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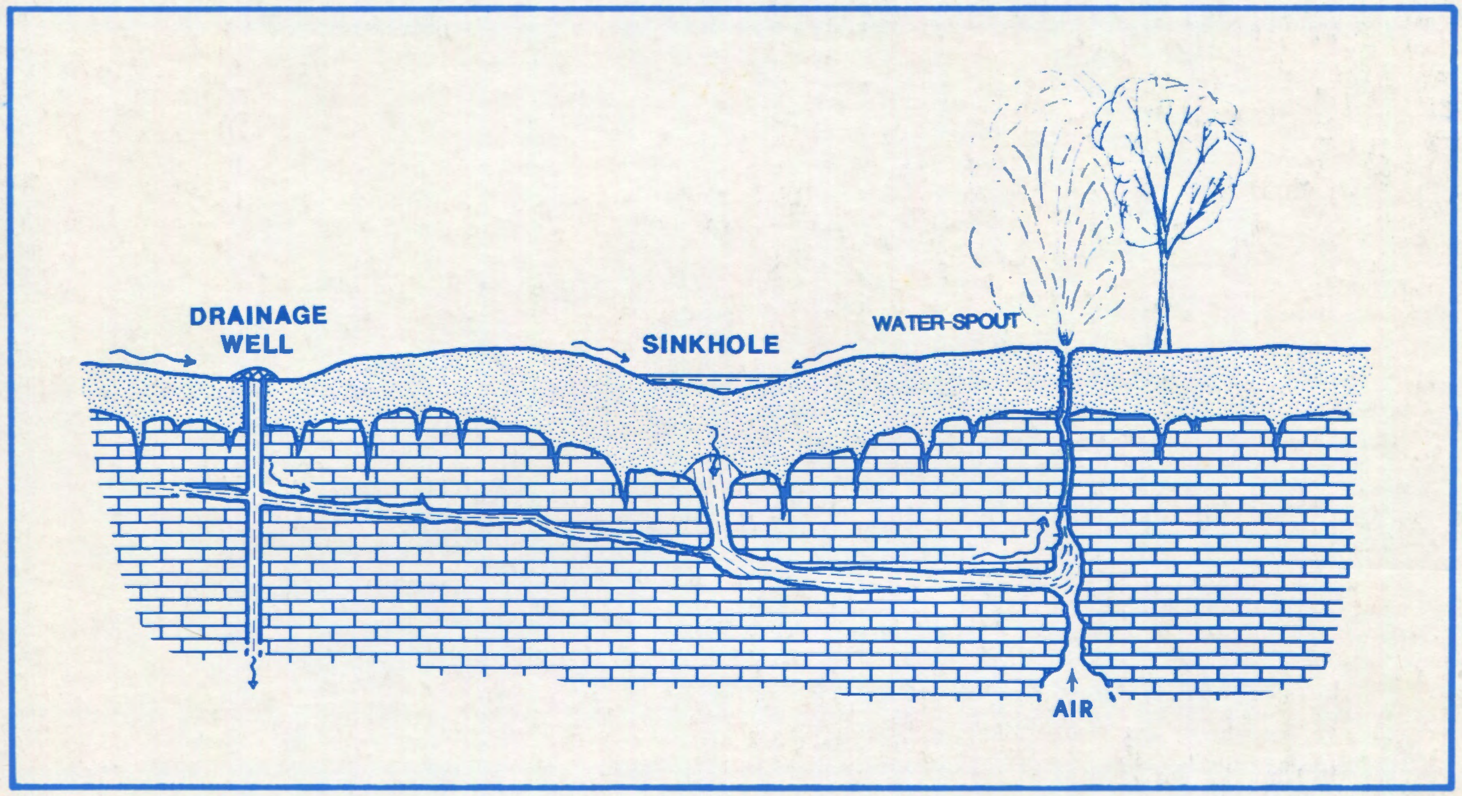
Journal of Caves and Karst Studies



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Cover: Possible water source for the Travelstead Water-Spout
(see Veni & Crawford, page 43)

Veni, George and Crawford, Nicholas C.—Origins of Water-Spouts in Karst Regions: *NSS Bulletin* **48**: 43-53.

ORIGINS OF WATER-SPOUTS IN KARST REGIONS

George Veni*

and

Nicholas C. Crawford**

Water-spouts, nonhydrothermal geyser-like discharges of groundwater, are known to occur in karst areas. Experimental modeling and field examinations of water-spout sites have subclassified them according to three possible mechanisms for their occurrence: impulse pressure (groundwater deflection), artesian pressure, and air pressure. All mechanisms require a constriction in the subsurface flow path to divert groundwater upward, and a constriction at the surface vent which increases water velocity to result in the geyser-like discharge. Analogous artesian pressure water-spouts have often been observed on glaciers. Water-spouts in karst regions are short-lived phenomenon and are most likely to occur in areas where moderately thick impermeable soils overlie the limestone.

INTRODUCTION

Water-spouts are geyser-like discharges of groundwater, upshooting into the air, which occur as a result of non-hydrothermal processes. Although they have been known in the glaciologic literature for over one hundred years (Nordenskiöld, 1879), water-spouts in karst regions have been virtually undescribed (the one exception being a brief reference by Milanović, 1981). This report examines known water-spouts, experimental modeling, and how the models fit the known situations. It also delineates areas of future water-spout activity in karst regions.

DESCRIPTIONS OF KNOWN WATER-SPOUTS

Water-spouts have often been observed to occur on glaciers (Nordenskiöld, 1879; Stone, 1899; Glen, 1941; Gertsch, 1955; Oechslin, 1955; Hinterberger, 1956; Rucklidge, 1956; Charlesworth, 1957; Brockamp, 1961; Wiseman, 1963; Wyllie, 1965; Ewing, Loomis and Lougeay, 1967; Stenborg, 1968; Paterson and Savage, 1970). Some occur only once, others at regular intervals, and other water-spouts flow continuously for up to several days. The mechanism by which they occur has not been thoroughly examined, however, we believe they are analogous to water-spouts noted in karst regions. The discussion that follows focuses primarily on water-spouts in karst regions. Glacial water-spouts will be addressed as such when mentioned.

*Department of Geosciences & Materials Research Laboratory, Pennsylvania State University, University Park, Pennsylvania 16802.

**Center for Cave and Karst Studies, Department of Geography and Geology, Western Kentucky University, Bowling Green, Kentucky 42101.

Following are all the water-spouts known to the authors. Most are located within the city limits of Bowling Green, Kentucky. Undoubtedly many others have occurred and their documentation would provide a valuable and informative inventory. Although it is not extensive by any means, the following listing and descriptions illustrate the diversity of water-spouts in form, size, and topographic location. With the exception of the Big Sink Cave, Merkle Cave, Pfeiffer and Polje Water-spouts, locations are provided on the map of the Lost River Groundwater Basin in Bowling Green, Kentucky (Fig. 1).

Travelsted Water-spout

This water-spout is situated on a hilltop near the main stream of the Lost River Cave System. Three times since about 1970 a strong spray of water has shot up to heights of 13 m. Its recurrence on 21 July 1979 was photographed and documented in the Park City Daily News (Fig. 2). A loud whistling sound has been associated with the water-spout which has been known to last in excess of 3 hours. (Goad, 1984; Wilson, 1984).

Griffin Water-spout

In June 1969 (estimated date), property owner Houston Griffin heard and felt a rumbling of the ground after a high intensity storm, and was surprised by an erupting column of water about one meter in diameter and 1.6 m high. Sizable rocks (Griffin estimates their weights at 35-40 kg) were moved by the water. The water-spout spewed from the flank of a large collapse sinkhole of the Lost River Cave System.

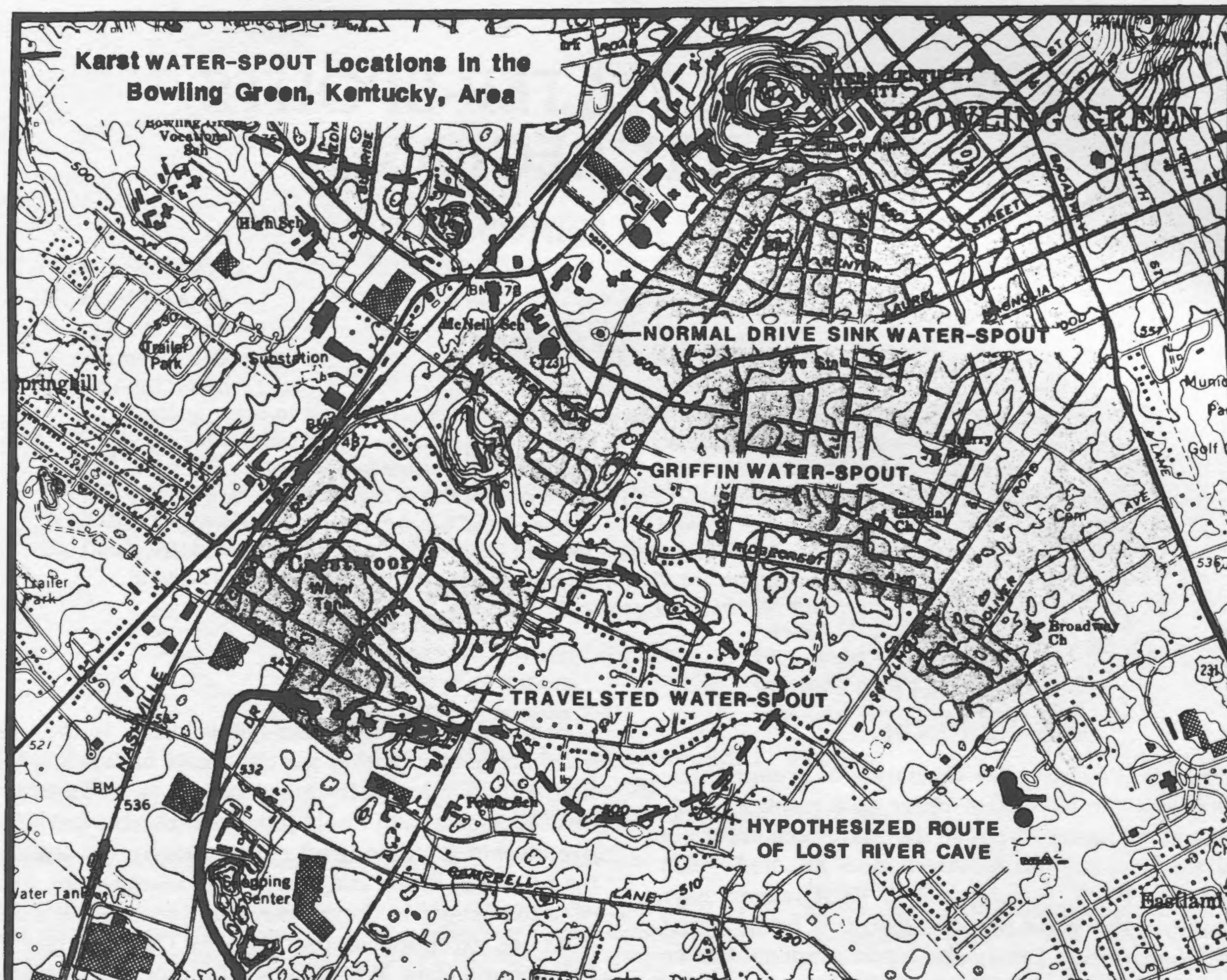

Figure 1. **Karst water-spout locations in the Bowling Green, Kentucky, area.**

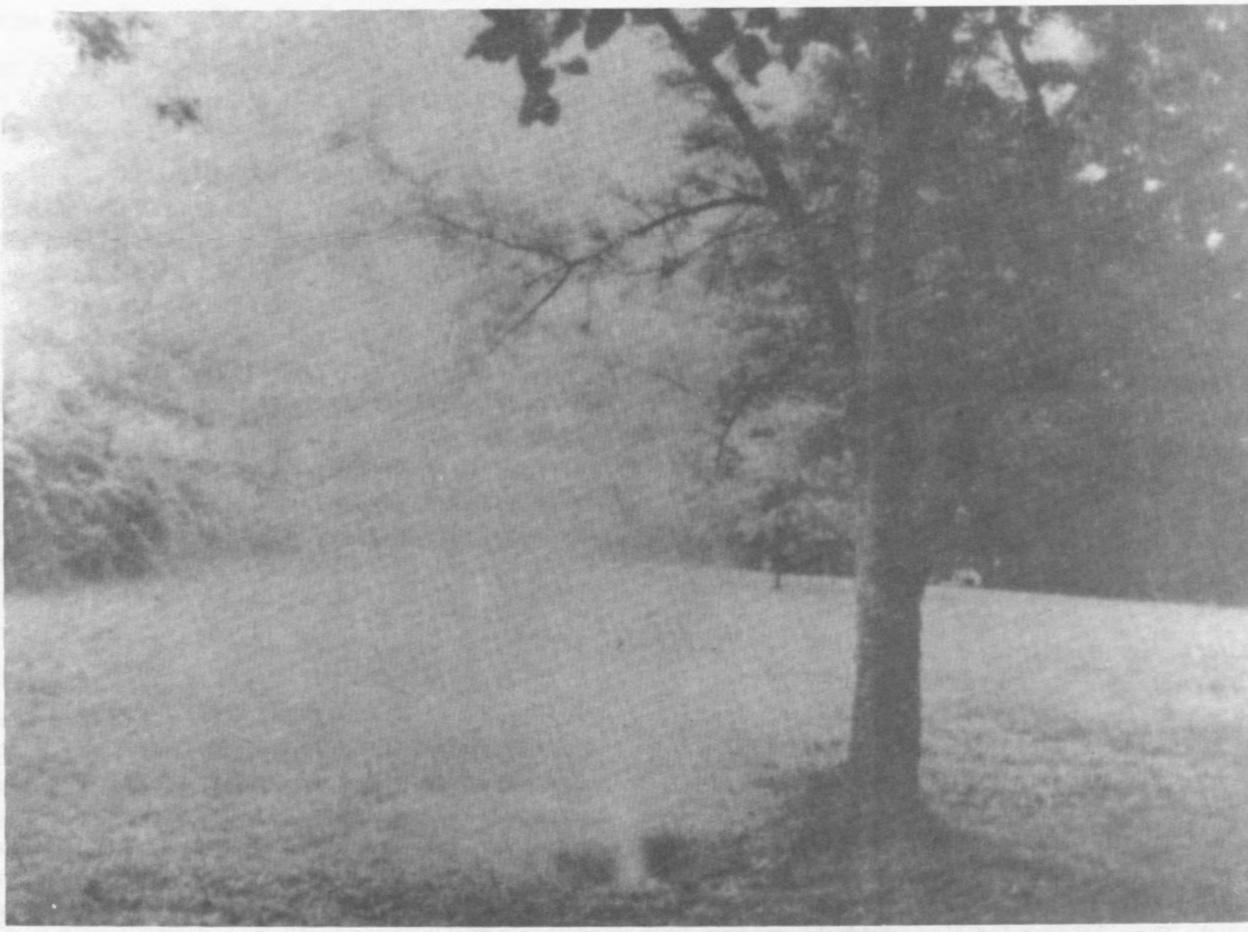

Figure 2. **Travelsted Water-spout on July 21, 1979 (courtesy Park City Daily News). Water-spout height achieved 13 m (upper 6–7 m not shown in photo).**

In little more than an hour the sinkhole floor was flooded and the water-spout inundated. During a similar recurrence, circa 1975, the water-spout erupted at only half its previous size. The site is presently buried by bricks and rocks (Griffin, 1984).

LONG WATER-SPOUT

Late one evening in March or April 1983, Joe Long heard a whistling sound in his backyard. It had been raining hard for the past couple hours. At a horizontal distance of 1.8 m he felt air and water spraying out of the sound's source—a 5 cm diameter hole. The spray reached a height of at least 2 m. It is uncertain how long the spray continued, but he noted it had diminished considerably when checked one and a half hours later, and had disappeared by morning. A few days later Long excavated the small hole (Fig. 3). At a depth of 0.5 m the hole enlarged to a diameter of 1 m and continued down for 0.6 m to a water well casing. Along one side of the 15 cm diameter casing was a pit in the regolith roughly 45 cm in diameter. Long used a weighted line to approximate its depth at 8 m. Soon afterwards the hole was filled

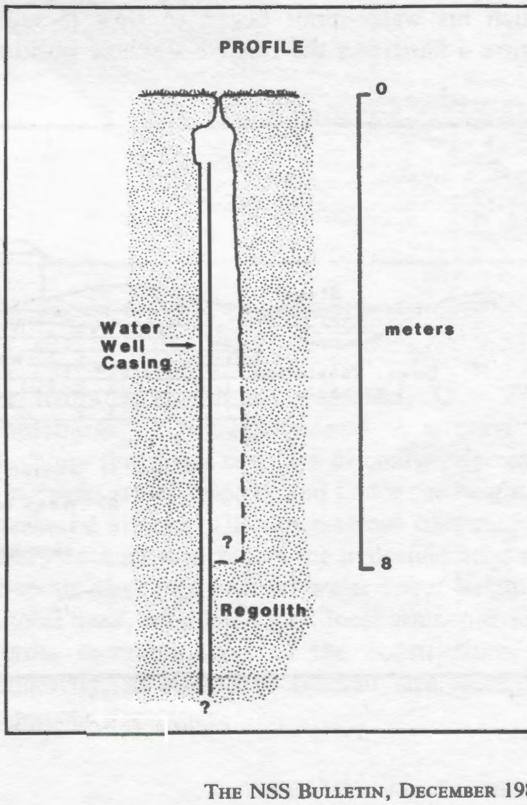

Figure 3. **(right) Long Water-spout.**

and the well reburied. Long had noticed that the well water had become increasingly muddier in the weeks prior to the water-spout's occurrence. Initially the water had become muddy only after major storms. This condition resumed following the hole's filling. The depth of the well is unknown (Long, 1984).

NORMAL DRIVE SINKHOLE WATER-SPOUT

This water-spout was observed around 1960 after a severe storm with very dry antecedent conditions. Appearing from the base of a broad and shallow sinkhole, the water-spout attained a height of almost 1 m for an undetermined period of time. Expansion of Normal Drive has since filled part of the sinkhole and there has been no known water-spout recurrence (Rider, 1983).

SCHNEIDER WATER-SPOUT

During early May 1984, a week of heavy rainfall caused the water table to rise and there was extensive flooding in the Bowling Green, Kentucky area. Nine centimeters of rain, from 2–5 May 1984, had saturated the ground. The 12 cm of precipitation that followed on 6–7 May 1984 resulted in large scale regional flooding. At 9:00 a.m., 7 May 1984, a 10 cm high water-spout rose from the bedrock under the house of Carl Schneider. The water-spout lasted four days. Its water flowed from the crawlspace into the den of the split-level home. Water depth was 13 cm where it flowed through the 61 cm wide doorway. Three sinkholes near the house were flooded. The power substation sinkhole, highest in elevation, was almost full. By stake placement and close observation Schneider determined the sinkhole flood level above which his water-spout began to flow (Schneider, 1984). Figure 4 illustrates the relative sinkhole positioning and how the water-spout resulted from a local water table rise which ponded water in the sinkhole.

BIG SINK CAVE WATER-SPOUT

Big Sink Cave is located approximately 72 km southeast of Lexington, Kentucky, in Sinking Valley. The cave is primarily a large stream passage, draining much of Sinking Valley, and has been surveyed at over 2.5 km long. In the early 1960's an 8 cm diameter well was drilled 41 m deep to where is intersected the cave about 200 m upstream of its terminal sump. In August 1962 the largest recorded flood at the Buck Creek gaging station (upstream from Sinking Valley) was measured at 9 m^3/sec. During this flood a column of water rose 7 m high from the well hole. In May 1984 the incident was repeated. This time the discharge of Buck Creek was measured at 6 m^3/sec and the column rose to a height of 5–7 m, persisting for over three hours (Hacker, 1985).

MERKLE CAVE WATER-SPOUT

Merkle Cave is located high in a ridge of moderately dipping Ordovician limestone beds in Berks County, Pennsylvania, 2 km northwest of Moselem Springs. The entrance is the highest point of the cave as its calcite-covered passages slope down-dip. During the initial exploration and survey in 1933, a hollow phallus size and shaped stalagmite was observed to be discharging water 0.3 m into the air. Charles Mohr (1986), the original explorer, did not believe there was any antecedent rainfall but could not be certain given the number of years since the event. The water-spout was about 22 m below the cave's entrance (Stone, 1953; Szukalski, 1986).

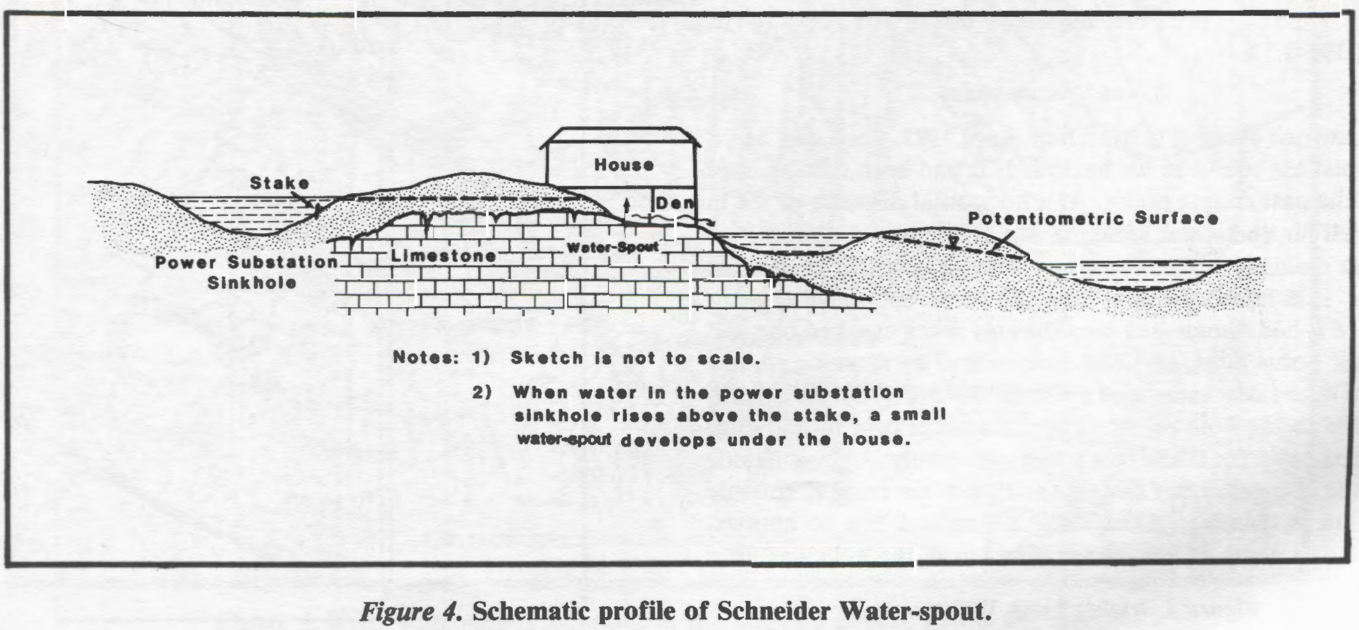

Figure 4. **Schematic profile of Schneider Water-spout.**

PFEIFFER WATER-SPOUTS

Chester Pfeiffer has often observed six to eight water-spouts in his cornfield, which is located in Kendall County, Texas, 5 km southeast of Boerne. The most recent water-spouts occurred in 1979 following 1.3 cm of local rainfall. There has been no discernible pattern to their occurrences. Usually the water-spouts have occurred after intense local rainfall but once they occurred with no rain at all. They have followed both wet and dry antecedent conditions, erupted in both spring and fall, have ranged in height from 0.15 m high "boils" to 1.3 m columns, and have lasted up to four days (Waters, 1984; Elliot, 1985).

POLJE WATER-SPOUTS

Milanović (1981) reports on water-spouts that occur in Yugoslavian poljes. The water-spouts erupt during floods and rise through the waters which cover the poljes' flooded floors. No details are given as to the water-spouts' numbers, duration, frequency or magnitude.

WATER-SPOUT MODELS

Due to the infrequent, unpredictable, and short-lived nature of water-spouts, it is very difficult to observe them as they occur. The authors constructed models made of water-filled barrels, buckets, and tubing to aid in the understanding of the water-spout phenomenon under various hydrologic regimes. The most important step in the modeling was to develop a mechanism that could create enough pressure to spray water over 13 m into the air or raise water columns to heights of over 7 m. The experiments led to the development of three possible models which would produce water-spouts—impulse pressure, artesian, and air pressure.

IMPULSE PRESSURE MODEL

This model is conceptually the simplest but probably the least common in karst systems. Impulse pressure water-spouts result from the sudden upward deflection of flood stage open conduit flow, to above the piezometric surface, by a constriction or an obstruction (Fig. 5). This model is similar to a wave breaking against a cliff to shoot water above the sea. According to the impulse model, water-spout discharge should rapidly taper off after the initial eruption. The duration of its geyser-type flow would be short-lived, dependent upon the continued availability of high velocity water and its head loss into the regolith, minor fractures in the rock, and around and beyond the obstruction itself. It was experimentally determined that placement of the deflecting obstruction at or near the point of discharge increases the water-spout's duration by decreasing the amount of head loss. A sufficient rise in the piezometric surface could change an impulse water-spout to an artesian water-spout.

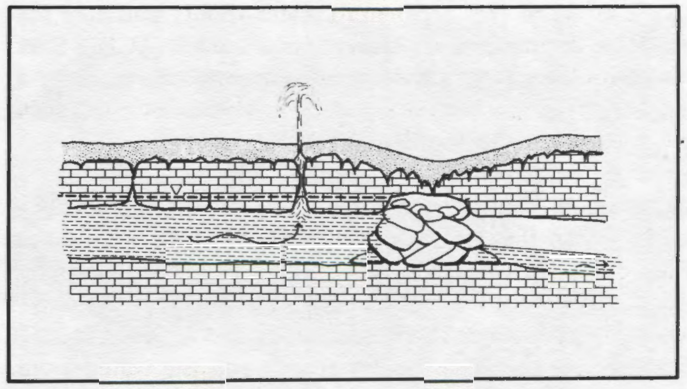

Figure 5. **Impulse pressure water-spout.**

ARTESIAN MODEL

Groundwater that is constricted in its flow builds up pressure (hydraulic head) and is referred to as artesian. Artesian springs are well known to sometimes manifest themselves as broad domal boils. Artesian water-spouts are intermittent springs whose form results from two constrictions. One constriction is located in the main conduit downgradient from the other constriction which is located at the surface. Water behind the conduit constriction is forced upward out the surface constriction under high pressure (Fig. 6).

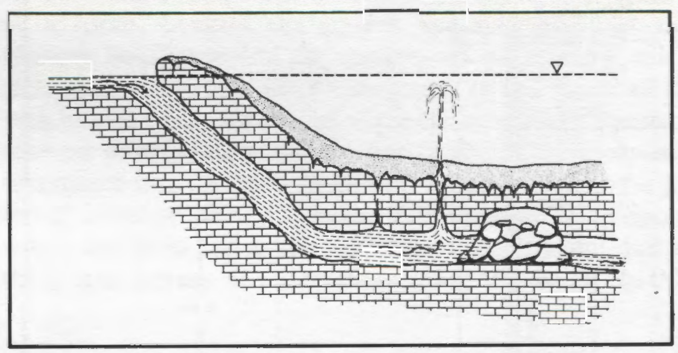

Figure 6. **Artesian pressure water-spout.**

The hydraulic continuity equation, $Q = VA$ (where Q = discharge, V = velocity and A = cross sectional area), shows that for a constant discharge, decreasing vent area increases water velocity and hence the height to which water can be ejected. The downstream constriction is also necessary because it increases the hydraulic head and hence water-spout discharge. Actual water-spout height depends upon total head, total head loss, local atmospheric pressure and cross sectional areas of the constrictions. Conduit transmissivity, as related to conduit size, determines the water-spout's duration.

Two artificial (yet accidental) water-spouts illustrate the principles of the artesian water-spout model. At Big Sink Cave the water-spout's narrow upper vent was created by a well hole. The downstream constriction was at or shortly beyond the sump (where the passage is filled with water) in the cave. Evidence for this constriction is indicated by a phenomenon known locally in Sinking Valley as "valley tides." When flood waters exceed the drainage rate of the Sinking Valley caves, the waters discharge from upper level entrances as wave-like surges (Hacker, 1985). If the caves transmitted the water more efficiently (had fewer hydraulic constrictions) then the "valley tides" and the water-spout would not occur.

The second example of an artificial artesian water-spout occurred at the Rich Pond Elementary School. Storm water collected from the school's roof, 4.6 m above the ground, fed into a buried cistern, then overflowed down an abandoned water well. For some time the cistern was also used for the disposal of ash from the school's furnace. In April 1983, following very wet antecedent conditions and an intense downpour of rain, a 2.4 m high column of water issued from the ground above the buried well and cistern. When the cistern had filled with furnace ash, storm water entering the cistern would flow over the ash and into the well (Fig. 7). Eventually the well, clogged with ash, could not accept any more drainage. Since the oversaturated ground could not store the water, the water pressure grew and discharged upward. The water-spout was observed to be active for over an hour (Melton, 1984).

Figure 7. **Rich Pond Elementary School Water-spout.**

AIR PRESSURE MODELS

The third and most complex water-spout model involves placing air under high pressure and using it to shoot water above the ground and piezometric surface.

Palmer (1984) suggested a possible model called "Hero's Fountain" (Fig. 8). This model uses air pressure as a means of displacing water up a vertical conduit. Although Hero's Fountain is easily set up in the lab, it is a very complex and unlikely system to occur in nature.

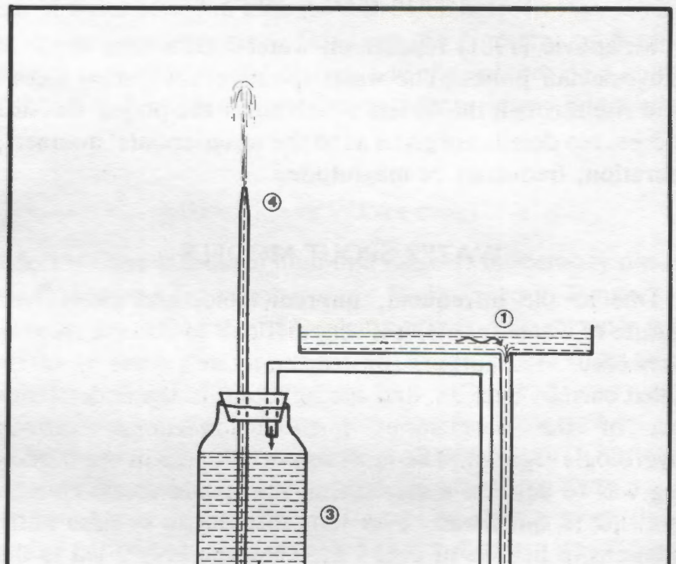

Figure 8. **Hero's Fountain.**

Figure 9 presents a similar yet somewhat simpler and more likely model for air pressure water-spouts. In Figure 9 a cave stream rises in response to large volumes of insurging runoff. A constriction in the stream passage results in an upstream stage rise into a chamber. The water rise is restricted by air trapped within the chamber and air pressure increases as the air is compressed. Eventually a small hole in

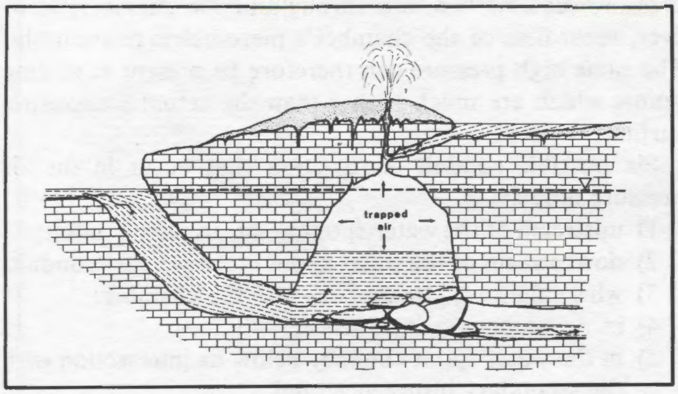

Figure 9. **Air pressure water-spout.**

the regolith blows open to vent the pressure. Water is provided for the water-spout by a second insurgence which attempts to drain to the chamber. This secondary insurging conduit, located above the piezometric surface of the swollen cave stream, is hampered from flowing freely into the chamber by the high air pressure and by constrictions in the secondary conduit which trap water and pressure-seal the chamber. The secondary insurgence can vary in size and volume from fracture flow and soil seepage to explorable cave passages. Water leakage into the water-spout chimney is shot out of the vent by the pressurized air in the chamber. The resulting water-spout is not a column of water, as with the other models, but a spray of water and air.

A most dramatic example of this scenario for high pressure within a cave stream passage occurred at the Doyel Valley Entrance to the Mammoth Cave System, Kentucky. This entrance was created during the winter of 1983–84 as a meter diameter drilled shaft. The shaft was cased by a 5 m long corrugated steel pipe. A locked metal lid covered the pipe to prevent unauthorized entry to the large rooms and passageways of the Hawkins-Logsdon River section of the cave below. Regional flooding in early May 1984 resulted in a rapid stage rise of 30–40 m within that portion of the cave. Displaced air moved up toward the new entrance, which is located at the top of a chamber overlooking the stream passage. Although the metal lid was not air tight, it did hamper air flow enough so that the 140 kg pipe was shot out of the hole, flipped upside down and banged against a tree 6 m away (Fig. 10, Quinlan, 1984)!

Three variations can occur in the air pressure model depending on:

1) the elevation of the primary piezometric surface relative to the secondary.
2) the elevation of the vent and chamber relative to the primary piezometric surface; and
3) the size and locations of constrictions within the conduit system.

An artesian modified air pressure water-spout occurs when the piezometric surface of the primary insurgence is

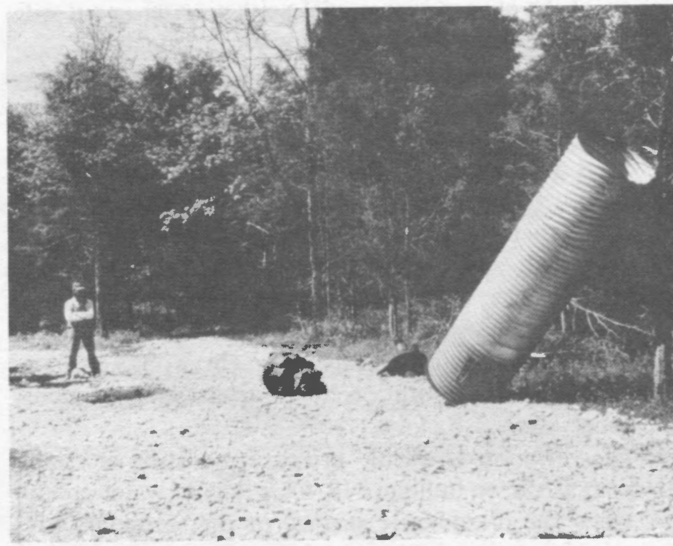

Figure 10. **Doyle Valley, entrance to Mammoth Cave. Casing blown out of hole due to high air pressure. Photo courtesy of James Quinlan.**

located higher in elevation than the secondary insurgence (Fig. 11). Air pressure builds in the chamber and is vented by the water-spout. Some air may even escape by bubbling up the secondary insurgence. Little water will be available for the water-spout, which would have a strong mist instead of a spray, because the greater hydraulic head of the primary insurgence and the compressed air prevents much leakage from the secondary insurgence. In this model all air may be eventually forced out of the chamber and a standard artesian water-spout would develop providing the secondary insurgence is sufficiently small to prevent venting of the internal pressure of the system. The artesian water-spout would not be as tall as the air pressure water-spout due to the greater density of water compared to that of air. In this

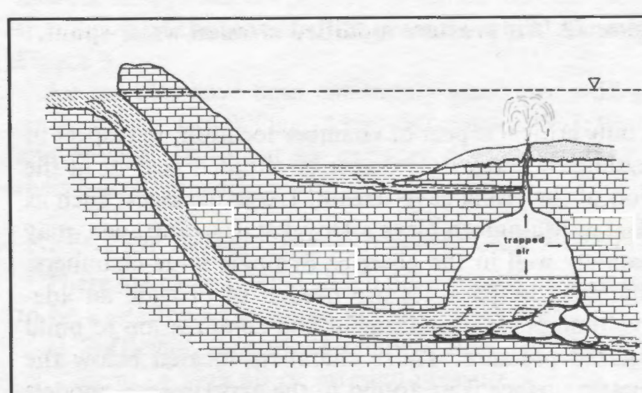

Figure 11. **Artesian modified air pressure water-spout.**

variation of the air pressure model neither water-spout will shoot higher than the primary piezometric surface.

If the water-spout vent is located below the primary piezometric surface, spray height would rise towards the elevation of that surface (frictional forces would prevent the water-spout from meeting or exceeding it). An artesian water-spout would eventually substitute for the air pressure water-spout when the trapped air has been vented. As the water-spout vent approaches the elevation of the primary piezometric surface, water-spout height would decrease correspondingly. If the water-spout vent is located above the primary piezometric surface, spray height would be less predictable and no substitution by an artesian water-spout would occur.

Another variation is an air pressure modified artesian water-spout as shown in Figure 12. This type of water-spout occurs when the piezometric surface of the secondary insurgence is higher than both that of the primary insurgence and the water-spout vent. In this case the water-spout would rise towards the height of the secondary piezometric surface. Given the appropriate conditions, Figure 12 also shows how an artesian water-spout could form by water from the secondary insurgence encountering a downward barrier of high air pressure.

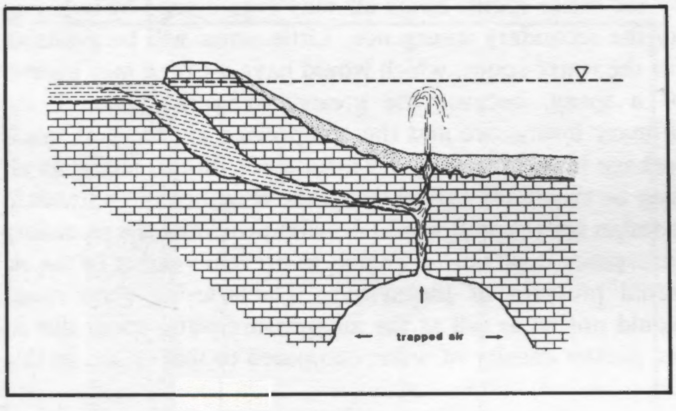

Figure 12. **Air pressure modified artesian water-spout.**

The only critical aspect of chamber location, in respect to the piezometric surface, is that it be situated near or at the elevation of the rising cave stream. Large passages, such as those below Mammoth Cave's Doyel Valley Entrance, may serve equally well in the absence of single large chambers. The chambers or passages are needed to provide an adequate volume of air displacement and compression to build the required pressure. Those chambers located below the piezometric surface were found in the experimental models to undergo greater compression, and thus greater pressure, than those chambers which extended above that surface. Air pressure remains constant throughout the chamber, however, regardless of the chamber's piezometric relationship. The same high pressure can therefore be present at venting points which are much higher than the actual piezometric surface.

Six possible conduit constriction sites occur in the air pressure model:

1) upstream of the water-spout in the primary conduit;
2) downstream of the water-spout in the primary conduit;
3) where the cave stream rises into the chamber;
4) in the secondary insurgence;
5) in the water-spout chimney below its intersection with the secondary insurgence; and
6) in the water-spout chimney above its intersection with the secondary insurgence.

These constrictions can occur in any of sixty-four possible combinations. Only two constrictions were found to be both necessary for water-spout development and to have an effect on water-spout behavior in the models. These two constrictions are located at the water-spout's vent and downstream from the chamber in the main stream passage. These constrictions control the pressure difference between the water-spout system and the outside atmosphere. The other constrictions are helpful in causing water blodkage which builds and maintains air pressure. Once these pressure sealing conditions are established, however, hydraulic pressure and trapped air pressure remain equal on both sides of those constrictions so they have little net effect upon the water-spout.

MODEL APPLICATIONS TO KNOWN WATER-SPOUTS

IMPULSE WATER-SPOUTS

Griffin Water-spout shows evidence of originating from impulse pressure. Buckberry Cave averages a 3–5 m depth below the ground surface, and trends towards the water-spout. During periods of intense rainfall a substantial amount of storm water runoff drains into the cave. In 1969 and 1975 downward movement of the cave's water was impeded by a high water table. The result, illustrated in Figure 13, was overflow routing of peak flow in the cave which erupted to the surface.

ARTESIAN WATER-SPOUTS

Water-spouts attributed to artesian pressure are Big Sink Cave, Merkle Cave, Normal Drive Sinkhole, Pfeiffer and Schneider Water-spouts. All these sites are topographic lows relative to the surrounding terrain. The Pfeiffer Water-spouts are examples of artesian pressure transmission over large distances because they have occurred without local rainfall.

Pressure transmission possibly of a different sort was displayed at Schneider Water-spout. Water rising from the

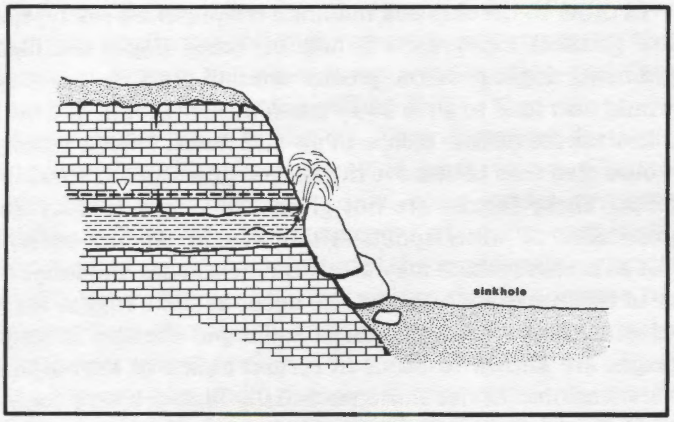

Figure 13. **Griffin Water-spout.**

water-spout was clear, yet water in the surrounding sinkholes (whose head apparently activated the water-spout) was very muddy. It is hypothesized that the clear water was groundwater either displaced upward by the rise in the water table, or perhaps that flow from the power substation sinkhole was pushing out the groundwater ahead of it before its muddy water could rise from the water-spout later (the water-spout remained clear for its entire duration). A third possibility is the filtration of the water by soil and bedrock, but this is unlikely given the conduit flow nature of karst and the short distances of travel involved.

Most glacial water-spouts are attributed or seem attributable to artesian pressure. However, hydrostatic pressure may be considerably increased by the dynamic tectonic and freeze-thaw nature of glaciers (Stenborg, 1968). Water trapped within the ice is often subjected to high pressures. Abrupt vertical release of that water can result in water-spouts (Paterson and Savage, 1970). Such water-spouts would usually occur only once.

Recurrent glacial water-spouts that have a regular periodicity also are a result of artesian pressure but are postulated to recur due to siphoning. Rucklidge (1956) describes how periodic overflow, and subsequent siphoning, from glacial ice-chambers may account for water-spout recurrence. Water-spouts in karst regions have not shown periodicities which could be explained by siphoning.

AIR PRESSURE WATER-SPOUTS

Long and Travelsted Water-spouts fit the criteria for air pressure water-spouts. They are located on topographic highs, are well above the highest local piezometric surfaces, sprayed air and water, made whistling noises and are located near major cave stream passageways (Wilcoxson's Cave stream is believed to extend under Long Water-spout). Reitz and Eskridge (1977) have described how blockage of cave streams results in increased upstream hydraulic pressure, regolith stoping and eventual sinkhole collapse by the upward injection of groundwater. Such a mechanism is likely to have occurred to develop the regolith shaft under Long Water-spout. At Travelsted Water-spout, downstream flow may be constricted by a very large collapse of the Lost River Cave's main stream passage.

A difference between the two water-spouts is the availability of a secondary water source. Travelsted Water-spout is located next to a sinkhole and storm water drainage well, either of which could serve as major secondary insurgences (Fig. 14). Long Water-spout, however, lacks a well defined secondary water source and probably obtains its water from seepage of the oversaturated regolith or small conduits, fractures or bedding planes in the limestone. Following heavy rains, the latter create small waterfalls in water wells of the Lost River Drainage Basin.

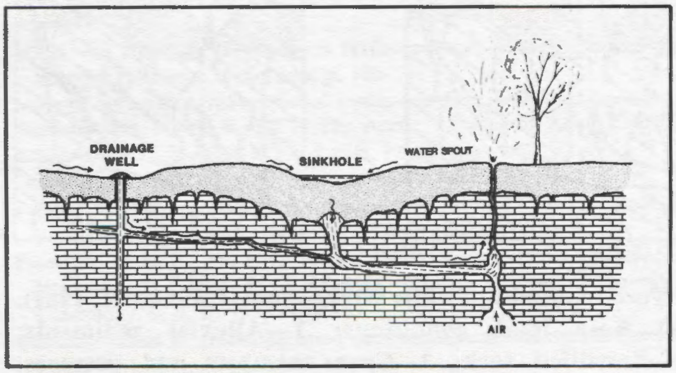

Figure 14. **Hypothesized water sources for Travelsted Water-spout.**

The polje water-spouts, described by Milanović (1981) are also air pressure water-spouts. As shown in Figure 15, air becomes trapped in caves by the rising water table. Concurrently, the floors of the poljes are flooded. Air pressure builds in the caves until vented through the regolith and the overlying floodwaters. The floodwaters on the floors of the poljes serve as the water-spouts' water source. When the air is fully vented floodwaters drain into the caves through the water-spouts' vents. The elevation of the water table, as shown in Figure 15, and the fact that surface water drains into the caves when the pressure is vented indicate the water-spouts are of the standard air pressure model illustrated in Figure 9.

Air bubbles have been commonly associated with glacial water-spouts (Rucklidge, 1956; Wiseman, 1963; Paterson and Savage, 1970) but air pressure does not appear to be their causative mechanism.

AREAS OF POTENTIAL WATER-SPOUT ACTIVITY

There are three factors which determine if an area is likely to be a site for water-spout activity. They are:

1) Sufficient subsurface conduit flow for the development of high air or artesian pressure.
2) A confining feature; usually a poorly permeable clayey regolith.
3) Low gradient topography.

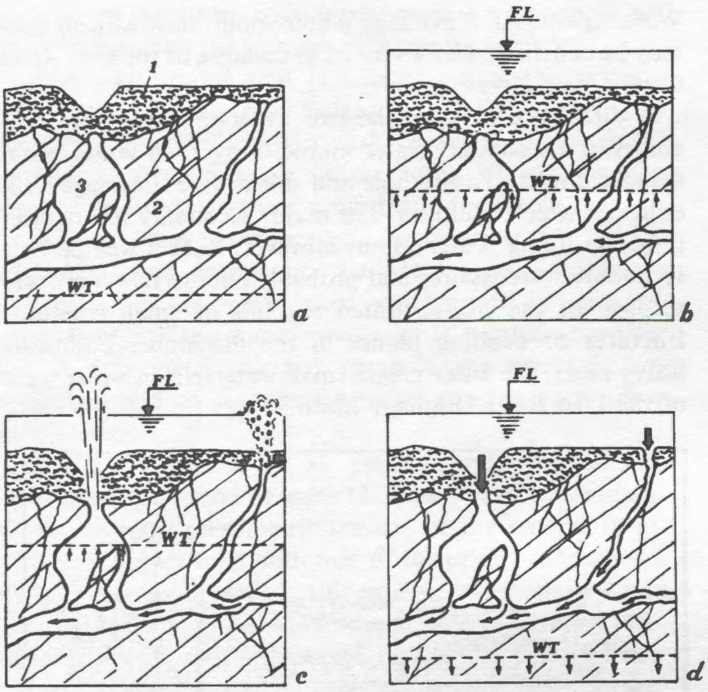

Figure 15. **Model of Polje Water-spouts (Milanović, 1981). A) Base level conditions: 1—Alluvial sediments; 2—Karstified rock; 3—Cave chambers and passages; WT—Water table. B) Polje is flooded (FL-Floodwater Level) and rising water table traps air in cave. C) Water-spouts erupt through the floodwaters as air pressure breaches the alluvial sediments. D) Trapped air has been vented and floodwaters descend through the cave channels to the water table.**

The first of these factors has already been discussed.

Many karst regions have only a thin veneer of soil covering the bedrock. Solutionally enlarged fractures often extend from the surface to the caves below. These open fractures allow ample opportunity for air to vent and water to discharge during rises in the water table. Under such conditions, subterranean air pressure would be atmospheric, artesian pressure would be non-existent, and no water-spouts would develop.

The known water-spouts occur under poorly permeable soils. The Lost River Groundwater Basin has a clayey regolith, often in excess of 10 m thick. Ponding is common in many of its sinkholes, illustrating the regolith's low permeability which effectively restricts air and water circulation. The same is true for Sinking Valley. Poljes are also known for their thick soil floors. Most of the central Texas karst has a very thin soil cover, yet the Pfeiffer Water-spouts are located within a relatively thick soiled, clay-rich area which is similar to the Lost River Basin/Sinking Valley regolith. The confining material of Merkle Cave's water-spout is a thick calcite deposit which blankets most of the bedrock in the cave.

In order to develop and maintain the preferred soil type, a low gradient topography is helpful. Steep slopes and high gradients might promote greater artesian pressure, but they would also tend to strip away much of the regolith and thus allow for the diffuse escape of air and water. High gradients would also tend to remove the needed downstream constrictions. These factors are not given to completely deny the possibility of water-spouts within steeply sloping terrain, but as matters which may affect their existence and longevity in those areas. Thick soils do occur in some rugged karst terrains, and exceedingly large and rapid changes in stage height are known to occur in certain alpine or near-alpine karst regions. Under those potentially high pressure conditions, water-spouts may occur.

A detailed plot is needed of the locations of glacial water-spouts to determine if impermeable cover and low relief are also important to their development. Seasonal thawing and refreezing could render surface ice impermeable in glacial ablation zones. Low relief areas of glaciers would tend to have fewer extensional fractures than high relief areas and would also drain less meltwater, hence increasing internal hydrostatic pressure.

CONCLUSIONS

Water-spouts are a phenomenon associated with the following factors:

1) Conduit flow.
2) Rapid and substantial flux in the conduit's stage height.
3) Features which confine air and water pressures until forceful venting of air, spray or water occurs.
4 Conduit system constrictions at the vent and downstream from the vent which create and maintain high air and water pressure.
5) Moderately thick impermeable soils.
6) Low gradient topography (tentative conclusion; more data is required).

Water-spouts can also be separated into three groups according to their origins:

1) Impulse Water-spouts—due to sudden upward deflection of peak conduit flow.
2) Artesian Water-spouts—due to artesian pressure.
3) Air Pressure Water-spouts—when trapped air within a subsurface chamber expels water descending from secondary sources.

Impulse and artesian water-spouts are found at relative topographic lows but air pressure water-spouts can be situated on topographic highs or lows and at elevations greater than the piezometric surface.

Water-spouts are geologically short lived features. Some occur only once to vent pressure and never recur because the vent remains open and prevents the buildup of pressure. Other water-spouts, especially those in regolith, may reseal with time and the process may be repeated. Eventually, the repetitive occurrence of high pressure will permanently enlarge or breach the water-spout's constriction and the pressure building mechanism will be lost.

Water-spouts occur in glaciers. Their form and development is analogous to water-spouts in karst regions. Glacial water-spouts are known to only occur under artesian pressure. Their greater frequency of occurrence and periodicity of eruption is a factor of the very dynamic glacial system. Future studies of water-spouts should continue to examine both glacial and karst water-spouts as each provides insight into the other.

An inherent bias and deficiency in this research is caused by the sparsity of karst water-spouts for examination and their limited areal extent to two Kentucky groundwater basins, an unusual Pennsylvania cave, poljes in Yugoslavia, and one Texas corn field. It is hoped that awareness of the water-spout phenomenon will soon increase, for only with a larger data base can a truly comprehensive and accurate appraisal be performed.

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Sincere appreciation is extended to Dr. William Beard, Department of Industrial Engineering and Technology at Western Kentucky University, for his aid in understanding fluid mechanics in confined pressure systems. Many thanks are given to Dr. Ronald R. Dilamater, Department of Geography and Geology at Western Kentucky University, Sara A. Heller, Associate Professor of the Geology Department at the College of Charleston, South Carolina, and Dr. James F. Quinlan, Mammoth Cave National Park, for their comments and suggestions on the manuscript. Deepest gratitude is also extended to all water-spout owners and other informants of water-spouts (recognized individually in the references) for sharing their knowledge and time.

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GROUNDWATER GEOCHEMISTRY IN WARM RIVER CAVE, VIRGINIA

JANET S. HERMAN

AND

MICHELLE M. LORAH*

Department of Environmental Sciences
Clark Hall
University of Virginia
Charlottesville, VA 22903

The processes of CO_2 outgassing, mixing of two carbonate waters, and calcite precipitation and dissolution define the chemical character of groundwater in Warm River Cave, Virginia. The compositions of the warm, cold, and mixed streams inside the cave are distinctive. The mixed stream is formed by the mixing of the warm stream, fed by a thermal spring, and the cold stream, fed by shallow carbonate groundwater. The water is always supersaturated with respect to CO_2 even relative to the elevated P_{CO_2} of the restricted cave atmosphere. Loss of CO_2 along the flow path drives the solution to supersaturation with respect to calcite. Physical evidence for calcite precipitation exists in the rimstone dams observed inside the cave. Greatest supersaturation with respect to calcite occurs during low-flow conditions in the summer when the cold shallow groundwater causes the least dilution of the concentrated thermal water inside the cave.

INTRODUCTION

Theoretically and experimentally, carbon dioxide outgassing, mixing of carbonate waters, and calcite precipitation have all been considered extensively. Still lacking in our approach, however, are field-based geochemical investigations of the interplay of these critical processes. Warm River Cave, Alleghany County, Virginia, has been of speleological interest for some time, mainly based on the reputation of the thermal spring issuing into the cave. In fact, Warm River Cave is the only known occurrence of a thermal spring in a cave in the Appalachians. There are other springs in the cave as well, however, providing some complexity to the hydrology and groundwater geochemistry of this system. The purpose of this paper is to describe the role of carbon dioxide flux, mixing of two carbonate waters, and calcite precipitation or dissolution in defining the geochemical character of the stream inside Warm River Cave.

The processes of carbon dioxide exchange and mixing of different carbonate waters exert a major control on the thermodynamic stability of calcite in a solution. The carbon dioxide content in carbonate groundwater typically reaches values ten to one hundred times greater than normal atmospheric P_{CO_2}, which is $10^{-3.5}$ atm or 0.03 vol % (Langmuir, 1971; Pearson et al., 1978; Butler, 1982). The CO_2 content of cave air has not been well documented (Troester and White, 1984), but it is generally lower than the values found in carbonate groundwaters (Ek et al., 1969; Troester and White, 1984; Villar et al., 1985). If a cave is well ventilated, the CO_2 content of the cave air will be close to that of the normal atmosphere. Thus, when carbonate groundwater enters a cave, the water typically loses CO_2 in an attempt to equilibrate with the lower CO_2 in the air (Holland et al., 1964; James, 1977). This exchange of CO_2 between solution and atmosphere is the dominant process causing supersaturation with respect to calcite in cave waters (Holland et al., 1964).

Mixing of one carbonate water with another solution that differs in chemical composition will also cause a shift in the saturation state of the water with respect to calcite. Mixing produces non-linear effects, because calcite solubility is a non-linear function of variables such as ion activity, partial pressure of carbon dioxide, ionic strength, and temperature (Wigley and Plummer, 1976). When all of these factors affect the mixing process, it is difficult to predict the thermodynamic state of the mixture. The relative volume proportions of each end-member in the mixture can play a large part in determining whether the resulting solution is undersaturated or supersaturated with respect to calcite. The theory describing the mixing process is well developed (for

*Present address: U.S. Geological Survey, 208 Carroll Bldg., 8600 La Salle Rd., Towson, MD 21204.

example, Bögli, 1964; Thrailkill, 1968; Runnels, 1969), but the relatively few field studies in limestone terranes have focused on the mixing of seawater with fresh carbonate groundwater (Back et al., 1986).

Field Site Description

The field site for this study lies in the thermal springs area of Virginia in the folded and faulted western anticlines of the Valley and Ridge province (Fig. 1). Warm River Cave is located along the western limb of the Warm Springs anticline at an elevation of 670 m. The Tuscarora Sandstone, which marks the Ordovician-Silurian boundary, forms the mountain ridges. The uppermost Ordovician section is comprised of interbedded sandstones, siltstones, and mudstones. The rest of the Ordovician section consists of a thick sequence of Lower Ordovician dolomites and Middle and Upper Ordovician limestones, many of which contain significant shale interbeds. Large joint openings in the Eggleston Formation, a gray limestone that lies beneath the Reedsville Formation, form the passages and crawlways of Warm River Cave (Rader and Gathright, 1984).

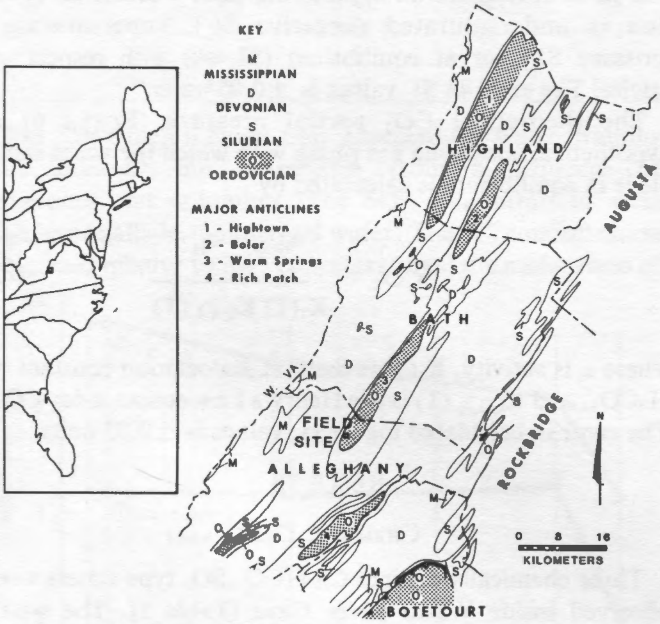

Figure 1. **Geologic map showing location of Warm River Cave and Falling Spring Creek, Alleghany County, Virginia (after Rader and Gathright, 1984).**

Like other thermal springs in this area of Virginia and West Virginia, the spring issuing in Warm River Cave appears to be fed by deeply circulated meteoric water that was heated under a normal geothermal gradient (Hobba et al., 1979; Severini and Huntley, 1983; Rader and Gathright, 1984). This spring water flows through the cave as a warm stream and converges with a cold stream derived from shallow groundwater. The mixed stream continues flowing through 290 m of cave passage, approximately 37 m below the surface, before resurging as Falling Spring on the surface (Holsinger, 1975). Although the warm stream can be followed all the way upstream from the junction of the two streams to where the hot spring issues, breakdown has made it impossible to traverse the entire length of the cold and mixed streams. On the surface, Falling Spring emerges from the large breakdown pile that closes off Warm River Cave.

METHODS

Field Methods and Sample Collection

Field trips for the collection of water samples from Warm River Cave were completed on May 20, July 28, and December 16, 1984. Sample collection sites were located along the accessible parts of the warm, cold, and mixed streams (Fig. 2). Along the warm stream, samples were col-

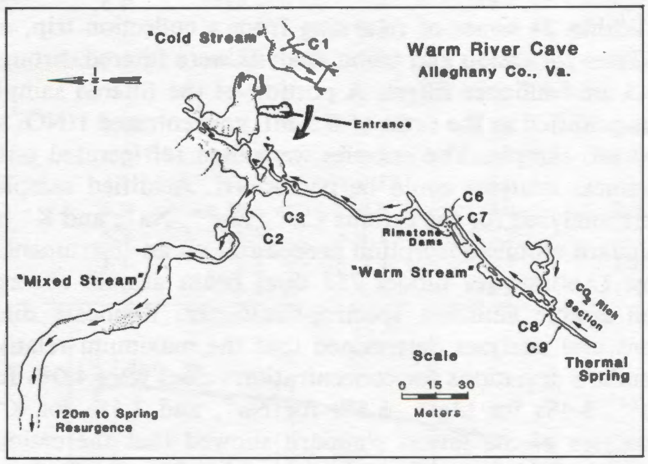

Figure 2. **Map of Warm River Cave showing locations of sample collection points.**

lected where the hot spring issues to form the stream (C-9, C-8), at two sites downstream of the hot spring (C-7, C-6), and directly above the junction of the warm and cold streams (C-3). One sample was taken from the mixed stream (C-2) approximately 25 m downstream of the junction and one from the cold stream (C-1) approximately 30 m above the junction.

At each site two 250-mL samples were collected in acid-washed polyethylene bottles for subsequent laboratory analysis. Additionally, a 100-mL sample was collected in an acid-washed polyethylene bottle for pH measurement. To minimize CO_2 loss from solution, all samples were tightly capped with no headspace in the bottle. Temperature was measured in the cave, but *in situ* pH measurements were impractical. The pH was determined in the laboratory after the May field trip. On the July and December field trips pH was measured at the mouth of the cave promptly at the end of the collection trip with an Orion model 231 pH/ion meter and an Orion Ross combination pH electrode. Before pH measurement the samples and buffers were placed in a water bath to bring them to the same temperature (22°C in July and 13°C in December).

The CO_2 content of the cave atmosphere was measured using Dräger tubes during the July and December field trips. A hand-operated bellows pump draws a known volume of air through a glass tube containing hydrazine hydrochloride which reacts with CO_2 and turns purple. The advance of the color front in the calibrated glass Dräger tube gives a measure of the CO_2 as volume percent of the atmosphere. This device has a precision of only ± 10% but is easily portable for field measurements (Troester and White, 1984). CO_2 measurements were taken at three sites in July (C-2, C-6, C-9) and at five sites in December (C-2, C-3, C-6, C-8, C-9).

LABORATORY METHODS

Within 24 hours of returning from a collection trip, all samples for cation and anion analysis were filtered through 0.45 μm Millipore filters. A portion of the filtered sample was acidified at the ratio of 0.5 mL concentrated HNO_3 to 100 mL sample. The samples were then refrigerated until chemical analyses could be performed. Acidified samples were analyzed for the cations Ca^{2+}, Mg^{2+}, Na^+, and K^+ by standard atomic absorption procedures on an Instrumentation Laboratories model 751 dual beam atomic absorption/atomic emission spectrophotometer. Replicate dilutions and analyses determined that the maximum relative standard deviations for concentration values were 4.0% for Ca^{2+}, 3.4% for Mg^{2+}, 6.8% for Na^+, and 3.5% for K^+. Analyses of the lowest standard showed that the cations were detectable at concentrations of 0.091 mg/L Ca^{2+}, 0.0096 mg/L Mg^{2+}, 0.074 mg/L Na^+, and 0.056 mg/L K^+. Unacidified samples were analyzed for the anions SO_4^{2-}, F^-, Cl^-, NO_3^-, and PO_4^{3-} by Ion Chromatography on a Dionex model 14 system. EPA standards for F^- and SO_4^{2-} were analyzed, and the concentrations were determined to be within the range given by EPA for a 95% confidence interval.

Duplicate alkalinity titrations were performed with 0.02 N Baker HC1 on 50 mL of each sample. Titration endpoints were taken to be the inflection points in the cumulative acid added *vs*. pH curve. Alkalinity values were converted to HCO_3^- which was assumed to be the only species contributing significantly to alkalinity. The duplicate titrations showed that analytical errors in HCO_3^- concentrations were less than 2%. An earlier comparison of titrations performed on both unfiltered and filtered portions of samples showed the differences between these alkalinities were within the error of titration, so all subsequent measurements were performed on unfiltered samples (Herman and Lorah, 1986).

Because a great deal of time was spent on exploring the cave during the May field trip, the pH samples were measured in the laboratory at room temperature. A Corning model 135 pH/ion meter equipped with an Orion Ross combination pH electrode was used.

DATA ANALYSIS

The data analysis rests primarily on defining the saturation state of the waters with respect to calcite and carbon dioxide. The raw chemical concentration data and the field pH and temperature for each sample were input to WATEQF, a computerized geochemical model (Plummer et al., 1976), using the program WATIN (Moses and Herman, 1986) to create input files. The WATEQF computer code, based on thermochemical data, calculates the distribution of species in solution. Appropriate temperature corrections are made to the equilibrium constants and activity coefficient expressions.

The saturation state of the water with respect to solid mineral phases is then obtained. The saturation index for calcite (SI_c) is the logarithm of the ratio of the ion activity product (IAP(T)) to the equilibrium solubility product (K_c(T)) at sample temperature.

$$SI_c = \log [\, IAP(T)/K_c(T)\,] \qquad (1)$$

The value of the saturation index indicates whether the solution is undersaturated (negative SI_c), supersaturated (positive SI_c), or at equilibrium ($SI_c = 0$) with respect to calcite. The error in SI_c values is ±0.05 units.

The theoretical CO_2 partial pressure (P_{CO_2}) of a hypothetical coexisting gas phase with which the water sample is in equilibrium is calculated by

$$P_{CO_2} = \frac{a_{HCO_3^-}\; a_{H^+}}{K_1(T)\, K_{CO_2}(T)} \qquad (2)$$

where a_i is activity, K_1(T) is the first dissociation constant of H_2CO_3, and K_{CO_2} (T) is the Henry's Law constant for CO_2. The error in calculated log P_{CO_2} values is ±0.03 units.

RESULTS

CHEMICAL DATA

Three chemically distinct Ca-HCO_3,SO_4 type waters were observed inside Warm River Cave (Table 1). The warm stream (C-9 to C-3) had higher concentrations of all dissolved species and higher temperatures than the cold stream (C-1) or mixed stream (C-2). In July, Ca^{2+} and HCO_3^- concentrations of the warm stream were as high as 232 mg/L and 393 mg/L, respectively, while the cold stream had 159 mg/L Ca^{2+} and 276 mg/L HCO_3^-. The temperatures of the warm stream ranged between 25° and 35°C, while the cold stream temperatures varied from 16° to 22°C. Mixed stream samples had concentrations and temperatures intermediate to those of the cold and warm streams.

The cave waters all had Ca^{2+} and HCO_3^- concentrations in the range commonly found in limestone groundwaters. The molar Ca^{2+}:Mg^{2+} ratios of the thermal spring varied from

Table 1. Chemical composition of water samples from Warm River Cave. Concentrations of all dissolved species are expressed as mg/L.

Sample	T (°C)	pH	HCO_3^-	Ca^{2+}	Mg^{2+}	Na^+	K^+	F^-	Cl^-	SO_4^{2-}
5-20-84										
C-9	28.0	6.72	335	180	32.7	4.3	18.2	1.2	3.6	341
C-8	28.0	6.66	338	177	32.0	5.3	18.2	1.2	3.6	343
C-7	26.0	6.86	315	162	28.8	4.4	16.1	1.2	3.2	301
C-6	26.0	6.88	314	161	28.6	4.6	16.0	1.1	3.2	295
C-3	24.5	6.99	299	142	25.0	2.9	8.0	1.0	2.8	248
C-1	16.0	7.12	210	94	14.1	2.0	6.5	0.5	2.3	140
C-2	18.5	7.11	219	102	15.8	3.4	8.4	0.6	2.4	161
7-28-84										
C-9	35.0	6.65	392	232	47.3	6.9	26.2	1.6	4.2	431
C-8	35.0	6.71	393	232	47.2	6.8	26.2	1.6	4.2	431
C-7	32.0	7.38	387	217	45.4	6.8	26.1	1.6	4.2	434
C-6	32.0	7.43	386	217	45.2	6.9	27.0	1.6	4.2	438
C-3	27.0	7.00	359	204	36.2	6.1	19.7	1.2	3.4	327
C-1	22.0	7.24	276	159	26.1	3.7	13.7	0.9	2.9	244
C-2	25.0	7.19	298	167	28.0	4.4	14.9	1.0	3.0	269
12-16-84										
C-9	27.5	6.69	300	168	21.8	3.9	13.5	0.9	3.0	266
C-8	27.5	6.66	300	168	21.5	4.2	13.4	0.9	3.0	270
C-7	27.0	6.89	299	167	22.2	3.7	13.3	0.8	3.0	256
C-6	27.5	6.90	299	166	22.2	5.9	15.8	0.8	3.0	256
C-3	27.5	6.86	296	171	25.9	5.5	15.1	1.1	3.2	287
C-1	17.0	6.93	212	111	12.7	1.8	6.7	0.4	2.7	128
C-2	21.5	6.95	239	120	14.6	2.4	8.5	0.6	2.8	171

2.9 to 5.3, which is lower than expected for water draining pure litestone but reasonable from a sequence of limestones and dolomites. The SO_4^{2-} concentrations were high, especially in the thermal water. The K^+ concentration is elevated relative to Na^+ concentrations; the molar ratio of

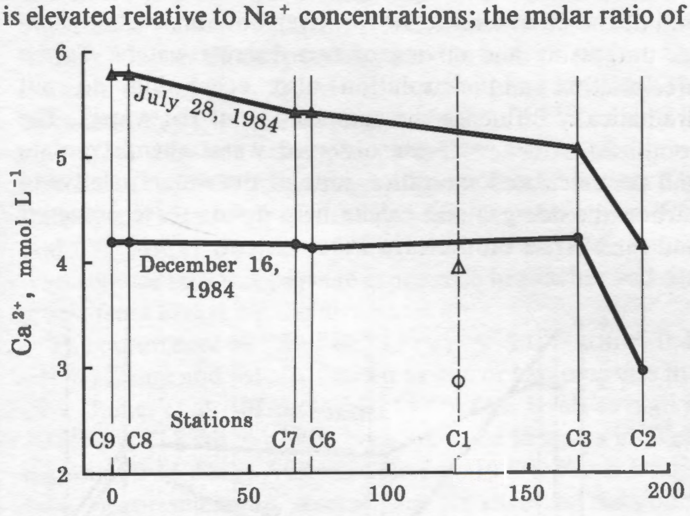

Figure 3. **Millimolar Ca^{2+} concentration *vs.* distance along the flow path. Warm stream samples are C-9 through C-3. The mixed stream was sampled at C-2. The open symbols indicate cold stream samples (C-1) collected above the junction with the warm stream, and they are not located directly on the same flow path as the other samples. July data are plotted as triangles, and December data are plotted as circles.**

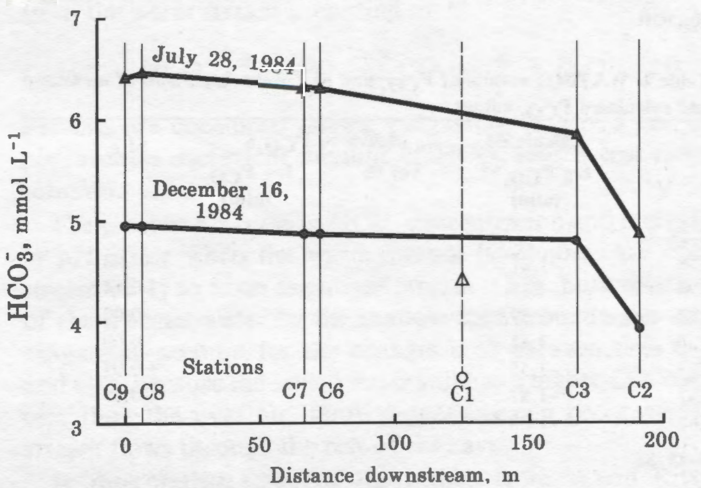

Figure 4. **Millimolar HCO_3^- concentration *vs.* distance along the flow path.**

K^+:Na^+ varied from 1.4 to 2.5. Cl^- and F^- are present in low concentrations. NO_3^- and PO_4^{3-} concentrations were below 5 and 1 mg/L respectively. The pH values of the waters ranged from 6.65 to 7.43. Seasonally, concentrations of dissolved ions were higher in July than in May or December.

Downstream decreases in concentrations, especially for Ca^{2+} and HCO_3^-, were observed (Figs. 3 and 4). The greatest drop in Ca^{2+} and HCO_3^- concentrations occurred between the warm stream at site C-3, which lies above the junction of the warm and cold streams, and the mixed water (C-2). Although some fluctuation in pH values was observed, pH generally increased downstream (Fig. 5).

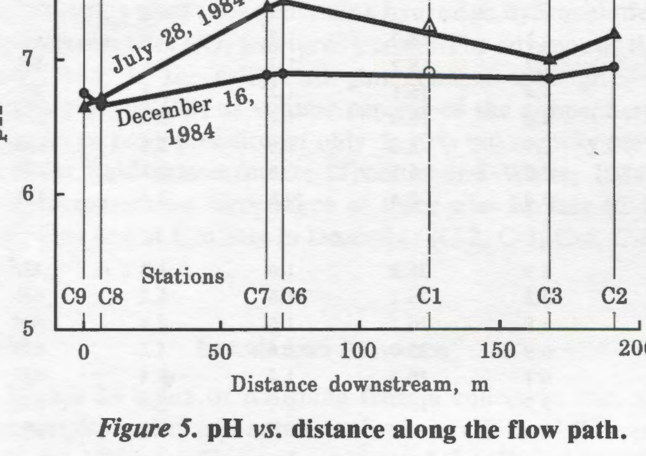

Figure 5. **pH *vs.* distance along the flow path.**

SATURATION STATES

The results of the WATEQF calculations show the theoretical P_{CO_2} and the saturation state with respect to calcite of the cave waters (Table 2). The waters were always supersaturated with CO_2. The saturation state with respect to calcite is more variable and is strongly influenced by season.

Table 2. WATEQF results of P_{CO_2} and SI_c, and comparison of measured and calculated P_{CO_2} values.

	Calculated log P_{CO_2}** (atm)	Measured P_{CO_2}* vol %	log P_{CO_2} (atm)	SI_c
5-20-84				
C-9	-1.21			-0.08
C-8	-1.15			-0.14
C-7	-1.39			-0.02
C-6	-1.41			0.00
C-3	-1.55			+0.03
C-1	-1.87			-0.23
C-2	-1.83			-0.16
7-28-84				
C-9	-1.04	1.5	-1.8	+0.08
C-8	-1.10			+0.14
C-7	-1.80			+0.73
C-6	-1.85	1.0	-2.0	+0.78
C-3	-1.47			+0.26
C-1	-1.85			+0.26
C-2	-1.75	0.3	-2.5	+0.29
12-16-84				
C-9	-1.23	1.5	-1.8	-0.17
C-8	-1.20	1.0	-2.0	-0.20
C-7	-1.44			+0.03
C-6	-1.44	0.6	-2.2	+0.04
C-3	-1.41	0.1	-3.0	0.00
C-1	-1.67			- 0.33
C-2	-1.62	0.1	-3.0	- 0.18

*P_{CO_2} obtained from Dräger tube measurements of the atmosphere.
**P_{CO_2} calculated from water analyses using WATEQF.

Inside Warm River Cave the theoretical P_{CO_2}'s are extremely high for the warm, cold, and mixed streams (Table 2 and Fig. 6). At the hot spring P_{CO_2} ranged from $10^{-1.23}$ to $10^{-1.04}$ atm. On each trip the lowest calculated P_{CO_2} for the cave samples occurred at the cold stream (C-1) with values ranging from $10^{-1.67}$ to $10^{-1.87}$ atm. These P_{CO_2} values, which were calculated for the hypothetical gas phase that would have been in equilibrium with the water samples, were distinctly higher than the CO_2 content of the cave atmosphere as measured by Dräger tubes (Table 2). Thus, the cave waters were supersaturated with respect to the CO_2 in the restricted cave atmosphere. Although both the calculated and measured P_{CO_2} values generally decreased downstream inside the cave (C-9 to C-2), the calculated P_{CO_2} remained consistently larger than the measured values at all sites.

The cave waters always reached supersaturation with respect to calcite at some point along the flow path (Table 2, Fig. 7). All of the warm, cold, and mixed stream samples were supersaturated in July. However, the warm stream was slightly supersaturated at only one site (C-3) in May and at two sites (C-7, C-6) in December. The cold and mixed stream samples were undersaturated in these spring and winter months. The calcite saturation indices increased along the warm stream and then dropped at the mixed stream.

DISCUSSION

The two major processes controlling the chemical evolution of the waters inside Warm River Cave are carbon dioxide outgassing and mixing of two discrete waters. Calcite precipitation and dissolution also occur but do not dramatically influence the composition of the waters. The combined evidence of the observed water chemistry data and the calculated saturation state of the waters relative to carbon dioxide gas and calcite help define these processes and their effect on the cave water system.

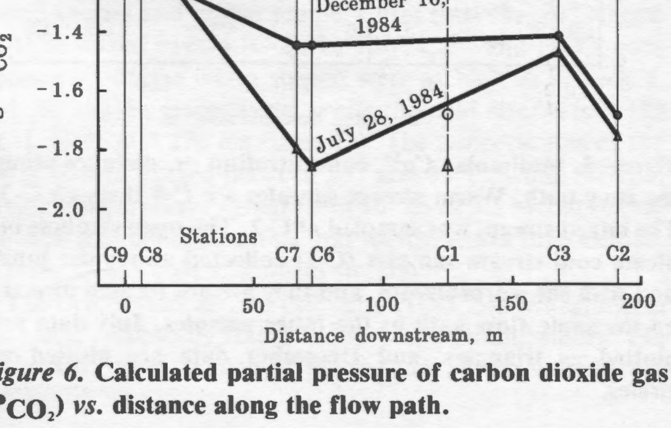

Figure 6. **Calculated partial pressure of carbon dioxide gas (P_{CO_2}) *vs.* distance along the flow path.**

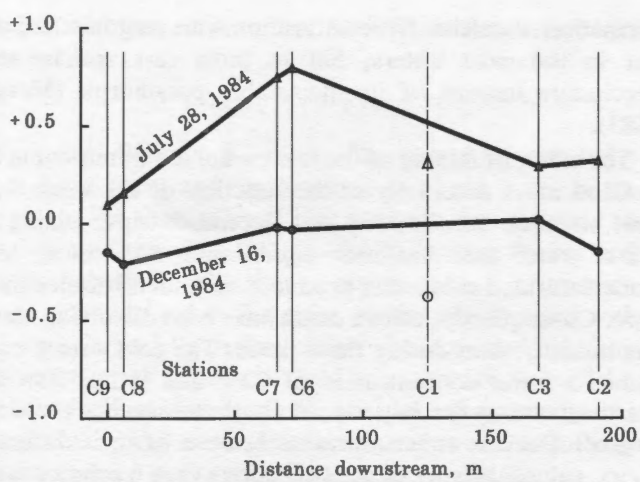

Figure 7. **Saturation state with respect to calcite (SI_c) *vs.* distance along the flow path.**

CARBON DIOXIDE OUTGASSING

Because the CO_2 content of all the cave waters is distinctly higher than the CO_2 content of the cave atmosphere (Table 2), a strong concentration gradient acts to drive CO_2 out of solution. As the thermal spring issues inside the cave, the CO_2 gas has its first opportunity to escape the hot carbonate groundwater. The thermal spring lies beyond a partial sump, which is an area where the cave ceiling nearly touches the water's surface and greatly restricts air circulation into the passage. The two sampling sites immediately downstream of the thermal spring, C-9 and C-8, are located beyond the sump in a narrow passage that contains approximately 8 inches of air space between the water's surface and the cave ceiling (Fig. 2). At the two sampling locations the calculated P_{CO_2} of the water is as high as $10^{-1.04}$ atm (9.12 vol %). A CO_2-rich atmosphere develops beyond the sump because of the CO_2 outgassing and poor air circulation. The directly measured P_{CO_2} of the cave air ranged between $10^{-2.0}$ and $10^{-1.8}$ atm (1.0 to 1.5 vol %) at sites C-9 and C-8. Cavers who venture into this passage experience headaches and dizziness from breathing the air.

The occurrence of "foul air" ($P_{CO_2} > 10^{-2.40}$ atm or 0.40 vol %) is rare and usually limited to one or two passages in a cave (James et al., 1975; James, 1977). CO_2 levels as high as $10^{-0.92}$ atm (12 vol %) have been reported in caves in Wellington and Molong, Australia (James, 1977). From Dräger tube measurements in several foul air caves in Bungonia, Australia, James (1977) found CO_2 concentrations in the air between $10^{-1.55}$ atm (2.8 vol %) and $10^{-1.35}$ atm (4.5 vol %). The major sources of CO_2 in the Bungonia caves are believed to include (1) evolution of CO_2 from carbonate waters, (2) production of CO_2 by microorganisms, and (3) respiration of plants and animals. The present work in Warm River Cave shows that foul air can be caused solely by CO_2 outgassing from CO_2-rich thermal water. Organic detritus on which microorganisms live could not be washed upstream to this isolated sump, and little plant or animal life exists in the cave.

As the warm stream leaves the restricted environment beyond the sump, the P_{CO_2} of the warm water drops significantly from continued outgassing (Fig. 6). Between the thermal spring (C-9) and the downstream end of the warm stream (C-3) the P_{CO_2} of the water decreases by approximately 65% to a value of $10^{-1.50}$ atm (3.16 vol %). Despite this decline in the CO_2 content of the warm water, equilibrium is not attained with the cave atmosphere. The CO_2 concentration of the cave air also decreases downstream of the sump from ventilation and mixing with normal outside air. At the downstream end of the warm stream the cave air has a low P_{CO_2} of $10^{-3.0}$ atm (0.1 vol %), which is a 93% decrease from the atmospheric CO_2 content upstream of the sump. The sampling sites downstream of the sump lie in more open passages and are closer to the cave entrance. For cave air measurements in Tytoona Cave, Pennsylvania, Troester and White (1984) observed that degassing from a carbonate stream raised the P_{CO_2} of an isolated cave atmosphere to a maximum of $10^{-2.40}$ atm (0.40 vol %), but then mixing with outside air diluted the CO_2 by as much as 50%.

A general decrease in HCO_3^- concentration (Fig. 4) and an increase in pH downstream (Fig. 5) reflect the loss of CO_2 from the warm stream according to

$$H^+ + HCO_3^- \rightleftarrows H_2CO_3 \rightleftarrows CO_2(g) \uparrow + H_2O \qquad (3)$$

Protons are consumed during outgassing to give a rise in pH, and an equivalent amount of HCO_3^- ions is lost from solution.

The greatest decrease in HCO_3^- concentration and increase in pH occur when the warm stream (C-3) joins the cold stream (C-1) to form the mixed stream (C-2). Both dilution of the thermal water by the shallow cold groundwater and outgassing account for the changes seen between sites C-3 and C-2. Because the mixed water still has a higher CO_2 content than the cave air, more outgassing can occur as the stream flows through the rest of the cave.

In interpreting some of the results from Warm River Cave, two possible sources of error must be considered. The pH values may be erroneously high if CO_2 outgassed from the water samples between the time of collection and measurement. The samples collected in May are especially suspect because they were taken to the laboratory before pH was measured. Calculations of theoretical P_{CO_2} values are strongly affected by inaccurate pH measurements. An error of 0.02 pH units would change the P_{CO_2} by approximately 5% in the opposite direction of the pH error (Hobba et al., 1979). Outgassing of CO_2 would have been limited by two factors: (1) water samples were collected in tightly capped polyethylene bottles with no headspace and (2) CO_2 is more soluble at cooler temperatures, and sample temperatures decreased during transport.

Dilution of the warm stream by shallow groundwater at poorly defined locations may complicate the simple concept of the flow path presented here. During the cave trips, seepage of colder water could be felt in some areas along the warm stream. Although the warm stream sample C-3 was believed to be upstream of the junction, cold water could have been seeping under the breakdown and already mixing with the warm water at that site. These undefined areas of dilution would account for the fluctuations that were sometimes observed in the chemical composition of the warm stream. For example, on the July trip pH increases along the warm stream until a sudden drop is seen between the last two sites (C-6, C-3). A decrease in temperature and concentrations of all dissolved constituents also occurs there (Table 1). Overall dilution of the warm water appears to be greatest during high-flow conditions in the winter and spring, when more shallow cold groundwater is available to enter the cave system. The water temperature immediately downstream of the thermal spring (C-9) was only 28°C and 27.5°C in May and December respectively, while a temperature of 35°C was observed on the July cave trip.

CALCITE PRECIPITATION

The thermal spring water is initially near equilibrium with respect to calcite (Table 2). This fact is not surprising as the groundwater feeding the spring travels to great depths through thick sequences of carbonate rocks. Long contact time with limestone and elevated water temperature allow the groundwater to reach equilibrium with respect to calcite (Helz and Sinex, 1974; Hobba et al., 1979). The calcite saturation index for the spring water indicates slight undersaturation in May and December (–0.08 and –0.17, respectively) when dilution of the deeply circulated groundwater by shallow cold groundwater was most likely.

As the water flows along the warm stream, the saturation state of the solution with respect to calcite increases (Fig. 7). The highest saturation states were observed on the July trip when saturation indices increased from +0.08 to +0.78 downstream. The shift in saturation state is linked to CO_2 outgassing. As CO_2 is lost from solution, the equilibrium solubility of calcite decreases, and the water becomes supersaturated (Jacobson and Langmuir, 1970). Consequently, calcite precipitation can occur

$$Ca^{2+} + 2HCO_3^- \rightleftarrows CaCO_3(s) + H_2O + CO_2(g)\uparrow \quad (4)$$

Rimstone dams provide physical evidence of calcite precipitation in Warm River Cave. These calcite dams are seen along the warm stream, particularly near site C-6 which lies in a large passage called the Rimstone Pool Room by cavers (Douglas, 1964).

Concentrations of Ca^{2+} and HCO_3^- generally decrease downstream, especially on the July trip (Figs. 3 and 4). The most likely chemical sink for Ca^{2+} in this system is in the formation of calcite. Supersaturation with aragonite did occur in the cave waters, but in most cases calcite will precipitate instead of its metastable polymorph (Morse, 1983).

The effect of mixing of the two carbonate waters could be defined most accurately at the junction of the warm and cold streams. On the May and December trips, mixing of warm water that was near equilibrium with calcite and undersaturated cold water produced an undersaturated mixture. Consequently, calcite could have been dissolving along the mixed stream during these times. The cold stream contained a lower concentration of Ca^{2+} and HCO_3^- than the warm stream on the July trip, but both streams had the same degree of calcite supersaturation because of their different P_{CO_2} values. Mixing of the two waters gave a solution with a slightly higher degree of supersaturation. For all three cave trips a great drop of Ca^{2+} and HCO_3^- concentration is seen between the warm stream sample, C-3, and the mixed stream, C-2. These compositional changes result mainly from dilution of the warm water during mixing, not from calcite precipitation.

The study of the streams in Warm River Cave reveals that the saturation state of the water issuing to Falling Spring on the surface is largely controlled by the mixing of the two carbonate waters. Other researchers (Hobba et al., 1979; Helz and Sinex, 1974) have postulated that Falling Spring consisted of a mixture of deep thermal groundwater and shallow groundwater; however, the waters inside Warm River Cave had not been investigated previously to confirm this hypothesis.

CONCLUSIONS

The processes of carbon dioxide outgassing, mixing of two carbonate waters, and calcite precipitation and dissolution all influence the chemical evolution of the stream inside Warm River Cave. The highly concentrated thermal groundwater emerging inside the cave is initially near equilibrium with respect to calcite but is supersaturated with CO_2. Because the water has a higher CO_2 content than the cave air, CO_2 outgassing occurs along the warm stream and drives the solution toward supersaturation with respect to calcite. Minor calcite precipitation forms rimstone dams in the warm stream. The thermal water mixes with the cold stream fed by shallow carbonate groundwater approximately 200 m downstream of the thermal spring. Some dilution of the thermal water also occurs at undefined locations along the warm stream, especially during high-flow conditions in the spring and winter. The shallow cold groundwater has a lower Ca^{2+} and HCO_3^- concentration than the thermal water throughout the year; but, the cold stream is undersaturated with respect to calcite in the spring and winter and slightly supersaturated with calcite in the drier months. During times of high flow, mixing forms a solution that is undersaturated; however, the mixed water is supersaturated with respect to calcite during low-flow conditions in the summer.

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We thank William B. White for suggesting we study Warm River Cave and for teaching us about caves in the first place. We thank David Hubbard for first showing us Warm River Cave. We are grateful to Burton Parker and Gusztav Asboth for allowing us access to their properties. We are also indebted to the many people who assisted with field work, especially Jeffrey Sitler who provided help and transportation on all of the field trips. Butler Stringfield, Rod Morris, Fred Daus, and Bill Murray led us through the cave, and they and Carol Wicks, Alan Howard, and Patsy Howard assisted in the collection of water samples.

We also thank Carl Moses for his patient instruction on the atomic absorption and Ion Chromatography instruments and Isabelle Cozzarelli for helping with the laboratory work. Kimberly Hoffer provided helpful comments on an early version of the manuscript. Financial support was provided by the U.S. Geological Survey (U.S.-Spain Joint Committee for Scientific and Technological Cooperation grant number 83-007) and the University of Virginia.

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Discussion: The Deflected Stalactites of Dan-Yr-Ogof. Donald G. Davis, 5311 309 Rd., Parachute, Colorado 81635.

John P. Sevenair's lucid and persuasive paper (*NSS Bull.* 47:28–31, Oct. 1985) considers two possible mechanisms for non-vertical stalactites: deflection during original growth; and deflection after growth by tilting of the attachment. I would like to point out a third possibility: deformation of old, originally-straight stalactites by differential impregnation with seepage-deposited minerals.

I suggest this as the most likely cause of curving in stalactites found in certain relatively dry caves in the western U.S., including Silent River Cave, Arizona, and Carlsbad Cavern, New Mexico. Such stalactites are scattered through various parts of Carlsbad, notably the Left Hand Tunnel. These are typically slender stalactites, up to four feet long, but unlike those in the Welsh cave, their deflection (frequently up to 10°, sometimes more) is attained in a smooth curve, not a series of variably-angled segments (Fig. 1).

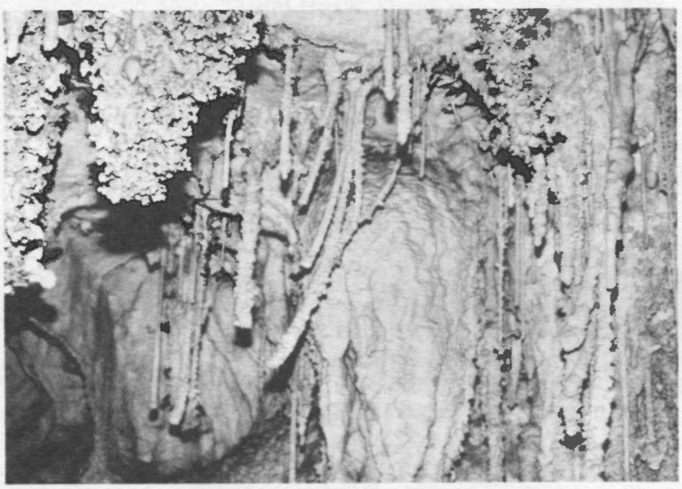

Figure 1. **Curved stalactites, left hand tunnel, Carlsbad Cavern.**

This curvature is seen only in stalactites which have ceased to drip and have been more or less coated with fine-grained crusty and/or coralloidal deposits which appear to have been deposited by slow seepage. Their directions are variable but the curvature is generally concave toward the cave's interior, convex toward the cave entrance. They are found in passages with noticeable air currents. Thicker stalactites in the same areas are usually vertical but frequently crusted on the entranceward side with preferentially outward-growing coralloids (Fig. 2).

Like the Welsh examples, these deflected stalactites appear to be air-flow-controlled, but by a different mechanism. I suggest the following sequence: A stalactite ceases dripping, but moisture remains available in the ceiling rock from which it grew. An evaporative gradient moves this moisture toward the drier air of the passage by slow capillary seepage along the surface and internal pores of the stalactite, depositing fine-grained mineral crust. Some of the deposition is interstitial, between the crystals of the original stalactite and between the particles of accumulating crust. When airflow is from the entrance, drier air impinging on the stalactite's outward-facing side causes preferential evaporation and crust deposition on that side. If the stalactite is slender, or very porous, differential interstitial deposition may deform it, causing it to bend gradually away from the more heavily crusted side. If the stalactite is too strong, it will not bend but will develop directional crust and coralloids on the outward-facing side. (Since we experience stalactites as brittle, the idea of bending them may seem absurd. However, if it is done by internal wedging in which close molecular contact is constantly kept between the original and intruding material, breakage need not result.)

Figure 2. **Differentially encrusted stalactite, left hand tunnel (coralloids face cave entrance).**

This mechanism is related to that which I have proposed for cave rims (Davis, in press; abstract in *Cave Research Fdn. Ann. Rep't,* 1982, p. 29). These shell-like protuberances appear to develop at passage intersections where there is long-term interaction between "exterior" and "interior" air bodies, causing condensation and corrosion on inward-facing walls, with seepage translocation and deposition of the corroded material on the outward side (Fig. 3). (These proposals are presently hypothetical; I have not applied laboratory examination or quantitative methods to either rims or bent stalactites.)

Concerning Robert Carroll's suggestion (as cited by Sevenair, p. 28) that deflected stalactites might be evidence for cataclysmic polar shifting, deflection by bending is no more compatible with violent causes than deflection during growth. It is hard to understand how any mode of stalactite

Figure 3. **Differentially corroded stalagmite with rims, left hand tunnel/Lake of the Clouds intersection.**

deflection could provide strong evidence relevant to such speculative catastrophes. If the polar shift was rapid but without tectonic disruption, then growing stalactites should not be subject to aberrant forces long enough to grow noticeably deflected segments. If the shift did involve tectonic disturbance, then stalactites might be mechanically tilted, but to distinguish this from tilts having less extraordinary causes, it would be necessary to show that similar effects had occurred worldwide at the same time and that the directional effects were in agreement with acceleration vectors predicted by theory.

Those interested in catastrophic geology would do better to look at sequences of breakage and regrowth in dripstone, which are abundant in the Guadalupe caves and elsewhere and some of which can only be interpreted as evidence of earthquake shock. Dating of such sequences could at the least extend the scientific record of seismic events in time.

Reply to Donald G. Davis. John P. Sevenair, Department of Chemistry, Xavier University of Louisiana, New Orleans, LA 70125.

Donald Davis has presented an intriguing, well-thought-out alternative mechanism for the deflection of stalactites. I would like to consider it from two viewpoints. Is it possible to extend the Dan-yr-Ogof proposal to explain the western U.S. observations? If so, is it possible to choose between the two proposals?

In Dan-yr-Ogof, deflection of soda straws is apparently a rare event. Most of the straws are undeflected, and most of the others have one or a few clearly defined deflections. Only a few have "curved" segments. If conditions are such that deflection is more common, a straw growing down into an air current might acquire an apparent curve, composed of a large number of short straight segments. The starting and stopping of growth, and the opportunity for deflection, will probably be more frequent in a cave with an irregular water supply or a dry air flow.

It seems, then, that both proposals can be used to explain the western American observations. The Davis proposal can be used to explain the Dan-yr-Ogof data as well, if pores in the Dan-yr-Ogof straws are infrequent, and if deposition in such pores can occur via the normal CO_2-loss mechanism as well as by evaporation.

The question then becomes: How can one choose? One possibility is the use of theoretical considerations. Donald Davis has pointed out two features of his mechanism. First, crystal growth can occur in pores, and secondly, breakage is unlikely if the crystal faces can remain in contact. These two statements are true taken individually, but it is difficult to imagine how both conditions could hold at the same time. That is, water flow (and therefore deposition) between two crystal faces in contact would be extremely slow.

An alternative is the deposition of $CaCO_3$ at an interior surface, followed by outward movement of the new crystal, wedging the older surfaces apart. This would keep the crystal faces in contact, and would make the flow of water between the faces in contact unnecessary. This alternative has a major drawback, as illustrated below.

ions before movement	upper crystal	+ – + – + –
	lower crystal	– + – + – +
ions after movement	upper crystal	+ – + – + –
	lower crystal	– + – + – +

If crystals in contact with each other move relative to one another, areas having the same charge will be brought opposite one another. The repulsion of opposite charges would then result in breakage of the straw. This feature of ionic compounds such as $CaCO_3$ is what makes crystals of them brittle, difficult to deform without breakage. Most compounds can be made to flow if the pressure is high enough, but such extreme pressures are not present in stalactites.

Test by experiment or observation is preferable to theoretical discussion. Examination of some vertical sections of deflected stalactites might be enlightening, but the gain in knowledge probably does not offset the loss of these rare and beautiful forms. Does anyone have any other ideas? This area is certainly open to further observation and discussion.

Mr. Davis' comments concerning Robert Carroll's catastrophic hypothesis seem valid, and are broader than mine (*NSS News* 36:240, 1978), since he considers deflection during acceleration in addition to deflection before and after the event.

BOOK REVIEWS

On the Track of Ice Age Mammals, by Antony J. Sutcliffe. Harvard University Press, 1985. 224 p., illus. $25.

This is a nice book that should please any caver interested in the mammal bones that are often found in caves and what they can tell about the past. The book first provides a solid background about the last ice age—the extent of ice sheets, the conditions in the periglacial and coastal zones, the changes in flora and fauna and in the oceans, the techniques of dating, the methods of paleoclimatic reconstructions, and the causes of climatic change. Because caves are one of the principal repositories of fossil mammals, there follows a chapter that deals with types of caves—caves in limestone, lava, rock fissures, coastal cliffs. It also describes types of cave fossils and cave sediments, as well as famous bone caves around the world. Another chapter describes the Paleolithic cave art of southern France and other regions, in which the contemporaneous game animals are beautifully depicted: woolly mammoth, woolly rhinoceros, horse, bison, ox, musk ox, ibex, deer, bear, lion. The book then describes the famous frozen mammoths of Siberia and Alaska and what they tell us about mammoth habitat and diet when they lived during the last glacial period. Succeeding chapters recount the changing mammalian faunas of the ice age in various parts of the world, especially the British Isles (with description of important cave faunas) but also East Africa, Rancho La Brea in California, Last Hope Cave in Argentina, and the Wellington caves and other sites with marsupial fossils in Australia. The last chapter treats the controversial subject of the extinction of large mammals at the end of the ice age, especially in North America—whether it was caused by environmental change or by "overkill" by human hunters, or both. The author conservatively (and wisely) appeals to multiple causes, with local circumstances different from one place to another.

The numerous photographs and diagrams in the book, with expansive captions, can give one an excellent taste of the subject matter. Included are five double-page spreads in color showing an artist's reconstruction of ice-age scenes of mammalian habitats in Siberia, South Wales (at two different times), Patagonia, and Australia, prepared at the British Museum (Natural History) under the direction of the author, who is Curator of Pleistocene Mammals there. Among the photographs of particular interest is one showing elephants filing into a cave in Kenya to recover glauber salt, which they break from walls with their tusks, to overcome a sodium deficiency in their diet.

In the preface the author sets out the approach for the book: "It is written primarily for the serious reader with little previous knowledge of the subject but who would like to be able to follow the way in which investigations are undertaken." The book is successful in this aim, being sufficiently detailed on the scientific side yet lucid in expository style. It should make good reading on a winter evening that might conjure an ice-age setting, and because of the strong emphasis of cave faunas it should make an appropriate gift from one caver to another.

H. E. Wright, Jr.
University of Minnesota

Paterson, Keith and Sweeting, Marjorie, 1986. New Directions in Karst. Norwich, England: Geo Books, Geo Abstracts, xxii + 613 pp. Cost: $77. Available: Regency House, 34 Duke Street, Norwich NR3 3AP, England.

New Directions in Karst is the Proceedings of the Anglo-French Karst Symposium, which was held in September of 1983 in England and Wales. This 613-page Proceedings contains thirty-three articles, twenty-seven in English and six in French. Each article has two summaries, one in English and one in French, to appeal to a wide international audience. The individual chapters are grouped under one of seven major topics: Karst Processes, Karst Rocks and Structures, Karst Hydrology, Karst Caves, Tropical Karst, Karst Pavements, and Evolution of Karsts.

The book is a storehouse of useful information on the current work of various notable karst researchers around the world. Some of the authors who are well-known to scientists in the United States are: Peter Smart, S. T. Trudgill, J. Nicod, Song Lin Hua, G. Rossi, J. Gunn, M. Day, M. M. Sweeting, A. F. Pitty, J. Crowther, and A. C. Waltham. The preceding litany of names should reassure readers of the high quality of work which produced the papers. Research localities of the various papers are worldwide, including England, France, Jamaica, China, and Belize, to name a few.

Many of the articles provide specific research methodology, which is quite useful information for those who are working on similar problems. For example, in the chapter entitled, "Alkalinity measurements in karst water studies," Rose and Vincent go into detail on the definition, properties, and the field measurement of alkalinity of karst waters. In two later chapters the same two authors present equally specific methodology for research on kamenitzas and the morphometry of grikes. All three chapters contain a wealth of instructions for duplicating the author's research techniques.

The last two chapters in the book are somewhat generalized descriptions of karst in China. Both present an interesting review of karst in an area little known to those in the West. Other articles concerned with the lesser known aspects of karst research are those on the palynology of cave sediments, caves in granite, and phytokarst. These three articles are welcome additions to the scant, but growing, file of data on such topics.

Of particular interest to me are the four chapters on limestone pavements, a topic rarely discussed in this country. I was specifically intrigued by H. S. Goldie's chapter entitled, "Human influence on landforms: the case of limestone pavements." These landforms are a karst conservation problem in Great Britain that generally has not been of concern to us in the United States. Many of the spectacular karst pavements of the British Isles are in danger of being destroyed by mining for its use as building and decorative stone. It was especially gratifying to find an article on karst protection among the otherwise strictly scientific papers.

Another chapter on a rarely studied karst topic is D. M. Carroll's "Soils associated with Carboniferous limestone in England and Wales." The author describes the various soils associated with limestone, its parent material, and its mode of formation.

As the few chapters that I have mentioned show, this book provides a tremendous amount of information on methodology and data which will be useful to karst researchers. The many other chapters in the book are equally informative. This is a book that should be on the shelf of any speleologist. I feel that it could become an important reference volume. However, there are some significant problems.

The problems with this book are not with the contents, but with the quality of the production. Reproduction of photographs is generally only fair in quality. Thin paper was used and one can see print through the pages; I find this rather distracting. The right page edges were cut rather close to the print (within 1/8"). This adversely affects the aesthetic appeal of the book. The binding is weak. My copy, after one thorough reading, looks like it might not survive another reading intact. These are minor problems that one apparently must accept in modern publishing. There are, however, more serious problems which remained even after the final editing.

Figures 13.4 a and b, and Figures 13.5 a and b have their labels reversed. Chapter 25 has a number of figures out of sequence. Chapter 27 has the worst problems. It seems that most of the figures do not match the associated labels, and one figure may actually be missing! A number of maps throughout the book have poor or no pattern distinction between categories. This is especially true on some of the geologic maps. Finally, there are some minor problems in the language translations in chapters 10 and 22, which may be typographical.

Many of the above problems might be the result of an effort to cut costs and produce a less expensive publication. This has not been the result, however. This book costs an incredible $77! The production quality does not justify such a high price. Even with a low potential sales market, this book should not cost more than $30. This high cost will insure low sale; that is unfortunate because there is much information of value in this significant volume.

Dr. George N. Huppert
Department of Geography and Earth Science
University of Wisconsin—La Crosse
La Crosse, WI 54601

Seminole Sink (41VV620): Excavation of a Vertical Shaft Tomb, Val Verde County, Texas. Solveig A. Turpin (Compiler). Texas Archeological Survey Research Report No. 93, 1985, xxi & 216 pp. (Available for $5.00 plus $2.00 handling from Texas Archeological Research Laboratory-Sponsored Projects, University of Texas, 10100 Burnet Road, Austin, TX 78758-4497).

Seminole Sink is a burial pit cave in southwest Texas investigated by the Texas Archeological Survey in 1984 and 1985. A total of 22 partial human skeletons were recovered from the small talus cone beneath the entrance shaft. Twenty-one of these individuals were deposited about 7,000 years ago, and the remaining burial—a cremation—was deposited about 400 years ago. The skeletons, artifacts, animal remains, and cave geomorphology were studied by an interdisciplinary group, and their findings are reported in five chapters and two appendices by nine authors.

After an introductory chapter concerning the site, archaeological background, and environmental setting, the archaeological techniques employed in the cave are presented, recovered artifacts described, and general introductions given to the talus cone and skeletal material. While most of the techniques employed are standard or slightly modified for work in the cave, many hard-core cavers will revel at the use of an above-ground generator to light and ventilate the cave.

The next chapter reviews the stratigraphy of the region, paleoenvironmental reconstructions, and earlier studies of cave deposits. Seminole Sink's deposits are described and correlated with those elsewhere in the region. The depositional processes in the cave and paleoenvironmental changes during the past 20,000 years are interpreted, but as the author notes, the conclusions suffer from inadequate chronometric dating. It is good to see that the long-term Texas marrige of geology and archaeology, which dates over 50 years to the days of E. H. Sellards, is continuing.

The following chapter describes and interprets the human remains, emphasizing taphonomy, demography, pathology, and diet. Most of these approaches have been emphasized in previous analyses, although several techniques new to the area are employed in this study. Prehistoric diet in the

Lower Pecos River area, which has been studied extensively from coprolites, is examined using dental microwear, chipping, and pathology. The results largely support earlier studies. Taphonomy is examined to better understand the processes influencing the distribution and condition of the skeletal remains. One important question deals with whether the bones were deposited originally as a whole, fleshed, articulated body or were deposited as disarticulated elements. Based on a single articulated limb and a nonrandom distribution of elements, it is concluded that entire bodies were deposited in the cave. A more detailed listing of minor elements—especially bones of the wrist, hand, ankle and foot—might have supported further this inference. Demography of the Seminole Sink sample is described, a frustrating task given the fragmentary nature of the material. It is surprising that the Seminole Sink demographic profile is more similar to that of a late prehistoric eastern Woodland sample rather than another Southwestern sample. Statistical tests of the demographic distributions as well as element distributions and paleopathologies may not have altered the conclusions, but the tests would have added credence to the analysis. These relatively minor criticisms aside, the osteological analysis is a fine contribution and sets high standards for future skeletal analyses in the region.

The final chapter interprets the social structure and ideological framework of the group using Seminole Sink as a burial place. There are also two appendices identifying the mammalian and invertebrate fauna in the cave.

There are two details which detract from this otherwise fine report. The monograph has many typographical errors, so many, in fact, that two of them even spill onto the cover. (As a consequence, the publication is very inexpensive). A careful editing would have eliminated these typographical errors. The second problem is the quality and duplication of photographs, especially those taken in the cave. Photographing in a cave is difficult, as anyone who has tried will testify, but the quality of the reproductions is so poor that some details noted in the figure captions are difficult to find.

This study, in spite of the problems just mentioned, is doubtlessly the best monograph-length report available on a burial cave located in the United States. It provides a solid background to the archaeology, osteology and burial caves of south Texas and provides valuable descriptions and comparisons. Seminole Sink is an important, early burial cave with previously undisturbed deposits, and this monograph is a valuable contribution to cave archaeology.

P. Willey
Department of Anthropology
University of Tennessee
Knoxville, TN 37996–0720

ERRATA

In Elizabeth L. White's review of *Sinkholes: Their Geology, Engineering, and Environmental Impact* (Vol. 48, p. 32), several sentences were missing.

Review should read:

VI. Engineering in sinkhole-prone areas; 8 papers.

Solutionally-formed sinkholes are a permanent part of the landscape; they usually form as shallow sinkholes and runoff is usually retarded because no channels are formed. Solutionally-formed sinkholes, ...

We regret any inconvenience this may have caused.

Editor

1987 SACS SESSION ANNOUNCEMENT

The Survey & Cartography Section (SACS) of the National Speleological Society (NSS) will be holding a technical session at the 1987 NSS Convention to be held in Sault Ste Marie, Michigan, during the week of August 3–7. The Section would like to solicit presentations to be given at this meeting on any subject related to cave survey and cartography.

In addition to general papers, we are soliciting papers dealing with regional and large cave projects. The session will culminate in a round-table discussion on this area. The Section is particularly interested in papers dealing with:

- **survey and cartography organizational aspects**
- **database applications**
- **archiving and organization of survey notes**
- **computer drafting applications**
- **cave map sectioning techniques**
- **uniform style drafting techniques**
- **telecommunication of survey data**
- **reformatting and integration of survey data**
- **large database techniques (10,000+ survey stations)**
- **topographic map overlay techniques**
- **team map drafting techniques**

Other papers of potential interest to regional and large cave projects are also solicited. Please send a letter of intent with a brief description of the proposed presentation to:

Dan Crowl
Vice-Chair, Survey & Cartography Section
1170 Torrey Road
Grosse Pointe Woods, MI 48236
(313) 881-5254

LETTER OF INTENT DUE NO LATER THAN APRIL 1, 1987

Index to Volume 46 of the National Speleological Society Bulletin

Ira D. Sasowsky
Department of Geosciences
The Pennsylvania State University
University Park, PA 16802

This index contains references to all articles and other items of importance published in volume 46 parts 1 and 2 including an un-numbered insert with the abstracts from the 1984 N.S.S. convention. These abstracts are identified by an "(ABS)" preceding the title in the citation.

The index consists of three parts. The first of these is a keyword index. Keywords include: unique words from the article title, cave names, geographic names, and descriptive terms. The second part is a biologic names index. These terms are Latin names of organisms discussed in articles. The third part is an alphabetical author index. Articles with multiple authors are indexed under each author.

Citations are of the following form: names of all authors in the order which they appear in the journal; title of the article or abstract; volume number and part number (separated by a colon); beginning and ending page (separated by a dash); and year of publication from the cover of the issue. Volume number and year are included in the citation so that their format will match that of the cumulative index of volumes 1 through 45 which is in preparation. Within an index group, such as Archaeology, the earliest article is cited first, followed by consecutive articles.

This index was prepared on an IBM 4341 computer running a VM/CMS operating system. Indexing was performed by the IBM KWIC/KWOC program. Formatting was accomplished using the SCRIPT text formater, with camera-ready copy produced on a Xerox 2700 laser printer.

The author wishes to thank Mark Kijowski, Andrew Stahl, and Tom Minsker for their assistance. Computer funds were provided by the College of Earth and Mineral Sciences, The Pennsylvania State University.

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Cave Avenue
Huntsville, Alabama 35810

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Lake Mills, IA 50450
PERMIT NO. 25

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HORTON H. HOBBS, III
601 WHITE OAK DR.
SPRINGFIELD, OH 45504