

MEMORANDUM

RM-3139-RC

JUNE 1962

**METEOROLOGICAL-GEOLOGICAL
INVESTIGATIONS OF
THE WUPATKI BLOWHOLE SYSTEM**

J. D. Sartor and D. L. Lamar

MEMORANDUM

RM-3139-RC

JUNE 1962

**METEOROLOGICAL-GEOLOGICAL
INVESTIGATIONS OF
THE WUPATKI BLOWHOLE SYSTEM**

J. D. Sartor and D. L. Lamar

Permission to quote from or reproduce portions of this Memorandum must be obtained from The RAND Corporation.

PREFACE

This RAND Memorandum serves as the final report on a project, supported by The RAND Corporation, with the objectives of testing research methods for investigating an inaccessible underground cavity. Because of the project's peculiar combination of techniques, the report should be of interest to both meteorologists and geologists. This work provides a technology applicable to studying other cavities for such purposes as underground storage, shelter, and basing.

The essence of this report was presented at the First Western National Meeting of the American Geophysical Union in December, 1961, and again in April, 1962, at the meeting of the Cordilleran Section of the Geological Society of America.

SUMMARY

A RAND team, using meteorological and geological methods, investigated a vast, inaccessible underground system of cavities in the Wupatki area of north central Arizona. The existence of some form of underground cavity is betrayed by drafts of wind, alternately entering and emerging from small blowholes and dry wells in the area. The blowhole-and-cavity system appears to be associated with fault fissures and solution-formed passages in the thick beds of the local Kaibab limestone and Coconino sandstone.

By comparing the air intake and output of the blowholes with barometric pressure, the investigators estimated that the cavity had a volume of at least seven billion cubic feet. Tracers proved the interconnection of blowholes in areas at least 24 miles apart. A gravity survey indicated the absence of large caverns (in the local area, at least), suggesting rather, sinuous or multiply branched passages linking the holes and wells. Besides developing a research tool of various potential uses, the project indicated a possible relationship between the system of caverns and the underground water drainage of the Flagstaff--Wupatki region.

CREDITS

ACKNOWLEDGMENTS

The authors gratefully acknowledge the invaluable assistance of the Museum of Northern Arizona and its director, Dr. E. B. Danson. The generosity of the Babbitt Ranches in lending the project an excellently equipped line cabin near Wupatki spared the investigators much commuting time; without this help, it is doubtful that the project could have been successfully concluded. Microbarographs, hand anemometers, and a thermograph were provided gratis, through the courtesy of Dr. James A. Eddinger, from the University of California at Los Angeles. Mr. W. L. Sibley's services in the computing program were indispensable in extracting meaningful conclusions from the raw data.

PERSONNEL

Meteorologist:	Doyne Sartor (Project Leader)
Geologist:	Donald Lamar
Consultant:	Robert Schley
Graduate Students:	Alan Miller John Moessler Karl Schwartz
College Students:	Patric Canan Karl Kellogg Arthur Wilson

CONTRACTED EQUIPMENT AND SERVICES

Meteorology Research, Inc., Altadena, California, furnished the recording anemometers, an electric-field meter, dispensing equipment for the zinc cadmium sulfide and a technician for servicing their equipment.

The North American Weather Consultants, Goleta, California, furnished a titrilog, a silver iodide burner and cold boxes, and two-way radios, together with the full-time services of a technician.

The Worden gravity meter was rented from the Texas Instrument Company.

Routine administration, laboratory space, and secretarial services were furnished by the Museum of Northern Arizona.

Housing in Flagstaff was furnished by the Arizona State College at nominal cost.

CONTENTS

PREFACE.....	iii
SUMMARY.....	v
CREDITS.....	vii
LIST OF FIGURES.....	xi
Section	
I. INTRODUCTION.....	1
II. METEOROLOGICAL STUDIES.....	7
III. GEOLOGICAL STUDIES.....	21
IV. CONCLUSIONS AND FUTURE PLANS.....	38
REFERENCES.....	41

LIST OF FIGURES

1. Blowhole No. 1, first investigated by Schley.....	2
2. Pressure and wind traces for a 24-hr period at Blowhole No. 1, taken by Schley, 30-31, July 1960.....	4
3. Flagstaff -- Wupatki region showing relationships of micro- barograph stations to blowhole locations.....	8
4. Plastic sheet and 18-inch elbow prepared for Blowhole No. 3e.....	10
5. Ambient air pressure and blowhole-wind velocity plotted against time (Blowhole No. 3e).....	13
6. Conventionalized concept of blowhole showing Helmholtz-resonator configuration.....	17
7. Local terrain view northward across site of Blowhole No. 1.....	22
8. Generalized geologic map of the Flagstaff -- Wupatki area, Arizona.....	23
9. Columnar section of rocks exposed in the Flagstaff -- Wupatki region.....	24
10. Geologic map of a portion of Wupatki National Monument and vicinity, Arizona.....	26
11. Diagrammatic sketch of inferred subsurface geologic relations in the Wupatki area.....	30
12. Map showing variations in gravity of a portion of Wupatki National Monument and vicinity, Arizona.....	32
13. Map showing variations in gravity in the Wupatki area with the regional gradient removed.....	33
14. Measured and theoretical gravity profiles across a negative gravity anomaly in the Wupatki area.....	35
15. Map of Flagstaff -- Wupatki area, Arizona, showing major structural features and direction of ground-water movement.....	36

I. INTRODUCTION

INTRODUCTORY NOTE

In the summer of 1961, the RAND Corporation and the Museum of Northern Arizona jointly sponsored a project to study the blowholes around Flagstaff, their behavior, and the relationship of this activity to the local atmospheric pressure. This is the report on that project.

Section I, Introduction, tells how the project came about and gives the results of the preliminary analysis. Section II, Meteorological Studies, tells of the measurements taken during the summer, describes their analysis, and discusses the inferences drawn. Section III, Geological Studies, reviews the geology of the area with emphasis on the conditions leading to the formation of the cavern--blowhole system. It also describes the gravity measurements taken during the summer and presents the inferences drawn therefrom.

HISTORY OF PROJECT

Preliminary investigation. In the area around Flagstaff, Arizona, are a number of holes in the ground, out of which air blows at a rate in excess of 30 mph during some periods. At other times, the air blows into the holes at similar speeds. During the summer of 1960, R. A. Schley,¹ a science teacher at Flagstaff High School, placed a recording anemometer, a hygrothermograph, and a microbarograph at one of the blowholes (Fig. 1) in the Wupatki National Monument, approximately 35 miles north of Flagstaff.

On this hole, Mr. Schley obtained data for a continuous period of over 24 hours. His records contain continuous traces of the temperature, the humidity, and the wind velocity at the mouth of the hole and the ambient atmospheric pressure. A condensation of the pressure and wind traces for the



Fig. 1 — Blowhole No. 1, first investigated by Schley

entire period is given in Fig. 2. The upper curve shows the pressure trace and the lower curve the blowhole wind, with time increasing from left to right. The inverse correlation between the air motion and the pressure can be clearly seen. The rapid fluctuations traced between 12 hours and 15 hours are due to the passage of thunderstorms.

In order to establish this inverse relationship between the pressure and the wind quantitatively, computations were made at the RAND Corporation of the correlation between these parameters over the full 24 hours and separately for a selected period covering the passage of the thunderstorms. Lag correlations were obtained at intervals of 30 minutes as well as instantaneously over the 24-hour period. These correlations are given in Table 1. Here we note that the instantaneous correlation is not the maximum. A lag of 90 minutes provides the greatest correlation, except during the thunderstorm period when the maximum correlation occurs after a 5-minute lag. Table 2 lists the correlations computed between the air motion and the change in pressure. Here, the maximum correlation is much less and occurs at 30 minutes lag. These results suggested that the cavern and its hole might be acting to a degree as a Helmholtz resonator. In an attempt to estimate the volume of the hypothesized underground cavity the equation of state was used; the resulting figures gave one billion cubic feet as a minimum estimate.

The intriguing nature of this speleo-meteorological phenomenon led to the establishment of a RAND-sponsored project. In general terms, the project proposed to use meteorological and indirect geological measurements to estimate the physical dimensions of the underground cavern or caverns that must be connected with these blowholes and with man-made air-blowing wells in the vicinity.

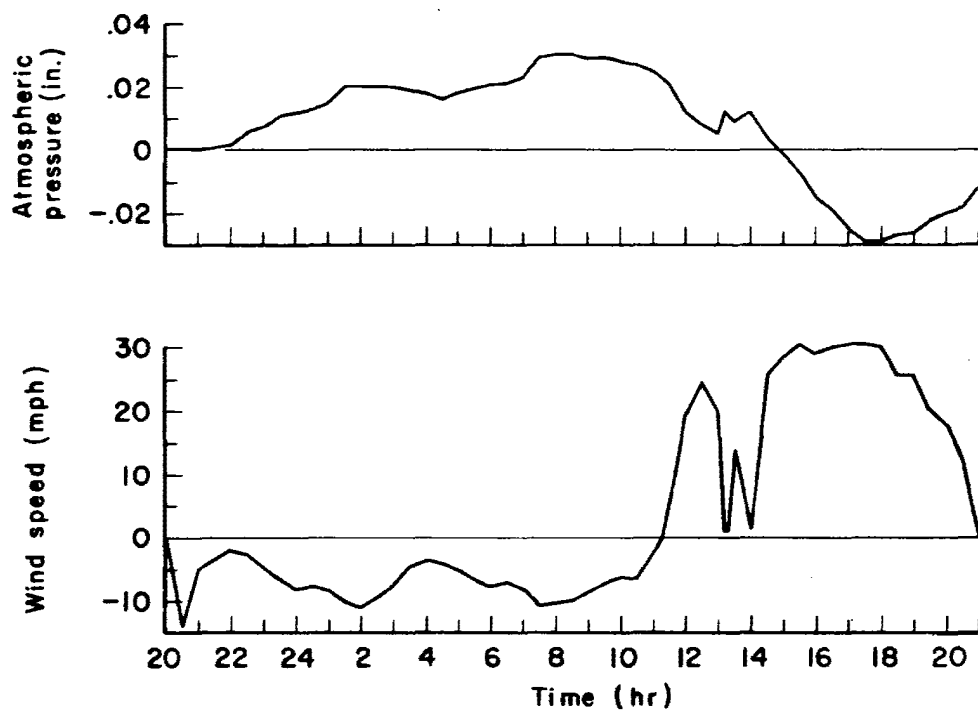


Fig. 2 — Pressure and wind traces for a 24-hr period at Blowhole No. 1, taken by Schley, 30-31, July 1960

Table 1

CORRELATION BETWEEN AIR SPEED AT ORIFICE AND AMBIENT AIR PRESSURE

24-hr Period		Thunderstorm Period	
Period of Lag (Minutes)	Correlation Covering 24 Hours	Period of Lag (Minutes)	Correlation Covering Thunderstorm Period
0	- .81	0	- .80
30	- .88	5	- .82
60	- .91	10	- .81
90	- .92	15	- .76
120	- .83	20	- .70

Table 2

CORRELATION BETWEEN BLOWHOLE AIR SPEED AT ORIFICE
AND AMBIENT PRESSURE CHANGE

Period of Lag (Minutes)	Correlation Covering 24 Hours
0	- 0.53
30	- 0.60
60	- 0.58

The meteorological work would consist of continuously recorded measurements of the ambient pressure and wind, the blowhole wind, and temperature and humidity, and airborne-tracer studies to reveal connections between the several blowholes. The geological studies would include a gravity survey of the area between some of the blowholes and a general geological exploration of the area including a search for other blowholes.

After the RAND project had been established, Dr. Edward B. Danson, Director of the Museum of Northern Arizona, at Flagstaff, offered RAND the use of the facilities of the research center supervised by him; he also proposed a joint archaeological—meteorological—geological study. The holes are generally surrounded by pueblo ruins and interesting archaeological sites of the prehistoric Sinagua Indians. The blowholes are known to have religious significance to the present-day Hopi Indians, and Dr. Danson was interested in attempting to determine whether this was true of the ancient Sinagua also. Dr. Danson feels that information about the behavior of the blowholes which RAND could supply will be useful to him. In return, he offered RAND the use of certain research-center facilities and his assistance in securing the necessary work permits for working on land controlled by the National Park Service and the State of Arizona. Also, it was possible that the archaeological study could provide valuable information for the final phase of the project, the phase of combining the geological, meteorological and archaeological information to see what would be the whole sum of knowledge that could be obtained indirectly about the cavern.

II. METEOROLOGICAL STUDIES

MEASUREMENTS

The first step taken in the measurement program was to explore for blowholes other than the one studied by Schley. The vicinity of the Wupatki National Monument (which is northeast of Flagstaff), the area across the San Francisco Mountains (northwest of Flagstaff), and the area southeast of Flagstaff were all searched.

The holes that were found (Fig. 3) required an identification check to reveal whether they were truly acting in the manner the investigators had come to associate with blowholes. To implement this check, two microbarographs were set up to form a triangle with the microbarograph at the Flagstaff Airport office of the U. S. Weather Bureau. One was placed at the Wupatki Monument Headquarters and one at the Cedar Ranch, about 20 miles north of Flagstaff (Fig. 3). This arrangement provided data for a small-scale pressure-gradient map of the entire region, which was a source for a check on the pressure change with time.

At each supposed blowhole, three measurements of both surface wind and blowhole wind were recorded for a duration of 1 minute each. Checks were made to determine whether there was any correlation between the two winds; these correlations all turned out to be effectively zero. Subsequently, each blowhole was visited again, and the same wind measurements were made. In this way it was possible to determine the behavior of the blowholes with respect to the pressure changes (over the period between visits) obtained from the microbarograph readings.

Nine blowholes having been identified, the next step was to choose three for more intensive study. The three chosen were in the Wupatki area.

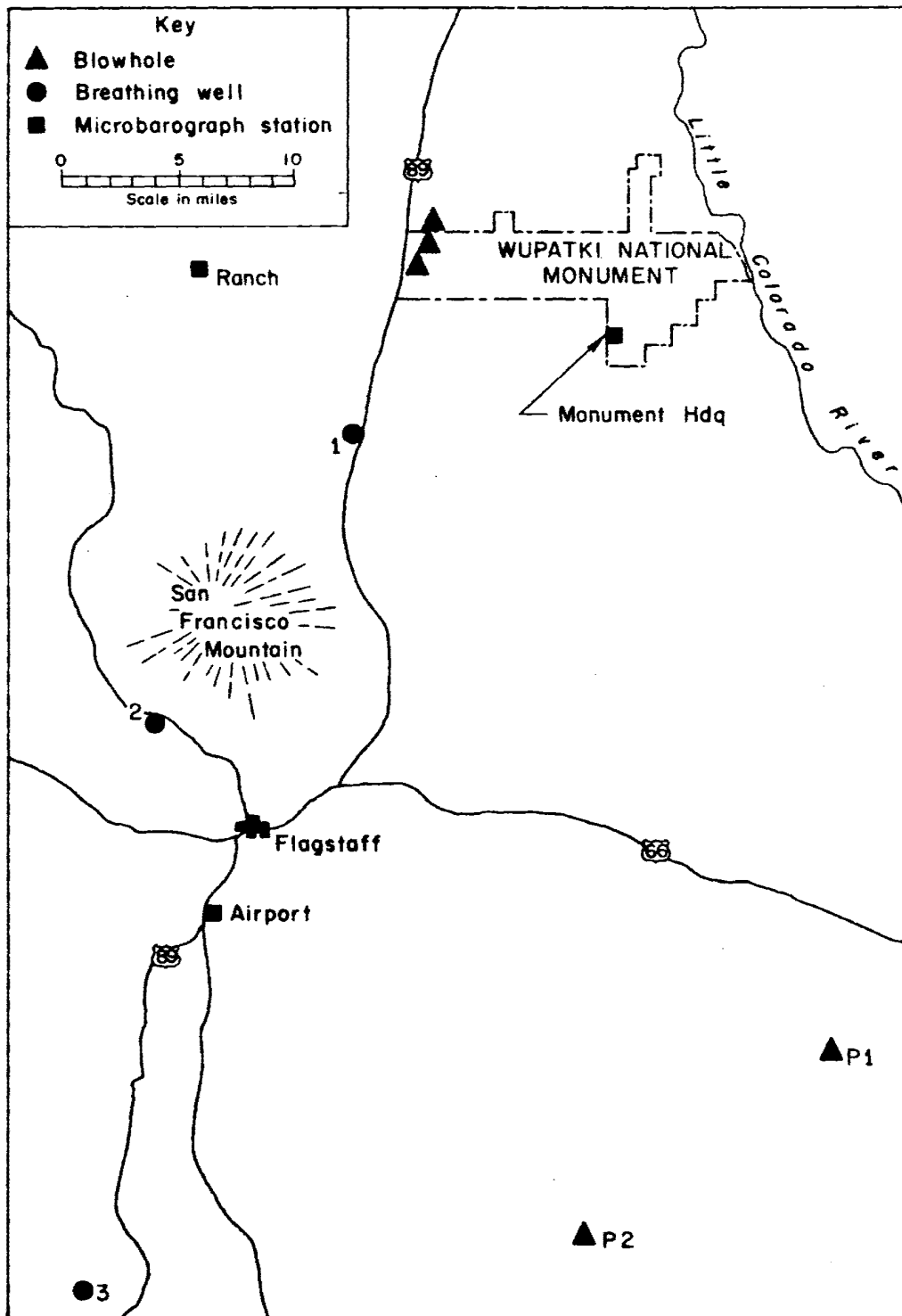


Fig. 3 — Flagstaff — Wupatki region showing relationships of microbarograph stations to blowhole locations

Their locations are identified in Fig. 3. These were within the area that later was to be covered by a gravity survey.

To prepare the blowholes for measurement, the emerging wind was confined and was directed horizontally, because the anemometers would not operate reliably unless their axes were vertical. Turning the wind to the horizontal also made it easier to place other instruments in the blowhole's air stream.

Elbows made from 14-inch conduit were used at two of the holes; an 18-inch elbow (Fig. 4) was required for the third. In order to ensure that all of the blowhole's wind was channeled across the anemometers, the elbows were sealed to the holes by spreading plastic sheets over a 9- by 12-foot area, and securely sealing the sheets — to the ground with dirt and rocks, and to the elbows with tape.

Even though no correlation had been found between natural atmospheric wind and blowhole wind, in order to eliminate the possibility of the natural wind's affecting the blowhole wind and in order better to protect the instruments, tents were set up over the sites of all three blowholes. Finally, the instruments were set inside the conduits and mounted securely.

A four-cup anemometer ordinarily used in micrometeorological diffusion studies was placed farthest in the conduit. The anemometer recorded the wind, producing a pip on an Esterline Angus Recorder for every mile of wind that passed across the anemometer. Inside the conduit, at each of the sites, was placed a recording thermograph. The recording microbarographs were placed on level sites outside the conduits.

Equipment to introduce hydrogen sulfide and silver iodide into the blowholes as tracers, and instruments to detect these tracers at other



**Fig. 4 — Plastic sheet and 18-inch elbow prepared
for Blowhole No. 3 €**

openings, were set up, but no data were obtained because of failure of the detection instruments. A more effective tracing device included a blower that could be introduced into the mouth of the conduit on occasion for the purpose of dispensing fluorescent particles of zinc cadmium sulfide into the in-blowing wind stream of Blowhole No. 1. To aid in detecting these particles at the distant holes, battery operated pumps were employed to trap particles on a millipore filter. The particles were detected by illuminating the filter with ultraviolet light and inspecting it through a microscope.

After the apparatus was in place at each blowhole, a procedure was set up for a routine check of the operation and of the accuracy of the instruments. Three teams of two men each were established to monitor the instruments, at each blowhole in turn, continuously around the clock for a period of at least three days. At each blowhole on each stop, a team would enter the time on the recording tapes of all the automatically recording instruments, and would manually record the atmospheric wind as determined by the hand anemometer, as well as the data on the air moving in or out of the conduit.

Hand readings also were taken of the ambient temperature and humidity of the air with a sling psychrometer, and readings were made of the wind coming in and out of the blowhole at several heights within the conduit itself to determine whether the wind measured by the automatically recording anemometer was representative of the air moving in and out of the conduit.

After the routine of monitoring and checking the instruments was well established and operating smoothly, the tracer studies were begun. When the detectors for hydrogen sulfide and silver iodide proved ineffective (even though the odor of hydrogen sulfide was plainly present at one remote hole),

the zinc cadmium sulfide powder was introduced into Blowhole No. 1 during an in-blowing phase. On subsequent days, particles of zinc cadmium sulfide were found coming out of other blowholes in the Wupatki region. Eventually they were discovered in the air coming out of a breathing well 24 miles to the south-southwest beyond volcanic peaks that rise to 12,670 feet. Fluorescent particles were also found in the air coming out of a blowhole on the Pollock ranch 44 miles from Blowhole No. 1, but in this case, contamination is a possibility, since fluorescent particles were found on the shoes of one of the investigators, who had been at the mouth of the Pollock ranch blowhole before the sampling.

RESULTS

Response of Wind to Pressure

As in all field projects, especially in the early stages, there were the usual breakdowns of the instruments and unfortunate accidents, but the essential information was obtained and used to shed further light on the behavior and characteristics of the Wupatki blowhole system. Figure 5 presents a plot of the pressure of the air ambient to Blowhole No. 3e and of the wind blowing in and out of the blowhole, both as a function of time. The values shown give the pressure excess or deficit with respect to an arbitrarily assigned zero. Blowhole No. 3e provided the most consistent and reliable set of data of all of the blowholes during this part of the study and its plot is presented for that reason. Data obtained at the other blowholes provided conclusive information to the effect that to a very high degree all the blowholes behave similarly and in unison. The close inverse correlation between pressure change and wind variation is quickly seen from the figure.

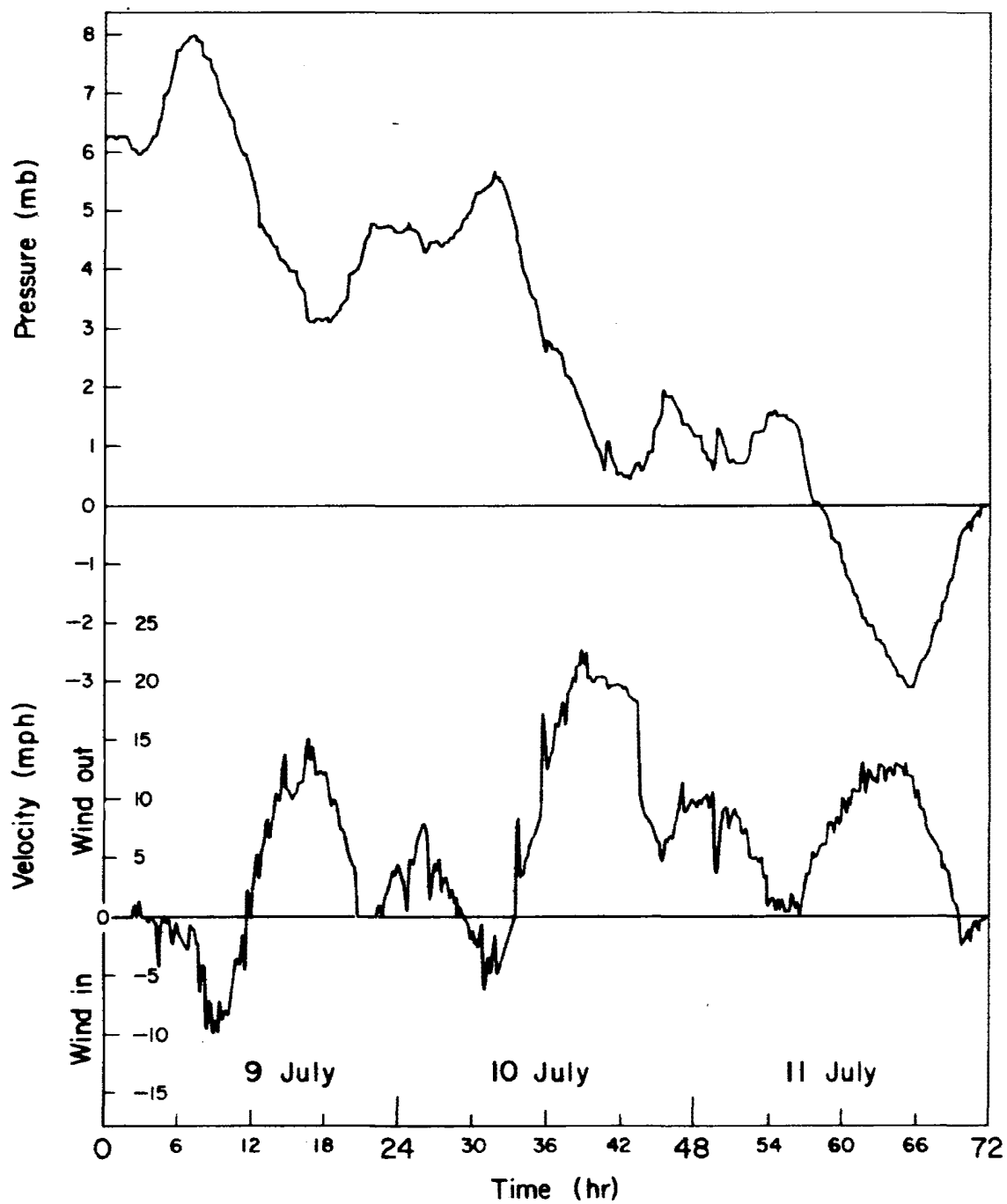


Fig. 5 — Ambient air pressure and blowhole-wind velocity plotted against time (Blowhole No. 3ε)

It is evident also from the data that because of the small dimensions of the blowhole openings, the air (for a given pressure change) blows in or out at a given maximum speed. The blowholes are acting like small leaks in a large container subjected to variations in the pressure outside.

The data may be ranked in the following way, so that time increases by 10-minute intervals as one goes from value to value down the column.

Time	Pressure (P_1)	Wind (V_1)
$t_1 = 0 \text{ min}$	P_1	V_1
$t_2 = 10 \text{ min}$	P_2	V_2
$t_3 = 20 \text{ min}$	P_3	V_3
$\vdots$	$\vdots$	$\vdots$
$t_N = (N-1) \times 10 \text{ min}$	P_N	V_N

Correlation coefficients were computed by pairing the pressure data and the wind data in various ways as follows: from the column of pressure data, the pressure differences ($p_{1+k} - p_1$) were formed for all values of k from 1 to $N-1$ for all intervals of k from 2 to K . For each set of differences and a given value of k , a correlation coefficient was computed using the set of wind values, $w_{(1+k)}$, for the same intervals of k from 1 to K .

Thus, $K(K-2)$ correlation coefficients in all are formed, and the maximum value is sought. In this way, the best response of the blowhole wind to the pressure impulses was determined.

A finite time is required for enough air to leave or enter the underground cavities that the pressure on the inside and outside become equalized. Because of subsequent changes in the pressure, and because the pressure underground is really unknown, it is difficult to assign (from the pressure changes observed) a pressure difference appropriate to an observed wind at any given time. Also, for the same reason, it is not obvious over what interval the pressure difference should be taken in order to provide the maximum correlation. Therefore, in order that a large number of correlations could be computed, a program was prepared by W. L. Sibley of the RAND Computer Sciences Department for use on the IBM 7090. With the program, it was possible to compute the correlation between the blowhole wind and the pressure differences ranging over any desired interval. The correlations reach a maximum and begin to fall off again, whereupon the machine's computational procedure automatically stops. In this manner, a maximum correlation of .82 was obtained for an eight-hour-period pressure difference with the wind at the end of this period.

One might expect that a better correlation would be found for the pressure change versus the square of the wind velocity since the wind could be expected to conform to the Bernouilli equation,

$$v^2 = \frac{2(P_1 - P_o)}{\rho} ,$$

where P_1 is the pressure inside the underground crevice, P_o , the pressure outside, and ρ the density of the air.

Replacing V in the previous computational procedure by its square produced a new set of correlation coefficients with a maximum value of .72. This maximum value resulted from correlating the pressure difference over a 500-minute interval (8 hours + 20 min) against the square of the wind at

the end of this period. This maximum value for the square of the wind speed is not as high as that for the first order wind (.82), but the difference is probably not significant.

The time interval between the pressure impulses and the maximum correlated wind could result from a resonance phenomenon of this period. The conjectured shape of the underground configuration of a blowhole looks very much like a Helmholtz resonator, with a long narrow neck connecting to a large cavity below, as suggested in Fig. 6.

The period, T, of resonance of such a system is given by the expression,

$$T = \frac{2\pi}{v} \sqrt{\frac{L \cdot S}{A}},$$

where v is the air velocity, L is the length of the neck, S is the volume of the cavity and A is the area of the opening. Using the volume estimated from the previous year's data, 10^9 cubic ft, for S, 250 ft for L, and 1 sq ft for A, the period T in hours becomes approximately

$$\frac{600}{v} \text{ hours}$$

for v in miles per hour. For a wind of 30 mph, a value not frequently exceeded, the period becomes 20 hours. A period of 20 hours is close to the normal period of the atmosphere, but is not in agreement with the period of 1/2 hour exhibited by the 1960 data or the 8-hour period characteristic of the 1961 data.

Two possible conclusions can be drawn from the lack of correspondence. Either the dimensions are incorrect or the blowholes are not acting like a Helmholtz resonator.

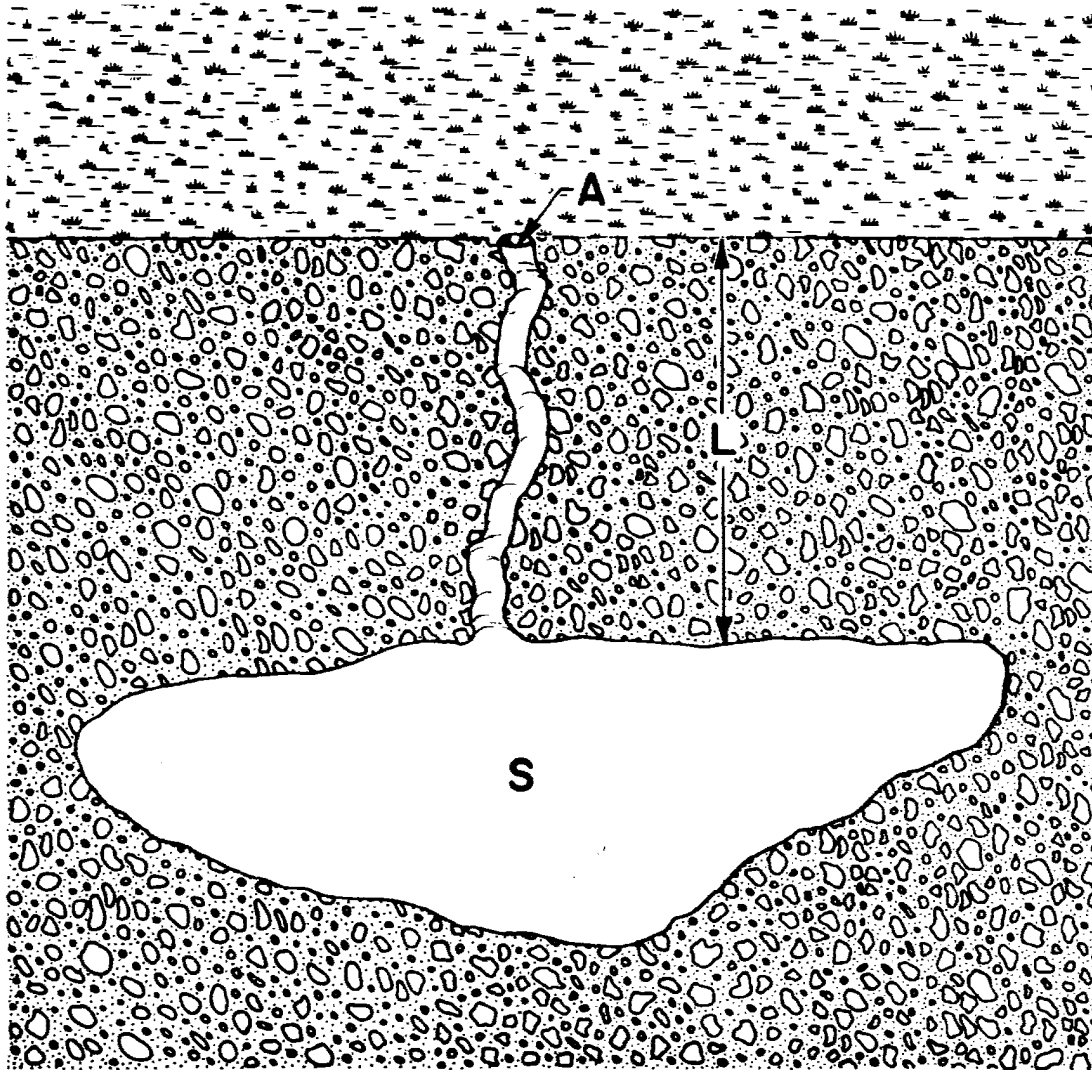


**Fig. 6 — Conventionalized concept of blowhole showing
Helmholz-resonator configuration**

The flattening of the wind-response curves under the corresponding peaks in the pressure trace strongly suggests that the air moving in or out of the holes acts like a slow leak in a large confined volume. One could explain the time lag as a measure of the time required for the pressure to equalize itself inside and out by the escape of the air. This is the time constant for the system.

Temperature and Humidity

After a period of transition, the air leaving one of the blowholes possesses approximately the same temperature and humidity as the air that entered the same hole during the previous in-blowing phase. During the hot desert summer, the air generally enters the blowholes during the late-night and early-morning hours. This means that the air that comes out so strongly during the heated afternoons is pleasantly cool. Perhaps this helps to explain the attraction of the blowholes for the contemporary and ancient Indians of the region; certainly it explains why they are favorite resting places of the rattlesnakes.

Volume Estimate

Assuming that air leaving the holes represents a change in volume that the underground cavity would undergo if it were free to expand under the observed pressure change at constant temperature, we can apply the equation of state to the problem, since we know also that the blowholes act in unison, i.e., that the transport of air in one hole and out another is negligible. Thus, the volume can be computed from the equation

$$S = \frac{P \Delta S}{\Delta P}$$

where S is the total volume, P the ambient pressure, ΔP the observed change in pressure and ΔS the change in volume obtained from $\Delta S = Av\Delta t$, where A is the total area of the mouth of the blowholes and v the average velocity over the interval Δt . The estimate of the volume of the underground cavern, using only the data from Blowhole No. 3e is 8×10^8 cu ft, which compares favorably with the estimate made the year before, 10^9 cu ft, from data on Blowhole No. 1, a blowhole that is known to be connected with Blowhole No. 3e. Considering the number of blowholes now known to be interconnected, at least nine, the underground caverns or crevices have a volume of at least 7.2 billion cu ft. In actuality, the air leaving the cavity under a given pressure difference never has an opportunity to act long enough to equalize the pressure inside and out. Therefore when we assume that the air leaving the holes during periods between pressure impulses has equalized the pressure inside and out, we make a gross underestimate. Consequently, all of the estimates of the volume of the underground cavern are minimal.

Electric Field Examination

If the air leaving the holes were significantly more radioactive, or even contained a larger number of ions than the ambient air, and, therefore, was more conductive, this fact would be evidenced by a change in the normal electrical field of the atmosphere. In order to test whether this might be the case, an electric-field (negative potential gradient) meter was moved into the air coming out of Blowhole No. 1 from well outside its zone of influence. No detectable difference in the atmosphere's electric field could be observed over a series of several trials. It was possible to check for proper operation of the instrument at a time close to its

employment at the blowhole by its reaction to the fields of atmospheric electricity associated with near-by thunderstorms.

Tracer Studies

The tracer studies with zinc cadmium sulfide proved that underground connections exist between all the blowholes of the Wupatki area and between these and the blowing well at the Keith Ranch on the far side of the 12,670-ft peak of the San Francisco Mountains. Connection between the Wupatki holes and a hole 44 miles to the south is suggested but unproven. Relationships between these findings and those of the geological phase of the project are presented in Section III.

III. GEOLOGICAL STUDIES

INTRODUCTORY NOTE

The meteorological data indicate that the natural blowholes and blowing wells in the Flagstaff—Wupatki region connect to an underground cavity whose minimum volume is about seven billion cubic feet. This cavity provides interconnections between the blowholes and a blowing well over a distance of about 24 miles.

Although the meteorological data reveal the existence of an extensive underground cavern system, investigators attempting speleologic exploration of fissures and small caverns in the Flagstaff—Wupatki region have been able to penetrate only about 300 feet before being stopped by too narrow an opening or a dead end. It was therefore necessary, on the project, to utilize inferences from the surficial geology and indirect geophysical measurements to characterize the underground cavern system.

A flat-lying to gently dipping sequence of sedimentary rocks of late Paleozoic to early Mesozoic age is exposed in the Wupatki—Flagstaff region. These rocks are cut by shallow intrusive rocks and overlain by discontinuous lava flows, visible in the background of Fig. 7. Volcanic cones and lava flows are large and numerous in the San Francisco Mountain area between Flagstaff and Wupatki National Monument. This relatively simple structure is, in places, interrupted by faults and gentle flexures. Figure 8 illustrates the regional geology (modified from Moore, Wilson and O'Haire²) and shows the location of the area in the National Monument that was studied in detail. Figure 9 is a diagrammatic section illustrating the rock units exposed in the region.

PREVIOUS INVESTIGATIONS

The volcanic rocks in the Flagstaff—Wupatki region have been described by Robinson³ and Colton⁴. The regional structure and geomorphology have



**Fig. 7 — Local terrain view northward across site of Blowhole No. 1.
Note margin of volcanic-ash-covered foreground,
archaeological site in middle background,
and skyline of basalt-topped mesas**

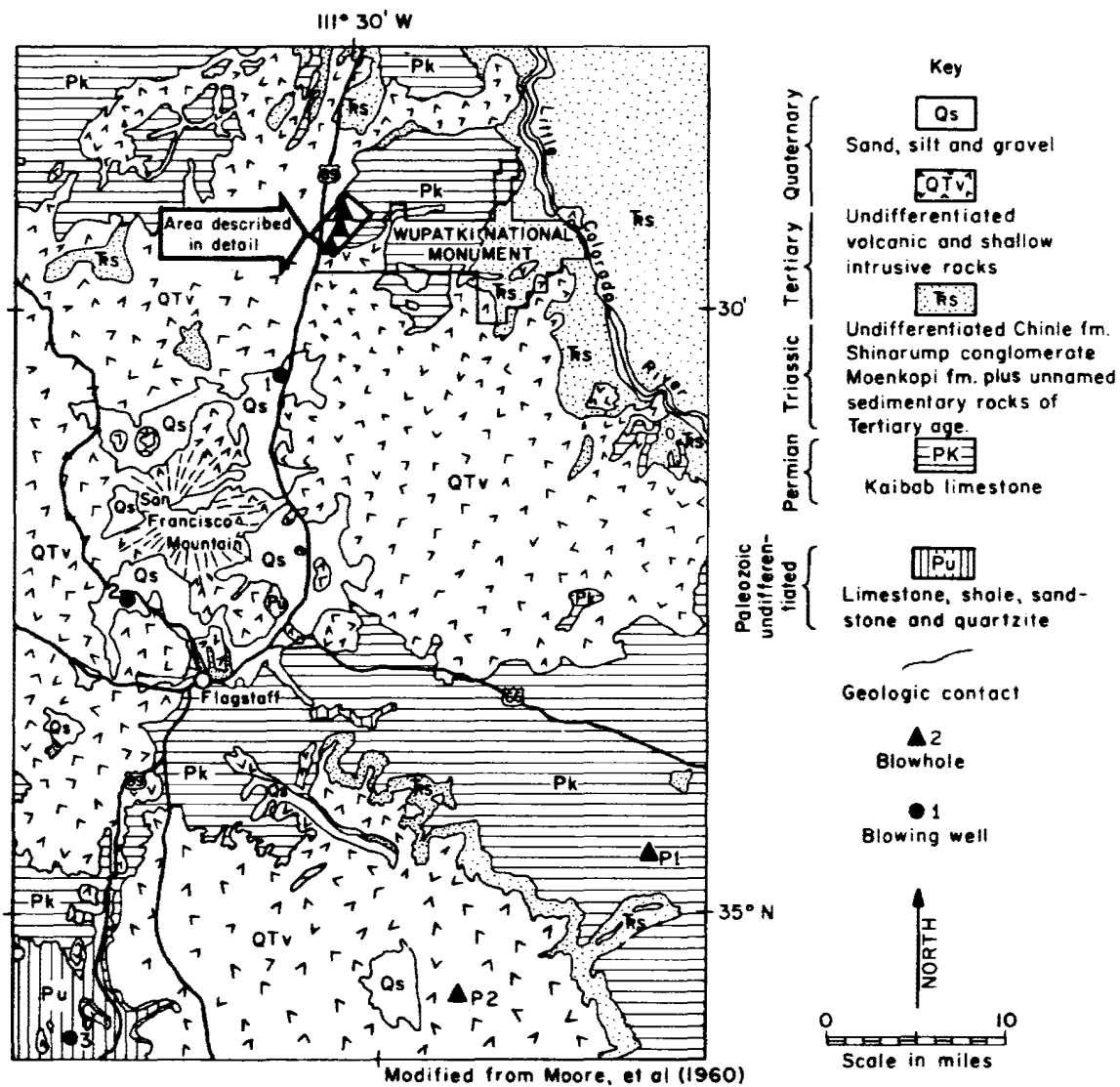


Fig. 8 — Generalized geologic map of the Flagstaff-Wupatki area, Arizona

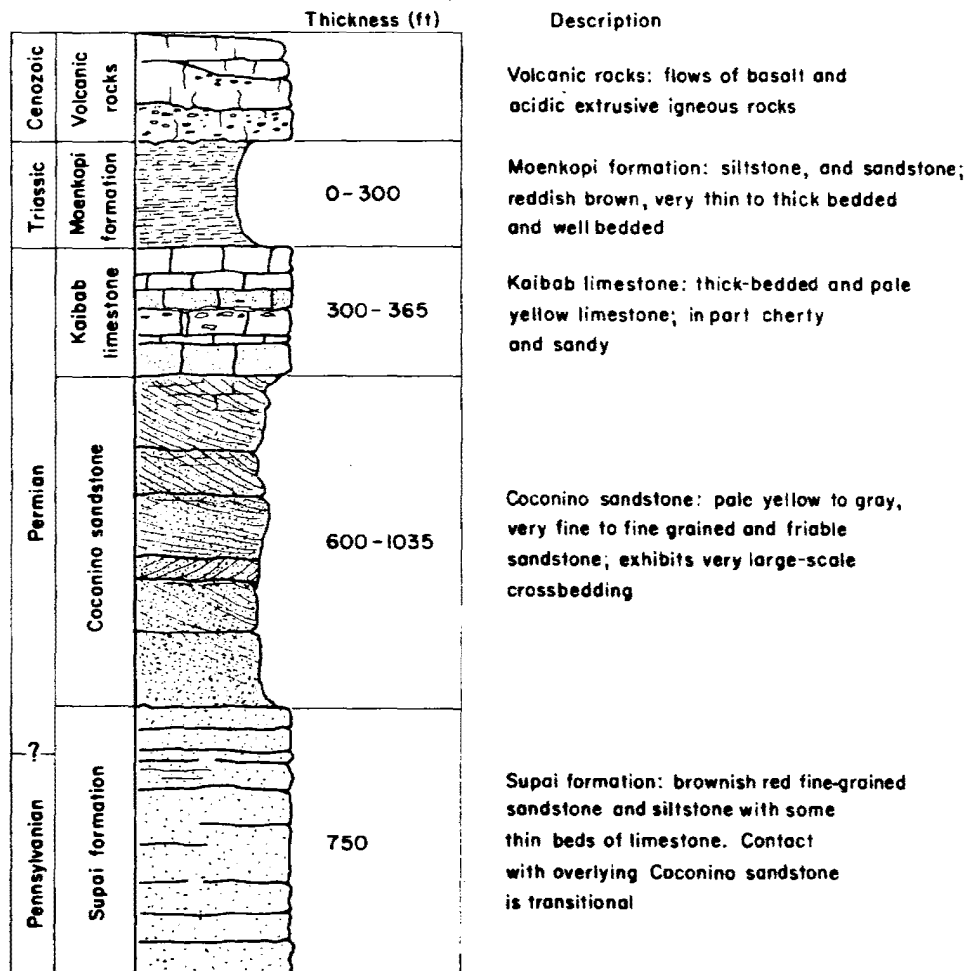


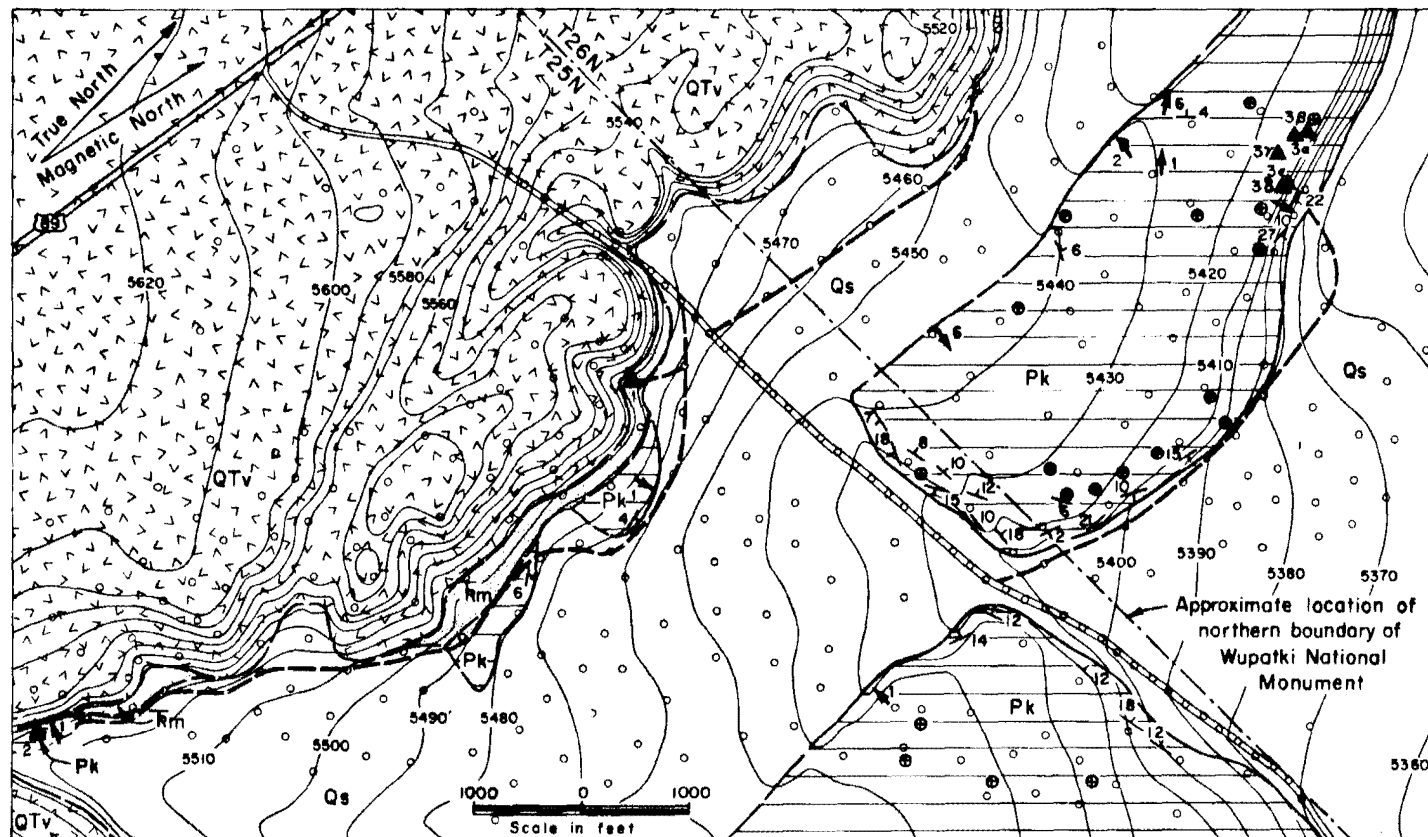
Fig. 9 — Columnar section of rocks exposed in the Flagstaff-Wupatki region

been studied by Babenroth and Strahler⁵, Childs⁶, and Kelley⁷. McKee has studied the Kaibab limestone⁸ and the Moenkopi formation⁹ in the region. Cosner¹⁰ studied ground-water conditions in the Wupatki area. Colton¹¹ described the exploration of limestone-solution cracks in the Monument, and Schley¹ described the airflow through a blowhole (referred to as Blowhole No. 1 in this Memorandum).

GEOLOGY OF THE WUPATKI AREA

The surface geology and the distribution of blowholes in the local Wupatki area are illustrated in Fig. 10. Except for the two blowholes on the Pollock ranch south of Flagstaff (Blowhole No. P1, Blowhole No. P2), all of the blowholes studied in the present investigation appear on this figure. The topographic base for the geologic map was prepared in 1961 by plane-table mapping; this mapping also yielded the elevations at individual stations necessary for the gravity survey. Elevations along the access road in the Monument were obtained from survey data on file at the Monument headquarters.

The terrain in the area shown in Fig. 10 is, in part, rolling hills and steep bluffs formed of basalt, and in part, alluviated lowlands and fairly smooth, plateau surfaces formed of Kaibab limestone. Within these outcrop areas, the Kaibab is flat-lying, but near the margins the strata dip beneath the alluvium. An anticline and a syncline parallel the southern edge of the northmost Kaibab outcrop in the map area. The fissure at Blowhole No. 3 δ and Blowhole 3ε parallels the edge of the plateau in which they occur. The fissure may be in part the result of a slump of the limestone toward the low area to the northeast. It is, therefore, possible that the dip of the limestone toward the margins of the outcrop areas is



-26-

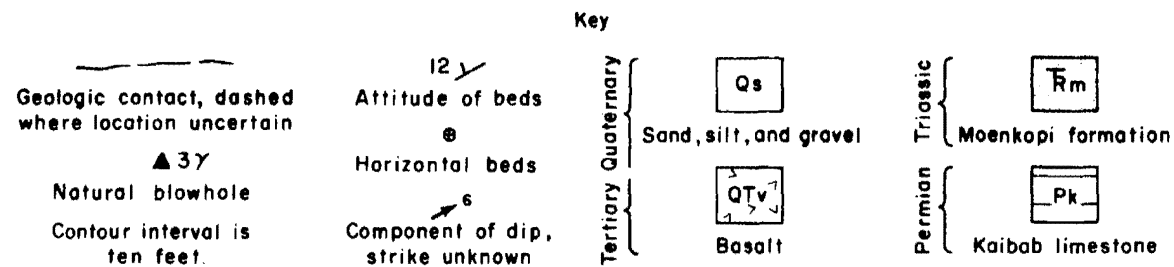


Fig.10 — Geologic map of a portion of Wupatki National Monument and vicinity, Arizona

the result of slump. However, on a regional map that includes the area shown in Fig. 10, Babenroth and Strahler⁵ show the outcrops of Kaibab limestone bounded by normal faults. The distribution and structure of the limestone could also be the result of gentle undulations in the structure of the Kaibab strata. In the central portion of the area, the Kaibab is overlain by the Moenkopi formation. The structural relations indicate that the smooth plateau surface of limestone in the elevated outcrop areas must be the top of the limestone, which has been stripped of the overlying, less resistant Moenkopi formation. At the western edge of the area vesicular basalt rests on the Moenkopi formation.

GEOLOGIC CONDITIONS CONTROLLING THE DISTRIBUTION OF BLOWHOLES

Of the nine blowholes (Figs. 8 and 10) identified in this investigation, all but two occur in the Kaibab limestone. Blowhole No. 1 occurs in the Moenkopi formation approximately 10 feet above the top of the Kaibab and Blowhole No. P2 (Fig. 8) occurs in volcanic rock. Notes on the drillers log of Blowing Well No. 2 indicate that the airflow originates from crevices in the Moenkopi formation and the Kaibab limestone. The total depth and the rock types penetrated by Blowing Well No. 1 are unknown. However, unverified reports from individuals familiar with the well suggest that the depth of this well may be over 800 feet, which is deep enough to penetrate into the Kaibab.

In the search for blowholes, reports from local residents were relied upon, and no systematic regional search for blowholes in terrain underlain by all types of rocks was attempted. It is, therefore, quite possible that the apparent concentration of blowholes in the Kaibab is biased because the

volcanic rocks commonly form rugged inhospitable terrain in contrast to the open plains and gentle hilly country on the Kaibab. However, in the discussion that follows, it is assumed that the cavern system occurs in the Kaibab limestone and in older rocks and that blowholes in the younger rocks are connected to this system through relatively minor cracks and crevices.

Closed depressions whose horizontal dimensions vary from a few feet to a few hundred feet occur in the Kaibab limestone. Most of the depressions are elongated and commonly have abrupt changes in trend. The strata in many of the smaller depressions are slumped and dip toward the center. The floors commonly consist of angular blocks and slabs of limestone. The bottoms of the larger depressions are often obscured by soil and tumbleweeds.

Fissures, locally called "earth cracks," also occur in the Kaibab. These are fairly straight openings with smooth vertical walls, which are from three to six feet wide and up to one hundred feet long. According to Colton,¹² one such fissure within the Wupatki National Monument was explored to a depth of 275 feet. At the Kaibab limestone—Coconino sandstone contact, at a depth of 240 feet, the narrow fissure was found to open out into a larger chamber over 100 yards long, 15 feet wide, and at least 50 feet high. This cavern is perhaps representative of subsurface relations in the region.

Some of the blowholes appear as narrow openings among the rock rubble filling the depressions in the limestone. Others are simply irregular openings and crevices that are unrelated to the depressions. Blowholes No. 38 and No. 3e were found to open into a narrow vertical fissure, which was explored. It had a depth of about one hundred feet. It is possible that some of the elongate depressions in the Kaibab limestone are

the surface expression of fissures choked with angular blocks of rock that have slumped into the opening. The depressions and fissures in the limestone may be tension fractures or fissures formed by the solution action of percolating ground water along pre-existing faults or joints or a combination of these. The earth cracks described by Colton¹¹ occur along minor faults that have displacements of up to two feet.

Inferences from the meteorological data suggest that the shallow crevices and fissures must open out into an extensive interconnected cavern system. Obviously, the portion of these caverns forming the air cavity must be above the present water table, which is about 1300 feet below ground near the Citadel ruin (Cosner¹⁰). The Citadel ruin is three miles east of the blowholes in the Monument. Citadel Sink, directly south of the Citadel, is a roughly circular depression in the Kaibab limestone, approximately 500 feet in diameter and 125 feet deep. The sink may have formed as a result of collapse of a solution-formed cavern. Figure 11 illustrates diagrammatically the inferred subsurface geologic relations in the Wupatki area.

RESULTS OF GRAVITY SURVEY

The available meteorologic and geologic data suggest that a system of interconnected caverns formed by solution action are present under the Flagstaff—Wupatki region. Using the relationships developed by Nettleton,¹³ it can be shown that the difference between the gravity at a point over a cylindrical cavern with a diameter of 200 feet at a depth of 500 feet and the gravity at a point 1000 feet from the axis of the cavern is approximately 2 milligals (mg). Differences in gravity as small as 0.1 mg can be determined. Therefore, a gravity survey of an area in the western portion

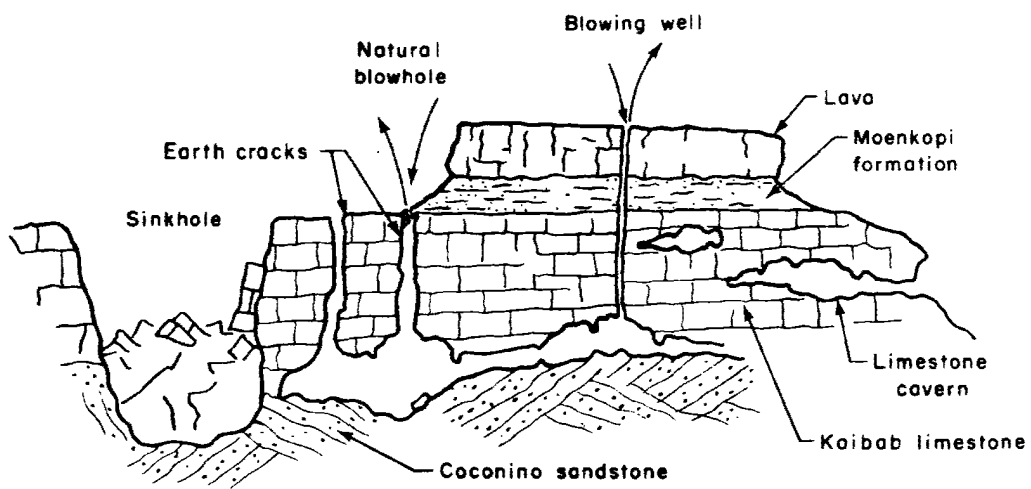


Fig. 11—Diagrammatic sketch of inferred subsurface geologic relations in the Wupatki area

of Wupatki National Monument was conducted in an attempt to set limits on the distribution, depth, and size of the inferred cavern system.

The values of gravity at approximately 350 stations were measured with a Worden gravity meter. The values were corrected for meter drift, latitude and elevation. A value of 0.06 mg per foot of elevation was applied for the combined free-air bouguer correction. Correction for local variations in topography was not made because it was found that the maximum value of the terrain correction in areas of irregular topography is only about 0.1 mg. As is illustrated in Fig. 12, the acceleration of gravity rapidly decreases from south to north. This regional gradient could be the effect of increasing distance from the mass of relatively dense volcanic and shallow intrusive igneous rocks of the San Francisco Mountain area combined with structural relief of the older rocks. According to Cosner,^{10*} the area is on the southwest flank of the Black Mesa basin and the regional dip of the rock strata averages between 1° and 3° to the northeast.

In order to remove the effects of this strong regional gradient, a uniform decrease in gravity of 1.0 mg per 795 ft in a N 18° W direction was assumed. Figure 13 illustrates the variations in gravity derived by subtracting this regional gradient from the values of gravity at each station. The contours do not indicate the presence of any large underground cavities related to the approximate north-south alignment of blowholes.

*Page 5.

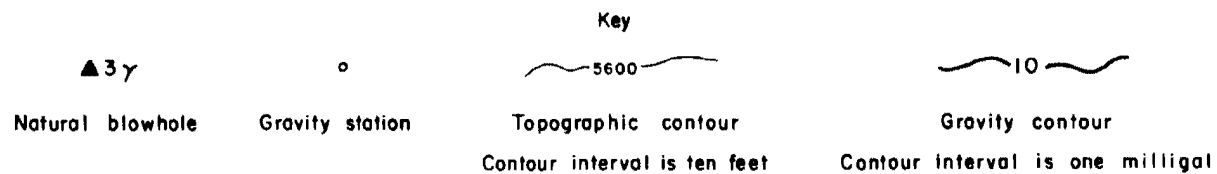
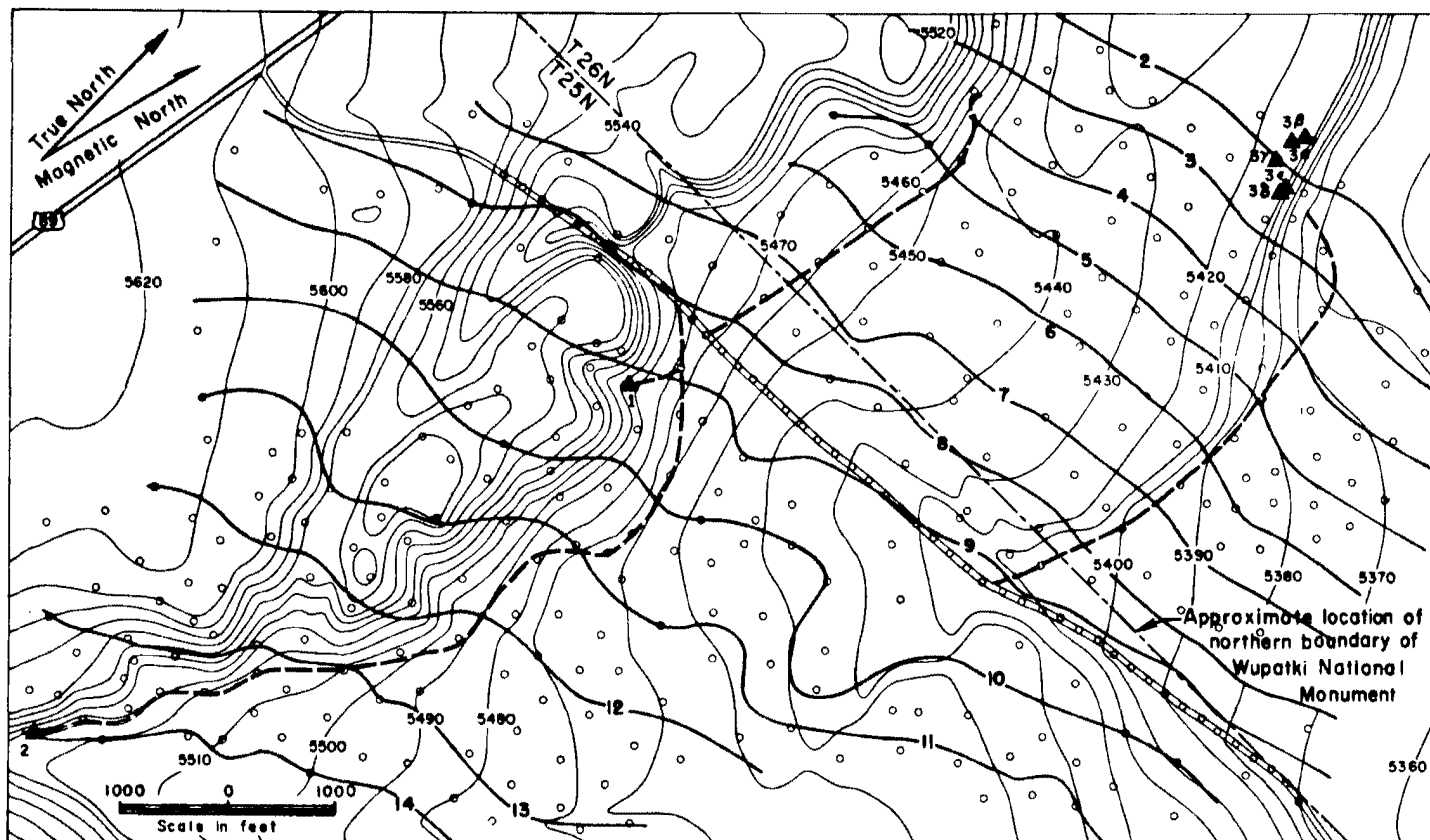


Fig. 12—Map showing variations in gravity of a portion of Wupatki National Monument and vicinity, Arizona

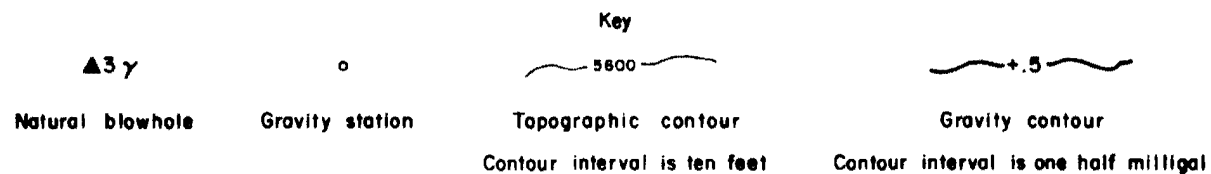
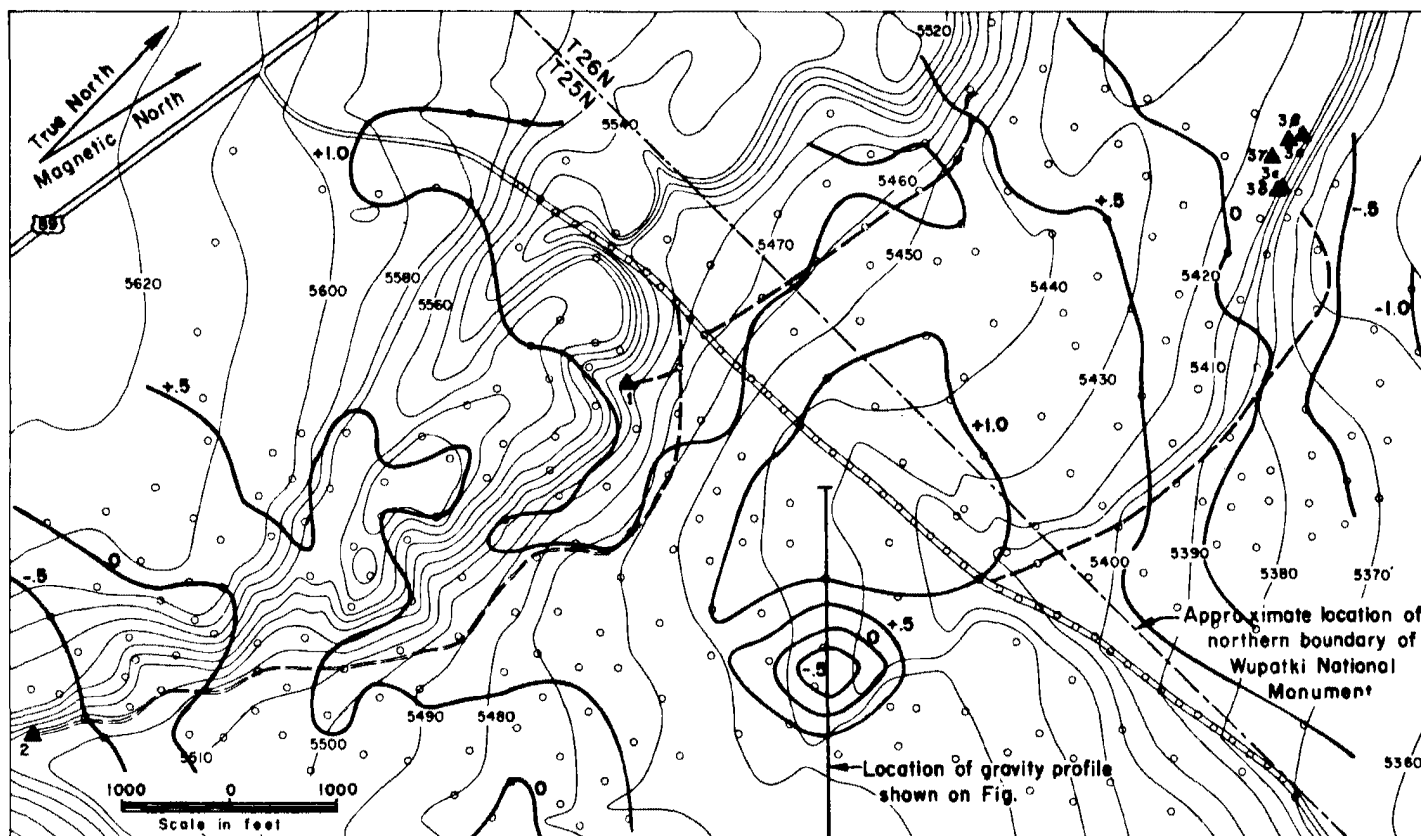


Fig. 13 — Map showing variations in gravity in the Wupatki area with the regional gradient removed

VOLUME ESTIMATES

Rough calculations indicate that if the caverns are of cylindrical form and occur in the Kaibab limestone, the maximum cavern diameter is 50 feet. Using the estimate of 7.2 billion cubic feet for the minimum volume obtained from the meteorological measurements, the minimum total cavern length would be about 695 miles. If we assume a complex or circuitous system and not a single direct path for the particles, the figure 695 is not inconsistent with direct distances of 24 and 44 miles.

A roughly circular gravity minimum occurs in the west central portion of the area and it seemed appropriate to determine whether this minimum constitutes evidence of an underground cavity. The curves shown on Fig. 14 indicate that the anomaly could be the result equally well of a shallow mass of material with a density contrast of 0.5 gm/cm^3 with limestone or an air-filled cavern. The shallow-mass anomaly could be a sink hole in the Kaibab limestone that has been filled with alluvium. The deep-cavity model would represent a solution-formed cavern. Insufficient data are available to reveal which subsurface interpretation is correct.

ORIGIN OF CAVERN SYSTEM

The fluorescent-particle tracer data and gravity study revealed that the natural blowholes and blowing wells in the Flagstaff—Wupatki region are connected to a system of small fissures and caverns that covers a very wide region, rather than to a few large isolated caverns. It is believed that the fissure system originated from the solution action of ground water on calcareous rocks. Figure 15 is modified from Cosner¹⁰ and shows the relationship between the interconnected blowholes and blowing wells, the

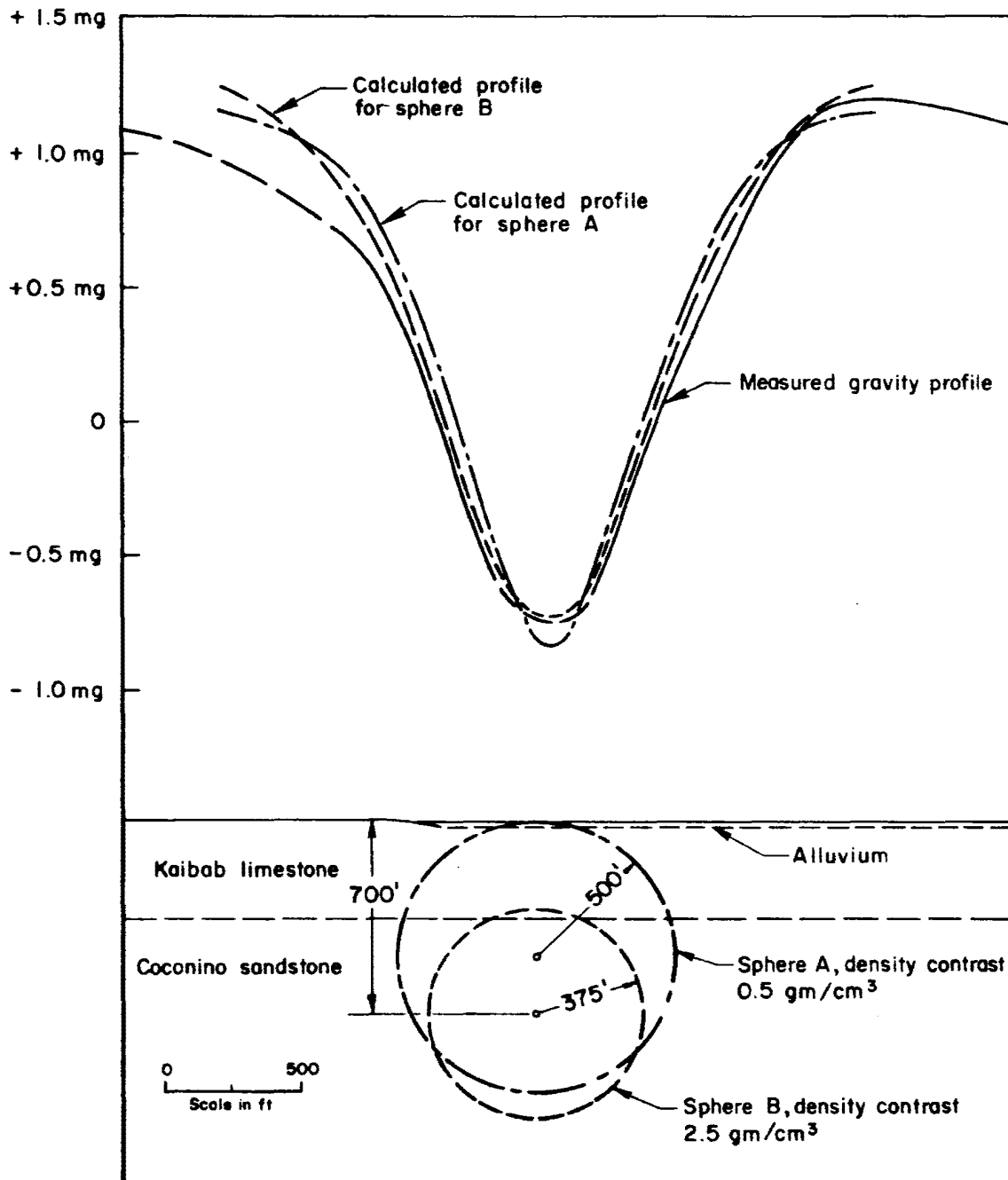


Fig. 14 — Measured and theoretical gravity profiles across a negative gravity anomaly in the Wupatki area

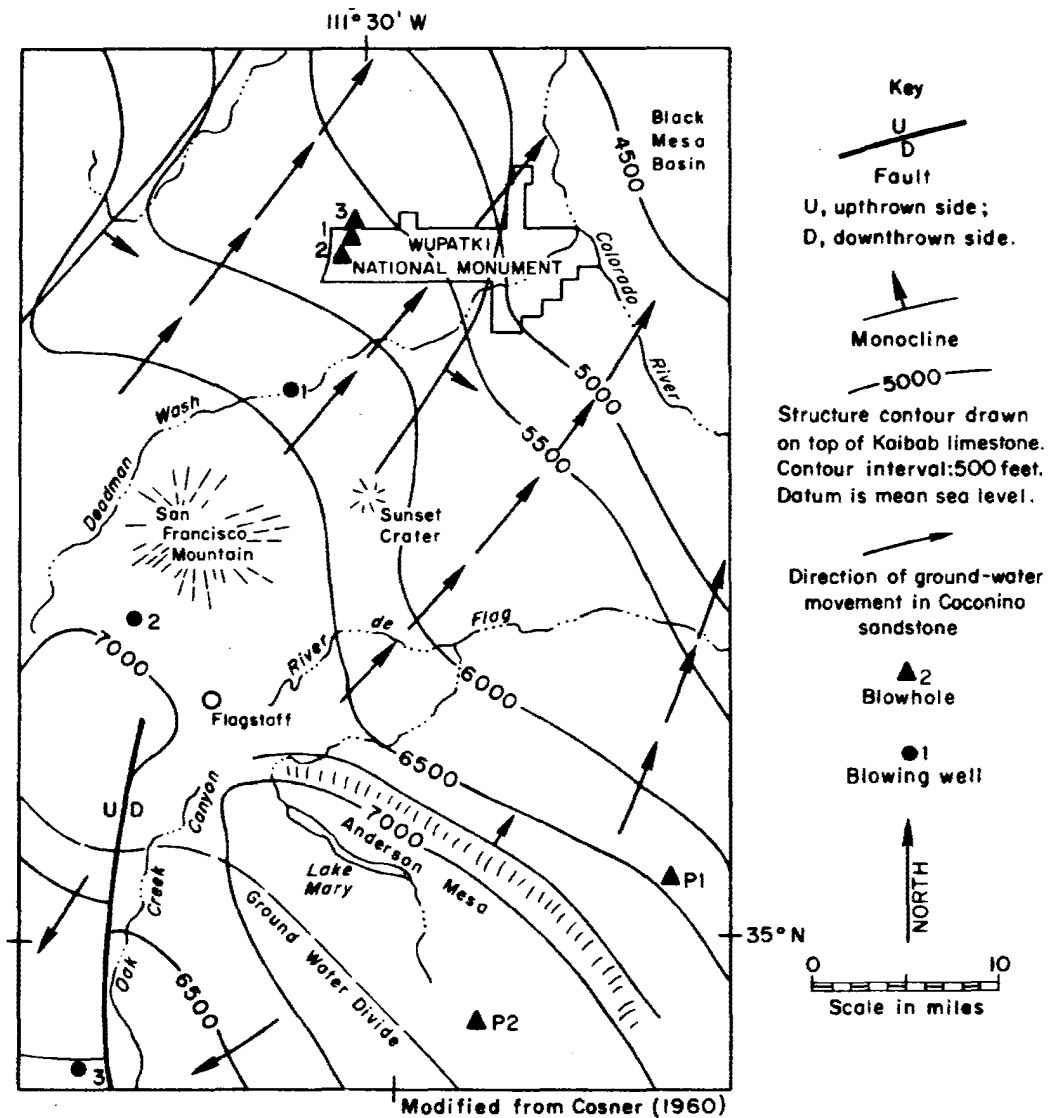


Fig. 15 — Map of Flagstaff-Wupatki area, Arizona, showing major structural features and direction of ground-water movement

subsurface structure and the flow of ground water. It should be noted that the natural blowholes in the Wupatki area and the No. 1 and 2 blowing wells lie along the direction of ground-water flow in the Coconino sandstone. The continuity of the cavern system parallel to the present direction of ground-water movement suggests that the solution action which formed the caverns was closely related to the flow and that the caverns provide channels for the ground-water movement. This suggests that much of the cavern formation occurred at the depth of the water table. Connections to the surface were formed by percolation of surface water to the water table.

It is unfortunate that the fluorescent particles noted in Blowhole No. P2 could have resulted from contamination, because this blowhole is in the Gila River drainage basin. The establishment of an interconnection between Blowhole No. P2 and the wells and blowholes to the north would suggest that the cavern system formed, at least in part, before the present subsurface structure and ground-water movement, shown in Fig. 15, had been established. However, the fact that fluorescent particles were not detected in Blowing Well No. 3 supports the inference that the particles noted in Blowhole No. P2 were the result of contamination.

IV. CONCLUSIONS AND FUTURE PLANS

CONCLUSIONS

Without being able to explore further than the first few hundred feet into any of the blowholes or fissures, it has been possible to show that there is an extensive underground cavern or crevice system in north-central Arizona. From a combination of the results from the meteorological measurements of the blowhole wind and ambient pressure and the geological gravity survey, further information of the spatial dimensions and extent has been derived. It appears that there is an extensive crevice or cavern system in the area around Flagstaff with many branches and inter-connecting channels spanning a distance of at least 24 miles and a total volume of at least 7.2 billion cubic feet. The cavern system may have a close connection with the underground water problems of the area, where even though considerable water collects on the slopes of the San Francisco mountains, the inhabitants are constantly in short supply.

It should be possible to use the combined geological and meteorological measurements in the manner presented in this paper to estimate the volume and describe the horizontal extent of other underground caverns of unknown dimensions which have small surface openings or which can be reached by surface drillings. The wind measurements at the mouth of the openings combined with the ambient pressure observations give an estimate of the minimum volume. The longer the period over which the wind—pressure measurements are made, the better the chance of obtaining the best combination and therefore most accurate estimate of the volume. The gravity survey provides quantitative information of the horizontal dimensions or an estimate of the depth of the cavern or both. Tracer studies offer

conclusive evidence of connection or separation between blowholes or well. By combining all these data, considerable information is obtained about a phenomenon that cannot otherwise be observed or measured.

FUTURE PLANS FOR GEOLOGICAL AND METEOROLOGICAL STUDIES

An attempt is going to be made, if financing is available, to improve on the accuracy of the wind and pressure measurements and to extend the tracer studies in a project to be carried out by the Museum of Northern Arizona during the summer of 1962. The data and results will be studied with the underground-water problem of the Flagstaff area in mind. Further studies will be useful for learning more about the circulation into and out of large underground shelters as well as evaluating the usefulness of combined meteorological and geological techniques for estimating the volume and other dimensions of large underground unsurveyed cavities.

REFERENCES

1. Schley, R. A., "Diurnal Air Flow through an Earth Crevice, Wupatki National Monument," Plateau, Vol. 33, No. 4, 1961, pp. 105-111.
2. Moore, R. T., E. D. Wilson, and R. T. O'Haire, Geologic Map of Coconino County, Arizona, Arizona Bureau of Mines, University of Arizona, 1960.
3. Robinson, H. H., The San Franciscan Volcanic Field, Arizona, U. S. Geological Survey, Professional Paper 76, 1913.
4. Colton, H. S., The Basaltic Cinder Cones and Lava Flows of the San Francisco Mountain Volcanic Field, Arizona, Museum of Northern Arizona, Bulletin 10, 1937 (rev. 1950).
5. Babenroth, D. L., and A. N. Strahler, "Geomorphology and Structure of the East Kaibab Monocline, Arizona and Utah," Geol. Soc. Amer. Bull., Vol. 56, 1945, pp. 107-150.
6. Childs, O. E., "Geomorphology of the Valley of the Little Colorado River, Arizona," Geol. Soc. Amer. Bull., Vol. 59, 1948, pp. 353-388.
7. Kelley, V. C., "Monoclines of the Colorado Plateau," Geol. Soc. Amer. Bull., Vol. 66, 1955, pp. 789-804.
8. McKee, E. D., The Environment and History of the Toroweap and Kaibab Formations of Northern Arizona and Southern Utah, Carnegie Institute of Washington, Publication 492, 1938.
9. McKee, E. D., Stratigraphy and History of the Moenkopi Formation of Triassic Age, Geological Society of America, Memoir 61, 1954.
10. Cosner, O. J., Ground Water in the Wupatki and Sunset Crater National Monuments, Coconino County, Arizona, U. S. Geological Survey, Dept. of the Interior, Open File Report, October, 1960.
11. Colton, H. S., "The Exploration of Limestone Solution Cracks," Mus. N. Ariz., Museum Notes, Vol. 10, No. 10, April, 1938, pp. 29-32.
12. Colton, H. S., "Sunset Crater," Plateau, Vol. 18, No. 1, July, 1945, pp. 7-14.
13. Nettleton, L. L., Geophysical Prospecting for Oil, McGraw-Hill Book Company, Inc., New York and London, 1940.

