RICHARD LAKE, AN EVAPORITE-KARST DEPRESSION IN THE HOLBROOK BASIN, ARIZONA

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ABSTRACT: Richard Lake is a circular depression 35 km SE of Winslow, Arizona, about 1.6 km wide and with topographic closure of 15-23 m. The depression is 5 km south of McCauley Sinks, another depressed area about 2 km wide which contains some 40 large sinkholes. Richard Lake formerly contained water after heavy rains prior to headwater drainage modification, but is now dry most of the time. It is situated within the Moenkopi / Kaibab outcrop belt, with Coconino Sandstone at shallow depth, near the southwestern margin of the subsurface Permian evaporite deposit in the Holbrook Basin. Outcropping strata are predominantly limestone, but the salt-karst features result from collapse of these units into salt-dissolution cavities developed in the Corduroy Member of the Schnebly Hill Formation of the Sedona Group (formerly called the Supai Salt) that underlies the Coconino. Richard Lake is interpreted as a collapse depression containing concentric faults, pressure ridges, and a 200m wide sinkhole in the center. A second set of pressure ridges parallels the axis of the nearby western end of the Holbrook Anticline, trending generally N 30° W. 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.

The presence of Richard Lake amidst the preponderance of salt-karst features along the Holbrook Anticline suggests a similar origin by salt dissolution, but with distinct manifestation resulting from variation in overburden thickness and consolidation. Similarities of origin between Richard Lake and McCauley Sinks seem likely, because of their similar geological setting, size, appearance, and proximity. Two lesser developed depressions of smaller 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.

INTRODUCTION

Richard Lake is an internally drained depression about 2 by 1.6 km, located in the western part of the Holbrook Basin. It is five km south of McCauley Sinks, a group of 40 large sinkholes. Richard Lake is not a permanent lake, having held water only intermittently (at most) for the past 60 years, although formerly it may have held water more frequently. A central sinkhole at the lowest elevation in the depression contains piping features which appear to drain the entire depression.

The Richard Lake depression is similar to more than 500 other dissolution features in the Holbrook Basin which have been ascribed to evaporite karst, but it is also distinctive in its geomorphic expression. The purpose of this paper is to describe Richard Lake and discuss the possible origins of this feature. We will also compare Richard Lake with other depressions and sinkholes in the region and their relationship to karst expression.

GEOLOGIC SETTING

Evaporite karst is well developed along and south of the Holbrook Anticline (Fig. 1), extending northwesterly along a dissolution front of more than 100 km from southeast of Snowflake, Arizona, nearly to Winslow, Arizona. Richard Lake is near the westernmost side of the basin, and the northwestern

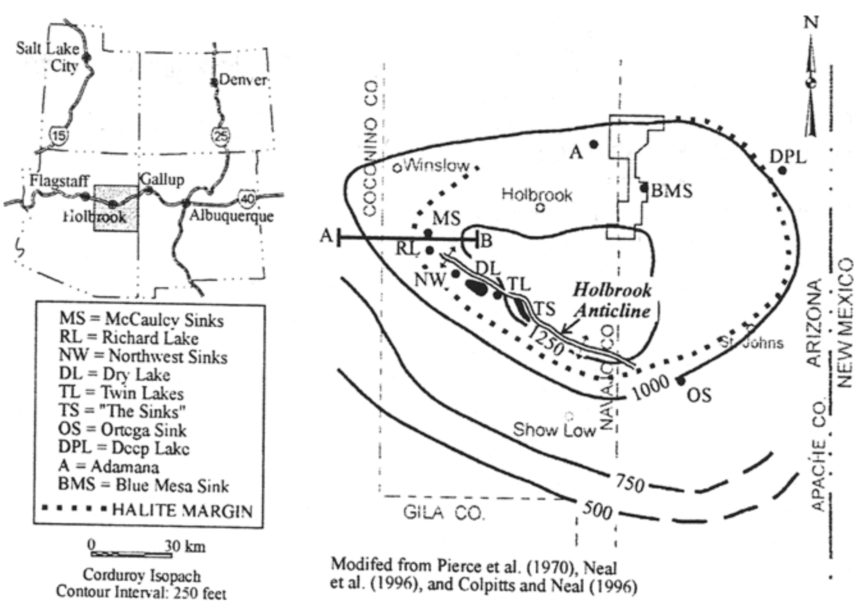

Figure 1. Isopachs of the Corduroy Member of the Schnebly Hill Formation, Sedona Group (upper Supai of Peirce et al. 1970, and others). Principal karst locations in the Holbrook Basin are shown, and approximate extent of the Holbrook Anticline.

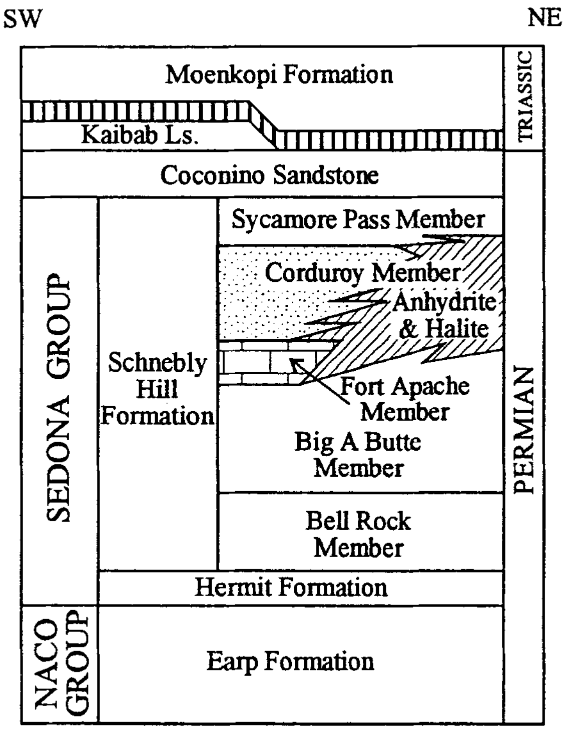

Figure 2. Stratigraphic units involved in karst development, southwestern Holbrook Basin, Arizona.

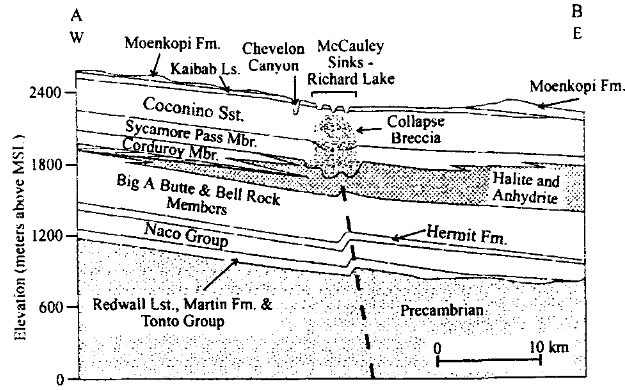

Figure 3. Cross-section A-B (see Fig. 1) through Holbrook Anticline and Richard Lake and McCauley Sinks vicinity showing inferred relation between deep-seated structure and dissolution.

end of the anticline. Other scattered depressions also occur around the eastern and northeastern edges of the evaporite deposits in the Holbrook Basin (Peirce et al. 1970; Neal et al. 1996; Colpitts and Neal 1996). The geology and stratigraphic setting of the area are described in general terms by Bahr (1962), Mytton (1973), and Peirce (1981). The stratigraphic section that is involved in the karst development includes reddish brown eolian and fluvial sandstones, siltstones and rare conglomerates, white to light gray anhydrite and halite, and light gray to light brownish-gray limestones and dolomites of the Sedona Group, Coconino Sandstone, and Kaibab Limestone of Lower to Middle Permian age and light reddish-brown to reddish brown sandstones of the Lower Middle Triassic Moenkopi Formation. All of these units were deposited in the Permian Holbrook Basin of northeastern Arizona. Figure 2 summarizes the stratigraphic units in the area. The units essential to this discussion are (in ascending order): the Corduroy and Sycamore Pass Members of the Schnebly Hill Formation, Coconino Sandstone, Kaibab Formation of Middle Permian age, and the Middle Triassic Moenkopi Formation. The evaporites in the Corduroy Member are of particular interest because of their potential for dissolution by ground water.

The Holbrook Anticline is a monoclinal flexure located immediately north of Snowflake, Arizona, on the Mogollon Slope. At the surface it deforms the upper part of the Schnebly Hill Formation and overlying Coconino Sandstone, Kaibab Limestone, and Moenkopi Formation (Figs. 1, 3). Its surface expression is locally named the Pink Cliffs, which derives its color from the redbeds in the overlying Moenkopi Formation. The Holbrook Anticline trends approximately N 55° W (Fig. 1) over a distance of about 100 km, nearly to Winslow. The gentle basinward dip of strata of 2° to the northeast of the Mogollon Slope is reversed at the anticline where dips locally exceed 15° to the southwest. The dip reversal is accompanied by numerous localized, internally drained depressions along the fold's southern flank. The structural style and relief ranging from 30 to 100 m made this surface feature an attractive exploration target for oil and gas from the 1920s through the early 1960s. However, only unverified shows of hydrocarbons have been reported.

INFLUENCE OF THE HOLBROOK ANTICLINE ON EVAPORITE KARST DEVELOPMENT

The most conspicuous expression of karst occurs in the southwestern portion of the Holbrook Basin along the Holbrook Anticline. The greatest concentration of sinkholes (~250) occurs along the central part of the Holbrook Anticline in the vicinity of The Sinks. Wider, shallower depressions (such as Richard Lake) combined with fewer discrete sinkholes are present west and northwest of there (Fig. 1). Understanding the origin of the Holbrook Anticline is central to explaining the concentration and development of karst features along its trace.

The origin of the Holbrook Anticline is the subject of some controversy. Originally it was referred to as the Holbrook Dome (Darton 1925), and once was 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 Corduroy evaporites. He believed that the structure is a flexure that resulted from dissolution and collapse of a narrow portion of the Mogollon Slope. Doeringsfeld et al. (1958) show that the Holbrook Anticline is parallel to many low-amplitude folds in the southwestern part of the Colorado Plateau. The persistence of parallel, regularly spaced, northwest-trending monoclines and anticlines over large areas of the Plateau (Kelley and Clinton 1960; Wilson et al. 1960; Davis 1978) is a strong argument that the Holbrook Anticline is the remnant of one of the northwest-striking anticlines on the Mogollon Slope. Peirce et al. (1970) also argued that based on his interpretation of drilling and well log records, the surface expression of the Holbrook Anticline is not present in the subsurface below the Corduroy Member

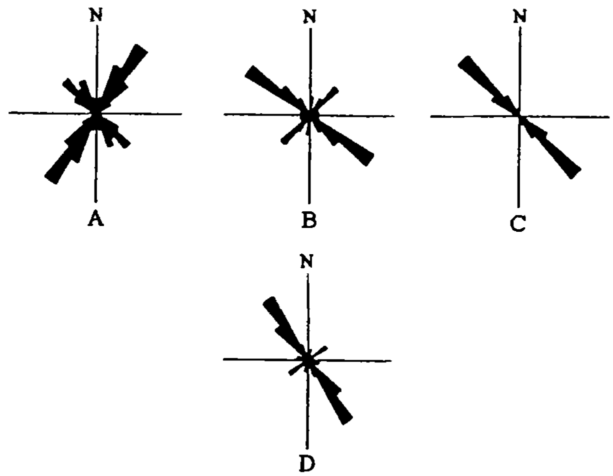

Figure 4. Polar diagrams of structurally oriented surface features in study area: (A) fractures, (B) sinkhole elongation, (C) anticlines and synclines, and (D) buckle folds around Richard Lake / McCauley Sinks area.

evaporites. He also suggested that dissolution played a major role in the formation of the anticline. Field evidence from monoclines in western New Mexico shows that their formation is related to basement-block uplift along high-angle reverse or normal faults. Whether there is basement faulting and uplift below the evaporites (see Fig. 3) as shown by Brown and Lauth (1958) is somewhat speculative but is supported by similarity of structural style and correlation with similar structures as noted earlier. Because the principal sinkhole occurrences are only on the steep southwestern side of the flexure at six distinct locations, we believe that Dry Lake Valley (also known as Zeniff or Dry Lake Syncline) south of the present-day flexure is the collapsed hinge of the former fold. The Holbrook Anticline also correlates with regional fracture and sinkhole elongation trends (Fig. 4).

Jointing in stratigraphic units above the Corduroy Member evaporites is a major control for all of the karst features, and the processes that produce them. The predominant regional northwest trend of all bedrock structures is about N 50° W. These are expressed in the Holbrook Anticline, open joint-fissures, graben-sinks, and in sinkholes. The walls of numerous sinkholes are aligned with dominant and secondary joint systems; many sinkholes at McCauley Sinks exhibit orthogonal corners, even though the overall impression is one of round features.

The Holbrook Anticline decreases in amplitude and essentially loses its surface expression at its northwestern end, southeast of Richard Lake and McCauley Sinks. Some apparent karst features extend further northwest beyond Richard Lake and McCauley Sinks, but their correlation with the waning anticline is uncertain.

The origin and timing of major dissolution and collapse is problematic. Sinkhole formation is ongoing, as noted previously, and probably began at least by Pliocene time. The uplift and tilting of the Colorado Plateau may have increased the regional hydrologic gradient, but the rates and timing of the uplift are imperfectly known (Lucchitta 1979). The close association of regional fractures and the Holbrook Anticline with sinkhole formation is conspicuous throughout the region. Accelerated dissolution of halite during pluvial stages of the Pleistocene seems likely, as intensified hydrogeologic processes are noted elsewhere in the arid southwest (Smith and Street-Perrott 1983).

CHARACTERISTIC FEATURES OF RICHARD LAKE DEPRESSION

Richard Lake depression has distinctive karst features quite unlike those seen elsewhere along the length of the Holbrook Anticline to the southeast.

Stratigraphy and Structure

Kaibab Limestone is the principal stratigraphic unit within and surrounding the depression, with Moenkopi sandstone and siltstone exposed at the south and west (Fig. 5). The underlying Coconino Sandstone is exposed in nearby canyon walls, in the core of some anticlinal buckles within the depression, and is underlain in turn by the evaporite sequence at moderate depth.

Figure 5. High-altitude view (looking south) of McCauley Sinks (foreground) and Richard Lake (top) depressions, both about two kilometers across. The arcuate array of sinks in nested form at McCauley is substituted by semi-concentric anticlinal buckles at Richard Lake (Fig. 7, 8), but formative processes are different. Many buckles follow trend of Holbrook Anticline (dotted line), which may reflect the dominant joint control of both features.

Buckle folds

Buckle folds (also termed pressure ridges by Bahr 1962; Neal and Colpitts 1997, and pop-ups by Adams 1982), joints, and minor faults are the most common structures in the Richard Lake - McCauley Sinks region. The buckle folds are, perhaps, one of the more conspicuous features (Figs. 5, 6, 7, 8) in and around Richard Lake depression. They vary considerably in geometry, ranging in height up to about 8 meters, in width to 35 meters, and in length up to 200 meters. Many buckles display right-echelon arrangement along strike.

In the Richard Lake area buckle folds occur in three distinct modes: (1) generally parallel to the Holbrook Anticline, (2) nearly parallel to the topographic contour in a semi-concentric pattern along the southeastern slope of the depression, and (3) generally parallel to regional structural trends (Fig. 4). The Holbrook Anticline, that is so prominent to the southeast is not evident at Richard lake. We observed buckle folds transecting and being cut by sinkholes at McCauley Sinks, suggesting that at least some existed prior to sinkhole development. The development of peripheral, nested buckle ridges within the Richard Lake depression suggest they may have developed synchronously with basin collapse. These buckles were further modified during subsidence which we believe is ongoing. Similar buckles that developed within a smaller sinkhole some 20 km to the southeast and north of Dry Lake result from a space problem where thin-bedded basal Moenkopi strata subsided into a progressively smaller space inside the sinkhole.

Mode 1 buckle folds occur at the toe of the Holbrook Anticline further southeast and were reported by Harrell and Eckel (1939) and Johnson (1962). Experimental studies by Sanford (1959) showed minor ridges formed at the toe of laboratory-produced monoclinal folds. The ridges produced in Sanford's experiment may be analogs of some of the buckle folds seen along the Holbrook Anticline. Mode 2 and 3 buckles generally predate the formation of the sinkholes. Such structures are interpreted as stress-relief features in areas where strata at the surface are under significant horizontal compression (Ramsey 1967; Adams 1982, Williams et al. 1985; Roorda 1995). The presence of these features in a basin where regional compression is not in evidence suggests lithostatic stress superimposed during burial and diagenesis of these strata, and exfoliation of thin-bedded strata at the surface for their formation (Adams 1982; Suppe 1985).

Faults

Faults are exposed at several locations but show only minor normal slip with no evidence of strike slip.

Sinkhole(s)

The principal sinkhole is 170 m in diameter and is situated in the center of the depression, occupying the lowest elevation at 1690 m (Fig. 9). Kaibab Limestone is exposed on the rim with the highest side about 20 m above the sinkhole floor. A second and much smaller sinkhole exists along the southwestern periphery of Richard Lake (Fig. 6) and may be the site of a disappearing arroyo draining the southern flank. The arroyo draining that portion of the depression may have been captured during basin subsidence.

ORIGIN OF RICHARD LAKE DEPRESSION

Richard Lake depression has many features in common with other evaporite karst phenomena in the southwestern United States. Lambert (1983) described a feature similar to Richard Lake in the eastern Delaware Basin, New Mexico, known as San Simon Sink. This feature lies directly above the edge of the evaporites in the Upper Permian Salado Formation along the crest of the Capitan Reef. He also observed similar geological occurrences of breccia pipes along the northern Capitan Reef margin and, following Bachman 1987, suggested that San Simon Sink was probably the surface expression of a breccia pipe forming above a dissolution cavern in the Capitan Limestone (Snyder and Gard 1982). A central sump feature at San Simon Sink, similar to the central sinkhole at Richard Lake, was reactivated in 1927 and experienced additional subsidence and concentric ring fracturing (Nicholson and Clebsch 1961). The similarity in size and geomorphic expression of San Simon Sink and Richard Lake/McCauley Sinks combined with their location near the edge of an evaporite deposit suggest a common mode of origin. However, limestone reef structures are unknown in the Holbrook Basin.

The very existence of the sinkholes at Richard Lake and McCauley Sinks near the edge of a thick halite sequence is a direct indication of evaporite dissolution and the collapse of overlying strata into voids in the underlying evaporite sequence. At Richard Lake, the broader sloping depression extending well beyond the central sinkhole suggests there is a substantial area of subsidence caused by collapse into a very large zone of dissolution in the underlying evaporites. Richard Lake depression may be a single point collapse, whereas McCauley Sinks involves multiple (40) sinkholes in the collapse mechanism. Two smaller depressions N 62° W of Richard Lake may have an origin similar to Richard Lake or McCauley Sinks but are at an earlier stage of development; both contain bedrock sinkholes within the depressions. Richard Lake contains two small grass-covered playas in the central part of the depression which may be the locations of older, stabilized sinkholes that are now filled with sediment.

Although sinkholes generally display a variety of geomorphic expressions throughout the region, the two most common types are discrete sinkholes with steep wall and relatively flat bottoms, and shallow depressions filled with recent sediments. The first type occur as both isolated sinkholes and as groups of scattered sinks distributed in a scattered fashion (as at "The Sinks") or in an orderly, arcuate arrangement (as at McCauley Sinks). The second type characterizes Richard Lake. Field data from Dry Lake Valley suggests that the small, grass-covered playas noted earlier are most likely older, stabilized, sediment-filled sinkholes. Observations from older aerial photographs covering the Dry Lake area to the southeast suggest that these broad depressions are actually nested clusters of sinkholes that have coalesced to form a single, shallow sink. By analogy this may be the case with Richard Lake, so that the depression is likely a multiple-sink phenomenon rather than a single-point collapse as suggested above.

Lambert (private communication 1997) has suggested that the McCauley Sinks could possibly be a younger variety of karst expression closer to the leading edge of the advancing dissolution front, whereas Richard Lake exhibits an older sediment-filled variation. The occurrence of buckle folds parallel to the waning Holbrook Anticline could be relict features of earlier structural expression, such as the buckles seen to the southeast along the toe of the present-day flexure. Such hypotheses are grist for future investigations.

SUMMARY AND CONCLUSIONS

Richard Lake depression is apparently an older locus of evaporite

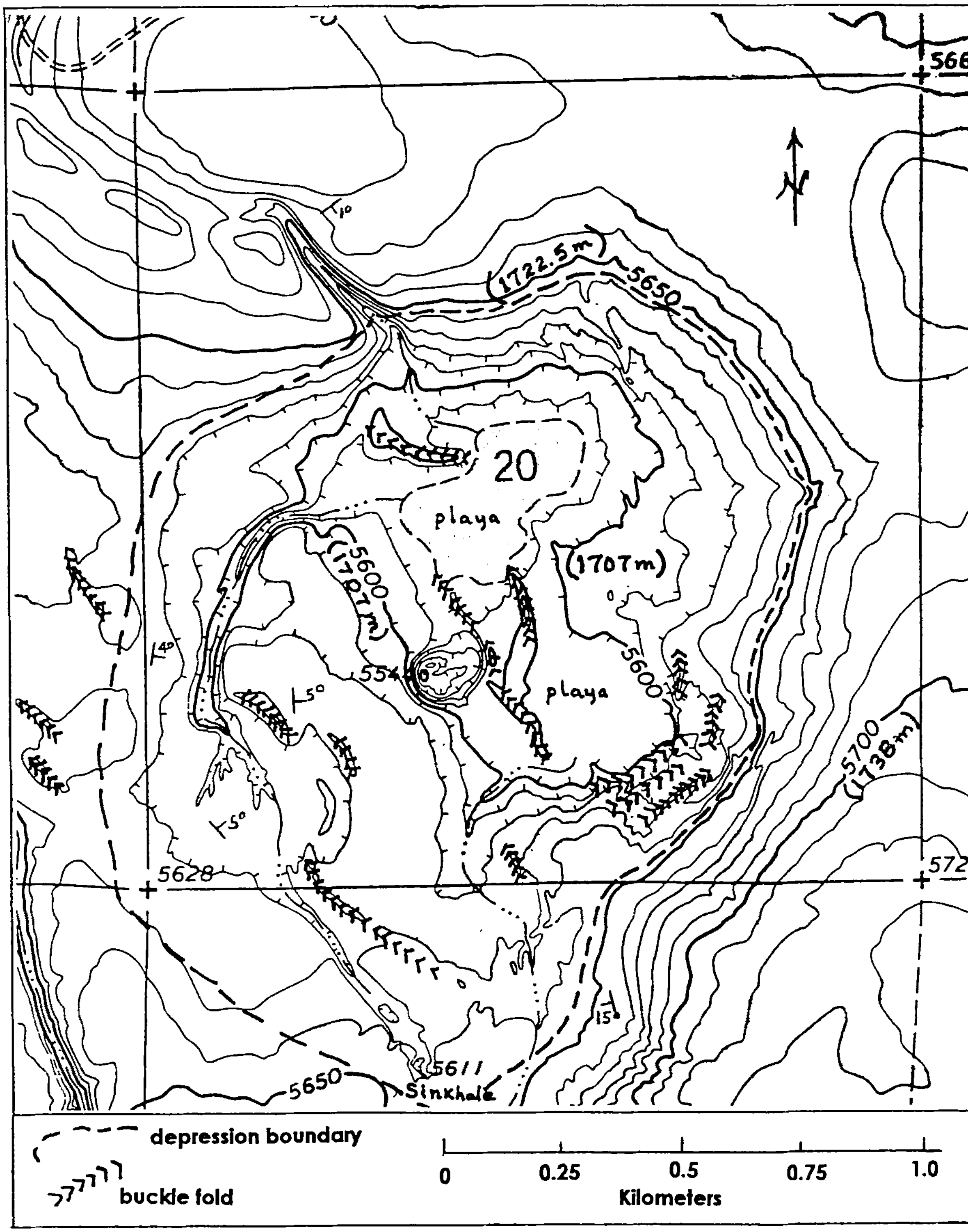

Figure 6. General geologic features of Richard Lake depression.

Figure 7. Richard Lake depression (center) with sinkhole sump in very center, occupying lowest elevation. Semi-concentric buckles are visible at right; linear buckle outlined by junipers at near side of depression is parallel to trend of Holbrook Anticline extension.

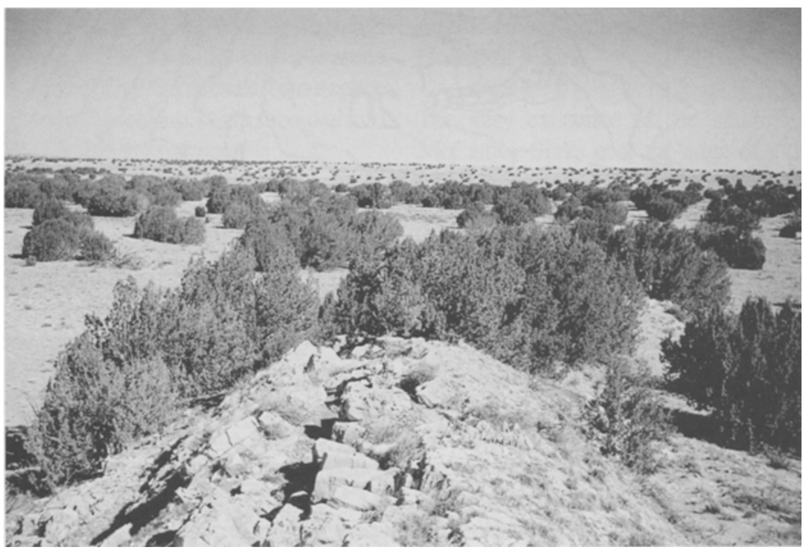

Figure 8. Buckle fold in Kaibab Limestone near Richard Lake showing symmetrical flanks dipping about 45 degrees locally. This ridge was about 5 m high and 25 m wide. Many are highly linear over distances exceeding 100 m.

dissolution, sinkhole formation, and subsurface collapse. Continued dissolution occurs because of joints sets that allow percolation of surface waters into underlying salt deposits in the Corduroy Member of the Schnebly Hill Formation. With the data at hand, we believe the area of Richard Lake and McCauley Sinks marks the northwestern-most limit of dissolution along the southwestern edge of the Corduroy salt deposits. This coincides with the apparent end of the deformation associated with the Holbrook Anticline.

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Figure 9. Aerial view showing 170 m-wide central sinkhole. Buckle folds outlined by linear growth of junipers are visible on all sides of the sinkhole; others trend diagonally across the photo about N 45° W, similar to the trend of the Holbrook Anticline.

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