Geology and Hydrology of Kartchner Caverns and their Relationship to the Vigneto Development

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Introduction

The proposed Vigneto development in Benson, Arizona has raised many concerns about the project's potential impacts on nearby Kartchner Caverns. This May, Robert Casavant, Resource Manager for Arizona State Parks and resident manager at Kartchner Caverns State Park, offered to give me a geologic and hydrologic overview and tour of the caverns after I provided him with the report by *Prucha* (2016), which modeled the 100-year effect of groundwater pumping by the development. I accepted his offer and visited the park on June 2-3. Casavant is a Ph.D. geologist with a degree from the University of Arizona and has spent more than a decade studying the geology of the caverns.

Since Arizona State Parks (ASP) acquired Kartchner Caverns in 1996, staff and independent researchers have gathered data and developed concepts about the groundwater resources of the park and their relationship to the greater basin geology and hydrology. In light of the inferred interconnectivity of the basin-margin hydrology with that of the Benson subbasin to the north and east, the following conclusion by *Prucha* (2016) raises concerns:

> "It is difficult to see how groundwater beneath Kartchner Caverns might be impacted by Vigneto pumping, as the hydrogeologic system and groundwater flow system appears isolated and located well above the basin aquifer system. Vigneto drawdowns range from about 10 to 20 meters within the basin aquifer system, downgradient from the caverns."

Casavant and others feel that Prucha's model could be improved by including hydrological connections between the water resources within the limestone bedrock along the basin margin and the alluvial aquifers within the basin. Limestone in the park and along the basin margin serves as an important aquifer with good lateral connectivity via faults and associated solution zones. While Vigneto pumping would not directly affect the caverns by draining water from them (they are currently above the water table), it could indirectly do so by affecting the water table beneath them. Water use by the development could also affect the park's limited water supply, which is a concern.

Arizona State Park records show that the park itself has already significantly overdrafted the park's limestone aquifer, and ASP would like to reverse this. If Vigneto itself overdrafts water resources along the basin rim, that could make aquifer recovery and restoration more difficult. One cannot determine the magnitude of Vigneto's effect, if any, however without a model that incorporates and links the basin aquifer with the more complicated hydrology of the basin rim.

General Geology Overview and Relationship to Whetstone Ranch Wells

Figure 1 is a geologic map of the Benson 15' Quadrangle made by *Creasey* (1967) overlain by the location of Kartchner Caverns State Park and the Vigneto development. The map shows how isolated the limestone outcrops (predominantly blue) of the park are from the main limestone outcrops within the Whetstone Mountains. The Kartchner Caverns block is down dropped several thousand feet by a major basin-and-range normal fault, and the block is cut again on the east by a second large fault having a displacement of at least 1200 ft, as indicated by a well drilled immediately east of the park (Caverns LLC well 2, Figure 1). I have added approximate traces of these faults on Creasey's map based on geologic relationships and well information.

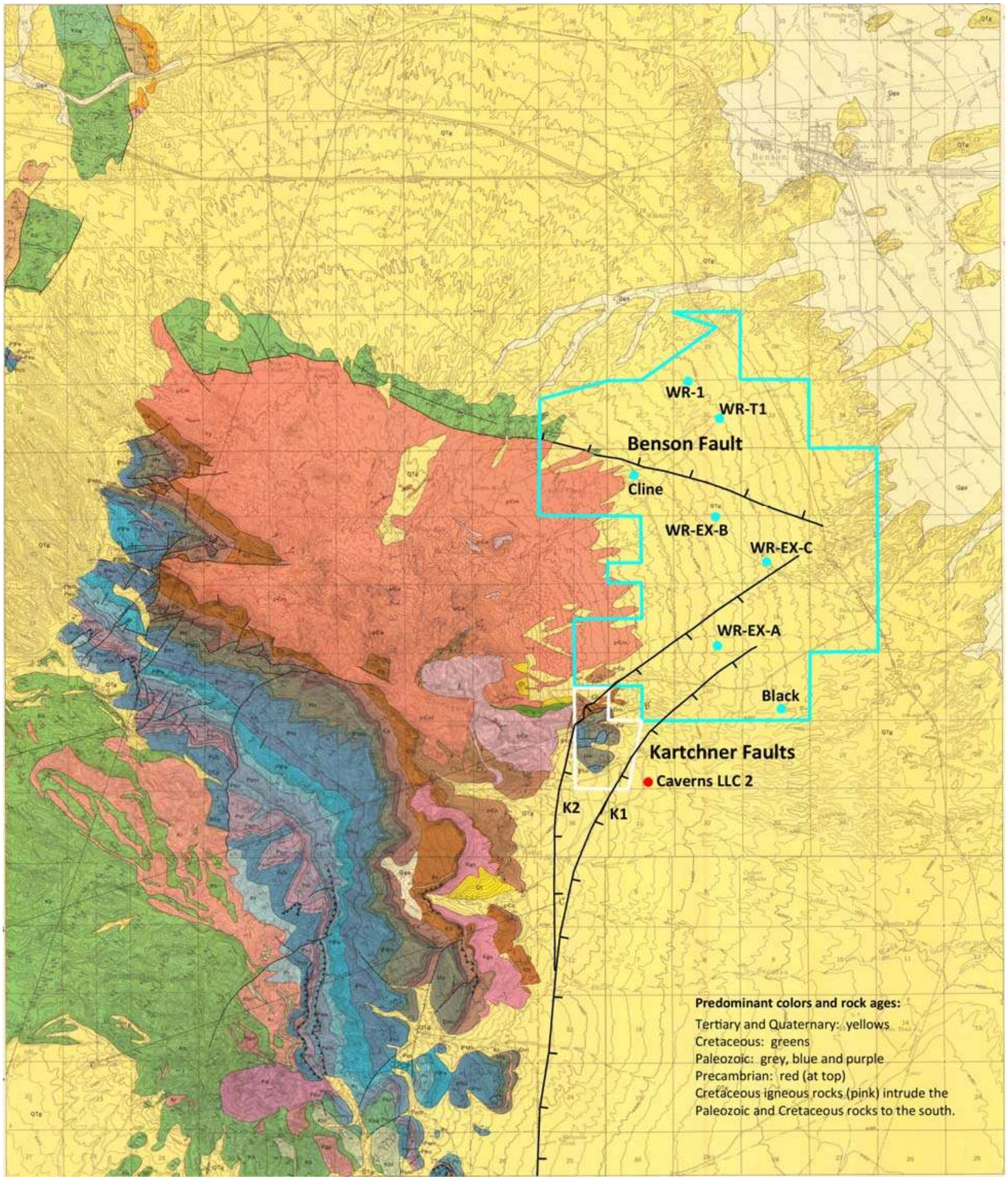

Figure 1. Geologic map of the Benson 15' Quadrangle by *Creasey* (1967), with the outlines of the Vigneto Development (blue) and Kartchner Caverns State Park (white) superimposed. Blue dots are wells. Wells WR-EX-A, -B and -C are Whetstone Ranch water exploration wells. Well WR-1 is the first and primary production well for Whetstone Ranch and now Vigneto. Well EX-A bottoms in limestone at a depth of 580 ft and was dry. Wells EX-B and -C penetrated several hundred feet of grus, or weathered granite, before stopping, although they are productive. These wells are the basis for extending the faults from the Kartchner area. All of Vigneto's production wells will be north of the Benson fault.

The map shows important existing wells (blue dots) on the former Whetstone Ranch parcel. Comparing this map with the proposed well field in Vigneto's Community Master Plan reveals that the entire well field will be drilled north of the Benson fault. Five of the blue dots are wells drilled by Whetstone Ranch, while two, Cline and Black, are historic ranching wells. Well WR-1 is the primary production well for Whetstone Ranch, and Well WR-T1 is a productive test well. Wells with the EX notation are exploratory. These wells are helpful in understanding the hydrological relationship between the Vigneto development and the park.

Rocks of the Kartchner block are intensely faulted, fractured and deformed in comparison with the same rocks exposed within the Whetstone Mountains (*Jagnow*, 1999). This intense deformation is partly related to the block's being caught between these two major bounding faults. Examination of smaller faults within the Kartchner block shows that they have experienced oblique-slip motion, that is, a component of strike-slip motion, rather than simple normal slip. Figure 2 is a Google Earth photograph of the limestone hill north of the caverns showing drag folds into a fault that has experienced a component of strike-slip offset. These oblique- or strike-slip offsets may be important to explaining anomalous bedrock relationships in the Kartchner block without resorting to unreasonable amounts of simple normal-fault offset.

Figure 2. Drag folds along an oblique-slip or strike-slip fault in the Paleozoic Escabrosa Limestone on the hill north of the caverns demonstrating right-lateral displacement. A second parallel fault is marked that truncates beds. This exemplifies the intense deformation of the Kartchner block.

Of particular importance on Figure 1 is Whetstone Ranch well WR-EX-A, which encountered limestone at a depth of 580 ft and was subsequently abandoned as dry at a depth of 600 ft. This well was originally proposed to a depth of 1140 ft based on the success of Whetstone production well WR-1. WR-EX-A establishes that a major normal fault separates the well location from the area of Precambrian granite to the northwest and that the underlying fault block may be the extension of the Kartchner block. The well did not encounter any water-bearing intervals even though the well record indicates that much of the alluvial section was sandy gravel. The majority of the section in the well is Lower Basin Fill, the unit from which Vigneto would draw water.

The bottom of this well is thus above the water-bearing interval of the Lower Basin Fill, and if water withdrawal from Vigneto wells affects the water table in this area, the effect would be within the bedrock aquifer, not the alluvial aquifer. Prucha's model shows a 50-m (165-ft) drawdown in water at this location in 100 years based upon the assumption that the area is underlain by a uniform sand and gravel aquifer with a far greater effective porosity than limestone. The relatively shallow occurrence of bedrock significantly diminishes the quantity of water available from this area and would change the results of his model. Exploratory wells EX-B and EX-C to the north were completed in granite wash and weathered granite and are productive. However, they apparently could not produce sufficient water for large-scale Whetstone Ranch use, and El Dorado does not plan to use them for the Vigneto development.

The first Whetstone Ranch well, WR-1, was drilled north of the Benson fault to a depth of 1140 ft and encountered water at a depth of 700 ft. The static water level in the well measured in 2003 was 650 ft below the land surface. A comparison of this well with WR-EX-A using surface well elevations shows that the static water level in WR-1 is 200 ft lower in elevation than the top of the limestone in the WR-EX-A well. Whetstone Ranch well WR-T1, noted on the map, was a test well and will be used by Vigneto for production.

The north end of the Whetstone Mountains is composed of Precambrian granite truncated by the Benson fault, which downdrops highly deformed Cretaceous Bisbee Group rocks against the granite. Exposures of these Cretaceous rocks immediately adjacent to the fault on the north indicate that the downthrown side of the fault does not contain a thick section of basin fill immediately adjacent to the fault that might serve as a good aquifer. While sands, gravels and granite wash that overlie the triangular area of bedrock between this fault and the Kartchner faults to the southeast do produce water, they are not as thick or as productive as Lower Basin Fill sediments north of the fault. This will restrict the area of high-quality water production for the development.

Of particular note is Black Well to the southeast of well WR-EX-A. This is an older well drilled in 1963 for cattle ranching southeast of the eastern bounding fault of the Kartchner block. The well was drilled to a depth of 575 ft and in 1989 had a static water level of 518 ft below the land surface (*Graf*, 1999). This well produces from Lower Basin Fill, the main aquifer for Vigneto and the City of Benson, and lies southeast of the two faults that bound the Kartchner block. The aquifer encountered in the well should fully connect with the aquifer of the proposed Vigneto well field. *Prucha*'s (2016) modeling indicates a 100-year drawdown of water in this area of 25 m (82 ft) or more, which will dry out the well in that time.

The other prominent, older well on the Vigneto parcel is the Cline Well, which was drilled in 1935 just 900 feet from exposed granite bedrock to a depth of 350 ft. This well has the longest water-level record of any well in this area of Cochise County (Figure 3). Presumably the well was drilled to granite basement. The static water level in this well has dropped 51 ft from 237 ft below the land surface in 1995 to 288 ft below the land surface in 2014, reflecting drought conditions. The well is located just south of the Benson fault, and the fault's proximity may partly explain why the water accumulates there so close to the outcrop. The water within the alluvium in this well should flow in the subsurface to recharge the Lower Basin Fill aquifer. *Prucha*'s (2016) modeling indicates that the water level at this location would fall ~100 m (328 ft) in 100 years with Vigneto use, meaning that the Cline Well would be dry within a few decades following Vigneto's completion.

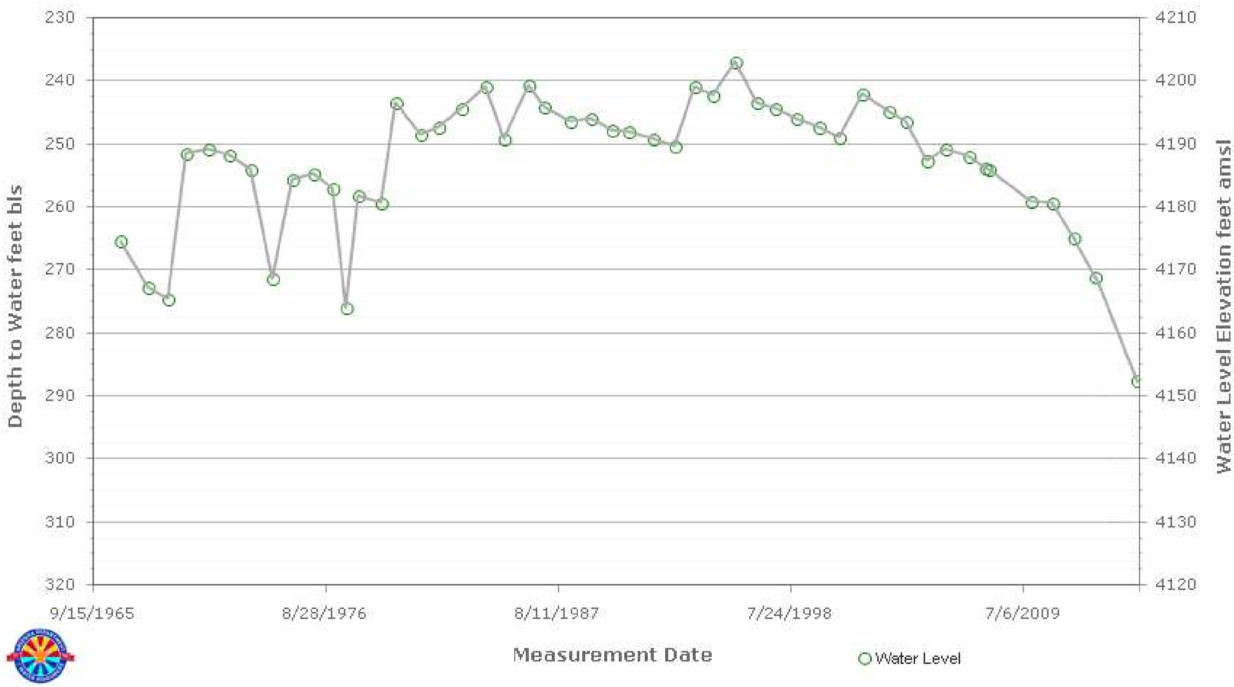

Figure 3. Water-level record from the Cline well located in the northwest portion of the Vigneto development (location noted on Figure 1). Water levels began to drop around 1995, when the current drought began. Modeling by *Prucha* (2016) indicates that this well would be dry within a few decades of Vigneto's completion. Data from Arizona Department of Water Resources (ADWR).

The Caverns LLC Well 2 (Figure 1) was drilled to a depth of 1200 ft in 2005 immediately east of the park on the downthrown side of Kartchner K1 fault. The well encountered water below 800 ft and in 2007 had a static water level of 743 feet below the land surface. This well is completed within Lower Basin Fill also, and the aquifer within it should be continuous with that of the Vigneto well field. Prucha predicts a 100-year drawdown of water in the area of the well of about 5 m (16 ft), which will not appreciably affect water levels in the well.

A Review of Cavern Geology and Hydrology

The Kartchner block (Figure 4), which hosts the caverns, is composed of intensely faulted Paleozoic limestone (*Jagnow*, 1999), and these faults are critical to water movement and supply for the caverns, both water that infiltrates the cavern roof to form speleothems and that which

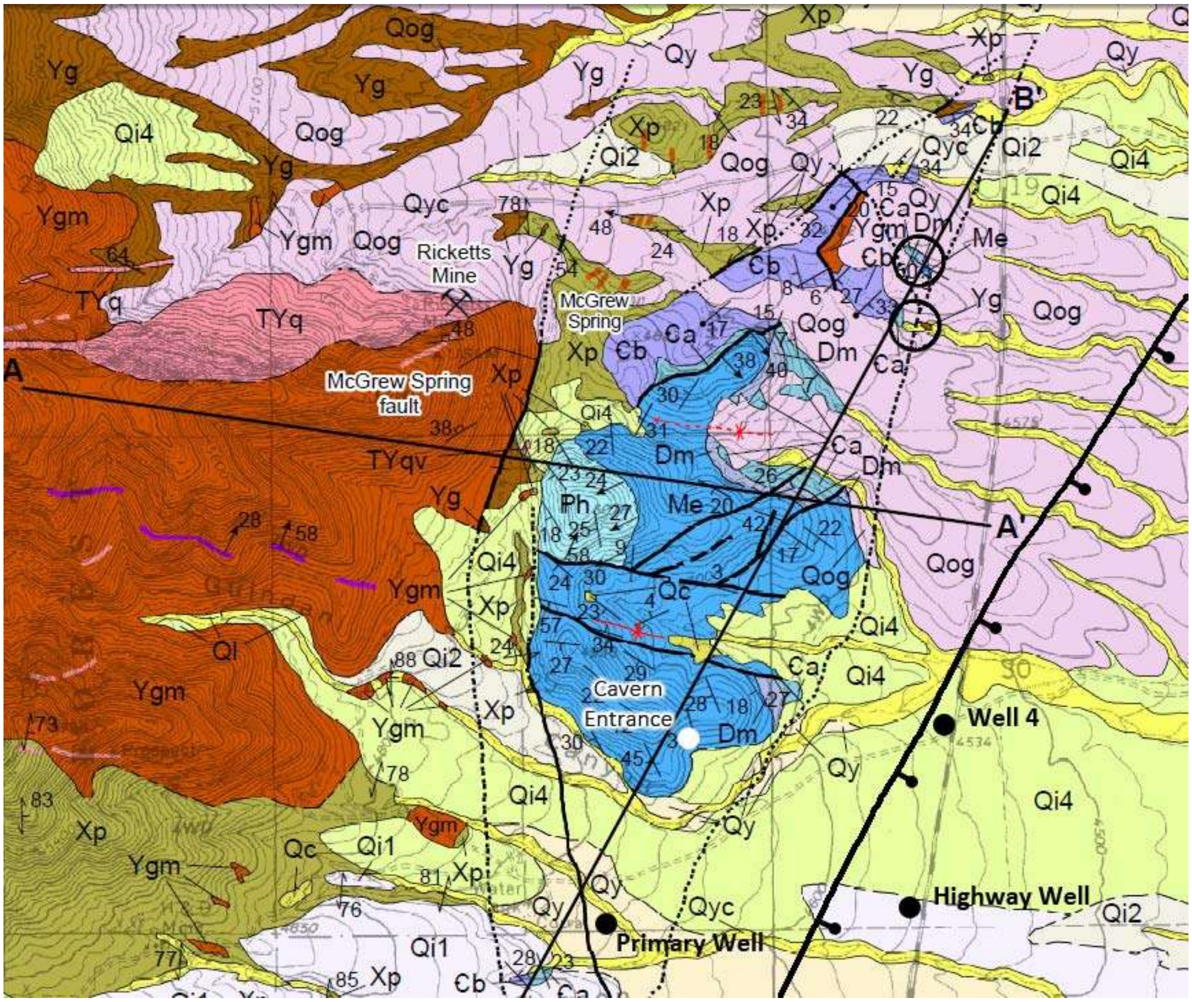

Figure 4. Geological map of the Kartchner Caverns area (from *Shipman and Ferguson*, 2003). The caverns occur in the southern portion of the dark blue area, or Kartchner block, which is composed of Mississippian-age Escabrosa Limestone (Me) and bordered on the south by Guindani Canyon or Wash. The caverns area is dominated by large north-northeast-trending faults (solid and dashed/dotted lines) that are connected by east-west-linking faults. This type of fault network provides the fundamental hydrological framework for the basin margin. I have added the location of important park wells and the eastern boundary fault of the Kartchner block deduced from well and gravity data.

periodically floods cavern floors. The faults that cut the roofs and walls of the caverns vary in thickness and displacement from a few inches to many feet, and water enters the caverns predominantly along these. A fault zone in limestone to the south serves as the primary aquifer for park facilities and visitors. I was able to tour the Rotunda and Throne rooms in the caverns with Casavant and park staff to observe subsurface faulting and geology and then walked the area above and around the caverns to examine the surface expression of these faults. I also had the opportunity to review a variety of imagery, published maps, and data that have guided State Parks in developing and managing the park.

While the dissolution of limestone that created the caverns occurred when the Kartchner block was below the water table, the cave speleothems (or formations) formed after the water table fell below the level of the caverns. The stalactites, stalagmites and other cave features form by meteoric water percolating through fractures and faults in the cavern roof, which collects rainwater and acts as a reservoir that slowly releases water into the void space below. Calcium carbonate is then redeposited from evaporating water and by CO_2 dissolution to form cave features. This process depends entirely on meteoric water rather than regional groundwater levels. Vigneto's pumping *per se* would not affect it.

The bottom of the caverns can flood after prolonged rains saturate the alluvium in Guindani Wash and its northern extension, Saddle Wash, which border the caverns on the south and west (*Graf*, 1999). Groundwater levels might affect this process by influencing the thickness of alluvium that must be saturated by rainfall before water will enter the caverns. A thicker interval of unsaturated alluvium would require greater and more prolonged rainfall to achieve flooding. In addition, a lower water table within the limestone beneath the caverns would cause the caverns to drain more quickly after flooding when retaining the water as long as possible is physically and ecologically advantageous. If Vigneto water pumping could lower water levels in the Kartchner block, these would be the primary effects on the caverns.

Periodic flooding is important to the physical and biological processes of the caverns and usually occurs in the winter when rains are more prolonged and gradual. This flooding provides 90% of the water budget of the caverns (*Graf*, 1999) and carries nutrients into them. Once the alluvium is saturated, water will enter the cave through fracture, fault and solution networks and fill the cavern's lowest levels with several feet of water, spilling from the floor of one room to the next. Once the bottom of the caverns is flooded, draining the water through the bedrock floor can take up to two months (*Graf*, 1999). The frequency of flooding has declined over the last 15 years because of the drought, and flooding last occurred in 2010, another potentially negative impact.

Shipman and Ferguson (2003) interpreted the faulting relationships within the Kartchner block from surface mapping and placed the limestone of the caverns in a graben bounded on the east by a west-dipping fault with a displacement of 1000 ft or more (Figure 5). Gravity and well data (*Lange*, 1999; *Graf*, 1999) clearly indicate that the trace of their inferred fault lies just west of the east-dipping fault that bounds the Kartchner block on the east, which has a displacement of up to 2,000 ft or more, given that no bedrock was encountered to a depth of 1200 ft in the Caverns LLC 2 well. I have added the approximate trace of that fault to their map (Figure 4). The trace of their graben-bounding fault is the dotted line. Shipman and Ferguson apparently did not consider Lange and Graf's gravity and well data in making their map. It is difficult to envision such large opposing displacements occurring back-to-back in this manner. The east-dipping fault noted by Graf and Lange will dominate the structural setting.

The geologic relationships that caused Shipman and Ferguson to postulate their down-to-the-west fault are circled in Figure 4. A fault is needed to explain the juxtaposition of Paleozoic rocks against Precambrian basement. The fault may possibly be much more local and shorter and accommodate the severe fragmentation of the Kartchner block, as the many other faults in the block do. The Kartchner block is part of a rotated fault block that has been highly deformed by being caught between two major basin-bounding, down-to-the-east faults (Figure 1) that potentially have a significant strike-slip component to them. Shipman and Ferguson's fault may terminate against other smaller faults and fault blocks or against the major basin-bounding fault on the east.

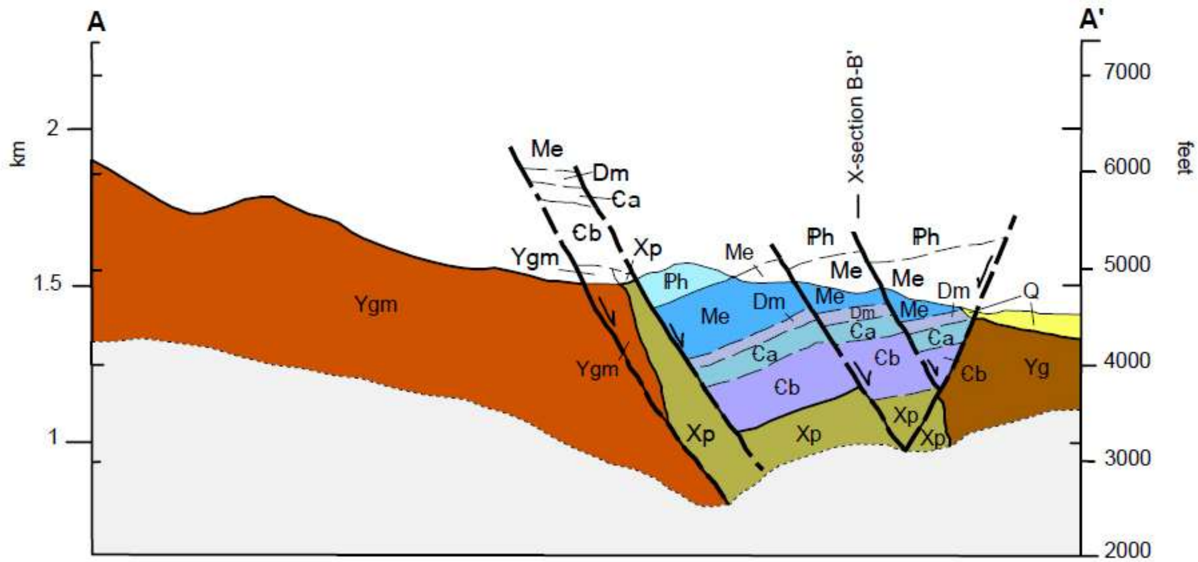

Figure 5. West-to-east cross section A–A' through Kartchner Caverns from *Shipman and Ferguson* (2003). Data from *Graf* (1999) and *Lange* (1999) show that this cross section likely needs modifying, as a major east-dipping fault with more than 1200 ft displacement must occur on the right side of the cross section nearly coincident at the surface with the west-dipping fault shown here.

Park Wells and Water Supply

Also of concern is how Vigneto pumping might affect the park's water supply. The primary aquifer around the basin margin and in the park is faulted, fractured and solutioned Paleozoic limestone in which the caverns themselves are formed. Only one well (Figure 6, Primary Well, denoted Well 2 in park records) is capable of producing sufficient water to supply the park even though other wells do produce water. This well was drilled to a depth of 420 ft south of the campground on the park boundary and first encountered water at a depth of 320 ft. Geophysical logs for the well (gamma ray and neutron) show limestone bedrock at a depth of approximately 200 ft and seven water-producing intervals within the limestone of varying thicknesses. These intervals are assumed to be individual fault splays within a fault zone.

The initial static water level in the well (the level to which the water naturally rises, elevation 4589 ft) was 80 ft below the land surface, or 240 feet above the water-bearing zone. This initial water level was only 4 ft below the lowest level in the caverns (elevation 4593 ft). The height of the water column in the zone creates a large head that undoubtedly helps drive water production. This zone is presumed to be a fault zone or associated dissolution zone and must be inclined. Water enters the dipping zone where it intersects the surface or shallow overlying alluvium. ASP later drilled an 860-ft test well 800 ft to the east of this well (Figure 6) that penetrated limestone, but the well did not encounter any water-producing intervals (R. Casavant, personal communication, June 23, 2016). Thus the test well did not appear to penetrate any faults.

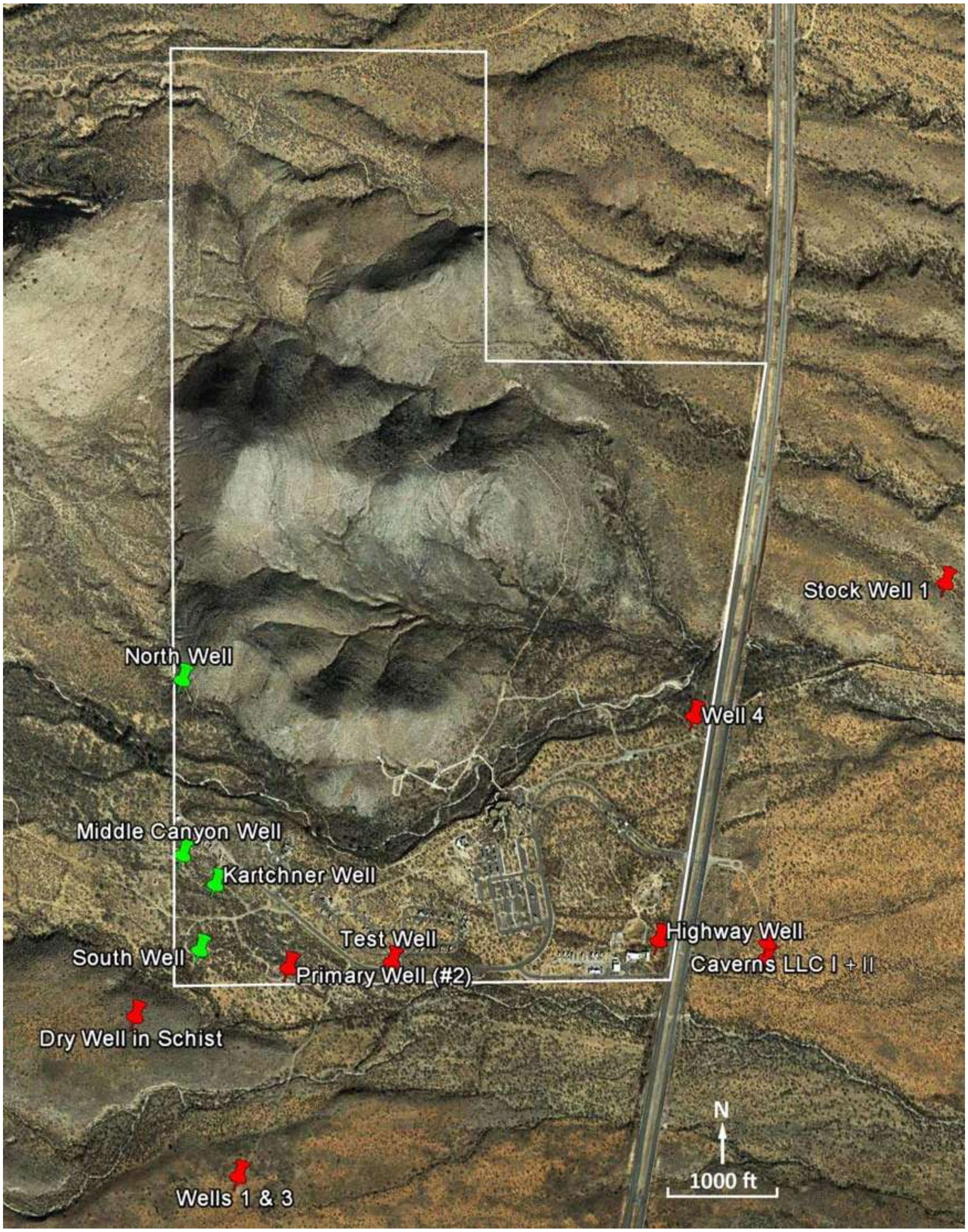

Figure 6. New (red pins) and old (green pins) wells drilled or dug in and around Kartchner Caverns State Park (white boundary). The Primary Well (Well 2 in park records) supplies the water for the park. Only the Primary Well has sufficient capacity to serve this purpose. The older wells were all for stock use, and the North and South Wells were hand dug. Park staff still monitor water levels in the Kartchner, Middle Canyon (Windmill) and North Wells.

Correlation of increases in water levels in this well and Well 3 to the south with water flows in area washes following storms indicates that the fault zone captures water from overlying alluvium once the alluvium becomes saturated. The water then spreads laterally in the fault zone to wells more distant from these points of entry. The Primary Well produces essentially all of the water for the park, about 10,000 gallons per day or 11 acre-ft per year.

This well was drilled in 1993, and by 2006 the water level had dropped 142 ft to 222 ft below the land surface (Figure 7). Casavant joined the park staff in 2006 and was alarmed by this rapid drop. In response, he instituted water-saving measures, which included changing to low-water-use fixtures. Since then the water level in the well has stabilized. The level as of June 2015 was 190 ft below the ground surface, or 114 ft below the lowest level of the caverns. While the water level in the Primary Well now appears stable (Figure 7), this water drawdown still concerns staff. It may permanently lower groundwater levels in and around the caverns and along Guindani Canyon, reducing the frequency of flooding of the caverns during storms and stressing vegetation along Guindani Canyon.

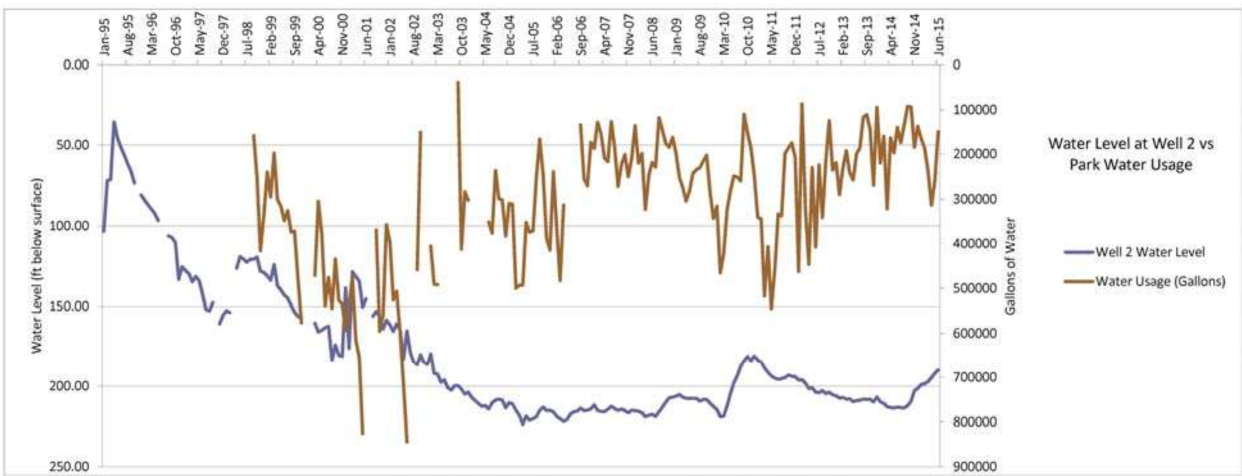

Figure 7. Water levels (blue line) in the Primary Well (Well 2) for the park versus park water usage (brown line). The water level in the well declined sharply in the first 10 years of use, much of it from water use for development, but then stabilized. Water use does appear to generally decline starting in 2002–2003, which contributed to this stabilization. Data provide by Arizona State Parks.

The two older, shallower wells (Middle Canyon or Windmill and Kartchner) drilled west of the Primary Well by the Kartchners for ranching produce water from granite wash. The current water level in the Kartchner well is 78 ft below the land surface. These wells presumably penetrated bedrock at depth, but well records do not indicate the lithology, which should be either limestone or schist. The Primary Well itself did not encounter any water in the granite wash above the limestone. The North and South Wells were hand dug and produce water from granite wash overlying Precambrian schist at depths of 20–25 ft.

For comparison, water levels for Well 3 to the south are shown in Figure 8. This well also shows a general decline in water level through time, although this decline is punctuated by positive events, which correlate with large storms that increase levels. The sharp increase in water level in 2014 is associated with the heavy rains of Hurricane Odile in the upper San Pedro basin. Park records show that the level also rose 11 ft in the Primary Well (Figure 7) in October and November 2014 following the storm and continued to steadily rise through June 2015, the latest date in the database provided by the park. Casavant notes that the water level in Well 3 drops when the Primary Well is pumped, indicating that the aquifer in the two wells is linked. Well 3 is completed in limestone and encountered two water-producing zones (R. Casavant, personal communication, June 23, 2016). A first attempt to drill the well (Well 1 in park records) resulted in collapse of the well bore, and the well was redrilled as Well 3.

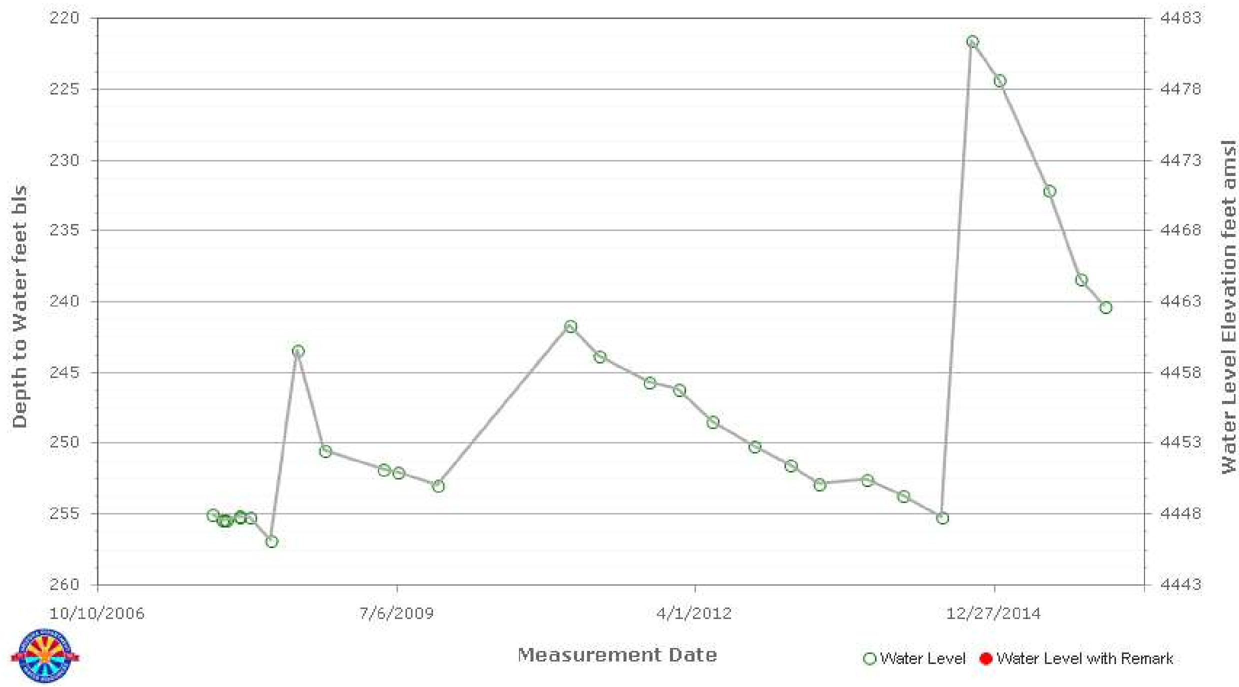

Figure 8. Water levels in park Well 3 (south of the park). The sharp spike in the water level in 2014 is associated with the heavy rains in the upper San Pedro basin resulting from Hurricane Odile. The graph shows how short lived this increase in water level was. The water in this well is produced from two faults in limestone, and the sharp decline is partly associated with water distributing itself laterally in these faults. Current water levels are not given online. Figure from ADWR.

The Kartchner Well, originally drilled for cattle ranching, has a well-documented record of water levels through time showing that the water level has steadily declined since 2008 (Figure 9). This decline is also reflected in the well east-northeast of the Discovery Center (Well 4, Figure 10), although the depth to water in Well 4 is much greater (currently 408 ft). Water in Well 4 occurs in sand and conglomerate immediately overlying granite, which occurs at a depth of 420 ft. Total depth of the well is 465 ft.

The drop in groundwater levels shown in Figures 8–10 indicates that water is currently not recharging fast enough to keep up with the constant flow of subsurface water down gradient toward the basin center and axis. This drop in part reflects the drought Arizona has experienced since 1995 (*Toomey*, 2009). Any effect that Vigneto may have on park groundwater levels must be combined with the projections of declining water availability over the next several decades resulting from climate change. In addition, groundwater pumping in the park has lowered water levels and may continue to do so. The effects of these two factors are likely to be large enough

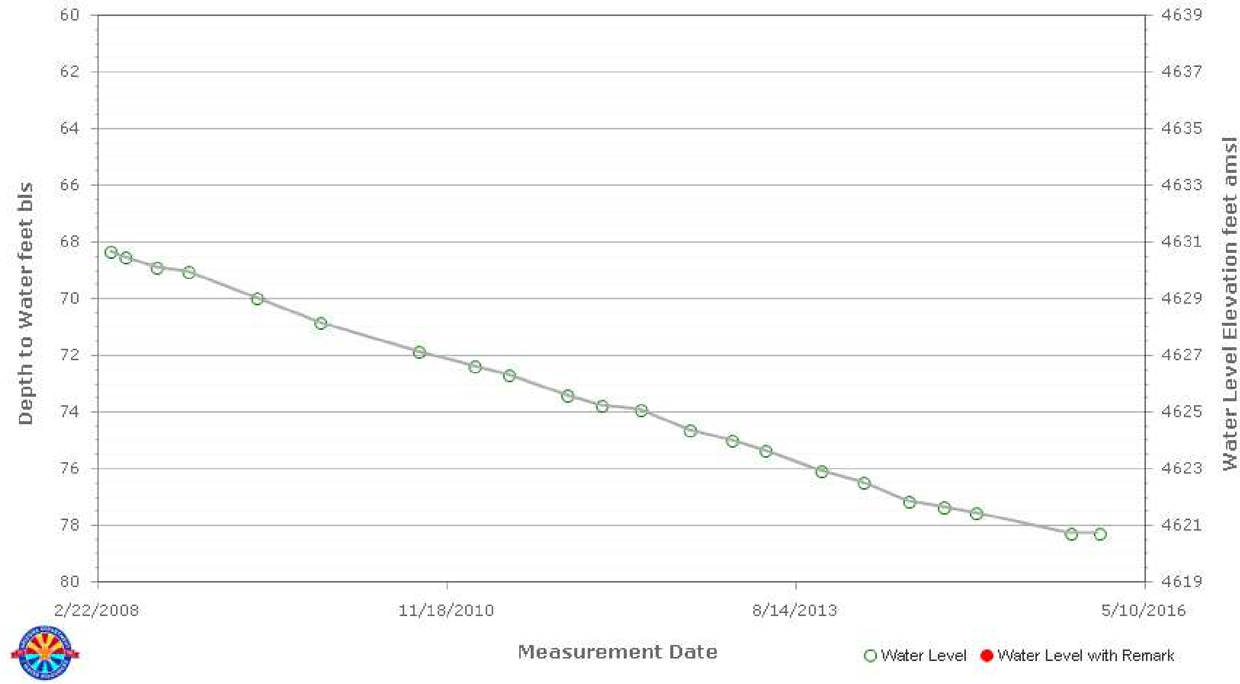

Figure 9 Decline in water level in the Kartchner Well from 2008 to 2016. This decline in part reflects the drought Arizona has experienced since 1995. Groundwater pumping by the park may also be a factor. Figure from ADWR.

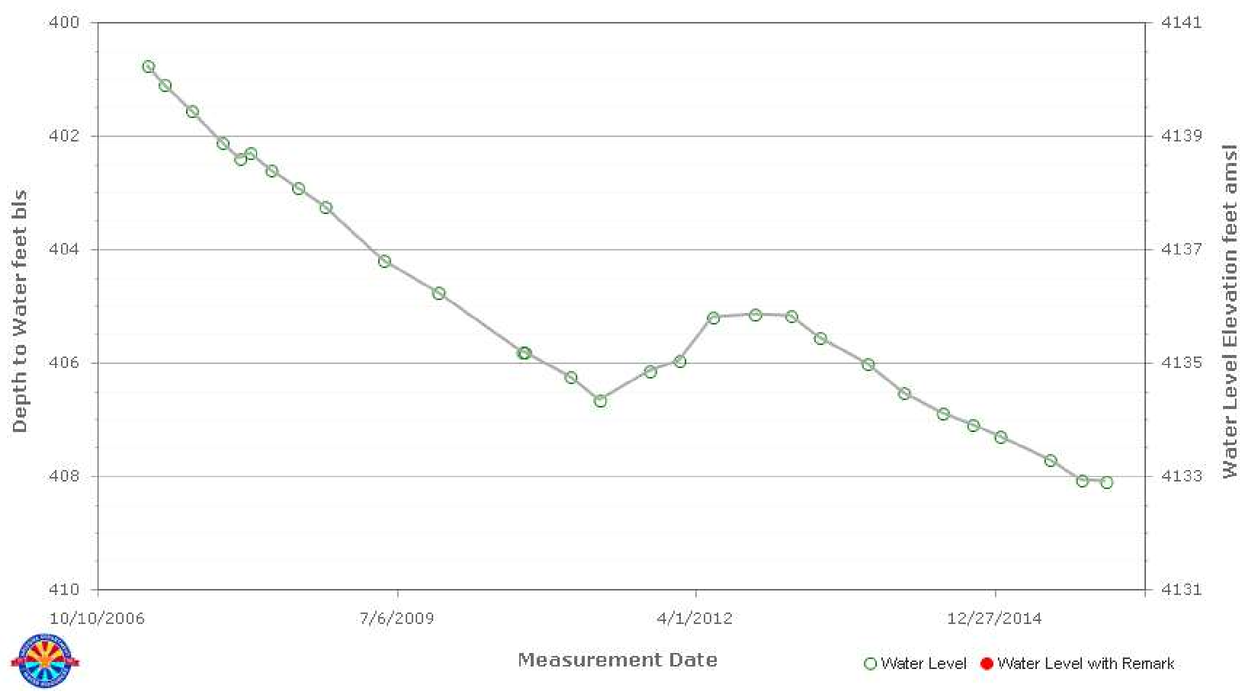

Figure 10. Decline in water level in the Well 4 (east) near Guidani Wash from 2006 to 2015. Note the far greater depth to water in this well (left axis). The water level is currently 408 ft below the surface. Granite bedrock occurs just slightly deeper at 420 ft. Figure from ADWR.

to override any effects from Vigneto pumping. While water withdrawals in the basin center will increase the subsurface hydraulic gradient between it and the basin margin, thus increasing the rate of water flow away from the margin, the impacts of this may be hard to discern in the Kartchner block given its distance from pumping and these two large, competing impacts.

The cottonwood trees along Guindani Wash south of the caverns have perished over the last 20 years (R. Casavant, personal communication, June 2, 2016), reflecting the drop in the water table and less available water within the alluvium. While the drought has undoubtedly contributed strongly to this, pumping from the primary park well and the subsequent increased capture of water from the base of overlying alluvium may partly be the cause. The water-bearing fault zone in the well extends upward to the base of the alluvium and draws water from it to replenish what the park withdraws. Because of the concern over falling groundwater levels and the potential impact on the caverns, park management would like to end groundwater pumping in the park if possible. This would require transporting water from Benson's water system, necessitating a pipeline that could cost several million dollars, which is not a viable option at this time. Taking water from other areas to replace park water is also a concern.

Relationships in Well 4 (Eastern Well)

Well 4 is somewhat enigmatic in that it lies on trend with the large normal fault that separates the Highway Well from the Primary Well, which forms the east margin of the Kartchner block (Figures 1 and 4). The thickness of alluvium in the well is more than 300 ft greater than in the pediment area around the Primary Well, suggesting that the well is drilled on the downthrown side of a fault. In contrast, the thickness of basin fill in the well is hundreds of feet less than in the Caverns LLC wells and the Highway Well to the south drilled on the downthrown side of the fault. Well 4 also did not encounter Paleozoic limestone, which should occur on the downthrown side of such a fault. These relationships suggest that the well is drilled into the fault surface, penetrating the granite beneath the Kartchner block but missing the limestones in the downthrown block because they are farther down dip. This relationship is shown in Figure 11.

Also enigmatic is the depth to water in this well, currently 408 ft, with a water-bearing zone above basement only 12 ft thick. This depth to water is more than 300 ft greater than in alluvium in the wells near the Primary Well, yet more than 300 ft less than the depth to water in alluvium on the downthrown side of the fault in the Highway Well (Figure 4). This suggests that as water moves down gradient, or eastward, in the alluvium on the pediment of the Kartchner block and encounters the fault, it follows the dipping fault surface downward, eventually percolating into the thicker alluvium on the downthrown side to the water level in basin fill (Figure 12). Contours on the water table surface should thus be more tightly spaced across the fault zone.

The dipping fault surface may act as a subsurface guide for water flow. One might expect the thickness of the water-bearing zone to thin above the fault surface because of the increased hydraulic gradient and velocity of the water. In addition, water that has penetrated bedrock in the Kartchner-block should exit the block where water-bearing fractures and channels intersect the fault plane and abutting alluvium. Water released from bedrock in this way would then follow the fault surface downward to the level in basin fill just as water from the pediment alluvium may do.

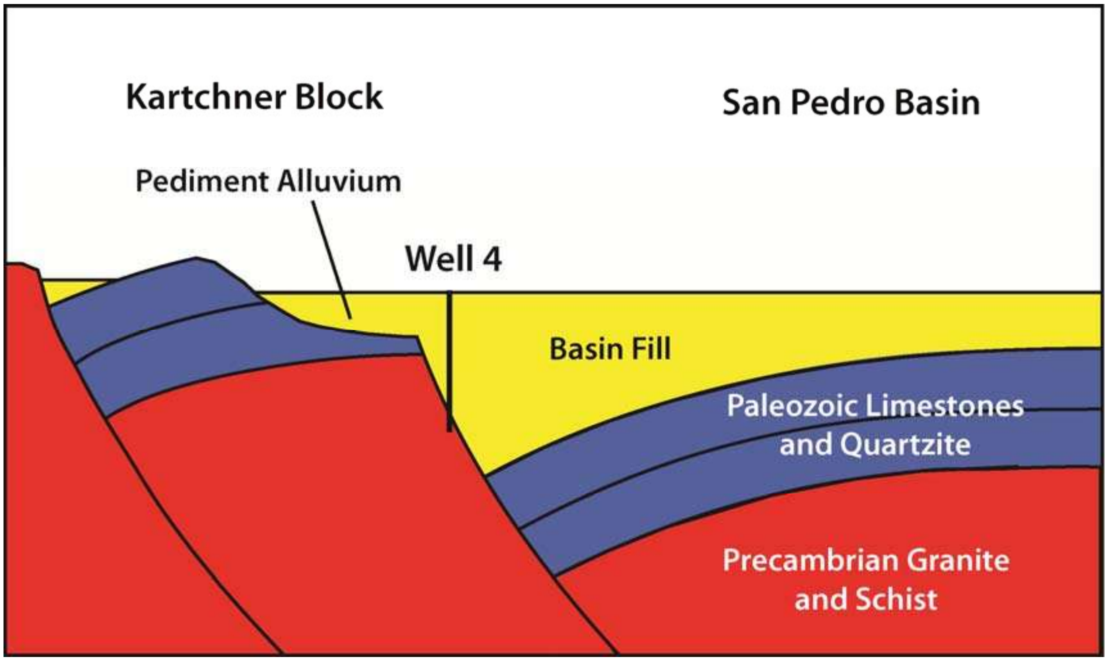

Figure 11. Schematic east-west cross section through Well 4 (eastern well) depicting a possible explanation of geological relationships. The thickness of alluvium in the well is more than 300 ft greater than on the pediment just to the west, suggesting the fault is on the downthrown side of a fault, yet the thickness is far less than that encountered in the Highway and Caverns LLC Wells, which are on the downthrown side of a major basin-bounding fault. If the well were fully on the downthrown side of the fault, it should encounter Paleozoic limestone in the hanging wall but does not.

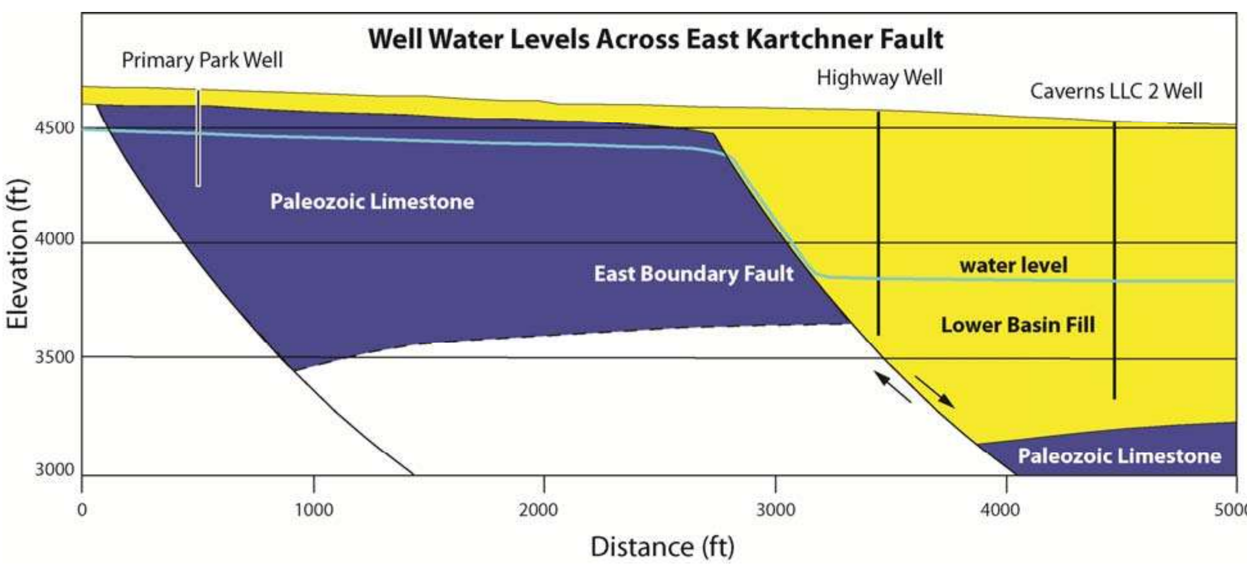

Figure 12. Change in well water levels across the east boundary fault of the Kartchner block along the southern boundary of the park. The elevation of the static water level in the Primary Park Well is ~650 ft above the static water level on the downthrown side of the fault. The fault surface must accommodate the change in levels on either side of the fault. This great difference in water elevation raises the question of whether lowering the water level on the downthrown side of the fault by 15–20 ft, as modeled by *Prucha* (2016), would appreciably increase the rate of water drainage from the Kartchner block. Drawing is to scale.

Other Wells and Their Implications

Around 1984 the Kartchner family drilled a 770-ft-deep well for livestock watering (Highway Well in Figure 4) in what is now the southeast corner of Kartchner Caverns State Park. This well did not reach bedrock, and the static water level in the well, measured in 1989, was 739 ft below the land surface. This level is 764 ft (233 m) below the lowest level of the caverns (*Graf*, 1999). The well was capped because of low water yield. After acquiring the land, Arizona State Parks deepened the well in 1991 to 970 ft hoping to use it for water production for the park but encountered no additional water-producing intervals. State Parks subsequently abandoned the well as dry. Bedrock was not encountered in deepening it.

The Kartchner family owns the land east of the park (now overseen by CSW Sands, LLC) across Highway 90 and drilled a deep well in 2003 to a depth of 980 ft (Caverns LLC 1), apparently in anticipation of developing their land. The Kartchners drilled a second well in almost the same location in 2005 (Caverns LLC 2, Figures 1 and 6) to a depth of 1200 ft and completed it, perforating the bottom 440 ft. The Kartchners apparently drilled the second well hoping to have sufficient water to support the development. The well record indicates that the entire section in the well was alluvial, mostly sand and gravel, although some limestone was recovered in the bottom 300 ft. It is unclear from the record whether the limestone was alluvial or whether bedrock was actually encountered. The original static water levels measured in 2003 and 2005 were 750 ft and 743 ft below the land surface, respectively, essentially the same as in the Highway Well. No shallower aquifers were encountered.

In 2006 Sands Properties, LLC, which became the formal owner of the Kartchner parcel, drilled a test well one mile southeast of the Caverns LLC wells that reached a depth of 1680 ft. The entire section was composed of mostly sand and conglomerate. This location was somewhat more than one mile due east of the fault that bounds the eastern margin of the Kartchner block, and the static water level in the well was 665 ft below the surface. This shallower depth to water reflects the more basinward position of the well.

The Highway and Caverns LLC wells were drilled in a thick section of Lower Basin Fill, indicating that a major basin-bounding fault lies between them and the primary park well 0.6 miles to the west. A cross section of this relationship is shown in Figure 12 and in Figure 13 taken from *Graf* (1999). Gravity data obtained over the caverns in 1989 by *Lange* (1999) (Figure 14) support the existence of this fault, which has a modeled displacement of at least 800 ft. The elevation of the static water level in the Highway and Caverns LLC wells is more than 650 ft lower than in the primary park well to the west and 350 ft lower than in the Well 4 on the park's eastern boundary.

This difference in elevation of the water table (Figure 12) should create a very strong hydraulic gradient between the Kartchner block and adjacent basin fill. This large, existing difference may isolate the Kartchner block to a degree from the effects of lowering the water table in Lower Basin Fill in the alluvium immediately adjacent to the fault. That is, increasing the depth to water on the down-thrown side of the fault by 5 m (16 ft) would result in a very small increase in the hydraulic gradient between the Kartchner block and the basin, which may not appreciably increase the rate of water drainage from the block to the east. The concern, however, is that the primary zones of permeability and porosity in the Kartchner block follow fault zones that parallel this bounding fault, making water transport parallel to it in a northeasterly direction much easier and more likely. It is this potential that various parties would like revised modeling to address.

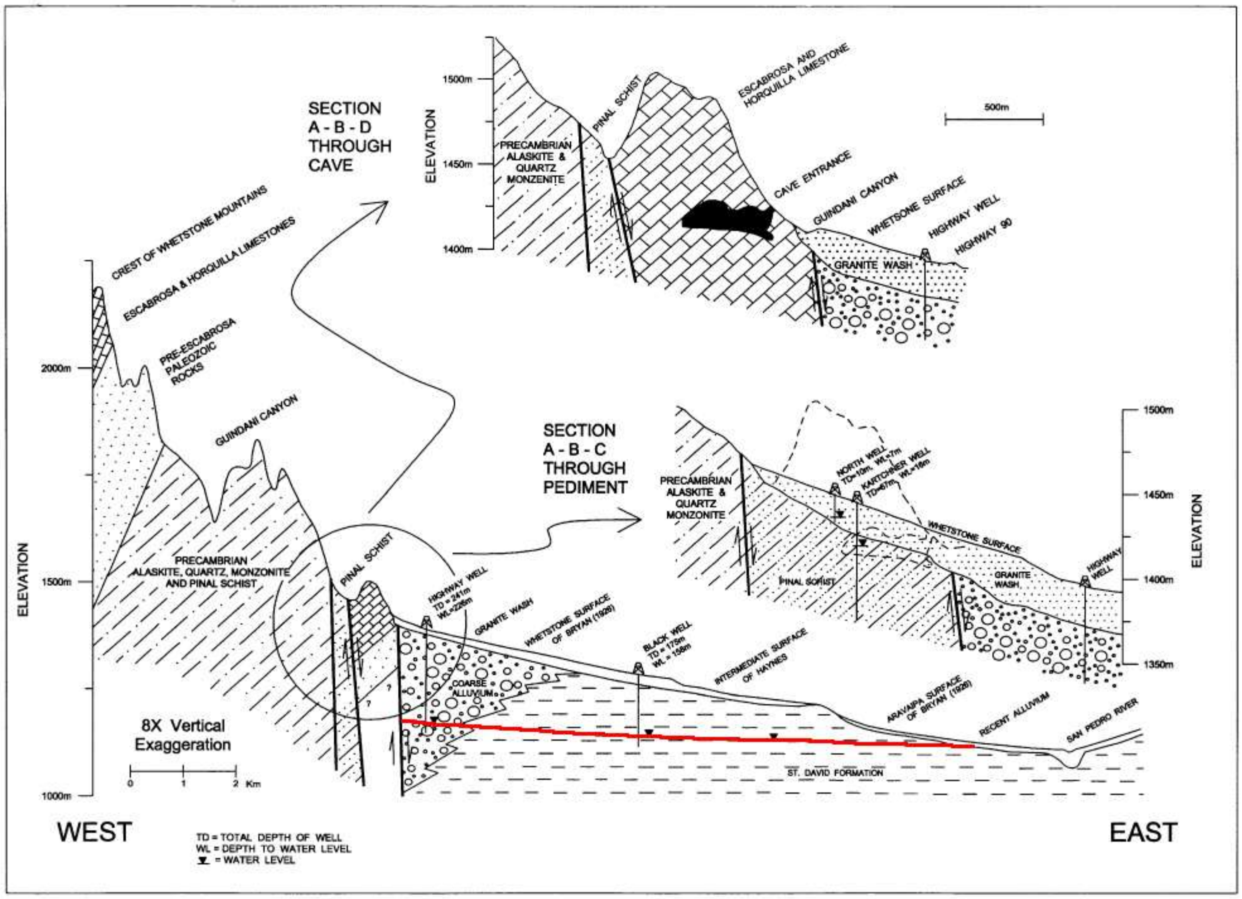

Figure 13. Cross section from the San Pedro River through Kartchner Caverns State Park (Figure 2 from *Graf*, 1999) showing the basin-bounding fault between the Highway Well and the Kartchner block. The downthrown side of the fault contains a thick section of coarse alluvium that led the Kartchner family to think the section might serve as an aquifer for development. The depth to water on the downthrown side of the fault is greater than 700 ft, and pumping capacity appears to be low. The red line is the static water level derived from three wells (denoted by partly covered black triangles).

Water coursing down streams from the Whetstone Mountains infiltrates the alluvium and bedrock of the Kartchner block, eventually flowing in the subsurface along multiple paths into the thick section of basin fill immediately east of the fault. The Kartchner block effectively acts as an intermediary reservoir that captures and then later releases water more gradually to the alluvial basin. *Graf* (1999) notes that when the caverns drain following flooding, all of the water must pass through fracture and channel systems in bedrock to escape. He speculates that all of this water eventually reaches the basin-fill aquifer to the east through this bedrock system.

The Arizona Department of Water Resources has records for two older, shallow wells east of the park drilled for cattle ranching (Stock Wells 1 and 2; Well 2 not shown). The depth to water in Stock Well 1 was 92 feet, measured in 1977. Stock Well 2 was drilled or dug in 1908 and said to be artesian, with water essentially at the surface. Thus shallow sand and gravel layers of younger basin fill do serve as aquifers east of the park even though the Caverns LLC 1 and 2 wells did not encounter water in them. Given the thickness of basin fill alluvium beneath these stock wells and the static water levels in the Highway and Caverns LLC wells, these aquifers are very likely perched and underlain by clay layers that inhibit percolation and loss of water to the deeper aquifer.

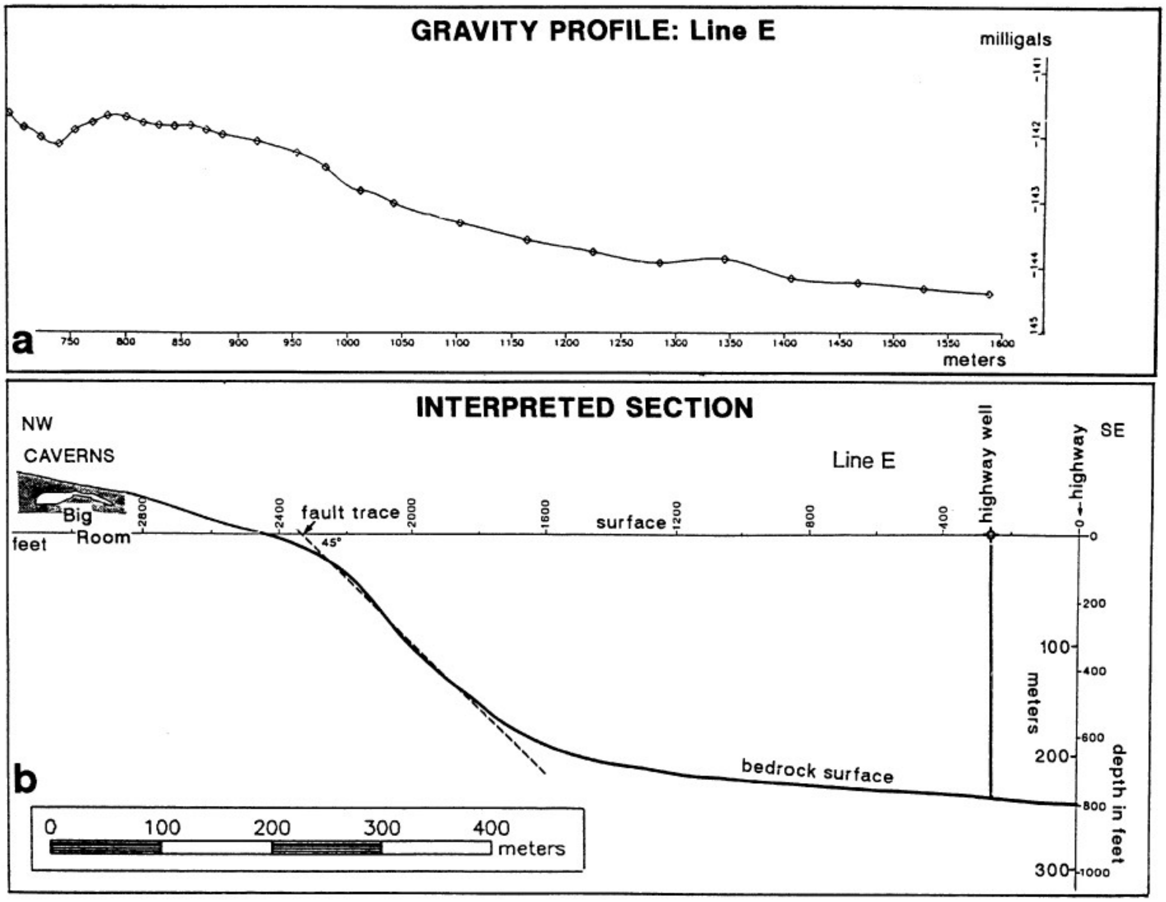

Figure 13. Gravity model from *Lange* (1999) along a transect from the Highway Well across the Big Room of the caverns. Modeling indicates a down-to-the-east fault with displacement of up to 800 ft, supporting the well data.

Integrating of the Alluvial Aquifer with the Bedrock Aquifer

A fundamental concern about the Prucha hydrological model for the Benson subbasin is that it assumes no hydrological connection between the alluvial aquifers of the basin and the limestone bedrock aquifers around the basin margins. This connection likely exists to some degree, resulting from the contact of fault and fracture zones in limestone bedrock with abutting sands and conglomerates of basin fill. Paleozoic limestone in fault blocks on the west side of the Benson subbasin serves as an aquifer around the basin margin (Figure 15), even though overall water production rates from it are much lower. The principal porosity and permeability in the limestone are localized in fault zones and associated fracture and dissolution networks, resulting in more-restricted zones of water storage and flow. These zones and networks must be modeled differently than the high-porosity and permeable sands and conglomerates of the basin center, which are gently dipping or nearly horizontal.

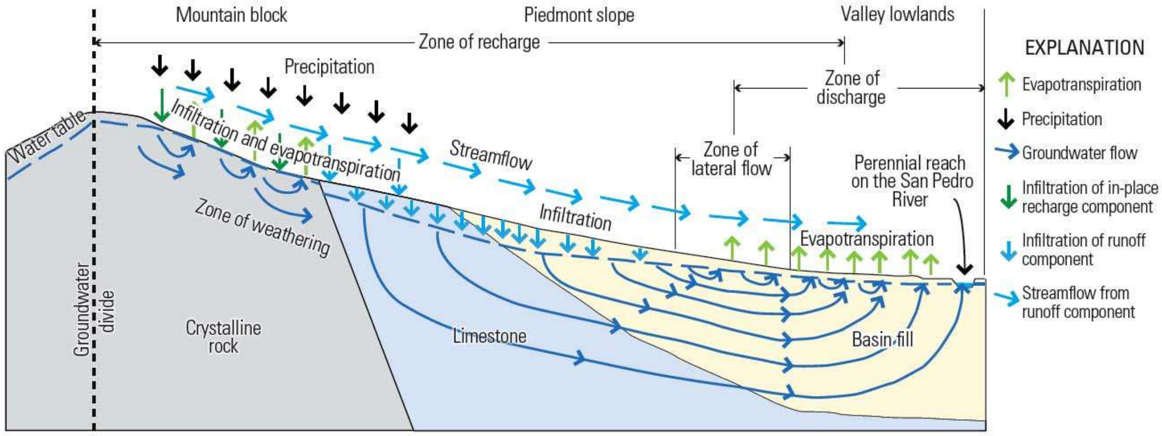

Figure 24. Conceptual illustration of groundwater recharge and discharge in the middle San Pedro Watershed.

Figure 15. Schematic groundwater circulation model for the Benson subbasin from *Dickinson et al.* (2010). This model assumes continuous water flow from and through the basin margin Paleozoic limestone.

The basin margin is characterized by multiple, large-scale east-dipping faults, resulting in several parallel, rotated fault blocks, as shown schematically in Figure 16, some of which are now buried east of the mountain front. Prucha's Figure 9, included here as Figure 17, hints at this stepped architecture. The well that the Kartchner family drilled east of the park in 2005 passed through 1200 ft of alluvium, indicating that an east-dipping fault with at least that much displacement lies between the park and the well. These long, linear fault blocks are cut by cross faults as illustrated in Figures 4 and 18, which provide a network of hydrological connections. The primary faults that bound the Kartchner block trend northeastward into the heart of the Vigneto development and may act as conduits for water flow in that direction.

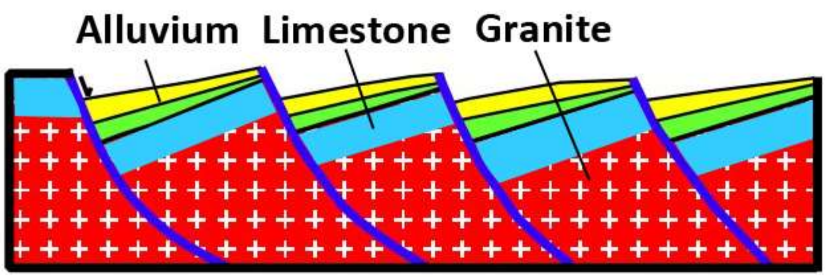

Figure 16. Schematic cross section showing the multiple fault blocks that bound and potentially underlie the west side of the Benson subbasin.

A more complete hydrological model for the Benson subbasin would combine the more horizontal and uniform porosity and permeability of the alluvial aquifers of the basin center with the more localized and dipping zones of porosity and permeability in the limestone aquifers around the basin margin. Determining the configuration of the network of faults, fractures, and dissolution channels in the limestone and their effective hydrologic conductivity would be the most difficult parameters to establish.

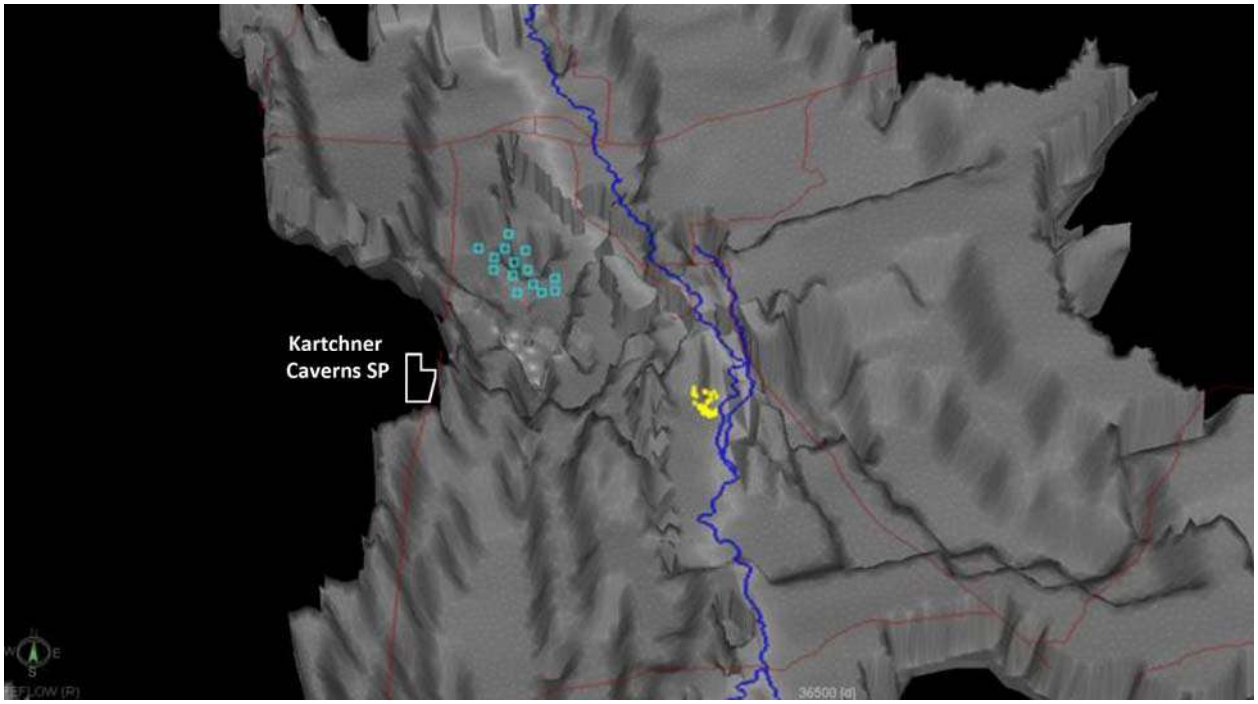

Figure 17. Modeled bedrock surface from Figure 9 of *Prucha* (2016). This model is taken from the original Modflow model for the basin done by *Goode and Maddock* (2000). The figure hints at a stepped-down basement architecture beneath the basin created by parallel Basin and Range normal faults.

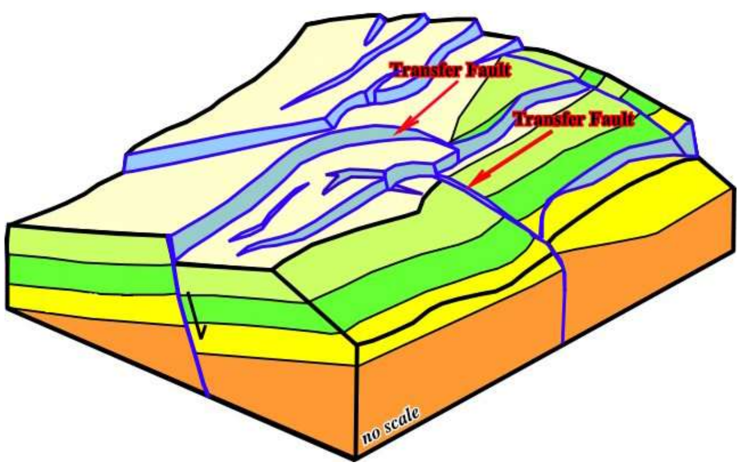

Figure 18. Schematic diagram showing how faults bounding individual blocks may be linked by cross faults.

Combining these two aquifers in an integrated model is worth considering given how water saturates and fills every possible pore and pathway beneath the water table. Water continuously flows down gradient through any available avenue depending on permeability and the hydraulic gradient. If the Prucha model is reasonable (Figure 19) in predicting the extent of water drawdown by Vigneto pumping, that drawdown might affect the limestone aquifers in fault blocks around the basin margin. While the predicted effect of drawdown opposite the caverns is small (5 m or16 ft) and would at first seem inconsequential, of greater hydrologic concern may be the increased transfer of water along strike to the northeast through the network of highly permeable faults and related solution channels. These faults and channels would facilitate much stronger water transport in that direction. The existence of limestone bedrock in Whetstone Ranch well EX-A supports this possibility.

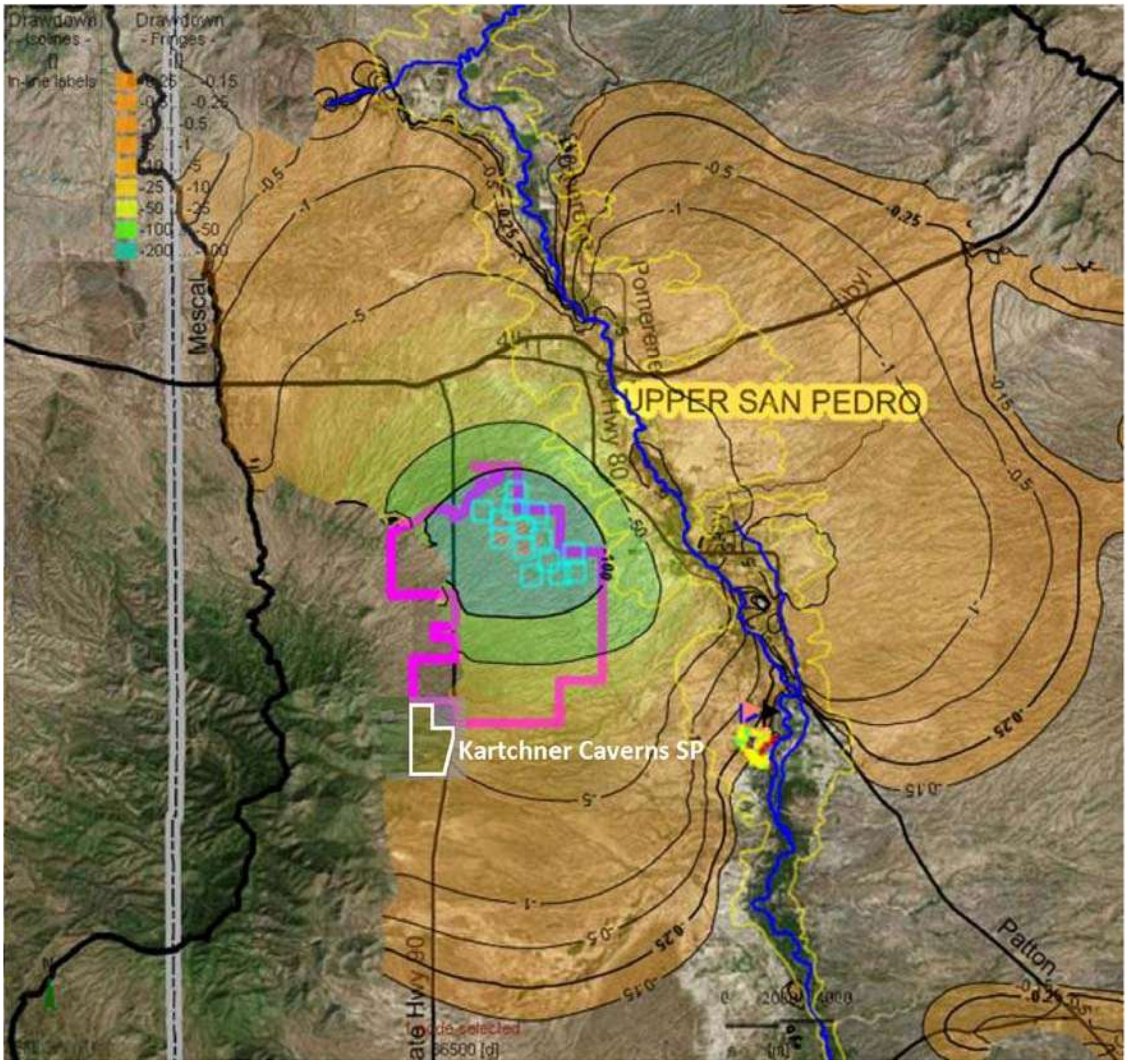

Figure 19. Figure 17 from *Prucha* (2016) showing the location of Kartchner Caverns State Park (white outline) with respect to the Vigneto development (pink outline) and simulated groundwater drawdown (in meters) for 100 years. The 5-m (16.4-ft) drawdown contour intersects the Kartchner block at the entrance to the caverns.

In the past Casavant has requested the U.S. Geological Survey and Arizona Department of Water Resources to model the hydrology of the Benson subbasin with an interconnection between the alluvial aquifer of the basin fill and the limestone aquifer of the basin rim. He feels this is needed to assess how water withdrawals in the basin may affect the basin rim area. A primary objective would be to determine the extent to which increasing water use in the basin could reduce the water resources within basin-rim limestone aquifers and how this reduction might affect the caverns and water supply for the park.

To fully assess impacts on park groundwater over the next 100 years, one would need to combine any effects from Vigneto with those resulting from climate change, which already appears to have significantly affected the caverns (*Toomey and Nolan*, 2005), and groundwater pumping by the park itself. The magnitude of these latter two factors could overwhelm and obscure the potential impacts from Vigneto. Park staff are already deeply concerned about these impacts and are trying to compensate for them. Diminishing water and warming temperatures, whatever the cause, will negatively affect the physical and ecological processes that govern the caverns and concern everyone who manages and appreciates them.

References

Creasey, S. C., 1967. Geologic map of the Benson quadrangle, Cochise and Pima Counties, Arizona, *U.S. Geological Survey Miscellaneous Geologic Investigations Map I-470*, scale 1:48,000. Available from http://ngmdb.usgs.gov/Prodesc/proddesc_1297.htm. Accessed June 5, 2016.

Dickinson, J.E., Kennedy, J.R., Pool, D.R., Cordova, J.T., Parker, J.T.C., Macy, J.P., and Thomas, B.E., 2010, Hydrogeologic framework of the middle San Pedro Watershed, southeastern Arizona, *U.S. Geological Survey Scientific Investigations Report 2010–5126*, 36 p. Available from http://pubs.usgs.gov/sir/2010/5126/. Accessed June 6, 2016.

Goode, T.C., and Maddock, T.I., 2000, Simulation of groundwater conditions in the Upper San Pedro Basin for the evaluation of alternative futures: University of Arizona, Department of Hydrology and Water Resources, catalog no. 2000-030, 113 p. Available for purchase only.

Graf, C.G., 1999, Hydrology of Kartchner Caverns State Park, *Journal of Cave and Karst Studies*, **61**(2), 59–67. Available from https://caves.org/pub/journal/PDF/V61/v61n2-Graf.pdf. Accessed June 4, 2016.

Jagnow, D. H., 1999, Geology of Kartchner Caverns State Park, *Journal of Cave and Karst Studies,* **61**(2), 49–58. Available from https://caves.org/pub/journal/PDF/V61/v61n2-Jagnow.pdf. Accessed June 4, 2016.

Lange, A.L., 1999, Geophysical studies at Kartchner Caverns State Park. *Journal of Cave and Karst Studies*, **61**(2), 68–72. Available from https://caves.org/pub/journal/PDF/V61/v61n2-Lange.pdf. Accessed June 10, 2016.

Prucha, R.H., 2016, Evaluation of impacts of proposed well pumping at the Villages of Vigneto Development, southwest of Benson, Arizona on groundwater beneath the Saint David Cienega, in the Northern San Pedro River National Conservation Area (unpublished report commissioned by the Center for biological Diversity), Integrated Hydro Systems, Golden, Colorado, 38 pp. Available from http://tucson.com/impacts-of-vigneto-pumping/pdf_c26a2483-ac8d-58c3-bff0-062d43f438d1.html. Accessed June 5, 2016.

Shipman, T.C., and Ferguson, C.A., 2003. Geologic Map of the McGrew Spring 7½' Quadrangle, Cochise County, Arizona, *Arizona Geological Survey Digital Geologic Map 35*, scale 1:24,000. Available from http://repository.azgs.az.gov/uri_gin/azgs/dlio/566. Accessed June 5, 2016.

Toomey, R.S., 2009, Geological monitoring of caves and associated landscapes, *in* Young, R., and Norby, L., *Geological Monitoring*, Boulder, Colorado, Geological Society of America, p. 27–46, doi: 10.1130/2009.monitoring(02). Available from https://www.nature.nps.gov/geology/monitoring/files/geomon-02.pdf. Accessed June 13, 2016.

Toomey, R. S., and Nolan, G., 2005, Environmental change at Kartchner Caverns: Trying to separate natural and anthropogenic changes, *USDA Forest Service Proceedings RMRS-P-36*, 264–270. Available from http://www.treesearch.fs.fed.us/pubs/23212. Accessed June 11, 2016.