AIR TEMPERATURE AND RELATIVE HUMIDITY STUDY: TORGAC CAVE, NEW MEXICO

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Torgac Cave, located in south-central New Mexico is remarkable for at least three reasons: its extraordinary gypsum speleothems, its large bat population, and the unusually cold temperatures within the cave. It has been proposed that the presence of the bats and the speleothems may be related to the anomalous temperatures observed in the cave. This paper reports the results of a five week study of cave air temperature and relative humidity conducted during January-February 1995.

Several different techniques were employed to measure the temperature and relative humidity (RH) of the cave atmosphere. A sling psychrometer was used to make spot measurements of temperature and RH at 11 locations throughout the cave on two successive dates. In addition, hourly measurements of air temperature and RH at a single location were recorded over a five week period using a capacitance probe and data logger.

A novel technique for inferring RH was also attempted in which kaolinite clay samples were placed at different locations throughout the cave, and at different elevations above the cave floor at a single location, and allowed to equilibrate with the cave air. Subsequent laboratory analysis of the water activity and gravimetric water content of the clay samples following equilibration allowed the time-averaged RH to be inferred, and these data were used to reconstruct the vertical RH profile of the cave atmosphere.

Cave air temperatures measured with the sling psychrometer ranged from 5.4 to 11.1ºC, while RH values ranged between 47% and 89%. The driest conditions were encountered close to the entrance, where cold, dense winter air sinks into the main entrance, drying the cave passages below as it warms. The data logger and capacitance probe recorded subtle, but distinct diurnal temperature and RH fluctuations in the Tray Room located some 75 m from the nearest entrance. These measurements suggest that the cave generally becomes progressively drier throughout the winter months, then again becomes wetter during the summer, both in response to inflow of surface water from summer thunderstorms, and stable thermal stratification of the cave atmosphere during the warmer months, which prevents the density-driven influx of outside air.

Values of RH inferred from laboratory analysis of clay samples placed in the cave correlated well with those measured directly using the sling psychrometer or capacitance probe. Analysis of the clay samples indicated the existence of large vertical variations in time-averaged RH from floor to ceiling of the cave passage. Based on these preliminary results, the clay equilibration method could prove useful in other studies of humidity stratification of cave air.

Torgac Cave is remarkable for its gypsum speleothems. These include claw-shaped gypsum stalactites, knobby gypsum stalagmites, and unusual gypsum trays (Doran & Hill, 1998). The cave is located in gentle, semi-arid, sparsely vegetated karst terrain in southern New Mexico at an altitude of about 1550 m (5075 ft) above sea level. The cave is located within the West Pecos Slope physiographic province of Kelley (1971).

Torgac Cave is a solution cave developed in Permian rocks of the Fourmile Draw Member (uppermost member) of the San Andres Formation, (Kelley, 1971). The Fourmile Draw consists of a nearly flat-lying alternating sequence of carbonate and evaporite sedimentary rocks, primarily dolostone and gypsum. While frequently described as a "gypsum cave," examination of the rocks exposed in the cave walls shows that the majority of passages are developed in thick dolostone units, and most of the gypsum visible in the cave actually consists of secondary gypsum dripstone deposits. The only significant gypsum beds observed in or near the cave are those exposed at the surface in the two entrance sinkholes. This uppermost gypsum unit overlies most of the cave passages, and the spectacular gypsum speleothems within the cave are derived from the dissolution and subsequent reprecipitation of this gypsum.

Torgac Cave has two known entrances (Fig. 1), including a large Main (west) Entrance and a smaller East Entrance. Because the large sinkhole surrounding the Main Entrance acts as a cold trap for outside winter air, the air temperature in the cave is noticeably colder than other caves in the vicinity. It had also been noted by cavers that some areas of the cave were much colder than others. This in turn raised the question of

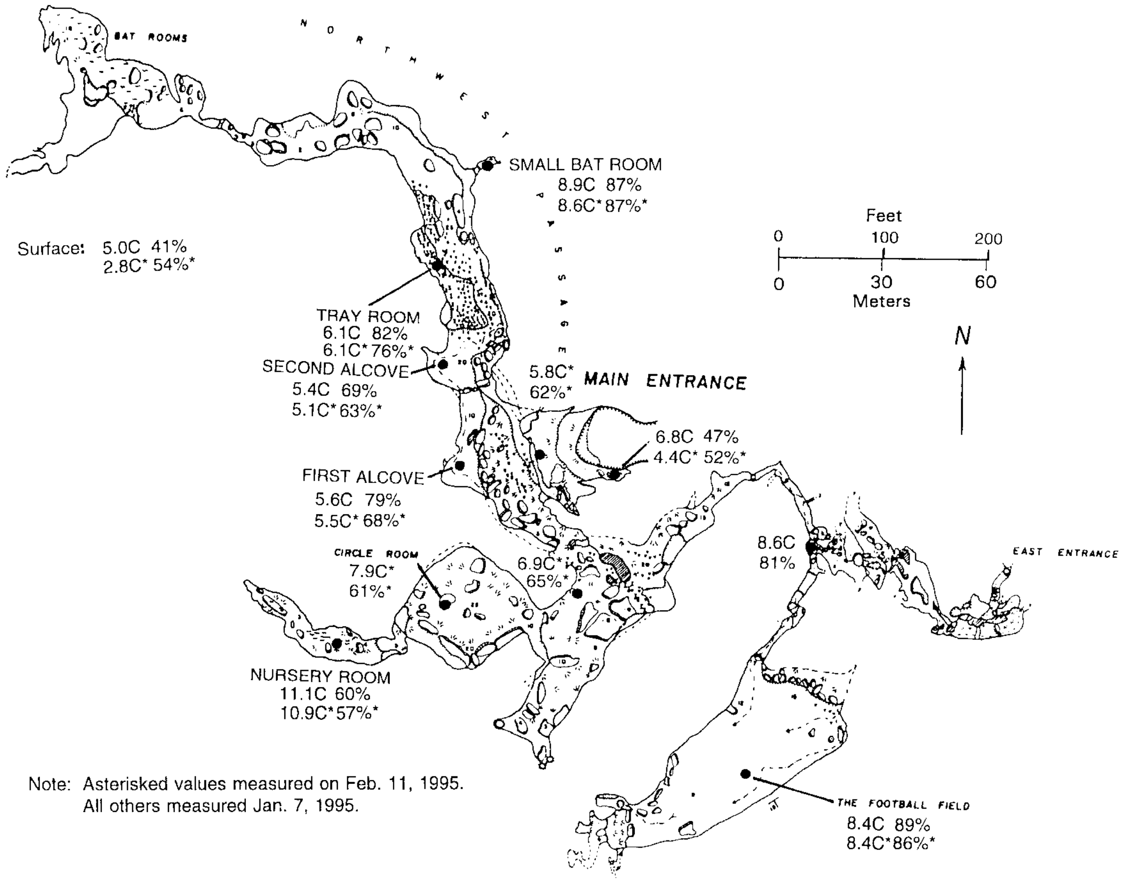

Figure 1.

Air Temperature and Relative Humidity in Torgac Cave.

whether spatial variations in cave microclimate could in some way account for the unusual speleothem development, particularly the gypsum trays (Doran & Hill, 1998).

In order to address this question, we conducted a study during January and February 1995 to measure air temperature and relative humidity (RH) in several areas of Torgac Cave. The impetus for the cave meteorology study was, in part, to ascertain whether vertical air temperature and/or humidity stratification could account for the growth of the gypsum trays in some areas of the cave. Specifically, it had been hypothesized that perhaps gypsum trays "refuse" to grow downward because the air below the level of the tray is drier than that above. The cave meteorology study was intended to test this hypothesis. Torgac Cave also serves as a winter hibernaculum for approximately 1000 bats (Jagnow, 1998), and the microclimate information was considered important with respect to the roost requirements of these bats.

MATERIALS AND METHODS

Air temperature and relative humidity were measured on January 7, 1995 and again on February 11, 1995 at the surface and at 11 locations throughout the cave (Fig. 1) using a research-grade sling psychrometer. The dry bulb and wet bulb temperatures were recorded to the nearest 0.1ºC using the psychrometer, and the barometric pressure (mbar) was determined to the nearest 5 mbar at each location using a Casio watch barometer. These data were subsequently used to calculate RH using the computer program HumiCalc™. At these temperatures and pressures, a change in temperature of 0.1ºC results in a change in RH of about 1%, which is taken to be representative of the magnitude of RH errors in our measurements.

In addition to the two psychrometer surveys, a portable data logger equipped with a temperature/RH sensor was used to continuously monitor air temperature and RH during the period between January 7, 1995 and February 11, 1995 at a single location in the Tray Room (Fig. 1) where gypsum trays are particularly well-developed. A Campbell CR-10 data logger was used for this purpose, along with a Vaisala capacitance-type temperature/humidity probe. The data logger was programmed to query the Vaisala sensor once every hour, and the sensor was placed about 0.3 meter (1 foot) above the floor of the Tray Room. The data logger collected data for 34 days in this mode.

A novel method for assessing vertical variations in RH in the Tray Room was also attempted. On the first day that the data logger began acquiring hourly temperature and humidity measurements, 11 small plastic cups containing 2 to 3 gm of dry, powdered kaolinite clay were suspended at different elevations above the floor of the cave, using a vertical piece of steel conduit pipe with clothes pins attached (Photo 1). The clay samples were spaced at 0.3-m (1-foot) intervals above the floor, and were allowed to equilibrate with the cave atmosphere for the five-week period of the study. The initially dry clay imbibes water from the cave air until at equilibrium the water activity (a_w) of the clay is equal to that of the surrounding atmosphere. This is the RH analogy of the temperature profile work reported by Benedict (1974).

In addition to the 11 kaolinite clay samples suspended vertically in the Tray Room, four identical clay samples were placed throughout the cave at some of the same locations where spot measurements of air temperature and RH were made with the sling psychrometer. These four samples were intended to check whether or not the clay equilibration method indicated similar time-averaged RH values to those measured during the two temperature surveys.

Following the five-week equilibration period in the cave, the cups containing the clay samples were capped and sealed with electrical tape, and returned to the laboratory, where a_w was measured using a Decagon Aqualab CX-2 water activity meter. The CX-2 water activity meter is a chilled-mirror psychrometer device, in which the clay sample is placed in a sealed chamber with a polished metal mirror that is alternately warmed and chilled. As the chamber is warmed, water in the clay sample evaporates into the air above it. When the mirror is chilled, condensation occurs and fog forms on the mirror, thereby altering its optical properties. The circuitry of the instrument allows precise determination of the temperature at which condensation first occurs (dew point), which in turn is related to the water activity of the sample. The instrument provides a direct readout of a_w, which is equivalent to the fractional relative humidity (a_w = %RH/100), with an estimated precision of ±0.5% RH. The water activity of the equilibrated clay samples should thus provide a measure of the time-averaged RH at the specific locations in the cave where the samples were placed.

Following the water activity measurements, the gravimetric water content of each clay sample was determined by weighing the sample, then reweighing it following drying overnight at 105ºC in a lab oven. The weight of the water lost during drying divided by the weight of the dried clay represents the gravimetric water content, expressed in grams water per gram of clay. The precision of the gravimetric water content is approximately ±0.005 g/g.

RESULTS AND CONCLUSIONS

Measured wet bulb and dry bulb temperatures and calculated RH values for the January and February monitoring events are shown in Table 1. Figure 1 shows the measured air temperatures and RH values at each monitoring location. The dry bulb temperature represents the temperature of the cave air. During January, cave air temperatures ranged from 5.4ºC to 11.1ºC, with the coldest temperatures being measured in the lowest part of the streamway passage directly inside the Main

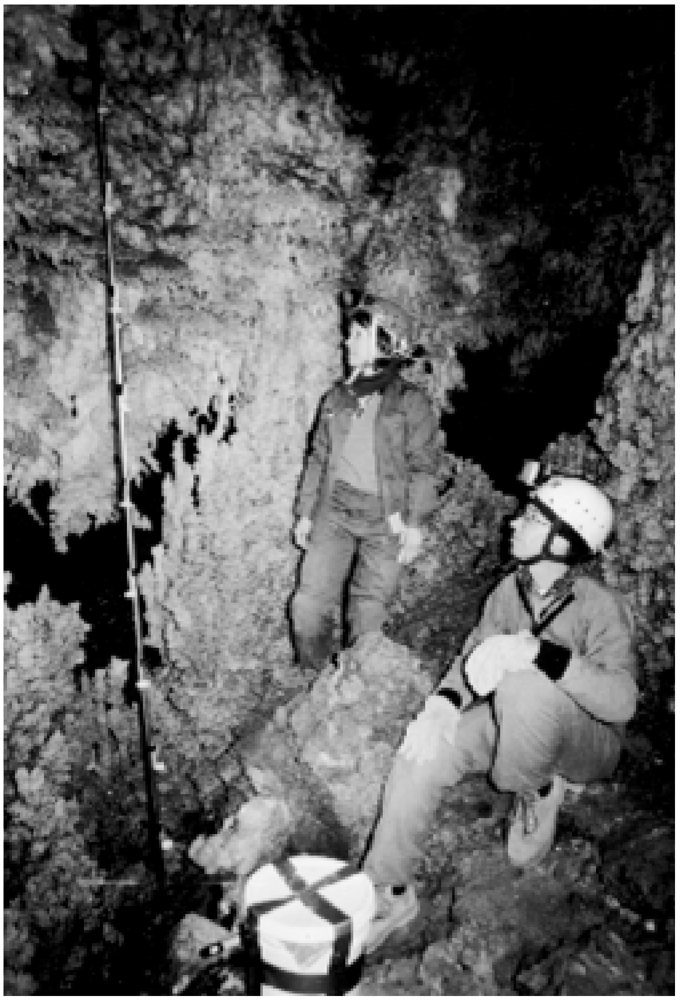

Photo 1. "Tray Room" in Torgac Cave showing kaolinite clay samples suspended at 0.3 m intervals along steel pipe (left) to monitor vertical variations in relative humidity. Data logger in sealed bucket in foreground makes hourly measurements of air temperature and relative humidity.

Entrance (First and Second Alcoves). The warmest temperature on that date was in the Nursery Room, a small area somewhat isolated from the rest of the cave by a constricted climb down that connects the Nursery Room with the Circle Room. The floor of the Nursery Room is covered with a blanket of dry bat guano approximately one meter thick; however, only a few bats were observed hibernating in the room during the period of this study.

Cave air temperatures measured during February were generally slightly colder than during January, although temperatures remained unchanged at two of the locations. All of the temperature values are significantly colder than the estimated mean annual temperature for this location of approximately 14.4ºC (Gabin & Lesperance, 1977). Cave temperatures depressed below the mean annual temperature are characteristic of "cold trap" type caves, including many ice caves (Halliday, 1954). In these instances, the cave entrance and pas-

Table 1. Temperature and Relative Humidity Measurements in Torgac Cave.

Location	Date	Time	Dry Bulb Temp[1] (C)	Wet Bulb Temp[1] (C)	Barometric Pressure[2] (mbar)	RH[3](%)
Surface (parking lot)	1/7/95	1905	5.0	0.3	846	41%
	2/11/95	1100	2.8	-0.6	844	54%
Main (west) Gate	1/7/95	1845	6.8	2.2	850	47%
	2/11/95	1125	4.4	0.7	846	52%
First Alcove	1/7/95	1425	5.6	3.9	852	79%
	2/11/95	1205	5.5	3.0	849	68%
Second Alcove	1/7/95	1500	5.4	3.0	852	69%
	2/11/95	1220	5.1	2.2	849	63%
Tray Room	1/7/95	1520	6.1	4.7	851	82%
	2/11/95	1310	6.1	4.2	846	76%
Small Bat Room	1/7/95	1620	8.9	7.8	850	87%
	2/11/95	1400	8.6	7.5	845	87%
Nursery Room	1/7/95	1400	11.1	7.2	852	60%
	2/11/95	1540	10.9	6.7	847	57%
Football Field	1/7/95	1800	8.4	7.5	853	89%
	2/11/95	1610	8.4	7.2	847	86%
Circle Room Ent.	2/11/95	1510	6.9	4.0	846	65%
Circle Room	2/11/95	1530	7.9	4.6	846	61%
Main Ent. Climbdown	2/11/95	1140	5.8	2.8	846	62%
East Ent. Climbdown	1/7/95	1825	8.6	6.9	852	81%

[1] Dry and wet bulb temperatures measured using sling psychrometer

[2] Barometric pressure measured using barometer function on Casio Alti-Depth wristwatch.

[3] Relative humidity calculated from dry & wet bulb temperatures and barometric pressure using HumiCalc™ software, available from Thunder Scientific (tel. 505-265-8701).

sage geometry permits cold dense air to sink into the cave during winter, where it pools in a low portion of the cave (Smithson, 1993).

During a previous study of bat roosting requirements conducted in Torgac Cave during the winter of 1966-67, Howell (1967) noted that between December and late April "temperatures remained low and constant with a 6.5ºC average in most rooms." This observation is consistent with the measurements shown in Table 1, except that the Small Bat Room was significantly warmer during this study (8.9ºC) than during the 1966-67 investigation, where temperatures of between 1.7ºC and 4.4ºC were noted in the "Velifer Room" (aka Small Bat Room). The reason for the difference is not known, but apparently cannot be ascribed to variations in the hibernating bat population in this room. During the 1966-67 study, approximately 560 *Myotis velifer* (Cave Bat) were counted in the room, whereas during bat counts at the start and end of the present study, about 270 of these bats were present (Jagnow, 1998). Thus, the higher temperatures reported here are not attributable to extra heat generated by greater numbers of bats.

Relative humidity values measured at waist-height (about 1 m above floor) during this study ranged from 47% to 89%, with the driest air found closest to the Main Entrance, as expected. There, cold, dry outside air sinks into the cave, warming slightly as it enters, lowering the RH even further as a result of the temperature dependence of this parameter. The highest RH values were observed in the Small Bat Room (87%) and the Football Field (86%-89%), both located in "dead end" areas with relatively poor air circulation from the entrances. At most locations, the RH values for February are several percent lower than those measured during January, which probably reflects the progressive drying of the cave throughout the course of the winter via entry of cold, dry outside air. Howell (1967) also observed that the Small Bat Room (aka Velifer Room) was among the most humid areas of the cave during the winter months.

Figure 2 shows variations in air temperature and RH recorded by the data logger in the Tray Room over the month-long monitoring period. Temperatures at this location ranged between 4.4ºC and 5.1ºC, while RH varied between 86% and 96%. Several trends are evident in the data. First, there is a small, but unmistakable diurnal fluctuation in both temperature and RH. The amplitude of the temperature oscillation is about 0.1ºC, while that of RH is 2% to 4%. Daily minimum temperatures occur at about 8:00 AM, and maxima at about 2:00 PM. The cave air temperature fluctuations appear to correlate with

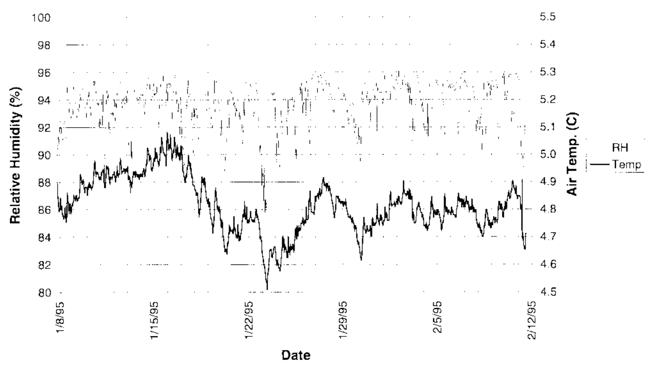

Figure 2. Temperature and RH recorded with data logger in Torgac Cave Tray Room.

external temperature cycles, with the coldest cave temperatures occurring near dawn following the end of a cold night. The Tray Room is located approximately 75 meters from the Main Entrance. Apparently, pulses of outside air are able to penetrate to this distance.

In general, the temperature and RH curves track each other, indicating that as temperatures fall, so too does RH. At first this appears counterintuitive, because cooling of an air mass should cause a rise in RH, not a decline. The explanation for this is probably simply that outside air is both colder and drier than "cave air." Pulses of outside air entering the cave cause both the cooling and the drying of the cave. Influx of outside air is facilitated when the temperature gradient between inside and outside is greatest, which occurs at the coldest time of day, generally in the early morning. This suggests that the RH in Torgac Cave should be lowest towards the end of particularly cold winters, and should reach a maximum in late summer or early autumn.

Upon close examination, exceptions to the positive correlation between temperature and RH sometimes occurred during the warmest part of the day. On these days, when temperature peaked in the Tray Room shortly after noon, a sharp downward spike in RH occurred at nearly the same time. The explanation for this phenomenon is unknown, but it is possible that strong outside winds that typically occur during the warmest part of the day caused short-duration pulses of dry outside air to move into the cave on those days.

As described above, small powdered clay samples were placed in the cave and left to equilibrate with the cave air. The clay samples were intended to serve as proxy recorders of the time-averaged RH at the location where they were left. To my knowledge, this technique has not been tried in previous studies, in caves or elsewhere.

Figure 3 shows the correlation between relative humidity measured with the sling psychrometer and that inferred from the equilibrated clay samples left in the cave. The two psychrometer values are the different readings obtained on the two days. This plot shows reasonably good agreement between the two methods, especially considering that the psychrometer values represent the RH at the moment of the measurement, whereas the values inferred from the clay samples are integrated over the clay equilibration time constant. This time constant is unknown, but is probably on the order of a week or two, based on experiments conducted in the laboratory with saturated salt solutions of known RH. Thus the clay equilibration technique appears to provide at least a qualitative indication of the average RH.

Figure 4 shows the RH inferred from clay samples suspended at different heights above the floor in the Tray Room. A large variation in RH is apparent over the vertical interval monitored. The highest RH is observed 0.3 m above the floor (92.4%), which correlates well with the average of the RH values recorded using the Vaisala sensor (Fig. 2), also located about 0.3 meter above the floor and approximately one meter away horizontally. Decreasing RH values were observed up to a height of 1.2 m where an RH minimum occurred at 83.4% (Fig. 4). This height generally corresponds with the point furthest from any cave wall, floor, or ceiling. Although air velocity measurements were not made, the low RH observed at the 1.2 m level also probably corresponds to the zone of maximum airflow, given that locations closer to the floor and walls are subject to the drag effects imposed by these surfaces.

Because the walls in the Tray Room are uniformly wet, it is reasonable to expect that the RH approaches 100% in the thin stagnant boundary layer immediately adjacent to the cave surfaces. Although the water films in Torgac Cave are saturated with gypsum, the effect of such calcium and sulfate concentrations on the vapor pressure of water in the solution is negligible, and equilibrium RH that would exist very close to such a wetted surface would be well over 99% RH.

RH increases gradually above the 1.2 m level to approximately 90% at a height of 3.3-3.5 m). These two samples were located within about one meter of the cave wall, and thus are probably also influenced by evaporation of water films from the wet surface.

As a check on the RH values measured using the water activity meter, the gravimetric water content of the clay sam-

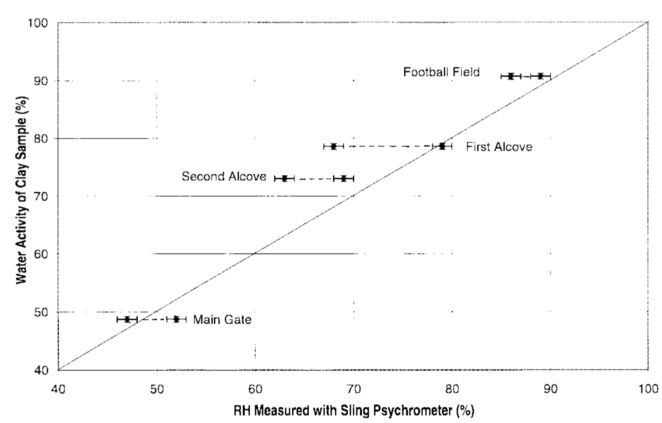

Figure 3. Measured RH vs. RH inferred from Equilibrated Clay Samples.

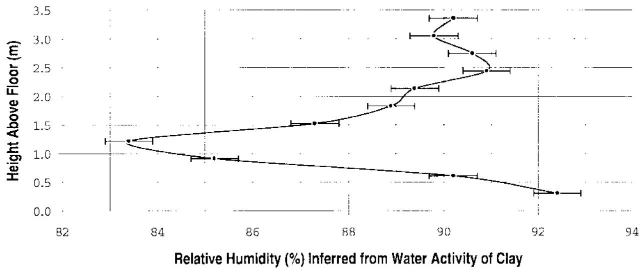

Figure 4. Water activity of clay samples suspended at different heights in Torgac Cave Tray Room.

ples was also determined. This provides an independent check on the water activity data. Figure 5 shows the gravimetric water content of the different clay samples versus height above the floor. The shape of the curve is qualitatively similar to that in the previous figure, indicating that the RH variations observed are real and significant.

Figures 4 and 5 demonstrate that the cave atmosphere within the Tray Room is vertically stratified with respect to RH, and can vary substantially over short vertical distances in a cave passage. The humidity profile (Fig. 4) suggests that maximum evaporation in the Tray Room should occur furthest from the ceiling, walls, and floor. This generally corresponds with the location of maximum gypsum tray development (Doran & Hill, 1998), although more measurements will be needed to verify this preliminary hypothesis.

Figure 4 raises the question of what is being measured when we determine “the RH” using a sling psychrometer or other device that stirs the air throughout a considerable volume. This study indicates that considerable “fine scale” variation in RH may exist, depending upon the measurement height and distance to the nearest wet cave surface. The role of such RH variations in speleogenesis or speleothem deposition is unknown, but recent studies of the condensation corrosion and evaporation deposition in caves of the Guadalupe Mountains of New Mexico indicate that this phenomenon could be important.

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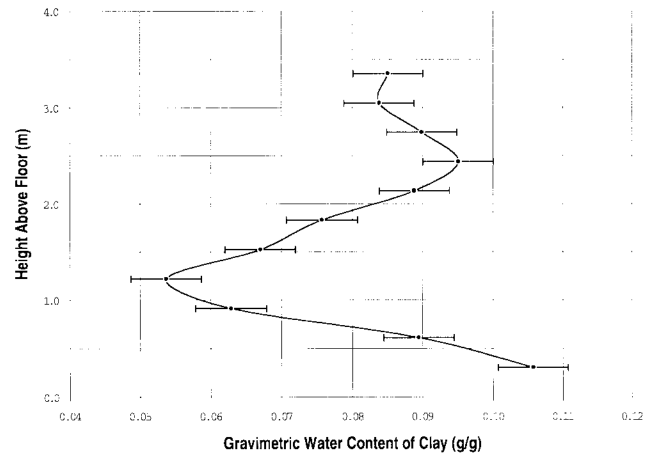

Figure 5. Gravimetric water content of clay samples suspended at different heights in Torgac Cave Tray Room.

REFERENCES

Benedict, E.M. (1974). Hot Air Rises. *Speleo Digest 1974*: 215-216.

Doran, L.M. & Hill, C.A. (1998). Gypsum trays in Torgac Cave, New Mexico. *Journal of Cave and Karst Studies 60*(1): 39-43.

Gabin, V.L. & Lesperance, L.E. (1977). *New Mexico Climatological Data: Precipitation, Temperature, Evaporation, and Wind Monthly and Annual Means, 1950-1975*. W.K. Summers & Associates.

Halliday, W.R. (1954). Ice caves of the United States. *National Speleological Society Bulletin 16*: 3-28.

Howell, D.J. (1967). *Bats of Fort Stanton Cave and Torgoc’s Cave*. Unpublished report from Bureau of Land Management files.

Jagnow, D.H. (1998). Bat usage and cave management of Torgac Cave, New Mexico. *Journal of Cave and Karst Studies 60*(1): 33-38.

Kelley, V.C. (1971). Geology of the Pecos Country, southeastern New Mexico. *New Mexico Bureau of Mines and Mineral Resources Memoir 24*: 75 p.

Smithson, P.A. (1993). Vertical temperature structure in a cave environment. *Geoarchaeology 8*(3): 229-240.