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SUPAI SALT KARST FEATURES: HOLBROOK BASIN, ARIZONA

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ABSTRACT

More than 300 sinkholes, fissures, depressions, and other collapse features occur along a 70 km (45 mi) dissolution front of the Permian Supai Formation, dipping northward into the Holbrook Basin, also called the Supai Salt Basin. The dissolution front is essentially coincident with the so-called Holbrook Anticline showing local dip reversal; rather than being of tectonic origin, this feature is likely a subsidence-induced monoclinal flexure caused by the northward migrating dissolution front.

Three major areas are identified with distinctive attributes: (1) The Sinks, 10 km WNW of Snowflake, containing some 200 sinkholes up to 200 m diameter and 50 m depth, and joint controlled fissures and fissure-sinks; (2) Dry Lake Valley and contiguous areas containing large collapse fissures and sinkholes in jointed Coconino sandstone, some of which drained more than 50 acre-feet (~6 x 10^4 m^3) of water overnight; and (3) the McCauley Sinks, a localized group of about 40 sinkholes 15 km SE of Winslow along Chevelon Creek, some showing essentially rectangular jointing in the surficial Coconino Formation. Similar salt karst features also occur between these three major areas. The range of features in Supai salt are distinctive, yet similar to those in other evaporite basins.

The wide variety of dissolution/collapse features range in development from incipient surface expression to mature and old age. The features began forming at least by Pliocene time and continue to the present, with recent changes reportedly observed and verified on airphotos with 20 year repetition.

The evaporite sequence along interstate transportation routes creates a strategic location for underground LPG storage in leached caverns. The existing 11 cavern field at Adamana is safely located about 25 miles away from the dissolution front, but further expansion initiatives will require thorough engineering evaluation.

INTRODUCTION

The Supai salt karst zone in northeastern Arizona appears over Permian evaporites, extending along a linear dissolution front for at least 70 km and showing a variety of features. The area has been described previously (Bahr, 1962; Peirce, 1982), but not in detail, and thus remains one of Arizona's lesser known geological wonders. Bahr offered evidence that the karst evolution is ongoing, with sinkholes appearing on 1953 airphotos which had been absent just 17 years earlier. The McCauley Sinks, only 48 km (30 Mi) from Meteor Crater, had been ascribed to limestone dissolution by early observers, and even to meteorite impact by some because of a distinctive ringlike pattern.

Evaporite karst topography is similar to limestone karst in many respects, but there are also significant geological distinctions. Evaporite karst has been studied much less than limestone karst until fairly recently, and in fact was only termed "karst" about 1960 (Korotkevich, 1961). Surface features in evaporites parallel those in limestone and dolomite: depressions, sinkholes, swales, breccia chimneys, subsidence valleys, and other features having both negative and positive relief have been noted. The increased interest in recent years results from the incentives provided by several types of geological storage, in both bedded and domal salt.

OCCURRENCE, LOCATION, AND FEATURES

The Supai Salt Basin, AZ, located along the southern border of the Colorado Plateau between the Mogollon Rim on the south and the Defiance uplift on the north, is underlain by some 1200 m (4000 ft) of Paleozoic rocks, including bedded Supai salt, extending some 6000 km^2 (2300 mi^2) (Figure 1). The Supai formation extends well beyond, but contains salt only in this relatively small area around Holbrook. The total formation is nearly 600 m thick, and the upper salt member ranges up to about 150 m (500 ft) thick, with some areas of sylvite concentrations along the northern portion. The Supai salt is overlain by Coconino sandstone (50-150 m thick), which is the principal aquifer in the region, and some local exposures of Kaibab limestone. Underlying the Supai are

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lower Paleozoic Redwall limestone, Martin formation, and Tapeats sandstone (0-225 m thick), all resting unconformably on the Precambrian crystalline basement.

The southern margin of evaporites is being dissolved by the encroachment of northward-flowing groundwater from the Mogollon Slope, producing a major subsidence and collapse zone. More than 300 sinkholes, depressions, fissures, and possible breccia chimneys occur adjacent to this zone (Figure 2).. This zone of salt removal has produced a gravity depression, coincident in general with the principal area of surface karst expression (Lysonski, et al., 1981) Peirce (1981) suspected that the regionally extensive development of these internally drained depressions occured where salt is within about 300 m (1000 ft) of the surface. Peirce (1994) also suggested this could be the largest active solution collapse feature in the world, being active since at least the Pliocene.

Regional structural trends along the Mogollon slope region are predominantly northwesterly, with joint systems in the study area striking about N 55^0 W and N 30^0 E (Kelley et al., 1960); locally they vary by about 10°. These conjugate intersections are frequently observed in sinkholes, joint-fissures, depressions, playas, and all along the axis of the "Holbrook Anticline". Knauth (1994) has noted the almost perfect linear coincidence of the Supai karst features with late Cenozoic volcanic centers at Grand Canyon, San Francisco Peaks, west-central New Mexico, and Meteor Crater. Correlations with deep-seated crustal features remain speculative.

Holbrook Anticline

The so-called Holbrook Anticline is in all likelihood a structural flexure caused by solution-induced subsidence (Figure 2). The gentle basinward dip of ~2° to the northeast is reversed at the flexure, approaching 15° and more locally. Surface relief of more than 30 m (100 ft) made this apparent anticline extending more than 60 miles a conspicuous possibility for oil entrapment. It was extensively explored for oil 70-30 years ago, but circulation problems apparently related to salt dissolution often precluded satisfactory well completions and thus stratigraphic definition, and only minor petroleum shows were identified.

Bahr (1962) provides ample evidence for this feature being of non-structural origin, pointing to divergent drainage indicating a former topographic high, and the preponderant solution collapse structures all along the surface expression. The correlation of the latter is compelling evidence for a dissolution origin, and it is hereafter referred to as the *Holbrook dissolution flexure.*

"The Sinks"

Field inspection of many of these sinks and fissures in early 1994 by the author showed apparent recent activity, whereas many others are conspicuously eroded, filled and obviously older. A wide range of sinkhole diameters and depths were noted, from very small and shallow, up to 200 m wide and 50 m deep (650 and 165 ft, respectively) (Figure 3). A common valley containing many recent collapse features was also observed, together resembling a chaotic jumble.

Some collapse sinks appeared to be forming along active joint-fissures that were propagating parallel to the dissolution front and the trend of the Holbrook dissolution flexure. This association is also evident northwest of Dry Lake Valley and appears to be developmentally related. The shape of individual sinks also reflects the regional joint trends in the surficial bedrock, primarily Coconino sandstone.

Dry Lake Valley and Adjacent Area

A major series of depressions and a playa lake basin called Dry Lake Valley, cover an area of more than 325 km^2 (130 mi^2) in the central part of the collapse zone. Recent reports of the shallow playa lake in the eastern part Dry Lake Valley draining more than fifty acre-feet (~6×10^4 m^3) of water overnight also substantiate the notion of active fissure formation [Wellendorf, 1994]. Evidently fissures beneath the water are sealed with sediment and periodically give way to piping, or else fresh openings are formed and allow drainage to occur. Bahr (1962) suggested all of the Dry Lake Valley area could have formed in this manner. The origin of playa basins by dissolution has parallels in New Mexico and West Texas (Neal, 1994).

The linear northeastern shore of the principal playa is parallel to the regional joint trend, suggesting structural control. The lake drainage from the eastern basin was reported to have occurred along a fissure, evidently parallel to the regional trend, although unconfirmed. Bahr [1962] noted that some deep sinks seen on 1953 air photos were absent on photos taken in 1936; thus, he showed that dissolution and collapse was ongoing, but the overall rate of advancement of this dissolution front has not been determined.

On the gradual downdip side of the scarp north of the largest playa lake, where the dip reversal of the Holbrook dissolution flexure occurs, numerous open fissures are seen intersecting along joint planes in the Coconino formation. These features are linear, up to 200 m (650 ft) long, 0.3 - 5 m (1-15 ft) wide, and up to 30 m (100 ft) deep. Local residents have legends surrounding these gaping fissures, some of which purportedly swallowed cattle, and others that were "bottomless."

The area of dip reversal into the subsidence basin would be expected to be in tension, and this may explain the open joint-fissures at the surface. Once open, the fissures form a ready conduit for groundwater to penetrate to the relatively shallow salt beds below. Some of these joint-fissures show evidence of subsidence near intersections, suggesting a possible initiation sequence of some sink-

hole development. The nearest confirmed sinkhole is about 1 km to the east; jointing was observed plunging into the sinkhole, similar to that observed at "The Sinks," but much older geomorphically, with much infilling having occurred.

A group of about 20 sinkholes occurs 10 km northwest of the open fissures, along the scarp of the Holbrook dissolution flexure, similar to the geologic setting observed at "The Sinks," but generally smaller. One particularly well developed sinkhole is conspicuously larger and deeper than all the others and may be younger.....PHOTO AFPO

McCauley Sinks

This group of some 40 sinks covers some 2 km^2 (1000 acres) along Chevelon Canyon, 25 km (15 mi) SE of Winslow (Figure 4). A cursory look at the overall grouping shows a roughly nested alignment of two arcuate rows of coalesced sinks. The topographic setting and field inspection suggests they may be the concentric stress-field expression of a larger, localized subsidence basin. The location immediately adjacent to the deeply entrenched Chevelon Canyon, an influent stream most of the time, may contribute some of the groundwater source locally, but doesn't appear to affect the pattern.

The conjugate jointing in the surface Cononino sandstone has an important bearing on the expression of individual sinks, with some having almost square corners. Steep sidewalls are frequently aligned along near vertical joint planes, and are up to 100 ft deep. Widths of 100 m (330 ft) are present in several sinks. Some depressions appear to be either old age sinks, or possibly some are loci of future collapse.

Surface pressure ridges or minor anticlinal buckles in the nearly horizontal Coconino beds are as anomalous as the sinkholesbut are not necessarily related to evaporite dissolution. The ridges are 15-20 ft high with beds dipping tangentially away, forming a linear hill some 50-75 ft wide. The ridges are parallel and extend for more than 100 m (Figure, MAP ???

COMPARISON WITH SALT KARST IN OTHER EVAPORITE BASINS

The *Delaware Basin* in Southeastern New Mexico and West Texas is largely contained within the Capitan Reef structure, an elongate limestone formation perhaps best known for the Carlsbad Caverns along the northwest margin. The Capitan limestone is noted for its porosity and fracture systems which readily transmit ground water; where overlain by evaporites it provides conduits for dissolution to progress, and numerous swales, sinks, breccia chimneys, and other subsidence-related features have been associated with it. The Delaware Basin is one of the most intensively studied evaporite basins in the world, having been the site of the Gnome nuclear test in 1962 and now the Waste Isolation Pilot Plant (WIPP). Thus a strong interest in salt karst features and other aspects of dissolution has existed for more than 30 years, especially with regard to process rates and locations Vine, 1963; Lambert, 1983].

The eastward dip of the sediments in the Basin cause groundwater to flow eastward and salt may have been removed as the dissolution front moved eastward. Bachman and Johnson estimated the horizontal migration rate of the dissolution front was about 6 to 8 miles per million years. The current Pecos River has migrated geologically; its earlier position was responsible for effecting substantial dissolution.

San Simon Swale is a 260 km^2 (100 mi^2) depression located at the eastern margin of the Basin, over the Capitan Reef. It has formed as a result of dissolution of evaporites in the underlying Rustler and Salado formations. San Simon Sink is the lowest point in the depression, some 30 m (100 ft) deep and 1.3 km^2 (0.5 $mi^{2)}$. It contains a secondary collapse sink several hundred feet across and 8-9 m (25-30 ft) deep, that 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 many other authors that the collapse originated in a groundwater cavity in the Capitan Reef and that the sink may be a modern analog of a breccia pipe.

Wink Sink in Winkler County, TX, formed suddenly on June 3, 1980 and within a day had spread to its maximum width of 360 ft and depth of 33 m (110 ft). Johnson [1986; 1993] believes the original cavity beneath the sink occurred as a result of dissolution in the Permian Salado Formation, at a depth of some 400 m (~1300 ft). This feature is also over the Capitan Reef, and is undoubtedly associated with that formation, similar to the San Simon Sink. Johnson points to the abrupt and unnatural thinning of the salt units in the vicinity, combined with the concurrent thickening of overlying units as proof of the natural dissolution. However, he also believes that nearby oilfield injection activities contributed to this particular event. Injection activities elsewhere have produced similar features.

"Breccia chimneys" are features of positive relief, originating by the gravity collapse of flanking materials into sinkholes and forming "chimneys" in the throat leading to the void below. Subsequent erosion and subsidence of the surrounding more soluble country rock leads to such features. 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. "Karst domes" may resemble breccia chimneys as features of positive relief, but their cores contain older, as well as younger, rocks than their flanks.

Nash Draw is a southwesterly trending depression some 26 km (16 mi) long and 5-15 km (3-9 mi) wide, with its sump in Salt Lake at the southern end. The underlying Rustler Formation has undergone dissolution of gypsum; more than 100 caves, sinks,

fractures, swallow holes, and tunnels exist in a complex karst topography, apparently still active today [Bachman, 1981]. An extensive drilling program conducted for WIPP showed that dissolution of halite in the Rustler and upper Salado formations is responsible for the subsidence and overall formation of Nash Draw [Lambert, 1983].

Solution Features in the Hutchinson, Kansas, Salt

The Hutchinson Salt member of the Permian Wellington Formation is up to 170 m (555 ft) thick and underlays much of central and south-central Kansas. Dipping slightly westward, a dissolution front occurs on the updip eastern edge where groundwater is actively removing salt. It is along here that the erratic "Wellington Lost Circulation" zone occurs, a very well known feature to oil well drillers. This zone extends for more than 160 km (100 mi). Surface subsidence and collapse have led to the development of sinks and valleys. Geologic investigations led Fent (in Walters, 1977) to conclude the rate of migration of this dissolution front is 3.2 km (2 mi) per million years since the late Pleistocene, somewhat less than in earlier Pleistocene. This updip area is the only known occurrence of dissolution within the salt mass, prior to man's drilling and mining activities during the past 70 and 100 years, respectively. Walters [1977] believes no solutioning from the top downward has been detected, unlike the Supai salt of Arizona.

The Meade Salt Well is a natural sinkhole in Meade County, Kansas, that formed suddenly in 1879 in an area that contains numerous hollows and sinks, some of which can be attributed to solution collapse into cavities in the underlying Permian salt beds. Some evaporites younger than the Permian salt may be involved here. Geological study some 60 years after the collapse showed that faults updip from the sinkhole transmit fresh groundwater under hydrostatic pressure and dissolve openings in the underlying salt beds [Frye and Schoff, 1942]. Evidence for the dissolution is seen at lower altitudes to the east where salt springs emerge.

CONCLUSIONS AND ENGINEERING CONSIDERATIONS

Jointing in the bedrock units overlying the Supai salt is a major influence on all of the karst features, and the processes that produce them. The predominant northwest regional trend of all the bedrock units is about N 50^0 W and expressed in the Holbrook dissolution flexure, open joint-fissures, and in sinkholes. The walls of numerous sinks express the dominant and secondary joint patterns, often being square-cornered.

Open joint-fissures along the Holbrook dissolution flexure probably result from subsidence and dilatancy as the overlying beds reverse their dip into the zone of dissolution in the Supai formation. The open fissures channel and funnel surface runoff directly into and through the Coconino aquifer to the relatively shallow Supai salt. The joint-fissures plunge into sinkholes, pointing up the common processes leading to the development of the latter. The predominant setting for the occurrence of more than 200 sinkholes is on the southward-dipping and steeper flank of the Holbrook dissolution flexure.

There are similarities and differences in Supai salt karst features, as compared with the Delaware Basin in New Mexico and Texas, and the Hutchinson salt of Kansas. The more pronounced regional dip and the occurrence of karst features directly associated with the Holbrook dissolution flexure are most conspicuous.

The most obvious practical considerations in this remote area relate to transportation, commerce, and human habitation, however sparse. The several hundred major sinkholes and open fissures are obvious hazards in their own right, and the areas immediately adjacent to them are of questionable safety. The overnight drainage of substantial amounts of surface water contained in a playa lake presents groundwater protection concerns. Also, 11 LPG storage caverns exist in the northern portion of the salt body at Adamana, AZ, on the side of the salt mass opposite from the dissolution front. All of these considerations require thorough site characterization in advance of construction.

Thus, the principal object of geologic site characterization must be to specify rates of removal, and where surface effects might occur. Even though dissolution rates can sometimes be specified only to accuracies of "miles per million years," these are beneficial if averaged over extended geologic time. Because many areas reveal quite recent activity, time sequence aerial photography can be particularly beneficial. Aerial photography taken in the 1930's is often of sufficient quality to serve as a "baseline" for 60 yr comparisons with more recent remote sensing imagery, including photography. High quality, large-scale color aerial photography is one of the best formats for observation of dissolution features. The use of geophysical techniques may include reflection seismic, electrical resistivity,and self potential methods.

ACKNOWLEDGMENT

This paper is dedicated to the memory of Dr. H. Wesley Peirce, who probably has spent more hours exploring the salt deposits of Arizona than anyone, and who helped and encouraged me immensely. His death in November 1994 leaves a major void in our collective knowledge base, but also presents a challenge for future geological investigations. We all shall miss him.

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FIGURES

1 Location of principal salt features in Holbrook Basin, including (1) "The Sinks." (2) Dry Lake Valley, and (3) McCauley Sinks. From Johsnson and Gonzalez,198X.

2 S-N geologic section, showing principal Paleozoic units and dissolution flexure historically known as Holbrook Anticline. Section location is shown on Figure 1. (From Johnson and Gonzalez, 198X).

3 Oblique aerial view of a portion of "The Sinks" showing relationship of joint-fissures and large sinkholes. Dominant northwest trending joints control trend of Holbrook Anticline, as well as shapes of individual sinks. Scale at center: 1 cm =~75 m.

4 McCauley sinks have apparent order in pattern as compared with other Supai sinks, which appear more randomly distributed. Coalescence and alignment are distinctive features, as are surface pressure ridges in Coconino sandstone.

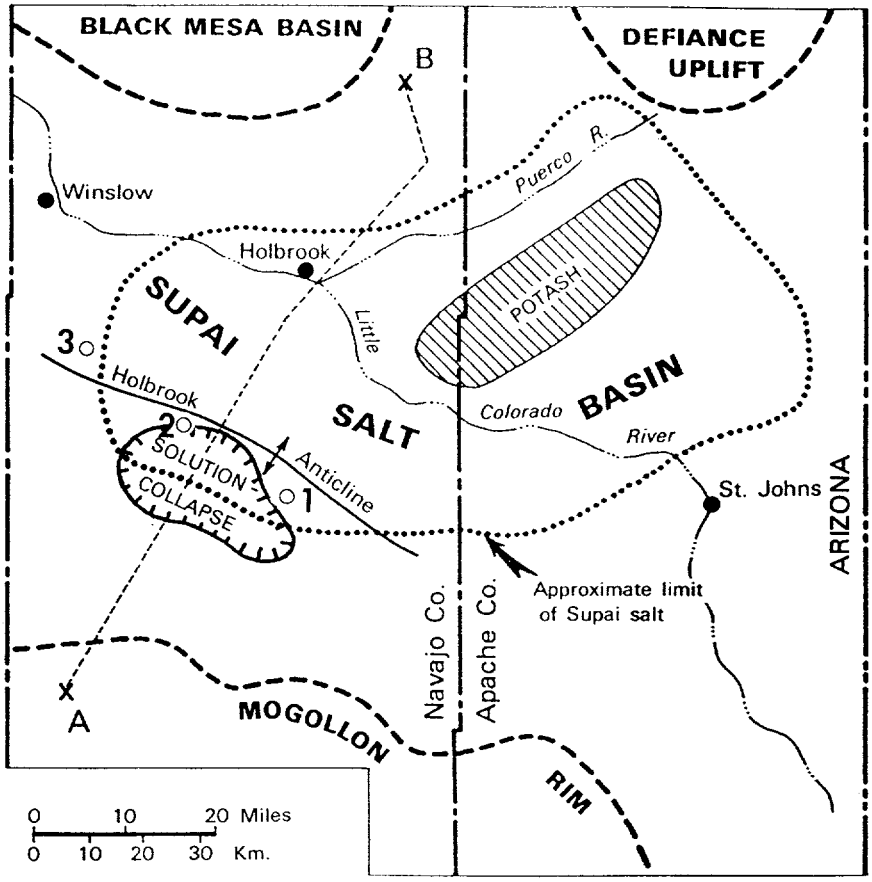

BLACK MESA BASIN
DEFIANCE UPLIFT
B
A
Winslow
Holbrook
Puerco R.
Little
POTASH
SUPAI
SALT
BASIN
Colorado River
3
2
1
Holbrook
SOLUTION
COLLAPSE
Anticline
St. Johns
Approximate limit of Supai salt
ARIZONA
NEW MEXICO
Navajo Co.
Apache Co.
MOGOLLON
RIM
0 10 20 Miles
0 10 20 30 Km.

Fig. 1

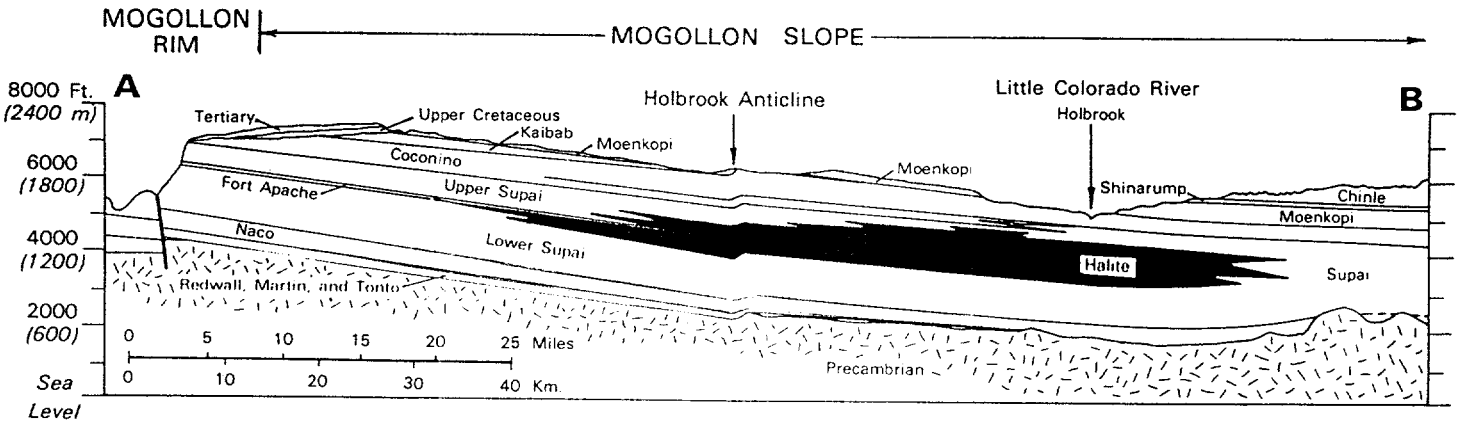

MOGOLLON RIM
MOGOLLON SLOPE
8000 Ft.
(2400 m)
6000
(1800)
4000
(1200)
2000
(600)
Sea Level
A
B
Tertiary
Upper Cretaceous
Kaibab
Moenkopi
Holbrook Anticline
Little Colorado River
Holbrook
Coconino
Fort Apache
Upper Supai
Moenkopi
Shinarump
Chinle
Moenkopi
Naco
Lower Supai
Halite
Supai
Redwall, Martin, and Tonto
Precambrian
0 5 10 15 20 25 Miles
0 10 20 30 40 Km.

Fig. 2

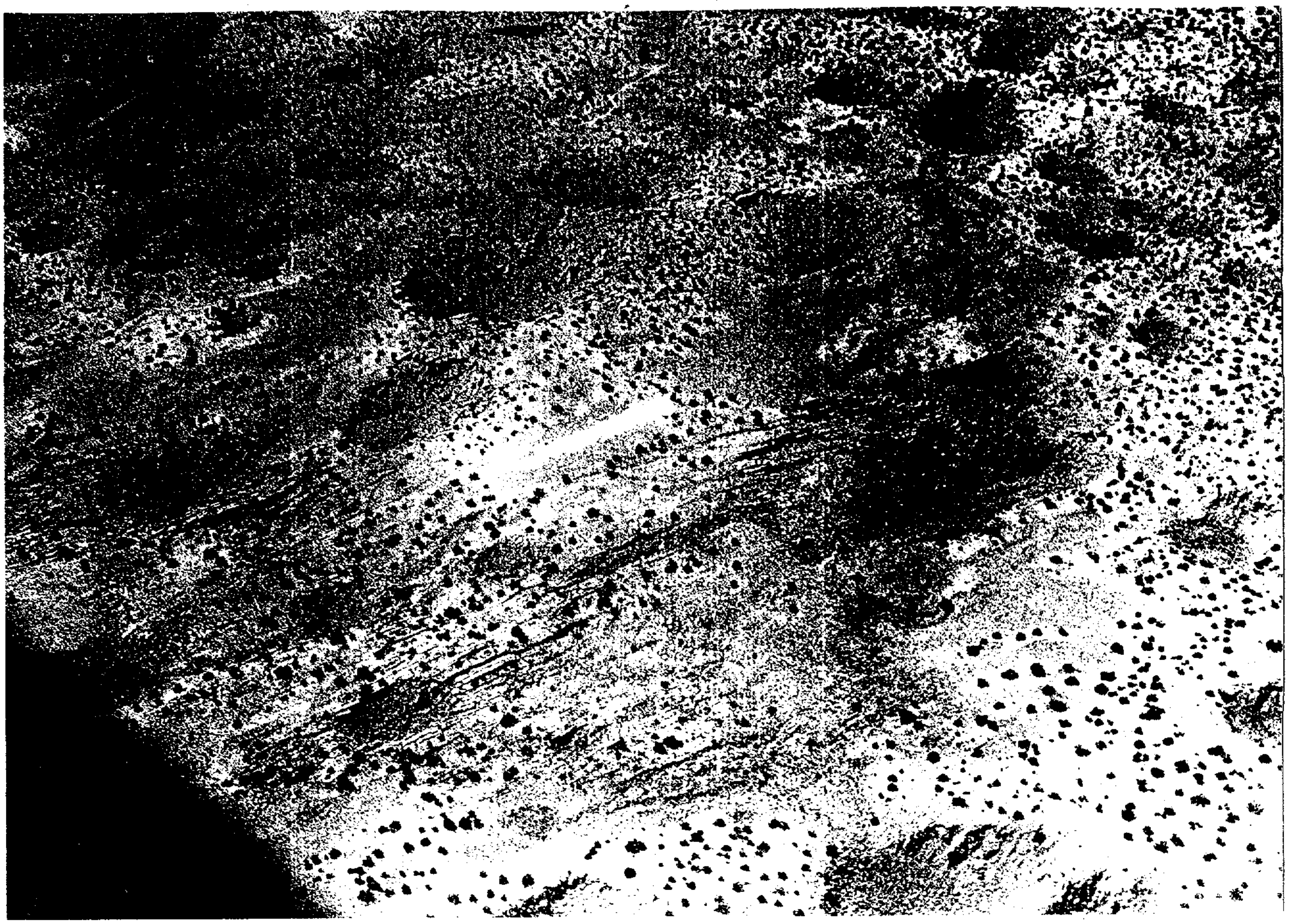
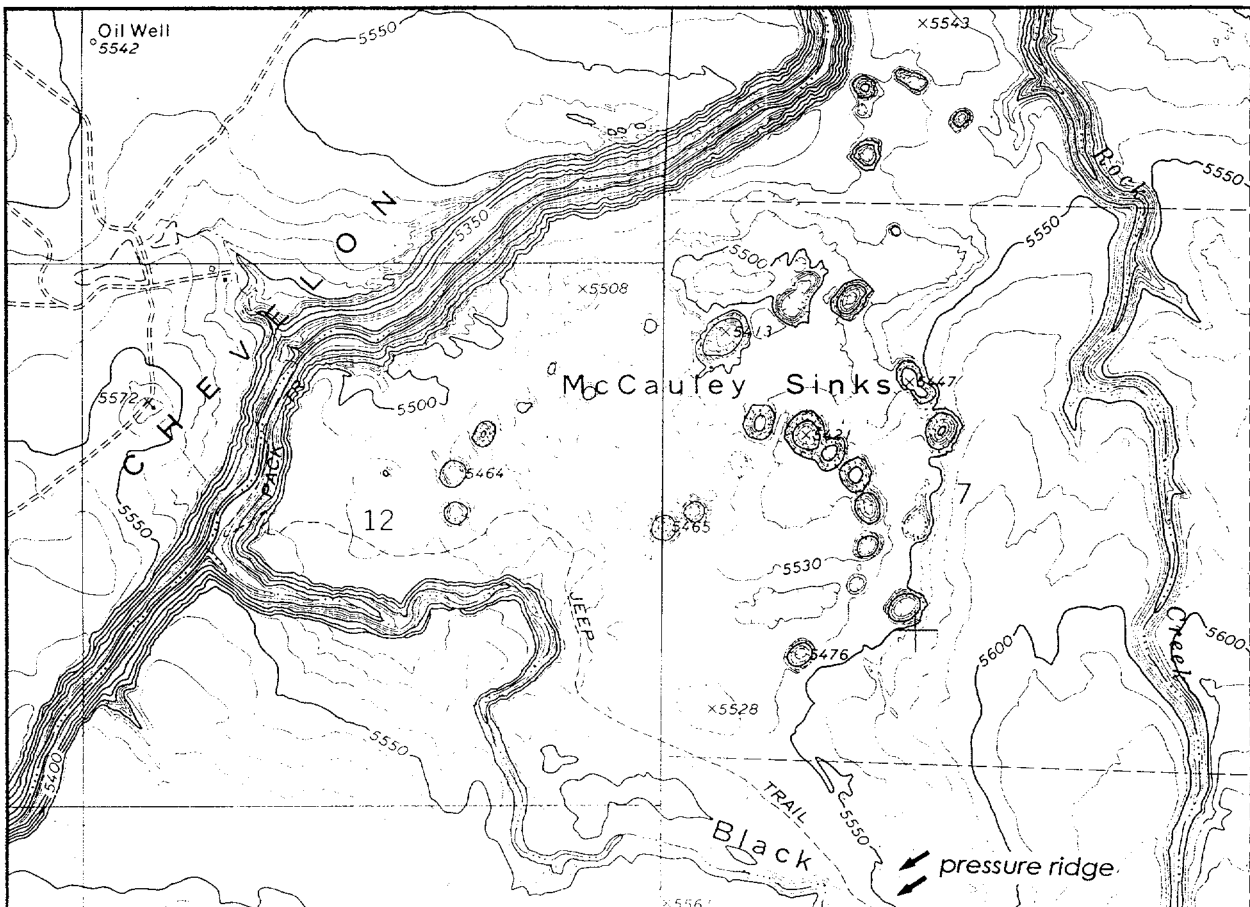


Fig. 3


Oil Well
5542
5550
×5543
Rock
Creek
5550
5600
CHEVELON
5350
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McCauley Sinks
5572
5464
12
5465
7
5530
JEEP
5476
×5528
5600
TRAIL
Black
pressure ridge
×5567
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1 MILE

Fig. 4