

A REVIEW AND BIBLIOGRAPHY  
OF KARST FEATURES OF THE  
COLORADO PLATEAU, ARIZONA

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## KARST TOPOGRAPHY

Karst is the name applied to topography that develops on land underlain by soluble rocks such as limestone, gypsum, and salt. Karst terrain is characterized by solution features such as caves, sinkholes, depressions, enlarged joints and fractures, and internal drainage. The name was derived from the Karst region of Slovenia (part of the former Yugoslavia), which is underlain by limestone.

This report summarizes the occurrence of karst features on the Colorado Plateau of Arizona. The first section briefly discusses the three major types of karst features on the Plateau: breccia pipes, surficial karst, and deep-seated salt karst. The remainder of the report focuses on salt karst in the Holbrook basin.

Karst feature descriptions in this report are based on previously published reports about breccia pipes in the Grand Canyon region (e.g., Sutphin and Wenrich, 1989; Wenrich, 1985, 1992), published detailed mapping of the Arizona Strip by the U.S. Geological Survey (e.g. Billingsley, 1992), published reports about salt karst in the Holbrook Basin (e.g., Bahr, 1962; Neal, 1995, 1999; Neal and Colpitts, 1997a, 1997b; Neal and Johnson, 1998) and AZGS field reconnaissance during summer and fall 2001.

## KARST FEATURES ON THE COLORADO PLATEAU

Karst features are common on the Colorado Plateau of northern Arizona. The Colorado Plateau, with extensive areas underlain by limestone, gypsum, and salt (Figure 1), has potential for property damage and severe water quality problems related to dissolution of these soluble rocks. Karst features are particularly abundant south of Interstate 40 from the Snowflake-Taylor area northwest to Winslow, and in the Grand Canyon region north of Flagstaff to the Utah border.

### **Breccia Pipes**

Solution-collapse features called breccia pipes developed in the Grand Canyon region of the western Colorado Plateau (Figure 1) 200-300 million years ago under a warm, humid climate. These ancient breccia pipes resulted from solution of the Redwall limestone, which is exposed in the Grand Canyon. Caves in the Redwall filled with rock debris (breccia) as their roofs progressively collapsed upward, sometimes reaching the surface as much as 3200 feet above the original cave level. The term “breccia pipe” is generally used in Arizona to refer to karst features of this particular age and origin. To date, 1300 breccia pipes have been identified (Sutphin and Wenrich, 1989). More than 900 have

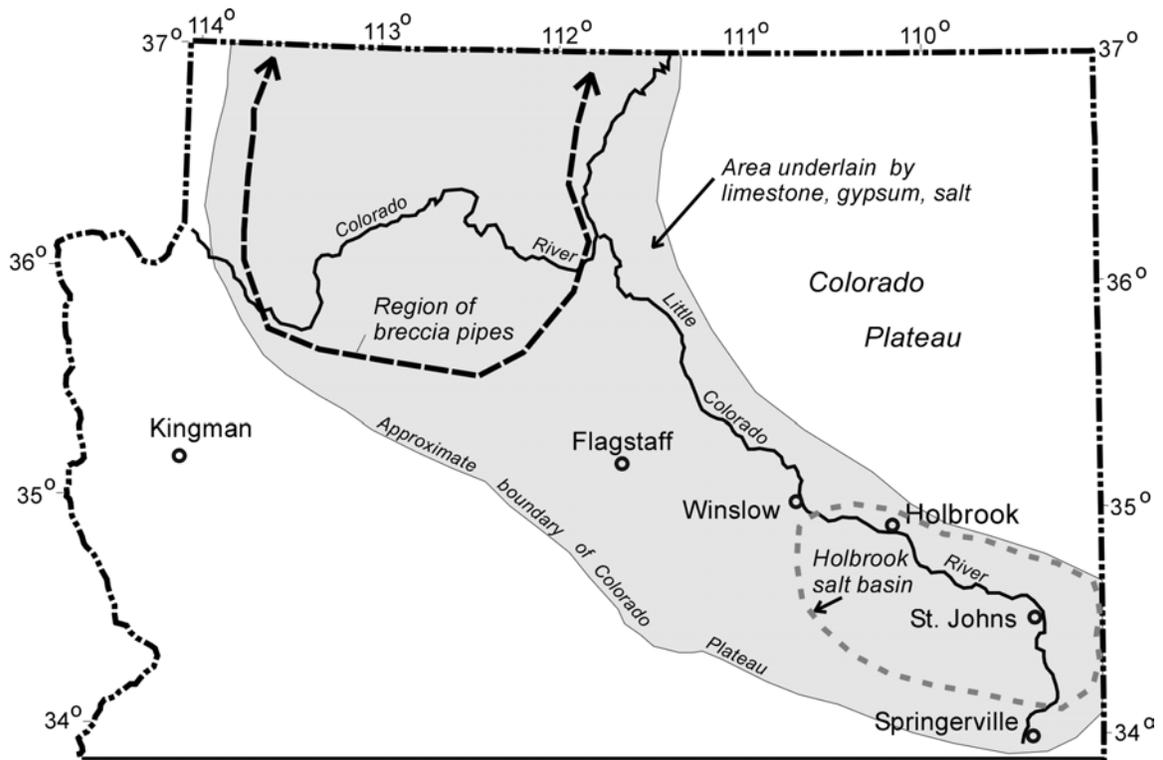


Figure 1. Location of Colorado Plateau and areas prone to karst.

been discovered on the Hualapai Indian Reservation, on the south rim of the Grand Canyon (Wenrich and others, 1986, 1987). Some of the breccia pipes host major copper and uranium deposits that formed more than 141 million years ago. Arizona's largest uranium mine, the Orphan mine, is in one of these breccia pipes. The mine is located in what is now Grand Canyon National Park, two miles northwest of the Visitor Center. The Orphan mining claims were staked in 1893 and patented by D.L. Hogan and C.J. Babbitt in 1906, before the National Park was created. Mining of the Orphan lode ceased in 1969, and the land was acquired by the Park Service. Production from the Orphan totaled 4,360,000 pounds of uranium ( $U_3O_8$ ) and 4,534,000 pound of copper (Keith and others, 1983).

Breccia pipes have been discovered as far south as Red Buttes, 12 miles south of Grand Canyon park headquarters (Sutphin and Wenrich, 1989; Wenrich, 1985; 1992). Breccia pipes may exist south to the Flagstaff region, but the area has not been surveyed as extensively as the Grand Canyon region, and is largely covered by young volcanic rocks of the San Francisco Volcanic Field. Recognition of breccia pipes is further hampered by young circular karst features that have developed largely by gypsum dissolution in the Harrisburg Member of the Kaibab Limestone (Billingsley, 1992). The Redwall Limestone, which is over 800 feet thick in northwestern Arizona, thins and pinches out southeast of Flagstaff (Peirce, 1979; Peirce and others, 1970) and breccia pipes are less likely to occur as the thickness of Redwall decreases. In the salt karst terrain of the Holbrook basin, the Redwall is thin or absent, so breccia pipes of the type found in the Grand Canyon region are not likely to be present. A bibliography of the distribution and geology of breccia pipes is presented in Appendix A.

### **Surficial karst**

Much of the western Colorado Plateau in Arizona is underlain by limestone and gypsum (Figure 1), and as is typical in such terrane, karst features are common. The most common features are enlarged joints and shallow sinks formed by near-surface dissolution of gypsum, and to a lesser extent limestone, in the Permian Kaibab Formation. The Kaibab crops out extensively in the Grand Canyon region north into Utah. Thousands of sinks have been plotted on geologic maps of the western Colorado Plateau, mostly north of Grand Canyon. A bibliography of maps that may show surficial karst features in the Grand Canyon region is included as Appendix B.

Although the Kaibab Formation is thin or missing in most of the Holbrook Basin, where it is exposed there is some karst development. Karst takes the form mostly of enlarged joints and solution pans (Figures 2 and 3). These features are generally too small to appear on topographic maps so their distribution can only be determined by detailed field surveys.

Another manifestation of karst development in the Kaibab Formation in the eastern Holbrook basin is numerous voids in the shallow subsurface. These voids are commonly encountered during drilling, causing lost circulation.



Figure 2. Example of ubiquitous surficial karst features in Kaibab Limestone. Dissolution of limestone by rain forms rough texture, small drainage rills, and enlarged joints.



Figure 3. Example of surficial karst developed in calcareous sandstone. Dissolution of calcite cement forms enlarged joints and "solution pans".

## **Salt Karst**

Karst in the southern part of the Colorado Plateau results from the dissolution of salt beds in the Permian-age (245-286 m.y.) Supai Formation, with collapse propagating upward through the overlying Coconino Sandstone and Kaibab Formation. More than 500 fissures and sinkholes have been identified in the area between Springerville and Winslow (Neal, 1998, Neal and Colpitts, 1997a). On topographic maps, large karst features appear as sinkholes or as basins that have internal drainage and commonly contain small lakes. The remainder of this report focuses on salt karst in the Holbrook basin.

### **SALT KARST IN THE HOLBROOK BASIN**

More than 500 fissures and sinkholes have been identified in the area between Springerville and Winslow (Neal, 1998, Neal and Colpitts, 1997a). Karst in this region of the Colorado Plateau results from the dissolution of salt and gypsum beds in the Permian-age (245-286 m.y.) Supai Formation. Collapse begins in beds of salt, where voids propagate upward by stoping through the overlying Coconino Sandstone and Kaibab Formation. A detailed description of the distribution and geology of the Supai salt, gypsum, and potassium deposits is given in Rauzi (2000; 2002). The extent of Permian salt is shown in Figure 4.

Descriptions of salt karst in the Holbrook Basin are based on previously published reports (Bahr, 1962; Neal, 1995; Neal, 1999; Neal and Colpitts, 1997a, 1997b; Neal and Johnson, 1998), and field reconnaissance during summer and fall 2001. Locations of large salt karst features on Figure 4 are primarily from U.S. Geological Survey (USGS) 7.5- minute topographic maps, which show such features as closed depressions. A few features were located based on aerial photos and fieldwork. It is common for karst features, such as cracks, to be too small to appear on topographic maps and they may not be visible on aerial photos. Because of these factors there may be more karst features on the ground than appear on Figure 4.

#### *SOUTHWESTERN HOLBROOK BASIN*

Collapse features are concentrated in a N 50° W trending, 60-mile long arc south of a flexure known as the Holbrook anticline (Bahr, 1962) at the southwestern margin of the basin (Figure 4). The monoclinical structure developed by the subsidence of rocks into a void formed by dissolution of underlying salt beds.

Permian salt beds thin rapidly south of the crest of the anticline. The solution front has propagated to the northeast, parallel to the regional slope of the Colorado Plateau. Wells along and north of the anticline have water with salinities as high as 2000 mg/L TDS, indicating dissolution of salt (Mann, 1976).

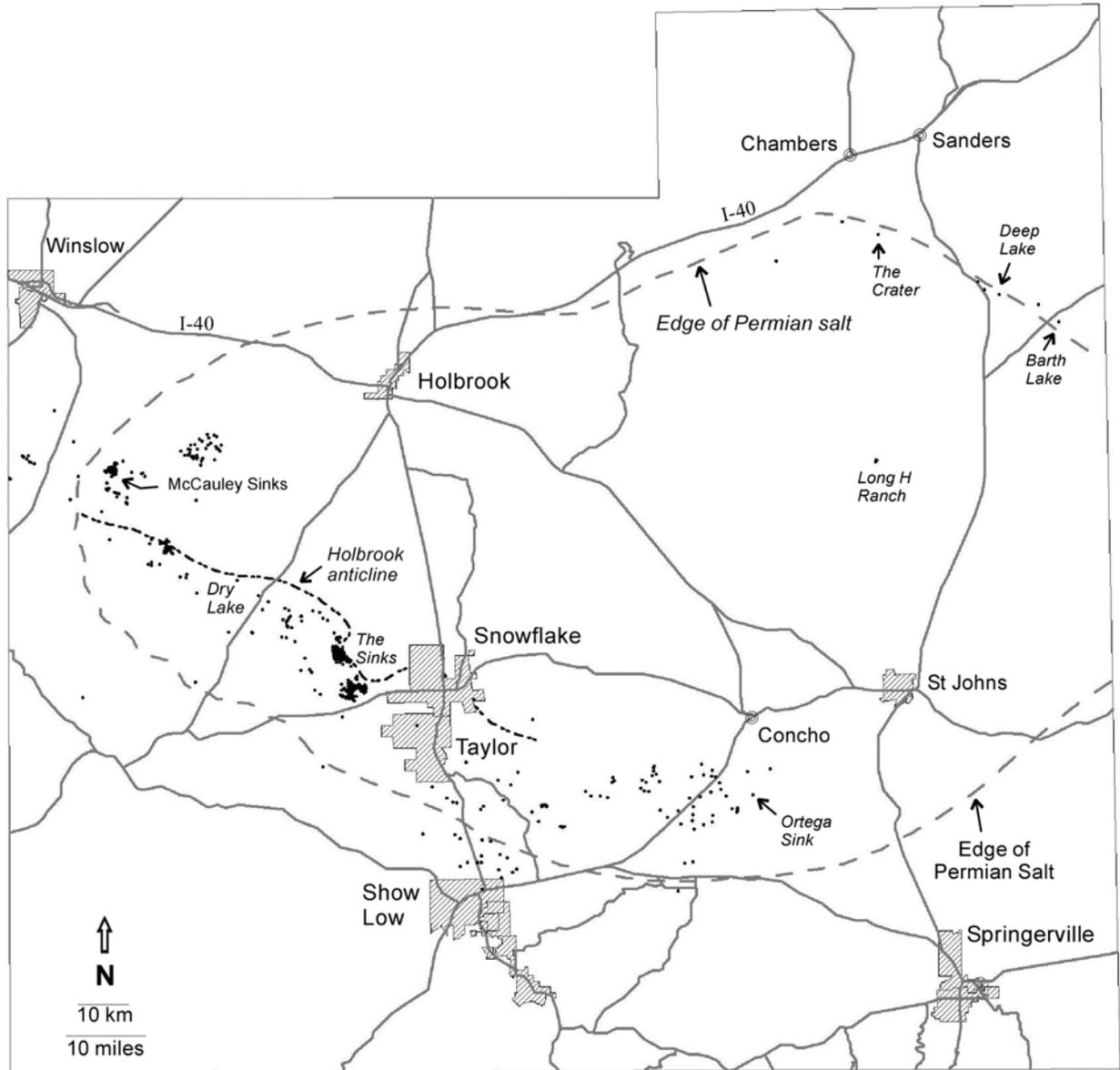


Figure 4. Location of Holbrook Basin salt karst region. Karst features and areas of internal drainage are indicated by dots. Extent of Permian salt from Rauzi (2000). Features between Show Low and Concho are areas of closed contours that may be related to lava flows and cinder cones.

Limestone such as that in the Permian Kaibab Formation has played no role in the development of the sinkholes of the southwestern Holbrook Basin (Bahr, 1962; Neal, 1999). The Kaibab Formation is absent over half of the Holbrook Basin and is generally less than 30 feet thick over the remainder. Where present, the Kaibab is predominantly sandstone or sandy limestone (Bahr, 1962). Minor karst that has developed in the Kaibab Limestone consists mostly of enlarged joints and solution pans (Figures 2 and 3). This type of karst is common in limestone throughout the state.

The Holbrook anticline (actually a monocline) passes through the northern limits of the town of Taylor and extends about eight miles southeast from there (Figure 4). Sinkholes and other karst associated with the anticline, however, appear to end about seven miles west of the Taylor-Snowflake area. Only a few salt-karst features are found east of Snowflake. Explanations for the lack of recognized karst in the southern part of the Holbrook salt basin east of Snowflake include volcanic cover, young eolian and sedimentary deposits, and a lesser degree of salt dissolution.

Several notable areas of salt karst have formed in the southwestern part of the Holbrook Basin along the solution front south of the Holbrook anticline and in the eastern part of the basin. The largest of these areas are discussed below:

#### *Dry Lake Valley*

Dry Lake Valley is situated on the south flank of the Holbrook Anticline (Figure 4). The internally drained basin covers an area of more than 125 square miles (325 km<sup>2</sup>) (Neal and Johnson, 1998). Evaporite solution remains active and new sinkholes are forming in Dry Lake Valley. Bahr (1962) reports the appearance of several sinkholes in Dry Lake Valley on air photos taken in 1953 that did not appear on photos taken 17 years earlier. In addition to salt-related karst, other less spectacular karst features such as solution-enlarged joints have formed and are still forming in the Kaibab Limestone exposed at the surface over the southwestern third of the Holbrook Basin. Such limestone-related karst is generally too small in scale to appear on topographic maps.

#### *The Sinks*

The largest concentration of sinkholes in the Holbrook Basin is in an area known as “The Sinks”, east of Dry Lake Valley and 6 miles west of Snowflake (Figure 5). The Sinks is near the eastern limit of the well-developed monoclinical fold expressed as steep slopes and prominent cliffs. More than 300 karst features (sinkholes and large cracks) occur in the area (Neal and Johnson, 1998). Figures 6 and 7 show typical sinkholes along the Holbrook Anticline.

#### *McCauley Sinks*

McCauley Sinks, an area of closed drainage 1.5 miles in diameter, contains about 50 sinkholes (Figure 8). This area is near the western extent of the salt solution front marked by the Holbrook Anticline. Although the solution front passes under this area, there is no obvious surface expression of a monocline as there is to the east. Sinkholes are up to 200 feet deep with vertical sides. Aerial photos and USGS maps (Figure 9) clearly show a nested pattern of two concentric horseshoe-shaped arcs of sinkholes. Outside the cluster of sinkholes is a circular pattern of large cracks. Compressional ridges have formed on the southern part of the sink (Neal, 1999) and these are faintly discernable on aerial photos.

Neal (1999) has postulated that the McCauley Sinks area is a composite breccia pipe. Classic “breccia pipes” of the Colorado Plateau formed when roofs of caverns in the Mississippian Redwall Limestone stopped upward. Mississippian strata under the

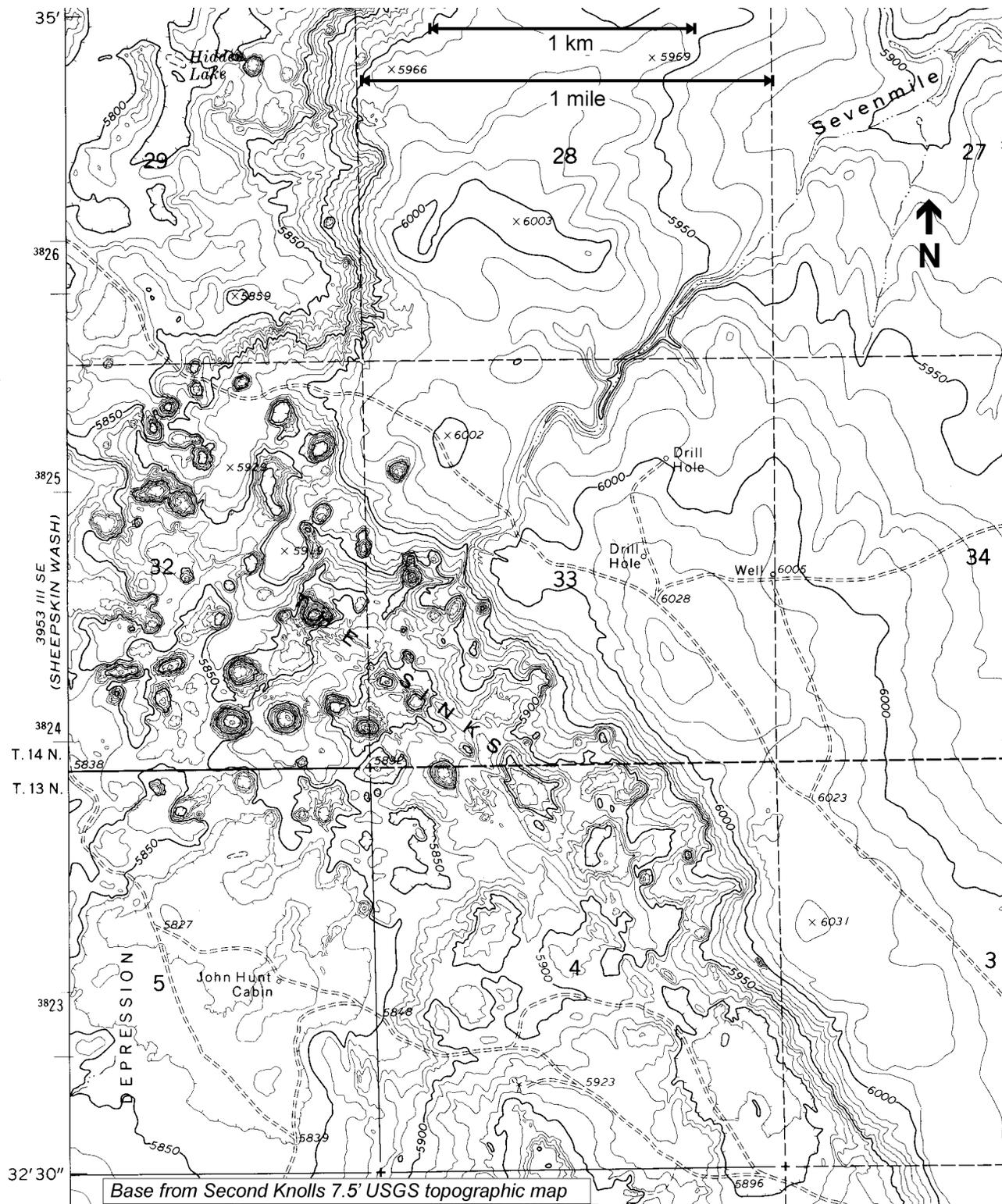


Figure 5. Location of cluster of sinkholes known as The Sinks. Another cluster is located about two miles southeast of this map area.



Figure 6. Sinkhole in northwest part of The Sinks. Size of sinkhole can be judged by the truck on the far side



Figure 7. Small sinkhole in cluster near New Round Tank, NW section 13, T15N, R17E.

McCauley Sinks are no more than 50 feet thick and pinch out to the northeast based on isopach maps for Arizona (Peirce and others, 1970; Peirce, 1979). Although theoretically there may be just enough Redwall at this location for a classic breccia pipe to exist, Neal (1999) argues that the Redwall is not a factor in karst development here. The interpretation for McCauley Sinks is that the broad depression and the numerous sinkholes formed from salt dissolution, as is the case elsewhere along the Holbrook anticline. In this sense the “breccia pipe” origin here is not the same as a breccia pipe in the Grand Canyon region.

#### *Richard Lake*

Richard Lake (Figure 8) is an area of internal drainage about one mile across, 2.5 miles southeast of McCauley Sinks (Neal and Colpitts, 1997b). One large sinkhole occupies the center of the depression, with other smaller sinks and fissures scattered around the margins of the basin. The larger features are discernable on the McCauley Sinks 7.5-minute quadrangle map. Buckle folds described by Neal and Colpitts (1997b) are faintly visible on the McCauley Sinks orthophoto quadrangle. Neal (1999) interprets the Richard Lake depression as being a composite “breccia pipe” caused by dissolution of salt.

#### *New Round Tank area*

A small cluster of sinkholes is situated northwest of Dry Lake Valley, in T15N, R17E. Sinkholes in this cluster are in a zone trending NW, parallel to the Holbrook anticline in this area. Figure 10 shows the location of the cluster. Figure 7 is a photograph of a sinkhole that is one of the smallest fully formed sinkholes in the region.

#### *Ortega Sink area*

Ortega Sink, an area of internal drainage, lies about 25 miles ENE of Show Low. North and east of Ortega Sink are other depressions including Little Ortega Lake and Laguna Salado. Ortega Sink is considered to be a salt karst feature (Neal and Colpitts, 1997; Neal and Johnson, 1998; Neal, 1999). Some other areas of internal drainage (closed contours) in the region immediately north of the road from Show Low to Concho may be due to salt karst, but most are probably due to lava flows and cinder cones in that region. On Figure 4, all areas of internal drainage except those obviously related to lava flows or cinder cones are plotted, but have not been confirmed to be karst. For example, none of the areas of closed contours on the Ortega Mountain quadrangle are shown as karst because they are all nestled between cinder cones.

#### *Cracks*

In addition to numerous sinkholes, dissolution of salt has caused the development of large cracks in zones along the monoclinical fold of the Holbrook Anticline. The zones of cracks are generally at the break in slope near the top to part way down the monocline. As salt dissolves at depth, bending of the overlying Coconino sandstone creates tension fissures in the upper portion of the thick sandstone layer.

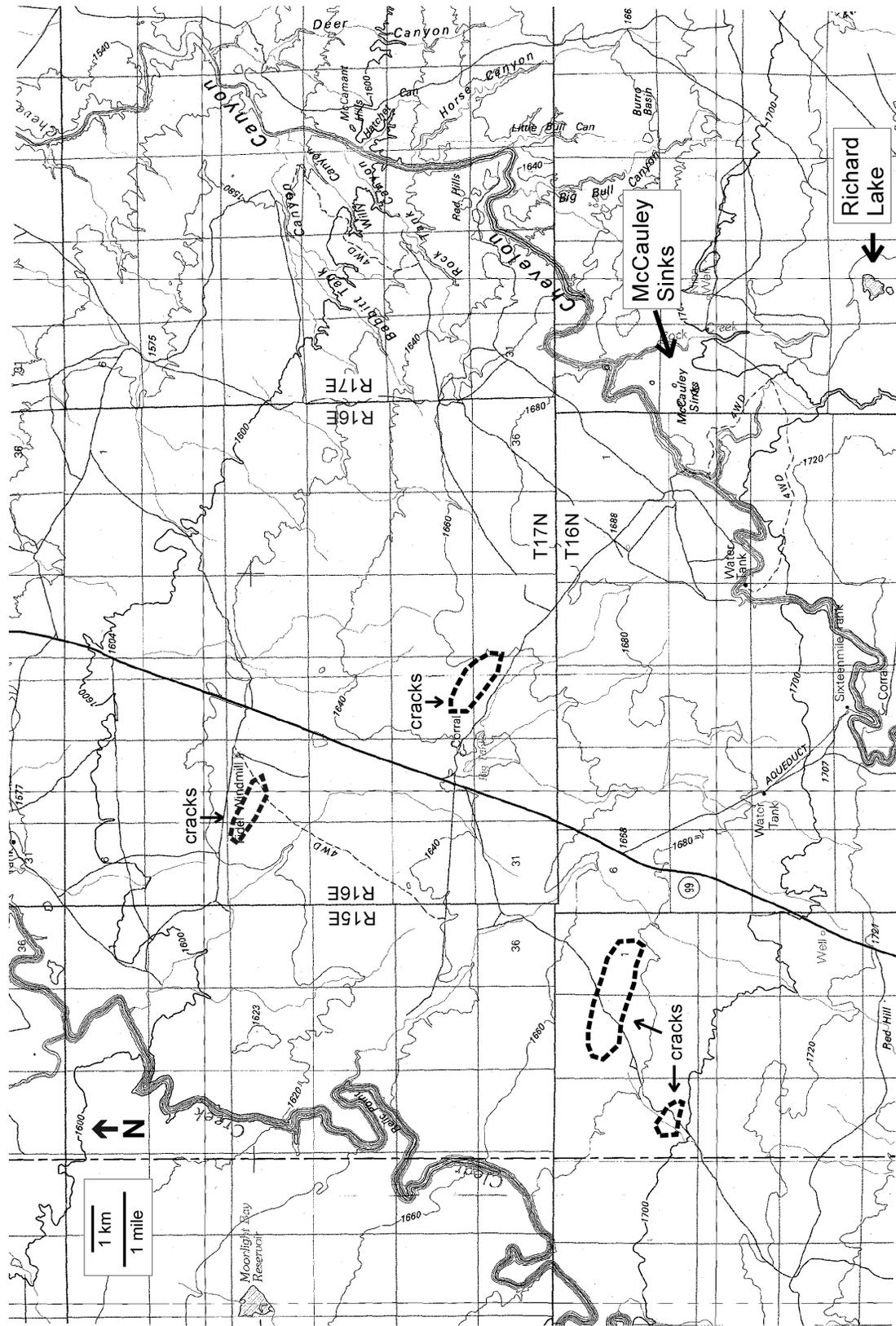


Figure 8. Map of western-most salt karst area along trend of Holbrook anticline.

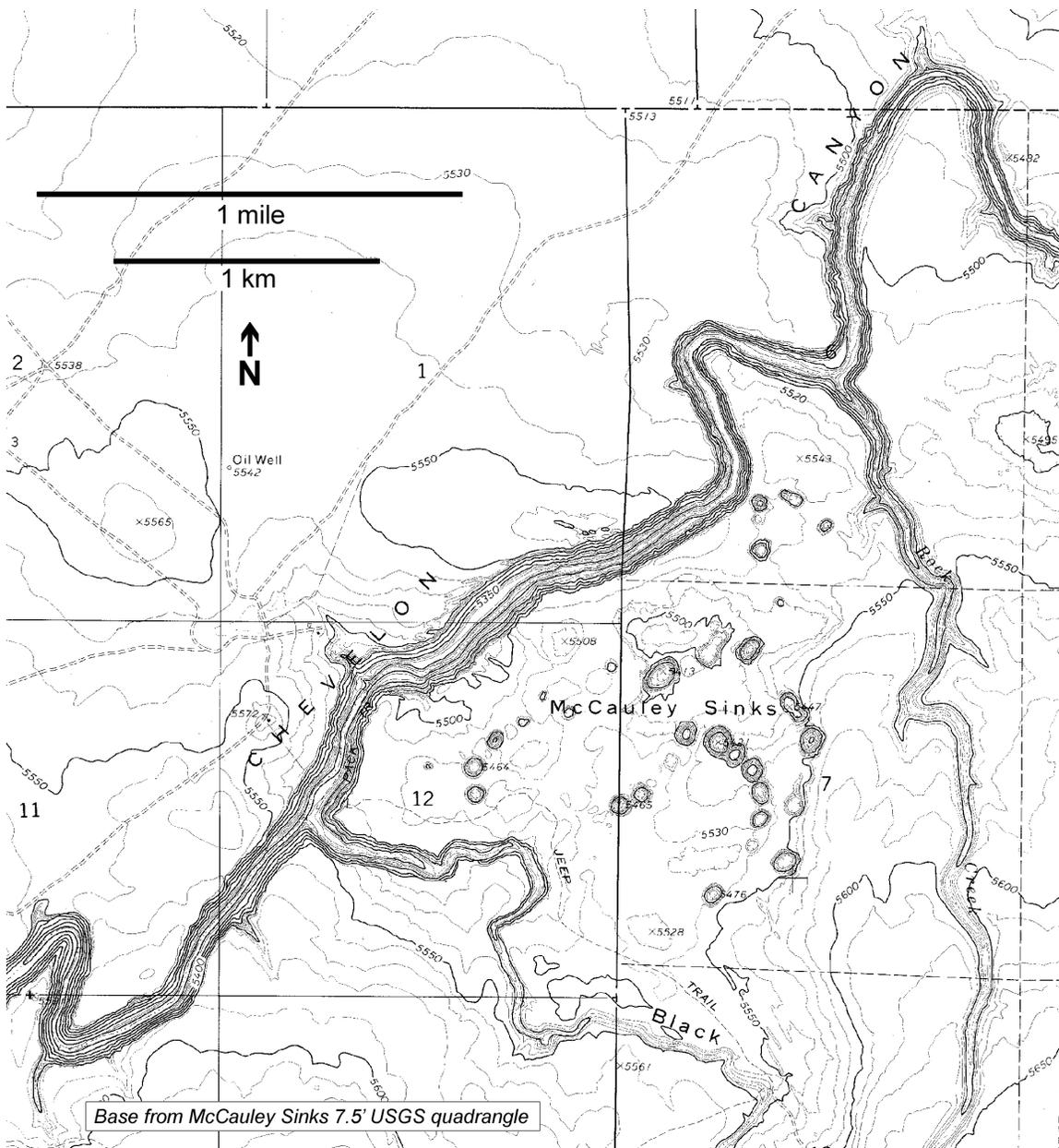


Figure 9. Topographic map of the McCauley Sinks area.

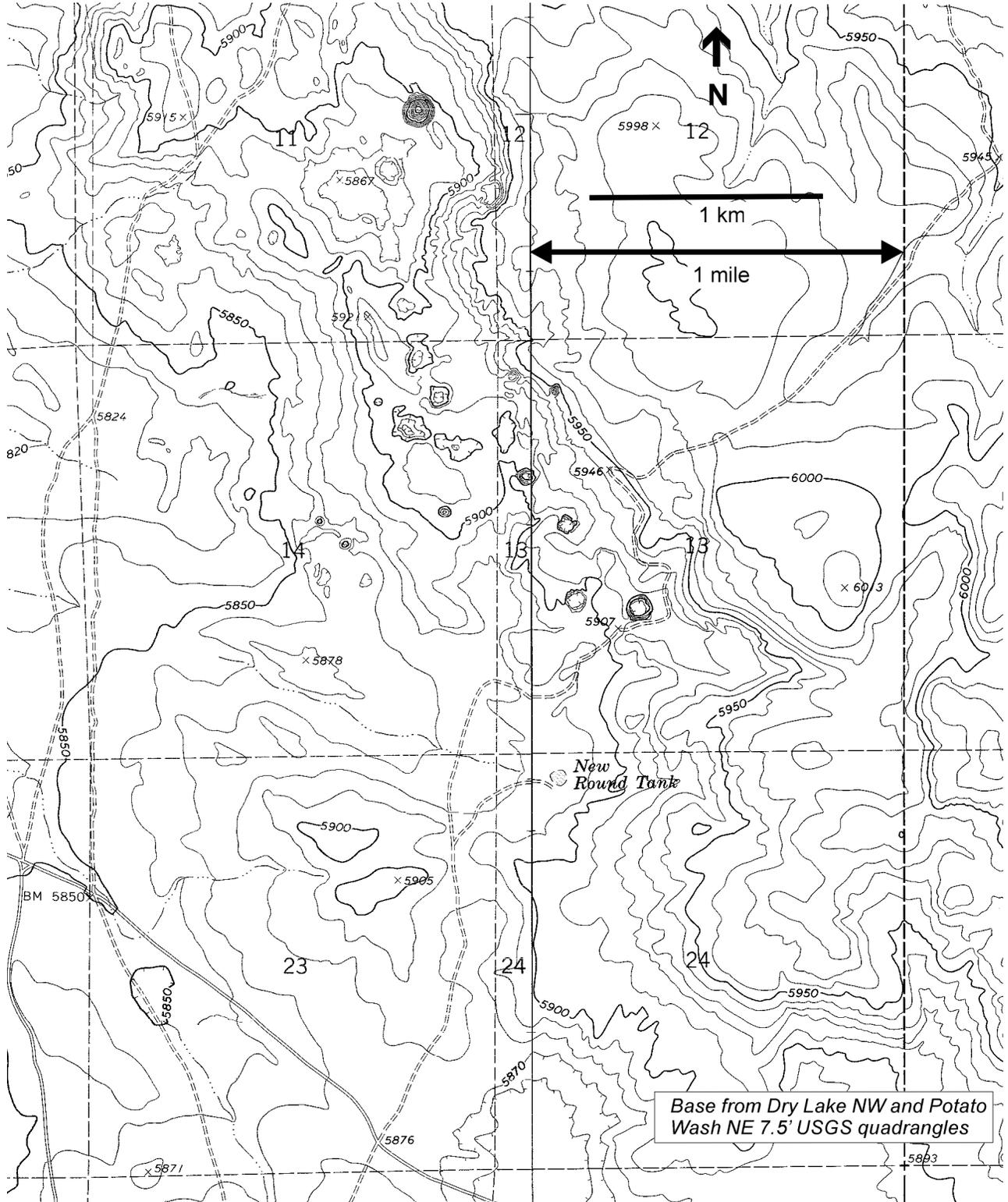


Figure 10. Group of sinkholes near New Round Tank, NW of Dry Lake, in T15N, R17E.

Well-developed regional joints in the Coconino sandstone trend about N50W and a less pronounced set trends NE. Where the local trend of the Holbrook anticline is close to parallel to the regional jointing, cracks (expanded joints) are relatively straight with few en echelon steps and can be very long and deep. At the surface the cracks are 1-20 feet wide and in many the bottom cannot be seen. Some cracks have the form of a graben. Where the anticline runs at an angle to the joint directions, cracks open in both sets of joints, forming a rectilinear set of conjugate cracks.

West of the McCauley Sinks are several sets of cracks (Figure 8) aligned in a northwesterly direction, roughly parallel to the regional jointing pattern and to the Holbrook Anticline. These cracks are large enough to be plotted on the Relic Point and McCauley Sinks 7.5-minute quadrangles and are easily seen on the corresponding orthophoto quadrangles. The mid-points of the largest cracks are indicated on Figure 4 by the eight points west of McCauley Sinks.

Immediately northeast of the area known as “The Sinks”, a cluster of cracks is situated on the crest of the monocline north of the area of sinkholes. Along the Pink Cliffs, north of The Sinks to northwest of Dry Lake, are zones of very large cracks at the crest of the monocline. Areas having abundant cracks are shown in Figure 11.

The process of crack formation is still active. Comparison of aerial photos of different ages reveals that there are visible changes in old cracks as well as formation of newer cracks and sinkholes (Bahr, 1962; Neal and Colpitts, 1997a). Field evidence shows that some cracks are very young and that crack formation is still an active process. Figures 12-19 are photographs showing typical features of these large cracks.

Relative ages of the cracks can be judged by the degree of weathering, development of varnish, and growth of lichen on exposed surfaces. Adjacent to old cracks most or all soil nearby has been washed into the voids, leaving bare rock. Old cracks are characterized by rounded corners, surface staining or varnish, and dense lichen coverage. Fresh cracks have sharp corners and no lichen. Some relatively new cracks still have a coating of caliche on the joint surfaces. In a few areas, such as northwest of Dry Lake, insipient cracks are so recent that soil has just begun to be eroded into the cracks via piping. At two sandstone quarries north of Dry Lake, young, narrow cracks are exposed in the quarry floor.

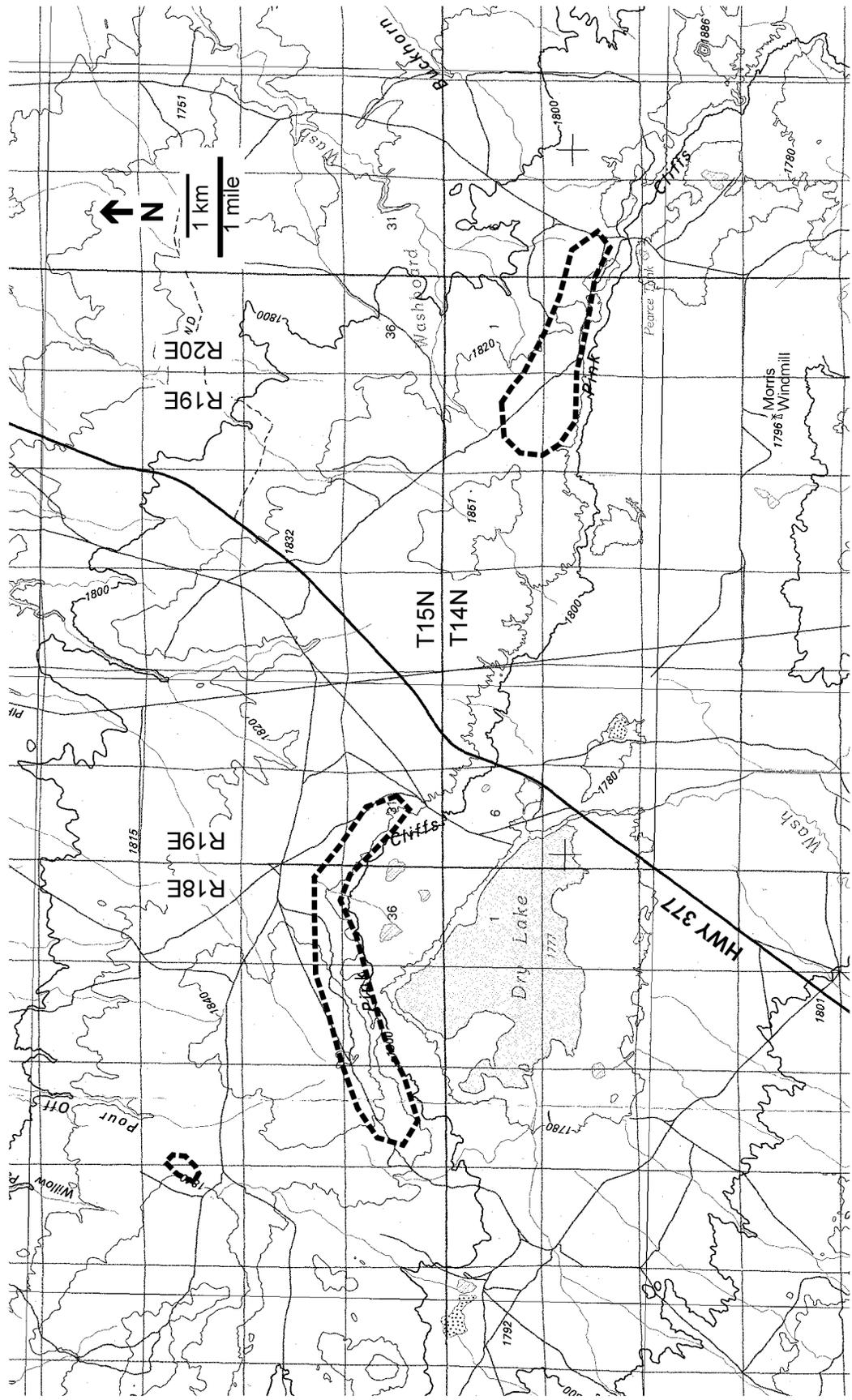


Figure 11. Notable areas north of Dry Lake where large cracks have developed along joints.



Figure 12. Large, old crack northwest of McCauley Sinks, caused by flexure along salt solution front.



Figure 13. Recent activity indicated by incipient crack. This opening is several hundred yards west of large crack in previous picture. Soil is just beginning to wash into hole.



Figure 14. Large, old crack north of Dry Lake. This crack has well developed staining and lichen growth, and all soil has been eroded.



Figure 15. Incipient crack exposed in quarry. Crack does not always follow joints because direction of stress is at an angle to the joint directions.

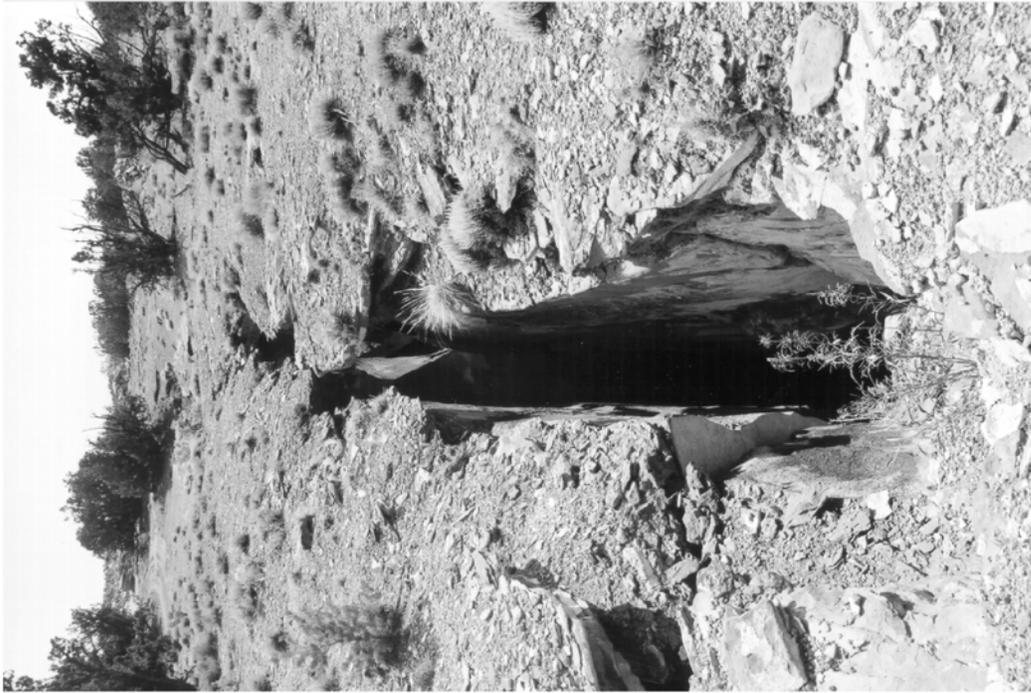


Figure 16. Relatively new crack NW of Dry Lake. Some soil has washed into the crack, leaving a lag of sandstone rubble.

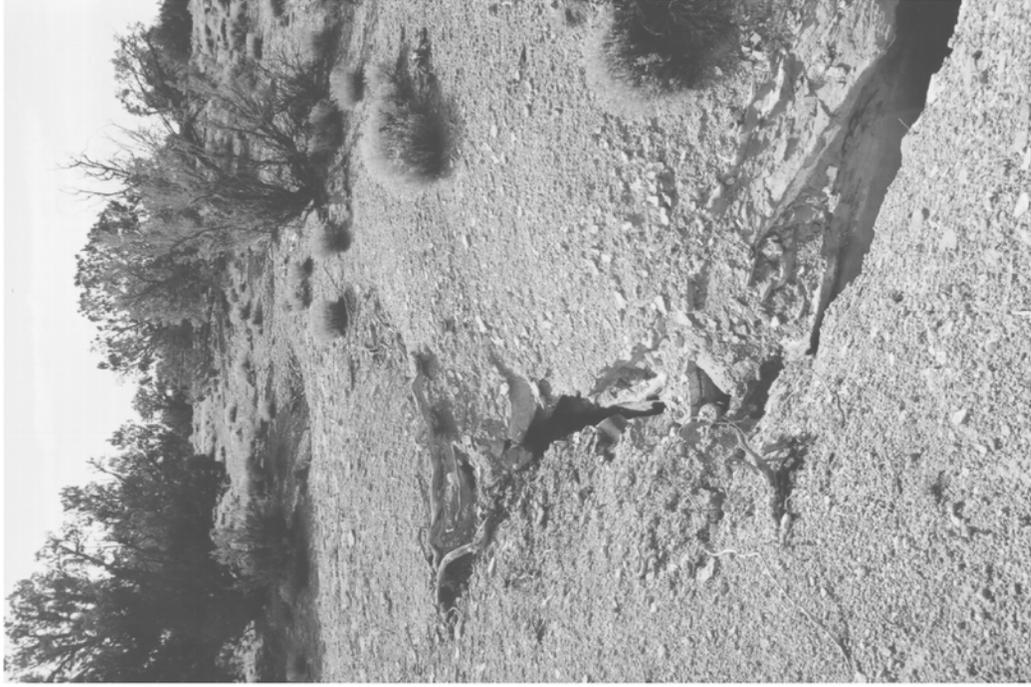


Figure 17. Recent crack west of previous picture. Soil and loose rocks have just begun to wash into the discontinuous crack.



Figure 18. Large NNE-trending crack system in section 22, T15N, R18E.



Figure 19. Large crack north of Dry Lake being used for dumping. Such dumping in deep cracks presents a serious threat to groundwater quality.

## *NORTHEASTERN PART OF THE HOLBROOK BASIN*

Scattered salt-related karst features occur in the northeastern part of the Holbrook Basin (Figure 4). These features are not as numerous as those in the southwestern part of the basin, but are still evidence that salt dissolution is occurring. Karst not related to salt also has developed in the Kaibab Limestone and its equivalent in New Mexico, known as the San Andreas Limestone. Drilling in the region between Saint Johns and Springerville has revealed numerous instances of lost drilling fluid and encounters with voids. Some of the loss of drilling fluid has occurred in the Coconino Sandstone and is believed to be the result of high porosity in parts of the formation that are poorly cemented.

Identification of karst features (closed depressions) on topographic maps of the eastern Holbrook Basin is severely hampered by the presence of dunes that form small depressions in the inter-dune areas. Topography associated with lava flows may also mimic karst depressions.

### *Deep Lake area*

In the northeast part of the Holbrook Basin are several areas of closed drainages that may be karst-related. These features are prominent on the Barth Lake, Wild Cow Lake, and Deep Lake quadrangles (Figure 4). Straddling highway 61 about 4 miles west of the New Mexico border and stretching across the corner of the three quadrangles is a NW-SE oriented closed depression almost a mile wide and more than 3 miles long having a depth of more than 70 feet. At the southeast end of the depression is Barth Lake. These features are close to the edge of Permian salt (Rauzi, 2000).

Two miles southwest of Barth Lake, adjacent to highway 61, is Wild Cow Lake, a depression about 0.3 miles wide and 20 feet deep. On the adjacent Deep Lake quadrangle are closed basins known as Deep Lake, Squaw Lake, and Hogan Lake. Deep Lake is almost a mile in its greatest extent and is 60 feet deep. Squaw Lake is about 0.3 miles wide and about 30 feet deep. Hogan Lake is about 1000 feet wide and 20 feet deep. Deep Lake is considered to be a karst-related feature (Neal and Colpitts, 1997; Neal and Johnson, 1998), but whether other closed depressions in the region are karst features, or rather, are the result of dunes, lava flows, or collapsed lava tubes could not be verified because this area is now part of the Navajo Nation and access is restricted.

### *Long H Ranch area*

Scattered areas of closed drainage occur in the northeastern part of the Holbrook Basin. At Long H Ranch (T16N, R28E, section 18), two sinkholes are apparent on the Long H Ranch 7.5-minute USGS topographic map (Figure 20) and aerial photos (Figure 20). The sinkholes are smaller than most of those near the salt solution front along the Holbrook Anticline. These sinkholes are not near the edge of the Permian halite or the edge of a sylvite layer that caps the salt near Holbrook (Rauzi, 2000). No other such sinkholes are observed in the area on topographic maps. Why only these two sinkholes have formed in the area is unknown.

The sinkholes at Long H Ranch have relatively straight edges and square corners rather than being round, probably reflecting regional jointing in the underlying sandstone. Both sinks contain reddish colored standing water of unknown depth.

#### *Navajo Springs area*

South of Chambers in the vicinity of Navajo Springs are two areas of internal drainage that may represent salt (halite or sylvite) dissolution. A feature called The Crater (T20N, R28E, section 32; Navajo Springs 7.5-minute quadrangle) is a circular area about 0.5 miles wide with springs issuing from the southeast side (Figure 22). Three miles to the northwest (T20N, R27E, section line of 26/27) is another closed depression with salt seeps. These two features coincide with the northern edge of the Permian salt and possible salt flowage features (Rauzi, 2000). Isopachs of the Permian salt indicate a more rapid thinning of the salt deposits on the north side of the Holbrook Basin than on the south side. Numerous springs in the area are described in Harrell and Eckel (1939). This area is on the Navajo Nation and could not be field checked to confirm if the depressions are salt related.

## KARST HAZARDS

The passage of groundwater through soluble rocks results in the formation of voids at depth. Collapse of the ceilings of the cavities may lead to the development of sinkholes, depressions, or fissures at the ground surface. Karst terrain commonly is characterized by highly uneven depth to bedrock, residual red, clay-rich soil, and surface drainages that disappear underground.

Hazards from karst include the formation of sinkholes or collapse pits, as well as cracking of walls, foundations, roads, and other structures caused by development of ground fractures marking the first signs of approach of a collapse feature toward the surface.

Voids in bedrock can capture surface water flow, disrupting the surface drainage network. Soil and other surficial material may be washed into the underground network of cavities where surface drainage disappears into the ground. This process, called piping, can be as damaging as collapse of sinkholes.

Less obvious but equally important are the impacts karst can have on water quality. Networks of interconnected caverns and voids allow contaminants such as sewage, landfill leachate, or hazardous chemicals to travel unimpeded into aquifers that supply drinking water. Solution features must be carefully considered in making land-management decisions, including protecting water supply, locating septic systems, and siting of waste disposal facilities.

When exposed at the surface, karst features are usually obvious. Depression, holes, and fissures are readily apparent on the ground, and, if large enough, can be distinguished on

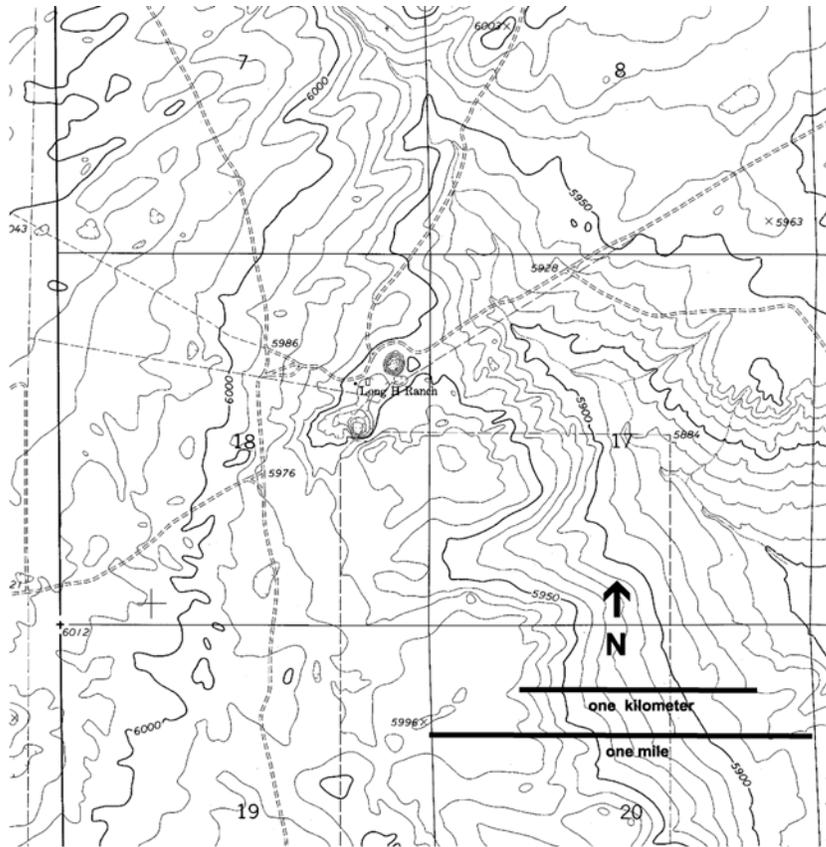


Figure 20. Location of sinkholes at Long H Ranch.

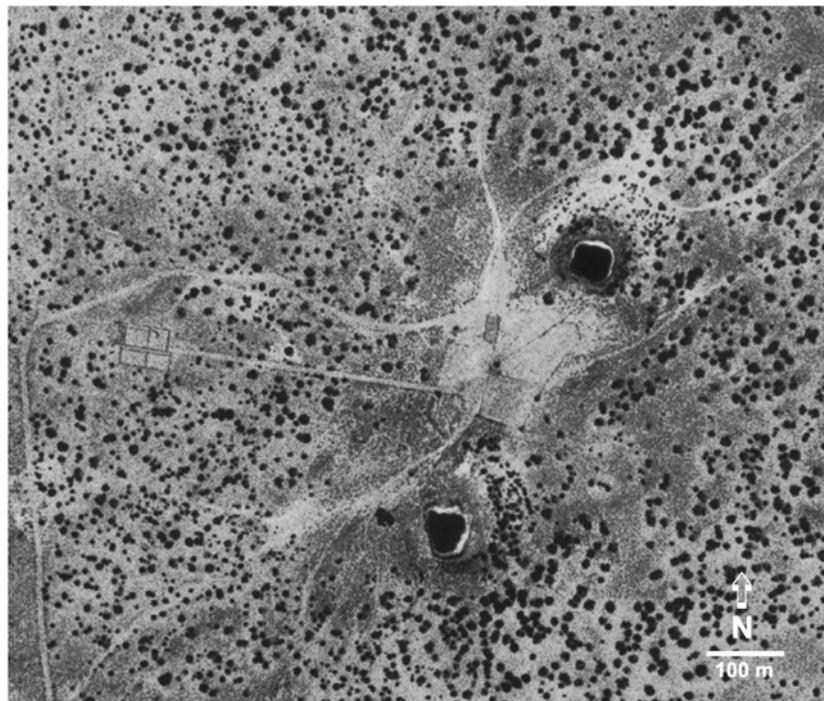


Figure 21. Aerial view of Long H Ranch sinkholes.



At sites where it is important to determine if karst is present underground, prospecting methods must be used to locate voids. Several geophysical methods are available for detecting the presence of near-surface karst. These include ground-penetrating radar, electrical resistivity, spontaneous potential, gravity, and magnetic surveys. These methods rely on differences in physical properties between the karst caverns or their filling materials and the surrounding rock.

An indirect problem associated with building on karst is that of differential settling. One characteristic of karst regions is variable depth to bedrock. A building may sit partly on soil and partly on solid bedrock. Settling of the soil may occur, causing cracking of foundations and walls. Compounding the potential for fill-related structural damage is the abundance of expansive clay in soils on the Colorado Plateau, which may cause its own problems.

## SOURCES OF INFORMATION ABOUT KARST

USGS topographic maps depict areas of internal drainage (closed contours), circular features related to sinkholes, and some cracks in numerous areas on the Colorado Plateau. Topographic maps may be purchased from the Arizona Geological Survey (AZGS), outdoor and sporting goods stores, map stores, or directly from the USGS. Geologic maps are available from the AZGS and USGS. Links to sites with information about karst are posted on the AZGS website.

If you are planning to build in an area with potential for karst, we strongly advise that you thoroughly examine a property for signs of karst features before construction. Consultants for karst problems may be found in the engineering (geotechnical or geological), hydrologist, or geologist sections of the phonebook yellow pages. Information on building restrictions in karst terrain may be available from county planning and zoning departments. Standard homeowners insurance may or may not cover damage from sinkholes. Check with your insurance agent to confirm if karst-related damage is included.

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## APPENDIX B

### Colorado Plateau surficial karst

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