Charles G. Graf - Hydrogeology of Kartchner Caverns State Park, Arizona. *Journal of Cave and Karst Studies 61*(2): 59-67.

HYDROGEOLOGY OF KARTCHNER CAVERNS STATE PARK, ARIZONA

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Three distinct hydrogeologic systems occur within Kartchner Caverns State Park, Arizona, each in fault contact with the other two. The southeastern corner and eastern edge of the park is part of the large graben that formed the San Pedro Valley during Miocene Basin and Range faulting. A thick alluvial sequence fills this graben and contains a regional aquifer covering 1000 km². One well in the park penetrates this aquifer. The groundwater level measured in this well was 226 m below land surface (1167 m msl), which is 233 m lower than the lowest measured point inside of Kartchner Caverns (1400 m msl).

A pediment occupies a small part of the southwestern corner of the park. Structurally, this feature is part of the Whetstone Mountains horst rising above the park to the west. The pediment consists of a bedrock surface of Precambrian Pinal Schist overlain by a few tens of meters of "granite wash" sediments. Groundwater occurs at depths of 4-18 m below land surface in wells tapping the granite wash sediments. Data from these wells indicate that the zones of saturation within the granite wash sediments are probably of limited lateral extent and yield little water to wells. At the boundary between the pediment and the carbonate ridge containing Kartchner Caverns, the water table in the granite wash aquifer is 20 m higher than the bottom of the nearest known cave passage, located about 200 m to the east.

The arid carbonate hills occupying the northwestern part of the park are the erosional remnants of a fault block (the Kartchner Block) that was displaced downward with respect to the Whetstone Mountains horst to the west. Kartchner Caverns is wholly contained in a ridge of highly faulted Mississippian Escabrosa Limestone and cuts conspicuously across Escabrosa beds dipping 10-40° to the southwest and west. Meteoric water enters the Kartchner Block and Kartchner Caverns from infiltration of runoff in washes that border the block and from overhead infiltration of precipitation. A small amount of groundwater also may flow into the Kartchner Block from the schist pediment to the south. Response in the cave to these fluxes is slow. As calculated from past records, the probability of flooding in the cave in any one year is about 57%.

Kartchner Caverns State Park, Cochise County, Arizona, encompasses 223 ha of arid limestone hills and adjacent alluvial slopes at the base of the eastern flank of the Whetstone Mountains. These mountains steepen rapidly west of the park, cresting 5 km away at 2252 m msl (above mean sea level). The

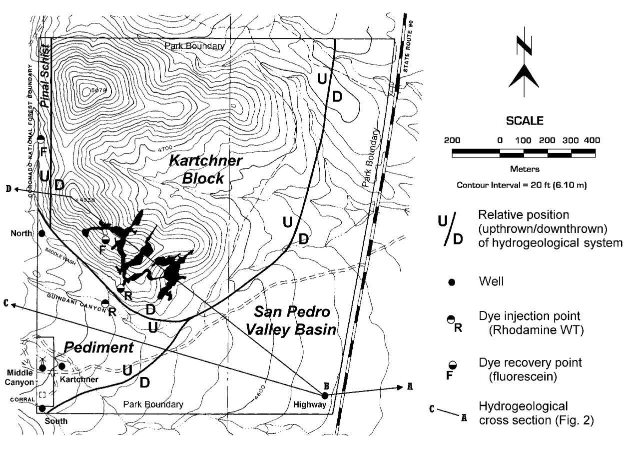


Figure 1. Hydrogeologic boundaries, well locations, and dye trace injection and recovery points.

park's highest point, a limestone hill near the northwest corner at 1548 m msl, overlooks the broad San Pedro Valley to the east. A pediment overlain by alluvium occupies the southern part of the park, forming the upper end of an alluvial plain that slopes gently to the San Pedro River 13 km to the east (Figs. 1 & 2).

Guindani Canyon cuts deeply into the mountains west of the park. Within the park, this drainage is an ephemeral desert wash (Guindani Wash) that flows along the limestone hills, separating them from the alluvium-covered pediment to the south (Fig. 1). Sporadic storm-water runoff from the Whetstones flows through the park in Guindani Wash, as well as calmer flows from undependable winter snowfalls. Runoff in Guindani Wash and its tributary, Saddle Wash, is the major source of water infiltrating to Kartchner Caverns.

FIELD INVESTIGATIONS

A variety of field activities have contributed to knowledge about the hydrogeology of Kartchner Caverns State Park. Graf (1989) inspected the park and surrounding area for water wells. Six wells were inventoried that bear on this report, four located within the park and two in adjacent areas (Figs. 1 & 2;

Table 1). Wellhead elevations were determined by spirit leveling, and water levels and well depths were measured. A continuous water level recorder was installed on the well nearest Kartchner Caverns (North Well) on 18 June 1988. Water levels in three other wells were measured weekly for more than three years. Water samples were collected from wells, and specific electrical conductance and temperature were measured. Pumping tests of three wells were conducted to assess well and aquifer yield for a potable water supply for the park (Johnson 1991; Buecher 1992).

Table 1. Selected water well data.

Well Name: Highway	Black	North	Middle Canyon	Kartchner	South
Arizona Well Identification Number:					
(D-18-20) 30cdc	(D-18-20) 21dcb	(D-18-19) 25dbb	(D-18-19) 25dcbl	(D-18-19) 25dcb2	(D-18-19) 25dcc
Well Depth (m):					
240.8 R	175.3 R	10.4 M	62.5 R	67.1 R	17.7 M
Well Diameter (cm):					
16.5	20.3	81.3	15.2	16.5	91.4
Construction Method:					
Drilled	Drilled	Dug	Drilled	Drilled	Dug
Date Constructed:					
ca. 1984	1976	1930s (?)	1948	1977	—
Use:					
Capped	Stock	Unused	Stock	Capped	Unused
Pump:					
None	Windmill	None	Windmill	None	None
Land Surface Elevation (m msl):					
1392.30	1286.9	1438.87	1436.61	1432.13	1427.59
Water Level Depth Below Land Surface, June 1989 (m):					
225.3	157.9	7.36	18.29	16.38	6.96
Elevation of Water Level, June 1989 (m msl):					
1166.47	1128.9	1431.40	1418.63	1415.76	1420.6
Water Temperature (°C):					
—	26.5	20.5	24.0	—	21.0
Specific Elec. Conductance at 25°C, (µS/cm):					
—	377	393	318	—	859

Notes:
1. Well depth measurements: R = Reported in driller's log, M = Measured during this investigation.
2. Samples for temperature and specific electrical conductance measurements were pumped from windmills and bailed from other wells.

Flows and floods in the normally dry surface drainages of the park were noted and correlated with water level changes in the wells and hydrologic observations in the cave. Precipitation and other data from the surface weather station augmented these observations, along with results of a cave drip water study, water quality measurements, and surface-to-cave dye tests (Buecher 1992). Jagnow (1990) mapped the subsurface geology of the cave, including paleocurrent directions based on analysis of solutional scallops. Hill (1992) and Jagnow (1990) interpreted 82 corrosion bevels in the cave as evidence of multiple late-stage flooding events. Lange *et al.* (1990) conducted surface geophysical surveys using natural potential (NP) profiling, electromagnetics (EM), and gravity techniques. These surveys further defined hydrogeologic relationships in the park and caverns.

REGIONAL HYDROGEOLOGIC SETTING

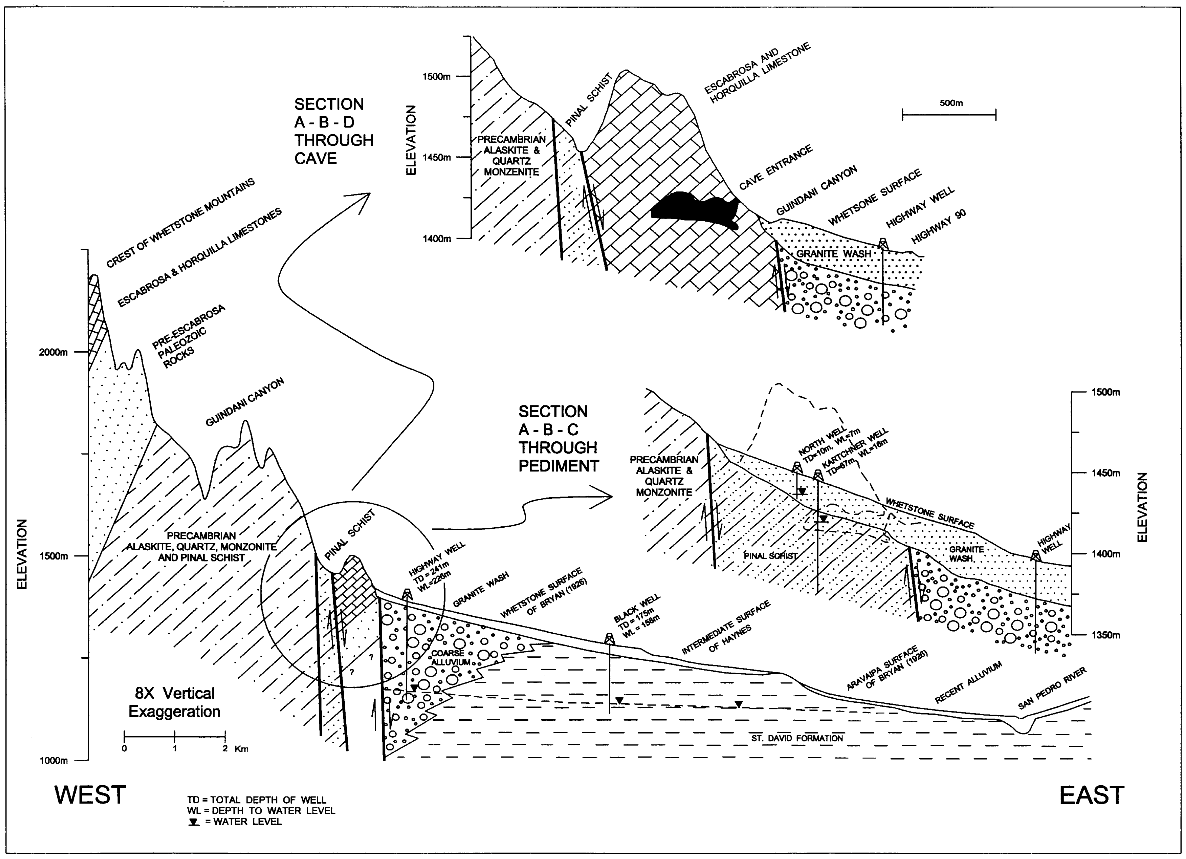
Basin and Range tectonism shaped the scenic landscape of the San Pedro Valley and bordering Whetstone and Dragoon Mountains. This tectonic event, the Basin and Range Disturbance, created a horst-and-graben topography throughout western and southern Arizona during Miocene time by uplifting ranges along generally north and northwest trends about 10-30 km apart and depressing the intervening basins. In the San Pedro Valley, the Basin and Range Disturbance probably began between 13 and 10 Ma and ceased between 8 and 5 Ma (Menges & Pearthree 1989).

As the San Pedro Valley graben subsided, alluvial sediments washed in, eventually accumulating to a substantial thickness. Most of these deposits are Pliocene and Pleistocene, fine-grained, fluvial and lacustrine sediments named the St. David Formation by Gray (1967). This sequence is overlain by younger deposits of "granite wash" and Holocene alluvium. The total thickness of the alluvial sequence is not known, but water wells drilled to over 300 m in depth near St. David bottom in sediments similar to those of the St. David Formation (Gray 1967). The St. David Formation extends across the basin and is bounded by the Basin and Range faults that coincide with the mountain fronts. Paleomagnetic dating of the St. David Formation indicates that the uppermost extant sediments were probably deposited soon after the Brunhes-Matuyama paleomagnetic chron boundary (Johnson *et al*. 1975), now dated about 780 Ka.

A well drilled for livestock watering in about 1984 at the southeast corner of the park establishes with some certainty the location of the main Basin and Range fault in the park area. This well, the Highway Well, was drilled to a depth of 241 m without encountering bedrock (see Fig. 1 for well locations and Table 1 for well data). The driller logged "fairly well cemented alluvial materials consisting of fragments of decomposed granite, limestone, and quartz" (Don Weber, pers. com.). These sediments probably represent a coarser, cemented facies of the St. David Formation deposited at the basin margin contemporaneously with fine-grained sediments deposited toward the basin center. The Highway Well is thus located on the basinward side of the main Basin and Range fault, placing the fault between this well and shallow wells penetrating bedrock 1.1 km to the west. Lange *et al.* (1990) and Lange (1999, Figs. 2 & 3) used data from these wells to calibrate a gravity survey that enabled further definition of bedrock topography and the location of Basin and Range faulting. The western limit of the San Pedro Valley hydrogeologic system, as depicted in Fig. 1, was drawn by the author to coincide with points in the gravity

Figure 2.

Hydrogeologic cross-sections through Kartchner Caverns State Park.



survey cross sections of Lange *et al.* (1990) where the underground bedrock surface steepens appreciably toward the San Pedro basin. This steepening generally was evident at a depth of about 30-60 m below land surface in the cross sections. Based on this delineation, the southeastern corner and eastern edge of the park (35% of the park area) lie within the San Pedro Valley hydrogeologic system.

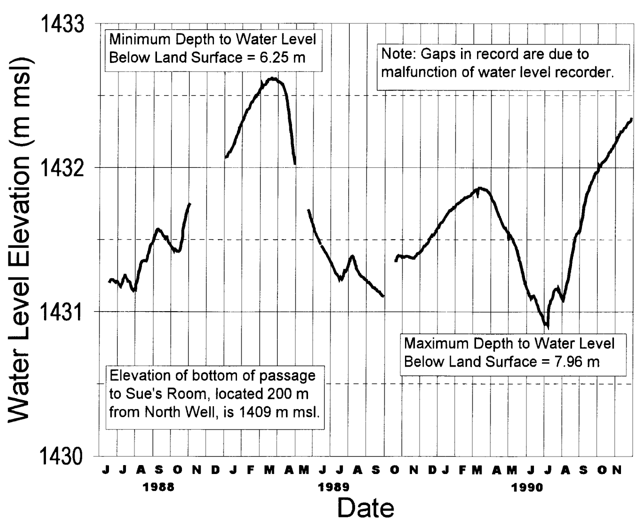


Figure 3. Hydrograph of water level in North Well.

The Highway Well was capped after drilling due to poor yield. A water level measurement of 226 m below land surface was obtained from the well on 24 June 1989, during this investigation. The water level in Black Well, located 4 km eastward in the San Pedro basin, was also measured on the same date and was 158 m below land surface. The altitude of these two water level measurements define a low apparent gradient (0.012), basinward potentiometric surface that probably represents the unconfined mountainward extension of the regional confined aquifer underlying the San Pedro River near St. David. The water level elevation in the Highway Well is 1166 m msl, which is 233 m below the lowest measured point inside of Kartchner Caverns (1400 m msl in the Red River Room). In 1991, the Highway Well was uncapped and tested again for production, but yield was too small for use as a park water supply.

HYDROGEOLOGY OF THE ALLUVIUM-COVERED PEDIMENT

The large number of wells constructed so close to Kartchner Caverns is fortuitous considering the paucity of groundwater development along the eastern side of the Whetstone Mountains. Originally constructed for stock watering and mining use, these wells have provided an understanding of the hydrogeology of the park that otherwise would have been largely speculative. This statement is particularly true in discerning the nature of the alluvium-covered pediment, which was penetrated by four wells (North, Middle Canyon, Kartchner, and South Wells; Fig. 1).

The pediment surface, mapped by Bryan (1926), extends along the base of the Whetstone Mountains and slopes eastward into the San Pedro Valley for a distance of about 6 km, where it is truncated by a lower erosional surface (Fig. 2). This pediment surface, termed the Whetstone Surface by most later investigators including Melton (1965), is underlain by bedrock near the mountains and older alluvial deposits toward the basin. In the park, the Whetstone Surface is at the top of a deposit of granite wash, which blankets an erosional surface of Precambrian Pinal Schist. Gray (l967), who applied the informal name "granite wash" to this deposit, describes it as reddish-brown alluvium resembling decomposed granite and consisting of alluvial fan, mud flow, and stream deposits. Melton (1965) suggested an Illinoian age (170–120 Ka) for the granite wash based on stratigraphic relationships, and a Sangamon age (120–70 Ka) for the development of the red soil that formed at the top the Whetstone Surface.

The thickness of the granite wash varies, but is not believed to be greater than a few tens of meters based on: 1) the depth of North Well and South Well (10.4 m and 17.7 m deep, respectively; Fig. 1), which appear to bottom at the schist contact; 2) the predominance of schist cuttings found beside the two drilled wells, Middle Canyon and Kartchner; and 3) the gradual slope of the schist surface exposed at the upper edge of the granite wash immediately west of the park boundary. Lange *et al.* (1990), using this information to calibrate the gravity survey, drew the trace of the main Basin and Range fault a short distance south of South Well. Based on this interpretation and the author's examination of the geophysical cross sections described in the previous section, the alluvium-covered pediment (Pinal Schist bedrock overlain by granite wash) comprises 9% of the park area (Fig. 1).

Non-pumping water table depths in the four wells penetrating the granite wash varied from 7-18 m below land surface in June 1989. Water table elevations of 1431, 1419, 1416, and 1421 m msl for the North, Middle Canyon, Kartchner, and South Wells, respectively, indicate that the water table probably lacks continuity over the area covered by these wells. In the North and South Wells, the source of groundwater is a zone of saturation above the schist bedrock surface within the granite wash sediments. The specific electrical conductance of water samples collected from the North and South Well differed considerably (393 µS/cm and 859 µS/cm, respectively), also suggesting a lack of connectivity of the saturated interval within granite wash sediments. At some locations, the granite wash may be unsaturated, and groundwater may occur within the schist below the alluvium contact.

Groundwater in the granite wash is assumed to flow in a generally southeast direction, consistent with the down dip direction of the underground Pinal Schist surface as depicted by Lange *et al.* (1990). East of the buried Basin and Range fault scarp, the groundwater level is more than 200 m deeper than west of the scarp. Groundwater flowing from the granite wash west of the scarp is assumed to contribute to recharge of the regional San Pedro basin aquifer east of the scarp. However, the volume of flow through the granite wash aquifer is very small based on tests of the Middle Canyon and Kartchner Wells. The Middle Canyon Well was drilled in 1948 to a depth of 62.5 m. This well, used for livestock watering, presumably penetrates the Pinal Schist to a significant depth. Despite the possibility of obtaining some groundwater yield from weathered or fractured schist, the well can produce only about 380 L/day (Buecher 1992).

The Kartchner Well was tested more rigorously to determine its suitability as a park water supply. This well, located about 120 m southeast of the Middle Canyon Well, was drilled to a depth of 67 m in 1977 and capped. It also probably penetrates the Pinal Schist to a significant depth. After pumping at a rate of 42.4 L/min for 100 min with a water level drawdown of 18.4 m below pre-pumping level, the water level recovered only 0.58 m in 1 hr. The well still had not fully recovered 8 days later (Johnson 1991). Based on these pumping test results and all other data, groundwater yield from the granite wash aquifer is considered to be very minor. This condition is probably due to a combination of small saturated thickness, low hydraulic conductivity, and limited lateral extent and continuity of the saturated zones.

KARTCHNER CAVERNS HYDROGEOLOGY

THE KARTCHNER BLOCK AND CAVE SOLUTIONAL LEVEL

Kartchner Caverns is wholly contained within a ridge of highly faulted Mississippian Escabrosa Limestone. This ridge is structurally part of a fault block (the Kartchner Block) that was displaced downward with respect to the Whetstone Mountains horst to the west. The fault along which displacement occurred is located a short distance inside of and parallel to the west boundary of the park. The fault juxtaposes Escabrosa Limestone in the downthrown Kartchner Block against Pinal Schist to the west (Thomson 1990). The Pinal Schist similarly is downthrown with respect to intrusive Precambrian alaskite along a parallel fault located a few hundred meters further to the west, a short distance west of the park boundary. On the upthrown side of this fault, the Whetstone Mountains rise steeply, exposing an upward sequence of outcrops of alaskite, intrusive Precambrian quartz monzonite, Pinal Schist, and nearly the entire Paleozoic section, including Escabrosa Limestone, near the crest of the mountains (Creasey 1967, Fig. 2).

The Kartchner Block comprises 54% of the total park area (Fig. 1). (A narrow zone of exposed Pinal Schist, comprising 2% of the park area, parallels the west boundary of the park immediately west of the Kartchner Block). Within the Kartchner Block, Kartchner Caverns cuts conspicuously across Escabrosa Limestone beds dipping 10°-40° to the southwest and west. The profile of the cave is nearly horizontal, reflecting its initial development under shallow phreatic conditions. The water table must have been stable between an elevation of

1408-1411 m for a long period of time in order for the cave to have developed across dipping beds, poorly permeable fault gouge, and quartz veins (Hill 1999b). The most plausible explanation for this cave profile is the presence of a regional water table that once extended from the San Pedro Valley basin into the Kartchner Block.

The regional water table responsible for initial dissolution of Kartchner Caverns could have existed no later than 70 Ka, nor earlier than 780 Ka based on stratigraphic and geomorphic relationships. The 1408-1411 m cave solutional level is inferred to be lower in elevation than the adjacent Pinal Schist pediment surface, interpreted from the total depths of the dug North Well and South Well. The bottom elevations of these wells are 1428 and 1410 m, respectively, which probably represent where digging stopped at the schist surface. This also places the cave below the level of the granite wash (Fig. 2), which is Illinoian (170–120 Ka) (Melton 1965). According to Melton, a red soil formed on the granite wash during Sangamon time (240–70 Ka). Therefore, it is possible that a regional water table in the San Pedro basin could have developed to a level high enough to extend into the granite wash and Kartchner Block at the 1408-1411 m level through Sangamon time. However, by early or pre-Wisconsin time (ca. 70 Ka), the San Pedro River had cut down through the Whetstone Surface (Haynes 1967), lowering the base level and, hence, causing a decline in the water table. This downcutting event establishes the youngest possible date for initial cave formation, because a high enough regional water table could not have developed thereafter. It is not known if the St. David Formation extended high enough above the 1408-1411 level to contain a regional water table at that level, but an erosional unconformity at the St. David Formation-granite wash contact indicates that St. David Formation sediments once extended higher (Gray 1967). Because these sediments were deposited after 780 Ka (Johnson *et al*. 1975), this date establishes the maximum age for initial cave dissolution. These minimum and maximum dates for dissolution of Kartchner Caverns are consistent with radiometric dates from speleothems reported elsewhere in this issue (Ford & Hill 1999).

SOURCES OF CAVE WATER

Determined by the water level measurement from the Highway Well, the regional water table southeast of the Kartchner Block is more than 200 m below any known passage in Kartchner Caverns. Current hydrologic processes in the cave are vadose. Meteoric water enters the Kartchner Block and Kartchner Caverns from infiltration of runoff in washes that border the block and from overhead infiltration from precipitation.

It is unlikely that much groundwater occurring in the granite wash aquifer flows toward the Kartchner Block. This assumption is based on the gravity survey (Lange *et al.* 1990; Lange 1999), which depicts the surface of the schist bedrock dipping to the south adjacent to the contact between the pediment and the Kartchner Block. Thus, most groundwater in the granite wash aquifer flows away from the block. However, some surface flow in Guindani Wash and its northern tributary, Saddle Wash, infiltrates into the granite wash aquifer immediately adjacent to the Kartchner Block and moves into the block.

The North Well provides further insight into the nature of the hydrogeologic relationships at this contact. This well, probably constructed in the 1930s for prospecting, was dug into the alluvium cover of the pediment less than 30 m from the south edge of the limestone ridge containing Kartchner Caverns. The water level in the North Well fluctuates between 6.3 and 8.0 m below land surface (1432.6 and 1430.9 m msl; Fig. 3). This level corresponds to a water table elevation that is more than 21 m above the bottom of the passage leading into Sue's Room (1409 m msl), which is located about 200 m from the North Well. However, water only enters Sue's Room if washes above are flowing, and then infrequently. Therefore, any groundwater moving from the alluvium-covered pediment into the Kartchner Block must drain deeper, bypassing all known passages of the cave. Although there appears to be no direct hydraulic connection between the water table at the North Well and known cave passage, measurement of the water level in this well is valuable as a sensitive indicator of the overall balance between groundwater recharge and discharge in the vicinity. Because there is no nearby pumpage of groundwater, rises and falls of the water level in the North Well reflect short- and long-term precipitation and climatological trends, which also affect cave microclimate and hydrology.

Meteoric water enters the cave through overhead infiltration of precipitation down faults and fractures, and on top of relatively permeable beds. The profusion of fractures and faults crossing cave passages is a major reason for the abundance and variety of cave decorations that distinguish Kartchner Caverns (Hill 1999a). Rows of stalactites grow on the ceiling along these weaknesses, sometimes accompanied by massive stalagmites below. Additionally, water from the land surface accumulates on and moves laterally into the cave

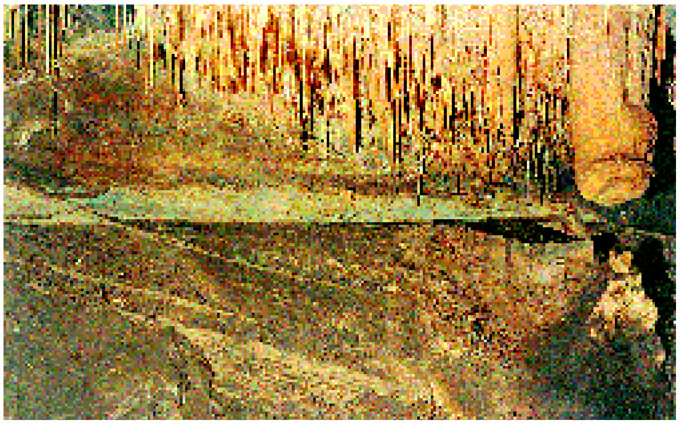


Figure 4. Corrosion bevel in passage off of Mushroom Passage cuts horizontally across dipping bedding planes and truncates a large stalactite. Photo by Bob Buecher.

on top of dipping, relatively impermeable beds within the Escabrosa Limestone. Jagnow (1999) mapped these beds inside the cave and noted rows of stalactites where the top of the beds cross cave ceilings.

Buecher (1992; 1999) conducted a drip study in the cave and estimated that ~230,000 L of water enters the cave by this mechanism per year, equivalent to a depth of 7.6 mm of water over the floor area of the cave. This rate corresponds to a recharge rate of about 2% of total precipitation on this limestone terrain. Buecher determined that drips form in response to storms within 4-12 days, depending on travel path length. The average flow rate of groundwater contributing to drips was about 15 m/day. The specific electrical conductance of the drip water increases with increasing flow path length, reaching a maximum of 450-490 µS/cm after 80-110 m of travel, at which point the drip apparently reaches saturation with calcium carbonate. Buecher (1992) noted that deposition of calcite from drip water does not occur if the specific electrical conductance is less than 330 µS/cm. Although drip water is important for speleothem formation and maintenance of high moisture levels in some parts of the cave, it is a small part of the cave water budget—10% or less—on a volume basis.

SURFACE FLOWS, CAVE FLOODING, AND CORROSION BEVELS

The most important component of the cave water budget is water entering the cave from infiltration of surface water flows into Guindani Wash and Saddle Wash (Fig. 1). Both washes trend adjacent to the limestone ridge containing Kartchner Caverns. Nonetheless, response in the cave to surface flows in the washes is slow. Sometimes significant surface flows do not result in any water entering the cave. For example, in August and September 1988, during a 30-day period when 158 mm of rain was recorded in the park's gage, Guindani Wash flowed almost continuously. Yet no flows or inundated areas were noted in any part of the cave.

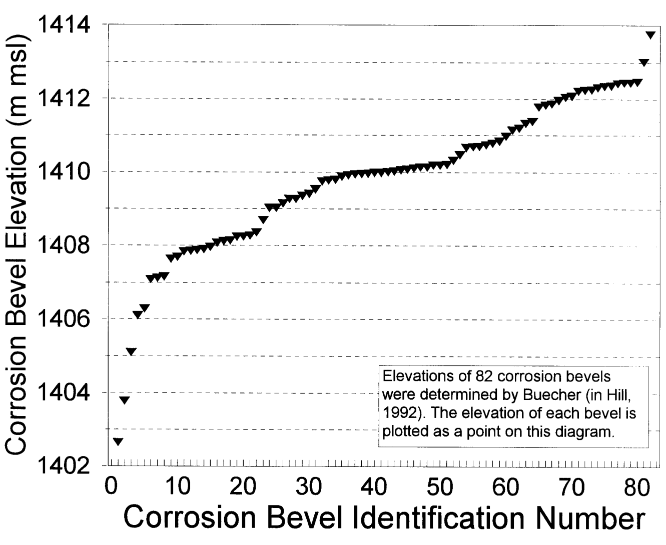


Figure 5. Distribution of 82 corrosion bevels by elevation (Hill 1992). Data supplied by R. Buecher.

Buecher (1992; pers. com.) studied flows and flooding of the cave during the flood events of August 1990, January through August 1991, and April 1992. He developed the following predictors for the onset of flow and flooding in the cave:

1. Surface flows in Guindani Wash or Saddle Wash for a week or more.
2. Excess soil moisture exceeds 30.5 mm for a single month, or 38.1 mm for two consecutive months, as computed by the Thornthwaite method for determining potential evapotranspiration.

Although not perfect, these predictors reflect the two main factors appearing to control the onset of water flow into Kartchner Caverns: antecedent moisture conditions and sufficient water in the surface washes. Applying the excess moisture criterion listed above, Buecher (1992) analyzed the weather records from September 1954 through February 1991 for nearby Fort Huachuca/Sierra Vista, which has similar altitude, ambient air temperatures, and precipitation as Kartchner Caverns. He accurately predicted flooding in the cave in December 1978 and March 1985. These flooding events are the only ones during prior years that had been observed in the cave. Perhaps the cave flooded more often, but the events were missed due to the infrequency of cave visits during those years. Buecher (1992) determined that the excess moisture criterion would signal onset of flooding in 21 of the 37 years of record, a 57% probability of flooding in any one year. On a seasonal basis, 60% of the probable floods occurred in winter, 36% in summer, and 4% in fall.

Corrosion bevels in Kartchner Caverns provide striking physical evidence of past flooding episodes. Corrosion bevels are sharp, horizontal indentations, notches, and overhangs cut into cave walls and ceilings (Fig. 4). In Kartchner Caverns, corrosion bevels also have been etched into breakdown blocks and speleothems, in some cases completely truncating large stalactites or notching stalagmites (Ford & Hill 1999, Fig. 3). About two-thirds of the 82 corrosion bevels catalogued by Buecher (Hill 1992) cluster within an altitude range of 1408-1412 m, and 20% are incised within an altitude interval of 1410 ± 0.25 m (Fig. 5).

Corrosion bevels typically form under static water level conditions when the water is undersaturated with respect to calcite (Ford & Williams 1989). Both Hill (1992; 1999b) and Jagnow (1990) considered the development of corrosion bevels in Kartchner Caverns to be the result of late stage flooding events under vadose conditions. They also noted that little speleothem growth has taken place since bevel incision, indicating a fairly late date of incision. Corrosion bevel development was probably aided by the aggressiveness of water entering Kartchner Caverns, inferred from the predominance of igneous and metamorphic rocks exposed in the catchment area of Guindani Canyon. Jagnow (1990) suggested that each bevel level corresponds to a nearby spillpoint, with the water surface stabilizing and then receding to a lower spillpoint as the cave drains. Jagnow noted that much more work is needed to fully understand the nature and significance of these features in Kartchner Caverns.

The mechanics of flooding in Kartchner Caverns were observed in detail by Buecher (1992; pers. com.). In some ways, the term *flooding* is inappropriate, as the process is prolonged over days and weeks—there is little danger of anyone being trapped in the cave. Inflows to the cave start on the land surface, where three infiltration points have been identified:

1. Saddle Wash downstream from North Well (1434 m msl, 23 m above Sue's Room, horizontal distance of 110 m from cave).
2. Junction of Guindani Wash and Saddle Wash (1423 m msl, 12 m above end of Granite Dells, horizontal distance of 49 m from cave).
3. Guindani Wash upstream of trail to cave (1419 m msl, 11 m above Crinoid Room, horizontal distance of 174 m from cave).

Lange *et al.* (1990) and Lange (1999) provided indirect evidence for the latter two locations, detecting natural potential (NP) anomalies that may indicate enhanced infiltration. The first two infiltration points were directly confirmed by use of a dye tracer during episodes of flow in the washes (Buecher 1992). In early September 1990, fluorescein dye was traced from Saddle Wash to a small stream emerging in Sue's Room after several weeks of intense rains and flooding on the land surface (Figs. 1 & 6). In January 1991, Rhodamine WT dye was traced from Guindani Wash to Granite Dells/Water Room. During the test, Guindani Wash was flowing, but Saddle Wash was dry, providing clear evidence of the linkage with Guindani Wash. Sustained flows in Guindani Wash are more frequent than in Saddle Wash due to a larger and higher drainage basin. Thus, Guindani Wash is expected to be a more frequent source of water to Kartchner Caverns than Saddle Wash.

CAVE FLOODING OBSERVATIONS

When Guindani Wash is the water source, flooding in the cave occurs from Granite Dells to the front of the cave (Fig. 6) in a relatively gradual, stair-step manner (Buecher 1992). Each chamber fills to a spillover point, then drains to another chamber. Flood levels are highest in the chambers closest to the points of inflow. Some lower chambers either do not fill or fill out of the stair-step sequence due to complex and incompletely understood connecting passages. The presence of granite wash in the cave (Hill 1999c) indicates that, at one time, a significant hydraulic connection was open to the surface. In Granite Dells, granitic material composed of sand, gravel, cobbles, and boulders up to 0.3 m in diameter is found in deposits as thick as 2.4 m. At present, flow into Granite Dells is relatively subdued. During the flood of early 1991, inflow into this room was estimated at about 0.8 L/s, which created a pool of water that rose at a rate of 18 mm/hr (Buecher, pers. com.).

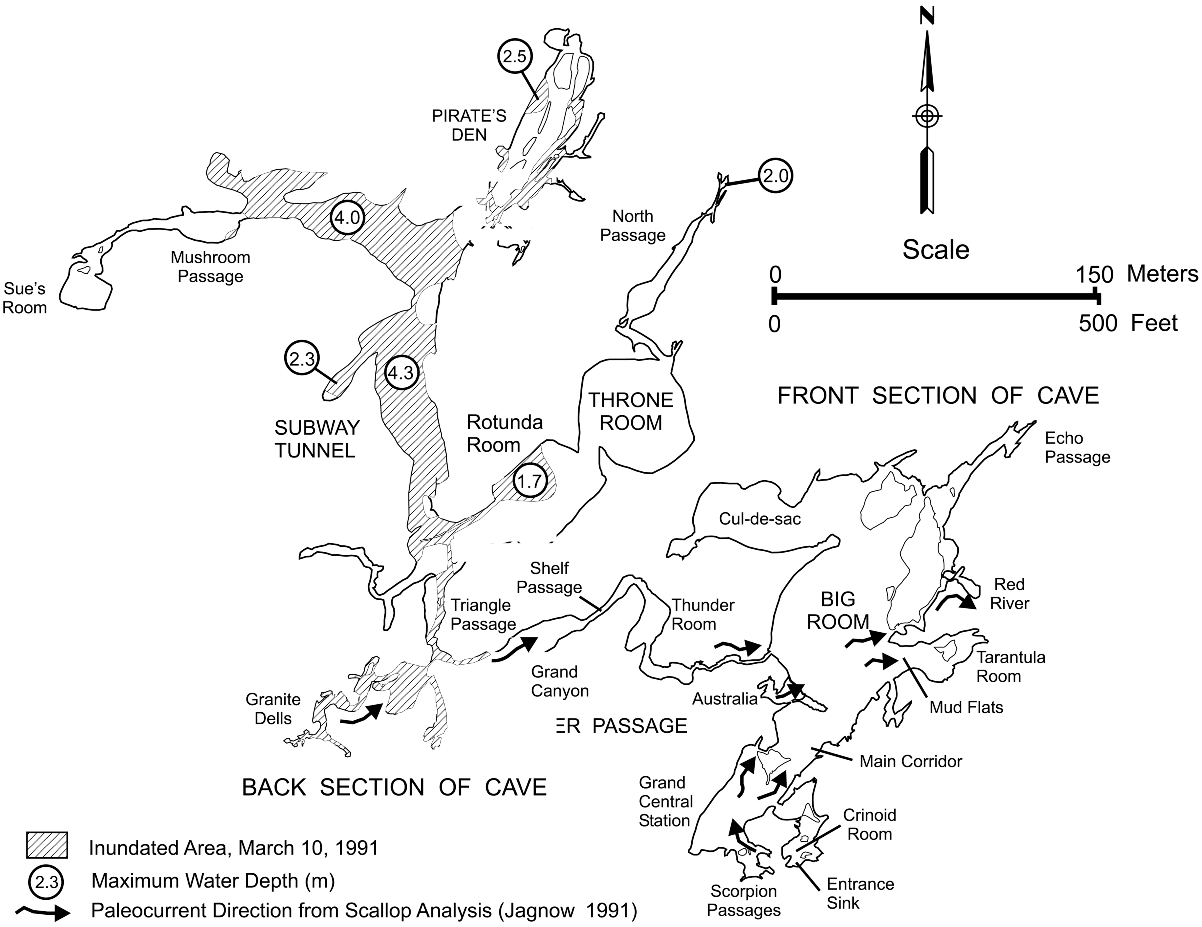
From Granite Dells, water flows through the Triangle Passage into the Back Section of the cave, where it rises to a maximum elevation of 1412.4 m msl and floods the Subway Tunnel, Mushroom Passage, Sue's Room, and parts of the Rotunda Room, Throne Room, and North Passage (Fig. 6). The Back Section of the cave becomes inaccessible through the Triangle Passage, which is the only natural entrance to this section, because water rises to a height of 0.2 m above the top of this passage at the maximum flood level. Water then spills over into Grand Canyon, where a flow of 14.4 L/s was measured during the flood of April 1992. From there, a stream forms in the Shelf Passage and cascades into the Thunder Room, so named for the noise during flooding. Although the Cul-de-sac Passage is 5 m lower than the Thunder Room and only 60 m away, it is not hydraulically connected and does not flood. Pools then begin forming near the start of the River Passage, in the Australia passage, and at the downstream (north) end of Grand Central Station. All of these chambers are at the same elevation and must be connected.

From Grand Central Station, water then starts to flow into Red River from under the breakdown pile in the Big Room. This discharge was measured at 12.5 L/s during the April 1992 flood. The drain in the Red River Room, the lowest point in the cave at an elevation of 1400 m msl, has little capacity, causing backflooding into Echo Passage up to an elevation of 1404 m msl. Finally, a stream emerges in the Crinoid Room, apparently due to a small connection to Grand Central Station. The above sequence reflects the scenario for a very severe episode of flooding. During lesser events, the primary impact is varying levels of inundation in the Back Section of the cave. During the August 1990 flooding, an estimated 1.9 x 10^6 L of water accumulated in the cave (Buecher 1992). The flood of early 1991 was much larger, with an estimated inflow of 3.7 x 10^6 L of water. Figure 6 shows the extent of inundation in the cave and maximum water depth at selected locations.

For the three modern flood events that have been observed in detail, draining of the cave is much slower than flooding. The flood of August 1990 took about two months to drain completely from the cave. This duration yields an overall drainage rate of about 22 L/min. Buecher (1992) measured significantly higher rates at individual drain locations, indicating that different sections of the cave do not drain equally. Flood pools linger in some areas of the cave while disappearing quickly in others. This is particularly evident in the Back Section of the cave, where deposits of mud in many passages impede drainage of pooled water. No water draining out of the cave resurges on the land surface. Instead, flood water exits the cave by percolating downward through the Kartchner Block. Then, this water descends to the water table and flows basinward to recharge the regional alluvial aquifer in the San Pedro Valley.

Figure 6.

Area inundated by flood water, March 1991. Paleocurrent directions determined from scallop marks are by Jagnow (1990).



Paleoflow From Scallop Marks

An earlier record of flow in Kartchner Caverns is preserved in the form of scallop marks. Jagnow (1990) analyzed the size and distribution of scallops to produce a paleocurrent map (Fig. 6). Scallops are spoon-shaped scoops dissolved into the walls, ceilings, and floors of a cave that indicate both water current direction and velocity at the time of scallop formation (Ford & Williams 1989). The downstream edge of a scallop is more broadly concave and the upstream edge more sharply concave, reflecting the configuration of the eddy that formed in the water next to the cave surface. As the velocity of the current increases, the eddies become more intense and shorten, forming shorter scallops. Curl (1966) developed an equation based on fluid dynamics that relates paleovelocity to scallop length. For the purpose of paleocurrent mapping, Jagnow (1990) divided the scallops in Kartchner Caverns into the following categories:

Class	Size (diameter in m)	Velocity (m/min)
Small	Less than 0.34	Greater than 3.05
Medium	0.34 to 0.91	3.05 to 1.07
Large	Greater than 0.91	Less than 1.07

In the areas where scallops can be observed (~25% of the cave), paleocurrent directions generally match observations of flows during recent floods (Jagnow 1990). Paleoflow was also from Granite Dells to the Red River Room in the Front Section of the cave (Fig. 6). Although paleoflows also probably originated in Sue's Room, which according to Jagnow may have been the most likely original inflow point for the majority of early cave development, most scallops in the Back Section of the cave have been obliterated by backflooding. Jagnow mapped the largest scallops nearer to the ceiling and the smaller scallops close to or at floor level. He proposed two possible interpretations for this distribution: (1) When the cave flooded to high levels, the velocity was slow, increasing as the cave drained; or, (2) significant dissolution of the cave occurred under very low-velocity vadose conditions, followed by higher velocity conditions as downcutting occurred.

Jagnow (1990) also noted some interesting paleocurrent relationships in the Front Section of the cave. At present, a dry drainage extends from the Entrance Sink through the Crinoid Room, reappears in the Scorpion Passages, and courses through Grand Central Station to disappear under breakdown near the start of the Main Corridor. When this channel flows, cavers have heard water moving down a drain near the Main Corridor trail. This water may flow to a point beneath the

Tarantula Room or Red River Room. Today, the only visible drain is in the Red River Room. Jagnow noted that medium-sized scallops flank this route, indicating that the Entrance Sink was once a significant source of inflow to the cave. The scallops also indicate significant paleoflows not only to the Red River Room, but to the Tarantula Room, which is now disconnected from the contemporary, visible flow system.

CONCLUSIONS

The hydrogeology of Kartchner Caverns State Park involves interactions among three distinct, mutually adjacent hydrogeologic systems within the park: 1) the San Pedro Valley basin, a deep, alluvium-filled graben; 2) an alluvium-covered pediment characterized by a few tens of meters of “granite wash” sediments overlying an erosional surface of Pinal Schist; and 3) a downdropped fault block of Paleozoic rocks, which includes the Mississipian Escabrosa Limestone containing Kartchner Caverns. Groundwater occurs within the San Pedro Valley basin at a depth more than 200 m below the lowest known Kartchner Caverns passage, and in the granite wash sediments at a level more than 20 m higher than nearby cave passages. The source of most water to the cave is meteoric water infiltrating from runoff in washes bordering the fault block and from overhead infiltration from precipitation. The cave floods relatively frequently (estimated at a 57% probability in any one year), when high antecedent soil moisture combines with sustained runoff in the washes flowing adjacent to the limestone ridge containing Kartchner Caverns. An abundance of corrosion bevels in the cave attests to past episodes of flooding. Mapping of solutional scallops reveals that paleocurrent directions generally correspond to historic flow patterns.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance of Bob and Debbie Buecher during this project. Bob is especially acknowledged for his superior observational skills, which contributed greatly to this paper, as well as for his assistance on several figures. The author also acknowledges all of the people who have directed or assisted in the work described in this paper, including those who have faithfully measured well water levels over the years. The author has not met many of these contributing individuals, but is impressed by their sheer number and is appreciative of their dedication. Finally, the author wishes to thank William Victor and Charles Barter, Montgomery & Associates, Tucson, Arizona, whose review of a draft of this paper was especially thorough and insightful.

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