CAVE MAPPING FROM THE SURFACE AT KARTCHNER CAVERNS STATE PARK, ARIZONA

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ABSTRACT

Kartchner Caverns, discovered in 1974, is Arizona's newest State Park. Geophysical investigations are underway to map the subsurface and to detect the presence of auxiliary caverns. Electromagnetics was employed to map near-surface groundwater levels, while a natural-potential survey over the entire Park identified zones of infiltration in the valley alluvium and likely cavern targets in the carbonate outcrop. A gravity survey delineated range-front faults and resulted in a map of depth-to-bedrock beneath the valley alluvium. Although the gravity survey could not resolve the carbonate/schist boundary, it portrayed the regions of shallow bedrock that control groundwater flow and storage. It is recommended that Park facilities, water wells and waste-disposal sites be constructed in areas of shallow schist bedrock or thick valley alluvium, in order to avoid subsidence problems over the carbonates and possible contamination of the karstwater system and caverns. The gravity survey also produced significant anomalous lows over two of the three main cavern sections and identified sites likely underlain by cave galleries not yet discovered. Four of these sites are possible targets for tunneling to provide visitor access.

INTRODUCTION

Kartchner Cavern is a beautiful limestone cave in pristine condition, considered by experts to be the premier cavern in Arizona. It will be protected and displayed to the public as the newest Arizona State Park. The caverns are over two miles long, with spacious rooms, two of which are as long as a football field. It is a wet, "live" cave into which water still percolates from the surface. Calcite deposition is currently taking place, so that we find an unusually wide variety of multicolored cave formations, including stalactites, stalagmites, flowstone, shields, helictites and soda straws. It is a summer home to a colony of approximately 700 bats.

HISTORY

The cave was discovered in 1974 by Randy Tufts and Gary Tenen of Tucson. They appreciated the cave's vulnerability to forced entry and vandalism and, therefore, kept it secret for 14 years until protection could be assured. They and the owners concluded that the State Parks Department could provide the best possible protection for the cave. As

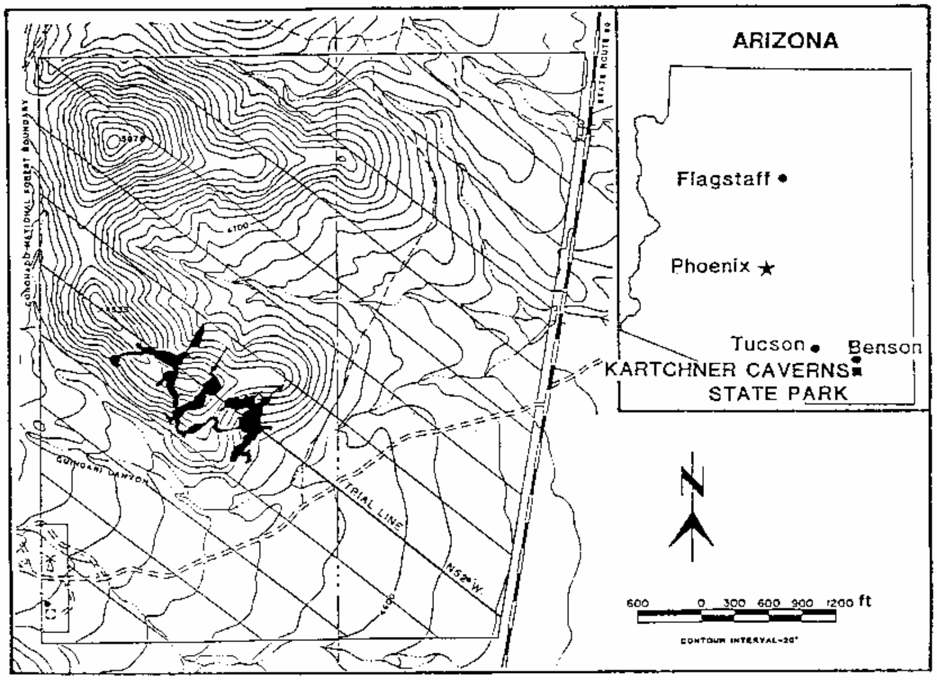

Figure 1. Location map of Kartchner Caverns State Park, showing cavern configuration and layout of geophysical profiles.

a result, the cavern became Arizona's 25th State Park on April 27, 1988.

DESCRIPTION

The State Park is located 8 miles south of Benson along State Highway 90 (Figure 1: Inset). It is approximately one section in area straddling the boundary between the Whetstone Mountains on the west and the San Pedro Valley on the east. Paleozoic carbonates--limestone and dolomite--form two steep ridges, and it is the southern of these that contains the caverns (Creasey, 1967; Wrucke & Armstrong, 1984).

PROGRAM AND OBJECTIVES

Arizona Conservation Projects, Inc., under contract to the State Parks Department is conducting multidisciplinary studies of the cave and outdoor environment, preparatory to development, in part, for public viewing. The many studies being performed include those of geology, cave origin, mineralogy and sediments, meteorological monitoring, water chemistry, and plant and animal life.

The Geophysics Group was engaged to provide surveys for the detection of other possible caves in the Park, to locate a favorable access site for a visitors' entrance, and to map structure and groundwater beneath the alluvium of the Park, for the siting of visitor facilities. The field studies were carried out during September and October of 1989.

Figure 1 shows the layout of the 13 main geophysical lines crossing the property, as surveyed by ACPI. A gravity survey was planned to run along all of the lines. First, however, two electrical techniques were to be operated over a trial line running directly over the caverns, to determine which would provide the best response, both to the voids and to groundwater in the alluvium. The methods tested were passive *natural potential (NP)* and active *electromagnetics (EM).*

ELECTROMAGNETIC TESTS

For the EM test, a Geonics EM-34-XL system was employed. This instrumentation provides a time-varying magnetic source-field by energizing a portable transmitter coil at frequencies between 400 and 6400Hz. The source-field causes a system of electric eddy currents to flow in the subsurface, whose strength depend on the electric conductivity of the earth materials. The eddy currents, in turn, generate secondary magnetic fields that are detected by a nearby receiver coil. Thus a strong signal is returned from a buried metal pipe or a wet clay zone, while a dry sand might stand out as an absence of response. A void, having almost zero conductivity, should register as a lack of signal, provided the surrounding rock is reasonably conductive or damp.

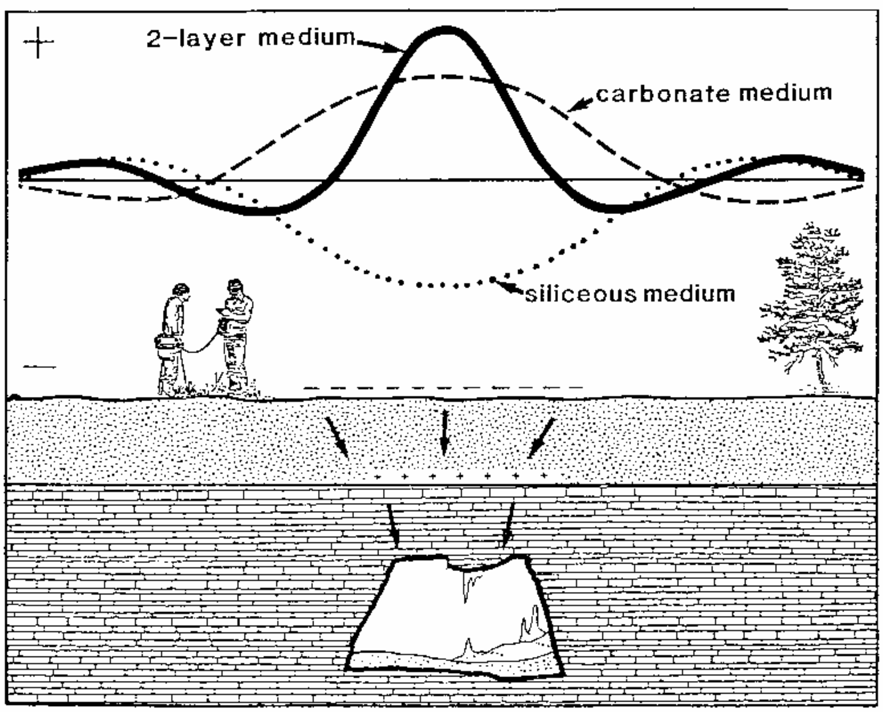

Figure 2. Natural-potential anomalies arising from infiltration in the roof of a cavern in different rock media. The dotted curve is the negative response expected over a single medium of *siliceous* material. The dashed curve is the positive response due to a purely *carbonate* medium. The solid curve is the compound response arising from a *combination of the two media*, as depicted in the cross-section.

The EM was operated using both vertical and horizontal coil orientations, and along the trial line both 20 and 40m separations were adopted. The receiver detected the subsurface boundary between carbonate rock and alluvium as well as underflow in the wash; however, it failed to resolve the cavern from the very resistive carbonate rock. Altogether three full lines were run, in addition to a short line connecting two wells.

NATURAL-POTENTIAL SURVEY

Natural d.c. currents occur everywhere in the ground. These give rise to a natural-potential (NP) distribution at the surface that can be detected by means of electrodes and a voltage-measuring device (Lange, et al., 1986). The currents can result from chemical reactions around natural conductors (e.g., metallic mineralization), diffusion-adsorption processes at lithologic boundaries, localized thermal heating, and chemical and fluid activity around plant roots (Corwin & Hoover, 1979). But by far the most prevalent effect derives from water infiltrating soil or rock. This *electrokinetic*, or *streaming* effect comes about from the selective displacement of ions from pore or fissure walls by a moving fluid, such that the electric potential measured between upstream and downstream points is linearly proportional to a driving pressure of the fluid (Bogoslovsky & Ogilvy, 1972; Ishido & Mizutani, 1981). The polarity of the potential depends on the chemical nature of both the solid and the electrolyte. The technique has found widespread application in the mapping of leakage in dams and pipelines and in the search for thermal and meteoric water plumes (Ogilvy, et al., 1969).

We illustrate the application of the method for cave detection as follows: In Figure 2, water percolates underground in a siliceous medium (soil or sandstone). The

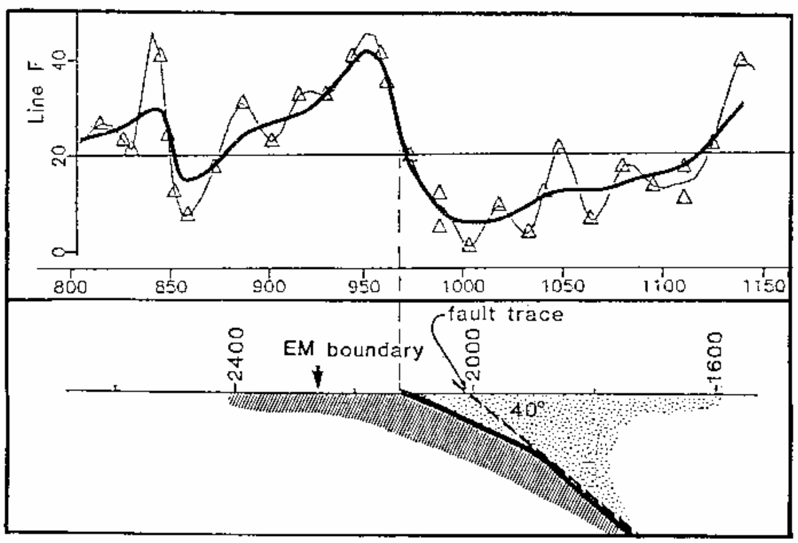

Figure 3. Natural-potential crossover-type anomaly due to the contact between carbonate rock and alluvium at Kartchner Caverns. Fault deduced from gravity analysis.

presence of a void acts as a localized zone of enhanced permeability, since it can accept much more flow than its surroundings. As a result, a negative voltage can be expected over the tunnel. In a carbonate environment, infiltration occurs primarily through joints and fissures. In the roof of a cave, flow is again favored, but because of the difference in rock chemistry, a positive anomaly can be expected. If soil overlies the limestone, as in Figure 2, the result is a compounding of the effects of the two media.

The Geophysics Group previously mapped NP responses over caves in the Ozarks, Kentucky and Nevada; however, polarities of the anomalies did not always conform to the rules just outlined (Lange & Quinlan, 1988). While the illustrated responses along two lines over Cave Valley Cave, Nevada exhibited sharp positives superimposed on broad lows, typical of a limestone overlain by alluvium, there occurred here at most only a few centimeters of soil over the rock, which for the most part outcrops.

At Kartchner Caverns, we made multiple NP observations at intervals from about 2 to 15m, or 6 to 50ft, on all the lines, plus two intermediate lines over the mapped caverns. We utilized the long-line method, wherein a common base electrode (non-polarizing) is established, from which a long wire is unreeled. The wire connected to a high-impedance (1000MΩ) multimeter and a roving electrode.

The character of the NP response changed noticeably at the limestone/alluvium contact, with the signal and noise levels diminishing on the soil. As at many lithologic boundaries, we can expect crossover-type anomalies at this contact, illustrated in Figure 3 by a positive and a negative lobe straddling the contact. The NP method also detected zones of underflow within the washes as negative infiltration anomalies. Particularly strong negatives may signify sites of increased infiltration induced by the presence of underlying openings in soluble bedrock. Another anomaly type is illustrated by Figure 4. These anomalies evidence infiltration laterally (into the banks) as well as vertically; these are compared with anomalies over riverbeds in the Caucasus.

Not knowing for certain what kind of a signal to expect over a cave in the Kartchner environment, we ran a short line over a shallow blind passage leading from a sinkhole. Here the response turned out to be symmetrical but complex, consisting of a twofold high-within-a-low over the passage (Figure 5). A similar signature was obtained from a second pass over the cavelet.

Over the mapped caverns, we observed a compound expression also; in this case one or two positives superimposed on a broad low, between the Big Room and the Subway Passage (Figure 6). Similar features appeared on successive lines elsewhere across the carbonate outcrop, so that distinct trends could be recognized. We regard these more generally as structural controls--contacts, faults, or bedding planes; however, these are the likely loci for infiltration

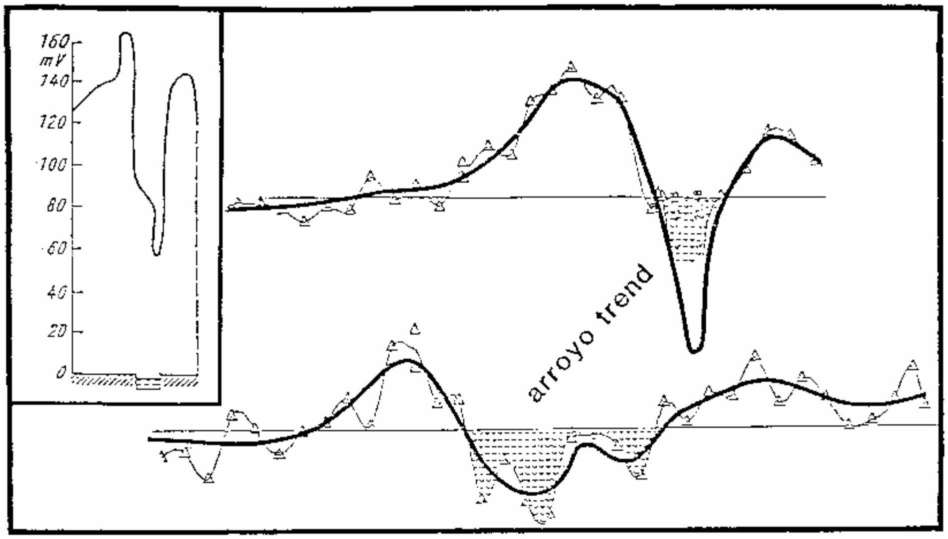

Figure 4. Infiltration anomalies along Guindani wash, showing the effect of underflow infiltrating laterally as well as downward. Inset: Similar anomalies on a larger scale: a riverbed expression from the Caucasus (from Krajew, 1957).

and solutional activity that give rise to caverns.

Potential measurements underground in the front section of the caverns revealed that the cave ceiling was, without exception, positively charged relative to the floor, with the difference ranging between +14 and +39 millivolts. This electrical gradient conforms to those measured in the two other cave systems in which we have made subterranean measurements (Lange & Quinlan, 1988).

GRAVITY SURVEYS

Gravity surveys utilize a gravimeter to measure variations in the gravitational field along the earth's surface (cf., Telford, et al., 1976). The field is expressed in terms of the acceleration of gravity acting on a unit mass, and is measured in *gals* (named for Galileo). At the earth's surface, the acceleration of gravity is approximately 980cm/sec^2, or 980gals. In exploration work, more practical units are the *milligal* (10^{-3}gal), or *microgal* (10^{-6}gal).

Spatial changes in gravity come about from changes in elevation, latitude and topography, for which we must make corrections. Earth tides and instrument drift produce temporal variations that must be subtracted from the observed data. Of particular importance to gravity surveys is the effect of density irregularities in the subsurface--variations in lithology, structure, groundwater level and the presence of voids. Because of this density effect, the gravity method is valuable in the mapping of faults, salt domes, bedrock relief, mineralization and caverns. Figure 7 illustrates the effect to be expected at the surface from an idealized two-dimensional cave gallery. Because the cavern represents the absence of rock, or a

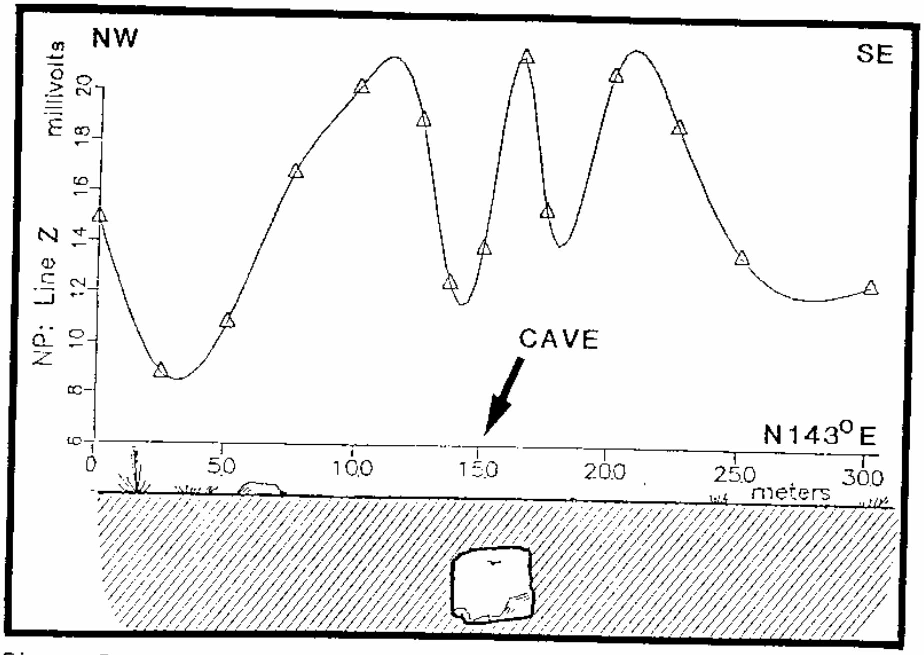

Figure 5. Compound natural-potential response over a shallow cave passage. Passage does not connect with main caverns.

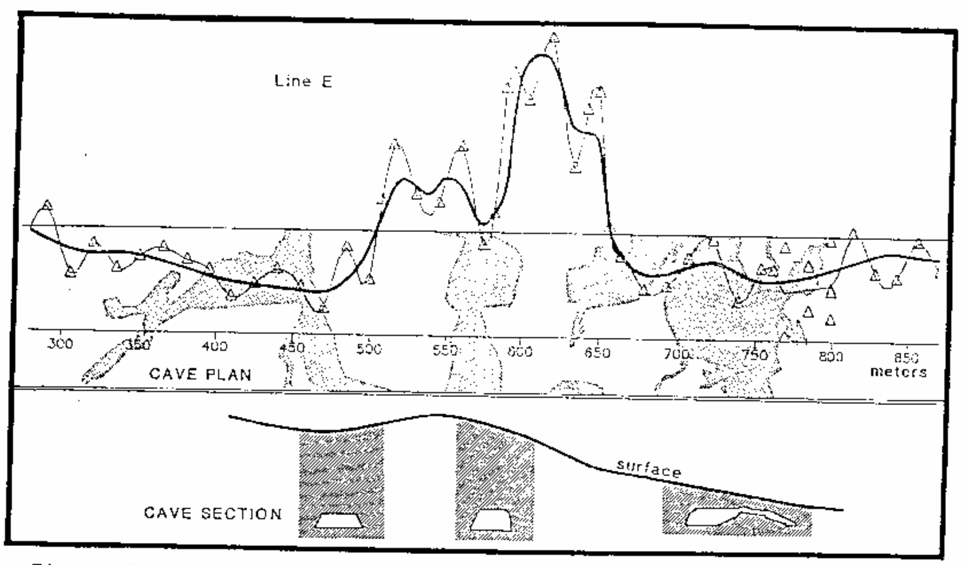

Figure 6. Natural-potential response (heavy curve = smoothed data) over Kartchner Caverns. Note that the surface expression is derived from void space off to the side of the line as well as directly underneath. The anomaly here is a compound effect of the caverns as a whole--consisting of a positive or positives superimposed on a broad low (or lows).

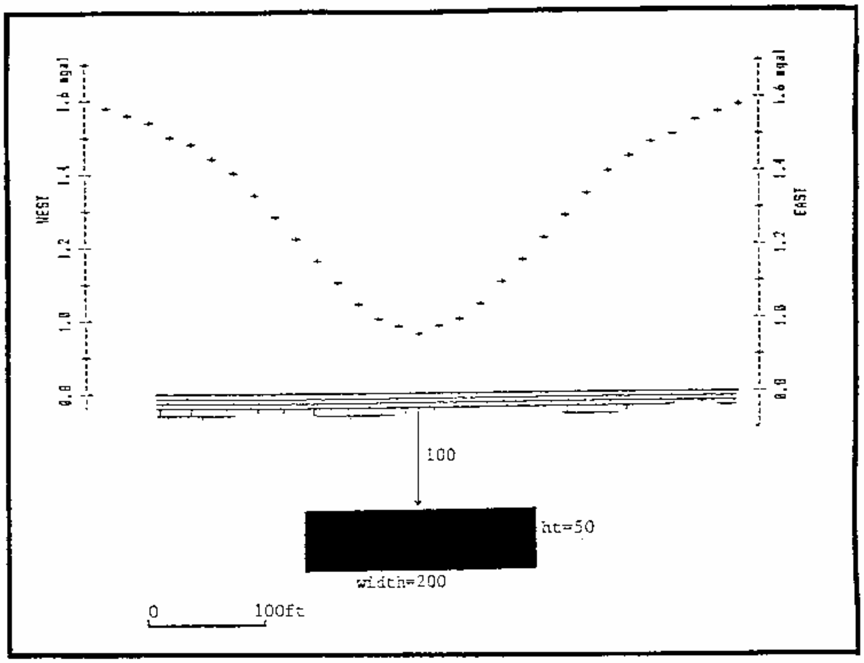

Figure 7. Gravity model of a 2D cavern in dolomite, yielding a 0.6mgal anomaly.

mass deficiency, it appears as a negative anomaly (Neumann, 1967). In the Kartchner environment of rather severe topography, this -0.6mgal feature is resolvable. Intuitively, the smaller the void and the deeper it lies, the smaller will be its expression at the surface; thus, small anomalies resulting from minor or deeper caverns could fall within the range of error of the instrument or of the terrain-correction process.

For the Kartchner survey, a LaCoste & Romberg Model G gravimeter was employed, which provided accuracy greater than that obtainable from the terrain-correction process in this topography. Readings were taken on all of the 13 survey lines at intervals of 100 and 200ft. Over the mapped caverns, the intervals were reduced to 50ft. Topography within 2m of the each station (the *A-zone*) was mapped in the field, and terrain corrections were made out to 21km.

Gravity readings over the alluvium provided sufficient detail that a map of minimum depth to bedrock could be generated (Figure 8). Ed Gustafson of The Geophysics Group carried out the computations using a mathematical inversion process of Cordell and Henderson (1968). Control was provided by the Highway well, which did not encounter bedrock within its 790ft depth. A minimum depth here of 800ft, resulted from a density contrast of $-0.2 g/cm^3$ between valley fill and bedrock; hence, the resulting contours represent a minimum rather than an absolute depth. These show a buried ridge east of the southern carbonate ridge, which may be a continuation of the ridge beneath the alluvium. South of the caverns, we note an area of shallow bedrock; while to the southeast appears a broad "channel" in the undulating bedrock topography. Cross-sections of this surface bring out the range-front faults demarcating the mountain block from that of the down-dropped valley. An apparent "hole" in the basement along the eastern edge of the map may signify a sharp drop-off in bedrock, or it may be the result of some defective data points. Along the western boundary of the Park, the results fit the data from three of four wells known to have bottomed in Pinal schist (Graf, 1989).

On the carbonate outcrop, gravity detected two of the three main galleries of the cave, where crossed by the survey line (Figure 9. In addition, 14 other gravity lows were mapped. Four of these were associated with significant NP anomalies; all of the lows are likely candidates for unmapped solution caves.

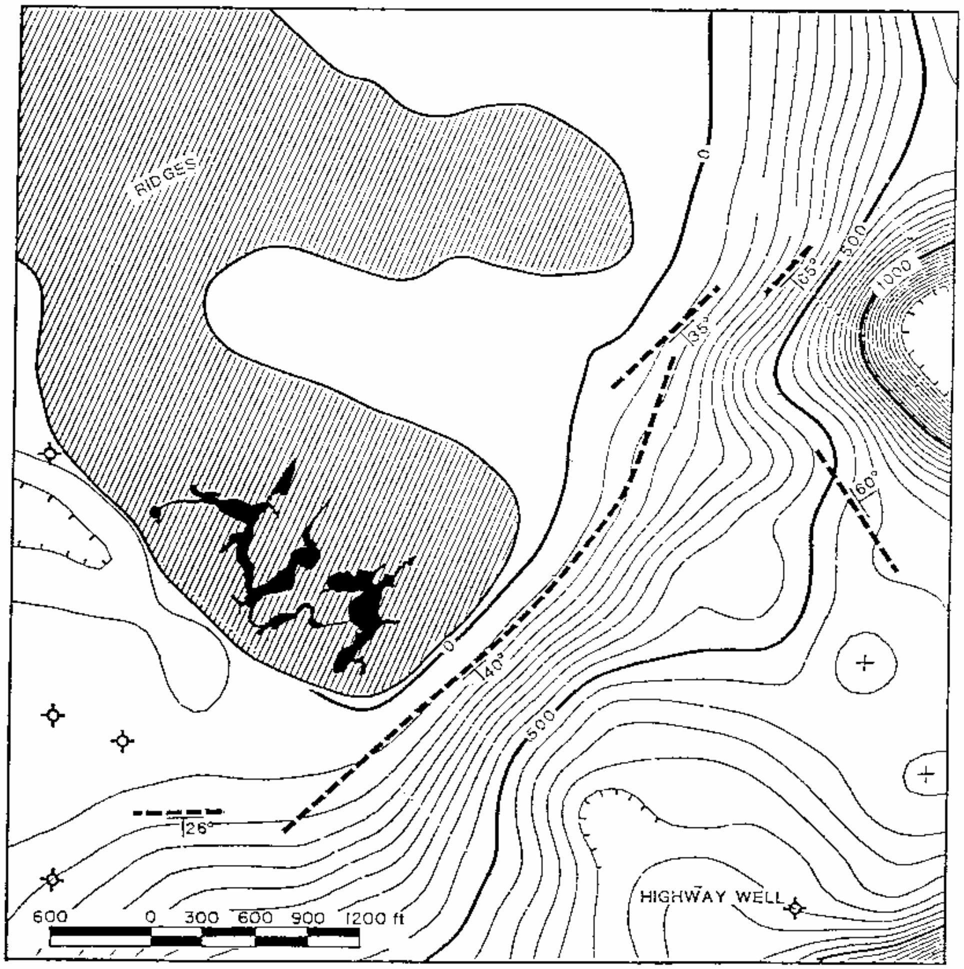

Figure 8. Map of Kartchner Caverns State Park showing cavern outline, water wells, carbonate outcrop and contours of depth-to-bedrock (in feet) and faults, as deduced from gravity data.

PLANNING AND DEVELOPMENT

For planning purposes, the deduced bedrock topography beneath the valley sediments provides a useful guide to the siting of water wells, Park structures, waste facilities and paved roads. Since groundwater tends to flow along the surface of the relatively impervious schist, the contours provide an index to depth to water over this rock type. This is the case in the southwest portion of the Park, where wells have tapped bedrock. The more abundant water supply can be expected in the alluvium-filled channels where greater storage capacity is probable.

Because of the similar densities of schist and carbonate rocks, we have not been able to map the boundary between these two media in the subsurface. This can possibly be done using a magnetometer or by drilling in the region of shallow bedrock south of the caverns. It is important to know the underlying rock type, because *if* soluble carbonates underlie this area, they are likely to be karsted; i.e., to contain solution caves and conduits along which groundwater can flow freely. In a karst environment, contaminants undergo little or no filtration in their vertical descent, and can be transported rapidly by underground streams (Lange & Quinlan, 1988). Furthermore, wells tapping solution conduits may affect the groundwater regimen of the caverns, while waste materials seeping into the conduit system may eventually reach the cave and contaminate it.

Thus, until the limits of the carbonate bedrock have been ascertained, wells, structures and roads should be sited either in the vicinity of the western boundary where schist bedrock has been exposed by wells, or in areas of thick

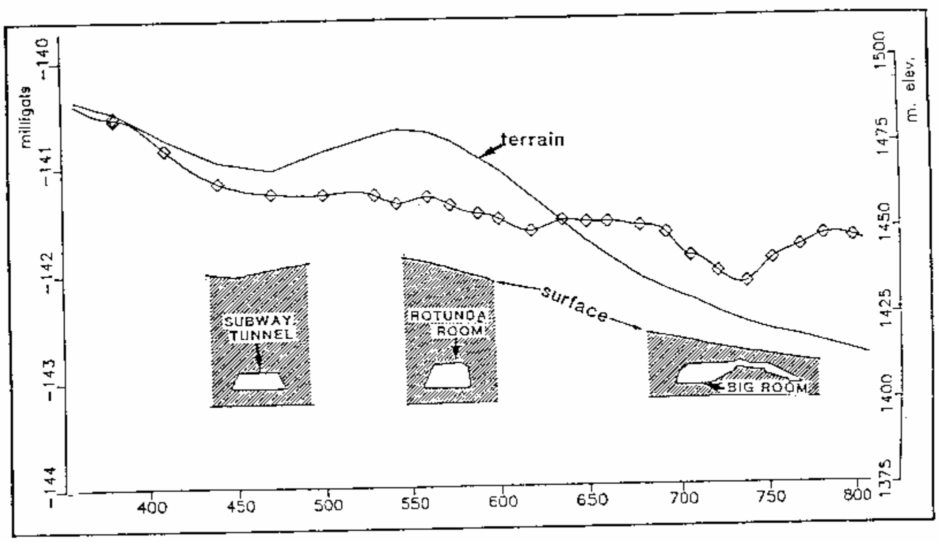

Figure 9. Gravity response over the caverns. The effect at the surface derives from void space adjacent to the line as well as that directly beneath (cf., Figure 6.) Negative anomalies resulted from the Subway Passage (and adjoining Hill Room) on the right, and the Big Room on the left. The Rotunda Room (center) could not be adequately resolved.

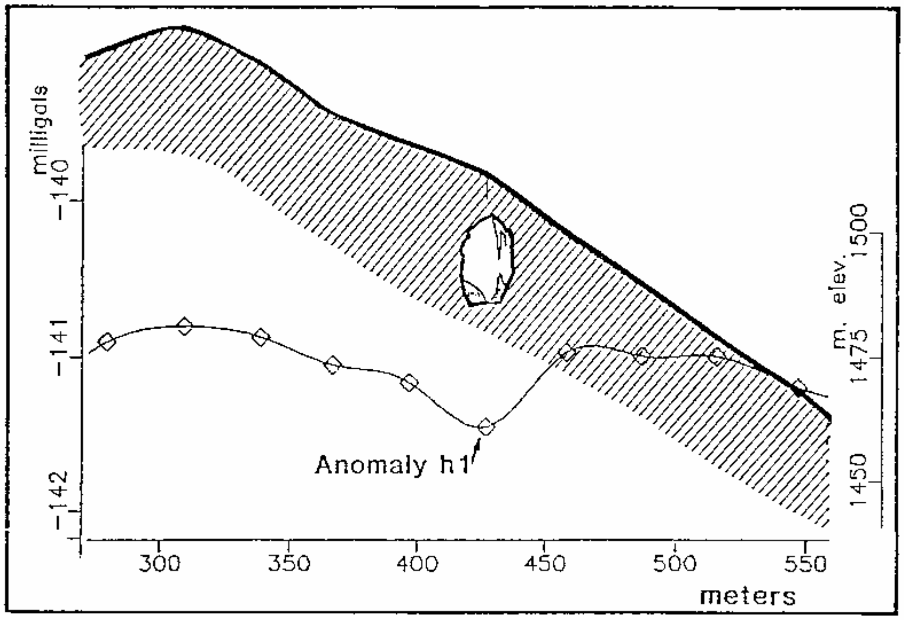

Figure 10. Gravity anomaly beyond mapped caverns, and one cave model that could produce such a feature. (Elevation scale exaggerated.)

alluvium, where an adequate filtration medium intervenes. Waste-disposal facilities should be sited in the valley and down-gradient of any wells and shallow carbonate aquifer.

Meanwhile, on the carbonate outcrop, a number of small gravity anomalies likely express underlying cave passages (Figure 10). These are prospective sites for tunneling to provide visitor access. We recommend some detailed gravity segments here to confirm the anomalies and facilitate their interpretation. Gravity lows elsewhere on the ridges may characterize peripheral subterranean cavities, related to, but not necessarily connected to the main caverns.

ACKNOWLEDGMENTS

The Kartchner project has been one of the most fascinating assignments that we of The Geophysics Group have undertaken. We thank the Arizona State Parks Department and ACPI for inviting us to participate in the study, and hope that our results will prove valuable in the planning phase and ensuing development of this remarkable resource.

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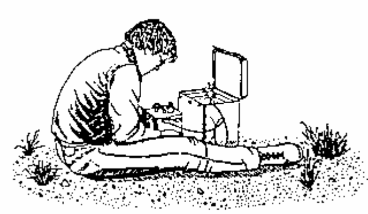

BIOGRAPHICAL SKETCHES

Arthur L. Lange is President of The Geophysics Group, a firm engaged in applied geophysics for exploration and environmental research. Mr. Lange holds a B.Sc. degree in Physics from Stanford University and has served as geophysicist for Newmont Exploration Ltd and SRI International and was Chief Geophysicist for AMAX Geothermal. He continues research in karst hydrology and is a Contributor to the current edition of *Encyclopædia Britannica* on the subject of *Caves and Cave Systems*. As a Registered Geophysicist, he is directing the geophysical studies at Kartchner Caverns State Park. In addition, he is presently developing methods for mapping caves and karst conduits from the surface.

Robert H. Buecher, P.E., R.L.S., is Project Manager for Arizona Conservation Projects Inc., the organization responsible for the environmental monitoring and technical studies at Kartchner Caverns State Park. As a registered Professional Engineer and Land Surveyor, he has completed the design of numerous water, sewer and highway projects and has managed roadway-bond and water-treatment plant designs. He was also Design Engineer for a 1.7-mile urban arterial for the City of Tucson. Mr. Buecher has been involved in many different cave-related projects as Chief Cartographer and Area Manager for the Cave Research Foundation. This service has included work in Grand Canyon and Carlsbad Caverns National Parks as well as Kartchner Caverns, where he is in his fifth year of active participation.

Phillip A. Walen is Project Geophysicist and Hydrogeologist with The Geophysics Group. He has 17 years of experience in applied geophysics, including intermontane-basin modeling, interpretation of high-resolution seismic data from platform sites in the Bay of Campeche, Mexico and the first complete gravity survey of Guam. He has managed large-scale hydrogeologic investigations relating to contamination and groundwater resource evaluation. He holds a B.Sc. degree from the University of Arizona and is a Registered Geophysicist with the State of California.

ARIZONA CONSERVATION PROJECTS INC.

Arizona Conservation Projects, Inc. (ACPI) was formed in January 1988 by the individuals who discovered and explored Kartchner Cavern. It is dedicated to the preservation of the cave and the education of the public about its features. As a private tax exempt corporation, its resources are directed exclusively into activities on behalf of Kartchner Cavern. ACPI was created out of the perception of the need for lasting stewardship of the cave. To this end the role of the discoverers and ACPI has changed to meet new requirements as the Kartchner Caverns State Project evolves.

The members of ACPI have been intimately involved in this project starting with the discovery and initial exploration of the cave in 1974. Early in the exploration it became apparent that due to the pristine nature and unique features of the cave it would require active protection to preserve its contents. The first steps were to establish trails, designate off-limits areas within the cave and enlist the landowners. As time passed it was realized that the only true long term preservation of the cave lay in opening it to the public. It was decided that public ownership by the State of Arizona offered the best avenue. Through the efforts of the original discoverers and the Arizona State Parks Department, the cave was made a state park in April, 1988.

The progress made to date owes much to the determination and vision of the original explorers. Over the years as the project evolved, the number of people involved has increased and other organizations have become involved. The role of ACPI has also evolved from a few individuals to a coherent, structured organization dedicated to providing the best available knowledge about the cave.

The Geophysics Group

THE GEOPHYSICS GROUP is a diversified geophysical firm engaged in data acquisition, processing and interpretation, leading towards the discovery and evaluation of mineral, petroleum and geothermal resources. We also apply geophysical methods to the solving of engineering and geohydrologic problems.

Services offered

Among the exploration and engineering services offered are:

* Gravity and magnetic surveys
* Active electrical surveys [including IP/resistivity and electromagnetics]
* Passive electrical surveys [including natural potential (SP) and VLF-EM]
* Magnetotelluric and audio-MT modeling
* Mineral & engineering seismic studies
* Microearthquake monitoring
* Near-surface temperature surveys

In addition, geologic, hydrologic and research studies are conducted, along with custom software development for specific tasks. Reporting is tailored to the client's needs, either in the form of listed data, maps and profiles, or as final presentation-style reports.

Emphasis on innovation

The Geophysics Group maintains an ongoing R&D program in order to stay in the forefront of geophysical processing and interpretation. Among these, the PREDICTOR-CORRELATOR processing system for on-site interpretation of induced polarization and resistivity data provides multicolor cross-sections in terms of real depth, suitable for targeting. Our G-BUG technique utilizes joint-inversion technology of two or more surface electrical data sets to generate equivalent electric logs of the subsurface. POLARVIEW provides 3-D views of the subsurface electrical properties from MT and AMT data. Current field developments in environmental techniques include the detection and mapping of karst conduits and coal-mine fires.

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