# MCCAULEY SINKS: A COMPOUND BRECCIA PIPE IN EVAPORITE KARST, HOLBROOK BASIN, ARIZONA, U.S.A.

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**ABSTRACT:** The McCauley Sinks, in the Holbrook basin of northeastern Arizona, are comprised of some 50 individual sinkholes within a 3-km-wide depression. The sinks are grouped in a semi-concentric pattern of three nested rings. 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; the limestone here is less than 15 m thick and is near its easternmost limit. Although surface rillenkarren are present, and the sinks are seen in the Kaibab limestone outcrops, the Kaibab is mainly a passive rock unit that has 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. Evaporite karst in this part of the Holbrook basin is quite different from the eastern part, probably because of the westward disappearance of the Holbrook anticline, a structure that has major joint systems that help channel water down to the salt beds farther to the east. Also, the McCauley Sinks are near the western limits of the evaporites.

The structure at McCauley Sinks suggests a compound breccia pipe, with multiple sinks contributing to the inward-dipping major depression. The Richards Lake depression, 5 km southeast of McCauley Sinks, is similar in form and size but contains only a single, central sinkhole. An apparent difference in hydrogeology at McCauley Sinks is their proximity to the adjacent, deeply incised, Chevelon Canyon drainage, but the hydrologic connections are unknown.

The 3-km-wide McCauley Sinks karst depression, along with five other nearby depressions, provide 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 a greater recharge efficiency here than in alluvial areas; thus concern exists for groundwater users downgradient from the karst area. Accordingly, sinkholes and open fissures should not be used for waste disposal.

## INTRODUCTION

The McCauley Sinks are a unique and conspicuous feature of the northern Arizona landscape, being striking from both air and surface. This group of some 50 sinkholes in the western part of the Holbrook basin, adjacent to Chevelon Canyon, occurs in a saucer-shaped depression that is unlike any other known sinkhole cluster. The 3-km diameter of the depression places McCauley Sinks on a scale similar to Meteor Crater and its ejecta field, located just 45 km northwest, but there is no genetic similarity between them. The McCauley Sinks result from dissolution in the underlying salt; Meteor Crater has been shown to be a meteorite-impact feature—beyond any doubt.

The ubiquitous Kaibab Formation limestone occurs practically everywhere at the surface around the sinks, prompting some early observers to believe the features were an example of limestone karst. But individual sinks transect the entire 12–15 m thickness of the Kaibab, and the collapse extends through the underlying Coconino Sandstone. Well records show that the Corduroy Member evaporites of the Schnebly Hill Formation beneath the Coconino have thinned markedly, so that evaporite dissolution and collapse is responsible for the karst. The area adjacent to the McCauley Sinks contains five other subsidence depressions, three of which have associated sinkholes. Richards Lake, the largest of the five depressions, is smaller than McCauley Sinks, and contains only a single central sinkhole. The saucer-like attributes of Richards Lake and the McCauley Sinks are similar to other breccia-pipe structures on the Colorado Plateau that are ascribed to dissolution occurring in the Mississipian Redwall Limestone.

The evidence for an origin similar to that of other Colorado Plateau breccia pipes (by dissolution of limestones) is examined here, along with hydrogeologic implications in this environment. The Holbrook basin is currently used for LPG (liquefied petroleum gas) storage in dissolved-salt caverns at one location, and the basin has the potential for development of additional caverns. Geologic site characterization that is required for future cavern development will need to consider the varieties of karst expression.

## GEOLOGY AND HYDROGEOLOGY

McCauley Sinks and five adjacent depressions are located in west-central Navajo County, 28 km southeast of Winslow, Arizona (Figs. 1, 2, 3). The Holbrook anticline, if extended westward from its more conspicuous expression to the southeast, would pass through a point near the Richards Lake / McCauley Sinks area. But surface manifestation of the anticline has virtually disappeared, except for en echelon swarms of buckle folds and open fissures in bedrock, aligned along the same northwesterly structural trend as the Holbrook anticline (Wilson et al. 1960; Neal et al. 1998). The western limit of subsurface salts in the Holbrook basin is near McCauley Sinks, and the limit line then extends back to the

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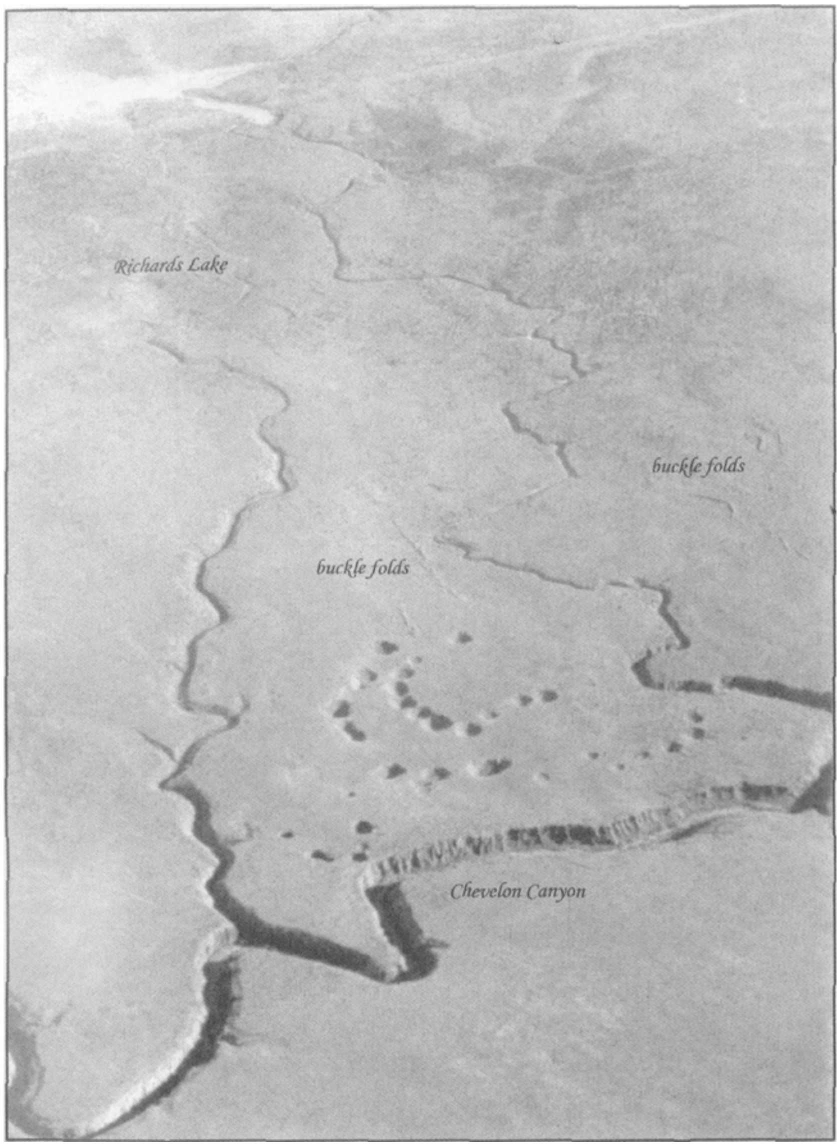


*Figure 1. McCauley Sinks, in the western part of the Holbrook basin, display entirely different karst characteristics from those in the eastern part of the basin, where graben-sinks and fracture-induced sinkhole patterns predominate. Some 50 sinks occur here in a semi-concentric pattern, consisting of three separate "rings." The outer ring is indistinct here, but is marked by surface fractures. Chevelon Canyon (foreground) and the two tributary canyons are some 75 m deep and may influence the local hydrologic flow pattern. Richards lake (upper left) is 5 km southeast of McCauley Sinks. Aerial view looking south.*

northeast (Fig. 2). Chevelon Canyon and the bounding tributary canyons of Black Creek and Rock Creek are major surface drainages and hydrologic pathways unlike any drainages to the southeast. Although it is part of the overall karst expression of the Holbrook basin evaporites, the McCauley Sinks area has totally different manifestation as compared with those features along the collapsing crest of the Holbrook anticline to the southeast (Neal et al. 1998).

The Permian evaporite sequence in the Holbrook basin originally was termed the Supai salt, and it was thought to be equivalent to Supai redbeds in the Grand Canyon (Bahr 1962; Peirce and Gerrard 1966). The Permian Grand Canyon sequence is traceable to the area of Sedona, Arizona, but has been renamed there for the type locality at Schnebly Hill (Blakey 1990). The respective members of the Schnebly Hill Formation are, in ascending order, the Bell Rock, Big A Butte, Fort Apache, Corduroy (the 400-m-thick evaporites of the Holbrook basin, isolated by the Sedona arch), and Sycamore Pass Members. The oldest, the Bell Rock Member, rests conformably on Permian Hermit Shale, which is underlain by Naco Group and Mississippian Redwall Limestone. The Redwall displays widespread dissolution in northern Arizona; it has at least six sinkholes in the Sedona area (Lindberg 1998), and hundreds of breccia pipes elsewhere on the Colorado Plateau (Wenrich and Billingsley 1986). The Redwall in the Holbrook basin is less than 30 m thick and is about 1,200 m below land surface; thus it is not a factor in the karst development at McCauley Sinks.

## Hydrogeology

The principal aquifer in southern Navajo County is the Coconino aquifer (Mann 1976). The Coconino Sandstone is the main water-bearing unit in the aquifer, but the overlying Kaibab Limestone and the uppermost beds of the underlying Schnebly Hill Formation are hydraulically connected as part of the aquifer. The Coconino Sandstone is fine- to medium-

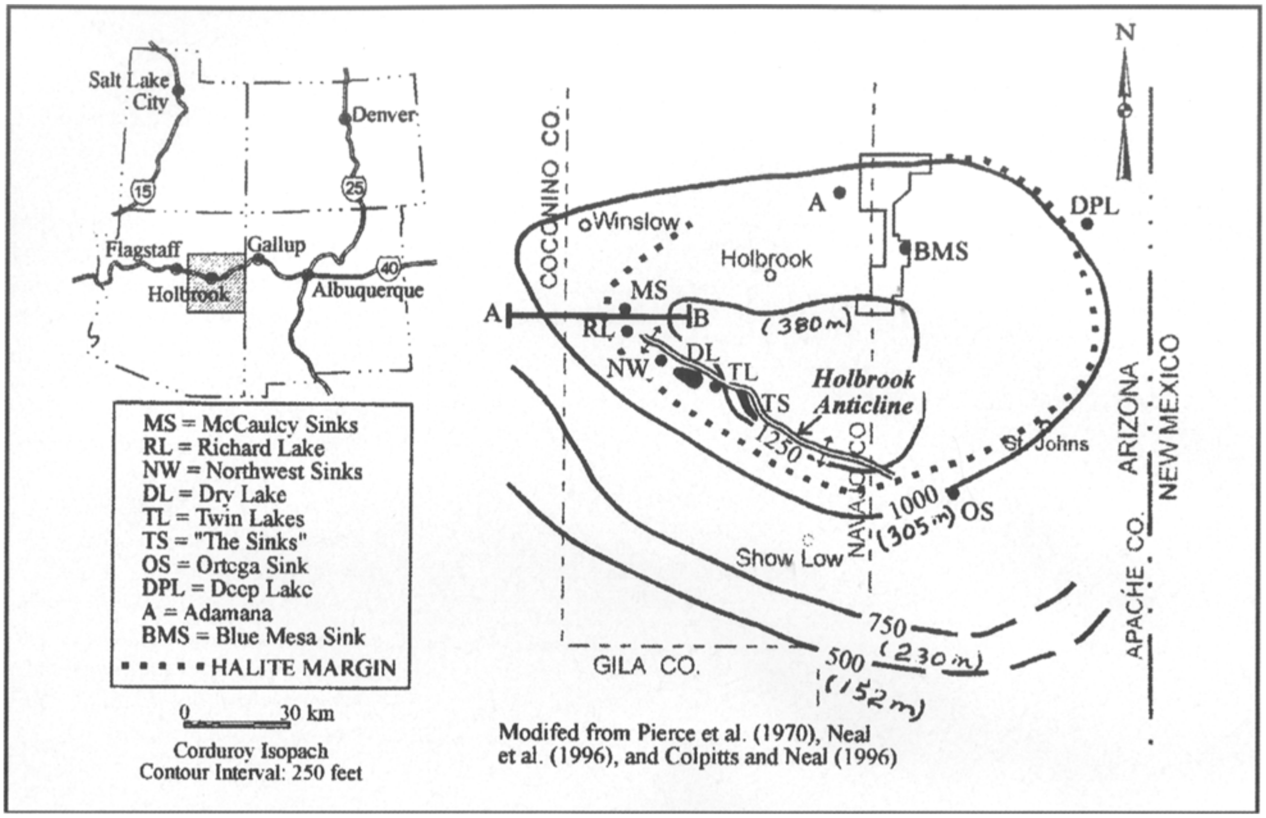


*Figure 2. Holbrook basin, in northeastern Arizona, showing thickness of Corduroy Member salt. McCauley Sinks are in the west side of the basin, near the edge of halite deposits and near the end of surface Holbrook anticline.*

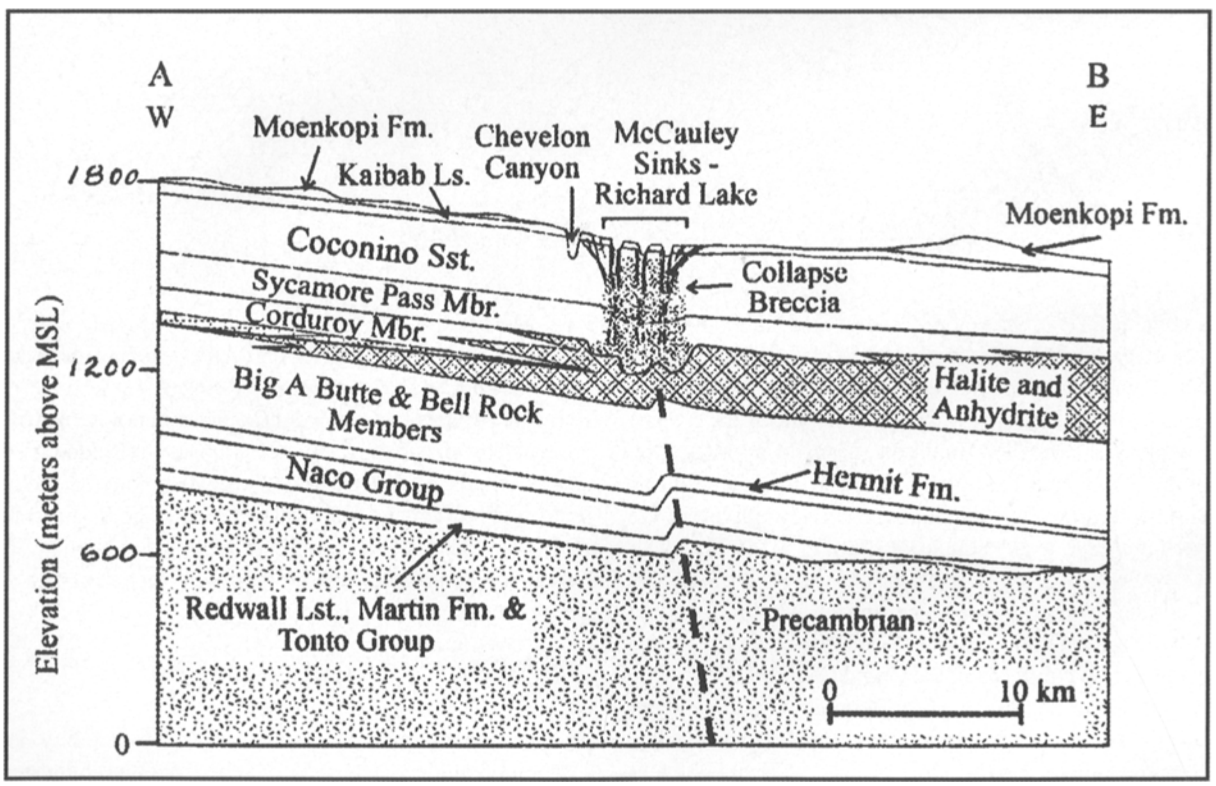


*Figure 3. Cross section A–B (location shown in Fig. 2), showing collapse area (diagrammatic) at McCauley Sinks caused by dissolution of Corduory Member evaporites. Fault offset in units beneath the salt is unproven, but thought likely by some geologists.*

grained quartz sand, light yellowish gray to tan, and is weakly cemented by quartz, iron oxide, and calcite. The sandstone is conspicuously cross bedded. 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 is mainly due to precipitation and streamflow (Mann 1976). Most recharge occurs along the Mogollon Rim, some 50 km to the south, where the average precipitation is 50–75 cm/yr. Some recharge also occurs along the Holbrook anticline, as a result of precipitation (which here averages 25–35 cm/yr) and consequent piping of surface waters downward through Dry Lake, sinkholes, and other karst-induced fractures 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 (Fig. 4). The Coconino aquifer is unconfined in most of southern Navajo County, but is confined by the overlying Moenkopi Formation to the north and near 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 Hills Formation; these strata do not yield much water. The Coconino typically yields 200–2,000

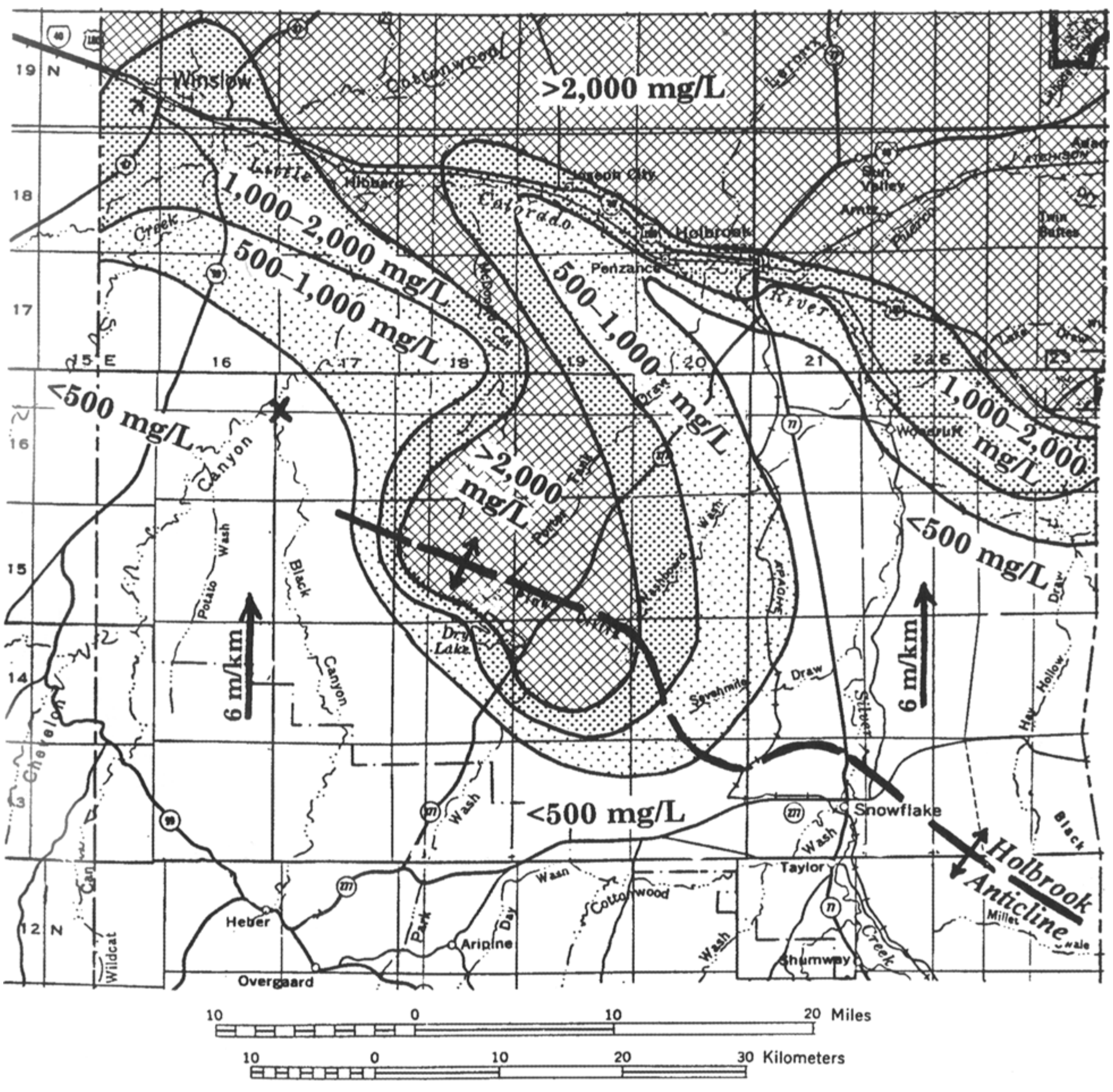


*Figure 4. Water quality of Coconino aquifer in southern Navajo County, Arizona (from Mann 1976). Map shows TDS of groundwater in mg/L. Also shown are Holbrook anticline, hydraulic gradient (arrows labeled 6m/km), and location of McCauley Sinks (X) in west-central part of map area.*

L/min, whereas the Schnebly Hill, along the Holbrook anticline, yields less than 200 L/min.

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). However, in the vicinity of the Holbrook anticline 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 (Fig. 4).

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 (Fig. 3) that enhance further flow of fresh water to the dissolution zone. Therefore, karst processes in this area are self-perpetuating.

Figure 4 reveals a substantially lower TDS range for the McCauley Sinks / Richard Lake area, suggesting that: 1) dissolution processes are less active now than in the past, and that the karst may be in a more mature stage of development; or 2) that water wells have not been drilled deep enough to encounter higher salinity waters in the area.

## Collapse Processes at McCauley Sinks and Richards Lake

McCauley Sinks comprise a group of some 50 sinks covering about 5 km$^2$ in a generally low-relief area adjacent to Chevelon Canyon, 29 km SE of Winslow (Figs. 1, 2, 4, 5, 6). A cursory look at the overall grouping of the McCauley Sinks shows a roughly nested arrangement of two arcuate rows of coalesced sinkholes. A third, and less distinct, outer arc is marked by several disconnected surface fractures. Field inspection of the topographic setting suggests the sinkhole and fracture arcs may be the concentric stress-field expression of a larger subsidence basin.

The location of McCauley Sinks immediately adjacent to Chevelon Canyon, a losing stream at this locale most of the time (partly because of a dam upstream), probably contributes

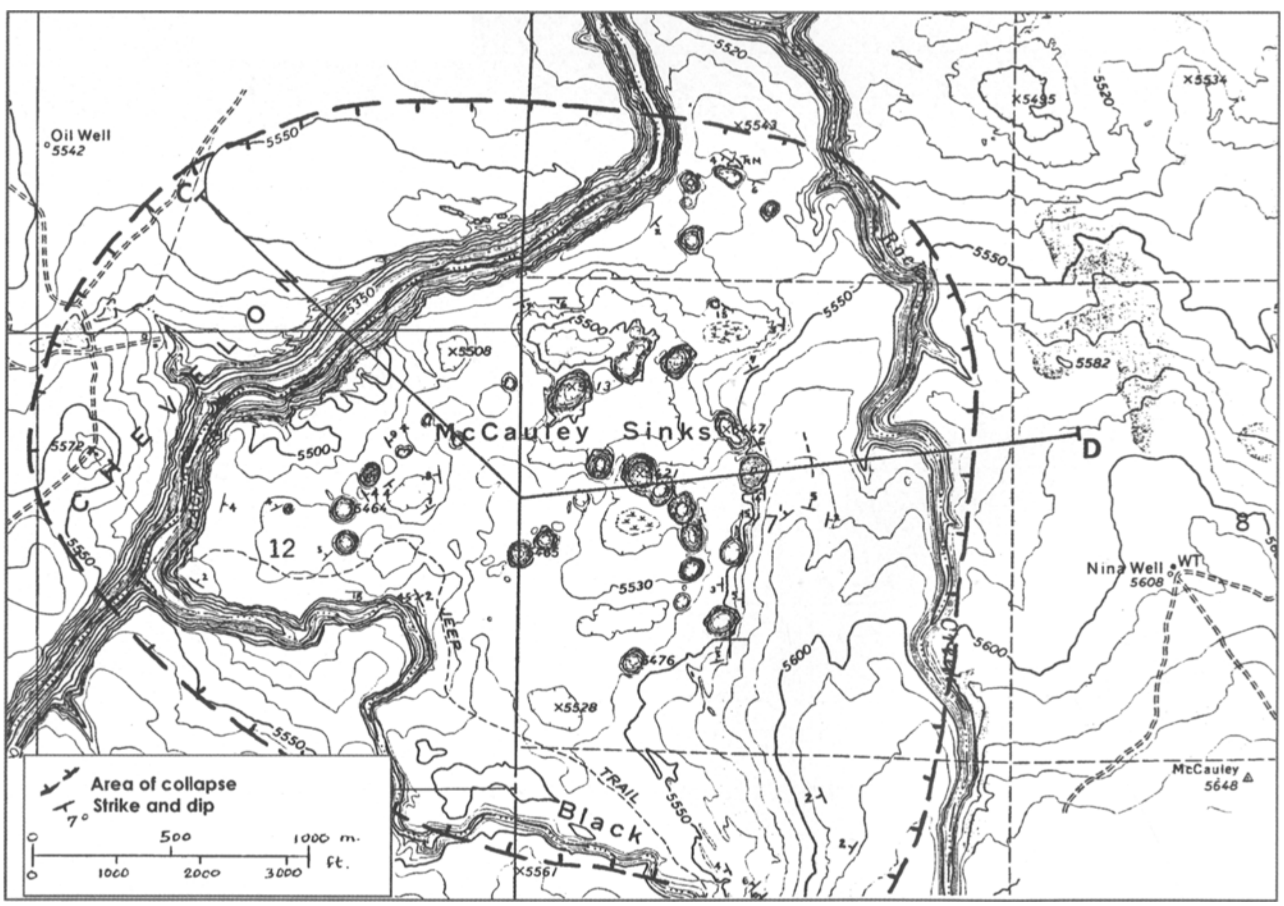


*Figure 5. Topography at McCauley Sinks (elevation in feet above MSL). Kaibab limestone is the only surface lithology, except one outcrop of basal Moenkopi Formation at northernmost sink.*

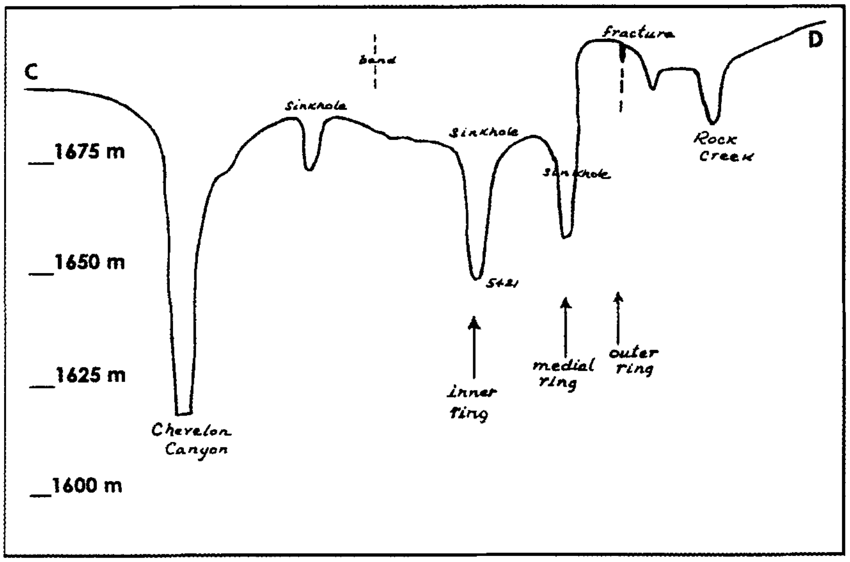


*Figure 6. Cross-section C–D (location shown on Fig. 5) across McCauley Sinks, showing arrangement and relative elevations of the three concentric rings of sinks. Upper limit of collapse structure is at approximately 1,690 m.*

less ground-water recharge than in the past. The substantially greater infiltration of the past, especially during pluvial stages of the Pleistocene, may have affected the sinkhole patterns that exist today.

Conjugate joints in the Kaibab Formation (limestone) and Cononino Sandstone have an important bearing on the expression and development of individual sinks: some sinks have nearly square corners. Steep sidewalls frequently are aligned along near-vertical joint planes that are parallel to regional structure. Several sinks are up to 100 m wide and 30 - 35 m deep; the largest is a compound sink that is 185 m in its long dimension. Some depressions appear to be either older (filled) sinks, or possibly the loci of a future collapse.

Pressure ridges, or local anticlinal buckles, that are seen principally in the nearly horizontal Kaibab Formation limestone beds are as distinctive as the sinkholes; they are identical to the features within the Richards Lake depression and to those that occur in association with other sinkholes along the Holbrook anticline. The pressure ridges are co-located within the area of karst expression and are likely compressional features that are due to subsidence (caused by evaporite dissolution). The ridges are 2-10 m high, with beds dipping away at low angles and forming linear hills about 15-25 m wide. The ridges are parallel and are often more than 100 m long (Fig. 1), trending generally N 30° W, which is about the trend of the probable northward-bending and waning Holbrook anticline. Similar buckles are interpreted as stress-relief features in other geological environments undergoing compression (Sanford 1959; Ramsey 1967).

Richards Lake is a 2-km-wide natural depression 5 km southeast of the McCauley Sinks (Figs. 1, 2, 7). The Richards Lake depression apparently once contained water for short durations after heavy rains and the diversion of Black Creek in 1902, but has been generally dry since the 1940s, according to local residents. It is situated within the Moenkopi/Kaibab outcrop belt, with Coconino Sandstone at shallow depth. Richards Lake occurs near the western end of the Holbrook anticline; it is interpreted as a large collapse depression with concentric faults and pressure ridges, with a 170-m-wide sinkhole near the center (Neal and Colpitts 1997). A second set of pressure ridges parallels the waning Holbrook anticline, trending N 30° W. In the alluvium at the bottom of the sinkhole, two secondary piping features were forming in early 1996, suggesting continuing dissolution at depth. A northwest-trending fissure was also observed, essentially parallel to the regional structure.

The presence of Richards Lake amidst numerous karst features suggests a similar salt-dissolution origin, but with somewhat different characteristics. A similar collapse origin for Richards Lake and the McCauley Sinks is likely, because of their close proximity, and their comparable geological setting, size, and appearance. Two lesser-developed depressions occur 1 and 3 km to the northwest, on an azimuth of ~N 62° W (Fig. 7), in tandem with Richards Lake. Secondary sinkholes occur within each of these depressions, as at Richards Lake. A similar, 1-km-wide depression, 2 km east of the McCauley Sinks (at Rattlesnake Bend), contains buckle folds, but no central sinkholes (Fig. 7). Similar processes appear likely for all of these lesser depressions, even though their development is less than at either Richards Lake or McCauley Sinks.

The shallow depressions adjacent to Richards Lake and south of the McCauley Sinks are near the suspected western limit of salt in the Corduroy Member (Figs. 2, 3). They also are near the western terminus of the Holbrook anticline; the precise

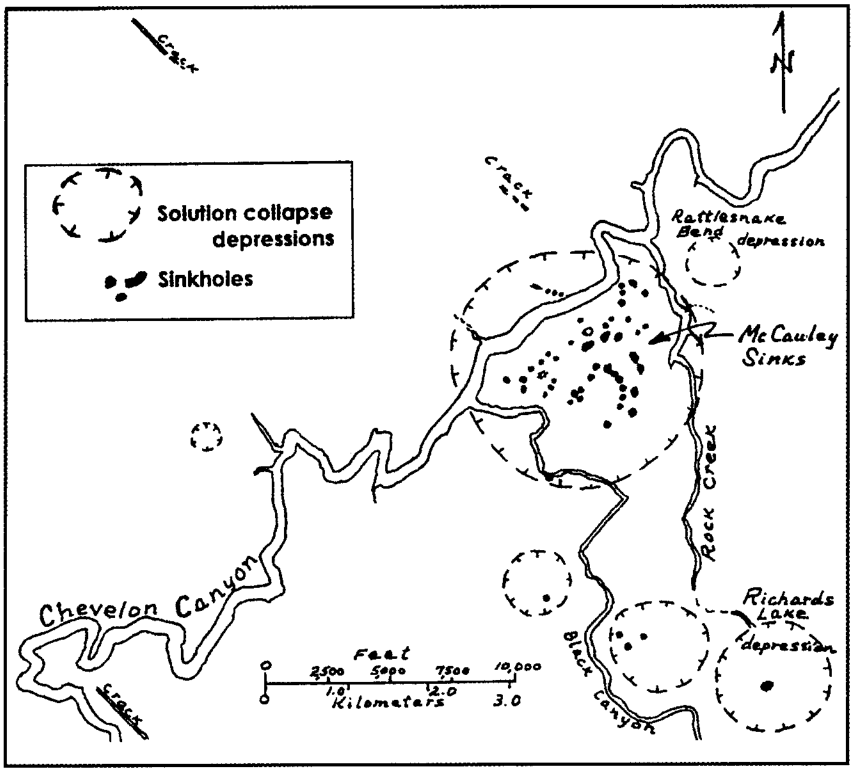


*Figure 7. Structural features, surface hydrology, and related depressions associated with McCauley Sinks. Trend of N45°W is predominant; orthogonal trend is about N45°E.*

locations of the salt margin and the anticline are not known. Unlike the sinkholes in Dry Lake Valley and other sites farther east, these westernmost depressions (including Richard Lake and the McCauley Sinks) appear to be a different karst style, with collapse related more to the dissolution front of the salt than to collapse along the Holbrook anticline. All six depressions in the study area are in the Kaibab Formation outcrop belt, and all have local basinward dips of 0–10 degrees. The pattern and geometry is similar to many breccia pipes in northwestern Arizona that are attributed to dissolution in Redwall Limestone, but clearly the structures in this study result from salt dissolution and collapse.

The topographic map and cross-section at McCauley Sinks (Figs. 5, 6) reveal the imperfect, nested arrangement of three concentric rings. The area involved in the collapse extends well beyond the sinkhole cluster, as shown by the local disruption of the regional dip of Kaibab outcrops, the topographic depression, and fractures in rocks on the north side of Chevelon Canyon.

Regional structural alignment of depressions and major surface fractures are shown on Fig. 7. McCauley Sinks and Rattlesnake Bend depressions are aligned N 45° E, along with the major trend of Chevelon Canyon. Richards Lake and the adjacent two depressions trend N 62° W, somewhat offset from the N 45° W trend of major fractures and Chevelon Canyon tributary channels, which are fracture controlled.

## Comparison with Other Breccia-Pipe Occurrences

The depressions at McCauley Sinks and Richards Lake are perennially dry, karst-subsidence basins. These features have no counterpart in the eastern Holbrook basin, but resemble breccia pipes elsewhere, such as San Simon Sink in the Delaware basin of southeastern New Mexico, and breccia pipes on the Colorado Plateau of northern Arizona.

San Simon Sink is the lowest point in the San Simon Swale, a 260-km$^2$ depression located along the eastern margin of the Delaware basin, over the Capitan Reef (limestone) that outlines the basin. It has formed as a result of evaporite removal by dissolution of salt in the underlying Rustler and Salado Formations. The San Simon Sink forms a generally oval depression about 30 m deep and 1.3 km$^2$ long. It contains a secondary collapse sink, about 100 m across and some 8-10 m deep, which subsided abruptly in 1927. Annular rings that cut the surface around the sink suggest continuing subsidence and readjustment to the earlier collapse. The position of the sink over the reef led to the suggestion by Lambert (1983) and Bachman (1984, 1987) that the collapse originated in a dissolution cavity in the Capitan Reef limestone, and that the sink may be a modern analog of a breccia pipe that is actively forming.

Breccia chimneys typically are features of positive relief, originating by the gravity collapse of flanking materials into sinkholes and forming indurated "chimneys" in the throat leading to the void below. Subsequent erosion and subsidence of the surrounding and more soluble country rock lead to surface features that stand in positive relief. While not nearly as common as sinkholes and other collapse features, breccia chimneys may be locally significant, such as on the northern border of the Capitan Reef, where they have been observed in potash mines. "Karst domes" may resemble breccia chimneys, as features of positive relief, but their cores contain older, as well as younger, rocks than their flanks (Davies 1984; Hill 1996). Several isolated hills in the eastern part of the Holbrook basin are possible karst-dome candidates, but this has not been verified.

Solution-subsidence structures are well known in the Devonian Prairie Formation of southern Saskatchewan, Canada. The Rosetown Low and the Regina Hummingbird Trough show formation thinning of several hundred feet, which has been attributed to interstratal dissolution of evaporites at depth (DeMille et al. 1964). Underlying reefs and bedrock fractures very possibly supply the necessary circulation channels for additional localized evaporite dissolution, similar perhaps to the Capitan Reef features. Surface expression of this dissolution is obscured by the presence of glacial drift.

Breccia pipes on the Colorado Plateau are often marked by surface depressions having dimensions and structural geometry similar to McCauley Sinks, and some of them are aligned with northwest-trending structural lineaments. They are believed caused by dissolution in the Mississippian Redwall Limestone and concomitant stoping to the surface (Wenrich and Billingsley 1986; Sutphin and Wenrich 1989). The karst openings in the Redwall are along solution-widened fractures and joint-controlled caves.

The similarity of structural alignment in the McCauley Sinks area with other Colorado Plateau breccia pipes is perhaps not surprising, given the relatively short distances between their occurrences, and similar hydrogeologic controls.

### Geologic Site Characterization (GSC) Considerations

Further development of this area for storage caverns, or for other industrial, agricultural, or commercial and residential purposes, must address the presence of active karst formation. Hundreds of square kilometers are potentially hazardous to some degree, but land-use classification that categorizes the elements of relative potential risk is achievable, so that limited industrial, agrarian, or residential use can continue safely. Such categorization may be useful in simplifying procedures for licensing new cavern fields for underground storage, or in updating and validating locations of existing caverns.

The 3-km-wide karst depression manifested in the McCauley Sinks, along with the five adjacent depressions, form a hydrologic catchment area that provides substantial hydrologic recharge. Because of widespread piping into karst features and jointed bedrock at shallow depth, it is difficult to pond water for either industrial or agricultural purposes, and recharge is greater than in alluvial areas. Assuming that a moderately high recharge efficiency exists, a condition of possible concern exists for groundwater users downgradient from the karst area. For this reason, sinkholes and open fissures should not be used as trash and garbage repositories, in contrast with previous widespread disposal practices.

Probable solution-induced subsidence features are also visible in the eastern and northern margins of the Holbrook basin, at Deep Lake and in the Petrified Forest National Park. The latter depression, termed Blue Mesa Sink (Colpitts and Neal 1996), is about eight km from the underground saltcavern, LPG-storage facility at Adamana, and presumably is well beyond its influence. The existence of Blue Mesa Sink was not identified at the time this storage facility was established.

The Holbrook basin has been studied geologically by numerous individuals, and yet is mapped incompletely. As land-use requirements expand beyond existing boundaries, more detailed understanding and geologic mapping will be required. New interpretations of karst features are modifying existing land-use concepts (Martinez et al. 1998).

## CONCLUSIONS

The McCauley Sinks, in the Holbrook basin of northeastern Arizona, are comprised of some 50 individual sinks, many of which are arranged in a semi-concentric pattern that resembles a partial bullseye. Three nested rings occur, with the outer ring being a tension zone and possible intermittent ring fracture. The two inner rings are manifested as clusters of large sinkholes, ranging up to 100 m across and 50 m deep. Several sub-basins within the larger depression display locally depressed downwarping and possible incipient sinkholes.

Kaibab Formation limestone is the principal surface lithology, occurring here near its easternmost limit and with thicknesses less than 15 m. Other than displaying surface rillenkarren and forming the topmost unit in sinkhole walls, the Kaibab is not a factor in karst expression. Underlying the Kaibab is Coconino Sandstone, which overlies the Schnebly Hill Formation, the unit containing the evaporite rocks, principally halite; all these rocks are of Permian age. The karst manifestation in this part of the Holbrook basin is quite different than that in the eastern part, possibly because of the essential disappearance of the Holbrook anticline, combined with its location near the western limit of known salt occurrence.

The structure at McCauley Sinks is suggestive of a compound breccia pipe, with multiple sinks contributing to the major depression. The Richards Lake depression, 5 km south of McCauley Sinks, is very similar in form and size, but contains only a single central sinkhole. The only apparent difference in hydrologic setting at McCauley Sinks is the adjacent Chevelon Canyon drainage, but the cause-and-effect relationship is not known.

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