

# BULLETIN

OF THE

## NATIONAL SPELEOLOGICAL SOCIETY

VOLUME 30

NUMBER 3

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A GLACIER CAVE IN ALASKA

METHODS OF TRACING SUBTERRANEAN WATER

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JULY 1968

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Subscription rate in effect January 1, 1968: \$6.00.

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# Observations of a Glacier Cave in Glacier Bay National Monument, Alaska

By D. N. Peterson and G. D. McKenzie

## ABSTRACT

In the summers of 1966 and 1967 a glacier cave was discovered and observed during a glaciological tunneling program on Casement Glacier, Alaska. Glacier caves are caves that occur within or at the base of a glacier, and are different from ice caves, which are subterranean caves in which ice forms and persists for some time. There are two types of glacier caves: those formed by the ablative action of englacial streams and circulating air, and those formed by the movement of ice over a bedrock protuberance. The Casement cave is of the latter type. Stalactites, stalagmites, draperies, deformed columns, cave coral, sublimation crystals, and hair ice were observed in the cave. Many of these speleothems are similar to those found in bedrock caves.

## INTRODUCTION

During the summers of 1966 and 1967 a large glacier cave was found and examined by members of the Casement Glacier Expedition from The Ohio State University Institute of Polar Studies. The Casement Glacier (58° 57'N, 135° 57'W) is located within Glacier Bay National Monument in southeastern Alaska (fig. 1). It is a temperate glacier with an area of 125 to 150 km<sup>2</sup>; the terminus lies at 150 m elevation and névé basins feeding the glacier are between 1200 and 1700 m. The terminus of the Casement has retreated 6.7 km northeastward from Muir Glacier since about 1900. The cave, located at the edge of the glacier, was broken into in the process of excavating a tunnel along the base of the glacier to study the mechanics of basal sliding of temperate glaciers. A temperate glacier is one in which the ice temperature is at the pressure melting point. During the winter, however, the temperature in the upper few meters of the glacier and

the cavity fell below 0°C, which permitted the formation of the observed speleothems.

## GLACIER CAVES

To many glaciologists or others studying glaciers, an opening beneath a glacier would be termed an "ice cave." To a speleologist, however, ice cave signifies a subterranean "... cave in which ice forms and persists through most or all of the summer and fall" (Halliday, 1966).

The term ice cave has been subject to many different interpretations. Balch (1900) and others believed that the term "ice cave" should be used for caves in glaciers, and that the French term *glacière* should be applied to a cave containing ice. This use of "ice cave" would be a logical one and would be analogous to sandstone and limestone caves as Halliday has pointed out. Through popular and scientific usage (Halliday, 1954; Henderson, 1933; Merriam, 1950) over the past half century, the term ice cave is now "... used to designate permanent caves in rock formations, in which ice forms and remains far into the summer or throughout the year" (Henderson, 1933). The term *glacière* has

\*Contribution No. 141 of the Institute of Polar Studies, Ohio State University, Columbus, Ohio.

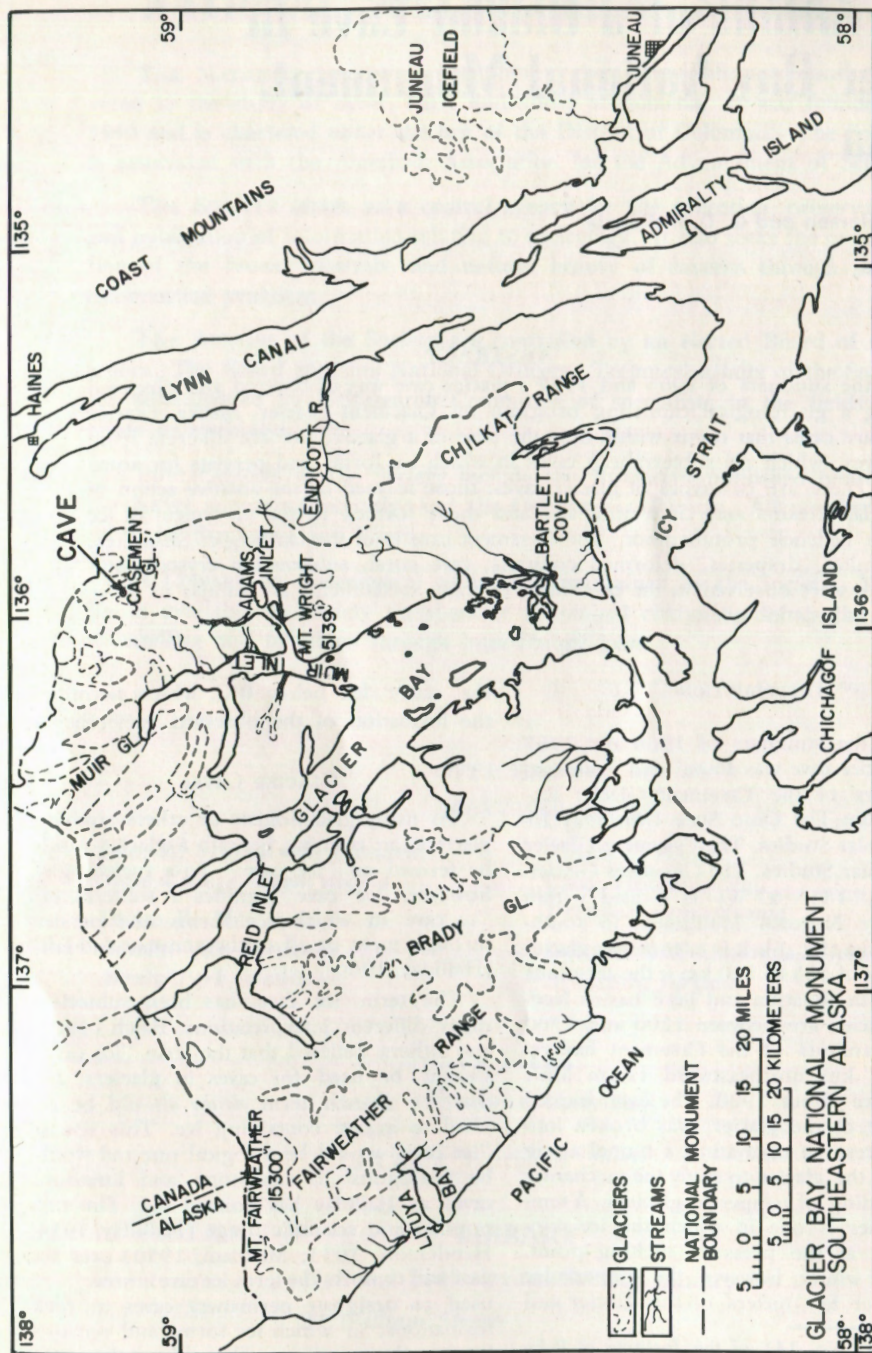


Figure 1.  
Location map.

been used interchangeably with ice cave (Halliday, 1954), but one of the latest definitions extends the use of the term to include "... cold-trapping sites of other kinds [other than ice caves] such as mines" (Halliday, 1966).

Caves formed within or at the base of a glacier are known in speleological literature as glacier caves (Halliday, 1966). This definition does not include subglacial bedrock caves such as those in Nordland, Norway (Horn, 1947). There are few descriptions of glacier caves, although, understandably, some of them have been called "ice caves." Glacier caves have been described by Bonney (1876), Balch (1900), Matthes (1928), and Potts (1900). Halliday (1954) lists seven fairly well-known glacier caves and notes that most of them are intermittent and subject to change since they are formed over the exit of a subglacial stream. Such caves are usually subject to rapid ablation due to circulation of relatively warm air into the cave. As melting proceeds, smooth, concave depressions develop in the walls and ceiling. Warm temperatures, rapid recession of the walls and floors occupied by roaring torrents or shifting streams, usually preclude the formation and preservation of speleothems and other features commonly found in ice and other bedrock caves.

A second type of glacier cave exists which has rarely been observed and seldom been described. These are caves formed not by the action of a meltwater stream, but by the obstruction of ice flow by bedrock or debris beneath the glacier. This modification of flow results in a cavity in the lee of the obstruction. The size of the cavity depends on the thickness of the overlying ice, velocity of the glacier, temperature of the ice, and size and shape of the obstruction.

Such caves, formed in the lee of the obstruction, have been explored as a result of studies on moraine formation and glacial erosion (Bonney, 1876; Carol, 1947). Access to these caves was gained at some suitable location at the side of the glacier. With the advent of tunneling for prospecting (Miller, 1952) and for glaciological research (Haefeli, 1951; Lewis, 1954), glacier caves were encountered deeper within glaciers. Little or no information has been included in the literature on speleothems that may have been

observed, although Lewis did note an unusual ice mantle on the rock and numerous icicles.

The Casement cave, which was formed in the lee of the bedrock obstructions, was found to contain many interesting speleothems similar to those found in bedrock caves.

#### MORPHOLOGY OF THE CASEMENT GLACIER CAVE

The cave was discovered in July 1966, when, during the process of excavating a tunnel (fig. 3) through solid ice, a hole was broken through in the tunnel floor 5 m from the portal and a blast of cold air gushed out. Enlargement of the hole permitted the lowering of a lantern to examine the cave. It revealed an extensive cave and a series of tunnel-like grooves produced by the flow of the ice over knobs of bedrock (see map of tunnel, fig. 2). The ceiling of the cave was formed by the bottom of the glacier and the floor consisted of bedrock or till resting on the bedrock.

The ceiling of the cave was fractured at regular intervals by the penetration of crevasses (fig. 4) through the ice from the surface, which was 10 to 15 m overhead. Toward the latter part of the season, when much of the snow on the surface of the glacier had ablated, it was found that at least one of the crevasses was large enough to afford entry into the cave using a caving ladder.

#### SPELEOTHEMS OBSERVED IN THE CASEMENT GLACIER CAVE

Many depositional features similar in origin to features found in bedrock caves were observed, the primary difference being that all of the features in the Casement Glacier cave were made of ice instead of calcite, gypsum, or other minerals.

#### *Stalactites, stalagmites, and columns*

Meltwater from the surface entered the cave through crevasses and incipient fractures in the ceiling producing features in ice which resembled stalactites, stalagmites, and columns (fig. 5). In some instances, because the bases of the columns were frozen to bedrock and the tops were attached to

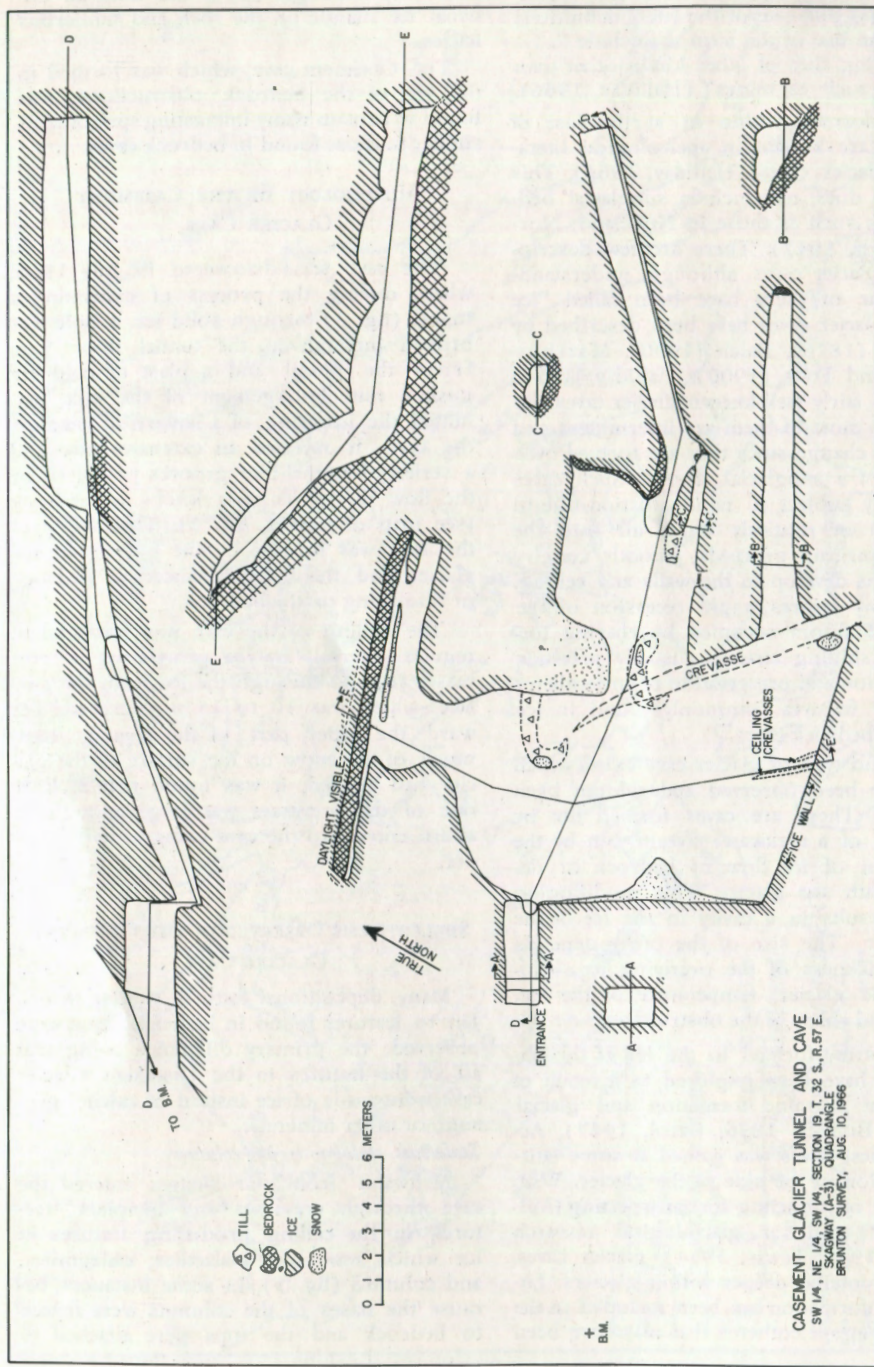


Figure 2.  
Map of Casement Glacier cave.



Figure 3.  
Entrance to tunnel.



Figure 4.  
Crevasse leading to cave.



Figure 5.  
Ice stalactites and draperies. Ice crystals on speleothems and ceilings.



Figure 6.  
Deformed columns. Glacier flow left to right.



**Figure 7.**  
Cave coral on floor of cave. Gloved hand on left.

the bottom of the glacier, columns were deformed (fig. 6) by the flow of the glacier, which was about 1.8 cm per day.

#### *Draperies*

These features formed where water percolated through a fracture in the ice, ran down the wall and deposited layers of ice (fig. 5). The draperies were 10 to 15 cm wide and extended down the wall a meter or more.

#### *Flowstone and cave coral*

Flowstone formed in the cave where the amount of meltwater entering the cave was too great or improperly positioned to be frozen into an icicle or drapery. This ice flowstone formed a smooth surface on the walls and floor of the cave.

In some parts of the cave, cave coral was deposited on boulders and on the floor of the cave. Smooth knobs of ice, 2.5 to 5 cm in diameter and usually less than 10 cm thick, formed as a result of dripping and splashing water (fig. 7).

#### *Sublimation crystals*

The ceiling of the cave was covered with sublimation crystals (fig. 8) similar to gypsum crystals that adorn the walls and ceilings

of some bedrock caves. Halliday (1966) has used the term frost crystals for a similar feature in ice caves. These fragile, ornate crystals in the Casement cave were produced by the sublimation of water vapor from the air. Some of the crystals were several centimeters wide with very intricate construction. Unfortunately these features were the first to melt when the cave was entered and outside air was permitted to circulate through it.

#### *Hair ice*

At several localities in the cave where the heavily debris-laden basal layer of ice had curved away from the ceiling, or had opened up cavities around pebbles, hair-like ice was found to protrude 6 to 8 cm from the till-ice mixture (fig. 9). Because of its appearance, it is here designated as hair ice. It is inferred that as the till-ice mixture separated, the ice within the mixture underwent plastic deformation into thin filaments. As the fracture widened, the filaments parted leaving one or both sides of the fracture with a coating of hair ice. Some of the fractures continued to widen, leaving gaps of 50 to 60 cm.

Another type of very fine ice has been reported (Kamb and LaChapelle, 1964) from



**Figure 8.**  
Sublimation crystals on ceiling of cave.

cavities beneath the Blue Glacier, Washington. There, regelation spicules have been formed by the refreezing of water at the base of the regelation layer where the ice separated from the bedrock. These crystals are usually associated with ice of low debris content, and their mode of formation is believed to be different from that of hair ice.



**Figure 9.**  
Hair ice on till.

#### SUMMARY

Glacier caves are caves formed beneath or within a glacier. The distinction between ice caves, which are ice-containing bedrock caves, and glacier caves, is now well engrained in speleological literature but not in glaciological circles. Glacier caves are of two types: those associated with subglacial streams, and those formed in the lee of an obstruction. The Casement cave, which is of the latter type, exhibits many interesting speleothems which are similar to those occurring in bedrock caves.

#### ACKNOWLEDGMENTS

The writers would like to acknowledge the help of the members of the 1966 and 1967 Casement Glacier and Adams Inlet Expeditions, with particular thanks to Mr. Fred

Erdmann who was responsible for mapping the cave. Logistic support in the field was provided by the U.S. National Park Service. Thanks are due to Dr. J. F. Bridge of the Cave Research Foundation, Mr. J. F. Spletstoesser and Mr. J. F. Lindsay of Ohio State University, and Professor A. Dreimanis of the University of Western Ontario, who reviewed the manuscript. Field work and manuscript preparation were financed by grants to the Ohio State University Research Foundation from the Atomic Energy Commission (contract no. AT(11-1)-1473) and the National Science Foundation (GA-403) respectively.

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Manuscript received by the editor  
23 February 1968

# Comparative Investigations into Recent Methods of Tracing Subterranean Water

By K. Buchtela, J. Mairhofer, V. Maurin, T. Papadimitropoulos, and J. Zötl

## ABSTRACT

The growing number of investigations involving the tracing of subterranean water has led to the improvement of old methods of water tracing, such as the use of dyes and salts, and to the introduction of new methods, such as radioactive tracers, neutron activation analysis, and dyed lycopodium spores. Experiments comparing various methods of subterranean water tracing were conducted in the Buchkogel area near Graz, Austria, using Rhodamine B dye, ammonium bromide, radioactive iodine, and dyed lycopodium spores, during 1963.

Results of the experiments showed that lycopodium spores travel faster than other tracers. Bromine and Rhodamine B travel at approximately the same rates, whereas radioactive iodine moved more slowly than other tracers.

While each of the tracers proved successful, each has certain limitations. If the area of investigation is large, radioactive isotopes method is virtually ruled out because of the large number of personnel required, but the method should prove useful where the water is thought to flow through fine clastic sediments. Lycopodium spores would seem to be most useful for large areas, where several colors of dyed spores may be used to trace flow from several swallow holes simultaneously. However, the method is restricted to areas where flow is thought to be through open conduits. Rhodamine B has proven utility, but it is adsorbed by clays. A combined use of spores and Rhodamine B is of great utility. The neutron activation analysis method allows a fair estimate to be made of the water in the underground system, a feature that is not possible with other methods, but the amount of ammonium bromide required is appreciably larger than the amount of spores or dye.

## INTRODUCTION

Investigations into the distribution, flow direction, and flow rate of underground water have become increasingly important in the solution of problems of water supply, water power, and mining and tunneling. The growing number of such investigations has led to the improvement of old methods of water tracing and the introduction of new ones.

The older methods of water tracing that are still used include the addition of salts and dyes. The usual salt employed is NaCl and the resulting increase in Cl<sup>-</sup> in the water

is determined by titration or electrical conductivity. In some instances the water being investigated has a high or variable Cl<sup>-</sup> content due to natural (*e.g.*, brackish water or saltwater springs) or artificial (*e.g.*, waste water) causes. In such cases LiCl or (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> have been used and determinations made for ions other than Cl<sup>-</sup>. The numerous dyes which have been tested include eosine, fuchsin, Congo red, safranin, auramine, and uranine. Of these, the fluorescein salt uranine has proved to be the best. In extremely sour water (*e.g.*, in brown coal mines), acid fuchsin is used.

Soon after the discovery of radioactivity, radioactive material and radiation-recording equipment was applied to the problem of tracing underground waterways. Such investigative procedures using radioactive isotopes have been steadily improved. In the beginning, maximum permissible dosages of radiation were greatly exceeded because the dangers of radiation were not yet known.

Only recently has a method involving later activation (neutron activation analysis) been applied. The tracer, which is ammonium bromide ( $\text{HN}_4\text{Br}$ ) in our case, is activated after collecting the samples. This has obvious advantages in that neither the half-life nor the radiation danger must be taken into account. For these reasons, this procedure and its future improvements deserve special attention. The method was developed by T. Papadimitropoulos and is treated in detail in this paper.

During the last few years, dyed lycopodium spores (*Lycopodium clavatum*) have been used with success in limestone and dolomite rocks (karst regions) where the subterranean water follows widened joints and clefts. This method is attractive because observation is simple and it is possible to conduct several tracing experiments simultaneously.

The tracing of bacteria has been used to solve special problems. This method requires much preparation and careful consideration.

Before deciding which method is to be used for the investigation of a specific area, several factors must be considered. If the area is large, the application of salt is almost ruled out. The transportation of large quantities of salt to a sinkhole, which may be situated in a relatively inaccessible area, as well as the observation of a large number of springs, presents tremendous difficulties. The use of dye is difficult if the water being investigated is turbid, and the calculation of the amount needed is often difficult. The considerable amount of necessary technical equipment limits the wide application of radioactive isotopes. Finally, the use of spores is not possible when fine clastic particles are present in the water. In many of our tests, therefore, it was necessary to use several methods simultaneously. This raised the question of how to compare data obtained by the various methods, and it was deemed neces-

sary to test the different methods under the same conditions in a special experiment.

Such an experiment, combining the application of salt, dye, and spores, was successfully performed in 1956 by V. Maurin and J. Zötl in the Buchkogel area in the outskirts of Graz, Austria. The subterranean drainage system in this area had been investigated previously by hydrogeologic mapping and experiments. A comparative experiment was conducted in the same area in July of 1963 using Rhodamine B, radioactive isotopes ( $\text{I}^{131}$  and  $\text{Rb}^{86}$ ), ammonium bromide, and lycopodium powder dyed various colors. This last experiment, which is the subject of this paper, had as its purposes the comparison of modern investigative methods and the acquisition of experience with some of the newer techniques.

The experiment was subsidized by the Vereinigung für hydrogeologische Forschungen in Graz and was organized by its representatives Dozent Dr. V. Maurin and Dozent Dr. J. Zötl. The following acted as Cooperators:

Dr. K. Buchtela, Atominstitut der Österreichischen Hochschulen, Vienna.

Dr. J. Mairhofer, Bundesversuch- und Forschungsanstalt Arsenal, Vienna, in cooperation with M. Borowczyk, civ. eng., and A. Zuber, civ. eng., Poland.

Dozent Dr. V. Maurin, Institut für Mineralogie und Technische Geologie an der Technischen Hochschule, Graz.

T. Papadimitropoulos, Nuclear Research Center "Democritus," Athens.

Dozent, Dr. J. Zötl, Geographisches Institut der Universität, Graz, Graz.

Altogether, a total of 23 persons took an active part in the work connected with the introductions of material and observations carried out during the six-day experiment.

Grateful acknowledgement is due our co-operators who performed the neutron activation and analyses at the Nuclear Research Center "Democritus" and in the Austrian Nuclear Research Institute.

#### THE AREA INVESTIGATED AND ITS DRAINAGE

Graz, the capital of the Austrian province of Styria, is situated in the northern part of the Pleistocene terraces of the Grazer Feld.

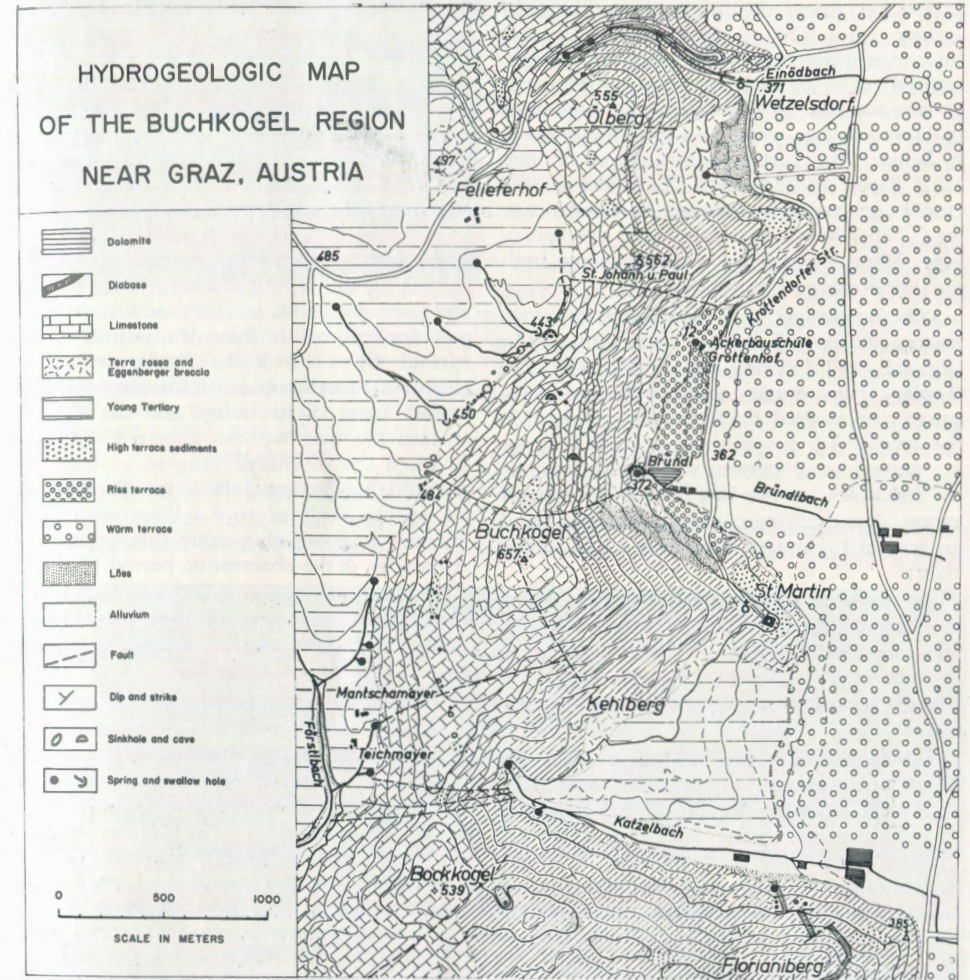


Figure 1. Map of the area investigated near Graz, Austria. The swallow hole is at point 443; Bründl Spring is at point 372.



The Buchkogel mountain range forms the western boundary of and lies about 300 meters (1000 feet) above the open and relatively level Grazer Feld. This 9 kilometer (5.6 mile) long north-trending range (fig. 1) is considered to be an outlying range of the Alps. It is underlain by limestones and dolomites of Devonian age which dip moderately steeply beneath the Tertiary sediments of the Styrian Basin to the east. The rocks of the Buchkogel range are broken by several east-west faults which have influenced the hydrology. Karst topography is developed on both the limestones and dolomites.

The Buchkogel range was completely buried during the early Tertiary. It was exhumed by regional uplift during the late Pliocene. The Tertiary clays, sands, and gravels east of the range are covered by Pleistocene gravels. In the area of Tertiary outcrop west of the range are several small streams which disappear into sinkholes at the foot of the Buchkogel range, thus draining completely underground an area of 1.4 square kilometers (0.54 square mile).

It was long assumed that the water which disappeared west of the range probably emerged at the Bründl spring at the east foot of the range. This spring rises 71 meters below the lowest swallow hole and 800 meters distant.

Furthermore, a chemical examination of all of the springs on the east, south, and southwest sides of the Buchkogel range indicated that the water which goes underground in the swallow holes emerges at the Bründl spring. This was confirmed by a salt-tracing experiment conducted May 12-14, 1956 (Maurin and Zötl, 1959, p. 16 and following).

Because the hydrogeology was so well known, the area was chosen for further experiments. After improving the practicability of spore tracing by dyeing the spores, a combined experiment using salt, dye, and spores was undertaken on June 22-28 in order to compare these methods (Maurin and Zötl, 1959, p. 21 and following). The success of this experiment encouraged us to undertake another comparative experiment in the same area. This paper describes the results of this last experiment, which was carried out during July 1963.

The injection of labeled material (Rhodamine B, ammonium bromide, dyed *Lycopodium* spores, and radioactive isotopes) took place July 1, 1963, from 1400 h to 1800 h.

Due to several weeks of dry weather preceding the introduction of labeled material, the small streams west of the Buchkogel range were nearly dry, and the rate of inflow into the swallow hole (fig. 1, point 443) was only 0.58 liter/sec. The discharge of the Bründl spring was also quite low: 7.5 liters/sec at the beginning of the experiment. Following a rainfall that started at 1400 h on July 2, the spring discharge rose to 14.9 liters/sec at 1900 h. This additional flow was derived mainly from the vicinity of the spring. By 2200 h the discharge had declined to 11.4 liters/sec. Infiltration from the higher parts of the range and the Tertiary area to the west was not apparent until July 3, when the discharge rose to 15 liters/sec at 0200 h. During July 3, the discharge of the spring declined to 8.4 liters/sec and remained at about this value throughout the remainder of the observation period (fig. 17).

The water temperature at the Bründl spring varied only from 9.8° to 10.0°C during the period of the experiment, in spite of the considerable variations in discharge.

#### THE SPORE METHOD

The spores of *Lycopodium clavatum* have been successfully used in hydrologic experiments in several Alpine karst regions (Zötl, 1961). *Lycopodium* spores have a diameter of about 35 $\mu$  and tend to remain suspended in moving water. They are thus able to pass through siphons which trap floating particles. The spores are caught at a resurgence with a plankton net (fig. 2). Because the net is in position continuously, it is sufficient to collect only one sample per day to determine the quantity of spores. One person is thus able to inspect a number of resurgences. An exact description of the method will be found in Maurin and Zötl (1959).

Spores cannot be used in areas of sand and gravel because they tend to be filtered out. In extensive limestone and dolomite areas, however, this method has proved successful.

The experiment reported here served several purposes. In addition to providing data

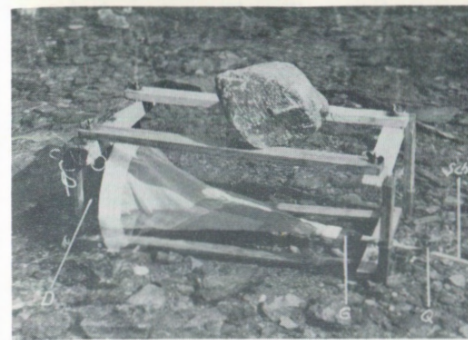


Figure 2. Plankton net in the Bründl Spring, showing the wooden frame used to support the net. D, wire mesh covering the front opening to exclude coarse material; G, glass funnel attached to net; Sch, rubber tubing; Q, pinch clamp.

for comparison with other methods, a new color of dye was introduced and nets of different sizes and fabrics were tested.

Two kilograms of *Lycopodium* powder dyed brown (the new color) were injected on July 1, 1963 from 1545 to 1555 h, and three kilograms of powder dyed blue (a color we have been using from the beginning) were injected from 1600 to 1610 h into the swallow-hole near Feliefferhof (fig. 1, point 443). As is the habit in precise experiments the plankton nets were installed at the same time. Samples were taken hourly from July 1, 1963 at 1800 h to July 6 at 1550 h.

The first spores appeared in the sample collected at 0100 h on July 3, and the first peak was reached in the sample collected at 0700 h on July 3 (this sample, which was collected from the standard net, contained 124 brown and 202 blue spores for a total of 326). The quantity of spores in the samples then dropped suddenly and the samples collected on July 3 at 1100, 1300, and from 1500 to 1700 h contained no spores at all.

Another wave of spores began at 1800 h and reached a second peak on July 3 from



Figure 3. Scene at the swallow hole showing the barrel used to dilute the ammonium bromide and the funnel for introducing spores. Entrance to Feliefferhof cave in background, through which stream flows for a short distance.

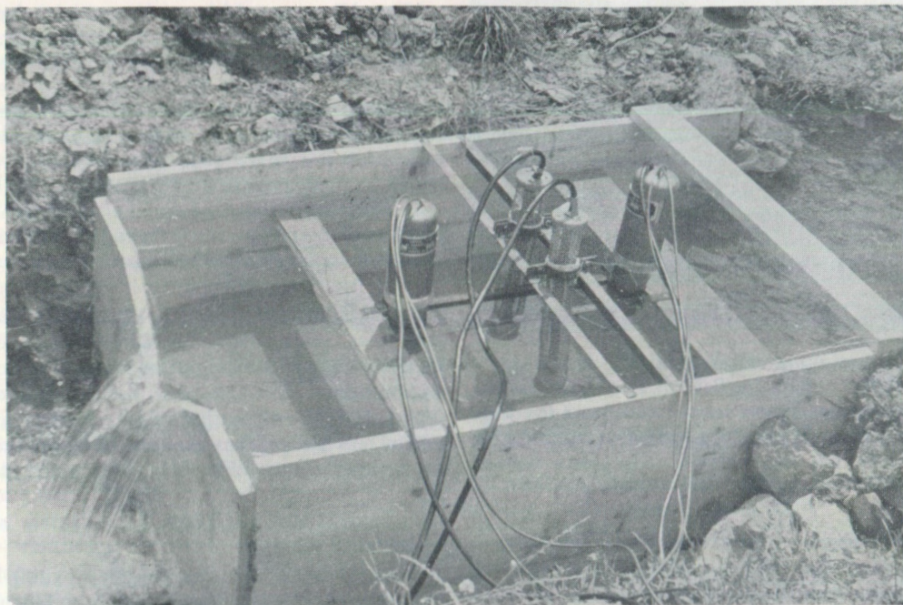


Figure 4.  
Radiation detectors and measuring box at Bründl Spring.

2000 h (52 hours after injection) to 2200 h (2000 h: 75 brown, 106 blue, 181 total; 2100 h: 65 brown, 98 blue, 163 total; 2200 h: 96 brown, 190 blue, 286 total). The number of spores then decreased fairly rapidly to 0400 h on July 4, and only occasional later samples contained a few spores. After 1900 h on July 5 all samples were free of spores.

A total of 440 brown and 696 blue spores were collected at Bründl spring. The ratio of the two colors was in approximate accordance with the 2:3 ratio of the amounts injected.

#### THE DYE METHOD

In earlier comparison experiments we had used the dye Uranine AP conc. (made by E. Merck in Darmstadt, Germany) together with other labeled material. Rhodamine B, a dye which had been used several times in other countries, was used in the present experiment. One and one-half kilograms of dye were diluted in an 80 liter barrel of water and introduced into the swallow hole southeast of Felieferhof (fig. 1, point 443) from 1450 to 1510 h on July 1, 1963. The amount used, which was rather large for this small

karst system, was about the same as the amount of Uranine which was used in the 1956 experiment. This offered further possibilities for comparison.

Samples were collected from the Bründl spring beginning at 1800 h on July 1. The first trace of dye was in the sample collected at 0900 h on July 3, 42 hours after introduction. The dye was detected in this sample by means of an ultra-violet lamp and the concentration was about  $10^{-9}$ . Two hours later, at 1100 h, a slight coloration could be detected with the naked eye, and an intense red color had developed in the water by 1300 h. The peak of the coloration (concentration about  $10^{-6}$ ) was in the sample collected at 1200 h on July 4, 69 hours after introduction (see fig. 17). The dye concentration then decreased slowly to 1200 h on July 7 and slight traces were apparent until July 14. After July 7 only two samples were collected daily.

About the same peak concentration was reached as in the 1956 experiment with Uranine. A striking difference between the two experiments was that the Rhodamine was adsorbed on and colored organic material and clays. This was well illustrated by

the plankton nets. The silk nets developed a distinct red color while the synthetic fiber net was unaffected. The dye was largely washed off the silk net after several days. This adsorption and slow washing-off process explains why the dye was present in the Bründl spring for such a long time.

#### THE RADIOACTIVE ISOTOPES METHOD

(J. Mairhofer)

For this experiment the Isotope Department of the Austrian Federal Testing and Research Institute Arsenal selected the radioactive nuclides I-131 and Rb-86 in order to compare their effectiveness in determining the flow velocities of karst groundwater. Earlier studies have shown that both of these nuclides are only slightly adsorbed. The energies of I-131 (0.36 million electron volts) and Rb-86 (1.078 mev) can be precisely separated and two one-channel analyzers (scintillation counters) were used for the separate determination of the two nuclides. In addition, a Geiger-Müller beta counter (Philips 19553) to determine I-131 plus Rb-86. The experiment included both (a) measurement of water flow rate and (b) measurement of the total amount of subsurface water by means of the Total Count Method described below. The detectors were equipped with scalers and multipliers as well as recorders.

The relationship of the various injection and measuring points is shown schematically in figure 5. In order to determine the flow volume above the swallow hole, I-131 was introduced at point  $I_1$  and measured with two Geiger-Müller tubes in parallel at point  $M_1$ , a short distance above the swallow-hole. Because the flow was small, it was also measured directly.

Forty-five minutes after the above injection, both I-131 and Rb-86 were introduced into the swallow hole just downstream from point  $M_2$ . Two scintillation counters and paralleled Geiger-Müller tubes (fig. 4) were installed at point  $M_2$ , a short distance downstream from the resurgence (point  $I_3$ ). Finally, I-131 was introduced at point  $I_3$  to determine the flow from the spring. The flow volume was also determined by direct measurement.

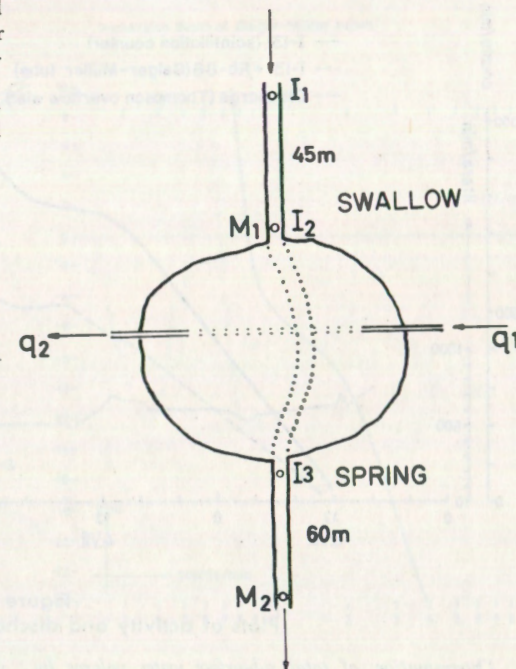


Figure 5.  
Diagrammatic representation of under ground water system. See text for explanation.

#### DETERMINATION OF FLOW TIME

Three hundred millicuries of I-131 as NaI was introduced at 1715 h and 100 mC of Rb-86 as RbCl was introduced at 1800 h on July 1, 1963 into the swallow hole. The first trace of activity at point  $I_2$  appeared at approximately 1300 h on July 3. Activity increased to a peak at about 1300 h on July 5 and then declined (fig. 6), giving a transit time of 78 hours. The activity had not yet returned to zero by 1500 h on July 6.

Unfortunately, the Rb-86 analyzer was inoperative during the experiment. Because both the I-131 scintillation counter and the Geiger-Müller tubes peaked at about the same time, it is concluded that the Rb-86 was either strongly adsorbed or swamped out by the I-131 radiation. Figure 6 also shows the flowrate at point  $M_2$  as measured by a Thompson overflow wier.

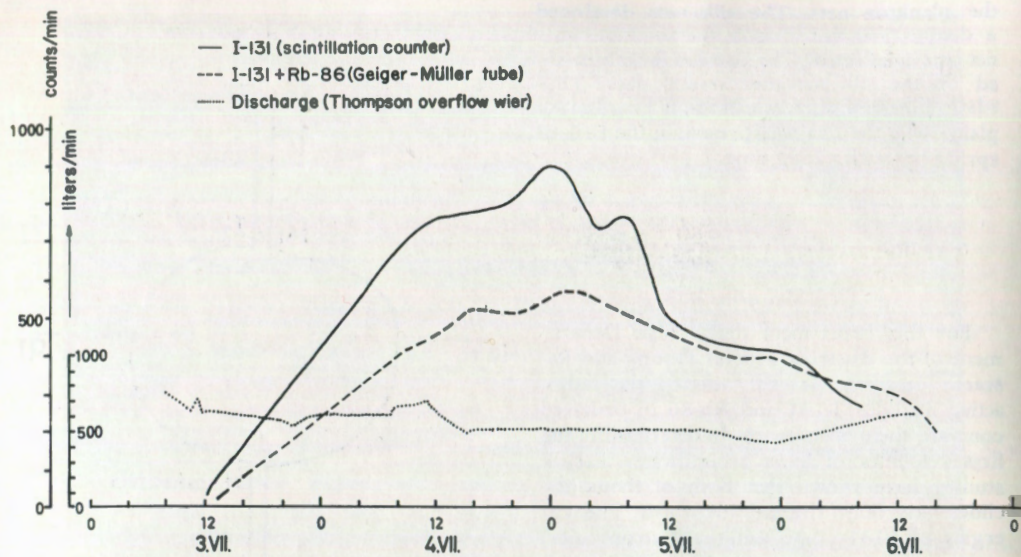


Figure 6.  
Plots of activity and discharge at Bründl Spring.

*Determination of total subsurface water volume by the Total Count Method*

The Total Count Method is based on the relationship that the water volume is directly proportional to the applied activity and inversely proportional to the total count, or

$$Q = F \cdot A / N$$

where Q is the water volume in liters per minute, A is the activity in millicuries, N is the total counts recorded, and F is a proportionality constant which depends on the detectors and the counting geometry.

The calibration factor F was determined for point M<sub>1</sub> with the small measuring box as

$$F = 7.3 \times 10^3 \text{ liter-counts/mC-min}$$

Thirteen mC of I-131 were injected at point I<sub>1</sub> and 3 to 4 minutes later a clear peak was recorded at point M<sub>1</sub>. The magnitude of the peak yielded a value for the flow of 38.2 l/min (= Q<sub>1</sub>), which was in good agreement with a wier measurement at M<sub>1</sub> of 34.6 l/min.

A value of F for the larger measuring box at point M<sub>2</sub> was determined for I-131 and Rb-86 as well as for the two together. Using this value for F, the flow at M<sub>2</sub> (= Q<sub>3</sub>)

was determined by injecting 10 mC of I-131 at point I<sub>3</sub>. The value obtained was 390 l/min, as compared to 470 l/min based on the Thompson overflow wier.

Because of the lack of agreement between the two values of Q<sub>3</sub>, tests were conducted in the laboratory subsequent to the field experiment. The geometrical conditions of these tests were the same as those at point M<sub>1</sub>, and the results are shown in figures 7 and 8. The calibration factor determined in the laboratory was slightly higher than that used in the field. Based on this new value of F, Q<sub>3</sub> = 700 l/min. This is higher than the value determined by direct flow measurements. It is apparent that the exact value of F is both difficult to determine and of great influence on the final flow determination.

Although I-131 and Rb-86 radiate different energies, the calibration factor for the two nuclides is nearly the same, as shown in figure 7. The dashed part of the Rb-86 curve in this figure is probably due to contamination from an earlier test with I-131 and hence spurious.

The counting response is very sensitive to the immersion depth of the probe (fig. 8). This may account for at least part of

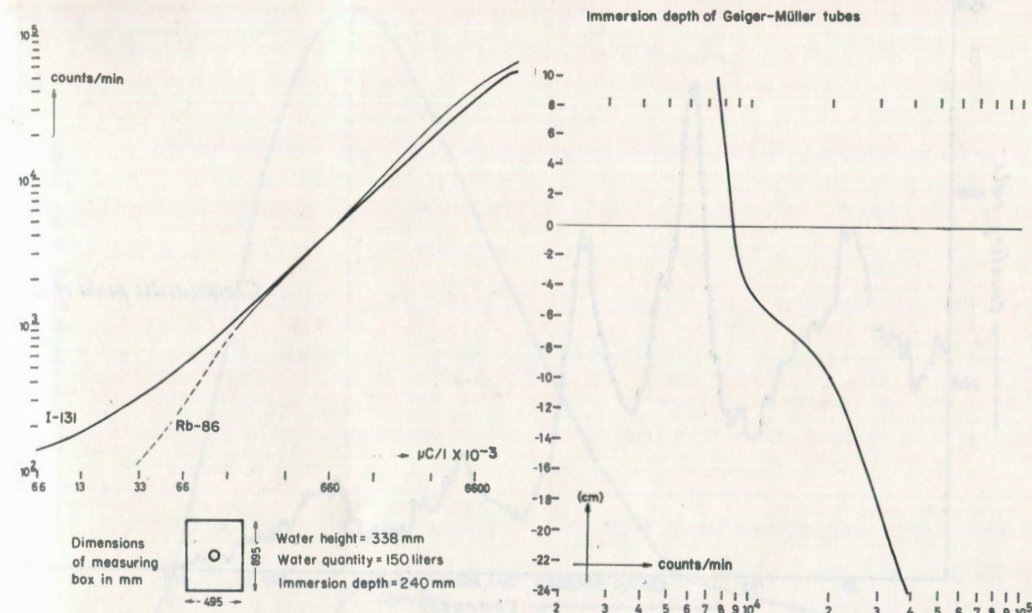


Figure 7.  
Results of adjustment test. See text for explanation.

the flowrate discrepancy. The high counting rate above the water is due to relatively large amount (2 mC) of Rb-86 used in the test.

Based on a comparison of the counting rate at point M<sub>2</sub> and the amount of radioactive material introduced at point I<sub>2</sub>, it can be shown that the flow from the swallow hole is augmented by other water before it reaches the spring. Based on the field value F, the maximum flow between the swallow hole and the spring is 690 l/min (Q<sub>2</sub>). The added flow, designated q<sub>1</sub> (= Q<sub>2</sub> - Q<sub>1</sub>) is equal to 650 l/min. Part of Q<sub>2</sub>, however, is diverted and does not emerge at the spring. This diverted flow, q<sub>2</sub>, (= Q<sub>2</sub> - Q<sub>3</sub>), amounts to 300 l/min. Thus the Bründl spring is not the sole discharge from the subsurface karst system.

If it is assumed that all of the radioactive material had been discharged through the spring in the 80 hours after the injection, the volume of the reservoir between the swallow hole and the spring is 3310 cubic meters.

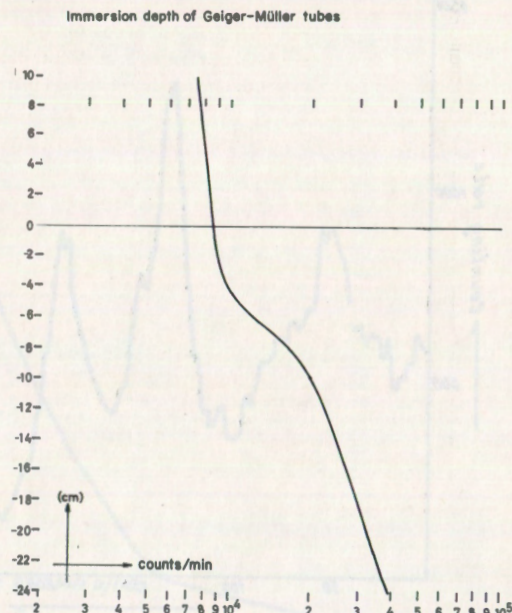


Figure 8.  
Results of adjustment test (immersion depth). See text.

THE NEUTRON ACTIVATION ANALYSIS METHOD, PART I

(T. Papadimitropoulos)

The neutron activation analysis method for tracing underground water involves the introduction of a non-radioactive nuclide into a swallow hole and the collection of samples at springs, the irradiation of the samples with neutrons, and the detection of the radioactive nuclide thus produced. The method had been used in a study in Greece (Dimi-troulas, *et al.*, 1962) prior to the present experiment.

Ammonium bromide, a cheap and easily available compound, was used in the experiment. The nuclide Br-81 has a natural abundance of 50% and a cross section of 3.1 barns. The radioactive nuclide produced by neutron activation, Br-82, has a half life of 35.9 hours.

This study was undertaken at the request of the Vereinigung für hydrogeologische Forschungen in Graz so as to demonstrate the method to a group of hydrogeologists studying different methods of water tracing and

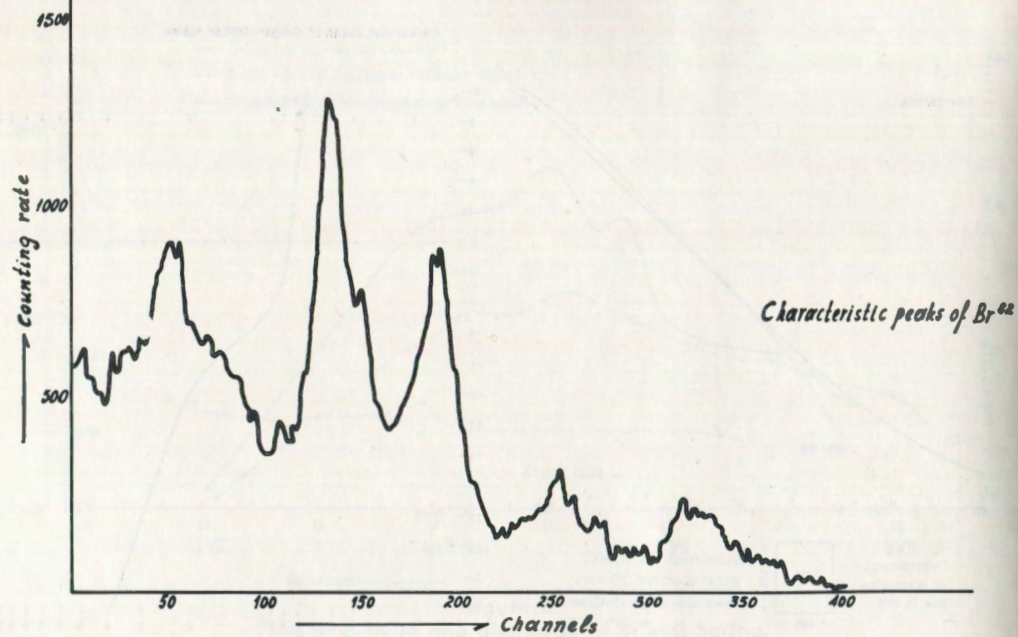


Figure 9.  
Energy spectrum of sample 69. See text.

to compare the data obtained with that derived from other methods of investigation. Activation and analyses of samples were performed both at the Nuclear Research Center "Democritos" in Athens and at the Atominstitut der "Österreichischen Hochschulen in Vienna. This section describes the results of the investigation done in Athens. The results of the Vienna work are discussed in the following section.

From 1515 h to 1538 h on July 1, 1963, 30 kg of  $\text{NH}_4\text{Br}$  dissolved in 120 liters of water was introduced into the swallow hole southeast of Felieferhof. Starting at 1800 h on 1 July, 100 ml samples were collected at the Bründl spring at 30 minute intervals (one liter samples were also collected hourly for the Vienna determinations). After 2000 hours on July 6 only two samples a day were collected through July 7.

Before starting the experiment, the water of the Bründl spring was analyzed for its bromine content. The amount of natural bromine was found to be negligible (about 0.05 mg/l). Ten liters of the uncontaminated spring water were also collected for later use.

Following the experiment, the samples were taken to Athens, where each was filtered to remove any soil contamination. A 5 ml fraction of each sample was placed in a polyethylene vial and irradiated in the reactor core with a neutron flux on the order of  $10^{10}$  to  $10^{11}$  neutrons/cm<sup>2</sup> sec. Five ml fractions of the uncontaminated spring water were also irradiated with the same flux. Qualitative analysis of each of the samples was done using a well-type of scintillation counter (Nuclear Chicago model DC-5) with an electronic circuit designed by the Electronics Department of the N.R.C. "Democritos". The gamma-ray spectroscopy was performed with a 400 channel analyzer of the Intertechnique S.A. France.

Of the 206 samples analyzed, Br-82 activity was found in 76. These were samples number 38, collected at 0900 h on July 3, to number 113a, collected at 2030 h on July 6. The spectra of these samples contain all the characteristic peaks on Br-82, which are well known. A typical spectrum of a sample (number 69) close to the concentration maximum is shown in figure 9.

Each of the 76 samples in which bromine

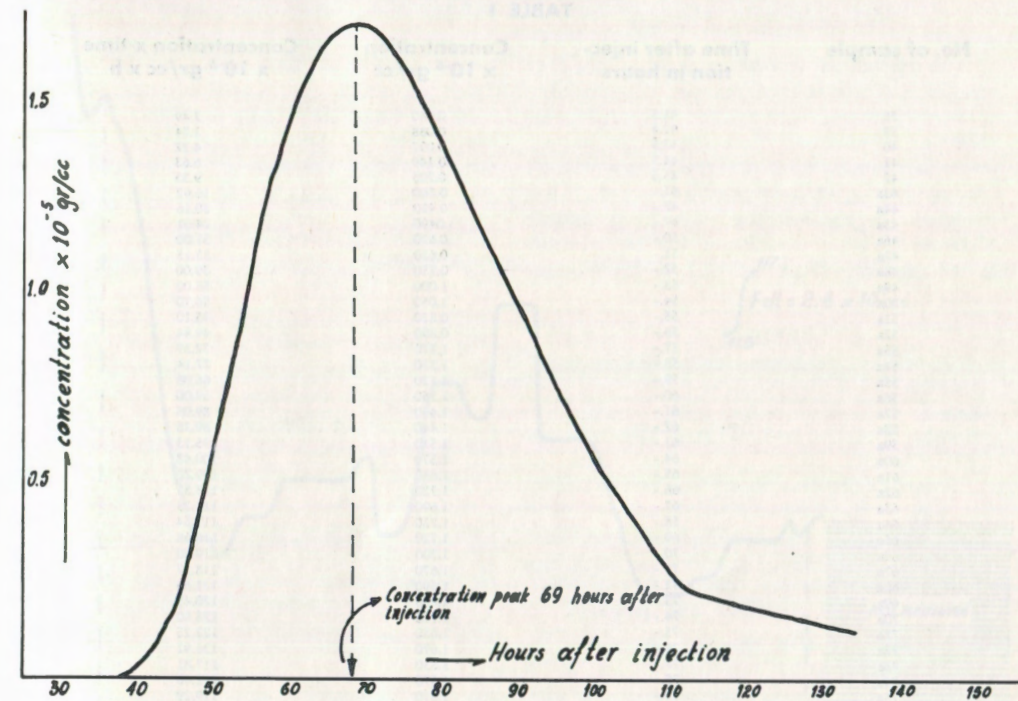


Figure 10.  
Concentration versus time curve. See text.

was detected was then analyzed quantitatively for bromine by irradiating a sample fraction together with a standard consisting of a 10 mg/l solution of  $\text{NH}_4\text{Br}$  made up using the uncontaminated spring water.

The first trace of  $\text{NH}_4\text{Br}$  was observed at the spring 41.5 hours after its introduction into the swallow hole (figure 10). Maximum concentration occurred 26.5 hours later (68.0 hours after introduction). After about 75 hours from the first appearance (117 hours after introduction) the concentration had decreased to the limits of detectability.

The discharge rate of the spring and its variation with time during the experiment are shown in figure 11. From these values the average discharge rate has been computed to be 8.795 l/sec ( $=3.17 \times 10^7$  cm<sup>3</sup>/hr). The volume of water discharged during the 75.5 hours during which the water was sampled (after the bromine appeared) is  $2.4 \times 10^9$  cm<sup>3</sup>. The average concentration of ammonium bromide calculated

from the data of Table 1 is about  $0.93 \times 10^{-5}$  g/cm<sup>3</sup>. The quantity of  $\text{NH}_4\text{Br}$  which emerged from the spring is therefore  $2.9 \times 10^9$  cm<sup>3</sup>  $\times 0.93 \times 10^{-5}$  g/cm<sup>3</sup> or 22.3 kg.

This amount is 76% of the 30 kg introduced into the swallow hole. The 24% not accounted for may have left the spring in concentrations too low to be detected, or may have remained in the underground water body.

Denoting the amount of tracer added to the system by  $m$  and the concentration at time  $t$  by  $c$ , the flow rate  $F$  at any point in the system is  $F = \int_0^\infty m/c \, dt$ . The volume of water  $V$ , underground between the swallow hole and the spring is equal to the product of the flowrate and the average residence time  $T$ , given by  $T = \int_0^\infty c \, t \, dt / \int_0^\infty c \, dt$ . Thus  $V = F \int_0^\infty c \, t \, dt / \int_0^\infty c \, dt$ .

These integrals may be computed from the areas under the curves of figures 10 and 12. Substituting the measured values of  $c$  and  $ct$  from table 1, the volume of water

TABLE 1

No. of sample	Time after injection in hours	Concentration x 10 <sup>-5</sup> gr/cc	Concentration x time x 10 <sup>-5</sup> gr/cc x h
38	41.5	0.060	2.49
39	42.5	0.088	3.74
40	43.5	0.097	4.22
41	44.5	0.149	6.63
42	45.5	0.205	9.33
43a	47.-	0.360	16.92
44a	48.-	0.420	20.16
45a	49.-	.0490	24.01
46a	50.-	0.620	31.00
47a	51.-	0.650	33.15
48a	52.-	0.750	39.00
49a	53.-	1.000	53.00
50a	54.-	1.050	56.70
51a	55.-	0.820	45.10
52a	56.-	0.890	49.84
53a	57.-	1.270	72.39
54a	58.-	1.330	77.14
55a	59.-	1.120	66.08
56a	60.-	1.150	69.00
57a	61.-	1.460	89.06
58a	62.-	1.440	89.28
59a	63.-	1.510	95.13
60a	64.-	1.570	100.48
61a	65.-	1.680	109.20
62a	66.-	1.720	113.52
63a	67.-	1.690	113.23
64a	68.-	1.730	117.64
65a	69.-	1.720	118.68
66a	70.-	1.700	119.00
67a	71.-	1.670	118.57
68a	72.-	1.690	121.68
69a	73.-	1.650	120.45
70a	74.-	1.700	125.80
71a	75.-	1.630	122.25
72a	76.-	1.670	126.92
73a	77.-	1.530	117.81
74a	78.-	1.570	122.46
75a	79.-	1.510	119.29
76a	80.-	1.500	120.00
77a	81.-	1.320	106.92
78a	82.-	1.360	111.52
79a	83.-	1.270	105.41
80a	84.-	1.260	105.84
81a	85.-	1.150	97.75
82a	86.-	1.130	97.18
83a	87.-	1.150	100.05
84a	88.-	1.120	98.56
85a	89.-	1.070	95.23
86a	90.-	1.080	97.20
87a	91.-	0.880	80.08
88a	92.-	0.840	77.28
89a	93.-	1.020	94.86
90a	94.-	1.000	94.00
91a	95.-	0.670	63.65
92a	96.-	0.640	61.44
93a	97.-	0.709	68.77
94a	98.-	0.697	68.30
95a	99.-	0.691	68.41
96a	100.-	0.608	60.80
97a	101.-	0.606	61.21
98a	102.-	0.583	59.47
99a	103.-	0.543	55.93
100a	104.-	0.472	42.09
101a	105.-	0.439	46.09
102a	106.-	0.405	42.93
103a	107.-	0.397	42.48
104a	108.-	0.359	38.77
105a	109.-	0.329	35.86
106a	110.-	0.274	30.14
107a	111.-	0.235	26.08
108a	112.-	0.231	25.87
109a	113.-	0.220	24.86
110a	114.-	0.220	25.08
111a	115.-	0.208	23.92
112a	116.-	0.205	23.78
113a	117.-	0.200	23.40

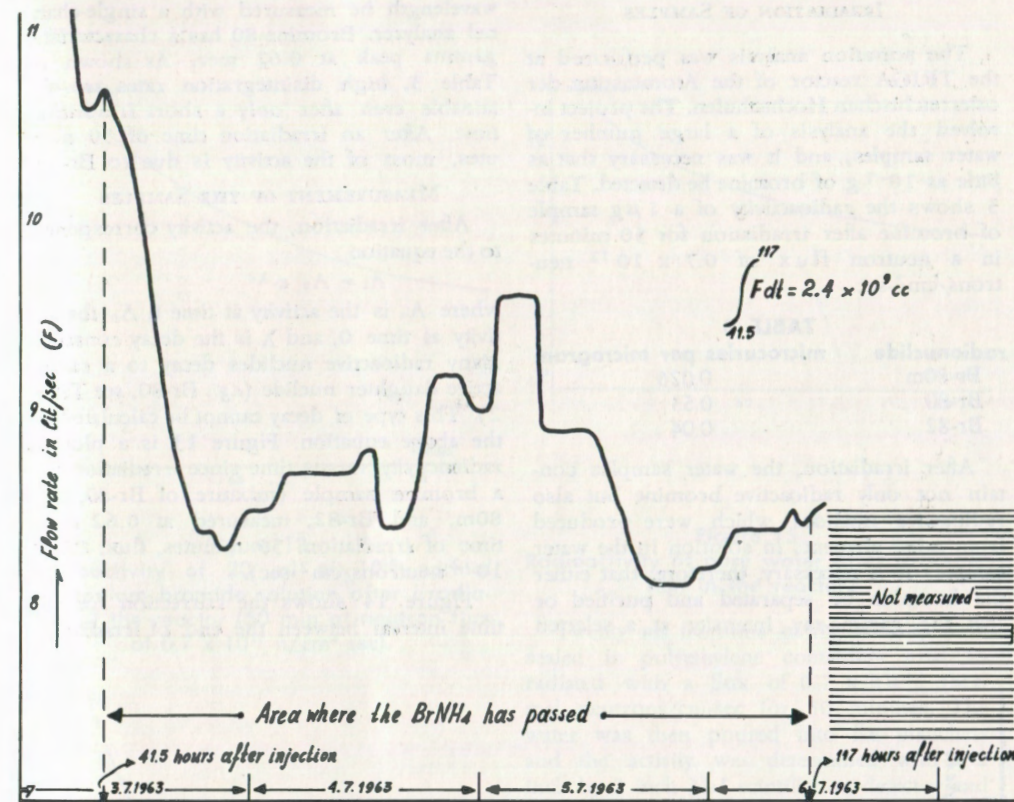


Figure 11.  
Flow-rate versus time curve. See text.

between the swallow hole and the spring is found to be 2240 m<sup>3</sup>. This value represents a lower limit, inasmuch as only 76% of the tracer was accounted for.

By employing separation procedures (which are often tedious and time consuming), as little as 10<sup>-9</sup> g of bromine can be determined.

THE NEUTRON ACTIVATION ANALYSIS  
METHOD, PART II  
(K. Buchtela)

Natural bromine consists of approximately equal amounts of Br-79 and Br-81. When these nuclides are irradiated with thermal neutrons, the nuclides Br-80, Br-82, and the isomer nuclide Br-80m are produced. The properties of these radionuclides are given in table 2.

Qualitative or quantitative analyses for bromine can be performed by measuring the radioactivity of the nuclide produced by irradiating the sample with thermal neutrons.

TABLE 2

nuclide	half life	radiation energy (mev)	daughter
Br-80m	4.4 hrs	0.04; 0.05	Br-80
Br-80	17.7 min	2.0 ; 1.4	Kr-80 (stable)
		0.86	
		0.62	
Br-82	35.9 hrs	0.46	Kr-82 (stable)
		0.55; 0.78	

The activation analysis was performed at the TRIGA reactor of the Atominstitut der osterreichischen Hochschulen. The project involved the analysis of a large number of water samples, and it was necessary that as little as  $10^{-7}$  g of bromine be detected. Table 3 shows the radioactivity of a  $1 \mu\text{g}$  sample of bromine after irradiation for 50 minutes in a neutron flux of  $0.7 \times 10^{12}$  neutrons/cm<sup>2</sup>-sec.

radioisotope	microcuries per microgram
Br-80m	0.026
Br-80	0.53
Br-82	0.04

After irradiation, the water samples contain not only radioactive bromine but also radioactive nuclides which were produced from other elements in solution in the water sample. It is necessary, therefore, that either the bromine be separated and purified or that the gamma-ray intensity at a selected

wavelength be measured with a single-channel analyzer. Bromine-80 has a characteristic gamma peak at 0.62 mev. As shown in Table 3, high disintegration rates are obtainable even after only a short irradiation time. After an irradiation time of 50 minutes, most of the activity is due to Br-80.

MEASUREMENT OF THE SAMPLES

After irradiation, the activity corresponds to the equation

$$A_t = A_0 e^{-\lambda t}$$

where  $A_t$  is the activity at time  $t$ ,  $A_0$  the activity at time 0, and  $\lambda$  is the decay constant. Many radioactive nuclides decay to a radioactive daughter nuclide (e.g., Br-80, see Table 2). This type of decay cannot be calculated by the above equation. Figure 13 is a plot of radioactivity versus time since irradiation for a bromine sample (mixture of Br-80, Br-80m, and Br-82, measured at 0.62 mev, time of irradiation: 50 minutes, flux:  $0.7 \times 10^{12}$  neutrons/cm<sup>2</sup>-sec).

Figure 14 shows the correction for the time interval between the end of irradiation

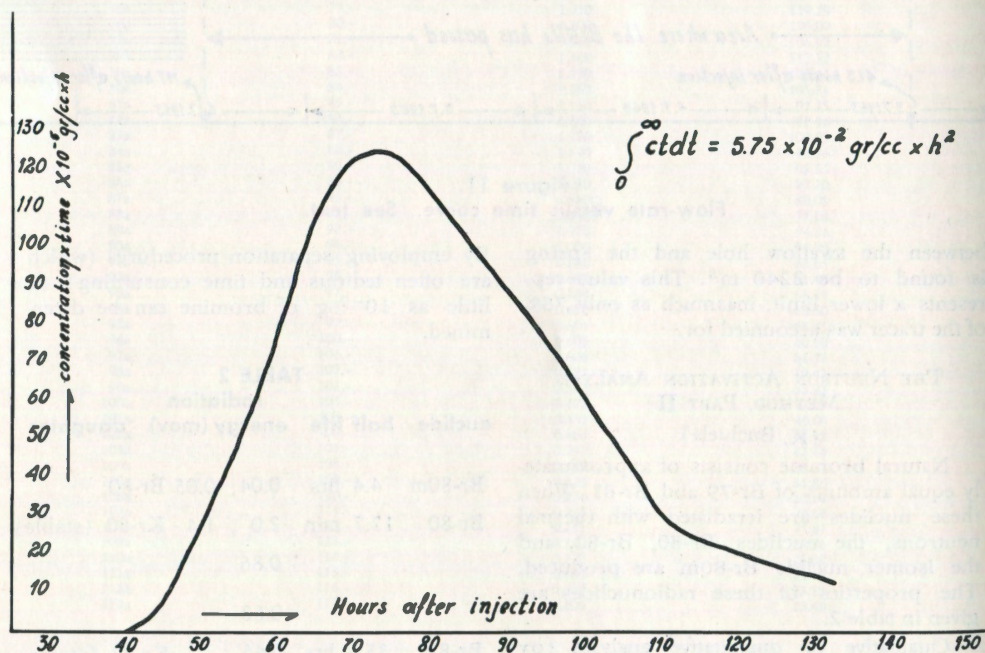


Figure 12. Concentration-time versus time curve. See text.

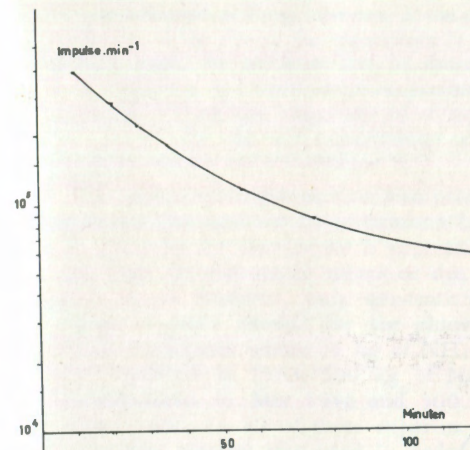


Figure 13. Radioactivity of 20 ml of  $10^{-5}$  normal ammonium bromide solution after irradiation of the reactor (50 min at neutron flux of  $0.7 \times 10^{12}$  n/cm<sup>2</sup>-sec).

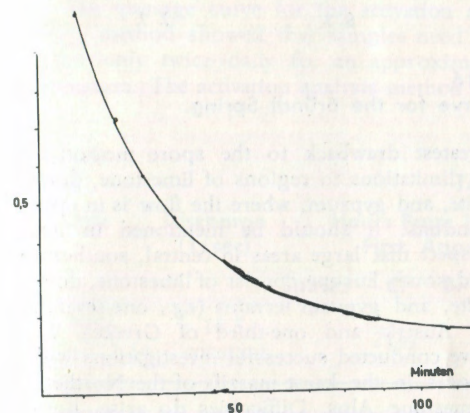


Figure 14. Correction curve for delay between end of irradiation and beginning of measurement. See text.

and the beginning of radiation measurement. In this plot all disintegration rates are corrected for the same time interval (10 minutes). Water samples without bromine show a small amount of radioactivity after irradiation, and the Compton effect of high-energy radiation also contributes some activity at 0.62 mev. Figure 15 shows the decay curve of a sample which contains no bromine.

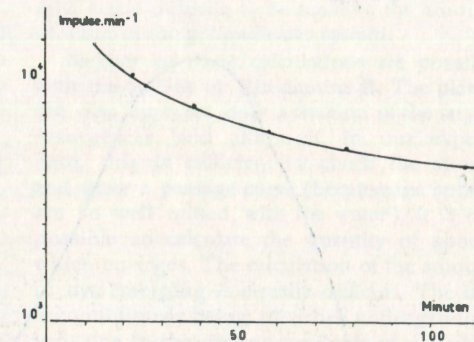


Figure 15. Radioactivity of pure water after irradiation in the reactor.

Twenty ml fractions of the samples were sealed in polyethylene containers and irradiated with a flux of  $0.7 \times 10^{12}$  thermal neutrons/cm<sup>2</sup>-sec for 50 minutes. The water was then poured into flat planchets and the activity was determined with a 2 inch by 2 inch NaI scintillation detector and a single channel analyzer (Tracerlab model SC 76) at 0.62 mev. All samples were measured under comparable conditions.

The count rate was corrected by the values shown in figure 13 (radioactivity due to other nuclides) and normalized (using figure 14) to an activity 10 minutes after the end of irradiation. Twenty ml samples of  $10^{-5}$  molar  $\text{NH}_4\text{Br}$  were also irradiated as standards. About 100 samples were analyzed, and the results are shown in figure 16.

The analyses could be performed quickly. It was only necessary to fill the irradiation vessels, prepare the samples for counting, read the counter, and perform a few sample calculations. Every five minutes a sample was removed from the reactor for counting and interpretation and the irradiation of a new sample was begun.

COMPARISON OF METHODS AND SUMMARY

Each of the methods used in this experiment was successful in tracing the flow from the western slopes of the Buchkogel range

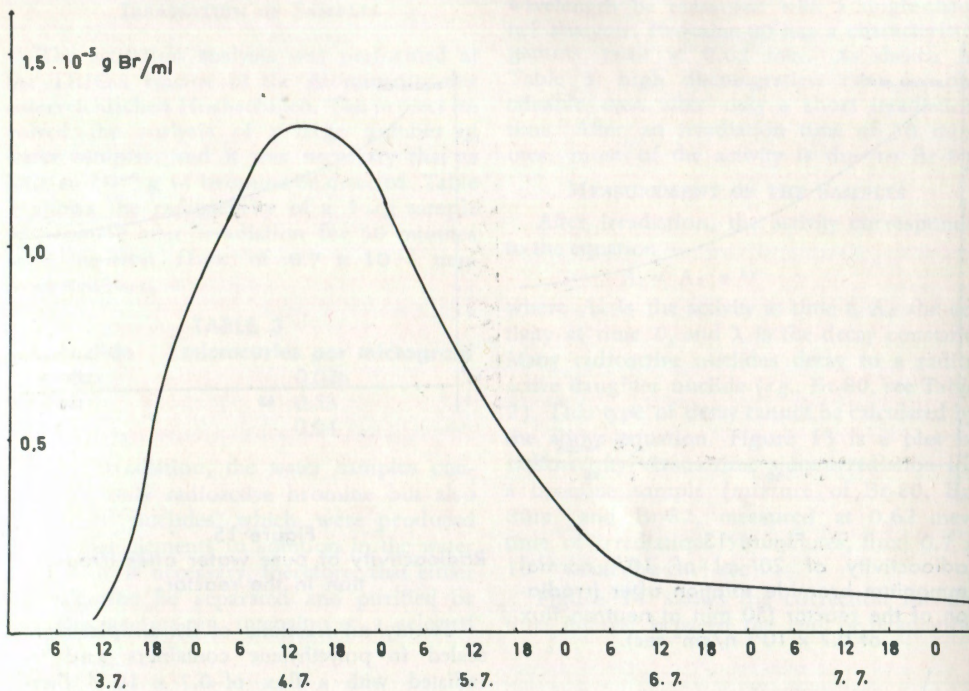


Figure 16.  
Bromine content versus time curve for the Bründl Spring.

to the Bründl spring on the east side of the range. Ideally, each of the methods used could be employed in the investigation of other karst water systems. In actual practice, however, each of the methods has certain limitations.

If the area to be investigated is large, with many springs to be watched and long passage times for the water, the use of radioactive isotopes is virtually ruled out, due to the considerable amount of equipment and large numbers of personnel needed. In small areas with self-contained water systems, and especially when the water is thought to flow through fine clastic sediments, the radioactive isotopes method could prove quite useful.

When an extensive karst terrain must be investigated, the use of dyed lycopodium spores is still the cheapest and simplest method. The application of five colors allows the simultaneous tracing of the flow from five different swallow holes, and the observation of springs using plankton nets is of impressive simplicity compared to other methods. The

greatest drawback to the spore method is its limitations to regions of limestone, dolomite, and gypsum, where the flow is in open conduits. It should be mentioned in this respect that large areas in central, southeast, and south Europe consist of limestone, dolomite, and gypsum terrains (*e.g.*, one-seventh of Austria and one-third of Greece). We have conducted successful investigations with spores in the karst massifs of the Northern Limestone Alps. Difficulties do arise, however, even in limestone regions, when the karst water flows through gravels. It is this fact which makes combined experiments necessary.

The comparative experiment reported in this paper has shown that a combined use of spores and Rhodamine B is of great utility. Uranine will, however, still be given preference in ground-water systems in gravels and clays, inasmuch as clay adsorbs Rhodamine B. The prolongation of the passage of Rhodamine B due to absorption may, however, be useful in tracing rapidly flowing water.

If only qualitative results are needed, samples may be collected at long intervals. If the concentration of the dye at the resurgence is sufficiently high, its presence can be detected by the coloring of cotton fabric suspended in the water. Thus the simplicity of observations favors the use of a combination of lycopodium spores and Rhodamine B.

The activation analysis method also proved successful. The amount of ammonium bromide required for clear proof is appreciably larger than the amount of spores or dye required. It is, however, only one-tenth the quantity of NaCl needed for the chloride tracing. In the area where 35 kg of  $\text{NH}_4\text{Br}$  was introduced in 1963, 500 kg of NaCl was introduced in May 1956 and 300 kg in June 1956. In all of these experiments an excessive amount was used in order to obtain clear passage curves in the comparative tests. Furthermore, it is basic from the point of view of economics to overestimate the amount of material needed rather than to endanger the results of the experiment by not using enough.

The passage curve for the activation analysis method showed that samples need be taken only twice daily for an approximate evaluation. The activation analysis method al-

lows the amount of discharging tracer to be computed with considerable accuracy, and permits a fair estimate to be made of the amount of water in the groundwater system.

Neither of these calculations are possible with the spores or Rhodamine B. The plankton nets intercept only a fraction of the larger resurgences, and although, in our experience, this is sufficient to check the spores and draw a passage curve (because the spores are so well mixed with the water), it is not possible to calculate the quantity of spores which emerges. The calculation of the amount of dye emerging is equally difficult. The dye is continuously being adsorbed underground, and, due to the varying amounts of clay present, behaves differently in systems which are otherwise similar. Another problem is the intensification of color in the water due to the presence of dyed clay particles. These factors prevent any meaningful calculations and are responsible for the overly large estimates of dye concentration in many investigations.

A comparison of the rates of travel of the various tracers shows that the lycopodium spores travel faster than the Rhodamine B dye, the iodine-131, or the ammonium bromide (figure 17 and Table 4). Spores were

TABLE 4

Date	Discharge (l/sec)	Hours From Injection to First Appearance				Hours From Injection to Passage Peak						
		Spores	Cl	Br	Dye	I-131	Spores	Cl	Br	Dye	I-131	
1956 May 12-14	16.5 constant	21½				55						
1956 Jun 22-28	23 constant	13½	19½	13½		19	31		31			
1957 Mar 23-25	23 init., later less	13				33						
1958 May 20-24	6 constant	34				49						
1963 Jul 1-12	7.5 init., 16 after 30 hrs., then 9 ave.	33		41½	42	44	44	first peak 39 second peak 52		68	69	78

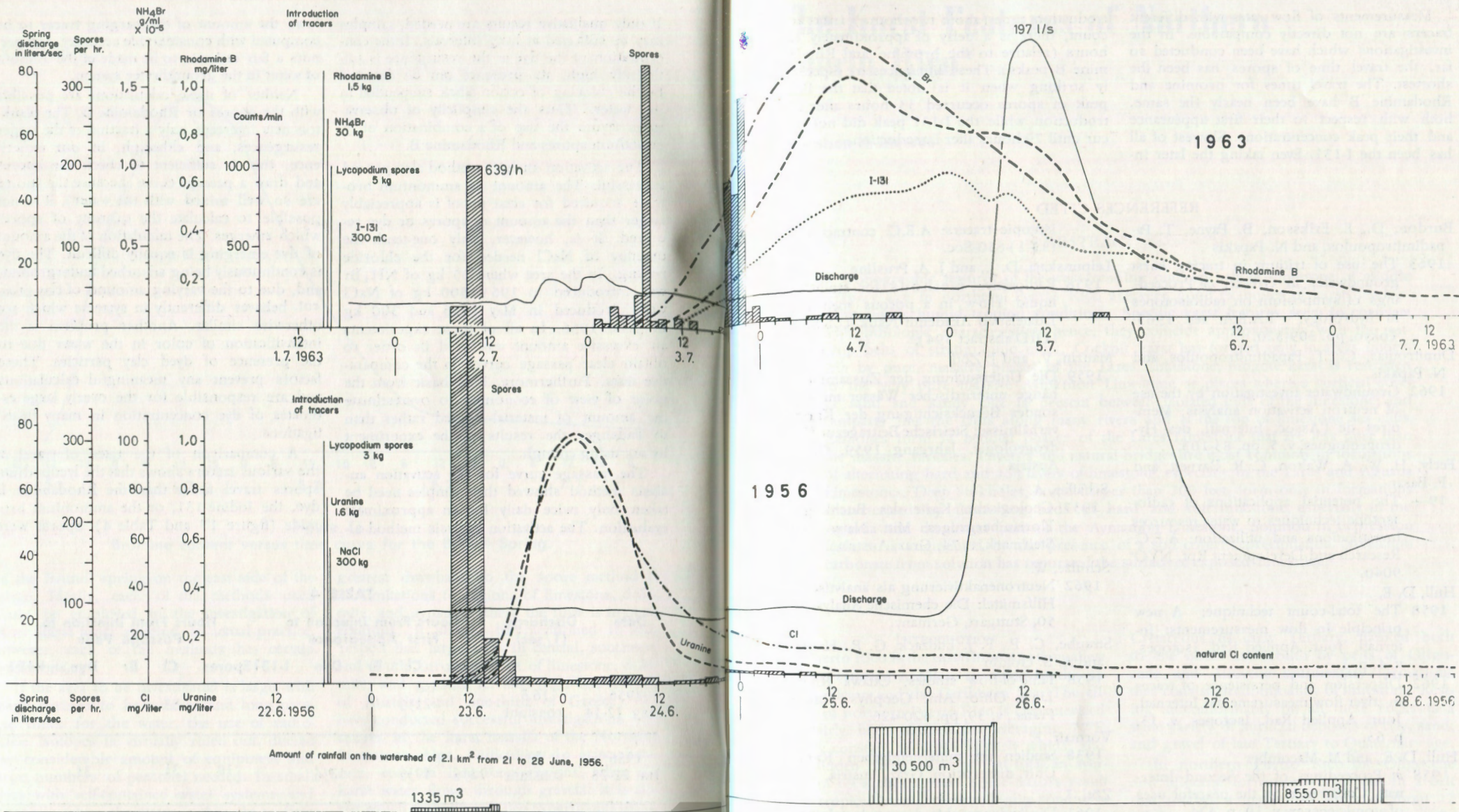


Figure 17.

first detected 33 hours after they were introduced, 8 hours before the appearance of either dye or the bromine (although these substances were introduced one hour before the spores). The passage curve for the spores showed two striking peaks. The first and higher peak occurred 28 hours and the sec-

ond peak 15 hours before the peaks in the passage curves of bromine and Rhodamine B (which occurred simultaneously). The occurrence of two peaks in the spores is attributed to the temporary rise in discharge. The passage curves of Rhodamine B and I-131 also showed two peaks (figure 17).

Figure 17.

The passage of the spores had abated by the time of the bromine and Rhodamine B peaks. The same phenomena was observed in June 1956 when spores, sodium chloride, and uranine were used. The interval between the spore and other passage peaks in 1956 was only 12 hours, which may be explained

by the larger discharge of the spring (23 l/sec in 1956 versus 10 l/sec in 1963) which shortened the travel time of all the tracers and reduced the time between the peaks. The larger discharge during the 1956 was also probably responsible for the larger fraction of spores recovered in 1956.



Measurements of flow rates with different tracers are not directly comparable. In the investigations which have been conducted so far, the travel time of spores has been the shortest. The travel times for bromine and Rhodamine B have been nearly the same, both with respect to their first appearance and their peak concentrations. Slowest of all has been the I-131. Even taking the later in-

roduction time (about two hours) into account, there is a delay of approximately 12 hours (relative to the bromine and Rhodamine B peaks). These differences are especially striking when it is noted that the first peak of spores occurred 33 hours after introduction while the I-131 peak did not occur until 79 hours after introduction.

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# The Karst Features of Northern Puerto Rico\*

By Watson H. Monroe

#### ABSTRACT

Topographic features of the west-trending outcrop belt of limestone of middle Tertiary age in northern Puerto Rico are very good examples of karst development under humid tropical conditions. Specific karst features seem to correlate with lithologic characteristics; hence, they coincide approximately with the outcrop belts of stratigraphic units. Cockpit karst has formed only in areas underlain by pure, massive phases of the Lares Limestone; mogote karst is restricted to the very pure massive Aymamón Limestone at places where a surficial cover of sand and sandy clay is present between isolated hills of the limestone; and ramparts line the cliffs along many rivers and at the top of limestone sea cliffs. Zanjones form in bedded phases of the Lares Limestone that are less pure than the massive varieties. Caverns and natural bridges are most common in formations of alternating hard and soft layers of limestone, especially in the Lares and Aguada Limestones. Deep sinkholes, some deeper than 200 feet, form only in formations characterized by alternating beds of hard and soft limestone, especially in the Aguada and the lower part of the Aymamón Limestone. Solution in depression features is augmented by the presence of a soil cover; reprecipitation of calcium carbonate from solution has indurated the surface of exposed limestone.

#### INTRODUCTION

Puerto Rico is the easternmost and smallest of the Greater Antilles, bounded by the Atlantic Ocean and the Caribbean Sea. The climate of northern Puerto Rico is characterized by fairly high temperature averaging 77°F, nearly constant moderate easterly winds, and by sudden torrential rains that total an average of 69 inches a year. These factors result in a tropical humid climate, highly conducive to intense weathering.

Geologically, Puerto Rico (fig. 1) consists of a central eastwest core of volcanic and intrusive rocks ranging in age from

Cretaceous to early Tertiary, flanked both to the north and south by belts of Oligocene and Miocene sedimentary formations that consist predominantly of limestone. Resting unconformably on all these rocks is a wide variety of surficial deposits of clay, sand, and gravel of late Tertiary to Quaternary age.

In northern Puerto Rico the Oligocene and Miocene formations crop out in a belt that reaches a maximum width of about 22 kilometers near Arecibo. The rocks consist mainly of limestone and marl that dip gently north toward the Atlantic Ocean. These strata have a total thickness of about 1,700 meters, divided into six formations of distinctive lithologic character.

At the base of the sequence is the San Sebastian Formation of clay, silt, gravel, and thin lenses of earthy limestone. The San Sebastian contains no karst features.

\*Publication authorized by the Director, U.S. Geological Survey Presented at the Annual Meeting of the American Association for Advancement of Science, December 29, 1966, Washington, D.C.

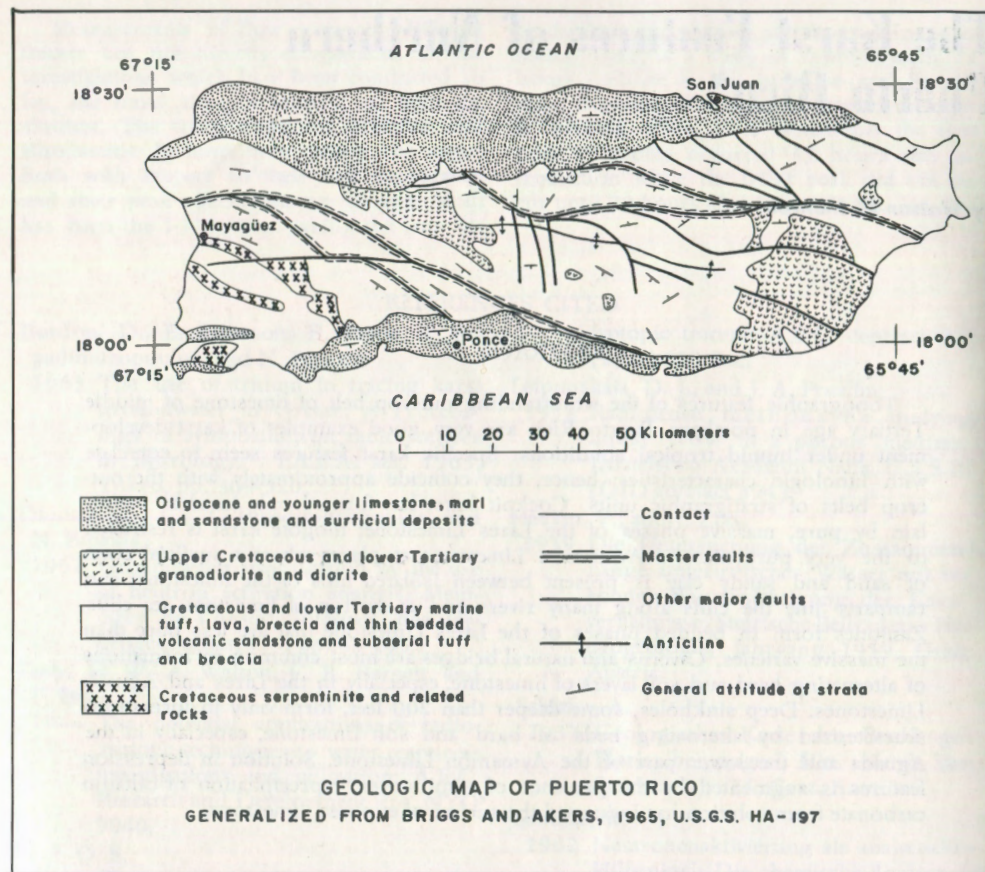


Figure 1.  
Generalized geologic map of Puerto Rico.

This formation grades upward into the Lares Limestone, which varies in lithology from very pure massive limestone to thin-bedded limestone. Each lithologic type gives rise to a distinctive type of karst morphology. The massive limestone gives rise to cockpit or kegelkarst, consisting of hundreds of subconical hills separated by steep-walled valleys; more strongly bedded varieties are cut by abundant caves, some of which have collapsed into sinks and long karst valleys; thin-bedded facies have been cut by long parallel enlarged joints known as zanjones. The boundaries of each type of lithology are sharp and karst types change abruptly at these boundaries.

The Lares is overlain very sharply by the Cibao Formation which contains a variety of

lithologic types. In the middle of the area the formation consists mainly of pure limestone. This phase of the Cibao has been weathered and dissolved into high hills separated by long, narrow, steep-sided karst valleys. Both toward the west and east the limestone grades laterally into calcareous clay and marl, typical Cibao, which contains no karst features.

The Cibao grades upward into the Aguada Limestone, which consists of layers of fairly pure, medium-grained calcarenite alternating with thick beds of rubby marlstone. The Aguada contains most of the deep sinkholes and also many caves.

Overlying the Aguada is the very pure Ay-mamón Limestone, much of which is friable soft limestone, almost a compressed

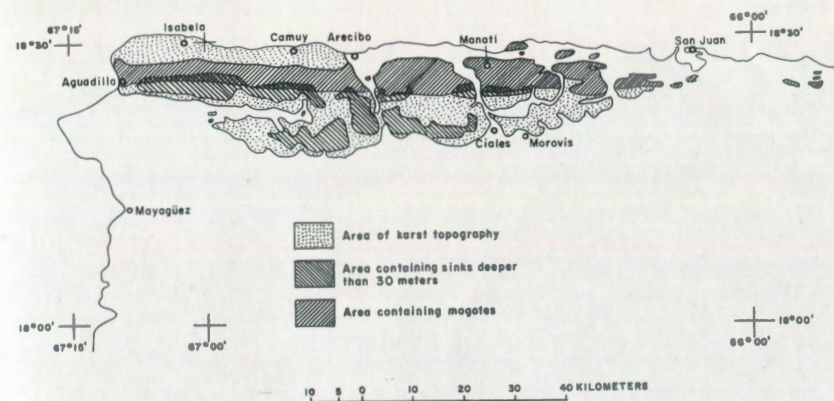


Figure 2.  
Karst area of northern Puerto Rico outlining areas containing mogotes and areas containing sinks deeper than 30 meters.



Figure 3.  
Lunar landscape of sinks in Aguada Limestone, 6 kilometers north of Ciales.



**Figure 4.**  
Closely spaced sinks in Aguada Limestone, 8 kilometers northwest of Morovis.

powder. On exposed surfaces this chalklike rock has been hardened into very dense limestone by solution and reprecipitation of calcium carbonate. Characteristic of the Aymamón are the mogotes, or haystack hills, that rise from intervening plains.

The Aymamón is overlain by very ferruginous limestone, sandstone, and chalk, the Camuy Formation, which commonly forms long, gently sloping hills of limestone whose only karst feature is an abundance of vertical shafts.

Resting unconformably on the Oligocene and Miocene rocks are surficial deposits of sand, clay, and soil that have played their part in developing the karst topography by storing acidified ground water that has led to solution of the underlying limestone.

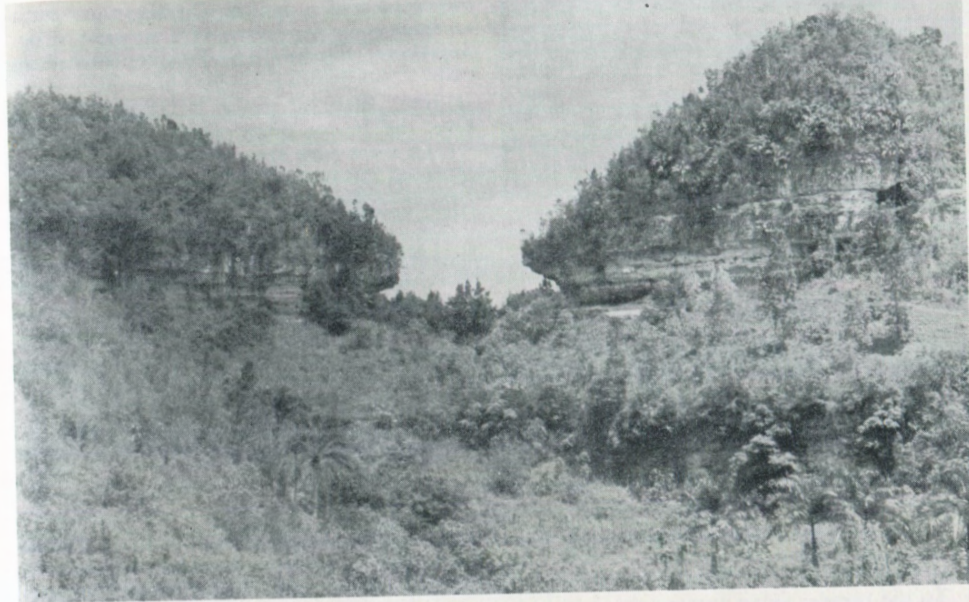
#### KARST FEATURES AND RELATION TO GEOLOGY

Figure 2 shows the parts of northern Puerto Rico where karst phenomena are present. The southernmost boundary marks the southern edge of limestone formations. The east-west indentations show the areas of the Cibao Formation consisting of clay. East of

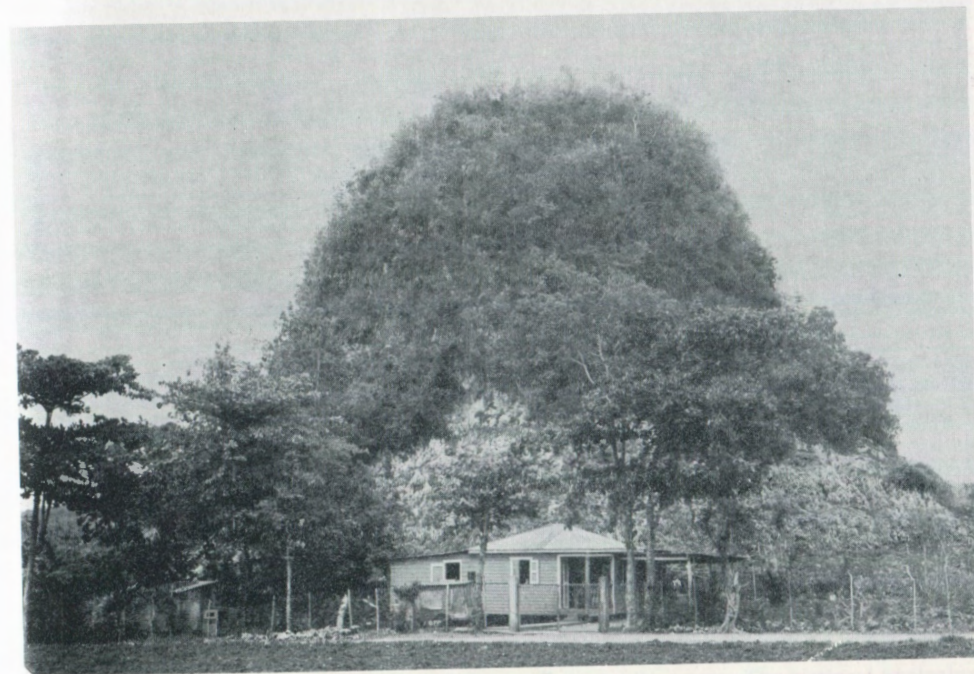
Arecibo much of the area of limestone formations has been covered by later Tertiary and Quaternary alluvial and shallow marine sand and clay deposits.



**Figure 5.**  
Natural bridge in Aguada Limestone, 16 kilometers southwest of Arecibo.



**Figure 6.**  
Collapsed natural bridge, 1.6 kilometers east of bridge in figure 5.



**Figure 7.**  
Mogote of Aymamón Limestone (20 meters high), 16 kilometers north of Morovis.



Figure 8.

Compact chalk of Aymamón Limestone in roadcut through mogote, 28 kilometers west of San Juan.

#### SINKS

To the traveler flying over northern Puerto Rico the most prominent karst features are



Figure 9.

Shell of indurated Aymamón Limestone over hollow interior, 21 kilometers east of San Juan.

the sinks and mogotes. The sinks present a veritable lunar landscape of thousands of depressions (fig. 3). The area contains more than 1,300 depressions in which the bottom is more than 30 meters (100 feet) deeper than the lowest point on the rim (see fig. 2). Of these nine are deeper than 70 meters. Most of the very deep sinks are in the belt of outcrop of the Aguada Limestone. The bottoms of the sinks are commonly covered by soil that contains water acidified with  $\text{CO}_2$  by plant respiration. Reaction of this soil water with the limestone causes the depressions to become deepened. As they become deeper the sides collapse to form nearly vertical cliffs.

Figures 3, 4, and 12 show the close spacing of solution sinks in the Aguada Limestone south of Manati.

#### CAVES

There are hundreds of caves in Puerto Rico, but very few have been explored thoroughly. No cave inventory has ever been attempted. Russell H. Gurnee, former president of the National Speleological Society,



Figure 10.

Asymmetric mogotes of Aymamón Limestone, 21 kilometers west of Arecibo. Gentle slope on east side, steep slope on west side.

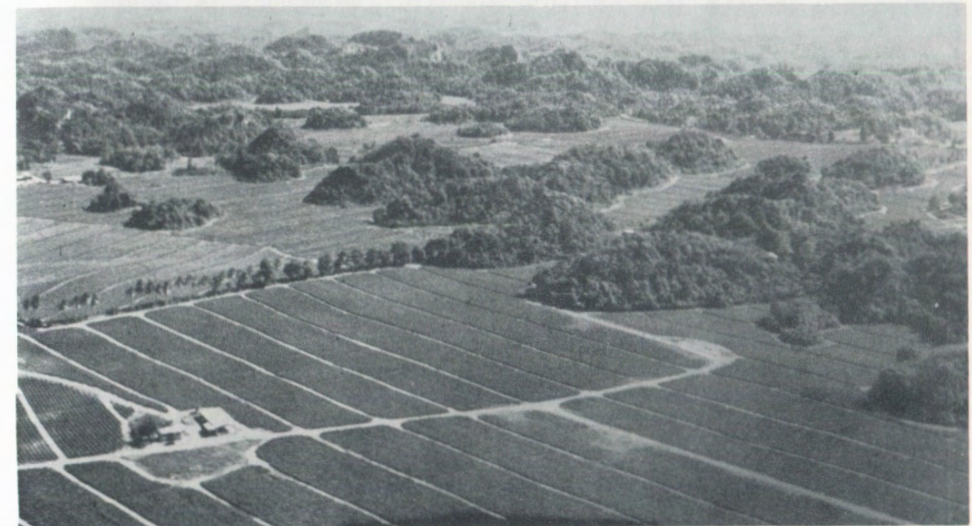


Figure 11.

Mogotes of Aymamón Limestone projecting through plain covered by sandy clay (blanket sand), 11 kilometers north-northwest of Morovis.

has mapped several caves and has probably explored more of them than any other single person.

The most extensive caves are within those parts of the Lares and Aguada Limestones in which the limestone is generally bedded. Two rivers in the west-central part of the karst belt, the Camuy and the Tanamá have long

underground courses, mostly within the Lares Limestone. These underground courses are marked on the surface by lines of steep-walled collapse sinks.

The Rio Camuy flows underground for about 7 kilometers. The National Speleological Society has sponsored several expeditions to the Camuy area (Gurnee, Thrailkill, and

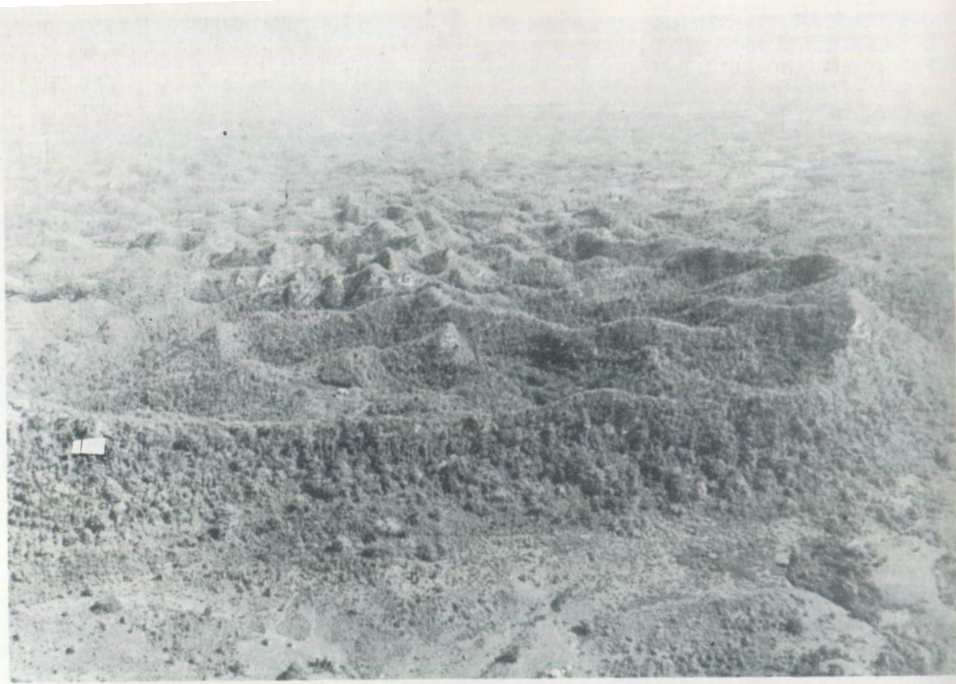


Figure 12.  
River rampart on east side of Rio Grande de Manati, 7 kilometers north of Ciales. Top of rampart is 150 to 225 meters above river and 15 to 30 meters above bottoms of sinks behind rampart.

Nicholas, 1966; Gurnee and others, 1967) and has mapped about 2.3 kilometers of the underground parts of the courses of the river and about an additional 2.3 kilometers of side passages. Near the entrance to the underground course the Lares Limestone is perforated by many caves and natural tunnels, which are probably ancient courses of the Rio Camuy.

The Rio Tanamá is mostly unroofed and now flows through at least 6 natural tunnels, plainly shown on the topographic maps of the Bayaney and Utuado quadrangles. Many of the smaller streams in the same general region have partial underground courses, also not explored. One stream (Monroe, 1963) passes underground from valley to valley and finally flows about 2 kilometers through a cave that is said to open on the Camuy Valley at the Boca del Infierno – the Mouth of Hell.

Very similar in origin to the caves are natural bridges. I have found two quite siz-

able bridges in the Aguada Limestone. The bridge in Figure 5 is formed of a thick bed of hard limestone that rests on more easily eroded friable crossbedded limestone. About 2 kilometers farther east at the same stratigraphic position are the remains of a similar bridge of which only the two buttresses remain (fig. 6).

#### MOGOTES

Mogotes, variously called pepinos, cerros, haystack hills, or pitons, are subconical steep-sided hills that rise up out of a flat plain. Mogotes range in height from a few meters to 50 meters (fig. 7). Figure 2 shows the area in which they are common.

All mogotes have steep sides and many, especially on their western sides, have vertical cliffs or overhangs. All are capped by very dense limestone, from a few centimeters to about 10 meters thick, that has dissolved into a badland of sharp spires and shallow



Figure 13.  
Small zanjón in Lares Limestone, 3.5 kilometers west-northwest of Morovis. Most zanjones are narrower and deeper and have steeper sides.

solution pits. Deep roadcuts and quarries show, however, that the hard limestone is merely a shell over rather soft, chalklike limestone (fig. 8) or over a rubble of solution cobbles in a matrix of terra rossa. In many mogotes the soft interior has been partially washed away, leaving the capping as a hollow shell (fig. 9).

The induration of the surface of the mogotes is a phenomenon of reprecipitation of calcium carbonate (Monroe, 1966). Apparently after each rain the soft powdery limestone of the Aymamon is thoroughly soaked under conditions of high humidity. This results in solution of the limestone into calcium bicarbonate. After the shower, the sun immediately dries the surface of the limestone and the rise in temperature tends both to drive off carbon dioxide and to evaporate some of the water from the interior parts of the limestone causing local reprecipitation of calcium carbonate from the bicarbonate solution. This results in cementation of the soft limestone to a hard rock.

The asymmetric shape of the mogotes, steeper on the western than on the eastern side (fig. 10), is definitely related to the trade-wind rains. The rim of indurated rock is much thicker on the eastern than on the western side. Apparently the thin caprock on the western sides of mogotes tends to spall off, exposing the relatively soft interior. This in turn spalls off, leaving a vertical cliff, or even an overhanging shelterlike cave at many places.

The surface plain surrounding the mogotes is covered by a mantle of sandy clay (fig. 11) under which there has been sheet solution leaving the mogotes projecting as residual hills of limestone.

#### RAMPARTS

Closely related in origin to the mogotes are limestone ramparts that are found at the tops of many river valleys and sea cliffs (Flint and others, 1953; Monroe, 1966). The most prominent of these is on the sides of



Figure 14.  
Vertical aerial photograph of area underlain by Lares Limestone from 2.1 to 4.5 kilometers west-northwest of Morovis. Thin-bedded limestone in eastern two-thirds of area weathered to zanjon karst; massive limestone along strike in western third weathered to cockpit or cone karst.

the Rio Guajataca in western Puerto Rico (see topographic map of the Quebradillas quadrangle). The slopes rise in steep canyon walls of casehardened limestone 155 meters up from the river. On both sides away from the river the surface then drops from the top of the wall some 25 meters to a plain covered by sandy clay. Rising out of this plain are mogotes that have about the same altitude as the top of the rampart and that also rise about 25 meters above the plain. As the underlying limestone contains no sand, and as the sandy clay occurs at about the same altitude and has about

the same composition for many kilometers both toward the east and west, it seems probable that the sandy clay was once a continuous sheet of alluvial or beach material that extended very widely across northern Puerto Rico at an altitude equal to or perhaps higher than the tops of the ramparts and mogotes (Briggs, 1966). Subsequently sheet solution of the underlying limestone has lowered the sandy clay to its present level about 25 meters below the tops of the residual limestone ramparts and mogotes.

Similar ramparts slightly less prominent than the one at the sides of the Rio Gua-

jataca are present at the sides of several other rivers in Puerto Rico, such as the Manati, as shown in figure 12. Very low ramparts, only about 5 meters high, have been noted at the top of sea cliffs in western Puerto Rico between Camuy and Isabela.

#### ZANJONES

An unusual kind of karst morphology present in Puerto Rico is the zanjon (Monroe, 1964). Zanjones are long vertical-walled trenches (fig. 13), that range in width from a few centimeters to many meters and in depth from about 1 to 4 meters. The bottoms of the trenches are covered by a rubble of broken pieces of limestone that have spalled off the sides and are mixed with forest litter. Zanjones occur as parallel trenches oriented generally in one direction. The intervening ridges are from 5 to 10 meters apart. The zanjones are found only in areas of thin-bedded, brittle limestone, mostly in the Lares. Where the thin-bedded limestone passes into massive limestone, the zanjones stop abruptly and are bordered by cockpit karst. The zanjones apparently form by solution along joints; as the joints get deeper, the sides spall off to form vertical walls, causing slow widening, accompanied by further deepening by continued solution of the bottom and of the accumulated talus. Zanjones are typically exposed in an area northwest of Ciales, but extensive areas of zanjones modified by great lateral growth are present between Ciales and Morovis (fig. 14), and in the area north of Lares where they show on the San Sebastian topographic map as lines of long depressions.

#### CONCLUSIONS

The karst features of Puerto Rico are extremely varied, and may be considered typical of the karst forms found in tropical areas around the world. Both the solution sinks and the mogotes seem to be dependent in large part on the presence of a soil cover accompanied by torrential rainfall. Plant respiration acidizes the soil water accelerating solution beneath the soil causing depressions to become deeper and hills to project higher. Exposed limestone, especially pure limestone, commonly has little if any soil cover and is casehardened by precipitation of calcium carbonate; under conditions of torrential rainfall followed by hot sun, weathering and erosion almost cease and the limestone stands as high hills and ridges. Much of the limestone underground has been dissolved into a honeycomb of interconnected small tubes rather like a sponge (fig. 8). Above the water table very little solution takes place in these passages, as the water passing through is saturated with calcium bicarbonate. At places where the water carries alluvium containing quartz sand, however, abrasion takes place and the passages are enlarged to a point that running streams flow through them.

The combination of sudden torrential showers followed by hot sunlight, a high content of CO<sub>2</sub> in the soil as a result of plant respiration, concentration of soil by its removal from hills and deposition in adjacent valleys, spalling off of nearly vertical walls of only slightly consolidated limestone, and variation in the lithology of generally calcareous rocks are all factors in producing Puerto Rico's karst topography.

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Manuscript received by the editor  
 29 June 1967

# The Earth Sciences and Speleology: Discussion

By James F. Quinlan

William E. Davies (1966) is to be commended for his attempt to write a summary of speleological studies in the earth sciences. What he has provided is interesting, but very misleading and incomplete. I realize that a thorough summary could easily fill a book, and that in a brief article choices must be made; no two karst bibliographers will agree on all inclusions and deletions. Even so, in Davies' review, which purports to be international in scope, there is a definite and misleading overemphasis on the importance and volume of American contributions to the world literature, and there is a very uneven consideration of the European literature. This provincialism, though internationally somewhat traditional, is so obvious as to be almost insulting to our colleagues in other lands. I would like to have seen Davies' figures or estimates on the distribution of the vast and widely dispersed quantity of karst and speleological literature. My own study places at least 80% of the world literature as being in the French, English, German, and Russian languages.

Even more misleading is Davies' lack of emphasis on the fact that the cave and karst sciences, in this country and elsewhere - in addition to continuing with the still very important tradition of description and interpretation - now tend to include more sophisticated considerations of the dynamics of processes, and especially of the interrelations between process and form rather than the relation between stage and an assumed historical development.

There are some bibliographic citations that are so conspicuous by their absence that their exclusion makes part of Davies' text false and erroneous. Specifically, mention should have been made of the important works by

Pfeiffer (1963), Pohl (1955), and by Gvozdetsky (1954). I shall comment briefly on the importance of these three works and I will mention several other significant publications.

Pfeiffer (1963) has written a monumental and scholarly account of the historical development of the concepts of karst groundwater from 600 BC to the present. His greatest emphasis is on the periods prior to 1830, and he clearly documents the fact that, contrary to Davies' statement about the first published observations on water in limestone terrain having been made in 1689, there were many earlier discussions and illustrations of the hydrology of limestones. For example, Felix Faber (1441 (42?) - 1502), in a work published posthumously in 1605, was the first to describe thoroughly and to understand the functions of dolines (sinkholes) as water collectors for karst springs (Pfeiffer, 1963, p. 46-48).

Pohl's perceptive analysis of the origin and development of vertical shafts in the Central Kentucky Karst (Pohl, 1935, 1955) is in itself an excellent study and it also probably marks the turning (in the American literature) from a consideration of form to a consideration of process. Another pivotal paper (which is cited by Davies) is that by Smith and Albritton (1941).

It seems appropriate to recognize here that E. R. Pohl has heretofore been an unsung hero of American cave geology. His publications (1935; with Born, 1935; 1936; 1955; with White, 1965) are distinguished by careful analysis of observations, and all are significant contributions. But Dr. Pohl's greatest contribution has been his influence. For more than 30 years he has guided and inspired geological investigations in the Cen-

tral Kentucky Karst. Emerson's opinion that an institution is the lengthened shadow of one man is certainly exemplified by the Cave Research Foundation and its fortunate relationship with Dr. Pohl.

Davies refers to D. V. Ryzhnikov (*sic*) and G. A. Maximovich (*sic*) as being among the leaders of a large school of karst geologists that has developed in the USSR during the last 25 years, and as authors who have published extensively and produced standard texts on the subject. Most certainly this statement describes Prof. Maksimovich, but it equally describes the influence of another distinguished investigator of karst, Prof. N. A. Gvozdetzky. (see especially Gvozdetzky, 1954), who is not mentioned by Davies. And while it is true that Ryzhnikov has written several papers and a monograph on karst (Ryzhnikov, 1954), it is quite inaccurate to refer to the latter as a "standard text." Actually Ryzhnikov's monograph was unfavorably received in the Russian literature (see his reply, Ryzhnikov, 1958), and its influence - as indicated by the infrequency of its citation in the bibliographies of recent Russian karst and speleological literature - has been very slight, especially as compared with the frequency of citation of Gvozdetzky (1954), Maksimovich (1963) and other works of these latter two investigators.

Mention might also have been made of the recent important monographs of Sokolov (1962) and Rodionov (1958, 1963), as well as the 10-volume compendium, "Methods for Studying Karst" (Vsesoyuznoe Soveshchanie Po Metodike Izucheniya Karsta, 1963- ). Volume 1 of the latter is to be by Maksimovich and the remaining volumes have been edited by various other karst specialists.

There is another error of fact on page 6. Davies refers to systematic regional studies of caves in areas outside of North America as having been "limited to Italy, Spain, France, Norway, and Belgium." But what of the important regional monographs by Kowalski (1951, 1953, and 1954) and by Pirker and Trimmel (1954)? And what of the remarkably comprehensive Jahrshefte of the Verband der deutschen Höhlen- und Karstforscher e.V. (München) that have been published annually since 1960? These are major contributions. Much more work is being done, as witnessed by two important

regional cave surveys (Wilford, 1964; Coleman, 1965) which appeared after Davies' manuscript was submitted.

Missing from Davies' Table 2, Regional Cave Surveys of the United States, is mention of the surveys of Texas beginning with NSS Bulletin 10 (1948) and continued by the Texas Cave Survey from 1958 to 1959 and subsequently by the Texas Speleological Survey from 1961 to date. Also unmentioned is the ambitious and pioneering survey work of the Association for Mexican Cave Studies that began in 1962 and was published beginning in 1965. The Cave Research Foundation is also doing extensive survey work in the Central Kentucky Karst, work begun more than 20 years ago.

It is also quite surprising that no mention was made of: 1) the existence of or various publications of the four international congresses of speleology as well as other national and international speleological meetings that have been held since 1953, 2) of the karst-oriented Memoires and Guidebooks published by the International Association of Hydrogeologists since 1959, 3) the important karst hydrological papers in the Bulletins and the Publications of the International Association of Scientific Hydrology, and 4) the regular publication of international bibliographies of contemporary karst and speleological literature by the Verband Österreichischer Höhlenforscher (compiled by H. Trimmel) and the Bureau de Recherches Géologiques et Minières (Paris) since 1955 and 1959 respectively. All of these organizations (and others) have disseminated the results of karst research and they have stimulated additional such research.

I also decry Davies' lack of proper acknowledgement of our debts to Jovan Cvijic and to E. -A. Martel for their work and for their many outstanding and influential publications (see especially Cvijic, 1893, 1960, and Martel, 1894, 1921). In my opinion, it is no exaggeration to state that Cvijic and Martel had as much influence on the study of karst and caves as did William Morris Davis on the study of geomorphology.

There are many other publications that are conspicuously absent and they too deserve citation in a discussion of historically and geologically significant karst and spele-

ological studies and reviews. These include: Bory de Saint Vincent (1819, 1821), de Serres (1839), Schmidel (1854), Prestwich (1855), Penck (1924), Cramer (1941), Cullingford (1953), Blanc (1958), Kukla and Lozek (1958), Schmid (1959), White (1961), Thomas (1963), and Burdon and Papakis (1963). There are additional names unfortunately missing from Davies' review and the listing above: Boegan, Segre, Jenko, Absolon, Kunsy, Casteret, Gèze, Renault, Andrieux, Meunier, Roglic, Llopis Llado, Jennings, Trimmel, Zötl, Biese, Lindner, Maull, and Reuter - all these and many more. Space limitations preclude an exposition here of their important contributions to karst and speleological knowledge.

Although not as historically significant, the following American works concerning karstification (*unterirdische Verkarstung*) are definitely more important than some of the other American papers cited by Davis: Morgan (1942), Bretz (1950), Maley and Huffington (1953), and Flint (1956).

Further, in his discussion of cave mineralogy Davies strongly implies that nothing of consequence was published on the subject during the "long gap in time" that ensued from 1929 to 1954. But what of the important papers by Huff (1940), Mackin and Coombs (1945), Hicks (1950), Hutchinson (1950), and Baker and Frostick (1951)? And what of the earlier work by Allison (1923), to say nothing of the more recent literature?

Interstratal karstification and cave mineralogy are only two of the subjects in which Davies' survey is far from complete or reliable in its coverage of just the more signi-

ficant papers - even for the American literature.

Some of the more sophisticated American work has appeared in the publications of the Cave Research Associates. Yet little consideration is given to many of the papers in *Cave Studies* and *Cave Notes* which CRA began publishing in 1953 and 1959 respectively. These publications have had much international attention and influence.

It is certainly appropriate to mention here that Davies' own influence upon the development of cave geology in America has been much more significant than his article indicates. Many of us are obligated to him for the stimulation given by his publications and for his work as the editor of the NSS *Bulletin* whereby he nurtured the growth of American speleological thought.

Finally, quite aside from the content of Davies' paper, there is inadequate citation of the Russian literature. If such citations cannot be printed in the Cyrillic alphabet, they should be given in transliteration or in both transliteration and translation. It is very difficult to go from translations alone - particularly erroneous and incomplete ones such as those given by Davies - to the originals. Transliteration removes the need for retranslation back into Russian, and thus eliminates the consequent difficulties and errors produced by the use of synonyms. Problems caused by use of English alone in giving Russian citations are forcefully discussed by Teichert (1965).

Davies' superficial review is useful once its limitations are recognized. Actually, I believe he would agree with my criticisms of his perhaps, makes all the more unfortunate the paper's deficiencies and provincialism.

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# The Earth Sciences and Speleology: Reply

By William E. Davies

As Mr. Quinlan cites in his concluding paragraph I agree with many of his points raised in the discussion. However, a few words of explanation should clarify some of the points. My review was heavily slanted toward American accomplishments in that Bulletin 28 was primarily a review of American speleology in relation to the 25th anniversary of the National Speleological Society. It was obvious, however, from the start that the story of speleology is international and that both American and European accomplishments are interwoven. In preparing the paper I expanded from a purely American to a general approach. Although 80 percent or more of speleological work is European it would not have been appropriate to devote that proportion of the paper to European accomplishments considering the goal of the Bulletin was to show American progress.

As for omissions in American publications one can only point out that when a reasonable limit on the size of a paper exists something has to give. In preparing the history I attempted to include those accomplishments that were illustrative of trends in speleology rather than including all that warrant citation because of merit. Some of the omissions cited in the discussion involve items that were published only as abstracts. Possibly I am a bit old fashioned but I have felt that abstracts are only temporary stop gaps and unless followed within a year or

two by fully explanatory papers they lose all right to scientific priority.

Concerning cave mineralogy 1929 to 1954; Mr. Quinlan cites only six papers for this period of 25 years. This in itself is proof enough of a long gap in achievement. The gap is even more prominent when it is realized that one paper cited refers to a mine, two to laboratory experiments and reviews, one to cavern deposits as incidental to a larger study of vertebrate excretion. Only one paper (Baker and Frostick) refers specifically to caves. One paper in 25 years appears to bear out the thought that pickings were slim in mineralogy.

The numerous European speleologists cited by Quinlan certainly merit recognition in a complete history of speleology but when emphasis is on American happenings, to use the words of Quinlan, "Space limitations preclude an exposition - of their important contributions to karst and speleological knowledge."

As for not looking more into my own contributions - well, maybe a man's severest critic is himself.

In writing history, especially where persons living are involved, I can only conclude, with due respect to Lincoln, that you can please some of the people all of the time, all of the people some of the time, but not all of the people all of the time.

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