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SCAPEGOAT ALPINE KARST

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Environments in Lehman Caves, Nevada

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ABSTRACT

Environments in Lehman Caves were studied with particular emphasis on seasonal and spatial gradients and stability. Parameters measured during a nine-month period at stations throughout the cave were air movement patterns, CO₂ concentration in the air, air and rock temperatures, and water chemistry.

Lehman Caves was found to be stable for the parameters measured, except that CO₂ concentration in the air varied with the season from a high in June (1040 ppm) to a low in December (390 ppm) and with daily air movement near the entrance. Other parameters had spatial and seasonal gradients of variability that were steep near the entrance and gradual or undetectable within the back sections of the cave.

INTRODUCTION

The environments in caves in dry climates are remarkably stable (Trexler, 1964; Wigley, 1967; Moore and Nicholas, 1964). The environments in caves in more humid regions vary to considerable depths and fluctuate widely during flooding and with changes in stream and air flows (Davies, 1960; Cropley, 1965; Reams, 1968). Recent interest (Poulson and White, 1969) has centered in the study of caves as natural laboratories with stable environments and simple ecosystems. According to Poulson and White, some controversy exists as to just how stable cave environments are.

As an assessment of daily and seasonal variation in a cave environment, I measured several parameters throughout the length of Lehman Caves in the Snake Creek Range of

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White Pine County, eastern Nevada. These parameters were CO₂ concentration in the air, air movement patterns, air and soil/rock temperatures, and water chemistry. In addition, qualitative observations on environmental and biological conditions were made throughout the caves. Periods of measurements in 1968 were: June 26 to July 3, September 22 to 28, October 23 to 27, and December 3 to 8. Another sampling was done on January 11, 1972.

METHODS OF MEASUREMENT

The CO₂ concentrations of the air were monitored (ppm by volume) with an infrared gas analyzer attached to a continuous recorder at a sampling station in the Gothic Palace, about 40 m from the natural entrance. In June, monitoring was conducted at a single station. For the rest of 1968, monitoring was conducted at three stations; an airstream switching device was used for measurements at minute intervals at each station. Throughout the caves, air samples were collected in large plastic bags at intervals during the test periods and immediately analyzed for CO₂ content.

Air temperatures were measured at six stations (Fig. 1), located from just past the Gothic Palace to the back of the Talus room. Thermistors, with 12-ft leads were installed and read with a YSI unit to the nearest 0.1°C, at a distance which permitted accurate, undisturbed readings. During the June visit, wall temperatures were measured with a radiometer. Spot temperature measurements also were taken in other sections of the caves. Wind speed and direction initially were measured by timing with a stopwatch the direction and fall of a piece of down. Later measurements were made throughout most of the caves using a sensitive hot-wire anemometer to measure air speeds and soap bubbles to find the directions of the air currents.

Water samples in 1968 were analyzed in the caves with a portable, battery-powered titration unit. The values measured or calculated were pH and ppm of anions. Simultaneous measurements of the water temperature, atmospheric pressure, and CO₂ concentration were also taken. These water samples were taken from pools unmodified by construction of visitor pathways in the back sections of the caves, mostly from the Talus room, and from drops on "soda straws" and other stalactites near the Grand Palace. Water in undisturbed pools in the caves in 1972 was measured for pH. Samples were then taken and analyzed for anions and cations in the laboratory.

RESULTS

CO₂ measurements: The CO₂ concentrations in the caves are shown in Figs. 2 to 5. In Figs. 3 to 5 simultaneous measurements from the three stations are indicated; spot readings are indicated by points.

The concentration of CO₂ was highest in June-July, when it ranged from 1040 ppm (July 2, 1968) to 550 ppm (June 30, 1968). The CO₂ concentration then decreased until December 6, 1968, when the lowest concentration of CO₂ (390 ppm) was recorded (Fig. 5). During September 27, 1968, a maximum of 1070 ppm CO₂

was measured in the Talus room after four days of quiet air.

Causes of this decrease from June through December apparently include an increase in air penetration into the caves during this period. The amounts of water entering the caves decrease rapidly after June, and less CO₂ is released into the air. In addition, lowered temperatures have been shown (Pitty, 1968) to result in reduced biological activity and release of CO₂ by soil organisms and, hence, in a reduction in CO₂ levels in the water of limestone regions.

Daily variations in CO₂ content are caused by air movement patterns, which can be related to several factors, including outside air temperatures. Air movement into the caves generally brings about lowered CO₂ concentration. In June, only one period of lowered concentration occurred. This took place when a cold night with temperatures below freezing resulted in flow of air into the caves. In September and October, the CO₂ content fluctuated, generally increasing during the day when outside temperatures were above 10°C (50°F) and either decreasing or remaining steady during the night when outside temperatures were near or below 10°C. In December, air flow generally was into the caves, and the low CO₂ content varied only 50 to 60 ppm during the entire month.

In general, the gradient of CO₂ content increased toward the Talus room in the back of the caves. The readings in the Lodge room ranged from 0 to 40 ppm above those in the test area near the Gothic Palace; and readings in the Talus room ranged from 20 ppm below to 270 ppm above those of air in the Gothic Palace. Differences were greatest when there was rapid air movement into the caves and smallest when mass air movement was toward the entrance. At no place in the caves was a great difference in CO₂ concentration found, indicating fairly good air circulation throughout the entire caves. No higher concentration of CO₂ was found in lower passages, in contrast to the findings of Delecour, *et al.* (1968).

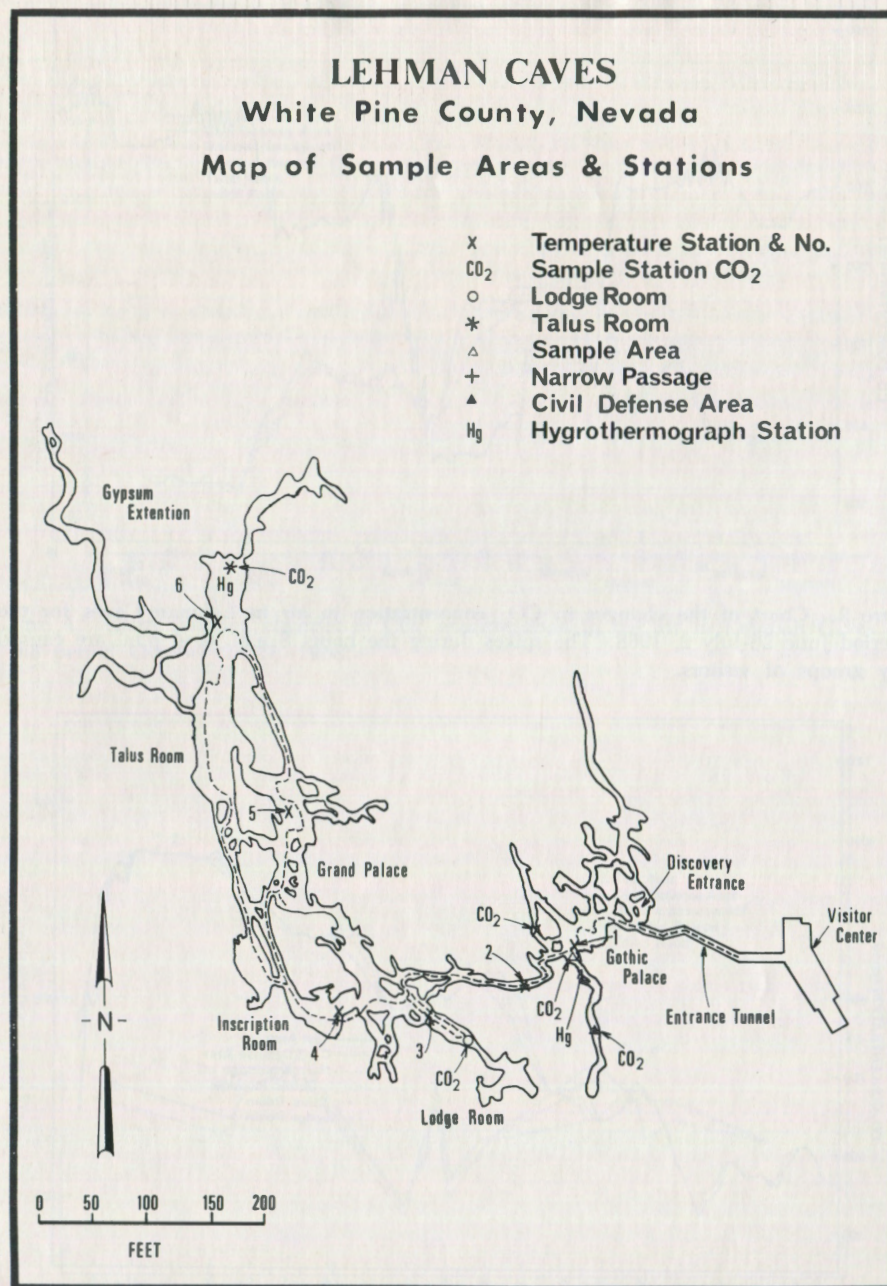


Figure 1. Map of Lehman Caves showing the locations of sample stations and measurement points (adapted from National Park Service map). Another entrance has been added off the Lodge room since this study.

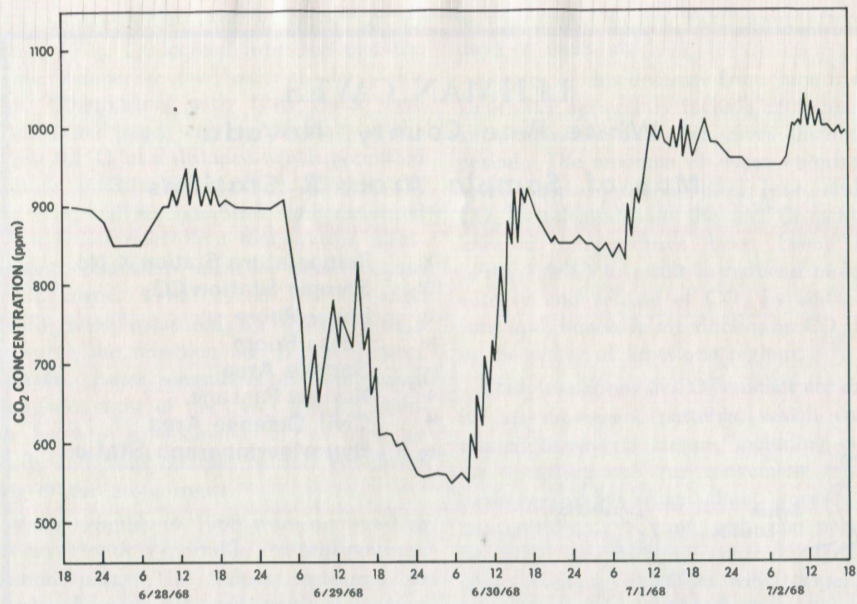


Figure 2. Chart of the changes in CO₂ concentration in air in Lehman Caves for the period June 28-July 2, 1968. The spikes during the hours 8 a.m. to 4 p.m. are caused by groups of visitors.

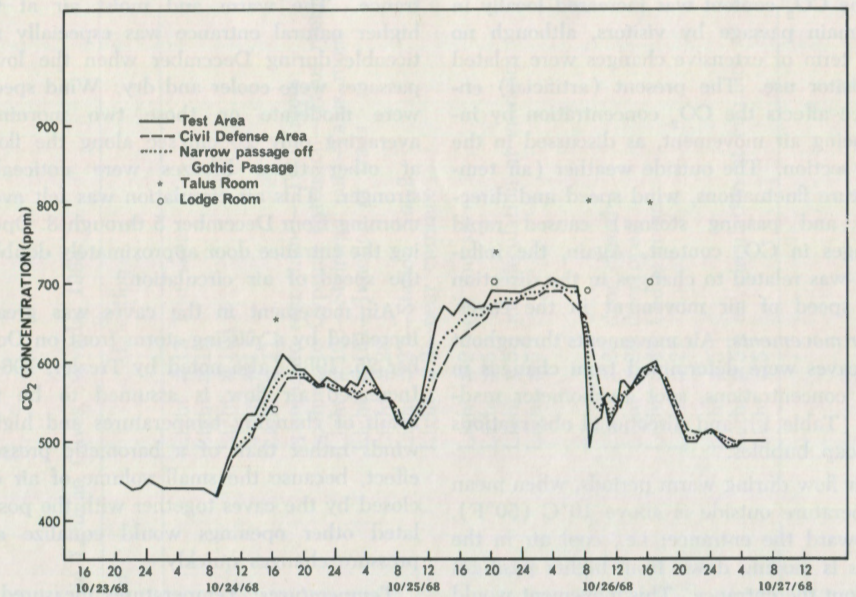


Figure 4. Chart showing changes in CO₂ concentration in the air in Lehman Caves for the period October 23-27, 1968.

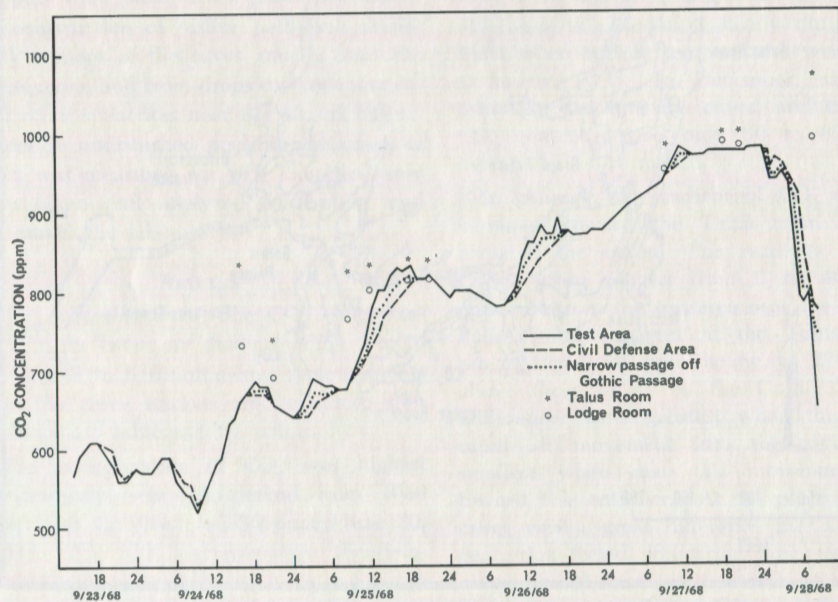


Figure 3. Chart showing changes in CO₂ concentration in the air in Lehman Caves for the period September 23-28, 1968.

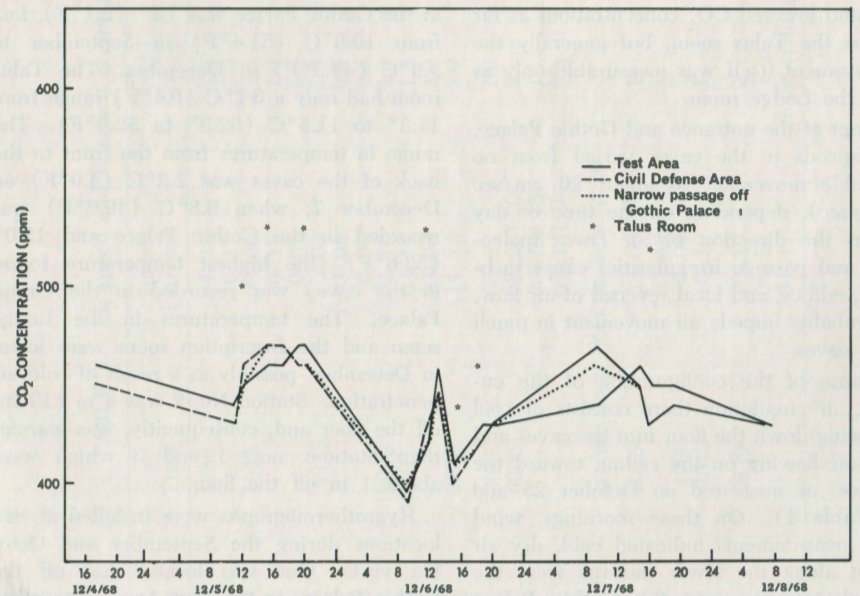


Figure 5. Chart showing changes in CO₂ concentration in the air in Lehman Caves for the period December 4-8, 1968.

The CO₂ content was increased locally in the main passage by visitors, although no long term or extensive changes were related to visitor use. The present (artificial) entrance affects the CO₂ concentration by influencing air movement, as discussed in the next section. The outside weather (air temperature fluctuations, wind speed and direction, and passing storms) caused rapid changes in CO₂ content. Again, the influence was related to changes in the direction and speed of air movement in the caves.

Air movements: Air movements throughout the caves were determined from changes in CO₂ concentrations, spot anemometer readings (Table 1), and directional observations on soap bubbles.

Air flow during warm periods, when mean temperature outside is above 10°C (50°F), is toward the entrance; i.e., cool air in the caves is moving down from higher passages and out the entrance. This movement would indicate possible higher openings to the caves allowing air to flow in, be cooled, and flow out of the entrance. With outside air temperature below 10°C, air flowed into the caves and lowered CO₂ concentrations as far back as the Talus room, but generally the air movement itself was measurable only as far as the Lodge room.

Except at the entrance and Gothic Palace, wind speeds in the caves varied from no detectable movement to about 20 cm/sec (8 in./sec), depending on the time of day and on the direction of air flow. Speleothems and passage irregularities cause turbulence, eddies, and local reversal of air flow, and probably impede air movement in much of the caves.

Because of the configuration of the entrance, air circulation there consists of cool air flowing down the floor into the caves and warm air flowing on the ceiling toward the entrance, as measured on October 25 and 26 (Table 1). On these mornings, wind speed measurements indicated cold, dry air flowing along the lower passage from the artificial entrance into the Gothic Palace and a reverse flow of warmer, moist air along the ceiling toward the natural en-

trance. The warm and moist air at the higher natural entrance was especially noticeable during December when the lower passages were cooler and dry. Wind speeds were moderate on those two mornings, averaging only 20 cm/sec along the floor; at other times breezes were noticeably stronger. This air circulation was felt every morning from December 5 through 8. Opening the entrance door approximately doubled the speed of air circulation.

Air movement in the caves was greatly increased by a passing storm front on October 25, 1968 (also noted by Trexler, 1964). Increased air flow is assumed to be the result of changing temperatures and higher winds rather than of a barometric pressure effect, because the small volume of air enclosed by the caves together with the postulated other openings would equalize any pressure changes quickly.

Temperatures: Temperatures measured in the caves (Table 2) show that the back of the caves is warmer and has fewer fluctuations in temperature than have the front portions. The range of temperatures in 1968 at the Gothic Palace was 1.2° (2.1°F), i.e., from 10.8°C (51.4°F) in September to 9.6°C (49.3°F) in December. The Talus room had only a 0.2°C (0.4°F) range from 11.3° to 11.5°C (52.3° to 52.6°F). The range in temperatures from the front to the back of the caves was 2.2°C (4.0°F) on December 7, when 9.8°C (49.6°F) was recorded in the Gothic Palace and 12.0° (53.6°F) (the highest temperature found in the cave) was recorded in the Grand Palace. The temperatures in the Lodge room and the Inscription room were lower in December, possibly as a result of cold air penetration. Station No. 2 was 4 m (13 ft) off the floor and, consequently, was warmer than Stations nos. 1 and 3 which were about 1 m off the floor.

Hygrothermographs were installed at two locations during the September and October visits. One was located just off the Gothic Palace, in the Test Area. The other was placed on a wooden stand in the back of the Talus room. The Talus room was

TABLE 1. Air speed and direction at several locations in Lehman Caves, Nevada, 1968.

Date	Time	Speed (m/sec)	Height (m)	Direction	Location
Oct. 24	1750	.04-.10	1.0	in	Light #12 Test area
	1915	.10-.17	3.0	out	Light #12
		.03-.06	1.5	—	Light #104
	1945	0-.17	1.0	—	Light #111
		0-.07	1.0	—	Light #111
		0-.03	1.0	out	opening to rear tunnel—Talus room
		.03-.08	0.5	out	opening to Gypsum Extension—Talus room
	2000	0-.08	0.5	out	Light #133—Stairway out—Talus room
	2015	.03-.10	1.0	—	Light #161—Junction of trails
	2030	.03-.14	1.0	—	Light #28
.03-.06		1.0	—	Light #27—Station No. 2	
Oct. 25	0845	.14-.22	1.0	in	Light #3—near entrance
	0900	.08-.22	1.0	in	Light #2 near entrance
		.08-.26 (.20)	2 cm	in	Light #5
	traced along floor to light #20	.05-.19 (.15)	1 m	in	Light #5
		.03-.18 (10)	2½ m	out	Light #5 } air circulation at entrance
Oct. 26	0915	.03-.06	1	in	Light #20 door closed
	1000	.03-.10	1	in	Light #20 door open
		0-.06	1	—	Light #47 Lodge room
	1515	0-.10	1	out	Light #27
	0830	.10-.29	2 cm	in	Light #5 } air circulation at entrance
	.06-.22	1 m	in	Light #5	
	.04-.17	along ceiling	out	Light #5	

TABLE 2. Air temperatures (°C) at several locations in Lehman Caves, Nevada, 1968.

AREAS SAMPLED *							
Date 1968	Time	Gothic Palace 1	Light 19 2	Lodge room 3	Inscription room 4	Grand Palace 5	Talus room 6
June 29	0855	10.6	11.3	11.1	10.9	10.9	11.5
30	1920	10.2	10.5	11.2	10.6	10.9	11.5
July 1	0645	10.1	10.8	11.2	10.7	10.9	11.4
	1900	10.5	10.5	11.6	10.5	11.0	11.5
2	1515	10.7	10.9	11.7	10.6	10.9	11.5
Sept. 23	2000	10.7	11.1	10.9	11.4	11.6	11.5
24	0900	10.8	11.3	10.8	11.4	11.4	11.4
	1100	10.8	11.3	10.8	11.1	11.5	11.4
	1600	10.8	11.2	10.8	11.2	11.4	11.3
	2030	10.6	11.0	10.8	11.1	11.4	11.4
25	0800	10.6	11.1	10.8	11.0	11.4	11.4
	1130	10.7	11.4	10.8	11.1	11.5	11.4
	1700	10.8	11.2	10.8	11.0	11.5	11.3
	2030	10.7	11.2	10.8	11.0	11.5	11.3
26	1630	10.8	11.5	10.9	11.1	11.6	11.3
27	1730	10.8	11.3	10.8	11.0	11.5	11.3
	2015	10.8	11.3	10.8	11.1	11.5	11.4
28	0700	10.7	11.2	10.8	11.0	11.4	11.4
Oct. 23	2000	10.4	11.3	10.8	11.3	11.7	11.4
24	0920	10.5	11.2	10.7	11.1	11.6	11.4
	1430	10.6	11.3	10.6	11.0	11.6	11.3
25	0915	10.8	11.3	10.7	11.1	11.4	11.3
	1455	10.6	11.4	10.8	11.1	11.6	11.3
	1945	10.6	11.4	10.7	11.0	11.6	11.3
26	0830	9.7	11.4	10.8	11.2	11.7	11.3
	1730	10.8	11.4	10.8	11.1	11.8	11.3
27	0700	10.5	11.4	10.7	11.1	11.1	11.3
Dec. 5	1030	9.8	10.9	10.3	10.9	11.4	11.4
	1150	9.8	10.9	10.3	10.9	11.5	11.4
	1515	9.8	10.9	10.3	10.9	11.7	11.5
	1915	10.0	11.2	10.4	10.9	11.7	11.5
6	0900	9.6	11.1	10.2	10.8	11.7	11.4
	1330	9.8	11.1	10.4	10.8	11.8	11.4
	1730	9.8	11.1	10.3	10.8	11.7	11.4
7	0915	9.7	11.2	10.2	10.9	11.8	11.4
	1430	9.8	11.0	10.2	10.6	12.0	11.4
	1930	9.8	11.0	10.2	10.7	11.8	11.4
8	0845	10.3	11.1	10.2	10.6	11.8	11.4
1972							
Jan. 11	1145	9.1	10.0	11.1	11.8	12.0	11.7

* See map (Fig. 1) for locations.

constant at 100% relative humidity and a temperature of 11.4°C (52.5°F), as corrected with a themistor unit. In the sample area, the temperature varied from 10.0° to 11.2°C (50.0° to 52.4°F) with relatively little change from 10.6°C (51.1°F) over this period. The relative humidity stayed at 100% until October 14, at which time it dropped to 90%; it remained between 88% and 100% until October 24. At this time of year, the winter cycle of cold air entering the caves through undiscovered higher entrances and also the gravity air exchange at the entrance begin.

A comparison of these measurements of temperature and humidity with those of Trexler (1964) shows that throughout the periods measured in this study there was less fluctuation than recorded by Trexler. My method of leaving thermistors in place reduced variations, relative to the values Trexler recorded; however, the trends found

are the same as those described by Trexler, except that Trexler was not aware of the extreme stability of the Talus room.

Water conditions and chemistry: The results of the analysis of the water samples taken in 1968 are presented in Table 3, and those for the water chemically analyzed in 1972 in Table 4. The pH of undisturbed water in pools is slightly higher than usual for water in limestone areas. Water in pools presumably fed by phreatic ground water has a higher and different mineral content than has water seeping into the cave from above. Compare, for example, samples 6 and 7 with samples 1 to 4 in Table 4. Bicarbonate is the principal anion present in all samples. Ca²⁺, Mg²⁺, and Na⁺ seem to have about equal concentrations in pool water, but there is a relatively high percentage of Ca²⁺ in seepage from the ceiling.

In order to determine if the water in the pool and the water in the drops are in

TABLE 3. Air and water characteristics at selected locations in Lehman Caves, Nevada, December 1968.

Date	Time	Sample number	pH	Anions (ppm)	Temp. (°C)	Pressure (inches)	CO ₂ in air		Location
							CO ₂ in air (ppm)	CO ₂ calculated (mg/l)	
1968									
Dec. 5	1215	1a	8.4	216	11.3	23.80	500	2.2	Talus room Pool 1
	1535	1b	8.4	221	11.3	23.85	530	2.2	
	2010	1c	8.2	216	11.3	23.85	530	3.2	
Dec. 6	1130	1d	8.2	214	11.3	23.90	460	3.2	Drops from passage off Grand Palace
	1745	1e	8.1	214	11.3	23.90	460	3.2	
	1135	2	8.1	107	11.9	23.90	530	2.6	Grand Palace pool
Dec. 7	1145	3	8.3	212	11.2	23.90	510	2.8	Passage off Grand Palace pool under sample #2
	1500	4	8.3	256	11.2	23.90	510	3.0	

TABLE 4. Chemical analyses of water samples measured and collected on January 11, 1972 in Lehman Caves, Nevada.

Sample number	Sample Location						
	Talus room Pool 1	Talus room Pool 2	Grand Palace (pool)	Passage east of Grand Palace (pool)	Passage northeast of Inscription (pool)	Passage east of Grand Palace (drops)	Passage northwest of Lodge Room (pool)
	1	2	3	4	5	6	7
pH in cave	7.6	7.9	..	..	..	..	..
*pH in laboratory	8.3	8.3	8.5	8.4	8.2	..	8.2
Temperature in cave	11.3	11.3	11.3	..	..	..	10.9
*Anions							
HCO ₃	181	170	201	156	160	97	115
Cl	20	23	17	16	22	..	12
SO ₄	20	22	27	35	42	..	10
Cations							
Ca	21	17	21	26	..	..	24
Mg	19	17	18	10	..	..	4
Na	17	17	20	12	..	..	7
K	2	3	3	1	..	..	1
P	0	0	0	0	..	..	0

* Analysis by Water Analysis Laboratory, Desert Research Institute, Boulder City, Nevada.

chemical equilibrium under conditions in the caves, two situations were measured. Since the CO₂ concentration in the air varied more than two-fold, the pH of a pool in the Talus room was measured under three situations: (1) the pH probe was carefully lowered into the pool with no stirring, and a pH of 7.55 was measured; (2) the pool was agitated as the probe was lowered, and the pH increased to 8.02 after 3 min; and (3) water was removed and stirred in a beaker (as in the titration measurements), and the pH was 8.36 after two min. Calculation of the pH of the pool under the existing conditions of temperature, pressure, and CO₂ concentration in the caves and under the assumption that the activities of the various ions present are approximately equal to those of Ca²⁺ and HCO₃ and approach unity at these low

molarities, indicates that the pH for a CO₂ concentration of 500 ppm is 8.2 and that for 1,000 ppm is 8.0 using the method of Garrels and Christ (1965, p. 76). The bicarbonate concentration calculated under these conditions is 67 ppm at 500 ppm CO₂ air concentration and 88 ppm when concentration is 1,000 ppm.

These two situations suggest, then, that the water in pools is not in equilibrium and that the pool water is supersaturated with bicarbonate and has a low pH due to a high level of dissolved CO₂. Fluctuating conditions in the caves probably play a minor role in determining water chemistry, although changing cave conditions bring about changes in water equilibrium with time. Although CO₂ concentration in the air varies seasonally, at no time is the CO₂ concentration high enough to cause dissolu-

tion of calcite in the back section of the caves.

The pH and alkalinity of water in the pools depend on the source of the water. The water evidently enters the caves from areas high in CO₂. After entry of the water into the caves, CO₂ is slowly released from the water to the cave air. Stirring the pools drives off part of the CO₂ by changing carbonic acid to CO₂ and water. The relatively lower pH of incoming water, also, permits more calcite and other minerals to be held in solution. During subsequent times of increasing pH, these would be deposited in the caves. That this process is going on under undisturbed conditions is evidenced by calcite rafts floating on the pools. Stirring the pool water would have the double effect of decreasing CO₂ in the water and of dissolving the calcite rafts, thereby accounting for the change in pH from 7.55 to 8.32 observed. Water from pools brought back to the laboratory also evolved CO₂ and, after standing a few weeks at room temperature, had a pH of 8.3 to 8.5.

It is noteworthy that water dripping into the caves had the least amount of dissolved solids (Table 3, sample No. 2), but that ground water from a pool in the same section of the caves had the most (Table 3, sample No. 4). It is assumed that the drops had already lost much of the CO₂ to the cave air and that the dissolved minerals had been deposited.

Samples taken from one pool in the Talus room (samples 1a - 1e, Table 3) over a period of 2 days in December, 1968, showed less than a 3% change in alkalinity over a range of 460 to 530 ppm CO₂ in the air. This range is less than the degree of accuracy of the methods, so that there may not have been a measurable change during this 2-day period. Conditions at this time were very stable with respect to air temperature, CO₂ concentrations, and barometric pressure. Comparison during other seasons having higher CO₂ concentrations and more water presumably would show changes in pH and in alkalinity.

How this cycle of CO₂ concentration and equilibrium changes with the seasons or with the rapid addition of percolating waters is not known. In December, when there was little change in CO₂ concentration of the air, water in the pools varied little in pH and alkalinity. This suggests that the water was at or near equilibrium, although this was not observed. Water collected from "soda straws" and from small conical stalactites had low alkalinity, possibly because the in seeping ground water at this time of year contains relatively less CO₂ or is under-saturated with respect to calcite.

In order to determine deposition rate or growth of formations in the caves, a series of measurements at different times of the year will be required. Observations made on water dripping on cables and lights in the Talus room and the Grand Palace indicate that calcite is being deposited at a slow rate under present conditions. Dissolution of some formations was observed near the Lodge room, and some of the permanent pools in this area occupy deep solution bowls in the calcite.

A few observations on possible additional entrances to the caves are pertinent to this study. In the Gypsum Extension, in the passage off the north end of the Talus room, and in the Talus room, relatively recent packrat trails and droppings were observed, indicating possible use until the lights were installed and the visitor path extended. Packrat trails in several places end abruptly at holes in the upper walls of these passages, indicating that entrance to the cave was gained here through small openings to the surface not penetrable by man. Bones of rodents in the spelunker section north of the entrance once were abundant at the end of the passage; however, this section of the caves is fairly near to the surface and to the natural entrance.

The walls from the Gothic Palace to the Inscription room once had a fairly thick cover of "lint", composed of threads, dust, fungal hyphae, and spider webs. This portion of the caves also was the driest.

Since closure of the natural entrance area, masses of fungal hyphae have developed on the abundant organic matter beneath the opening and fruiting bodies are common here. New fruiting bodies were observed both in September and in December. The warm, moist air trapped in this higher section has undoubtedly increased the rate of decomposition of organic material since the entrance was sealed.

DISCUSSION

Temperature and humidity are fairly stable in the Lehman Caves. There is a stability gradient from the front to the back of the cave. Temperature in the Talus room and Grand Palace remained almost constant at 11.4°C (52.5°F) and relative humidity remained at 100% during the period of study. The front of the caves from the Gothic Palace to the Lodge room varies seasonally as much as 2.2°C (4.0°F), and the relative humidity decreases after about the middle of October. The back portions of the caves are little influenced by fluctuations at the entrance or by outside environmental conditions.

Factors important to cave processes which change seasonally are the direction of air movement, the rate of air movement, and the relationship of CO₂ concentration to air movement. The concentration of CO₂ varies from an average of 1000 ppm (0.1%) throughout the caves in the early summer to an average of 450 ppm (0.045%) in December. The predominant direction of air movement in summer and early fall is toward the entrance. This is reversed about the middle of October and, presumably, remains reversed until late spring. This means that the front of the caves is subjected to drying conditions at the time when the volume of water entering the caves is minimal.

The concentration of CO₂ in air in the caves is a function of the rate of the diffusion of CO₂ out of water percolating into the caves. CO₂ is carried throughout the caves by air currents and its concentration in most of the caves is equalized within

two to three days, in periods of fairly stable air. Changes in concentration of up to 500 ppm CO₂ are brought about by reversal of air flow in the front portion of the cave. A fairly continuous exchange of cave air with the outside atmosphere prevents the building up of high concentrations of CO₂ which would slow the rate of calcite deposition, especially in early summer when CO₂-rich water percolates into the cave.

Lehman Caves is representative of a type of cave which is quite stable in temperature, humidity, and moisture. Environmental factors in caves such as these, located in arid or semi-arid regions and having only one main entrance, respond slowly to external seasonal influences. There is no rapid flow-through either of air, or of water. Thus, the cave lacks the high heat exchange capacity which would be required for it to rapidly alter its internal environment. Air flow from the entrance into the obstructed and highly decorated passages, is quickly slowed, so that there is created a gradient of increasing stability from the entrance toward the back of the caves. The most variable factor measured was CO₂ concentration, but some other seasonal trends and changes do occur. The most rapid fluctuations are found near the entrance, due to reversals of airflow into the caves.

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Scapegoat Alpine Karst, Montana

Newell Campbell *

ABSTRACT

The Scapegoat Mountain alpine karst area is a high plateau lying in the center of the Scapegoat Wilderness, 75 miles west of Great Falls, Montana. The plateau is underlain by more than 1,700 feet of Cambrian rocks, part of the upper plate of a large thrust sheet. Nearly 1,000 feet of Middle Cambrian carbonates cap the 8,000 foot plateau and solution features are widely scattered over the plateau surface. Solution features range from pits several hundred feet deep to small karren less than an inch wide. All of the karst is developed along three joint sets, N20E, N35W and N65W.

The location of the larger sinkholes is controlled by the position of large north-south trending snowbanks that drift in during the winter months. More melt-water is available for solution beneath these snowbanks, allowing larger pits to develop there than elsewhere.

All runoff from the Scapegoat Plateau is channeled underground through sinkholes and resurges from caves in the canyon walls 1,000 feet below. Mapping of several of these caves revealed that the joint pattern is consistent throughout the carbonate section. The age of the karst probably is post-Pleistocene.

INTRODUCTION

The Scapegoat Mountain karst area is located between Observation Peak (elev. 8,522 ft) and Scapegoat Mountain (elev. 9,207 ft) in sections 3, 4, 9, 10, 14, 15 and 16, T18N, R10W, Lewis and Clark County, Montana. The area lies about 25 airline miles southwest of Augusta, Montana, and 20 miles north of Lincoln, Montana (Fig. 1). Scapegoat Mountain is shown on the Cooper Lake Quadrangle (1:125,000) and the new Crown Mountain Quadrangle (1:24,000), now available only as a preliminary sheet.

The karst region, a high plateau 8,000 feet above sea level, is included in the new Scapegoat Wilderness and lies more than 15 miles from the nearest road. Access usually is made from Benchmark via the Straight Creek Trail. In this paper, the high karst area will be called the Scapegoat Plateau.

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The plateau is quite barren of vegetation, although a few scattered patches of small trees and grass occur in the central part of the area. The precipitation averages nearly 50 inches per year, most of it as snow falling between the months of October and May. Strong westerly winds create large snowbanks on the plateau. Some of the drifts exceed 100 feet in depth and do not melt completely away during wet years. Temperatures range from highs around 80°F during summer to lows far below 0°F during winter. The coldest temperature ever recorded in Montana (-77°F) occurred only a few miles to south, at an elevation of 6,000 feet. The harsh climate makes effective study possible only during the months of August and September. Many of the karst features are completely free from snow only during very dry years.

Scapegoat Mountain ranks as one of the finest alpine karst areas in the United States but, because it is so isolated, it remains relatively unknown. Reports by hunting parties

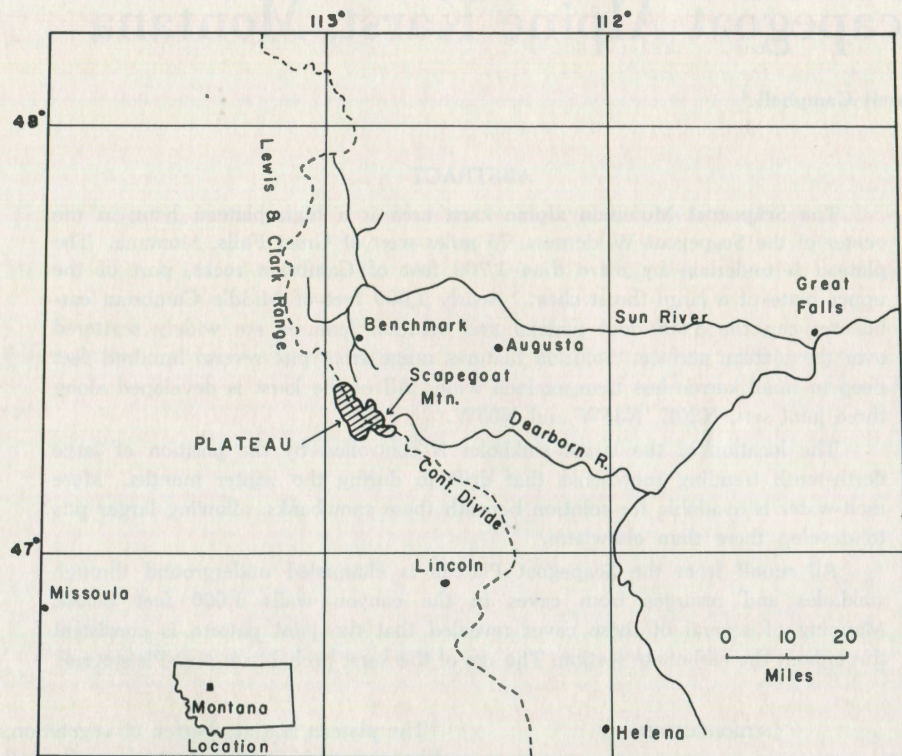


Fig. 1. Index map of northwestern Montana, showing location of Scapegoat Plateau.

during the 1950's told of numerous caves and deep pits, but no explorations were made at that time. In 1968, the area was flown for the U. S. G. S. wilderness mapping project and the resulting photos showed hundreds of sinkholes on the plateau. Two trips into Scapegoat Mountain to map the caves for the Montana Bureau of Mines cave project were made by the author in July, 1971 and August, 1972. These trips were only partially successful due to heavy snow cover, but they did show that the area had great potential for deep caves and as an alpine karst study area.

GEOLOGY

Regional Setting

Scapegoat Mountain is part of the Lewis and Clark Range in the Rocky Mountain Province. The range is composed of Pre-

Cambrian, Paleozoic, and Mesozoic sedimentary rocks that have been thrust-faulted into a series of blocks known as the Disturbed Belt. Thrusting was from the west and created a series of north-south trending linear ridges and valleys. In general, resistant carbonates hold up the ridges while softer shales and sandstone underlie the valleys. In addition, normal faulting occurred during the thrusting and further complicates the geology. An excellent article by Mudge (1970) contains more information on the geology and origin of the Disturbed Belt.

Structure

The Scapegoat Plateau consists of an elevated block of Cambrian carbonates about 5 by 10 miles in size that is folded into a broad, shallow, southeasterly-trending syn-

cline (Fig. 2). Dips seldom exceed 10°. An exception is the extreme southern portion of the plateau, where a large normal fault has tilted the rocks into a nearly vertical position (Fig. 3).

According to Mudge (personal commun., 1972), the rocks of the Scapegoat Plateau are part of the youngest major thrust sheet in the region. The front of the thrust runs southeastward along Straight Creek, near Halfmoon Park, and along Dearborn Creek (Fig. 3). Mudge states that "the rocks at Scapegoat have been transported eastward on this fault, possibly as much as 10 miles". It was this thrust which moved the large carbonate block of the Scapegoat Plateau upward and eastward to its present position.

Stratigraphy

A thick Cambrian section is preserved in the Scapegoat Mountain area. The Cambrian rocks here have been divided into the

following units: Flathead sandstone, Gordon shale, Damnation limestone, Dearborn limestone, Pagoda limestone, Steamboat limestone, and Switchback shale, all of which are Middle Cambrian in age, and the Devil's Glen dolomite of Upper Cambrian age. Fig. 4 contains brief descriptions of all units. Deiss (1938, p. 1,084) measured a section on Observation Peak, at the west end of the plateau. A total of 1,723 feet of Cambrian rocks are present at this point. Scapegoat Mountain also contains approximately 1,700 feet of Cambrian rocks. Both peaks are capped by Devil's Glen dolomite, which contains no sinkholes in this area. On the plateau proper, the Devil's Glen dolomite and Switchback shale have been removed by erosion and the Steamboat limestone is uppermost over most of the area. Below the Steamboat limestone, exposed in cliffs surrounding the top of the plateau, are in



Fig. 2. Aerial photo of Scapegoat Plateau. Scapegoat Peak is at center of photo. Over 1,700 feet of Cambrian rocks, including 1,000 feet of carbonates, underlie the plateau. Note large snow drifts.

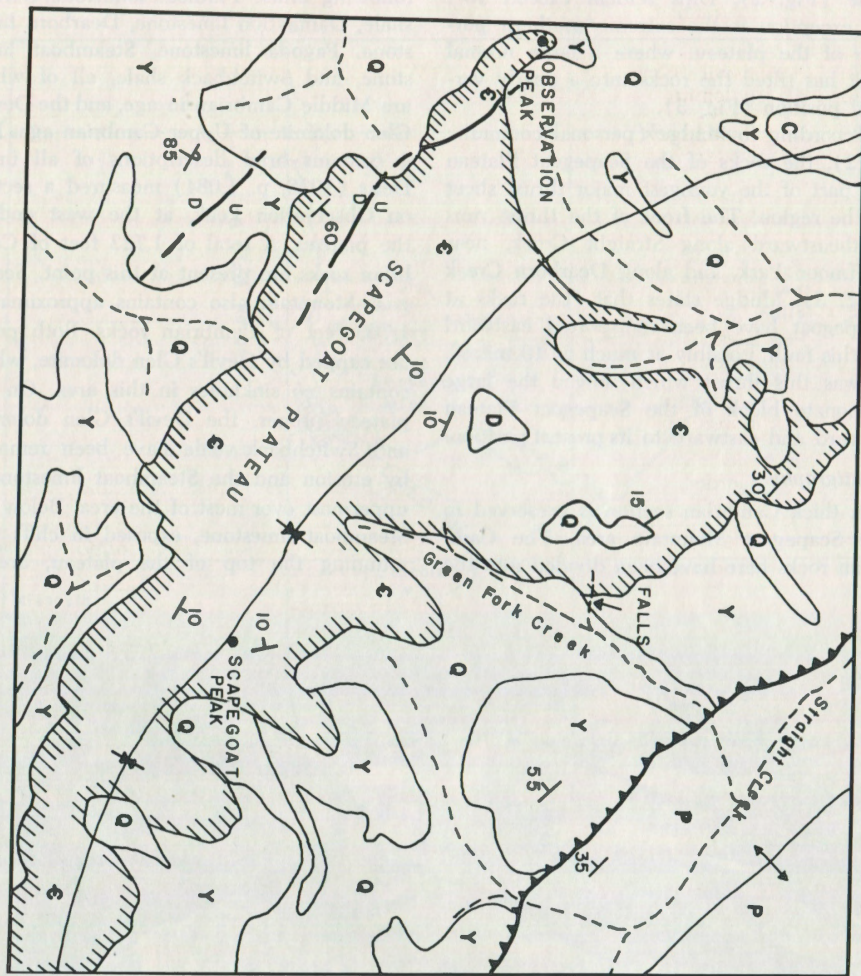


Fig. 3. Geologic map of the Scapegoat area (modified from U.S.G.S. open file map by M. R. Mudge and R. L. Earhart, 1969-1970). Q—Quaternary landslide debris, colluvium, and alluvium. D—Devonian rocks. C—Cambrian rocks. P—Paleozoic rocks (undifferentiated). Y—Pre-Cambrian rocks (undifferentiated).

descending order the Pagoda, Dearborn, and Damnation limestones. These four carbonate units together have a thickness of 951 feet. The Gordon shale and Flathead sandstone are largely concealed by a talus slope below (Fig. 5).

Meltwater is funneled into sinkholes and open joints in the Steamboat limestone,

passes entirely through the carbonate section, and resurges at the base of the Damnation limestone.

SOLUTION FEATURES

Scapegoat Plateau is scarred with many kinds of solution features. These range in size from sinkholes 50 feet wide and hun-

AGE	NAME	THICKNESS (feet)	DESCRIPTION
Upper Cambrian	Devil's Glen dolomite	350	White, massive, medium crystalline dolomite
Middle Cambrian	Switchback shale	70	Green-gray, fissle shale with thin interbeds of brown dolomite
	Steamboat limestone	255	Gray, thin-bedded, mottled limestone with some thin mudstone layers
	Pagoda limestone	296	Gray - brown, medium - bedded, fine - grained limestone and dolomitic limestone; argillaceous in lower part
	Dearborn limestone	251	Dark gray-brown, massive, fine-grained limestone with some mottling
	Damnation limestone	149	Dark-brown, medium-bedded, medium-grained limestone; thin bedded and sandy in lower part
	Gordon shale	274	Gray, fissle shale, calcareous and sandy in lower part
	Flathead sandstone	78	Red, coarse-grained, poorly sorted, quartz-rich sandstone
1723 feet (total thickness)			

Fig. 4. Cambrian rocks cropping out in Scapegoat Plateau area (modified from Deiss, 1939).

dreds of feet deep to karren only a few millimeters wide (Fig. 6). All of the solution features are developed along three sets of vertical joints that run N35W, N65W, and N20E. These joint directions are consistent throughout the whole carbonate section. Passages in caves at the base of the Damnation Limestone follow joints having the same directions as do those followed by karren at the top of the plateau (Fig. 7). It is this consistency in joint pattern that allows ground water to penetrate the entire carbonate section.

Large Features

Several hundred of the larger sinkholes and pits (those more than two feet wide and 20 feet deep) were measured to see if any one joint set contained more sinks than the others. It was found that 50% of the large solution features are developed along N20E joints, 32% along N35W joints and 17% along N65W trending joints. Smaller karren were not measured for trends.

Large sinks are not scattered randomly over the entire plateau, but are concentrated in groups. Although some of the larger sinks have formed at the intersection of two prominent joints, this does not appear to be a dominant factor in determining where the larger pits occur. More important is the relationship between joints and large snowbanks on the plateau. Snow is blown in large drifts along the lee sides of ridges on the plateau. The ridges usually trend from north to south. Since the wind blows mostly from the west, snow is piled up in long north-south banks. More water is available for solution beneath these drifts than anywhere else on the plateau and the location of the snowbanks appears to have been responsible for controlling the location of the largest sinkholes. Meltwater tends to select the joints that most nearly parallel the snowbanks (those trending N20E and, in part, N35W) and seldom travels over 50 feet before sinking into the ground.

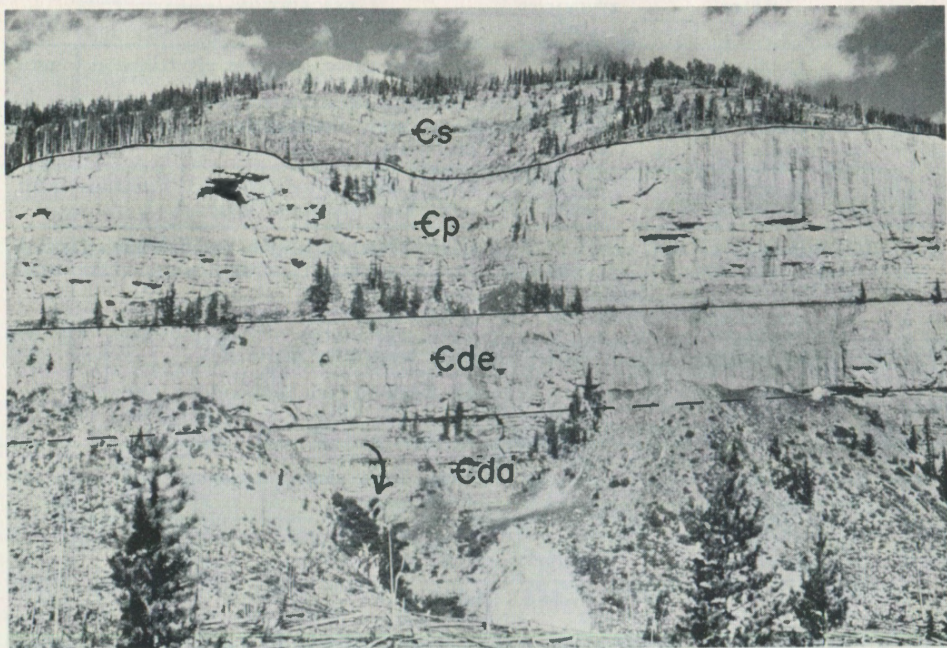


Fig. 5. Cambrian carbonate section in Green Fork Canyon. Cs—Steamboat limestone. Cp—Pagoda limestone. Cde—Dearborn limestone. Cda—Damnation limestone. Arrow points to small stream resurging from a cave in the Damnation limestone. Photo by Charles Pease.

In areas where the snow is normally blown off the ground, only small karren can be observed. All of the larger features form in more protected areas. There is little or no soil cover on much of the plateau. In a few areas where soil (and some sub-alpine fir) are present, almost no karren can be found even though such areas should yield far more CO₂ for solution. The soil must effectively shield the limestone from solution. In soil- and tree-covered areas, small surface gulleys have formed and water may flow several hundred yards to more barren areas before sinking.

Attempts were made to follow some of the deeper pits to their end, but these attempts were largely unsuccessful because many holes were found to be plugged with snow and the rest pinched out at vertical depths of not more than 250 feet. It was found in the deeper sinks that the water

almost never followed bedding planes but flowed rapidly down joints, probably all the way to the base of the Damnation limestone. Sinks tend to be elliptical or linear in shape at the surface. Circular openings were found only at joint intersections. Pits along single joints tend to be long narrow openings with vertical sides.

Small Features

Small-scale karren are widespread on Scapegoat Plateau, although their formation is somewhat restricted where soil mantle exists. Karren and larger solution features occur together without regard to elevation. Both karren and sinkholes occur between 7,700 feet and 8,200 feet. The dominant karren are cleft karren (classification of Pluher and Ford [1970]). Cleft karren have relatively flat walls and penetrate many successive carbonate beds. Minor amounts

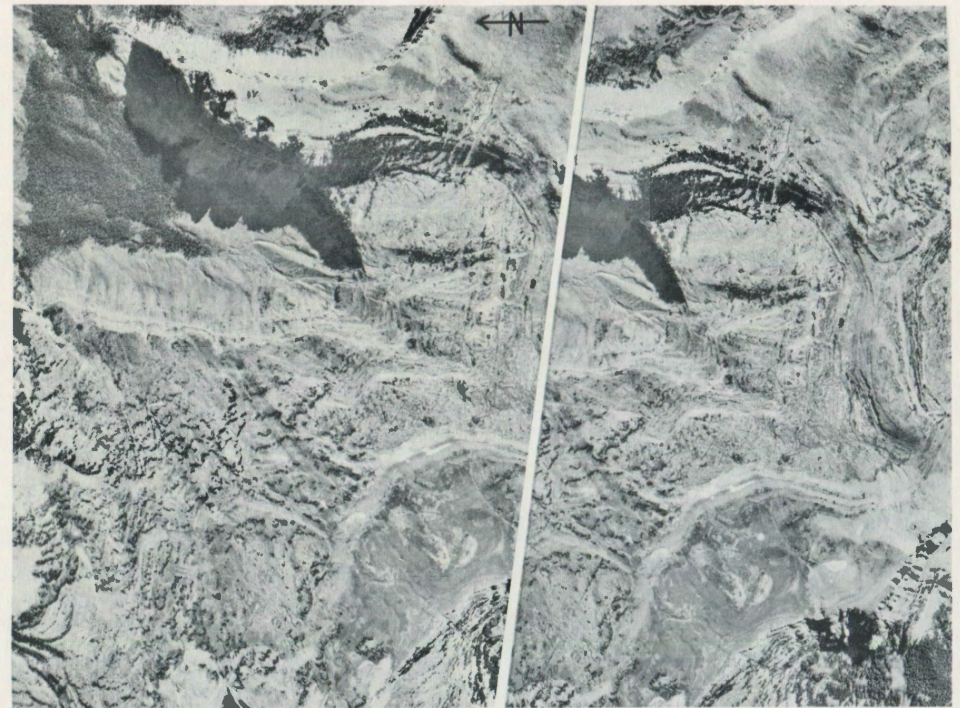


Fig. 6. Aerial photograph of part of Scapegoat Plateau, oriented for stereoscopic viewing. North is to left. Three joint directions and numerous pits are visible in the photo.

of trench karren were observed. Trench karren occur on Scapegoat only where frost wedging has loosened the uppermost carbonate bed, usually on the most exposed parts of the plateau, and allowed meltwater to escape laterally.

Groove karren and runnels were observed at the surface only where thick-bedded carbonates are exposed. Where the rock is thin-bedded, grooves and runnels are absent, probably having been destroyed by frost action. In some of the deeper pits, well-developed runnels and grooves remain primarily because they are better protected.

Resurgences

There is no surface runoff from Scapegoat Plateau. All melt- and rain-water is quickly channeled underground. In some places, a sort of "reverse" drainage has developed where the drainage thalwegs

slope toward higher peaks and ridges in the center of the plateau and away from the main canyons below. Although the west side of the plateau was not checked closely, the bulk of the ground water is thought to flow eastward toward Green Fork Creek. Some of the water may flow southward toward Cabin Creek, as two small springs were seen in Cabin Creek Canyon. In Green Fork Creek, one stream with a discharge of several hundred cfs and three smaller streams can be observed issuing from the west canyon wall at or near the base of the Damnation limestone. All of the streams emerge from caves developed at the 6,800-foot level, several hundred feet above the valley floor. Three of these caves were entered and one was mapped for a distance of nearly 2,000 feet. The last cave is narrow and high and trends in directions cor-



Fig. 7. Upper photo shows joint pattern on Damnation limestone, near base of the Cambrian section; lower photo shows karren developed along the same joint sets in Steamboat limestone at the top of the Plateau.

responding to those of the joint pattern observed previously—N20E, N35W, N65W. The joint pattern visible on the plateau must extend downward through the entire carbonate section. Ground water is channeled vertically downward over 1,000 feet along these joints to the base of the carbonates, where it is diverted laterally to the canyon walls. The cave gradients are quite flat, indicating either that an impermeable zone (the Gordon shale?) has stopped the downward movement of ground water or that the rocks below the 6,800 foot level are not broken by jointing.

Cave Passages

Cave passages at the 6,800 foot level generally are wider than those observed on the plateau. Apparently, rainwater can remove enough CO₂ from the atmosphere to dissolve limestone, because there is little opportunity for it to pick up CO₂ from the soil. There is no evidence that mechanical abrasion occurs on the passage walls either on top of the plateau or at the resurgence level. It would seem that passages are larger at 6,800 feet solely because ground water here remains in contact with the rock for a longer period of time, in relatively slow lateral motion toward the canyons. Vertical cave passages at the top of the plateau are narrow because of the rapid downward movement of meltwater during spring and summer runoff. Solution may be further retarded at high elevations by the extremely low cave-air temperatures (32° to 33°F). Ice coats the cave walls during much of the year. Water may flow over the ice and never actually came into contact with the rock walls of the caves.

One might consider that there may be little or no solution going on today and that all cave development may have taken place during the retreat of the last glaciers from the area. A much larger amount of meltwater would then have been available for solution. However, since the largest sinks are concentrated only where present day snowbanks exist and because no glacial debris has been found in any of the caves, it is likely that solution is occurring at the present time. Because an ice field probably covered the whole plateau during the last glacial stage, sinks formed by glacial meltwater should have been uniformly distributed across the whole plateau.

AGE OF THE KARST

All evidence suggests that the Scapegoat karst is of Pleistocene or younger age. The plateau probably was covered by an ice field that fed a series of valley glaciers. Upper Green Fork Canyon, Half Moon Basin and Cabin Creek Canyon are all cirques (Fig. 6). Very little glacial material

was seen on the plateau and none of the solution features are filled by debris. The cirques do not appear to have truncated caves at the 6,800 foot level or sinks along the canyon rims. There is no evidence that a fossil karst, such as that found in Mississippian Carbonates in other parts of Montana and Wyoming (Keefer, 1963), exists in Cambrian rocks of the Scapegoat area. Finally, as previously mentioned, large sinkholes are concentrated only near modern snowbanks, suggesting that modern climatic conditions control the location and formation of the caves. Glacial meltwater may have initiated formation of the karst, but conditions since glaciation must have played the major role in its development. One can only conclude that the karst is late Pleistocene to Recent in age and probably is less than 10,000 years old.

FUTURE STUDIES

Much work remains to be done on the Scapegoat karst. Completion of cave mapping, geochemical work, ground water tracing, and other studies is needed in order to complete our knowledge of the area. The plateau, although very inaccessible, would be a superb locale for more-detailed studies of alpine karst.

NEARBY ALPINE KARST AREAS

At least two other alpine karst areas occur in the nearby Bob Marshall Wilderness, but these areas have not been studied in detail. However, an alpine karst developed in Middle Cambrian carbonates in the Mt. Castleguard area, Canada, has been extensively studied by Ford (1971). Mt. Castleguard is bounded by active alpine glaciers. Karst features there appear on surfaces recently abandoned by glaciers. Sinkholes often are found near moraines, suggesting that they are directly related to recent glacial activity (Ford, 1971, p. 239). In contrast, the

Scapegoat karst does not seem to be glacially controlled. There are no moraines on the Scapegoat plateau, and frost action has destroyed any glacial polish which may have existed. There is some benching due to glacial activity, as may be seen in Fig. 6. All debris found in sinkholes on the plateau was produced by frost wedging. There appears to have been no infilling of any solution features by glacial debris. There is no direct evidence suggesting that sinkholes existed under the glacial ice that once covered Scapegoat Plateau but, in light of findings in the Mt. Castleguard area, such a possibility should be kept in mind during future studies. It is interesting that Ford should mention one sinkhole related to a large nearby snowbank (1971, p. 245 and Fig. 5). There is no question that meltwater, whether glacial or from yearly snowbanks, plays a major role in karst formation in both areas.

SUMMARY

The Scapegoat Plateau is underlain by flat-lying Cambrian carbonates having a total thickness of nearly 2,000 feet. Large sinkholes, pits, and various kinds of small-scale karren are developed in the Steamboat and Pagoda limestones on the plateau. All solution features are joint controlled and occur along three sets of joints: N20E, N35W, and N65W. Many of the larger sinkholes lie along joints trending N20E, because those joints closely parallel many of the long snowbanks on the plateau. The locations of the snowbanks control the locations of the sinks, as more water is there available for solution. The joint system penetrates the entire carbonate section. A series of horizontal, resurgence caves formed in the base of the Damnation limestone at the 6,800-foot level have passages corresponding in trend to the joint trends observed above. The age of the karst probably is Pleistocene or Recent.

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A narrative style of writing is preferred. Fine prose is terse yet free from lacunae, sparkles without dazzling, and achieves splendor without ostentation. Data and interpretations blend effortlessly along a logical continuum so that the reader, having read, neither knows nor cares how many pages he may have turned while following the author's exposition.

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Two double-spaced, typewritten copies of each manuscript, including all illustrations, are required. Manuscripts should not exceed about 10,000 words in length (approximately 40 pages of typescript), although this limit may be waived when a paper has unusual merit. Photographs must be sharp, high in contrast, and printed on glossy paper. All line drawings should be neatly rendered in "india" ink or its equivalent; the smallest lettering must be at least 2 mm high after reduction. Typed lettering is not satisfactory. Captions will be set in type and added in proof. The dimensions of original drawings and of cropped photographs should be made some multiple of the length and width of a column or of a page, when possible, in order to avoid problems with the layout. In case of doubt regarding length or illustrations consult with the editors.

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