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Fife Symington
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Larry D. Fellows
Director and State Geologist

May 25, 1994

Mr. Roger P. Slayton, President
Mountain States Petroleum Corp.
P. O. Box 1936
Roswell, New Mexico 88201

Dear Mr. Slayton:

I recently received word that Mountain States Petroleum Corporation has purchased Kerr McGee's interest in the Dineh-bi-Keyah Field on the Navajo Nation of northeastern Arizona. On behalf of the **Oil and Gas Conservation Commission** of the State of Arizona let me take this opportunity to welcome you to the State of Arizona. We truly hope that your operations in Arizona are profitable.

Since you have bought Dineh-bi-Keyah Field, a unique field that has produced over 17.5 million barrels of oil from an igneous reservoir rock, I am taking the liberty of enclosing an article on an interesting geothermal test from the January 3, 1994, issue of *Oil & Gas Journal*, a Preliminary Geochemical Report on that well, and a flyer on Open-File Report 94-1, *Implications of Live Oil Shows in Eastern Arizona Geothermal Test*. Just for good measure, I have also enclosed a few photographs of the bleeding oil show (indicating rock is tight, a source not reservoir rock) at about 4,028 feet in the Alpine hole.

In my opinion, the geochemical analysis confirms the presence of hydrocarbon source rocks as postulated in the *OGJ* article. It records several albeit thin zones with significantly high amounts of total organic carbon. In addition, Permian rocks in the early to mid oil window in the Alpine hole further confirms that the volcanism in east-central Arizona and west-central New Mexico has not been detrimental to the source-rock potential of these units. Doesn't it seem likely, therefore, that commercial accumulations of oil and gas, including accumulations similar to Dineh-bi-Keyah, could very well be sleeping in this region?

Sincerely,

Steven L. Rauzi

Steven L. Rauzi
Oil & Gas Program Administrator

Enclosures

P.S. Please feel free to Contact Humble Geochemical Services directly if you have any questions or comments on the preliminary geochemical report. SLR

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THE HOLBROOK ANTICLINE, NAVAJO COUNTY, ARIZONA

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INTRODUCTION

The Holbrook anticline is by far the largest such structure exposed in the Holbrook region. In the past 45 years some 14 exploratory wells have been drilled in the vicinity of the anticline. Unverified shows of oil were reported from several of the earlier tests, and at least one well obtained verified, but apparently sub-commercial, shows. In addition, several recently completed wells were rumored to be capable of producing up to 1000 MCF/day of gas of reportedly "high" helium content.

The post-Cambrian sedimentary section on the Holbrook anticline is thin. Drill depths to basement average 3800 feet. Drilling objectives of primary interest have been the Permian Fort Apache limestone of the Supai formation, Pennsylvanian Naco formation, Mississippian Redwall limestone, and the Devonian Martin formation. Of these, the Fort Apache and Martin appear to offer the best, however limited, potential for oil production.

Solution-collapse phenomena, most notably indicated by the local development of karst topography, are a characteristic feature of the anticline, and have highly modified the appearance and extent of the surface structure. A careful examination of the relationship between the surface structure and the solution features indicates that the subsurface crest of the anticline may lie as much as 5 miles south of the surface crest — the displacement resulting from the modifying influence of solution and collapse upon the surface structure.

The drainage pattern in the vicinity of the Holbrook anticline provides perhaps the most direct of several lines of evidence of the extent to which solution phenomena have affected the surface structure. Two major drainages diverge around Dry Lake Valley, a broad sunken area of internal drainage bordering the south flank of the surface anticline. The pattern of divergence is such as to indicate that a topographically high area previously existed in the area now occupied by this valley. Because of the importance of solution-collapse structure and drainage pattern to an understanding of the evolution of the Holbrook anticline, both are discussed at some length below.

STRUCTURE

The axis of the Holbrook anticline is mappable at the surface for a distance of more than 60 miles. The trend is markedly sinuous, and locally the structure entirely disappears. Although a number of separate closures occupy this trend, there is little doubt that the anticline is essentially one continuous structural feature. The north flank of the anticline is formed by beds with a regional north dip averaging approximately 2 degrees. The north flank's having only regional dip causes the crest of the structure, as viewed from the north, to be evident only as a skyline ridge.

The south flank of the Holbrook anticline is formed by a rather sharp reversal of the regional northerly dip. Dips on the south flank range up to near vertical, but representative dips average less than 15 degrees. Even this magnitude is somewhat higher than dips associated with the majority of structures in the Holbrook region, and the prominence of this flank accounts for the early recognition of the Holbrook anticline.

The structurally highest portion of the crestal area of the Holbrook anticline extends approximately from section 33, T.18 N., R.20 E., through the south half of T.15 N., R.19 E. to the west center of T.15 N., R.17 E. Three separate local closures occupy the highest crestal area, the approximate center of each being marked by the locations of the two Union-Continental wells and the L. M. Lockhart well. Of these closures, the L. M. Lockhart area appears to be structurally highest. For the reasons presented below, the two Union-Continental wells may have been off-structure at depth, whereas the Lockhart well may have been relatively nearer the subsurface crest.

There is a close correlation between topography and surface structure in the area of the Holbrook anticline, as well as generally throughout the Holbrook region. The correlation is sufficiently close that the topography as shown on the Army Map Service Holbrook topographic sheet fairly well outlines the surface structure of the Holbrook anticline, despite its small scale.

Discussion of Solution Phenomena

The most striking single feature of the Holbrook anticline and immediate vicinity is the large number of sinks and related solution-collapse structures. The topography in several areas (as in the vicinity of the L. M. Lockhart well) is typically karst, and the south flank of the structure is pockmarked with potholes and sinks — in many places to such an extent that detailed surface structure mapping results in nothing short of a chaotic picture.

The Zeniff syncline, which occupies Dry Lake Valley, and borders the Holbrook anticline on the south, is similarly the locus of numerous sinks. Most of these are filled with alluvium and, although not obvious at the surface, show clearly on air photos. Sinks of this area have coalesced to such an extent as to suggest that much, if not all, of the Dry Lake Valley synclinal area is the result of subsurface solution and collapse. The walls of some of the open sinks in Dry Lake Valley expose alluvial-filled older sinks. That solution is a continuing factor in the structural development of the area is evidenced by the appearance of several deep sinks on air photos flown in 1953, which are absent on photos flown only 17 years earlier.

The sinks and related features are the result of solution of Permian evaporites, which, with interbedded red shales and siltstones aggregate some 1400 feet in thickness. The evaporitic section includes both anhydrite and salt and probably attained a depositional thickness of some 700 feet. The Coconino sandstone is the major aquifer of the Holbrook region, and directly overlies the evaporitic section. Juxtaposition of this aquifer and evaporites handily accounts for the development of the solution phenomena. It should be pointed out that, despite the existence of karst topography, there is nowhere, in the vicinity of maximum sink development, sufficient thickness of limestone to account for the existing topography. Indeed, as the walls of the sinks as well as logs of nearby wells attest, limestones are virtually absent either in outcrop or in the near subsurface of that area.

The close association of the various and extensive solution phenomena with anticlinal structure suggests that,

Figure 1. Holbrook anticline in vicinity of SW¼ T. 14N., R. 20 E. Note abrupt reversal of smooth northeast regional dip into sinks of Dry Lake Valley.

Figure 2. Sinks on southwest flank of Holbrook anticline, approximately 1 mile west of L. M. Lockhart well. Subsurface crest may approximately underly surface axis in right center, despite numerous sinks.

as in many other areas containing near-surface evaporites, the location of the present crest of the Holbrook anticline may be the result of the modifying influence of extensive evaporite solution on regional dip, and that either no subsurface anticlinal structure exists or, if it does, the subsurface crest may lie some distance to the south of the surface anticlinal crest. As can be seen on the photograph of Figure 1, dip directions on the south flank of the Holbrook anticline are everywhere directly into sinks. In this view it is apparent that the south flank is the result of sink encroachment upon regional northeast dip. The structure clearly lacks the appearance of a tectonic anticline.

That some sort of tectonic structural reversal must exist in the area is indicated by the fact that the elevation of the Coconino sandstone on the crest of the surface anticline is several hundred feet higher than in the area immediately south of Dry Lake Valley. In other words, the elevation of the Coconino sandstone north of the area of maximum collapse is higher than in the area immediately south. This is the reverse of the situation that should result from the superimposition of collapse structure on beds of regional dip.

It has been suggested that the south flank of the Holbrook anticline marks the present position of a regionally retreating collapse front and that this front may have originally developed near the Mogollon Rim, some 27 miles to the south, when Permian evaporites were exposed there. Such a circumstance could explain the observed structure, but there is no evidence of solution-collapse phenomena of any magnitude far south of Dry Lake Valley. It is clear that, whatever the cause of the Dry Lake Valley solution structures, it is local in nature.

Relationship Between Drainage Pattern and Structure

The accompanying drainage map (in pocket) illustrates the topographic modifications resulting from solution, and also suggests the magnitude of these effects on the location of the surface axis of the Holbrook anticline. The large area of internal drainage is evidently the result of subsurface solution. Direct evidence of this is provided by the courses of the two major external drainages bordering the collapse area on the south: Pierce Wash and Day Wash-Cottonwood Creek. Both of these northeasterly draining streams diverge abruptly, their courses becoming northwest and east, respectively, along the southern margin of the collapse area. This divergence extends for a number of miles and, being at right angles to the drainage pattern of the surrounding region, forms a prominent anomaly in that pattern.

The abruptness and extent of the divergence is all the more strikingly shown by the elevations of these streams in the area of divergence, which are more than one-hundred feet higher than the area about which they diverge. The evident conclusion is that a topographic high existed in the area of internal drainage previous to collapse. This is further emphasized by several drainages, whose earlier northeasterly direction clearly has been reversed by subsidence of the Dry Lake Valley area. There are a number of such occurrences in the area. Several are shown on the drainage map.

As noted above, there is generally a remarkable coincidence between topography and surface geologic structure throughout much of the Holbrook area. The existence of a pre-collapse topographic high further implies the presence of a pre-collapse structural prominence.

Test Drilling in Dry Lake Valley

Several lines of evidence, including some geophysical work not described, indicate that the subsurface crest of the Holbrook anticline lies beneath Dry Lake Valley, some miles south of the position of the surface axis. The California Oil Company located their "State 2516 No. 1" well late in 1961 with the intention of better defining the subsurface location of the Holbrook anticline, as well as to gain information concerning the subsurface stratigraphy.

12-14N-19W

The well was programmed as a slim-hole stratigraphic test. Unfortunately mechanical difficulties were encountered, apparently due to caving of the evaporitic section, and the well was abandoned at a total depth of 1596. A second attempt, drilled 50 feet from the first location, ran into similar difficulties and was abandoned in the Naco formation at 2862 feet. At this depth, the well appears to have been at least as high, structurally, as the wells drilled on the surface crest of the Holbrook anticline, although some 3 miles south of these wells. While

these lithologies are thin and discontinuous. For this reason the Naco appears to offer a very limited potential for oil production on the Holbrook anticline.

The Redwall limestone consists of fine- to coarse-crystalline, locally abundantly fossiliferous limestone. Pre-Pennsylvanian erosion has resulted in carvernous porosity, as is apparent in outcrops south of the Mogollon Rim. This porosity appears to be "filled" in the subsurface of the Holbrook area, but where open, would offer an attractive drilling objective. The Redwall may be locally absent, as a result of pre-Pennsylvanian erosion, over portions of the Holbrook anticline.

The Martin formation comprises a variable assortment of lithologies ranging from conglomerate, through sand and shale to a variety of carbonate rock types. These lithologic varieties appear to be more or less regularly distributed about a series of approximately northeast-trending highs, several of which crop out south of the Mogollon Rim. Another appears to cross the Holbrook anticline in the vicinity of Dry Lake. The Martin is thin or absent on the crests of these highs. The near margins of the highs characteristically are occupied by conglomerate and sandstone, which gave way laterally to shale interbedded with thin biostromal units. The biostromal units consist of gastropod-brachiopod-coral coquinas and/or coral-stromatoporoid masses. Individual thin beds locally are composed entirely of colonial coral. Adjacent to the shale-biostromal lithologies and farther from the "highs" are interbedded shale and thicker units of dense, fine-crystalline, dark-colored dolomite. The dolomite is petroliferous in outcrop, yielding a strong odor of petroleum on fresh fractures. The petroliferous character, combined with carbonate rock types of sufficient thickness and similarity to those that are oil-productive in other areas, suggest that the Martin offers the best potential for oil production on the Holbrook anticline.

SUMMARY OF DRILLING ON THE HOLBROOK ANTICLINE

The chart below summarizes the results obtained in

WELL	LOCATION	DATE	T. D.	REMARKS
Adamana Oil Co. Adamana #1	4-14N-20E	1918-1927	3390' Miss.(?)	Blowout of 48 degree gravity oil reported @ 3387'.
Holbrook Oil Co.	23-15N-18E	1925	3775' Dev.	Gas shows reported.
Hopi Oil Co.	21-15N-19E	1927	2420' Supai	No information.
Union-Continental Aztec L. & C. #1	19-15N-18E	1943	3850' Dev.	Oil staining reported in Ft. Apache, Miss. & Dev. carbonates; 3 DST's recovered mud & mud filtrate.
Union-Continental New Mexico & Arizona Land Co. #1	34-15N-19E	1944	3609' Precamb.	Shows of oil as above; reportedly lost hole and unable to test.
L. M. Lockhart Aztec L. & C. #1	33-14N-20E	1949	3734' Precamb.	Numerous substantial shows of oil; core analysis saturations up to 41% in Dev. carbonates; Ft. Apache tested for 250 MCF/D flammable gas; mechanical difficulties prevented tests of Naco, Redwall, and Martin.
P. D. Lynch Aztec L. & C. #1	3-13N-20E	1951-1954	3140' Naco	No information.
J. A. Eisele McCauley #1	1-16N-16E	1954	4231' Precamb.	No shows reported; 2 DST's recovered salt water from Precamb. granite.
L. Johnson Aztec Trustee #1	33-14N-20E	1958	3737'(?)	Rumored to have been capable of small helium production from Ft. Apache.
Pan American New Mexico & Arizona Land Co. #B-1	25-12N-23E	1959	4497' Precamb.	Oil shows reported in Ft. Apache and Martin; DST's recovered salt water from Martin.
L. Johnson Aztec Trustee #2	33-14N-20E	1959	1750' Supai	Rumored to have made 780 MCF/D 6% helium from Ft. Apache.
L. Johnson Aztec Trustee #3	33-14N-20E	1960	185' Coco.	No information.
California Oil Co. State 2519 - #1	12-14N-18E	1961	1569' Supai	Slight shows in Ft. Apache; no tests; abandoned due to mechanical difficulties.
California Oil Co. State 2519 - #1A	12-14N-18E	1962	2947' Naco	50 ft. from #1; no shows reported; abandoned due to mechanical difficulties.

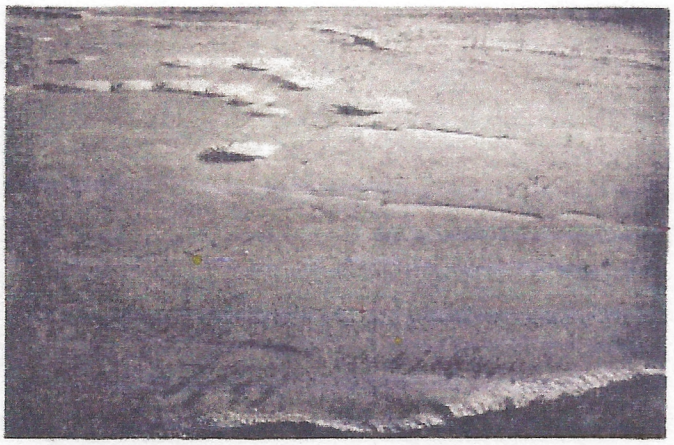

Figure 5. Sinks and pressure ridges in vicinity of Eisele "McCauley" well. Ridges are anticlinal in form, and range up to 20 feet in height.

the 14 wells drilled to date in the vicinity of the Holbrook anticline. It should be emphasized that the shows of oil noted under "Remarks" are based on reports of variable reliability. It is significant that mechanical difficulties were encountered in a surprisingly high percentage of the wells drilled in the last 18 years. These difficulties either prevented reaching the Redwall and Martin formations or prevented adequate testing. Finally, it should be noted that, if the interpretation of the structure presented above is correct, none of the deeper wells listed below tested the structurally highest portion of the Holbrook anticline.

ACKNOWLEDGEMENTS

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