GEOPHYSICAL STUDIES AT KARTCHNER CAVERNS STATE PARK, ARIZONA

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Geophysical studies over Kartchner Caverns State Park mapped structure and groundwater patterns beneath valley alluvium and determined the geophysical expression of the caverns at the surface. Three techniques were employed: electromagnetics (EM), gravity, and natural potential (NP). Electromagnetic traverses in the area failed to detect the voids, owing to the very low conductivity of the carbonate rock. On the other hand, the EM method succeeded in defining the boundary between carbonate rock and alluvium, and in detecting the high-conductivity underflow beneath the drainage system. Resolution of the gravity survey over outcrop was limited to ~0.1 mgal, due to severe terrain effects. Nevertheless, two of the three major cavern passages were expressed as gravity lows at the surface, and fifteen additional small gravity anomalies could be the effect of fracture zones or unexposed caves. East of the carbonate block, the gravity profiles delineated the range-front fault and afforded interpretations of bedrock structure beneath valley fill.

Natural-potential profiles, coincident with those of the gravity survey, produced a prominent compound anomaly over the mapped caverns. The 55 mV NP high was flanked by broad lows measuring ~15 mV over two of the main cavern galleries. The high was incised by a third low over a middle passage of the caverns. The lows are tentatively attributed to filtration downward toward the cave ceilings; the highs, to evapotranspiration from a deeper groundwater reservoir. Elsewhere over the outcrop, continuous NP trends are the likely expressions of faulting and fracturing, possibly accompanied by solution activity.

During September and October 1989, The Geophysics Group, under contract to Arizona Conservation Projects, Inc. (ACPI), carried out geophysical studies over Kartchner Caverns State Park. The caverns consist of three main chambers and connecting passages, whose ceilings are beautifully decorated with dripstone and flowstone (Hill 1999). The caverns are situated in west-dipping Paleozoic carbonate rocks of an outlier on the east flank of the Whetstone Mountains in Cochise County, Arizona. The State Park, which surrounds the caverns, consists of one section of land (2.23 km²) located 13 km south of the town of Benson (Fig. 1). The purpose of these investigations was to map structure and groundwater beneath the alluviated portions of the park and to characterize the surface geophysical expressions of the mapped caverns and other likely voids beneath the areas of rock outcrop. Three geophysical methods were employed: electromagnetics (EM), gravity, and natural potential (NP). Results of the work were documented in a project report (Lange *et al.* 1990a) and summarized in a paper by Lange *et al*. (1990b).

SURVEY GRID

The layout of the geophysical grid consisted of thirteen primary traverses, designated *A* through *M*, oriented in a direction 127°(NW-SE). The lines were ~150 m apart and extended between State Route 90 on the east and the south boundary of the Park northwestward to the west and north boundaries of the park (Fig. 1). The EM measurements were made along Lines D, E and F, while the gravity and NP surveys occupied the entire grid. In addition, two intermediate natural-potential traverses—Lines X and Y—were run over the area of mapped caverns.

ELECTROMAGNETIC SURVEY

The EM study was undertaken in the hope of mapping low conductivity zones in bedrock corresponding to voids, and to

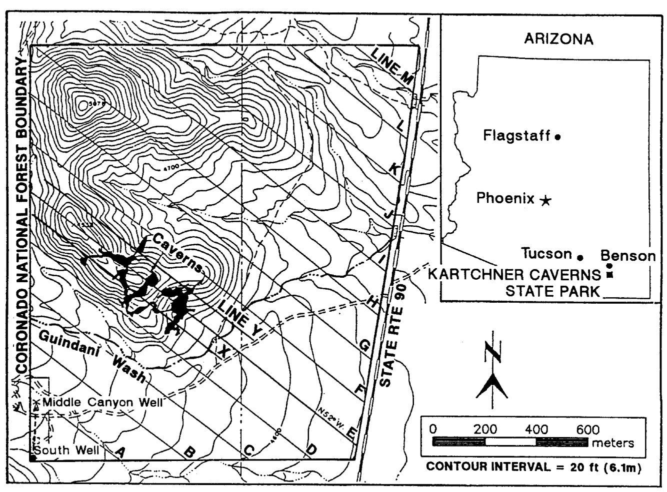


Figure 1. Location map of Kartchner Caverns State Park, showing the cavern configuration and layout of the geophysical lines. Base map from Wrucke & Armstrong (1984).

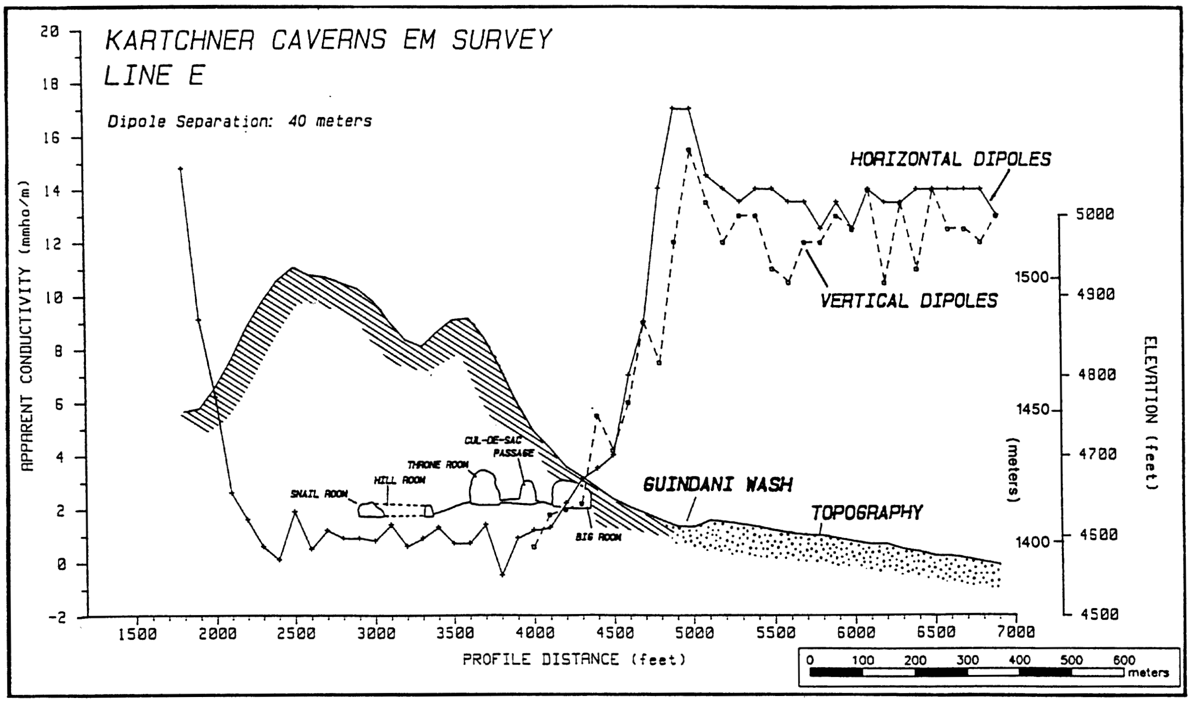


Figure 2.

Electro-magnetic profile on Line E, illustrating the contrast between the high conductivity valley fill and the very resistive carbonate rock of the hill above the caverns. Note the conductivity peak over Guindani Wash.

determine if water-table depths could be resolved beneath the alluvium. A Geonics Ltd EM-34XL Terrain Conductivity Meter produces a time-varying magnetic source field by energizing a portable transmitter coil (McNeill 1990). This source field causes a system of electric eddy currents to flow in the ground, whose strengths depend on the electrical conductivity of the earth materials. The eddy currents, in turn, generate secondary magnetic fields that are detected by a receiver coil at the surface. A coil spacing of 40 m was adopted on Lines D, E and F, while a spacing of 20 m was also employed on Line E.

The background response of 0-2 mS/m of the limestone was at the lower limit of the operational range of the instrument; hence, it proved not feasible to resolve the cavern voids with the method. On the other hand, the EM data were effective in defining the boundary between limestone and alluvium and the high conductivity underflow zone of Guindani Wash, south and east of the rock outcrop (Fig. 2). A calibration traverse between Middle Canyon Well and South Well (Fig. 1), having water depths of 20 and 7.3 m, respectively, showed a net change of +3.5 mS/m in the direction of shallower water, demonstrating that relative changes in groundwater depth of 2-3 m (corresponding to an instrumental resolution of ±0.5 mS/m) could be detected using the coils in horizontal mode.

GRAVITY SURVEY

A gravity meter measures variations in the gravitational field at the ground surface, which correspond to density changes in the subsurface. Density variations come about, for example, when crossing from soil to rock and from less dense sedimentary to denser volcanic rocks. By virtue of the absence of rock, air- and water-filled caves are ideal targets for exploration by the gravity method (Neumann 1967). At Kartchner Caverns, a gravity survey was implemented to detect likely unmapped voids in the bedrock and to delineate geologic structure beneath the alluviated portion of the Park.

Underlying voids give rise to corresponding gravity anomaly lows (expressed in milligals) at the surface. Because of the severe variations in relief over the survey grid, errors in the estimated terrain effects were as great as 0.1 mgal. For this reason, the normal exploration instrument—a LaCoste & Romberg Model G gravimeter—was employed, rather than a machine of greater precision applicable to a *microgravity survey* in more gentle terrain. ACPI personnel measured station coordinates and elevations to within 1.5 cm using a transit and spirit level. Terrain elevations were mapped within a radius of 2 m of each gravity station and combined with measurements from a topographic map to generate complete Bouguer profiles and the corresponding anomaly contour map supplied in the project report (Lange *et al.* 1990b, Pl. VI).

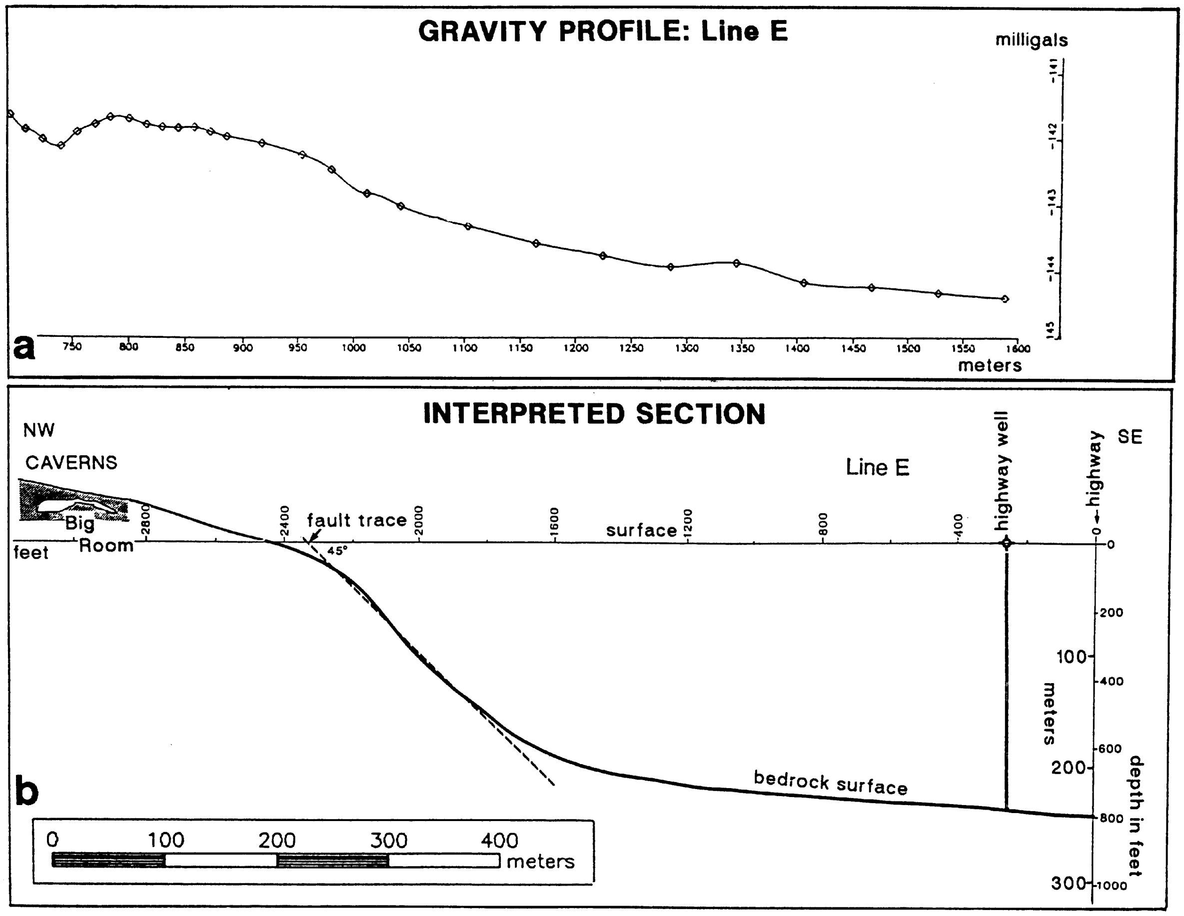
A prominent feature of the final gravity profiles is a sharp gravity gradient delineating the range-front fault system (Fig. 3). By applying an inversion procedure for interpreting gravity data (Cordell & Henderson 1968), profiles of bedrock structure were generated for each of the gravity traverses, utilizing a density contrast of 0.2 mgal. These profiles were intended to aid in the siting of roads, water wells, and a waste disposal facility at the Park.

On bedrock, gravity lows typical of voids turned up at a number of places, including the cavern site itself. Figure 4 shows the gravity profile on Line E over three of the cave pas-

Figure 3.

3 a) The eastern portion of the gravity profile along Line E between the Big Room of Kartchner Caverns and a well in the valley.

3 b) Configuration of bedrock surface beneath valley fill on Line E, as derived by modeling of the gravity profile.



sages. The largest expression (-0.65 mgal) occurred over the Big Room, whose minimum ceiling depth is only ~8 m. Two-dimensional modeling, utilizing the Talwani algorithm (Talwani *et al*. 1959) and a rock density of 2.67 g/cm³, yielded a calculated anomaly of -0.50 mgal. A marginally detectable gravity low of only -0.13 mgal appeared over the 55-m deep Subway Passage/Hill Room, where modeling produced a theoretical anomaly of only -0.10 mgal. The intervening Rotunda Room, at a depth of 58 m, produced no resolvable gravity anomaly at the surface, while modeling yielded a value of -0.1 mgal. The discrepancies between the observed and calculated anomaly amplitudes are very likely due to the fact that the cave passages open out into larger galleries beyond Line E, while the modeling procedure views the passages as simple tunnels.

Fifteen gravity anomalies having amplitudes ranging between -0.15 and -0.50 mgal were noted elsewhere over the carbonate outcrop. While some of these may relate to fractures or filled fissures, four were associated with natural-potential anomalies and are likely the expression of underlying voids (Lange *et al.* 1990a).

Natural-Potential Survey

The flow of water underground generates minute dc electric currents that can be measured at the ground surface as a voltage, or *streaming-potential* distribution. This *electrokinetic* phenomenon has been demonstrated in the laboratory by passing water through a container of sand and measuring voltage and pressure differences along the flow path (Ahmad 1964). The resulting streaming potential is linearly proportional to the driving pressure. Similar results have been obtained from aqueous solutions flowing in simulated fractures (Bogoslovsky & Ogilvy 1972) and in open tubes up to 2.54 cm (1 in) in diameter (Binder & Cernak 1963).

In field practice, differences of potential along ground-surface traverses are measured in millivolts (mV) using sealed non-polarizing electrodes, a color-calibrated cable on a reel, and a high-impedance multimeter (a meter having a 1000 MΩ input impedance used for desert work). One electrode is fixed near the center of the survey and implanted in soil at shallow depth, while a second staff-mounted electrode samples the earth in shallow holes at regular (typically 3 to 4 m) intervals along the survey lines. Due to temperature variations of the electrodes and soil, drift measurements must be made periodically at the base electrode, and a corresponding correction applied over time to all of the data readings along a line. In moist and hilly terrain, elevation corrections may also be necessary, though they were not needed at the Kartchner site. The corrected survey data are then plotted out as profiles, line-by-line, and as areal maps of natural-potential contours. The more

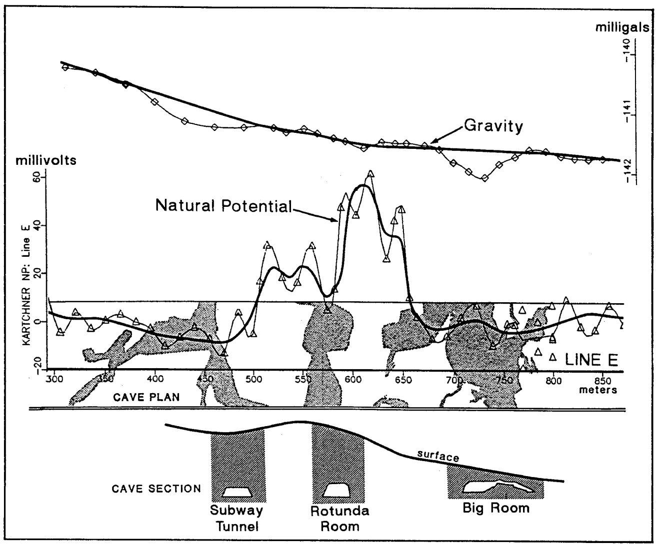


Figure 4. Gravity and natural-potential profiles over three portions of Kartchner Caverns. The heavy curves are smoothed from the original data (fine curves). The caverns are shown partially in plan view and as cross-sections beneath Traverse E. NP lows occur over the void space of the three galleries, while highs appear over the intervening rock. Gravity lows are associated with the Big Room and Subway Tunnel. Void space off to the side of Line E contributes to both the NP and gravity lows.

difficult task of interpreting the results must then be undertaken.

Natural-potential anomalies (both positive and negative) have been observed over air-filled caverns (Lange & Kilty 1991), and attributed to the downward filtration of meteoric water through the more permeable rock comprising the cave roof. Under hot, dry conditions, typical of summer at Kartchner Caverns, evapotranspiration and capillary flow can transport water upwards towards the surface, giving rise to corresponding inverted NP anomalies.

Laterally moving water, as in the case of a cave stream, has been found to generate a streaming potential generally, but not always, positive in the direction of flow (Kilty & Lange 1991). This effect gives rise to the more complex (sombrero-like) anomaly observed over karst springs, where not only the ends of the flow system become polarized, but the walls of the flow path as well.

At Kartchner Caverns, NP data collected from the sparse soil on outcropping rock produced very noisy records due to high contact resistance and solar heating of the ground. The NP work on the hills had to be suspended in the afternoons and deferred to the cooler morning hours. Collecting data in the relatively level valley area was easier, due to greater soil moisture and some shading by vegetation. Along the arroyo of Guindani Wash, distinct M-shaped anomalies were encountered (Fig. 5), wherein downward percolation (alternatively underflow) may account for the central lows, while lateral filtration into the banks may explain the positive shoulders of the anomalies.

Figure 4 displays a portion of the NP profile obtained on Line E over the cavern system. The overall anomaly is a compound affair (a double sombrero) made up of three NP lows over particular cavern passages, and two exaggerated highs associated with the intervening rock walls. The peak-to-peak amplitude of the anomaly measured 70 mV.

Without additional NP measurements made both underground in the caverns and above ground during winter conditions, it is difficult to conceptualize the electrokinetic mechanisms contributing to the complex NP expression registered at the surface. Considering that the cavern system represents the solutional enlargement of a fractured carbonate mass, one can deduce that downward percolation towards the cavern ceiling (evidenced by the stalactite deposits) brings about the observed NP lows. The intervening fractured rock, meanwhile, may serve as pathways for upward capillary movement of water derived from a groundwater reservoir beneath the cavern floor which at times rises to flood portions of the caverns. This upward water movement is locally interrupted by the presence of the galleries, leaving the NP highs coincident with the underlying wall rock and absent over the void space.

In addition to the NP anomalies associated with the mapped caverns, three major anomaly trends could be traced across adjacent traverses. These trends may relate to fault- or fracture zones as well as to associated voids.

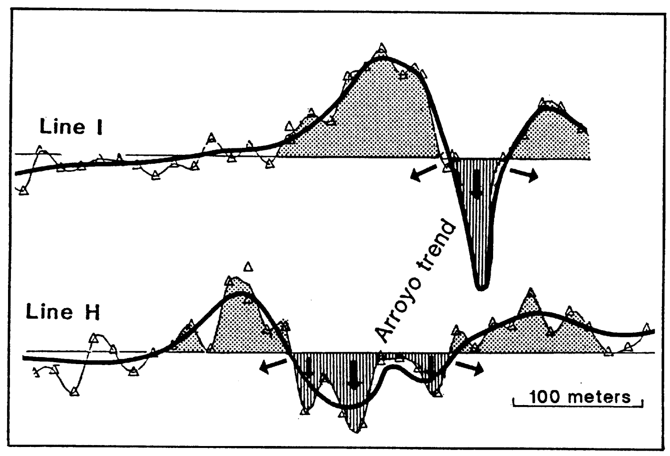


Figure 5. Natural-potential profiles over streams: Two typical profiles across Guindani Wash in Kartchner Caverns State Park. Water was not flowing at the surface at the time of the survey. The M-shaped (inverse sombrero-type) anomaly suggests underflow beneath the gravels of the wash and/or electrofiltration both downward into the channel and laterally into the stream banks.

Conclusions

Although the electromagnetic survey failed to detect voids in the carbonate bedrock, it successfully mapped the boundary between carbonate rock and valley fill where buried beneath soil cover. The gravity survey was most effective in mapping the bounding fault and contours of the bedrock surface beneath alluvium, facilitating the siting of water wells, roads and other construction features. Gravity anomaly lows over two of the cave galleries demonstrated the suitability of the method for detecting voids even in terrain as rugged as the carbonate outcrop at Kartchner Caverns.

The natural-potential survey mapped zones of underflow and infiltration in the washes, where its strongest expressions may be indicative of underlying voids. Structural features—faults and pervasive fractures, possibly enlarged by solution—were indicated by throughgoing NP anomaly trends. One of these anomaly trends is associated with the cavern system, which is expressed as a prominent compound anomaly consisting of highs associated with the interior cave walls, and lows related to the cavern galleries.

Acknowledgments

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