



Douglas A. Ducey
Governor

State of Arizona
Oil and Gas Conservation Commission

1110 W. Washington Street, Phoenix, AZ 85007
602-771-4501

www.azogcc.az.gov
Dennis L. Turner, Oil and Gas Administrator

Commissioners:
Frank Thorwald, Chair
J. Dale Nations, Ph.D., Vice Chair
Stephen R. Cooper
William C. Feyerabend

September 7, 2018

IN THE MATTER OF APPLICATION TO:
EXCEPTION TO SPACING RULE, FILED BY:

ARIZONA ENERGY PARTNERS, LLC

ON SECTION 16, TOWNSHIP 14 NORTH
RANGE 25 EAST, G&SRM,

FOR THE PREVIOUSLY PERMITTED WELL
AEP 16-1 (PERMIT 1215)

NOTICE OF HEARING

ARIZONA ENERGY PARTNERS, LLC., having first filed application and notice of intention to drill, and having received approval on April 18, 2017 to drill the AEP 16-1 for oil on Section 16, Township 14 North, Range 25 East, on the Gila and Salt River Base and Meridian, the location being in Apache County, Arizona, and having requested in an application dated August 14, 2018 that an exception be made to Arizona Administrative Code R12-7-107(B) relative to the spacing of gas wells,

IT IS HEREBY ORDERED, under the provisions of Arizona Administrative Code R12-7-107(E) that a public hearing be held at the office of the Arizona Department of Environmental Quality, 1110 West Washington Street, Phoenix Arizona on the 14th September 2018, Room 3100B at the hour of 10:00 a.m. at which time and place any and all interested parties may produce evidence as to why said application should or should not be granted.

GIVEN under my hand and the seal of seal of the State of Arizona this 7th day of September, 2018.

A handwritten signature in cursive script, reading "Frank Thorwald".

Frank Thorwald

Chairman, Oil Gas Conservation Commission

AGENDA FOR PUBLIC HEARING FOR ARIZONA ENERGY PARTNERS, LLC.

September 14, 2018

10:00 a.m., Room 3100B

Arizona Department of Environmental Quality

- Presentation by Arizona Energy Partners, LLC. (AEP): Justification for well spacing exception for AEP 16-1, including all relevant subsurface data.
- The Commission shall discuss, consider and vote to grant or deny the well spacing exception.

By ruling of the Arizona Oil and Gas Conservation Commission, any members of the public wishing to speak at this hearing are limited to three (3) minutes.

NOTE: IMMEDIATELY FOLLOWING THE CONCLUSION OF THIS HEARING, THE COMMISSION WILL RECONVENE FOR A REGULAR PUBLIC MEETING. SEE SEPARATE AGENDA.

For additional information about this meeting, contact Dennis L. Turner, Oil and Gas Program Administrator, ogcc@azdeq.gov or (602) 771-4501. A copy of the agenda and background material provided to Commission members (with the exception of material relating to possible Executive Sessions) is available for public inspection at the Arizona Department of Environmental Quality (ADEQ), Records Management Center, 1110 W. Washington Street, Phoenix, AZ 85007, or online at <http://www.azogcc.az.gov/meetings>.

ADEQ will take reasonable measures to provide access to department services to individuals with limited ability to speak, write or understand English and/or to those with disabilities. Requests for language interpretation, ASL interpretation, CART captioning services or disability accommodations must be made at least 48 hours in advance by contacting Ian Bingham, Title VI Nondiscrimination Coordinator at 602-771-4322 or idb@azdeq.gov. Teleprinter services are available by calling 7-1-1 at least 48 hours in advance to make necessary arrangements.

ADEQ tomará las medidas razonables para proveer acceso a los servicios del departamento a personas con capacidad limitada para hablar, escribir o entender inglés y / o para personas con discapacidades. Las solicitudes de servicios de interpretación de idiomas, interpretación ASL, subtítulos de CART, o adaptaciones por discapacidad deben realizarse con al menos 48 horas de anticipación contactando a Ian Bingham, Coordinador de Anti-Discriminación del Título VI al 602-771-4322 o ibd@azdeq.gov. Los servicios de teleimpresores están disponibles llamando al 7-1-1 con al menos 48 horas de anticipación para hacer los arreglos necesarios.

To request an auxiliary aid or service for accessible communication, please contact Ian Bingham, (602) 771- 4322, idb@azdeq.gov



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Public Hearing of the Arizona Oil & Gas Conservation Commission

Arizona Energy Partners Well Spacing Exception

10:00 a.m., September 14, 2018, ADEQ Conference Room 3100B

Name / Organization – please print	email	phone
FRANK THORWALD, OGCC		
Bill Feyerabend, OGCC		
NOA BRUHIS, ASU		
Todd Clement, Cobalt Group		
Scott Barnes, Corsant Group		
STEPHAN ROMANOVSKY, ASU		
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Jamie Hogue - AEP	jrhogue@azogccmail.com	
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Joe Dixon AZ State Land	jdixon@azland.gov	602-542-2685

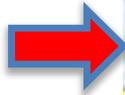
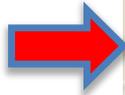
Name / Organization – please print	email	phone
Rich Zeise	Rich.Zeise@azogc.gov	542-8553
Bailey Reynolds / ASU		
DR. DACE NATIONS, OGCC	VIA PHONE	
DENNIS TURNER, OGCC Admin.		
LISA TEST & OTHERS, NO FRACKING AZ	VIA PHONE	



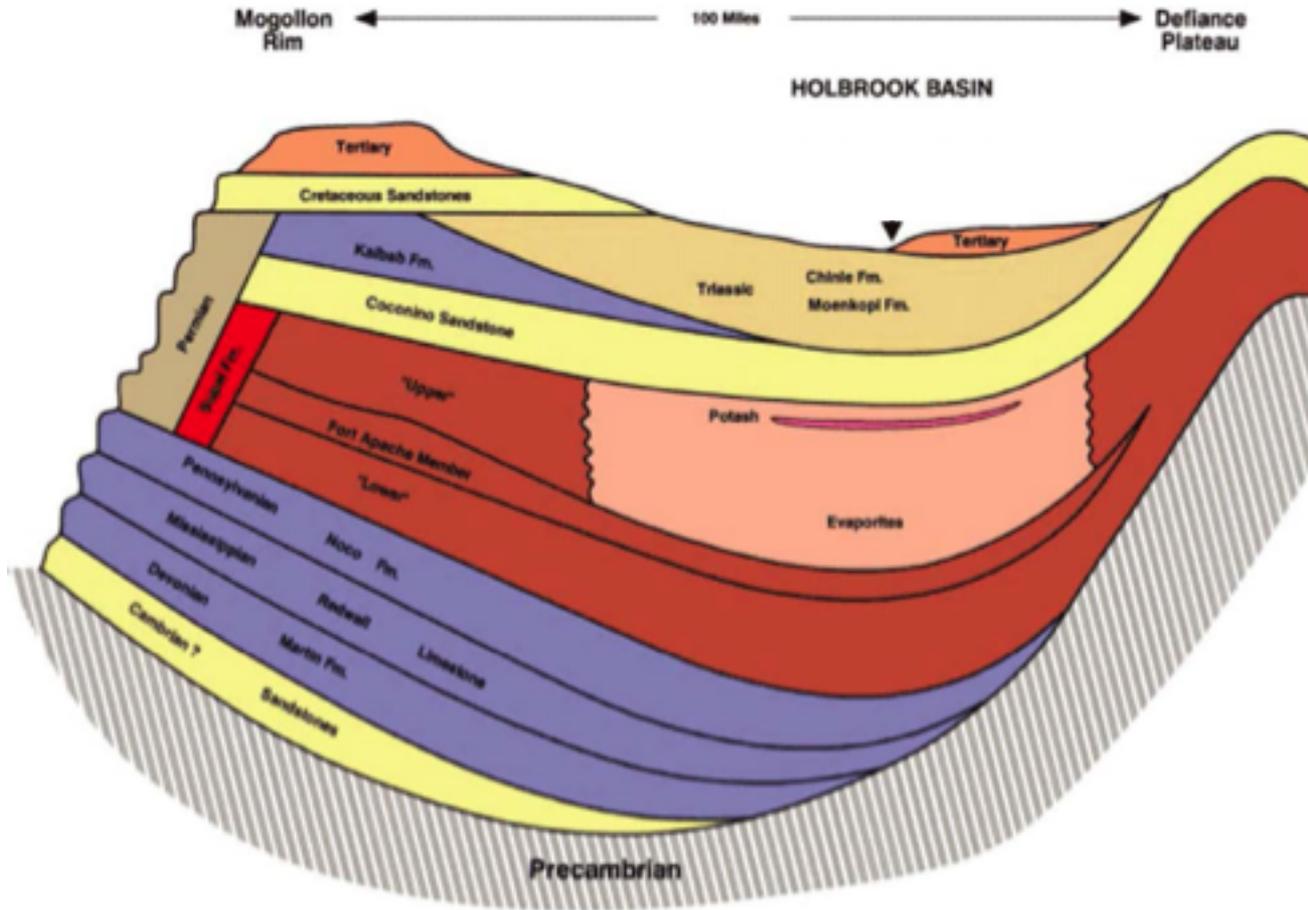
**ARIZONA OIL AND GAS CONSERVATION COMMISSION
JULY 13, 2018**

Formation Descriptions

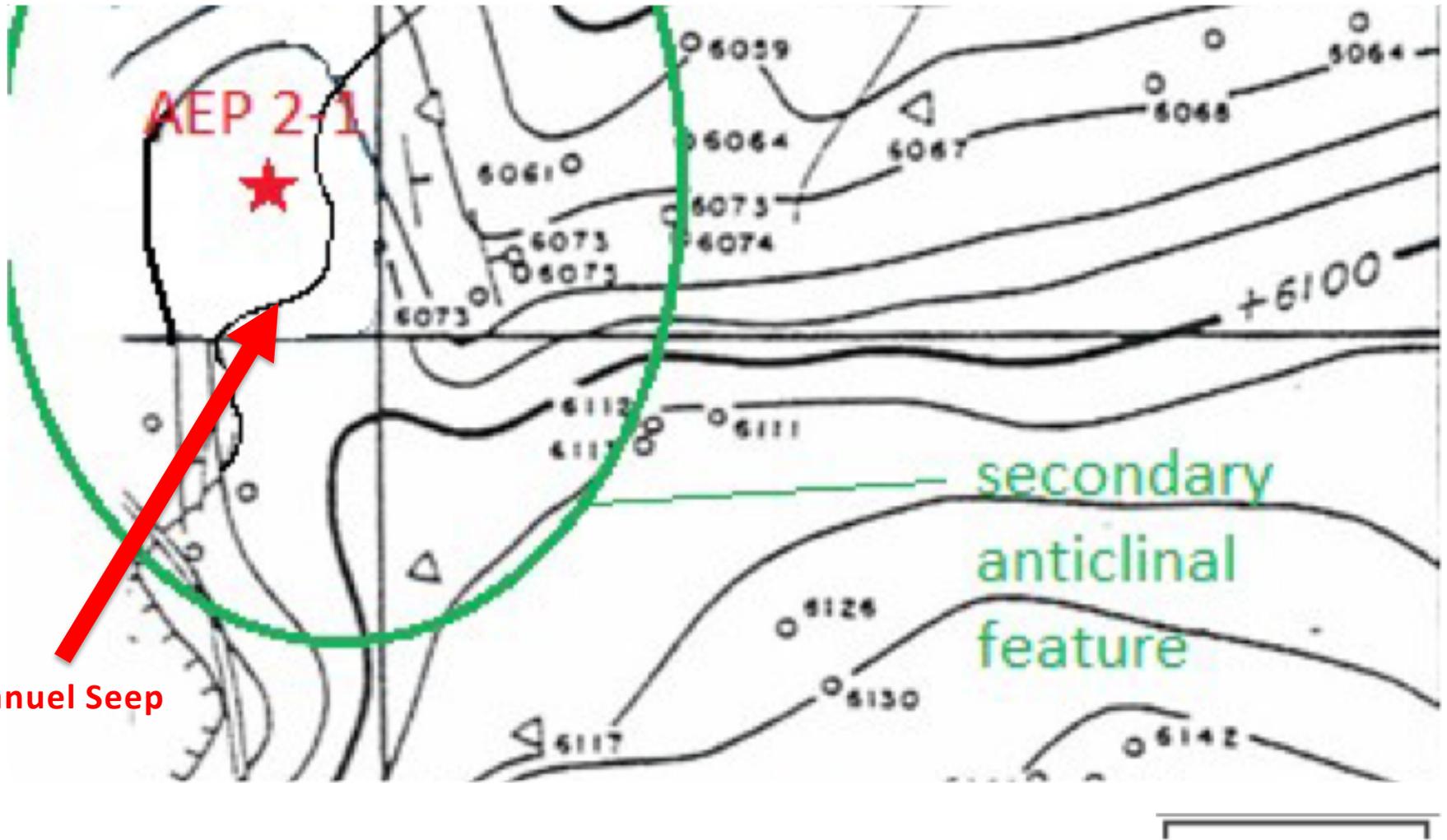
Age	Formation Name	Thickness and Description
Triassic	Moenkopi	0-420' of shale, some sandstone
Permian	Kaibab Limestone	0-75' of limestone, some dolomite and sandstone
Permian	Coconino Sandstone	350-400' of light-colored sandstone, to tan and red in lower part, w/ quartz overgrowths on grains
Permian	Supai Group	200-750' of dark mudstone and siltstone at base, overlain by 600-900' of red siltstone and sandstone with some interbedded carbonates and evaporites, overlain by 0-80' of the Fort Apache Member (limestone and/or dolomite, porous, some shale and evaporites); overlain by 450-1300' of evaporites (halite & gypsum), some carbonates and redsiliciclastics.
Pennsylvanian	Naco	790-1100', more carbonate to the south, more shale to the north. Consists of alternating gray limestones, reddish-brown calcitic shale some dolomitic limestone, generally non-porous, equivalent to Molas formation in Utah, Colorado, New Mexico
Pennsylvanian	Hermosa	0-250' of interbedded shale and lesser limestone
Pennsylvanian	Molas	karst breccia and red shale
Mississippian	Redwall	0-100' of fossiliferous limestone, some dolomite
Devonian	Martin	0-130' of porous dolomite, some interbedded limestone, sandstone and shale
Cambrian	Tapeats/McCracken Formation	0-90' of sandstone
PreCambrian	Basement	granite and local metamorphics



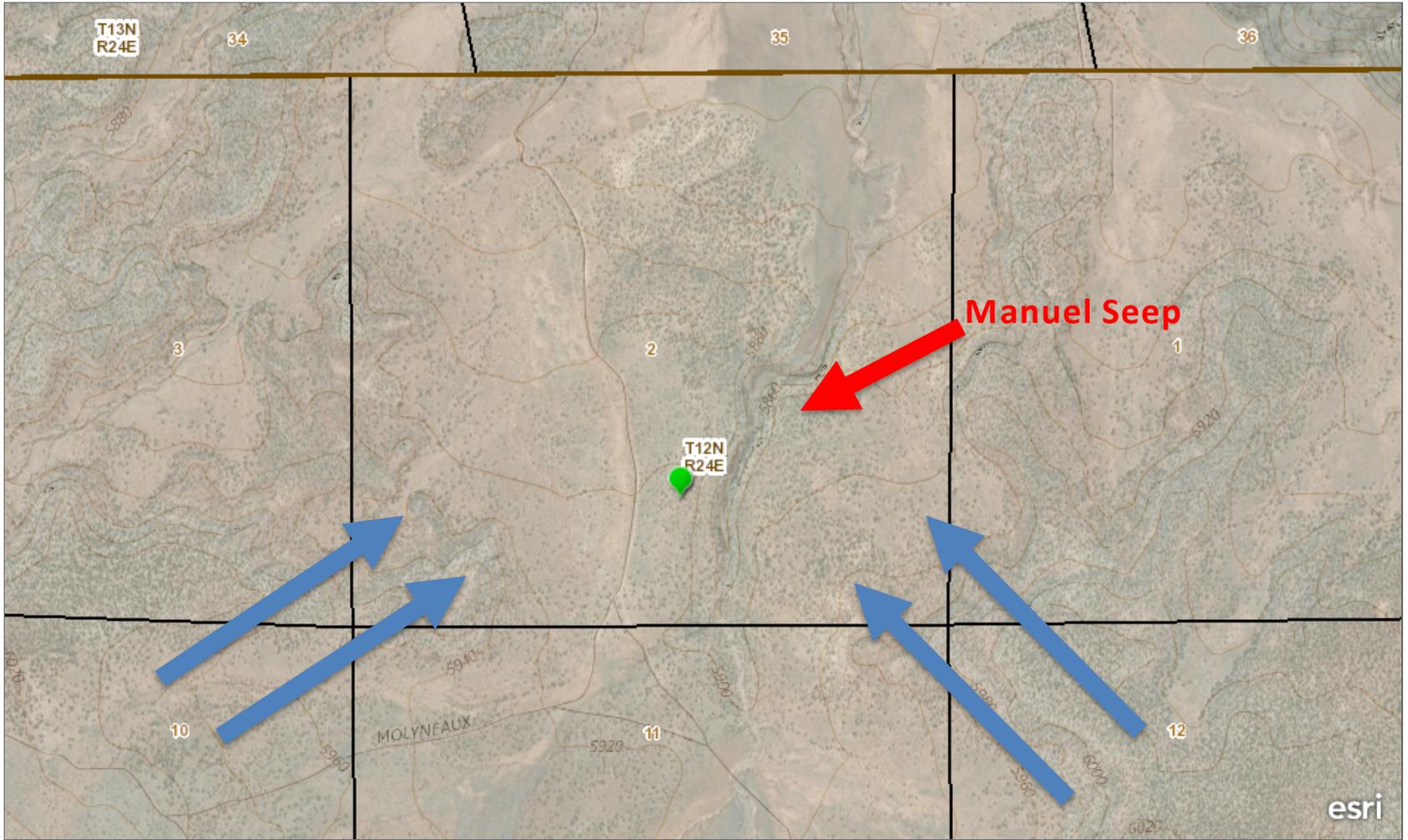
Simplified Stratigraphic Section Holbrook Basin



Target: Regional Anticlinal Feature



Regional Drainage



AZ OGCC Administrator

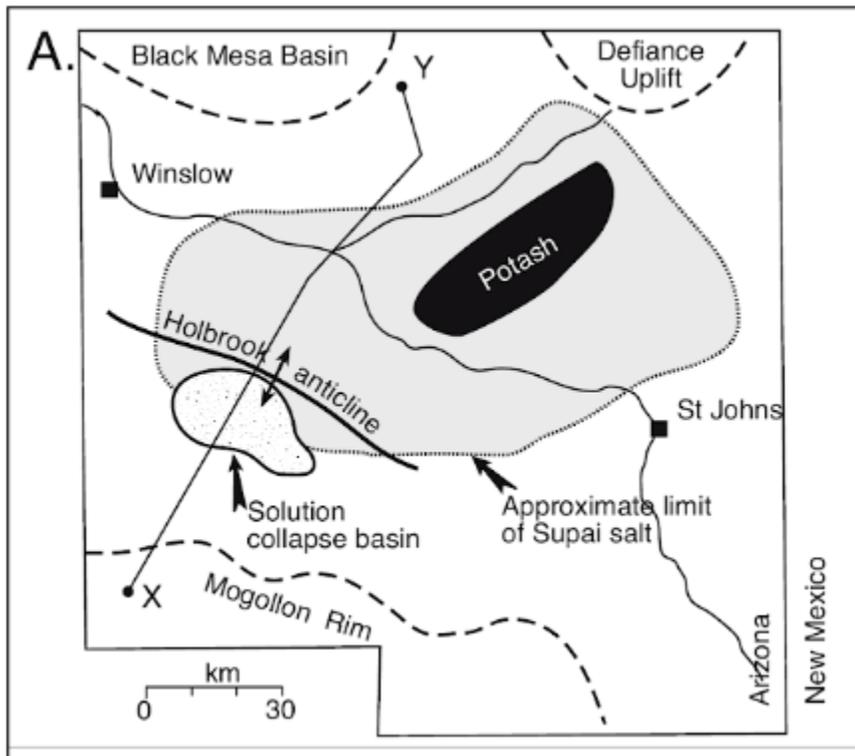
From: Lisa Test <nofrackingaz@gmail.com>
Sent: Friday, September 14, 2018 12:19 AM
To: AZ OGCC Administrator
Subject: Document submissions
Attachments: Variations in Evaporite Karst in the Holbrook Basin Arizona (1).pdf

Follow Up Flag: Follow up
Flag Status: Flagged

Dennis,
I would like to submit these two documents for the AZOGCC meetings on Friday September 14th, 2018 starting at 10am. I will be attending by phone.

Thank you,
Lisa Tes

This information came from the book...
Evaporites: Sediments, Resources and Hydrocarbons
By John K. Warren



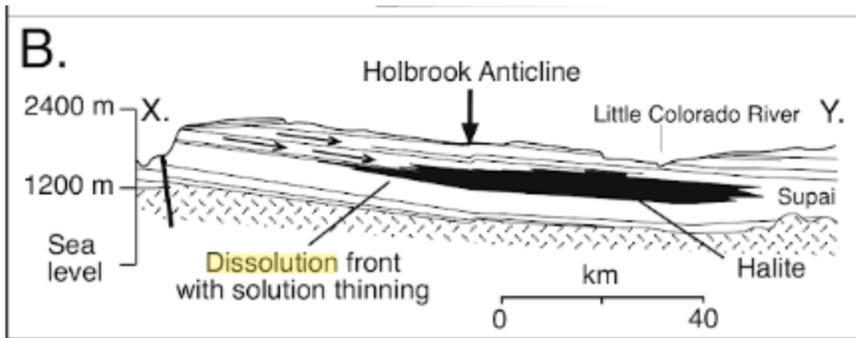
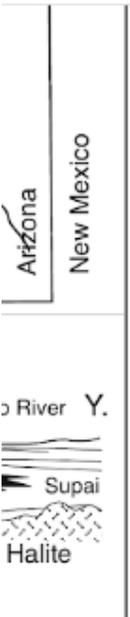


Figure 7.11. Holbrook Anticline, Arizona. A) Distribution of **dissolution** features seen at the surface and their relationship to the underlying Permian Supai Salt. B) Cross section showing how the Holbrook Anticline is a monocline **flexure** created by **dissolution** of the underlying Supai Salt (after Neal, 1995).



Holbrook Anticline, Arizona

Subsidence driven by natural salt solution at depth generates regional-scale drape or monoclinal folding in strata atop the retreating salt edge. This is the corollary of the formation of a subsidence trough (Figures 7.7a, 7.8b). The 70-km long **dissolution** front in the Permian Supai Formation of Arizona is defined by more than 300 sinkholes, fissures and subsiding depressions (Neal, 1995). Away from the **dissolution** zone the northeasterly-dipping Supai Formation is composed of up to 150 metres of bedded halite, with local areas of sylvite along its northern extent (Figure 7.11a). Atop the solution front there are a number of topographic depressions with playa lakes that in total cover some 300 km². This expanse of salt removal has produced a regional gravity depression, largely coincident with a surface topographic depression where as much as 100 metres of collapse and topographic displacement has occurred. The solution front is also essentially coincident with the updip end of the Holbrook Anticline, a **flexure**

dissolution
underlying
Holbrook Anticline
Permian Supai Salt

defined by dip reversal in an otherwise northeasterly dipping succession (Figure 7.11b).

Rather than orogenically driven, the Holbrook Anticline is a subsidence-induced monoclinial **flexure** created by the northward migrating **dissolution** front (Figure 7.11b). It may be the largest single solution-collapse fold structure in the world (Neal, 1995). The reverse dip of the **flexure** directly overlies the salt-**dissolution** front and marks the location of two major collapse depressions known as The Sinks and Dry Lake Valley, both occur where salt is within 300 m of the surface (Peirce, 1981). Although it has periodically held surface water, reports of several hundred acre-feet of flood water in the Dry Lake Valley playa draining overnight supports the notion of active fissure and cavern formation related to salt removal at depth. Major surface drainage events took place in 1963,1979,1984

and 1995, with more than 50 new sinkholes forming in the valley during that period. The continuing rapid appearance of new sinkholes testifies to the ongoing nature of **dissolution** in the underlying evaporites. According to Neal (1995), **dissolution** front features began forming in the landscape in the Pliocene and continue to form today.

Other karst features attributed to evaporite **dissolution** in the Holbrook basin are; pull-apart fissures, graben sinks (downward-dropped blocks), breccia pipes and plugs, and numerous small depressions with and without sinkholes (Neal et al., 1998, 2001). The presence of the more than 500 karst features in the Holbrook basin, some of which formed in days, evokes practical karst hazard and infrastructure concerns, even in such a sparsely populated region (Martinez et al., 1998).

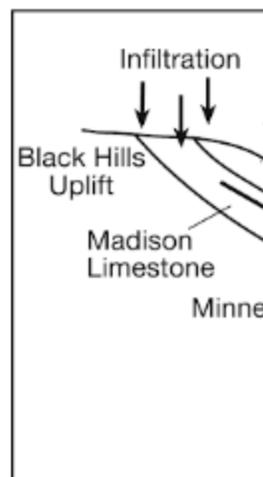


Figure 7.12. Minnelusa the anhydrite **dissolution** away from the centre of the outflow pipes dry

VARIATIONS IN EVAPORITE KARST IN THE HOLBROOK BASIN, ARIZONA

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Abstract

At least six distinct forms of evaporite karst occur in the Holbrook Basin—depending considerably on overburden and/or bedrock type. Early Permian evaporites in the 300-m-thick Corduroy Member of the Schnebly Hill Formation include halite, sylvite, and anhydrite at depths of 215-250 m. Karst features result from collapse of overlying Permian and Triassic strata into underlying salt-dissolution cavities.

Evaporite karst occurs primarily along the 100+ km-long dissolution front on the southwestern edge of the basin, and is characterized by numerous sinkholes and depressions generally coincident with the axis of the Holbrook Anticline—in reality a dissolution-collapse monocline. “The Sinks” comprise ~ 300 individual sinks up to 200 m across and 50 m deep, the main karst features along the dissolution front. Westerly along the dissolution front, fewer discrete sinkholes occur, and several breccia pipes are believed to be forming. Numerous pull-apart fissures, graben-sinks, sinkholes, and broad collapse depressions also occur.

A newly recognized subsidence/collapse area of some 16 km² occurs in the western part of the basin, northward from the extension of the Holbrook “anticline.” The Chimney Canyon area is some 12 km east of McCauley Sinks, a postulated breccia pipe exemplified in, and possibly manifested in at least four other closed depressions. Interferometric Synthetic Aperture Radar (InSAR) data of one depression shows active subsidence of ~4 cm/yr.

Karst formation is ongoing, as shown by repeated drainage of Dry and Twin Lakes into newly opened fissures and sinkholes. These two playa lakes were enlarged and modified in recent years into evaporation

impoundments for effluent discharge from a nearby pulp mill. Four major drainage events occurred within these playa reservoirs during the past 45 years, collectively losing more than 1.23 x10⁷ m³ (10,000 acre-feet) of water and playa sediment. Drainage occurs through piping into bedrock joints in Triassic Moenkopi Formation (sandstone) in the bottom and along the margins of these playas. Effluent discharge has been discontinued into these playas, although recurring precipitation can fill the basins.

Introduction

Evaporite karst in the Holbrook Basin of northeastern Arizona occurs above interstratal bedded evaporites, principally halite, in Permian sediments. The karst displays a variety of geomorphic features common to many carbonate-karst terrains (Jennings, 1985), including more than 500 sinkholes, fissures, depressions, and other features (Neal et al., 1998). The karst features are the subject of environmental concern because of increasing encroachment of residential and industrial development, and because of potential groundwater influx through surface karst openings.

Bahr (1962) was among the first to show that karst formation is still active, noting that a sinkhole visible on 1953 air photos had not existed 17 years earlier. New fissures and sinkholes have been observed many times since, with more recent activity in December 1995 on the south side of the collapse basin, and during 1996-8 in Dry Lake Valley, a major collapse depression that contains several artificially impounded playa lakes.

Local ranchers have continued to report periodic sinkholes forming when the valley floor flooded. These karst features are among the lesser known geomorphic curiosities in Arizona, but surely one of the most spectacular displays of evaporite karst in the United

States! Newly discovered (2012) InSAR anomalies in the Chimney Canyon area reveal active subsidence depressions that are described by Conway and Cook (2013, this volume). Active karst is likely to play a major role in the development of the Holbrook Basin.

Evaporite Deposition and Geologic Setting in the Holbrook Basin

Holbrook Basin evaporites originated in an inland sea, part of the Pangean supercontinent and perhaps not so different from today's Caspian Sea, having encroached from the oceanic south for some five million years during early Permian time—280 mya. The Paradox and Eagle Basins in the Four Corners area to the northeast had formed 30 my earlier, but from a northern access to open ocean. The current cycle of plate tectonics did not begin to break up Pangea until ~195 mya. Holbrook Basin evaporite deposition, while roughly equivalent to Supai Group rocks in Grand Canyon, existed only in present-day northeastern Arizona and extending into New Mexico. The similar rocks in Sedona and Holbrook basin are now termed Schnebly Hill Formation (Blakey, 1990; Blakey and Ranney, 2008), although the Corduroy Member of the Holbrook evaporite basin did not extend as far west as Sedona (Figures 1, 2).

Sabkha deposits (moist, playa-like saline basins) characterize the upper Schnebly Hill rocks, as seen in outcrop in Sedona. In time the Pedregosa Sea retreated southeasterly and desert erg conditions existed in northern Arizona and western New Mexico—resulting in Coconino Sandstone deposits. Upper Coconino (called Toroweap at Grand Canyon and Sedona) did not extend this far eastward. A later marine transgression at 270 mya resulted in Kaibab Formation thinning rapidly eastward to as little as 5 m in Chevelon Canyon in the western part of Holbrook Basin and disappearing altogether farther east. Triassic Moenkopi Formation outcrops overlie Coconino Sandstone locally and in turn Chinle Formation in the eastern part of the basin.

Economic interest in the Holbrook Basin centered on petroleum potential during the mid-20th century, until being shown unsuccessful; since then, storage of LPG (liquefied petroleum gas) products within salt caverns started in 1973, and now in the 21st century intense current interest is seen in potash mining (Rauzi, 2008).

Additional exploration for uranium is known to have occurred earlier in depressions now considered to be breccia pipes. Topographic expression of the Holbrook Anticline, directly related to evaporite dissolution and collapse, has led to major wind farm development in the 21st Century. With each such interest, new exploration has occurred, revealing more subsurface data regarding the evaporite deposits.

Hydrogeology

The principal aquifer in southern Navajo County is the Coconino Sandstone Formation aquifer (Mann, 1976), but the overlying Kaibab Limestone and the uppermost beds of the underlying Schnebly Hill Formation are hydraulically connected. The Coconino Sandstone is conspicuously cross bedded, is fine- to medium-grained quartz sand, light yellowish gray to tan, and is weakly cemented by quartz, iron oxide, and calcite. It thickens from 120 to 250 m towards the northwest across southern Navajo County, and is about 200 m thick in the vicinity of the Holbrook Anticline.

Recharge of the aquifer results mainly from precipitation and streamflow (Mann, 1976). Most recharge occurs near the Mogollon Rim, some 50 km to the south, where the average precipitation is 50–75 cm/yr. Some recharge also occurs in the vicinity of the Holbrook Anticline by way of precipitation (here averaging 25–35 cm/yr) and piping of surface waters downward through Dry Lake, sinkholes, and other karst features in the area. Ground water flows to the north, towards the Little Colorado River, with a hydraulic gradient of about 6 m/km (30 ft/mi) in the vicinity of the Holbrook Anticline. The Coconino aquifer is unconfined in most of southern Navajo County, but is confined by overlying Moenkopi Formation north of Holbrook and the Little Colorado River (Mann, 1976).

The water table of the Coconino aquifer typically is 120–200 m below land surface in most areas along, or adjacent to, the Holbrook Anticline (Mann, 1976). Therefore, in several areas near the crest of the anticline the Coconino Sandstone is dry, or nearly dry, and the water table is in the uppermost layers of the underlying Schnebly Hill Formation; these strata do not yield much water. The Coconino typically yields 200–2,000 L/min, whereas the Schnebly Hill, along the Holbrook Anticline, yields less than 200 L/min.

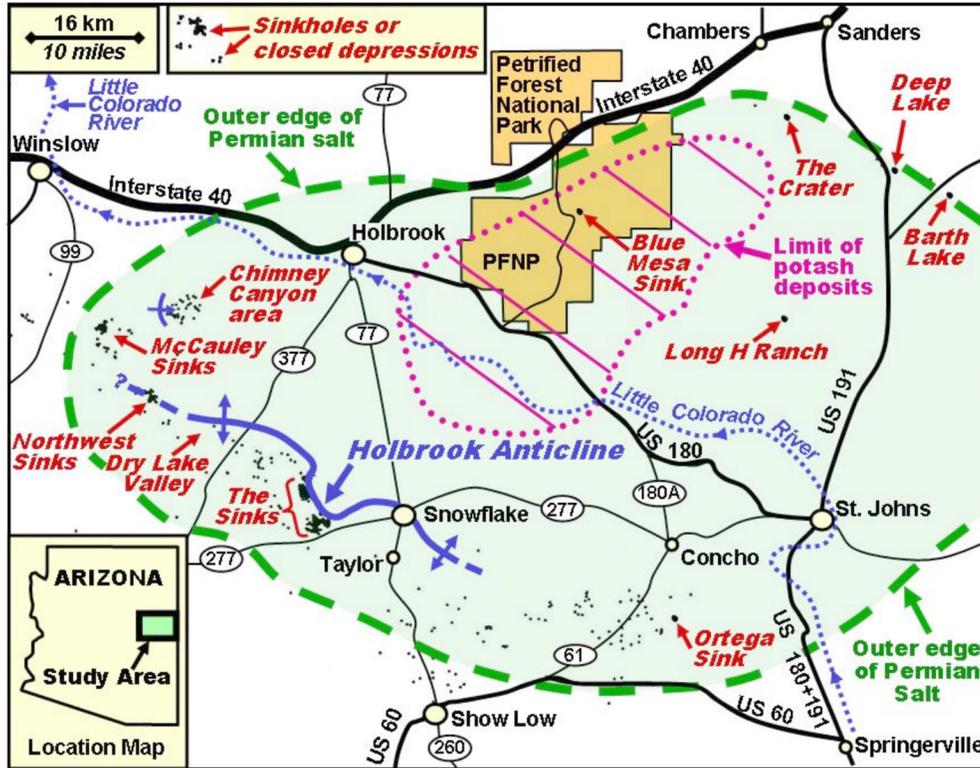


Figure 1. Extent of Corduroy evaporite member with overlay of surface areas of karst features referenced in this article.

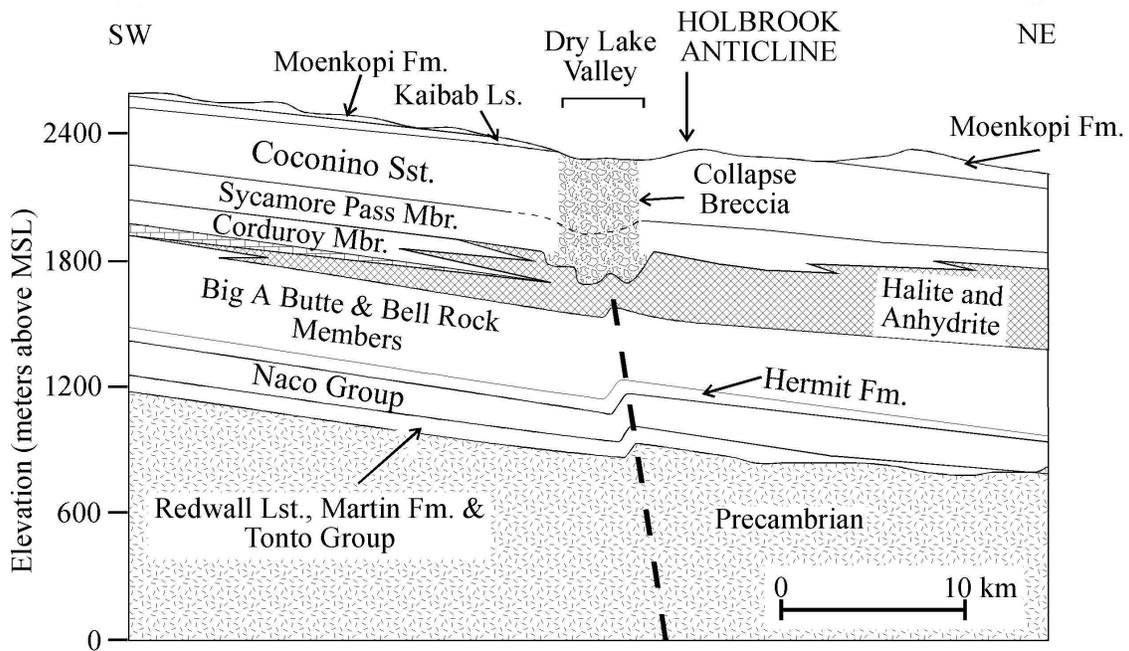


Figure 2. Principal stratigraphic units associated with evaporite karst in the Holbrook Basin, Arizona. The Corduroy Member of the Schnebly Hill Formation (below Coconino Sandstone and above Hermit Formation) is the principal unit undergoing dissolution. Fault in Precambrian basement and pre-Corduroy Member strata is speculative.

In most of southern Navajo County the quality of water in the Coconino aquifer is good, typically with 200–400 mg/L TDS (total dissolved solids), and the principal constituents are calcium, magnesium, and bicarbonate (Mann, 1976). In the vicinity of the Holbrook Anticline, however, the water is much less desirable, with 500–4,410 mg/L TDS. This water is high in sodium chloride, and is present mainly in the lower part of the aquifer; undoubtedly it is part of the brine formed by dissolution of salt in the immediately underlying Corduroy Member of the Schnebly Hill Formation. A plume of this brine extends northward from the Holbrook Anticline,

flowing in the direction of the hydraulic gradient (Figure 3). This plume is adjacent to the Chimney Canyon subsidence area—only recently recognized as a major evaporite karst area.

Karst activity in the area involves lateral and downward percolation of fresh water through the Coconino aquifer until it encounters the uppermost salt layers in the Corduroy Member, about 215–250 m below the land surface. Salt dissolution is accompanied by development of sinkholes and collapse structures in overlying strata that enhance further flow of fresh water to the dissolution zone. Thus, evaporite karst in this area

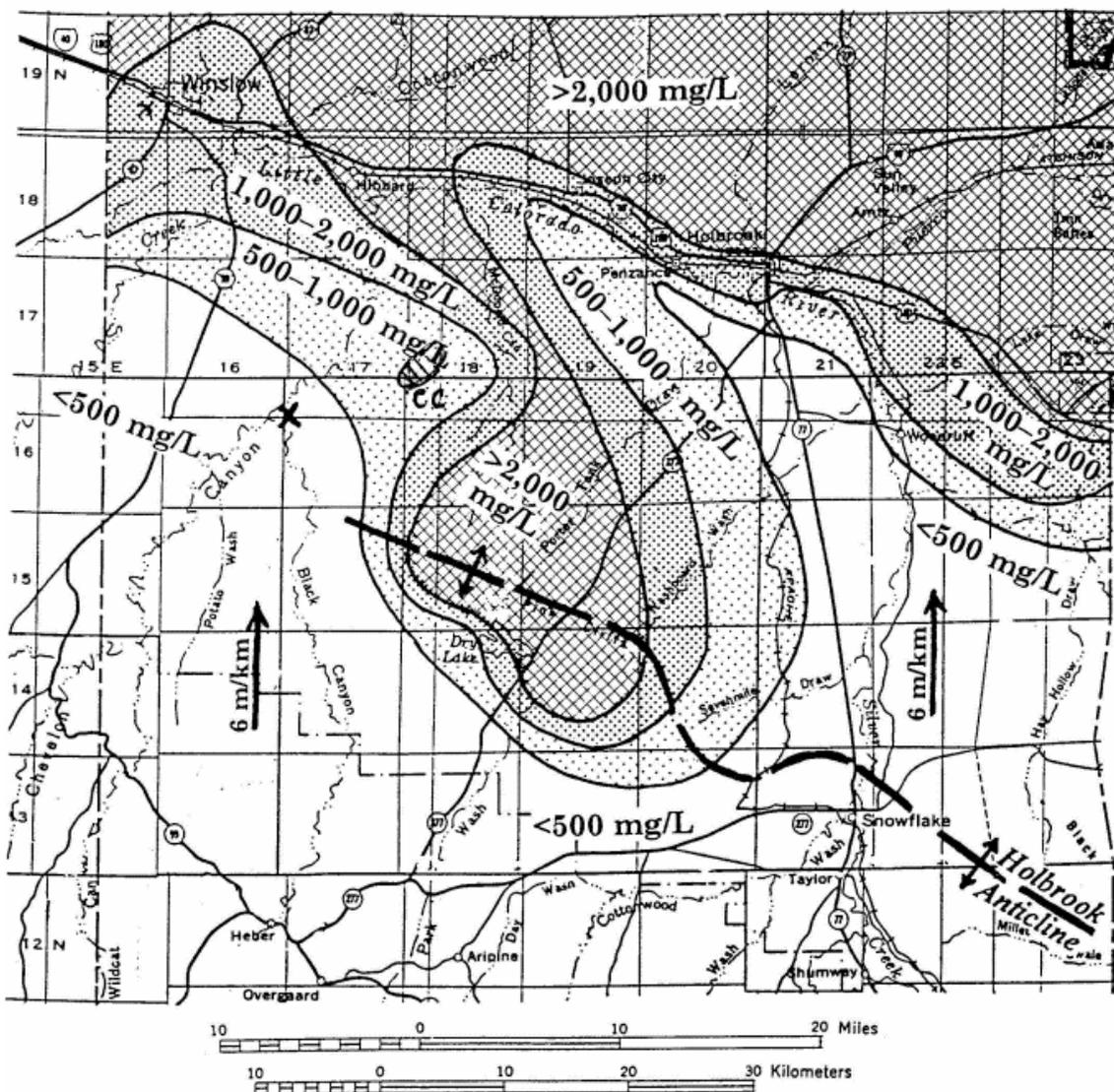


Figure 3. Water quality in Coconino aquifer in western part of Holbrook Basin (from Mann, 1976), showing total dissolved solids in mg/L and direction of hydraulic gradient (6 m/km). Holbrook Anticline, McCauley Sinks (X) and Chimney Canyon (CC) subsidence areas are shown.

is self-perpetuating. Depressions and areas of possible breccia pipes conspicuously are near the outer limits of evaporites (Figure 1).

Initiation of Karst Development

Karst development required elevation of the Colorado Plateau, which began during the Late Cretaceous some 75 mya, with intensity increasing during the Neogene combined with northward movement of groundwater downslope from the Mogollon Highlands toward the integrated Colorado River drainage system.

Groundwater moved through the overlying Coconino Sandstone aquifer and began salt removal of the Corduroy evaporite member, continuing to the present. The groundwater encroachment upon evaporite beds and its consequent dissolution is particularly manifested in the southwestern part of the basin; the area of Dry Lake Valley resulted from the collapse of overlying strata into dissolution voids. The area along the Holbrook Anticline includes The Sinks, which contains 250 plus prominent sinkholes, and is perhaps the most conspicuous of karst features expressed in the Holbrook Basin.

The Holbrook Anticline, in fact a monoclinial dissolution flexure, extends northwesterly for more than 100 km from southeast of Snowflake, Arizona, nearly to Winslow, Arizona. Locally the flexure deforms the upper part of the Schnebly Hill Formation and the overlying Coconino Sandstone, Kaibab Formation (limestone), and Moenkopi Formation (Figures 2,4). The flexure produces tension along the top of the fold and compression at the bottom, creating significant open cracks at the top, and buckles at the bottom. The surface expression is locally named the Pink Cliffs, deriving its color from red beds of the Moenkopi Formation.

Originally the structure was referred to as the Holbrook Dome (Darton, 1925), and was once thought to be a combined fault and solution-related feature (Holm, 1938). Bahr (1962) suggested a non-tectonic dissolution origin for the structure and argued that the anticline apparently does not extend below the salt. He believed the structure is a flexure that resulted from dissolution and collapse of a narrow portion of the Mogollon Slope. Doeringsfeld et al. (1958) show this feature is parallel to many low-amplitude folds in the southwestern part of the Colorado Plateau.

The persistence of parallel, NW-trending monoclinial structures over large areas of the Plateau (Kelley and Clinton, 1960; Wilson et al., 1960; Davis, 1978) is a compelling statement for structural control of dissolution effects. Peirce et al. (1970) also argued that the surface anticline expression is not seen in the subsurface beneath the salt, suggesting that dissolution played a major role; whether there is basement faulting at depth, as shown by Brown and Lauth (1958), is speculative. The principal sinkhole occurrences are in the Coconino Sandstone, almost exclusively on the steep, southwestern side of the flexure at six distinct locations.

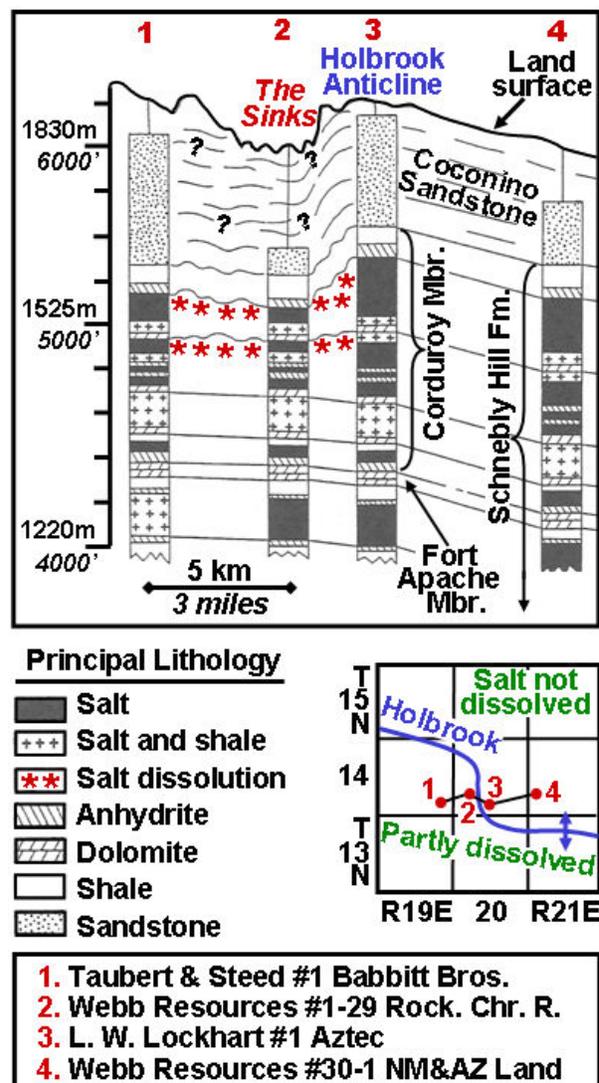


Figure 4. Mechanism of sinkhole collapse along Holbrook Anticline at The Sinks, showing thinning of Corduroy member evaporites in well records (Dean and Johnson, 1989).

The origin and timing of major dissolution and collapse is problematic, but sinkhole formation and collapse are ongoing, as noted previously, and probably began at least by Pliocene time. The uplift and tilting of the Colorado Plateau likely intensified the hydrogeologic environment, but the rates and timing of the orogenic processes are imperfectly known (Lucchitta, 1979). The close association of the dominant regional fractures and the Holbrook Anticline with sinkhole formation is conspicuous throughout the region, but this was not understood by early investigators. Accelerated dissolution of halite during pluvial stages of the Pleistocene seems likely, as intensified hydrogeologic processes are often noted elsewhere in the arid southwest (Smith and Street-Perrott, 1983).

Principal Varieties of Karst Expression The Sinks and Adjacent Areas

The Sinks and adjacent areas are associated with the topographic expression of what has historically been called the Holbrook Anticline—perhaps originally named to foster interest in petroleum exploration. In fact, the ~50 m vertical-relief structural feature in bedrock is monoclinical and now known to result from dissolution of underlying salt beds. Near-orthogonal joint openings in Coconino sandstone follow a NW/NE direction common in this part of the Colorado Plateau (Kelley and Clinton, 1960). At many places along the dissolution monocline are collapse grabens that locally form incipient sinkholes, which may be the primary sinkhole-forming mechanism.

Numerous open fissures and sinkhole-growth patterns coincide with intersecting joints in the Moenkopi and Coconino Formations on the crest of the Holbrook Anticline adjacent to Dry Lake Valley (Figure 5). These fissures are up to 200 m long, 0.3-15 m wide, and as much as 30 m deep. Numerous stories surround these gaping features, some of which purportedly swallowed cattle and possibly two people, and have been described as “bottomless” by local residents. Field observations show that soil is collapsing into joint-fissures at depth, suggesting a similar mechanism for the appearance of piping features in the Dry Lake Valley drainage incidents. The crest and south flank of the Holbrook Anticline are in tension, which explains the open joint-fissures at the surface. Once open, these fissures form a conduit for ground water to penetrate to the relatively shallow (~250 m deep) salt beds below. Near the intersections of some fissure sets, joint-fissures show evidence of subsidence,



Figure 5. Aerial view of The Sinks, looking south down monoclinical flexure toward collapsed Dry Lake Valley (see Fig. 4). Sinkhole locations are strongly influenced by joint openings and collapse grabens in Coconino Sandstone. Nearly 50 sinkholes are shown in this one view, the largest being 100m across.

suggesting how some sinkholes are initiated. The sinkholes occur less than one kilometer to the west and southwest of the monoclinical crest; one of these showed draping and overturning of beds in its collapse. Similar features in the Chimney Canyon area suggest common mechanisms of formation.

A group of 24 sinkholes, termed here “Northwest Sinks,” occurs 10 km northwest of the open fissures, along the southwest-dipping crest of the Holbrook Anticline. Two particularly well developed sinkholes are conspicuously larger, deeper, and more regular than the others in this group and they may be younger. The surficial jointing that is so prominent at The Sinks is not nearly as evident here.

Playa Depressions

A series of major depressions and a playa-lake basin, called Dry Lake Valley, cover an area of more than 325 km² in the central and western part of the larger collapse zone. Sinkhole development and collapse are ongoing here, as attested to in local newspaper reports (Snowflake Pioneer, 1984). The artificially impounded Twin Lakes playa (reservoir) in the eastern part of Dry Lake Valley lost more than 6.8×10^5 m³ (550 acre-feet) of water and sediment into open fissures connected to subsurface piping channels. These fissures occurred along a N 53° W trend, generally parallel to the regional structural trend (Sergent et al., 1984). The piping occurred along the reservoir margin during the first filling; presumably the newly formed surface fissures in the playa sediments, which extended for about 1.5 km in a 200-m-wide zone, overlie joint-fissures in Moenkopi redbeds that extend into the dissolution zone of the salt layers. The surface-drainage features filled with suspended sediment after

the water surface dropped 0.6 m, and standing water remained in the surface expression of features within the reservoir (Rucker, personal communication, 1996). The water table in the Coconino aquifer is about 100-120 m below the land surface in Dry Lake Valley (Mann, 1976).

Major drainage incidents occurred at least four times during the 20th century, including nearly 7.4×10^6 m³ (6,000 acre-feet) of industrial wastewater draining into open fissures in the northwest part of Dry Lake in March 1963 (Stone Container, 1991). Multiple clusters of some 40 sinkholes formed in recent lacustrine sediments over an area of about three square kilometers. Nine sinkholes in this group are aligned along a N 44° W trend and some of the others are oriented orthogonally to them. These were still visible in 1996, as subsequent lowering of the reservoir, combined with the arid climate, has effected little erosion since their formation. Loss of water during these drainage events occurs when subaqueous joint-fissures sealed with sediment periodically give way to piping, or when new openings form and rapid drainage results. A new sinkhole was observed forming in 1996 at the northwestern edge of the basin at an elevation of 1,780 m; apparently it formed in response to normal runoff rather than lake filling, as the lake levels have been maintained below a threshold level of 1,777 m for many years.

A December 1995 incident of rapid water flow into a piping feature occurred about 13 km south of the Holbrook Anticline (AGRA, 1995) and may have an origin similar to the 1984 fissures. Piping occurred along the downdropped side of a steeply dipping fault oriented N 40° W, apparently through joint/fault intersections (Rucker, personal communication, 1996).

Water flowing into piping channels includes substantial amounts of suspended silt and clay, which in turn seals the fissures and permits more water to accumulate above. Comparison of more recent aerial photos taken in 1977 and 1990 shows new fissures and sinkholes formed in the area adjacent to Highway 377, which crosses Dry Lake Valley; this area was perennially moist in 1996 because of effluent discharge. Local ranchers report draining of stock ponds and playas into piping features at other locations in the valley. According to local reports, the abandonment of Zeniff townsite by Mormon settlers in the early 1900s was prompted in part by the inability to

contain irrigation water in Dry and Twin Lakes. Bahr (1962) suggested that all of the Dry Lake Valley area could have formed in this manner, noting numerous sinkhole scars along the base of the Pink Cliffs. The many recent drainage events support his hypothesis.

The linear northeastern shore of Dry Lake is parallel to the regional joint trend and the Holbrook Anticline, suggesting a possible structural control as is seen at many Great Basin playas (Neal, 1969). The origin of playa basins by deep-seated dissolution and gradual surface lowering has parallels in New Mexico and West Texas (Gustafson et al., 1980), but not necessarily on this scale or by the same mechanisms.

Breccia Pipe Structures

The McCauley Sinks are comprised of some 50 individual sinkholes within a 3-km wide depression, grouped in a semi-concentric pattern of three nested rings (Figure 6). The outer ring is an apparent tension zone containing ring fractures. The two inner rings are semi-circular chains of large sinkholes, ranging up to 100 m across and 50 m deep. Several sub-basins within the larger depression show local downwarping and possible incipient sinkholes.

Permian Kaibab Formation limestone is the principal surface lithology—less than 10 m thick and is near its easternmost extent. Although surface rillenkarren are present, and the sinks occur within the limestone outcrops, the Kaibab is a passive rock unit that has



Figure 6. McCauley Sinks, a group of 50 sinkholes in a concentric, nested pattern showing three imperfect rings. The outer and uppermost is a ring fracture; the two inner rings are sinkholes with the innermost at the lowest elevation. A compound breccia pipe origin is suggested for this structure.

collapsed into solution cavities developed in underlying salt beds. Beneath the Kaibab is Coconino Sandstone, which overlies the Permian Schnebly Hill Formation, the unit containing the evaporite rocks—principally halite in the Corduroy Member. The karst in this part of the Holbrook basin is very different from that to the southeast, probably because of the virtual disappearance of the Holbrook Anticline, a structure with major joint systems that help channel water down to the salt beds. McCauley Sinks are also near the edge of the evaporite basin, as are the several other broad depressions of unknown origin. The structure at McCauley Sinks suggests a compound breccia pipe, with multiple sinks contributing to the inward-dipping major depression (Neal and Johnson, 2003).

Richard Lake depression, 5 km southeast of McCauley Sinks, is about 1.6 km wide and with topographic closure of 15-23 m. It is similar in form, but smaller in diameter and contains only a single, central sinkhole. Richard Lake formerly contained water after heavy rains prior to headwater drainage modification but is now dry most of the time. Both are proximate to the adjacent, deeply incised, Chevelon Canyon drainage, but the hydrologic connections are unknown. The larger McCauley Sinks karst depression, along with five other nearby depressions, provides substantial hydrologic catchment. Because of widespread piping into karst features and jointed bedrock at shallow depth, runoff water does not pond easily at the surface. There appears to be much greater recharge efficiency here than in alluvial areas; thus concern exists for groundwater users downgradient from the karst area. A nearby set of pressure ridges trend generally N 30° W, subparallel to the axis of the Holbrook Anticline. In the alluvium at the bottom of the central sinkhole, two secondary piping-drain holes were observed in early 1996. Northwest-trending fissures also were observed on the depression flanks, essentially parallel to the regional structure. Two smaller depressions of lesser dimensions occur in tandem immediately west along a N 62° W azimuth. Secondary sinkholes occur within each of these depressions, as at Richard Lake. Breccia pipes are apt to be found beneath all of these structures.

Blue Mesa Sink is a semicircular collapse feature about one kilometer in diameter just south of the Puerco River within the Petrified Forest National Park (Fig. 1). The depression, with some 15-25 m of topographic closure and with 5-15 degree dip of surface rocks, is similar to

that seen in many breccia pipes on the Colorado Plateau, and to the collapse depressions at and near McCauley Sinks. The horst in the depression center is not seen at other breccia pipe structures that overlie evaporites, however; potash thickness beneath the structure may be a developmental factor. The structural framework of this depression may involve concentric ring fractures of unknown attitude. There are no central sinkholes, such as at Richard Lake near McCauley Sinks. The evaporites at shallow depth and similar structure suggest a breccia pipe origin is possible (Colpitts and Neal, 1996), similar to McCauley Sinks and Richard Lake. Other probable solution-induced subsidence depressions occur in the southeastern and northeastern margins of the Holbrook Basin at Ortega Sink, The Crater, Deep Lake, and elsewhere (Peirce and Gerrard, 1966; Harris, 2002).

The geometry of all these depressions bears some resemblance to the San Simon Sink, located above thick Permian salt deposits in the Delaware Basin of southeastern New Mexico. At San Simon, a central sinkhole within a broader depression showed renewed growth and concentric fracturing in 1927, and has been interpreted as a possible breccia pipe being formed (Lambert, 1983). San Simon sink occurs over Capitan Reef, the source of many carbonate karst features at the edge of the evaporite basin (Martinez et al., 1998).

Dissolution of Redwall Limestone beneath these structures in the Holbrook Basin is problematic, but because of the size of these depressions combined with thinner salt in this part of the basin, its involvement is unknown yet seems likely—similar to the many other breccia pipes formed by the Redwall Limestone in the Grand Canyon region.

Chimney Canyon – subsidence depressions

The Chimney Canyon dissolution area includes ~16+ km² of karst development and occurs coincidentally along the powerline that extends southwesterly from the Cholla Power Plant at Joseph City. Along the western edge of the karst features is a monoclinical flexure that is smaller but not unlike the “Holbrook Anticline,” now recognized as a dissolution monocline. At the crest of the monoclinical flexure are large cracks in the upper Coconino/Moenkopi outcroppings, typical of tensional features in folded rocks (Sanford, 1959; Ramsey, 1967). Downtip from the crest are numerous collapse depressions (Figure 7) and buckle folds, typical of karst



Figure 7. Chimney Canyon cracks and depressions in Coconino Sandstone at top of monocline are similar to those near The Sinks, but at an earlier stage of development. Circular-shape sinkholes were not observed.

features and monoclinical folding elsewhere. This area appears less mature than the main Holbrook Anticline structure—created by dissolution of the underlying evaporites. Yet the similarity leads one to suspect a similar origin in groundwater movement toward the Little Colorado River drainage system. The prominent surface manifestation of the Holbrook Anticline seen at The Sinks gradually is less developed progressing northwestward, virtually disappearing at a point that is only about 15 km south of the Chimney Canyon structures. This close association suggests a possible connection of the two collapse and fold belts that is not apparent at the surface.

Surface drainage reversal was noted along several arroyos in the Chimney Canyon drainage, similar to the drainage reversal noticed along Seven Mile Draw at The Sinks to the southeast. Regardless of the uncertainties noted above, it is clear that salt removal and subsidence are ongoing, but perhaps at a slower rate, or more recently than in the thicker part of the salt basin to the southeast.

In early 2012 two anomalous subsidence areas were reported on InSAR data (Conway and Cook, 2013, this volume). A reconnaissance of this area revealed a broad depression similar to those at and around Richard Lake (Neal and Colpitts, 1997). Linear tension cracks were noted along joints in Coconino Sandstone, along with buckle folding near the low point in the depression.

Summary and Conclusions

Evaporite karst is displayed over some 9000 km² of Permian-age evaporites in the Holbrook Basin, creating a variety of expressions that includes major regional collapse, monoclinical folding, drainage reversal, tension-joint expansion, buckle folding, graben collapse, sinkholes, and breccias pipes. Well over 600 such features are readily visible on air photos, and many more of smaller scale exist. Karst expression is manifested differently in the western portion of the Holbrook Basin as compared with the east. The west contains substantially more sinkholes, with more mature development and greater relief along the southwestern part of the basin. And whereas individual collapse depressions in the west are of wider dimension and have fewer discrete sinks, they also are present in the east, but to a lesser extent. Surface lithology, alluvial cover, and evaporite thickness combined with groundwater flow create different karst features. The surface conduits through the many areas of karst expression create multiple avenues for potential entry of salt-water brines to aquifers and potential water supplies in downstream communities, requiring continuing vigilance.

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