber and the opening around Ent. U is smaller than that at Ent. L.

Throughout the day during the Sm season, air flows from Ent. U to Ent. L through stations 3, 2 and 1, and from the inner cave to Ent. L through stations 5, 2 and 1. Although air temperatures at stations 1, 2 and 3 are synchronized with the OAT, their variation ranges are smaller than those during other airflow seasons. This is because the air around the stations is mixed with cold airflow from Station 5 (stations 1 and 2), and buffered by a relatively larger chamber (Station 3). On the other hand, the air temperature at Station 5 fluctuated inversely to the OAT: i.e., it dropped during the daytime and rose during the night. This is because, during the daytime, airflow increases due to the large difference between the OAT and the IAT, and because cool air is supplied from deeper in the cave (Fig.3).

The airflow pattern in the "A" season is the same as that in the "Sp": i.e., air flows from Ent. U to Ent. L through stations 3, 2 and 1, and from the inner cave to Ent. L through stations 5, 2 and 1 during the day, whereas it flows from Ent. L to Ent. U through stations 1, 2 and 3, and from Ent. L to the inner cave through stations 1, 2 and 5 during the night. The DVT is also similar to that in the "Sp" season (i.e. the air temperatures at stations 2 and 3 do not fluctuate as such, but they are also synchronized with the OAT; air temperature at Station 1 at night-time is well synchronized with the OAT).

In the "W" season, air flows from Ent. L to Ent. U through stations 1, 2 and 3, and from Ent. L to the inner cave through stations 1, 2 and 5 throughout the day. Air temperatures at stations 1, 2 and 3 are synchronized with the OAT, but at Station 5 the air temperature is approximately constant without such synchronized changes. In addition, temperatures at stations 2 and 3 are synchronized all through the day, while those at Station 1 are synchronized only during the night and are constantly below 0°C during the day because icicles and ice-stalagmites formed around Station 1 act as an air temperature buffer. Icicles and ice-stalagmites were also observed around Station 2 from January through to March (Fig.2h).

Comparison with previous studies

The present data reveal that air temperature near the entrances shows a seasonal fluctuation affected by the OAT, whereas that in the inner cave is stable throughout the year. This observation is similar to those made in previous studies (Buecher, 1999; Spötl *et al.,* 2004). In Hokkai Cave air temperature fluctuation is observed at localities less than about 15m away from the entrances. This is similar to Kartchner Caverns (15m: Buecher, 1999) but less than in the Heshang Cave (200m: Hu *et al.,* 2008). Heat transfer by advection from the entrance of Hokkai Cave is less than that at Heshang Cave because the entrances of Hokkai Cave are smaller than that of Heshang Cave.

The seasonal fluctuation of airflow direction is also similar to that reported in previous studies (Buecher, 1999; Spötl *et al.,* 2004). Additionally, airflows driven by chimney and reverse-chimney effects are observed between the lower and upper entrances in Hokkai Cave. Winter inflow near the cave ceiling, which was reported by Ohsawa (2009), was not observed during this study. Nevertheless, it remains possibly that such an effect does occur, because airflow near the cave ceiling was not measured specifically during this study.

Implication for paleoclimate reconstruction

The possibility of carrying out a palaeoclimate study based upon stalagmites in Hokkai Cave is discussed below. Hokkai Cave is located in Hokkaido, and is at the northern limit of the Asian Summer Monsoon (ASM). Some stalagmites in Hokkai Cave might be suitable for U–Th dating because they are actively growing and their pure white colour suggests that they contain few impurities (Figs 2f and 2g). Hence it should be possible to reconstruct temporal fluctuation of the ASM by carrying out time-series analysis of carbon and oxygen stable isotopes along the growth axis of stalagmites in the cave.

Conclusions

1. The geomorphology of Hokkai Cave is documented for the first time in this paper. Hokkai Cave is a zigzag, essentially horizontal, system with two entrances and is 479.8m long. Much of the cave floor is covered by clay and breakdown gravels and an underground river flows in the center of the cave. Some actively-growing speleothems exist in the cave.
2. The study suggests that a preliminary model for the speleogenesis of the Hokkai Cave includes three broad stages: (I) before cave formation; (II) cave formation in the phreatic zone; (III) cave formation in the vadose zone.
3. Cave air temperatures are synchronized with outside air temperature (OAT) near the entrances, whereas they are stable throughout the year in the inner cave (>15m from the entrances). Airflow direction fluctuates with the OAT variation; it affects the diurnal variation of air temperature near the entrances.
4. Pure white stalagmites in Hokkai Cave have clear central parts, and these might be suitable for palaeo-climate reconstruction studies.

The long term monitoring of Hokkai Cave revealed details of the cave geometry and micro-meteorology. These basic data related to the cave have great importance in helping to improve palaeoclimatic speleothem sample selection, because speleothem geochemistry is also controlled by cave geometry and micro-meteorology (Fairchild and Baker, 2012). Recently, it is suggested that drip rate (Day and Henderson, 2011) and air CO_2 concentration (Baker and Fairchild, 2012) are also significant influences on speleothem geochemistry, and therefore, drip rate and CO_2 monitoring are suggested as avenues for future study.

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