FAVORABLE AND POTENTIALLY FAVORABLE AREAS FOR HYDROCARBON AND GEOTHERMAL ENERGY SOURCES IN NORTHEASTERN ARIZONA

by

J. N. Conley and Salvatore Giardina, Jr.

Arizona Geological Survey
Oil and Gas Publication OG-28
Originally published as OGCC Report of Investigation RI-7
1979

Arizona Geological Survey
416 W. Congress, Suite #100, Tucson, Arizona 85701

A Report of Work Performed Under Four Corners Regional Commission
FCRC Contract Number 181-099-058-1

This report is preliminary and has not been edited
or reviewed for conformity with Arizona Geological Survey standards

O&GCC REPORT OF INVESTIGATION 7

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ARIZONA OIL AND GAS CONSERVATION COMMISSION
Phoenix, Arizona

March 1979

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ABSTRACT

The report area encompasses most of the eastern portion of the Colorado Plateau tectonic and physiographic province. The oil and gas accumulations found to date occur in the northeastern part of the area on the south flank of the Paradox basin. The production from the small pools near the Utah state line has been from carbonate reservoirs in Paleozoic Pennsylvanian, Mississippian, and Devonian rocks. The principal pay zones are in the Hermosa Formation of the Pennsylvanian. Hydrocarbon accumulations are controlled primarily by a combination of favorable stratigraphic and structural conditions. The Dineh-bi-Keyah field, 36 miles south of the northeast corner of the state, is the largest accumulation in the area. The reservoir for the 15-plus million barrels of oil produced to date is a Tertiary igneous sill intruded into Pennsylvanian Hermosa strata. Structurally the field is on an anticline but the oil accumulation is primarily stratigraphic.

The northeastern part of the report area on the outer rim of the proved petroliferous Paradox basin offers the most attractive potential for new hydrocarbon production from Pennsylvanian, Mississippian, and Devonian reservoirs. Southward toward the Mogollon slope the decrease in the frequency of occurrence of organic limestone beds and the absence of carbonaceous shales in the Pennsylvanian suggest that source rocks adequate for the generation of hydrocarbons are not present. However, the Devonian Aneth Formation present in the Oraibi trough may be an adequate source rock. The temperature versus time relationship could have been favorable for the generation of hydrocarbons. The McCracken Sandstone of the Devonian Elbert Formation exhibits good reservoir characteristics. Numerous shows of oil have been recorded in the reservoir and some oil produced in the Walker Creek pool. This trough offers both structural and stratigraphic traps for hydrocarbon accumulations in the McCracken Sandstone reservoir.

The potential for Pennsylvanian and Mississippian hydrocarbon accumulations elsewhere in the report area cannot be evaluated satisfactorily at this time, but it does not appear to be very favorable. The local Devonian basins in the southernmost portion of the area possibly have some potential.

The heat source of most of the thermally anomalous wells and springs identified in the study is postulated to be the heat within the Earth's crust under conditions of normal geothermal gradient. Heated waters rise along fracture or fault systems and may migrate laterally into shallow aquifers. Hydrothermal waters in the general area between St. Johns and Springerville in southeastern Apache County possibly offer a potential for geothermal energy. Hot dry rock in the San Francisco volcanic field in Coconino County may have a significant potential for geothermal energy.

INTRODUCTION

General Statement

A preliminary general review of the known energy resources of northeastern Arizona indicated that the Black Mesa coal field in northern Navajo County is presently the state's most abundant energy resource. Additional hydroelectric generating capacity is physically and economically feasible at two sites on the Colorado River. The potential of uranium resources is being investigated currently under the National Uranium Resource Evaluation program sponsored by the federal government. This report presents the highlights of a study pertaining to the probable existence of additional hydrocarbon accumulations in the proved gross productive area and the potential of hydrocarbon and geothermal energy sources elsewhere in the study area. The work involved in preparing the report was performed under the Four Corners Regional Commission Contract Number 181-099-058-1.

The metric system of measurement is used in the geothermal portion of the report. The English system is used throughout the remainder of the report.

Purpose and Scope

The primary purpose of this study was to assemble and evaluate available data needed to isolate or semi-isolate those portions of northeastern Arizona favorable or potentially favorable for hydrocarbon and (or) geothermal energy sources. The data assembled is presented in readily usable formats for the convenience of energy-oriented workers. The subsurface geologic structure and other maps have been prepared at scales sufficiently large for semidetailed interpretation of the data and alternate interpretations by users of the report.

Revisions of the interpretations are anticipated as more subsurface control points become available. Most of the pre-Permian control, which contains approximately 31,000 square miles, is restricted to the north portion of Apache County (Four Corners region). In the large areas of sparse or no control the interpretations are based on the available supplementary shallow control furnished by water wells penetrating Permian Coconino-De Chelly sandstones, surface structure, and structure-thickness relationships inferred from the aeromagnetic and gravity maps included in the report.

Acknowledgments

We wish to express our deep appreciation to the American Stratigraphic Company, Denver, for extending permission to use their excellent graphic well logs for lithologic and other information. Also, we thank W. Richard Hahman, Sr., Arizona Bureau of Geology and Mineral Technology, Tucson, for

permission to incorporate into illustrations age dating data by P. E. Damon and others and LANDSAT lineaments mapped by L. K. Lepley, presented in the Bureau's preliminary map of geothermal energy resources of Arizona, February 1978. A. K. Doss and John Kellogg, Arizona State Land Department, were very helpful in furnishing water well data. Robert L. Laney, Water Resources Division, United States Geological Survey, Phoenix, generously discussed many geothermal problems with us. The services of Mrs. O. A. Stacey, Secretary to the Geology Section of the Commission, in researching and tabulating needed data and in typing the report, are gratefully acknowledged.

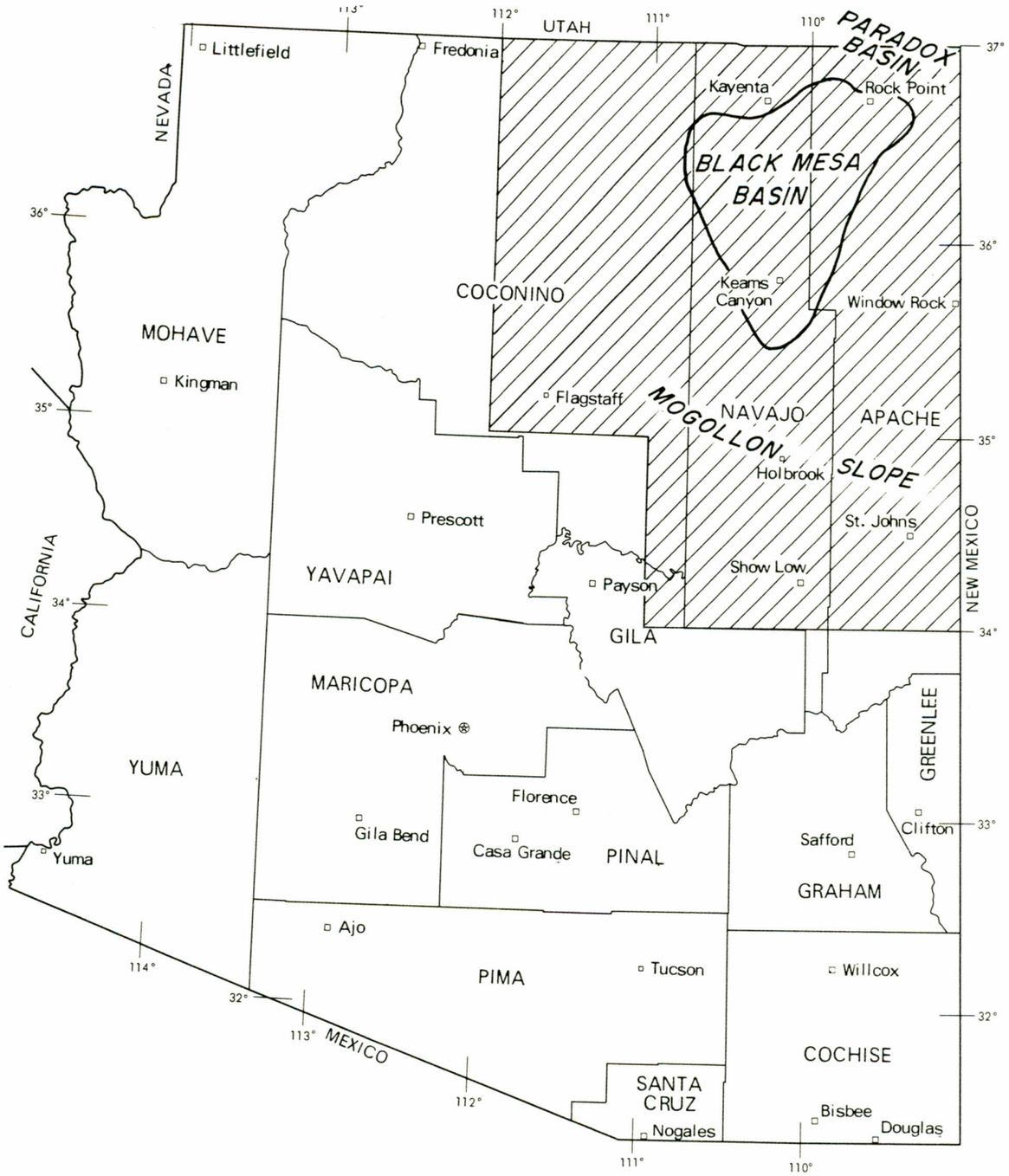


Figure 1.- Map showing location of report area, Paradox basin-Black Mesa region, and Mogollon slope region in the Colorado Plateau province of Arizona.

OIL AND NATURAL GAS

by

J. N. Conley

General Statement

The study area, largely within the Navajo and Hopi Indian Reservations, encompasses the southern shelf portion of the Paradox basin, the Black Mesa basin, and most of the Mogollon slope region (fig. 1 and sheet 1, plate 2). Throughout most of Paleozoic and Mesozoic time this region occupied the shelf area between the Ancestral Sierra Grande part of the Transcontinental Arch to the east in New Mexico and the Cordillerian geosyncline to the west in Nevada.

A detailed discussion of the geologic framework is beyond the scope of this study. The tectonic elements and structural geology have been discussed in considerable detail by many authors, including: Kelley (1955, 1958), Peirce (1976), Peirce and others (1970, 1977), Woodward (1973), and Davis (1975). The various tectonic events affecting the report area are shown on figure 2, Geologic highlights of the gross Plateau region of Arizona, from Peirce and others (1970). The time scale data is from Elsevier (1975).

The oil and gas potentialities of northern Arizona or portions of the region have been discussed by numerous authors. The most comprehensive reports reviewed were by Brown and Lauth (1958), Lessentine (1965), and Peirce and others (1970).

Brown and Lauth conclusion:

> The largest oil and gas wells have been and shall probably continue to be found along the southern edge of the Paradox basin in its foreland facies zone...The Pennsylvanian formations have good potentials along the southern edge of the Black Mesa basin. Based on shows in wells, petroliferous indications along the outcrop areas and the regional thickening of the Mississippian, Devonian, and Cambrian, potential producing reservoirs may be developed in rocks in these systems.
>
> The [Permian] Fort Apache member of the Supai, the De Chelly member of the Cutler, and the Coconino sandstone have excellent potentials for shallow production.
>
> ...The dry holes do not condemn large areas, for various reasons, such as being off structure, or on young trends. Favorable anticlinal structure and stratigraphic traps are expected within portions of the...potential areas.

ERAS		Periods and Epochs	Age-millions of years	Geologic Highlights of Plateau Region of Arizona	
CENOZOIC	Quaternary	Recent	.01	Alluvial sediments; volcanics.	Volcanism. Uplift and erosion.
		Pleistocene	1.8	Stream, river, and lake deposits; volcanics, glaciation on San Francisco Peaks near Flagstaff and in White mountains.	Local sedimentation.
	Tertiary	Pliocene	5.0	Continental sedimentation: Bidahochi and Verde Formations. Uranium occurrences.	Mogollon Rim faulting.
		Miocene		Unconformity	Regional uplift of large magnitude. Volcanism and erosion.
		Oligocene	22.5	Chuska Sandstone, "Rim" gravels, Datil Formation.	
			38±	Unconformity	
		Eocene	55	Rock units not generally recognized.	Laramide Revolution. Folding, monoclinal flexuring. Formation of Kaibab, Monument, and Defiance uplifts, and Black Mesa basin. General uplift.
		Paleocene	65	Unconformity	
MESOZOIC		Cretaceous	141	Up to 2,000 feet upper cretaceous marine and non-marine sediments, principally sandstones and shales; important coal deposits in Black Mesa; local uranium occurrences. Unconformity	Northward tilting of Black Mesa basin region-erosion. (Nevadan?)
		Jurassic	195	Up to 2,000 feet largely non-marine sediments, principally sandstones. Morrison Formation important uranium host rocks.	
		Triassic	230	Up to 1,500 feet non-marine sediments, principally shales and sandstones. Contains host rocks for major Arizona uranium deposits and reservoir rocks for helium. A Black Mesa basin objective. Unconformity	General uplift and erosion.
PALEOZOIC		Permian	280	Up to 2,000-3,000 feet marine and non-marine sediments. Contains principal reservoir rock for helium at Pinto. Local petroleum, natural gas, and helium potential. A Black Mesa basin objective. Locally, a host for important uranium deposits. Minor coaly occurrences.	Local basining.
		Pennsylvanian	312±	Up to 2,000 feet of marine sediments, principally carbonates and shales. Important reserves and objectives for oil and gas in Black Mesa basin area. Unconformity	Local basining. Regional erosion.
		Mississippian	345	Up to 800 feet marine sediments, principally carbonates. Local petroleum, natural gas, and helium production in Black Mesa basin area. A drilling objective throughout N. Arizona.	Local erosion.
		Devonian	395	Up to 600 feet marine sediments, principally carbonates with locally important sandstones. Local petroleum production and helium occurrences. A drilling objective in Black Mesa basin area.	
		Silurian	435	Not recognized.	General emergence.
		Ordovician	500	Marine sediments in extreme NW. Arizona. Unconformity	
		Cambrian	570	Up to 1,500 feet marine sediments, principally sandstones, shales, and carbonates. Limited drilling objective in NW. Arizona. Sandstone beneath Devonian to SE. is a local objective. Unconformity	
YOUNGER PRECAMBRIAN				About 10,000 feet quartzite, shale, and limestone. Unconformity	Grand Canyon disturbance.
OLDER PRECAMBRIAN			4000±	Granitic and metamorphic rocks constitute basement rocks of region. Local outcrops in Defiance and Grand Canyon regions.	Mazatzal Revolution.

Figure 2.- Time scale (after Elsevier, 1975) and geologic highlights of the Colorado Plateau province (after Peirce and others, 1970).

Lessentine states that large anticlinal features occur in the Black Mesa basin and that they "appear to have had an early history of growth and offer possibilities for oil and gas production. More difficult to define are the numerous stratigraphic terminations which may prove to be the traps of large petroleum accumulations." With respect to Devonian, Mississippian, and Pennsylvanian rocks in the Black Mesa basin, he concludes:

> Regionally, the petroleum possibilities of Devonian rocks should be good...Many interesting potential oil and gas stratigraphic traps may be awaiting the diligent and persistent searcher.

> ...the Mississippian should be a prime objective for future oil and gas exploration.
>
> [Pennsylvanian Hermosa Formation]...Benthonic and pelagic organisms flourished in a normal neritic environment along the southwestern flank of the Paradox basin, and coral biostromes and small bioherms are common. In the Black Mesa basin area the frequency of occurrence of organic limestone beds decreases except in its northern part adjacent to the typical Paradox facies.
>
> On and near the Kaibab-Zuni uplift, petroleum possibilities from carbonate rocks seem minimal, but are not precluded, and numerous facies changes in a dominantly clastic phase offer possibilities for stratigraphic traps.

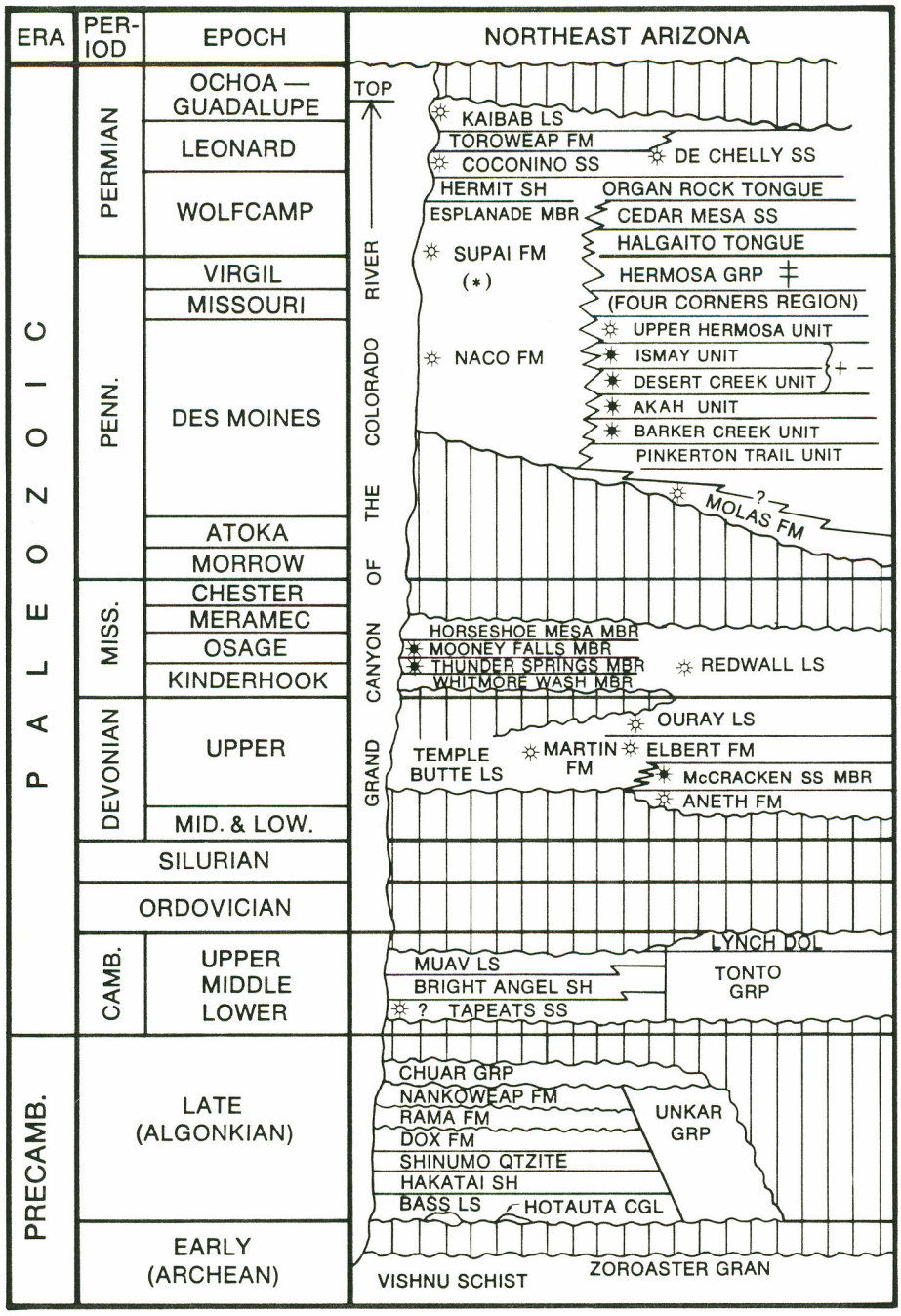
Peirce considers that Devonian, Mississippian, Pennsylvanian, and Permian rocks offer drilling objectives for hydrocarbons. Picard and others (1960) state that the general area along the outer rim of the Paradox basin appears favorable for gas accumulations.

Exploratory drilling subsequent to the published work of Brown and Lauth, Lessentine, Peirce, and Picard indicates that the foreland facies zone of the Paradox basin in northeastern Arizona (Four Corners region) continues to offer the most attractive potentialities for undiscovered hydrocarbon energy resources. Too few wells within the remainder of the southwestern shelf portion of the Paradox basin have been drilled to evaluate the potential of Paleozoic rocks. Those drilled in the Mogollon slope region, mostly on surface structural anomalies in the general Holbrook area in Navajo County, have been dry holes. Although numerous shows of oil on cuttings, along with some indications of the presence of porous zones, have been logged in thin Permian Fort Apache carbonate beds, the prospects for finding economic hydrocarbon accumulations in these beds are not encouraging at this stage of evaluation. A few very minor shows have been noted in Devonian, Mississippian, and Pennsylvanian carbonates. Generally, these carbonates lack zones of good porosity. Siliceous clastic zones are more abundant than carbonates in the Pennsylvanian section.

Theses by Harrison (1975), Kent (1975), and Pope (1976) pertaining to Devonian, Mississippian, and Pennsylvanian rocks in northeastern Arizona, respectively, also indicate that the Four Corners region offers the most attractive possibilities for oil and gas accumulations.

Stratigraphic Occurrence of Oil Shows and Productive Units

A "show" is considered to be any indication of oil occurring naturally in rocks. Figure 3 shows the various Paleozoic stratigraphic units that have produced economic or noneconomic quantities of oil and units in which shows of oil have been noted on drill-bit cuttings. Tables D, E, and F in the appendix list wells in which shows in Pennsylvanian, Mississippian, and Devonian rocks, respectively, have been noted. An explanation of the various types of shows noted precedes the tables. Figures 4 and 5 show also the location of most of the wells in which oil or a show of oil was recovered on drill-stem or production tests and nonquestioned oil staining



NOTE: VERTICAL TIME SCALE NOT UNIFORM

(Adapted from compilation by Molenaar and Halverson, 1969)

LEGEND:—

‡ Oil-bearing reservoirs in Dineh-bi-Keyah field are Tertiary igneous sills intruded into rocks of this group

✷ Commercial and/or non-commercial oil/natural gas production established

☼ Show of oil/natural gas

\+ Principal oil/natural gas productive units

(*) Numerous shows of oil in Fort Apache Member of Permian Supai Formation in Mogollon Slope region

Figure 3.- Stratigraphic occurrence of oil shows and productive units. (Stratigraphic column modified from Molenaar and Halverson, 1969.)

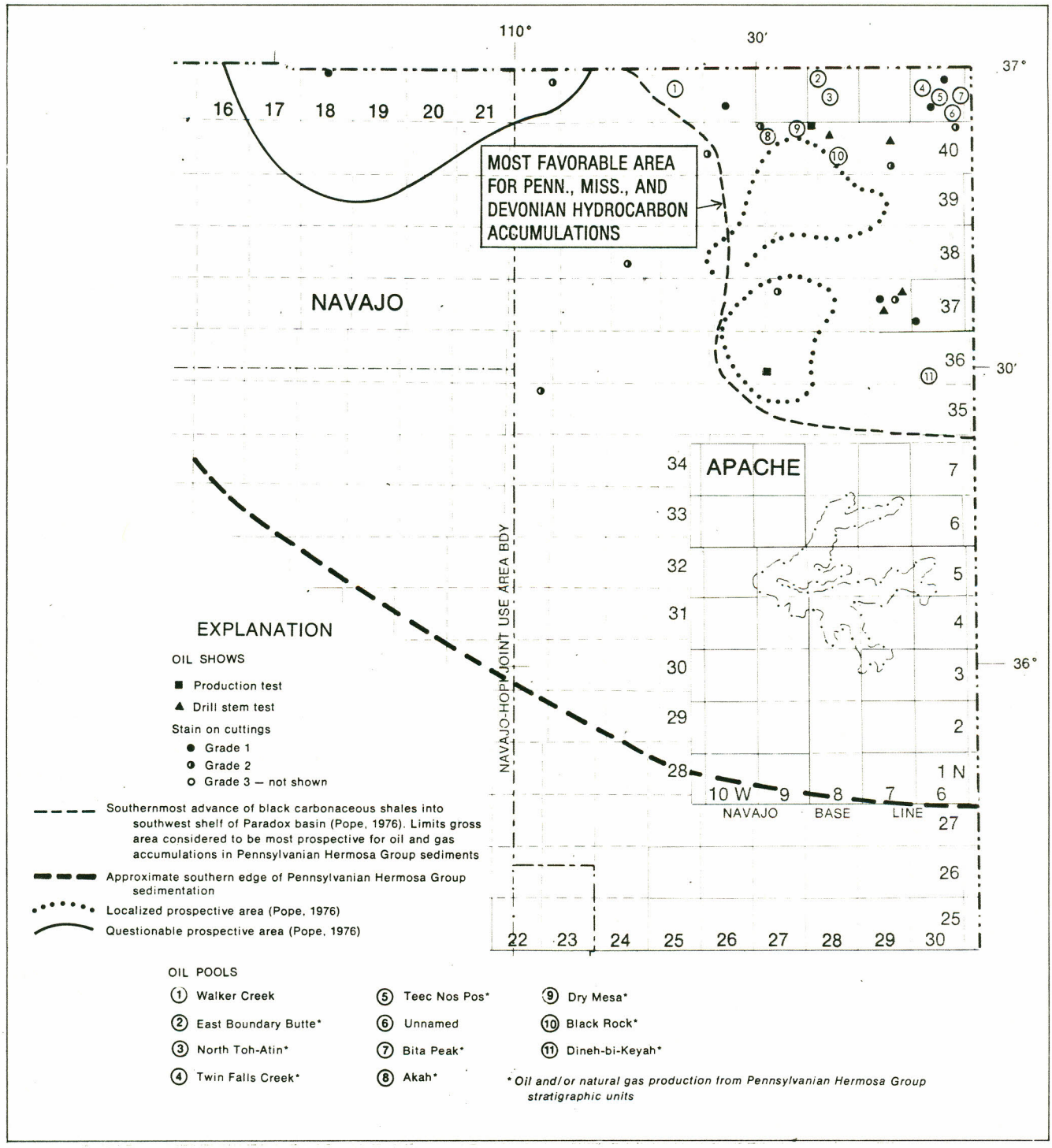


Figure 4.- Map showing location of area considered to be most favorable for Pennsylvanian, Mississippian, and Devonian hydrocarbon accumulations.

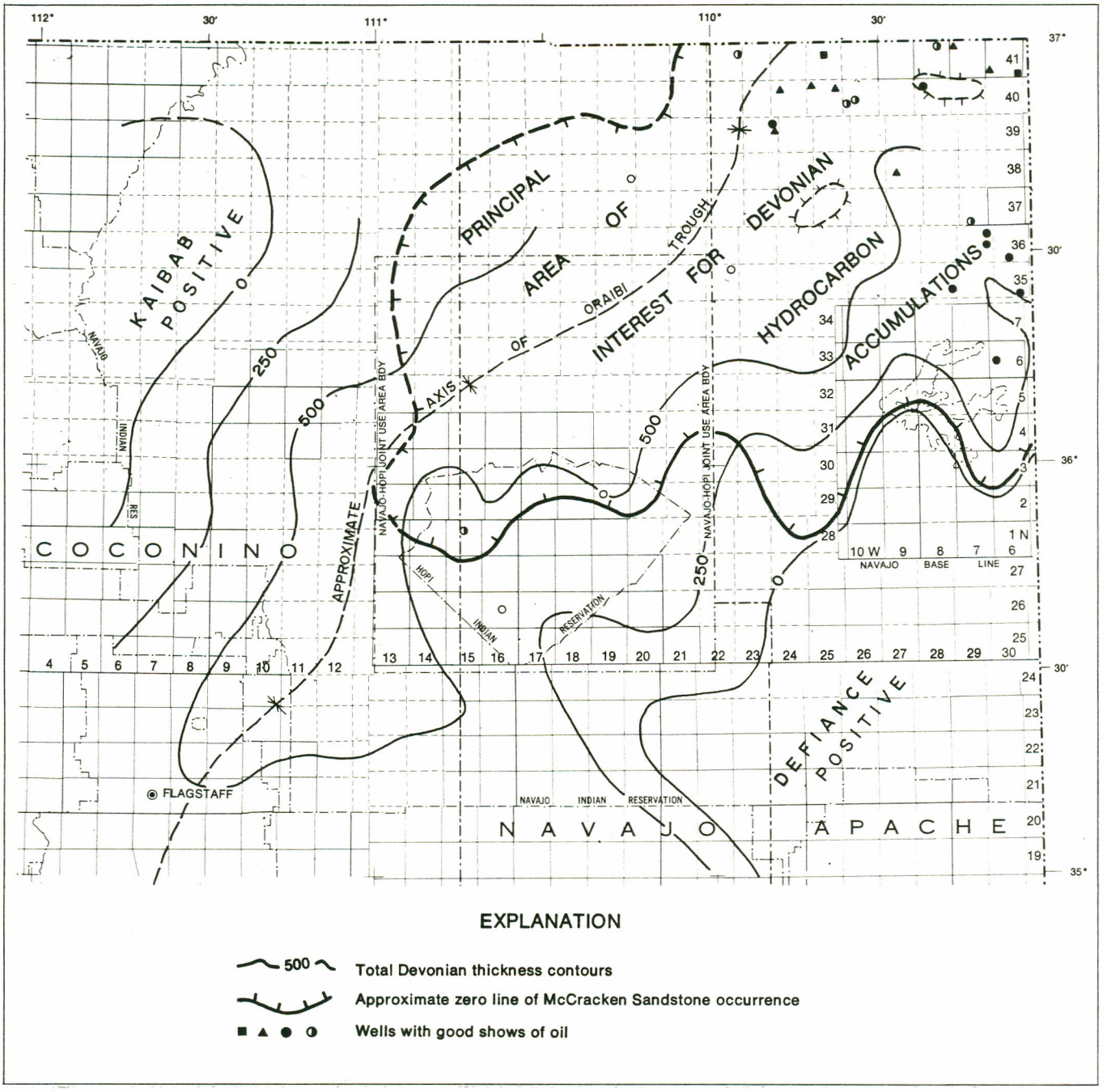


Figure 5.- Map showing gross area considered to be favorable or potentially favorable for Devonian hydrocarbon accumulations.

on cuttings in Pennsylvanian and Devonian rocks, respectively, in the northeastern part of the study area. The graphic location of wells with oil shows in Mississippian rocks in the Four Corners region and the few widely scattered shows in Devonian, Mississippian, and Pennsylvanian rocks elsewhere, which consist principally of light, questionable, or dead oil staining on cuttings, have not been shown on the maps.

In most instances the nomenclature assigned to the stratigraphic unit in which the show occurred is that reported by the well operator or shown on American Stratigraphic Company lithologic logs.

Productive Areas

The location of hydrocarbon-productive areas and the local pools within these areas is shown on sheets 1 and 2, respectively, of plate 2. Table 1 presents statistical well and production data and the hydrocarbon-productive stratigraphic unit. Total oil production from these pools to January 1, 1979, was 16,877,386 barrels. Production from the Dineh-bi-Keyah pool accounted for approximately 90 percent of this total.

A review of pertinent published material and a cursory investigation of subsequent development indicates that the entrapment of hydrocarbons is controlled by a combination of favorable stratigraphic and structural conditions. East Boundary Butte and Dry Mesa are mapped as faulted anticlines at Pennsylvanian Hermosa depth by Scurlock (1971). Picard and others (1960, p.1558) state that Laramide faulting is present at East Boundary Butte, that many of the surface or subsurface highs in the gross Four Corners region were probably also ancient structures possessing much less structural relief, and that their present positions reflect at least two major periods (late Pennsylvanian-Permian and late Cretaceous-early Tertiary) of movement. Precambrian structural control (pl. 4) indicates that both Black Rock and Dry Mesa overlie the north edge of an uplifted block of basement rock.

In this same area, Strobell (1956) noted a ridgelike basement high trending northwest from the Carrizo Mountains. Subsequently (1962, p. A38) he reported:

> ...The ridge...is bounded on the northeast by a fault that has been active intermittently since the Devonian and has possibly existed since Precambrian time. The Ouray Limestone of Devonian age is displaced a total of 1,550 feet by the fault, but stratigraphic changes indicate that this displacement was achieved in steps...During the Laramide orogeny lower beds were faulted, whereas shallower beds were only folded...The ridge and its boundary fault influenced migration of oil and gas, helium, and presumably other fluids of deep origin within the Paradox basin...

Both the Dry Mesa and Black Rock pools are probably on the northwest extension of the tilted fault block described by Strobell.

The Aneth Complex of Pennsylvanian oil pools in the Paradox basin is primarily a stratigraphic trap because of the excellent development of permeable bioclastic beds in the Hermosa Group of rocks. Picard and others (1960, p. 1558) state:

> ...entrapment was effected by the change from permeable reservoir beds to impermeable lateral units surrounding the accumulation. Structure is a minor factor, but important to the extent that the various water levels are controlled by their structural position on the flanks of the closed and open parts of the fields constituting the Aneth Complex.

The Teec Nos Pos pool is a stratigraphic trap of this nature.

POOL	LOCATION T-R-S	Discovery Yr	WELL STATUS 1-1-79				PRODUCTION DATA Cumulative To 1-1-79		PRODUCTIVE STRATIGRAPHIC UNIT
			Producing	Shut-in	Temp Abd	Abandoned	OIL Barrels	GAS Thousand Cubic Feet	
Akah	40N-28E- 6	1961				1	6,898	19,765	Akah Unit Pennsylvanian Hermosa Group
Bita Peak	41N-31E-19	1956				1	12,531	2,376,743	Ismay & Barker Creek Units Pennsylvanian Hermosa Group
Black Rock	40N-29E	1971		4			1,329	14,687	Ismay & Barker Creek Units Pennsylvanian Hermosa Group
Dineh-bi-Keyah	35N-30E 36N-29 & 30E	1967	24	1	1	2	15,089,238	2,558,667	Tertiary igneous sills in Pennsylvanian Hermosa Formation
Dry Mesa	40N-28 & 29E	1954	3			1[1]	608,143	108,715	Marble Falls & Thunder Spgs Mbr Mississippian Redwall Fm & Akah (?) Unit Pennsylvanian Hermosa Group
East Boundary Butte	41N-28E	1954	4	2	2	5	755,632	9,219,334	Undifferentiated units Pennsylvanian Hermosa Group
North Toh-Atin	41N-28E-22	1956				1	289	915,340	Akah Unit Barker Creek Units Pennsylvanian Hermosa Group
Teec Nos Pos	41N-31E	1963	4		1	1	304,811	1,070,066	Ismay Unit-Penn Hermosa Group
Twin Falls Creek	41N-30E-16	1957			1	1	622	194,264	Ismay Unit-Penn Hermosa Group
Unnamed	41N-30E-36	1960				1	764		McCracken Mbr-Devonian Elbert Fm
Walker Creek	41N-25E-16	1963				1	97,129		McCracken Member Devonian Elbert Fm

Table 1.- Oil and gas pools - name, location, and development data. Well (1) in T. 40 N., R. 29 E., originally reported to be in Dry Mesa pool, produced 6,163 barrels of oil prior to abandonment. Subsequent development indicates that it may be located on the northwest flank of the Black Rock structure.

Structurally the Dineh-bi-Keyah field is on the northwest portion of the Toadlena anticline on the northeast flank of the Defiance uplift, but the oil accumulation is primarily stratigraphic (McKenny and Masters, 1968). This field is unique. The oil production is from a Tertiary igneous sill intruded into Pennsylvanian Hermosa rocks. According to McKenny and Masters the "porosity, permeability, and oil-saturation values measured in the igneous rock are similar to the reservoir parameters of many oil-producing carbonate rocks."

Reservoir Rock

A detailed discussion of the lithology of the several Pennsylvanian pay zones of the oil and gas pools is beyond the scope of this report. A summation of the lithology of the various Pennsylvanian stratigraphic units in the gross Four Corners region has been made by Picard and others (1960). The lithology of the carbonate facies of the Hermosa Formation in northeastern Arizona is discussed by Pope (1976). Several types of porosity are present in the carbonate reservoirs. The types, including algal, oomoldic, and dolomitic, are discussed in detail by McComas (1963). The reservoir rocks with algal porosity are some of the best producing intervals. The productive intervals of Bita Peak, East Boundary Butte, and Twin Falls Creek have this type of porosity.

The principal pay zone of the Hermosa Group carbonates is the Ismay unit (table 1). Figure 6 shows the lithology of the Hermosa Group rocks penetrated in the discovery well of the Black Rock pool and the gas-productive intervals in the Ismay and Barker Creek units.

The reader is referred to the work of McKee and Gutschick (1969) for the lithology and stratigraphy of the Mississippian Redwall Formation in the Colorado Plateau province of Arizona. The lithology of the subdivisions of the formation in the Black Mesa basin region is discussed by Kent (1975). The Mississippian dolomite pay zone of the Texas Pacific 1 Navajo in the Dry Mesa pool (well 77) has intergranular, intercrystalline, or interfragmental and vuggy types of porosity.

The only oil production from the Devonian has been from the Walker Creek pool and an unnamed pool (table 1). The pay zone in each pool is the McCracken Sandstone Member of the Elbert Formation.

Hydrocarbon Sources

The marine carbonates and shales of the Devonian, Mississippian, and Pennsylvanian systems have generally been considered to be the probable source of hydrocarbons in the report area by most geologists in past years. However, the possibility exists that nonmarine sediments could be hydrocarbon sources. Extensive exploration in recent years in various kinds of basins throughout the world has resulted in the discovery of both small and large fields in continental depositional environments, once regarded as unfavorable for the source of hydrocarbons in large quantities. In the United States the best known examples of oil fields in nonmarine sequences are in the Tertiary Eocene of the Uintah basin in Utah. In the Cook Inlet-Kenai basin of coastal Alaska early to late Tertiary continental strata contain oil-productive reservoirs. Closer to Arizona, Picard (1975) has suggested that oil and gas in the Jurassic Nugget Sandstone of southwest Wyoming and northeast Utah may have been generated in nonmarine depositional environment. There is insuff

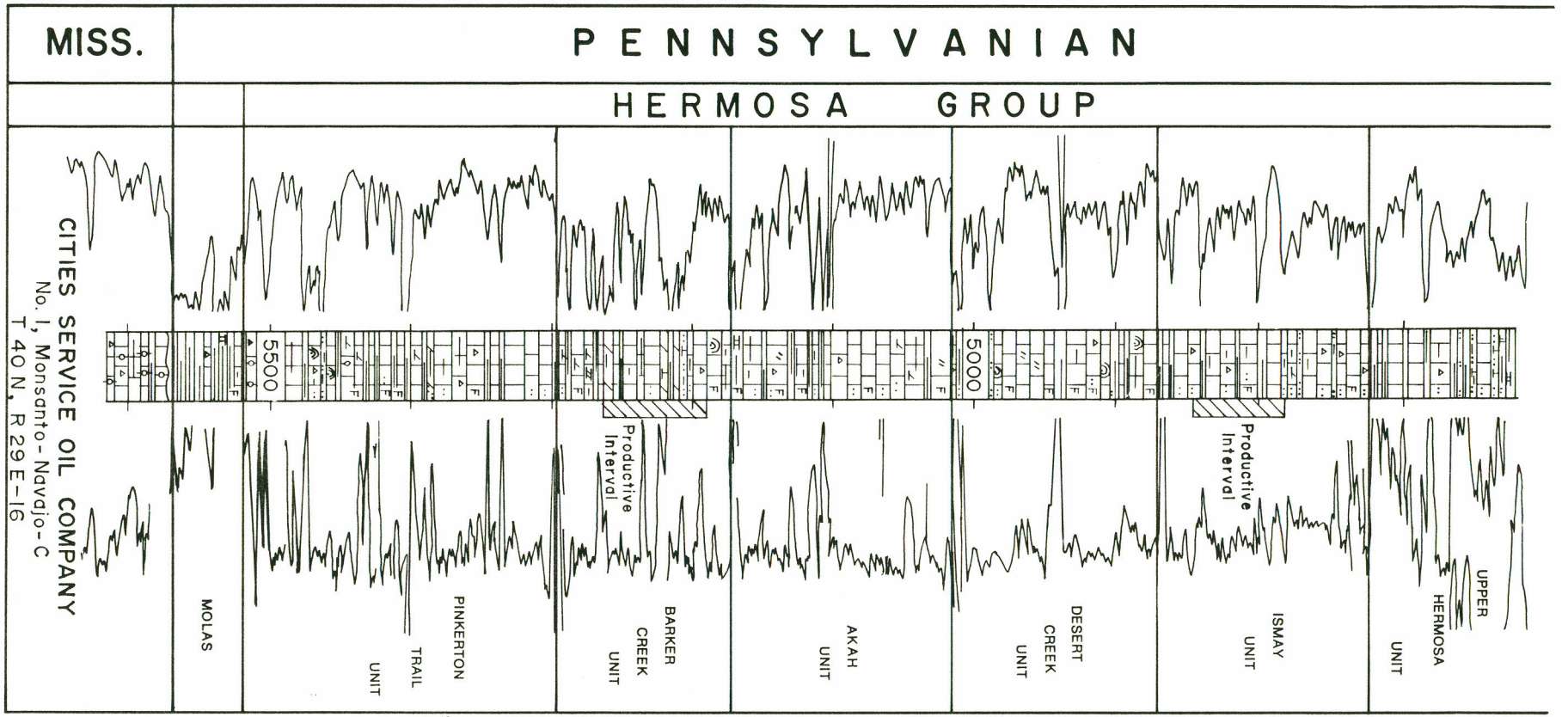


Figure 6.- Lithologic/geophysical log of discovery well of Black Rock pool. (Unit correlation from Cities Service Oil Company. Lithology from American Stratigraphic Company.)

Wyoming and northeast Utah may have been generated in an aeolian depositional environment. There is insufficient information available at this time to attempt an evaluation of the possibilities of finding hydrocarbon accumulations in the nonmarine sediments of Paleozoic and younger rocks.

Recent facies investigations by Harrison (1975) and Kent (1975) indicate that Devonian sediments are more likely to be a source of hydrocarbons than Mississippian sediments. Harrison states that the Aneth Formation carbonates can be considered as a possible source. Its dark color and fetid odor indicate the presence of organic material. Most of the best shows of oil listed for the Devonian rocks in table F have occurred in the McCracken Sandstone Member in contact with the overlying Aneth Formation.

According to Picard (1962, p. 1694) the origin of the hydrocarbon gases in Mississippian reservoirs has not been established with certainty. Further, "they are probably indigenous to Mississippian reservoirs, but may have migrated into Mississippian sediments from Devonian, or, more likely, from Pennsylvanian beds." The Pennsylvanian source appears most probable. The major hydrocarbon production in the Paradox basin is in the Lisbon field in Utah. In this field the reservoir zones are in contact with petroliferous limestones of the Pennsylvanian Paradox Formation (Heylmun, 1965). The Mississippian gas in the Dry Mesa pool probably migrated upward from Pennsylvanian beds along fractures associated with the fault on the north side of the anticline.

Pope (1976) considers the black carbonaceous shales of the Hermosa Formation to be the primary Pennsylvanian source rock. A secondary noncarbonate source may be dark carbonate muds (Peterson, 1966). The areal distribution of the black carbonaceous shales, as determined by Pope, is shown on figure 4. The organic content of the carbonates decreases southward from the northeast portion of the study area. The approximate southern edge of Hermosa Formation sedimentation is shown on this same figure. The abundant siliceous clastics and dense carbonates of the Pennsylvanian Naco Formation, in conjunction with the few minor shows of oil noted in wells drilled, indicate that this portion of the report area probably lacks source rocks of any significance.

Hydrocarbon Generation

Some workers have expressed concern about the time span and depth of burial factors required for the generation of hydrocarbons in the Devonian rocks of northeastern Arizona. According to Tissot and Welte (1978, p. 200-201):

> The succession of main steps of evolution of organic material...is common to all types of sediment...The most important parameters are the nature of the organic matter and the temperature versus time relationship...
>
> The threshold corresponding to the beginning of significant oil generation varies with the geothermal gradient, the depth and the duration of burial. The related temperature ranges from 50°C [122°F] in basins of Paleozoic age to 115°C [239°F] in Mio-Pliocene sediments.

> The timing of oil generation may also vary. The principal phase of oil formation may follow source rock deposition after a delay ranging from a few million years to 300 million years. In particular, a large number of the present oil fields have been generated during the Cretaceous and Tertiary, regardless of the age of the source rock [underlining added for emphasis with respect to Devonian in report area].

The Devonian period in northeast Arizona had a time span of 50 million years (fig. 2). Nonequilibrium temperature measurements (obtained from geophysical logs and production and drill-stem tests) as high as 114°F (45.6°C) have been recorded in the Devonian interval of boreholes (Conley and Stacey, 1977). The 97,000-plus barrels of oil produced in the Walker Creek pool indicate that the Devonian Aneth Formation, considered to be the source rock, at least locally contained sufficient organic material for the generation of oil. The thickest sections of Aneth noted during the course of this study occurred in the Gulf 1 Navajo, T. 41 N., R. 15 E., 146 feet, and in the Atlantic 1 Hopi, T. 28 N., R. 15 E., 136 feet. Unanswerable presently is the question as to whether the total volume of Aneth sediments contained sufficient organic material for the generation of the large quantities of oil required to effect economic accumulations.

The timing factor for oil generation in the Aneth may not be critical. Generation could have occurred during Devonian time or during subsequent burials in post-Devonian time (fig. 2). However, Wilson (1975, p. 69) states that many experienced geologists believe that numerous "oil accumulations call for early, short-lived expulsion of hydrocarbons shortly after the burial of source and reservoir sediments." One of his examples is the Devonian Aneth-type limestone closed-system trap that occurs in southeastern Utah. In support of early expulsion, possibly applicable to Aneth source rocks, Halbouty and others (1970) state:

> ...Although the relative richness of argillaceous to carbonate organic sources generally favors the former, the efficiency of primary migration probably is greater in the carbonates, because much of the petroleum in some thick mud and clay sections (now shale) remained locked *in situ* because of the lack of interbedded porous zones.

Hydrocarbon Traps

Most of the rank wildcat wells drilled in the report area have been on surface anticlinal features (pl. 1 and sheet 1, pl. 2). Many of these features are evident on subsurface structure maps (pls. 3 and 4). Probably most of these wells were drilled on seismic closures by major companies. With the exception of Dineh-bi-Keyah, all exploratory wells south and southwest of the productive area adjacent to the Utah state line have been dry holes.

Lessentine (1965) states that the large anticlinal features appear to have had an early history of growth and offer possibilities for oil and gas production. The structure mapped on top of the Precambrian basement (pl. 4) and on top of the Permian Coconino-De Chelly sandstones (pl. 3) and the surface structural features shown on plate 1 certainly suggest an

early history of growth and the concomitant creation of structural traps for hydrocarbons. The possibility exists that there are hydrocarbon accumulations on the "dry" anticlines but not on the crestal portions tested. The Paleozoic rocks have been subjected to several periods of uplift and northward tilting of the general Black Mesa region in Jurassic time (fig. 2). Studies by Wilson (1975, 1977) and others have established that presence of hydrocarbons inhibits the diagenetic processes which continue unabated in water-bearing reservoirs as time elapses and burial continues. With sufficient time, the resultant cementation below the oil-water contact would create a seal at this contact. Therefore, the oil accumulation could be "locked" in place. Paleotilting could shift the position of the reservoir but it would not destroy the accumulation.

Wilson (1977, p. 487) defines this type of diagenetic trap as follows:

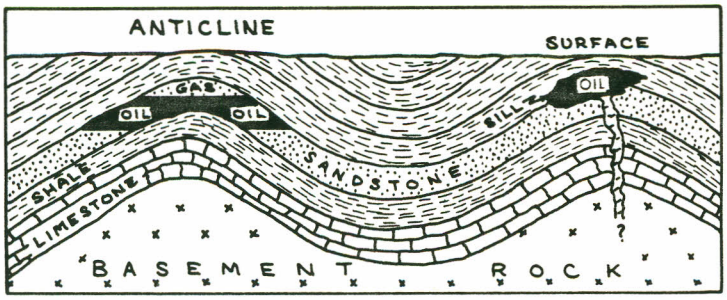
> A diagenetic hydrocarbon trap is a hydrocarbon charged paleotrap in which the paleostructural or paleostratigraphic closure has been rotated from its original attitude. The time of opening of the paleotrap postdates the time of diagenetic plugging of the water leg so that the hydrocarbons are retained by a permeability barrier in what is now a new updip direction.
>
> Thus the creation of a diagenetic trap is diachronous, being the resultant of late tilting of an early oil-bearing structure. This differs from a stratigraphic trap, sensu stricto, in which the updip trapping agent is a contemporaneous facies change of reservoir rock to nonreservoir rock.

Idealized portrayals of the various types of traps, with the exception of the diagenetic type, that exist or may exist in northeastern Arizona are shown in figure 7.

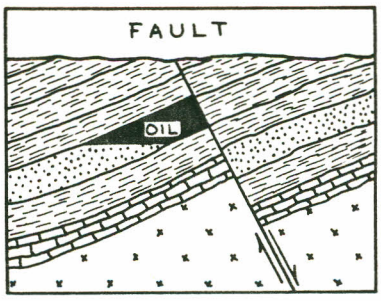
Regional Structure

Surface structural elements are shown on plate 1, adapted from a map prepared by Davis and Kiven (1975). A few structural features mapped by Hackman and Olson (1977) have been added in the east-central part of the map. Plate 3 presents an interpretation of the subsurface structure on top of undifferentiated Permian Coconino-De Chelly sandstones. These sandstones, penetrated by numerous water wells, furnished the only Paleozoic subsurface control available in much of the area. The principal sources for this control were water-resources reports by Davis and others (1963), McGavock and others (1966), and McGavock (1968). Most of the larger surface structural features are evident at this stratigraphic position in the subsurface.

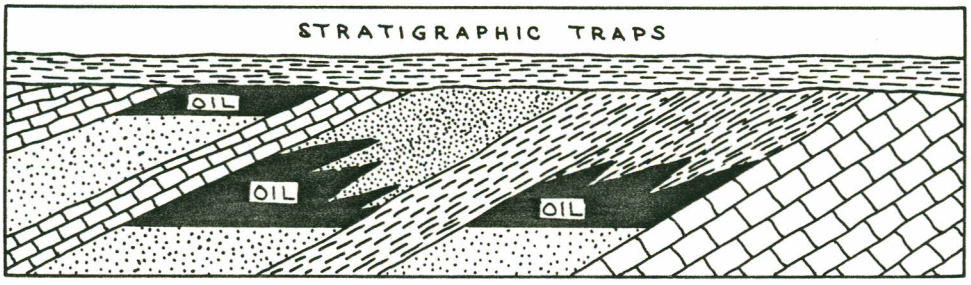
To the author's knowledge no structure contour maps on top of the Precambrian basement surface in the study area have been published, probably because the subsurface control outside of the Four Corners region is extremely sparse. The interpretation shown on plate 4 represents an initial effort to map the configuration of the basement surface using supplemental control furnished by hydrocarbon test holes and water wells bottoming in Paleozoic strata and structure-thickness relationships inferred from the aeromagnetic and gravity maps included in this report.



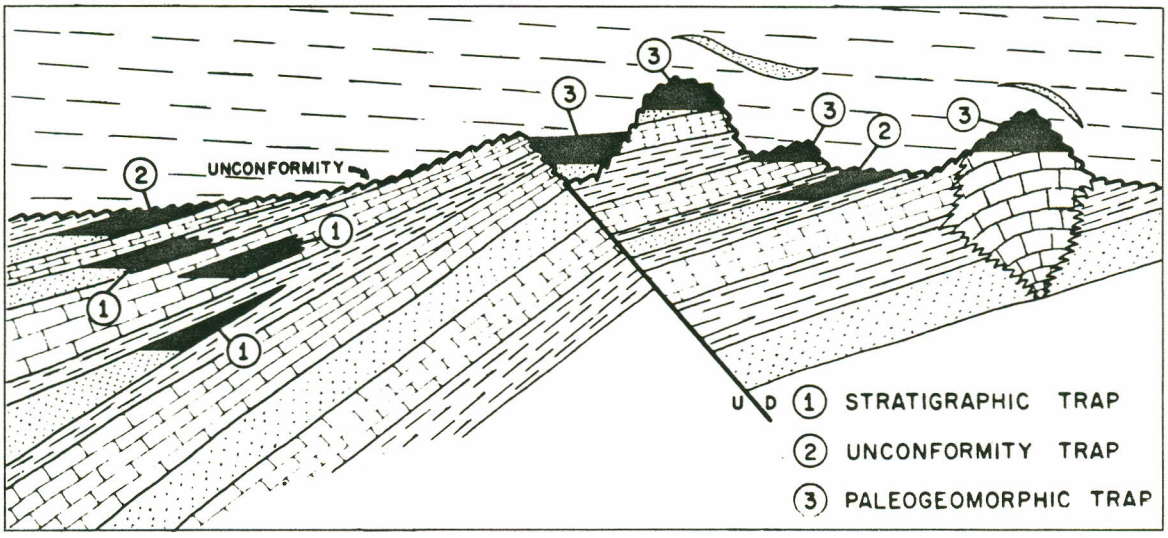
A The anticline is, in its simplest form, a dome caused by folding of rock strata. Oil and gas are trapped in porous rock strata at the tops of these domes, with impervious shales above and below. In most reservoirs, the oil floats on salt water. Free gas may occur above the oil. On the right side an igneous sill is shown intruding sedimentary strata. The sill reservoir in the Dineh-bi-Keyah field has good fracture porosity and has localized oil and gas possibly derived from the surrounding shales. A non-sedimentary rock reservoir, particularly an igneous sill, is very uncommon.



B Faults result from a break or slip in the earth's rock crust. When a fault places a porous stratum against an impervious one, a natural petroleum trap is formed. The occurrence of faults in oil and gas fields is rather common.



C The three trapping conditions shown from left to right are defined as stratigraphic traps because each represents some change in the rock strata. To the left a porous sandstone bed has been truncated by erosion and later sealed off by a shale. In the middle the top part of an inclined sandstone bed is better cemented (pore space filled), decreasing porosity and permeability. To the right a porous sandstone grades into shale, a rather impervious rock. The gradation from sandstone to shale took place at the time of deposition on the seafloor when the beds were more or less horizontal. Later tilting of the beds created the potential reservoir.



D. Idealized portrayal of types of "hard-to-find" subtle traps. Note relationships of stratigraphic traps to lateral changes in facies and relations of unconformity and paleogeomorphic traps to erosional surfaces and relief features buried beneath them.

Figure 7.- Idealized portrayal of types of hydrocarbon traps that exist or may exist in report area. (Subfigures A, B, and C from University of Arizona, 1975, and D from Halbouty, 1972. Diagenetic type of Wilson, 1977, not illustrated.)

The dominant structural feature of exploratory interest is the syncline in the central portion of the map. The axis of this feature extends from a point near the southwestern corner of Navajo County to a point near the northwestern corner of Apache County. The lowest portion underlies Black Mesa as mapped by Peirce and others (1970). Without any allowance made for probable steep dip off of the Cow Springs monocline, more than 9,000 feet of sedimentary rocks may be present at the site of water well 177 in T. 36 N., R. 18 E., which bottomed in undifferentiated Permian Coconino-De Chelly sandstone at a total depth of 5,149 feet.

In his paper on lineament-block tectonics in the Williston-Blood Creek basin in Montana and North Dakota, Thomas (1974) states: "In influencing the stratigraphic and structural conditions, the basement block framework has affected directly the localization of oil and gas in the area." Davis (1975) reached the same conclusion in his analysis of tectonic folds in the Colorado Plateau province of Arizona: "As loci of major fracturing, folding, and probably facies changes, the fracture zones have exerted control(s) on the entrapment of oil and gas." His inferred fracture zone system is shown in figure 8. Gutman and Heckmann (1977) in the 1978 revision of the residual magnetic intensity map, showing the configuration of Precambrian basement (pl. 5), interpret numerous faults of considerable linear extent. Figure 9 is a compilation of these interpreted basement faults, inferred faults shown on the residual Bouguer gravity map of Gutman and Heckmann (pl. 8), LANDSAT lineaments mapped by Lepley (1977), Saunders and others (1973), and thermal wells and springs.

The dominant syncline of the Precambrian basement structure map occurs between two northeast-trending fault systems that can be interpreted from both magnetic and gravity data. Different patterns of tectonic blocks can be interpreted within and outside of the major synclinal feature. The logged lithology of the igneous and metamorphic rocks penetrated by wells is listed in table A. Presently insufficient well control is available outside of the Four Corners region, and possibly a limited portion of the Mogollon slope region, to utilize petrological and geophysical data in defining the boundaries of tectonic basement blocks as Case and Joesting (1972) have done on their basement map of the central portion of the Colorado Plateau. Gutman and Heckmann (1977) show some interpreted discontinuities in basement rock on plate 5. The common occurrence of thermal water wells and springs along the faults and LANDSAT lineaments shown in figure 8 may be indicative of extensive fracture systems in the sedimentary column resulting from intermittent movement of basement tectonic blocks.

Thickness Maps

The dominant feature of exploratory interest evident on the Devonian thickness map (pl. 6) is the trough extending northeastward from the vicinity of Flagstaff in Coconino County to a point near the northwest corner of Apache County. Turner (1958) postulated the existence of this feature, naming it "Oraibi" trough. It exhibits fair to good conformity with the dominant syncline present on the Precambrian surface. Structurally it is between the Kaibab positive to the northwest and the Defiance positive to the southeast (fig. 5). Several local areas with thin sections of Devonian rocks are mapped in the southwest part of the Mogollon slope region. These local thin areas are also evident on the Mississippian

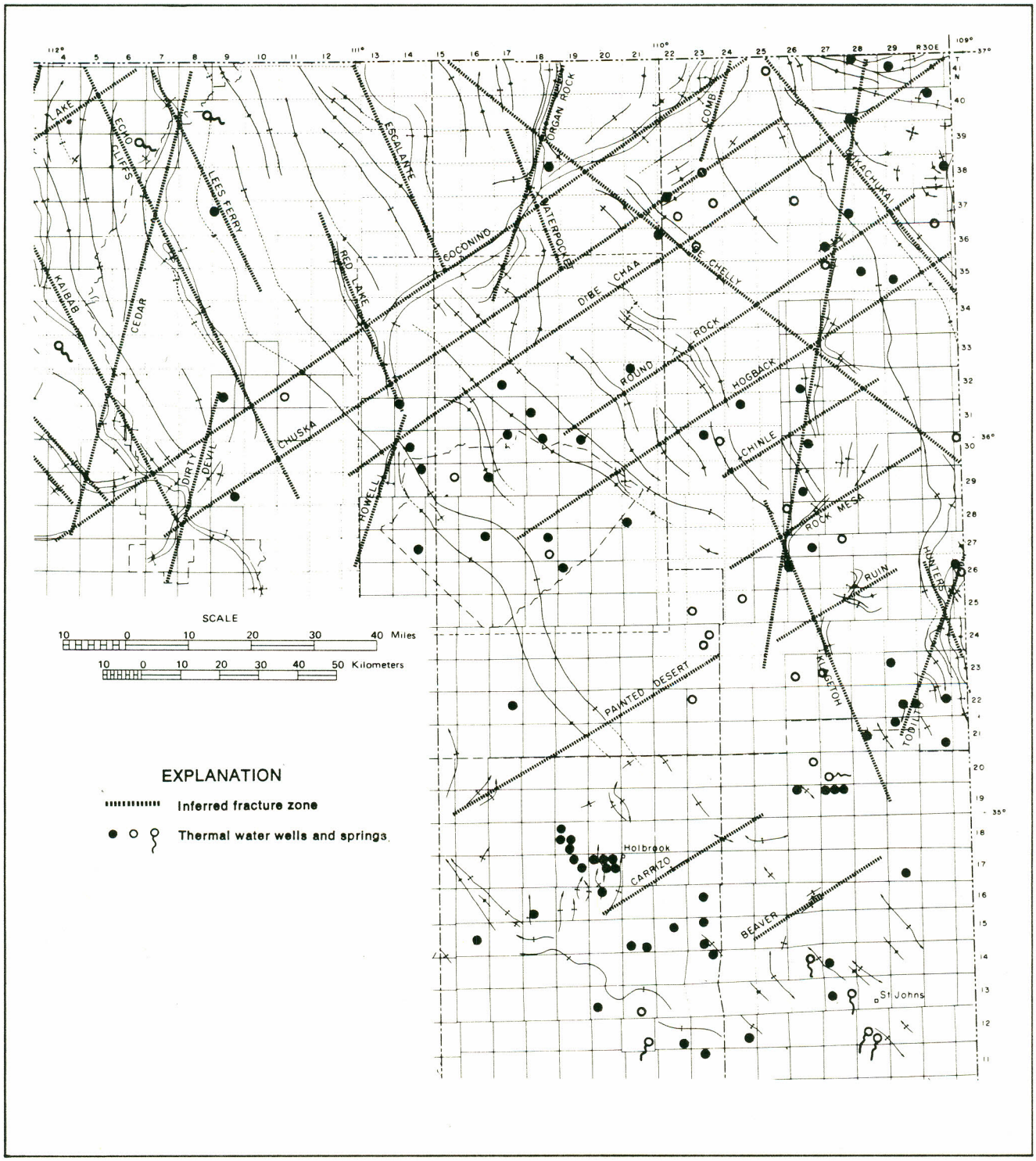


Figure 8.- Map showing occurrence of thermal water wells and springs with respect to structural elements and inferred fracture zone system of Davis (1975).

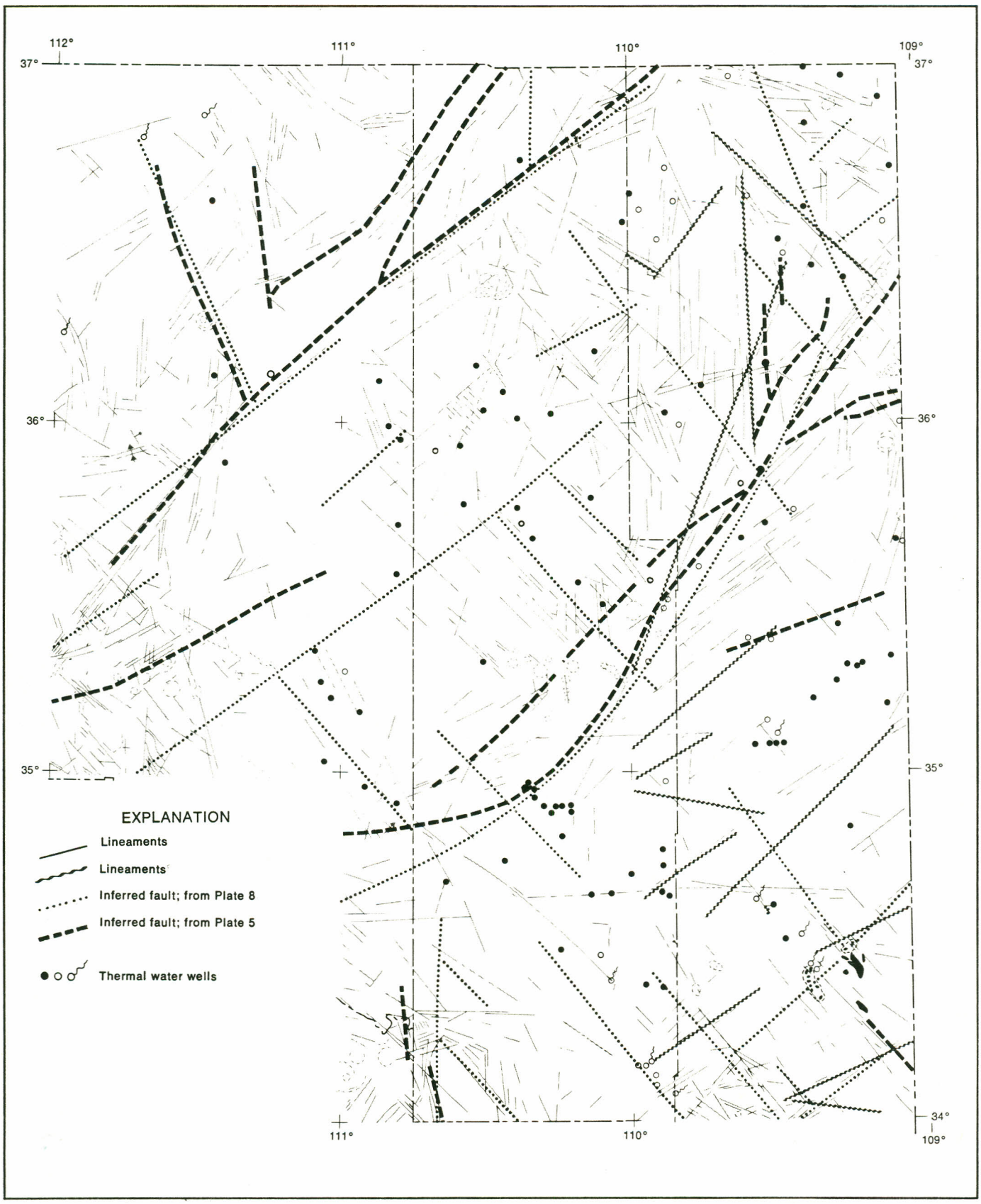


Figure 9.- Map showing occurrence of thermal water wells and springs with respect to LANDSAT lineaments (Lepley, 1977; Saunders and others, 1973) and inferred geophysical faults (Gutman and Heckmann, 1977).

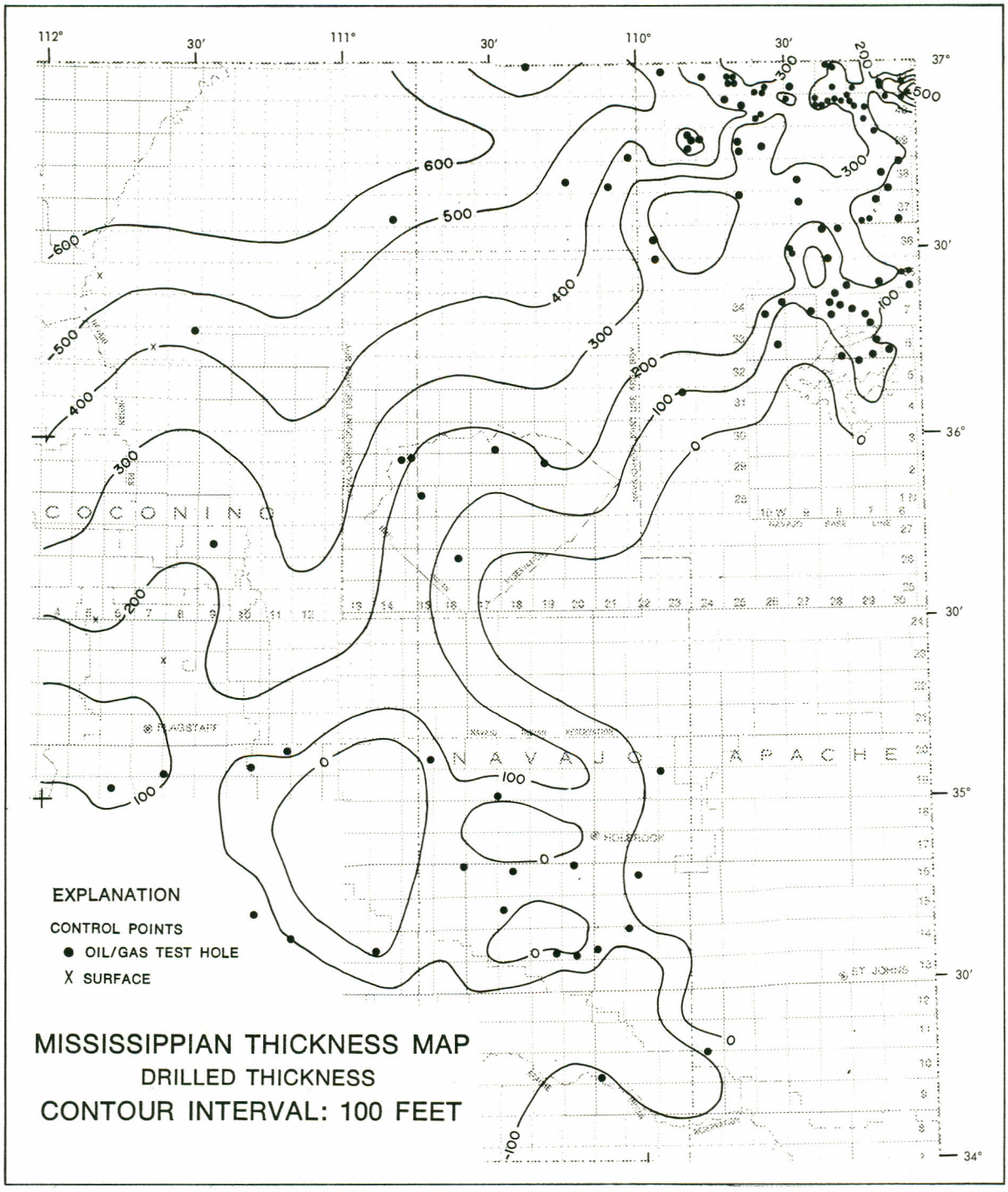


Figure 10.- Map showing drilled thickness of Mississippian rocks.

thickness map, figure 10. These features occur north and northeast of the series of isolated, local, Precambrian quartzite islands along the Mogollon Rim (Teichert, 1965). The intervening basin appears to be coincident in position with the west-central portion of the Pennsylvanian St. Johns sag of Kelley (1955, p. 77). Oil-productive unconformity traps are frequently associated with buried topographic highs. The general absence of good shows of oil and reservoirs in the Pennsylvanian, Mississippian, and Devonian rocks penetrated in wells drilled on and adjacent to these features dim their oil-productive potential. However, the interior portions

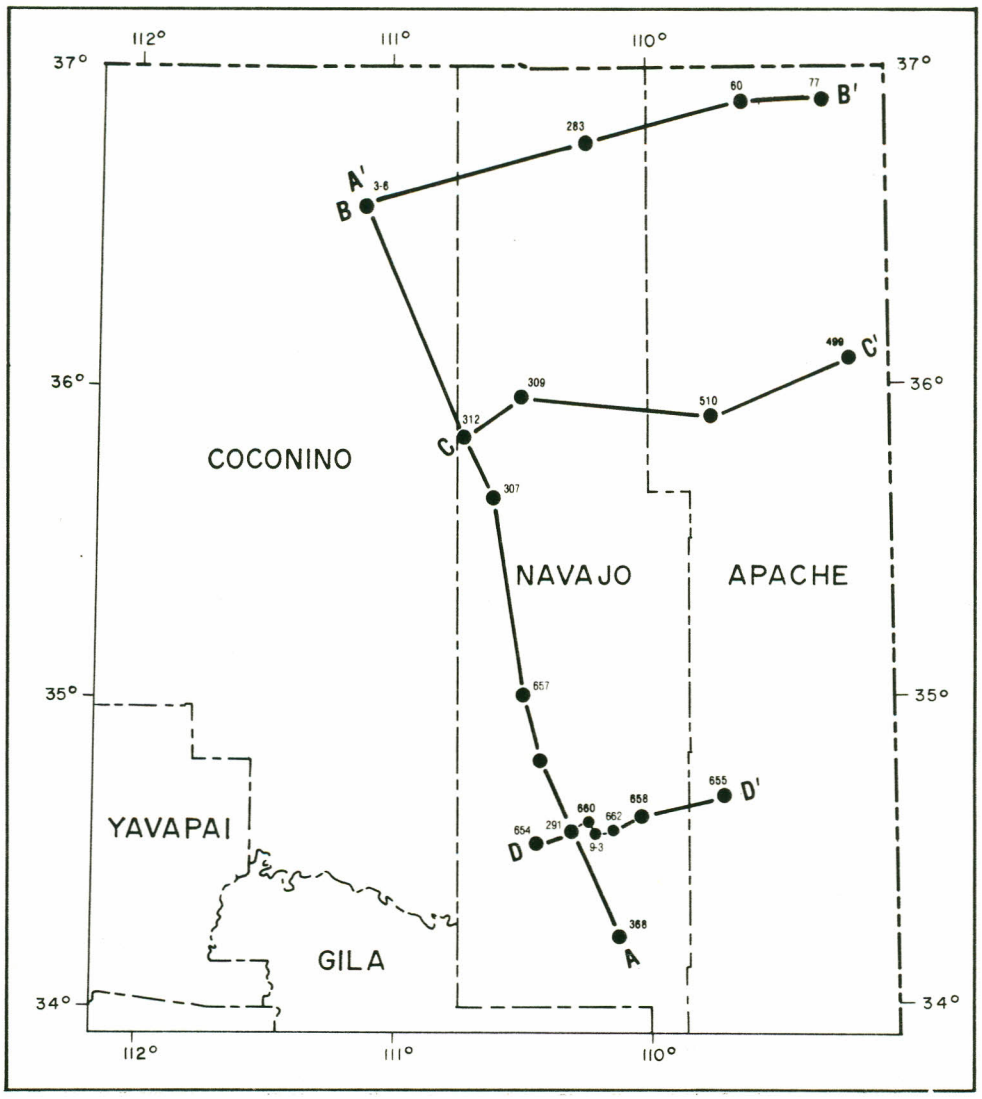


Figure 11.- Location of stratigraphic cross sections and wells, figures 12, 13, 14, and 15.

of the local basins possibly offer preserved paleotraps in the Devonian section. The reservoir for such traps is discussed subsequently.

Stratigraphy

Figure 11 shows the location of four stratigraphic cross sections (figs. 12-15). The correlations shown, based largely on geophysical log characteristics, must be considered to be preliminary in nature and subject to revisions. This is particularly the case for the Devonian Aneth Formation or Aneth Member of the Elbert Formation. Parker (1961) suggested that the Aneth is a basal facies of the Elbert Formation and Rothrock (1960) thought it to be an euxinic facies of the Elbert. Harrison (1975, p. 33, 44) believes that the Aneth Formation should be referred to as the Aneth Member of the Elbert Formation (see fig. 16).

The Devonian correlations shown on stratigraphic cross section A-A' (fig. 12) suggest strongly that the lowermost unit or member of the Martin Formation in the Mogollon slope region is equivalent to the Aneth Member of

Harrison. If this correlation is valid, the Devonian basins north and west of well 368 shown on plate 6 may have an appreciable thickness of the Aneth. The equivalent fetid dolomite unit of Teichert (1965) is present in outcrops to the south along the Mogollon Rim. He states that in many places the upper few feet of this unit consists of highly porous dolomite. The possible presence of preserved oil-bearing paleotraps in this porous dolomite reservoir exists if the Aneth is present in these local basins. The most attractive Devonian reservoir rock, the McCracken Sandstone Member of the Elbert Formation, does not appear to be present in any of the wells drilled in the report portion of the Mogollon slope region.

Favorable and Potentially Favorable Areas

The general area along the outer rim of the Paradox basin in the Four Corners region appears most favorable for oil and gas accumulations in Pennsylvanian, Mississippian, and Devonian rocks (fig. 4). On the basis of exploratory and development drilling to date the productive carbonate zones of the Pennsylvanian Hermosa Group are the most attractive reservoirs. Porous sand bodies within the Hermosa possibly are potential reservoirs. Past exploration has largely been for traps on anticlines. The potential of stratigraphic traps, such as occurs in the Teec Nos Pos pool, remains unevaluated. There is a possibility that accumulations comparable to Dineh-bi-Keyah exist in the area. Minor shows of oil have been noted in igneous sills intruded into Hermosa strata in three wells between this field and the northeast corner of the state.

Pope (1976) considers a localized area west of the Dineh-bi-Keyah field (fig. 4) to be prospective for Pennsylvanian Hermosa petroleum accumulations primarily on the basis of: 1) presence of black carbonaceous shales (hydrocarbon source); 2) shows of oil found in several wells, including one well in T. 36 N., R. 27 E., that produced some free oil on production tests; and 3) presence of reservoirs in Chaetetes boundstones with characteristic high porosities. He considers the localized area south of the Dry Mesa pool stratigraphically attractive with algal mounds and oolite shoals possibly occurring in the north part and Chaetetes boundstones in the south part. Only two wells have been drilled in the questionable prospective area along the state line. Oil shows were noted in both holes. Pope believes that oolite shoals and porous sandstone bodies could offer adequate reservoirs for stratigraphically or structurally controlled entrapment of hydrocarbons.

Mississippian hydrocarbon production appears to be closely associated with faulted anticlines having productive Pennsylvanian zones. Initial exploratory wells situated on structural anomalies should be drilled sufficiently deep to test the entire Paleozoic section of rocks.

The widespread occurrence of oil shows, and some oil production in the one-well Walker Creek pool, is highly suggestive that the Devonian Sandstone Member of the Elbert Formation should be considered as an attractive target for both structurally and stratigraphically controlled traps in the most favorable area shown in figure 4.

Outside of this area the hydrocarbon potential of the Pennsylvanian and Mississippian rocks cannot be adequately evaluated currently. However, the decreasing amounts of organic material in the carbonates and

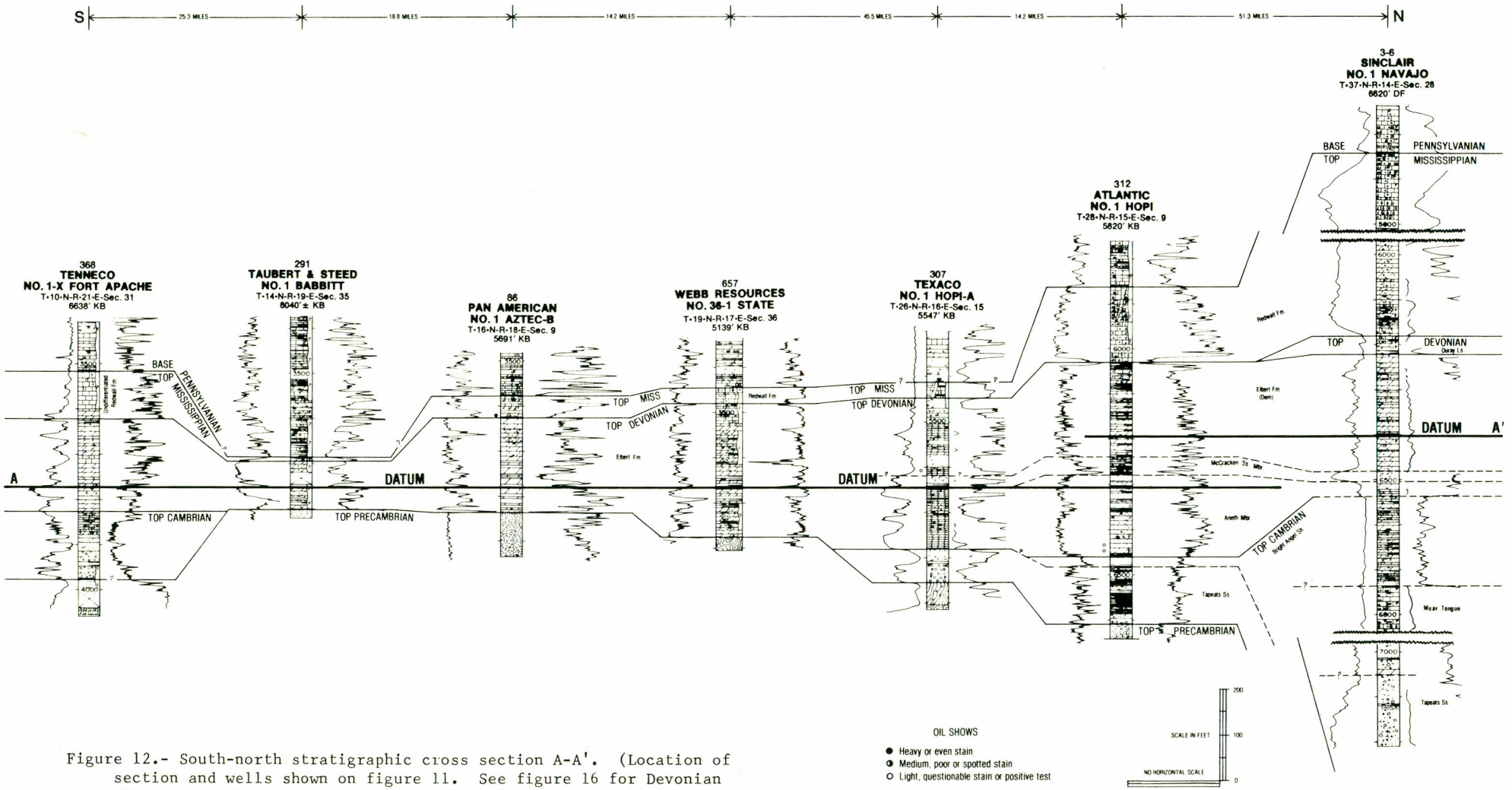


Figure 12.- South-north stratigraphic cross section A-A'. (Location of section and wells shown on figure 11. See figure 16 for Devonian Elbert Formation nomenclature. Log lithology from American Stratigraphic Company.)

SOUTH-NORTH STRATIGRAPHIC CROSS SECTION A-A'

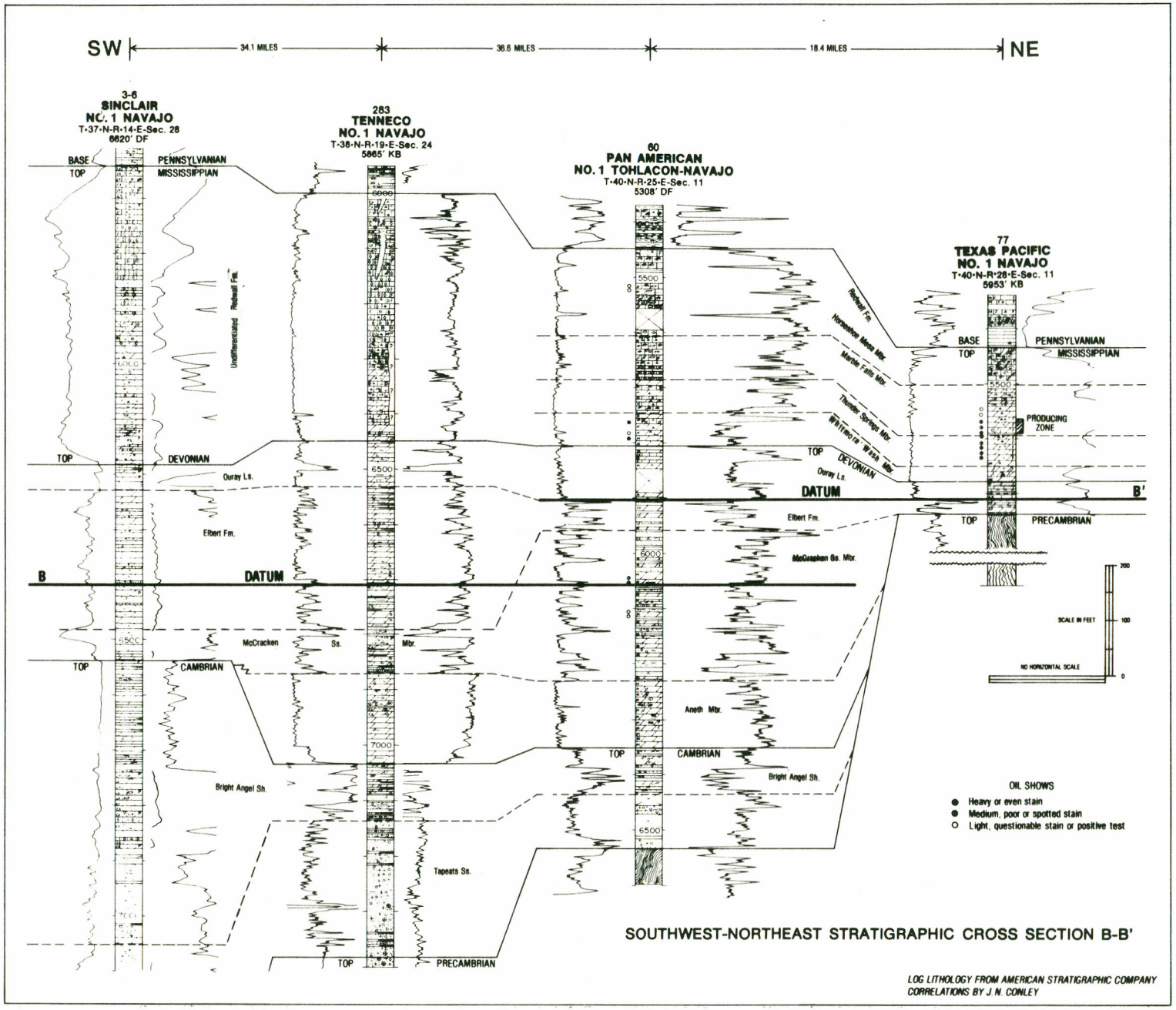


Figure 13.- Southwest-northeast stratigraphic cross section B-B'. (Location of section and wells shown on figure 11. See figure 16 for Devonian Elbert Formation nomenclature. Log lithology from American Stratigraphic Company.)

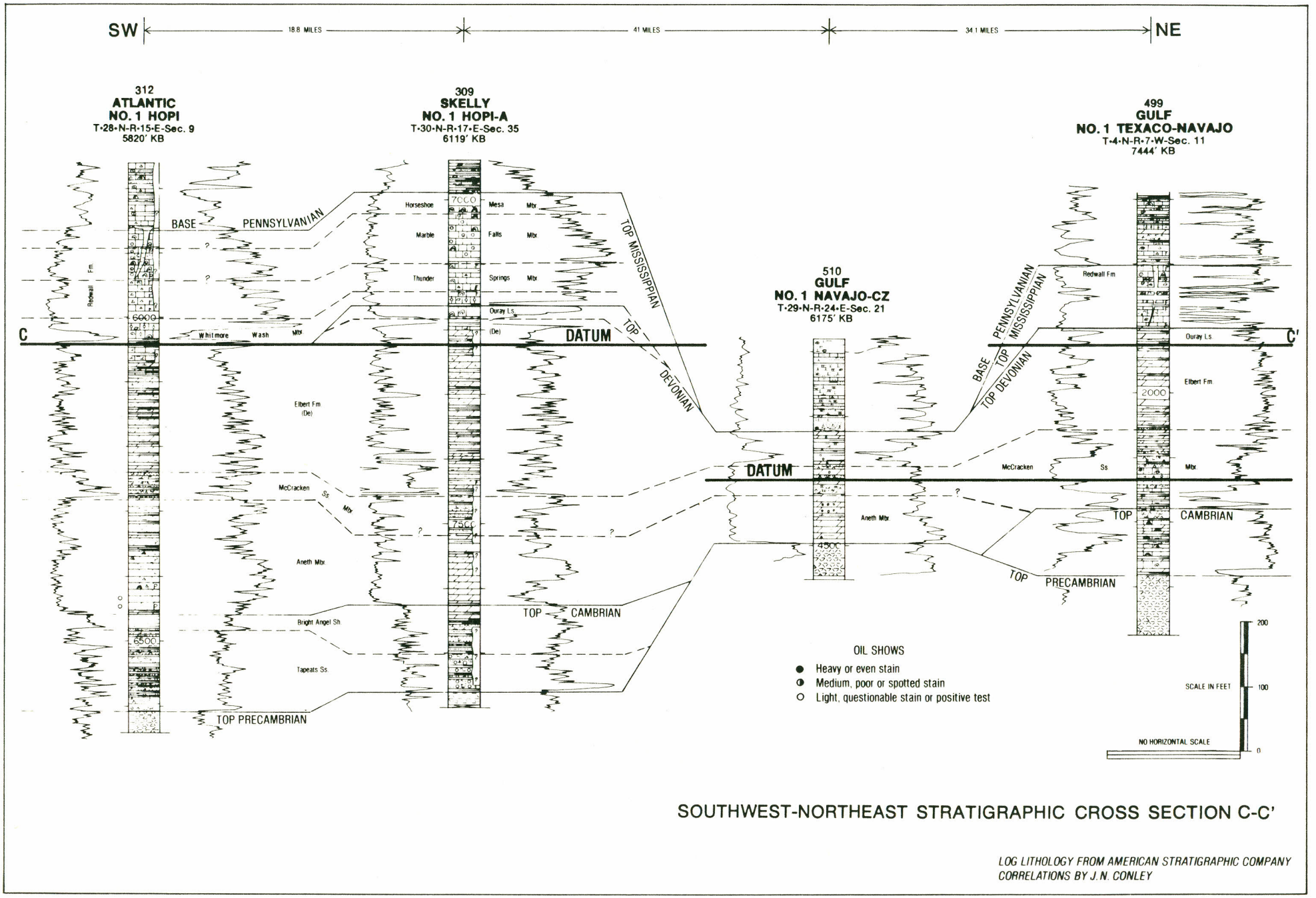


Figure 14.- Southwest-northeast stratigraphic cross section C-C'. (Location of section and wells shown on figure 11. See figure 16 for Devonian Elbert Formation nomenclature. Log lithology from American Stratigraphic Company.)

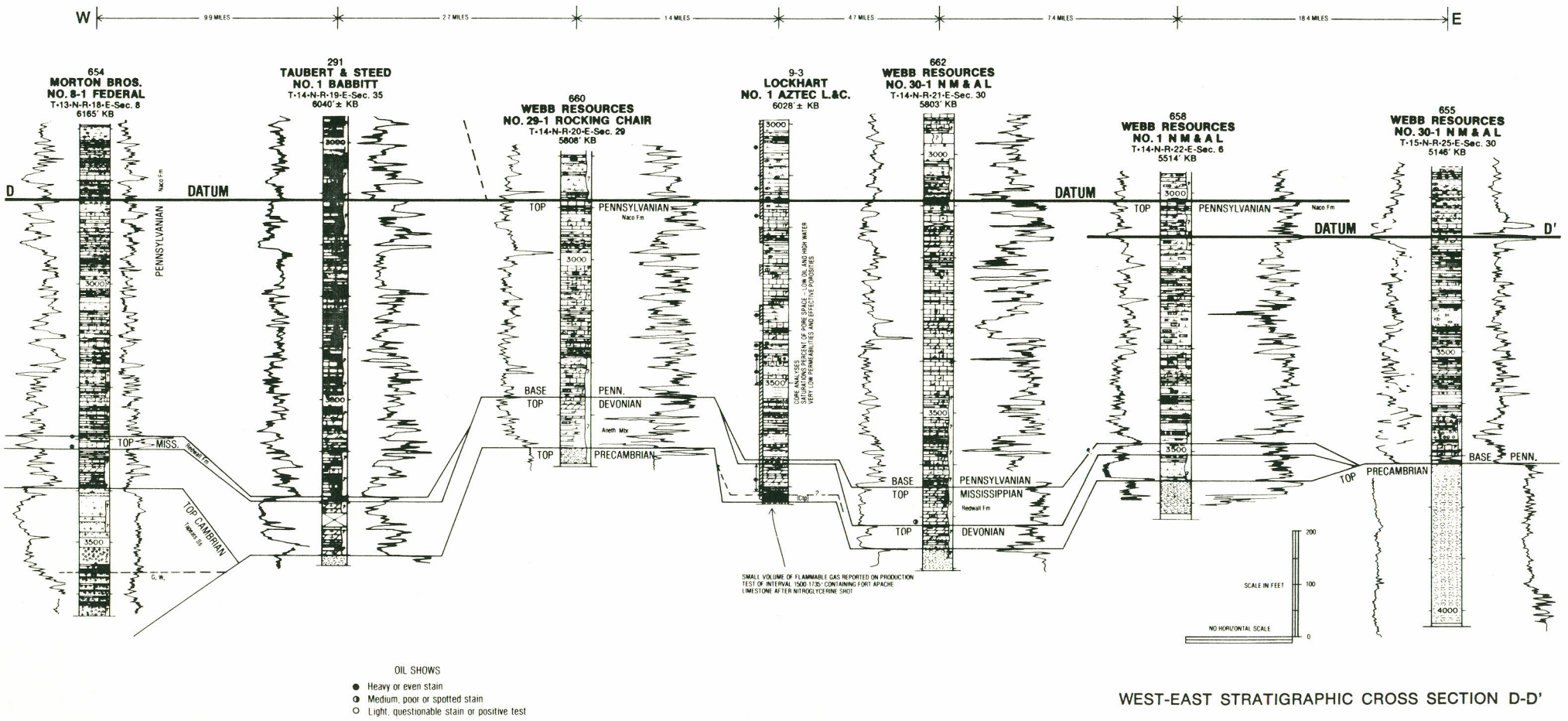


Figure 15.- West-east stratigraphic cross section D-D'. (Location of section and wells shown on figure 11. See figure 16 for Devonian Elbert Formation nomenclature. Log lithology from American Stratigraphic Company.)

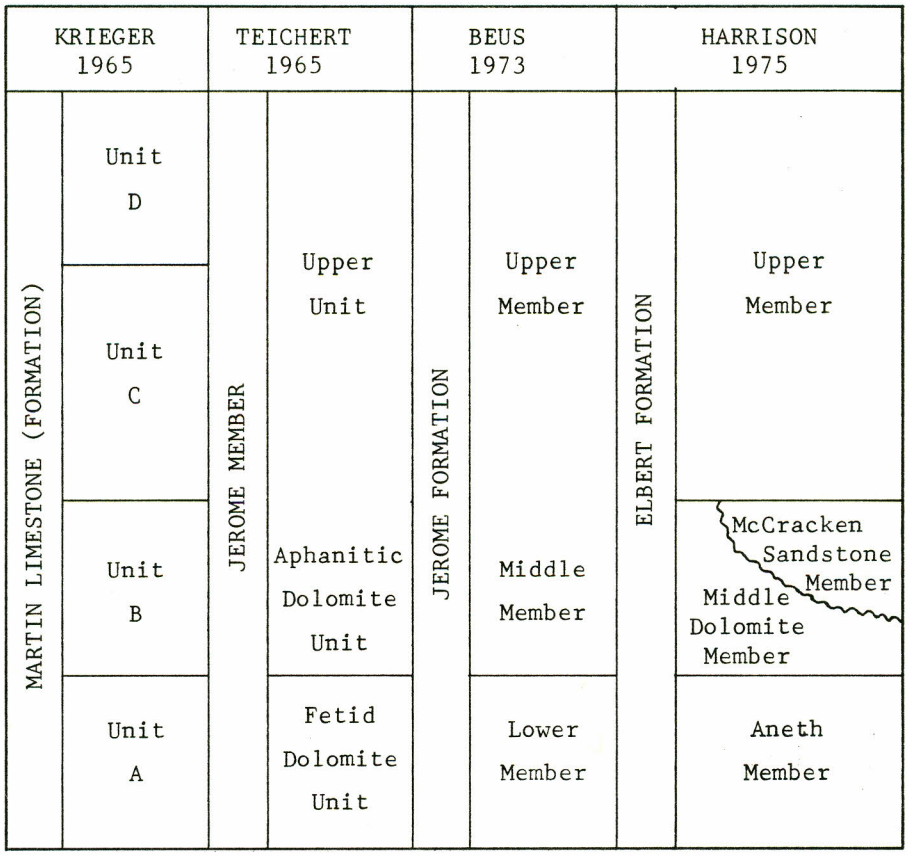


Figure 16.- Nomenclature applied to pre-Ouray Devonian strata. Harrison (1975) believes "the Aneth Formation...is equivalent to the lower member of the Jerome Formation as defined by Beus (1973)...they are both aphanitic dolomites. Beus describes the lower member as being dark to medium gray and strongly fetid." According to Harrison, in the Four Corners-Black Mesa region, "the Aneth is dark gray and fetid in some core chips. At the type section in the Paradox Basin the Aneth is described as a dark argillaceous dolomite (Parker and Roberts, [1966]). Both the Aneth Formation in Black Mesa Basin and lower member of the Jerome Formation are laminated and contain no fossils in Arizona. Thus on the basis of composition, lithology, and stratigraphic position, the Aneth Formation is equivalent to the lower member of the Jerome Formation."

pinchout of black carbonaceous shales southward toward the Mogollon slope indicate the probable absence of these principal oil-generating source rocks.

The gross area considered to have moderately good to good potential for Devonian hydrocarbon accumulations in the south-central and northeast parts of the study region is shown on figure 5. The McCracken sandstone present in this area could be a good reservoir for both paleostructurally and paleostratigraphically controlled accumulations. The possibilities of the latter type of trap appear to be very attractive along the zero thickness line on the flanks of the Defiance positive.

Drilling exploration in the southern part of the report area has not indicated a good potential for Paleozoic hydrocarbons. However, the interior portions of the local Devonian basins adjacent to the Mogollon Rim have not been explored. The objective reservoir would be a porous dolomite at the top of the Aneth, which is conjecturally present in these basins.

Primary production methods normally recover less than 30 percent of the oil in reservoirs. Water in the quantities required is not available in northeastern Arizona for the commonly used water-flooding secondary recovery method. One tertiary method using carbon dioxide is being used successfully in recovering oil left in place by primary and secondary methods. Picard and others (1960) and Picard (1962) have reported on the uncommon amounts of carbon dioxide, nitrogen, and helium occurring in carbonates of Pennsylvanian and Mississippian age in the Four Corners region. Numerous wells in the Arizona portion of this region have tested appreciable volumes of these inert gases. If available in sufficient volume and economic factors are favorable, these gases might be used in recovering much of the oil that will be left in place by primary recovery methods in the currently productive pools.

In conclusion, the northeastern part of the report area offers very favorable opportunities for more oil and gas accumulations. This is particularly the case for new discoveries in the Pennsylvanian section. Finding these new pools will be dependent upon the result of detailed stratigraphic studies of the various zones in the Hermosa Formation and their relation to structure. Most of the hydrocarbon accumulations found will probably be comparable to those near the Utah state boundary, but the possibility exists that there are some unique accumulations similar to Dineh-bi-Keyah.

The favorability of other potentially hydrocarbon-productive areas cannot be evaluated adequately with the subsurface information currently available. Additional geologic studies, geophysical mapping, and exploratory drilling is needed. The most attractive potentially productive area appears to be the central and north portions of the Oraibi trough. The Devonian McCracken Sandstone possibly offers an oil-bearing reservoir in both structurally and stratigraphically controlled traps in this trough.

GEOTHERMAL ANOMALIES

by

Salvatore Giardina, Jr.

General Statement

This report is based on a study of temperature data abstracted from the records of 450 water wells. The study was undertaken to: 1) identify thermal gradient anomalies potentially prospective for geothermal energy resources; 2) present graphically the spatial relationship of identified thermal gradient anomalies to the location of known surface structures, inferred subsurface faults, lineaments, and geothermally anomalous localities and regions determined by previous studies; and 3) process and present the data in a format suitable for use by other workers.

Data Quality

True geothermal gradients, representing the rate of temperature increase in the Earth with depth, require accurate temperature and depth measurements after establishment of thermal equilibrium. Most of the well completion records available lack these accurate measurements. The temperature gradients have been calculated from the limited amount of data contained in the records and, therefore, are called thermal gradients.

In many instances these data are very incomplete. The records of most water wells reflect only a measurement of the temperature of the water at the wellhead and in many instances do not indicate the depth of the producing zone. Well perforations or open hole completions generally cover considerable intervals of water-bearing section. Consequently, the empirical value of the thermal gradients obtained under such conditions is apparent. In the case of no information as to the producing interval, it has been assumed that the highest recorded water temperature measured at the wellhead was produced from a zone at or near the total depth of the borehole. However, in the case of a dually completed well, this assumption may effect a conservatively low gradient if there is commingling of the water from the deep zone with that of cooler water from a shallower zone.

Temperature-Gradient-Depth Profile

In order to identify thermal gradient anomalies based on the preponderance of relatively shallow well temperature data, a maximum gradient profile has been constructed for the study area (fig. 17). This profile generally demarcates the magnitude of the highest gradient values indicated by a plot at any given depth. Data plotting to the left of this profile may be considered to be anomalous. A maximum temperature profile corresponding to the constructed maximum gradient profile is also shown. This profile may be interpreted as the limiting profile of the maximum expected temperatures corresponding to the maximum gradient profile.

Figure 17 may be used to estimate whether similar nonequilibrium temperature data, furnished by new wells, are indicative of thermal anomalies. It is apparent on the illustration that the temperatures of many wells completed at depths shallower than 150 meters will exhibit gradients greater than 60°C/km. The gradient of most of these wells will invariably decrease with depth and the corresponding temperatures will plot to the left of the maximum temperature profile. Therefore, an estimate of whether a new temperature data point represents a thermal anomaly (relative to the data set) is obtained by plotting it on the maximum temperature profile chart. Data plotting on or to the right of this profile may be considered anomalous. This appraisal method was used in this report to identify potential thermal anomalies based solely on well temperature and depth data. The anomalous wells are listed in table G.

The study area is also characterized by very high gradient shallow wells (<70 meters). Thermal gradients of most of these wells are expected to decrease with depth as shown on figure 17. However, those shallow wells exhibiting exceptionally high gradients (>98°C/km) were isolated (table H) in order to study their spatial distribution. The thermally anomalous wells, shallow wells with very high thermal gradients, and thermal springs (table I) are shown on figures 8, 9, and 18.

Data Interpretation

Computation of thermal gradients based on the reported water temperatures and depth data of numerous shallow wells frequently produce abnormally high values which invariably are not characteristic of *in situ* temperatures existing at greater depths. The computed gradients within the upper 150 meters exhibit an extremely wide variation, generally ranging from 20 to over 300°C/km. A plot of the calculated thermal gradients (fig. 17) shows that the magnitude of the maximum calculated gradients decreases rapidly from the surface to depths of about 100 to 150 meters. A comparison of the plotted data for Apache, Coconino, and Navajo Counties indicated that the gradient-depth distribution appears similar. In addition, the profile of the maximum temperature curve alludes to local temperature inversions within the uppermost 75 meters. This characteristic is similar to that observed in temperature curves representative of the Basin and Range province (Giardina and Conley, 1978). However, the zone of temperature inversion is closer to the surface in the Plateau province. The maximum expected temperatures in the study area average about 15°C cooler than Basin and Range temperatures at depths of 400 to 500 meters. Correspondingly, the entire maximum temperature profile (fig. 17) for the Plateau is displaced to the left (lower temperatures) relative to similar curves for the Basin and Range province.

Within the study area, a mean thermal gradient of 22.5°C/km was calculated for 173 water wells whose depths ranged between 150 and 670 meters. This is contrasted with a mean thermal gradient of 31°C/km calculated for the Basin and Range province of Arizona (Giardina and Conley, 1978). The approximate average geothermal gradient in the Earth's crust is about 25°C/km (American Geological Institute, 1972).

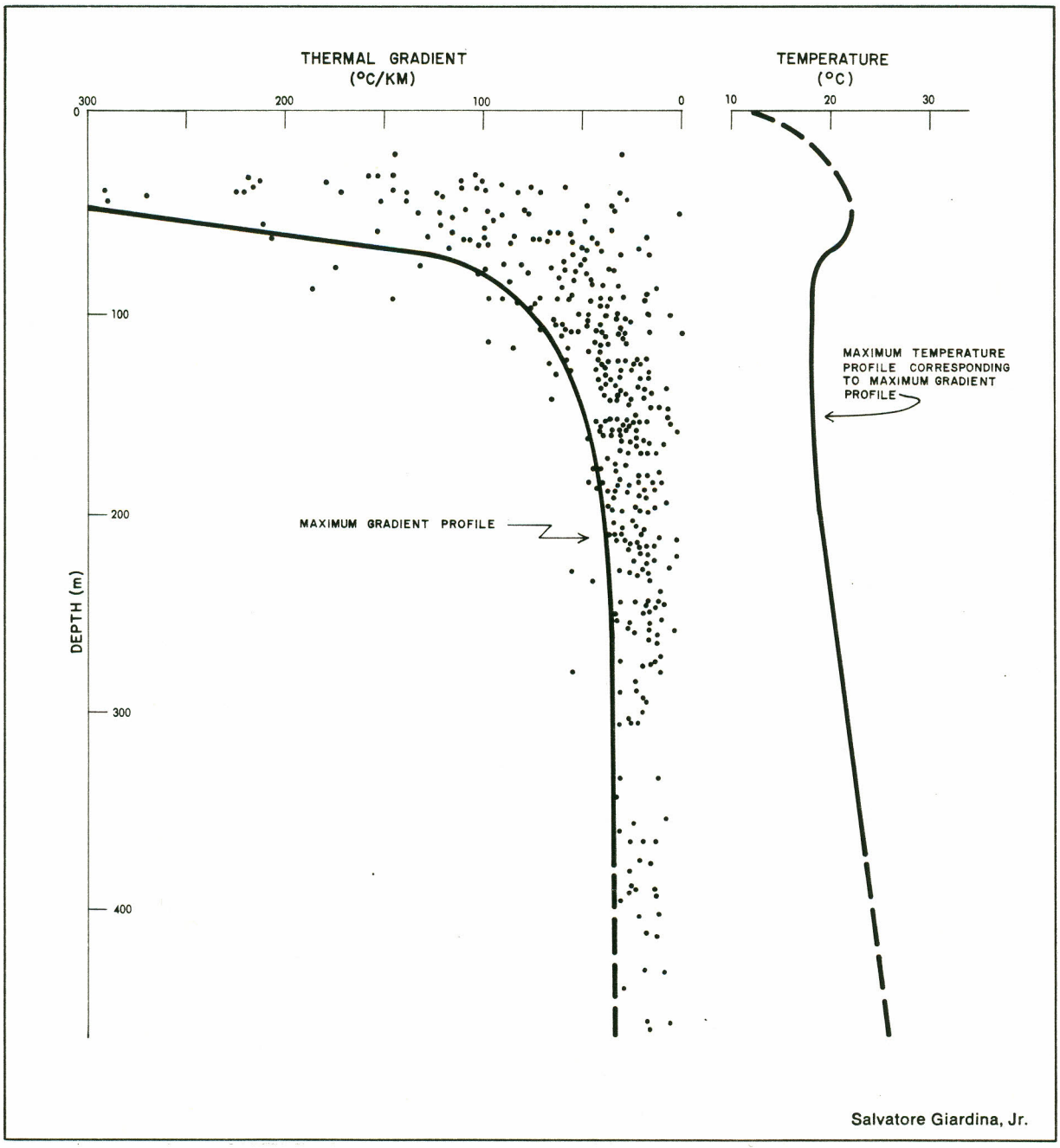


Figure 17.- Maximum gradient and temperature profiles based on plot of calculated thermal gradient data of water wells in northeastern Arizona.

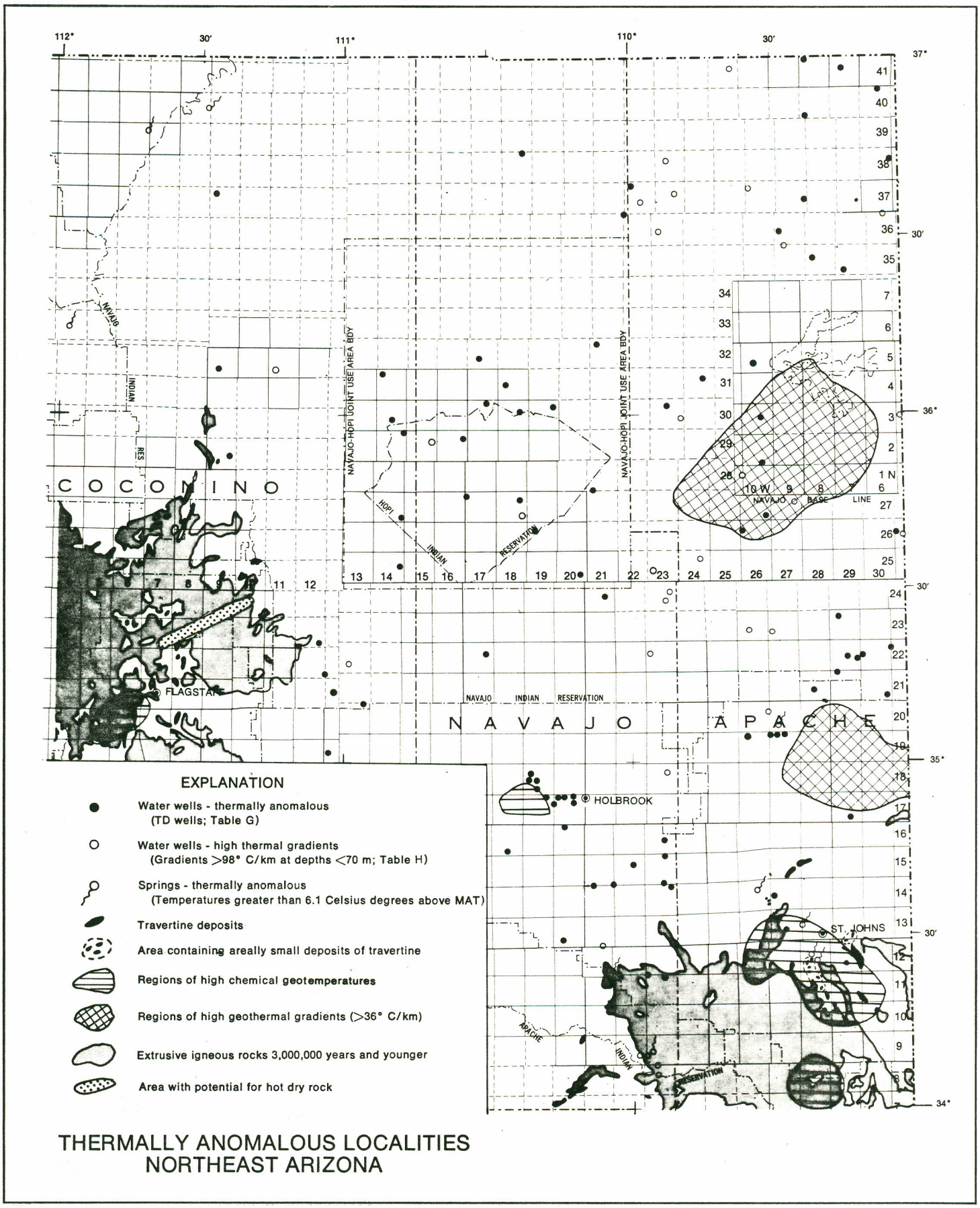


Figure 18.- Map showing location of thermally anomalous localities in northeastern Arizona. (Data sources: Travertine deposits, from Akers, 1964; regions of high chemical geotemperatures and high geothermal gradients, from Swanberg, 1977, p. 27; extrusive igneous rocks, from Damon and others, 1978; and hot dry rock, from Wolfe and others, 1977.)

Geographic Distribution

The spatial distribution of identified thermal anomalies, shallow high-gradient wells, and thermal springs is illustrated in figures 8, 9, and 18. Interpretation of this distribution and synthesis of data from a similar analysis conducted in the Basin and Range province (Giardina, 1978) have permitted the following observations: 1) most Plateau thermal anomalies are spatially associated with known surface structures, inferred basement fracture zones, or lineaments; 2) temperature-gradient-depth curves for both the Basin and Range and Plateau provinces are similar; and 3) most thermal anomalies of the Basin and Range province of Arizona are related to major basin margin faults.

It is tentatively concluded, therefore, that the common factor is probably the existence of deep-seated fault control. Thermal anomalies of the study area may be produced by local upwelling of warm water through the mechanism of hydrothermal convection along deep crustal fractures. Many basement fractures partially extend into the Phanerozoic cover as discrete faults. Permeable fracture zones are also conceived as having been formed above basement faults in response to deformation of the sedimentary section.

Mundorff (1970) made a similar observation regarding the thermal springs of Utah:

> ...Nearly all thermal springs in Utah are in or near fault zones. Very few of these springs issue from volcanic rocks, but several springs are close in areas of late Tertiary or Quaternary volcanic rocks.

Additional indirect data which alludes to potential fault control for most anomalies is indicated in figure 17. The shallow temperature inversion noted on the maximum temperature profile is postulated to result from rising thermal waters along faults and subsequent mixing and lateral migration of thermal waters in the shallow aquifers. Anomalies which are not spatially associated with known or inferred structures could conceivably represent wells which intercept warm waters that have migrated a considerable distance from the thermal source. This is particularly relevant to the shallow, high-gradient wells. About half of these wells are not located near known structures but their shallow depth places their producing intervals within the warm zone of temperature inversion. The deeper anomalous wells exhibit a greater correlation with structures (table 2).

Inspection of figure 8 indicates that most of the thermal anomalies are located on or near surface structures or inferred fracture zones. Table 2 delineates the spatial association of all anomalies. Of the 123 plotted anomalies, 45 did not appear to be located near structures. However, 25 of the latter lie on or near a major lineament or inferred basement fault, indicated in figure 9.

Hot Dry Rock - San Francisco Volcanic Field

The southwest portion of the study area is characterized by a potential hot dry rock (HDR) geothermal resource. The resource lies within the central portions of the San Francisco volcanic field. Several anomalous

	Thermal Anomalies	Shallow Wells >98°C/km	Thermal Springs
Anticlines	33	5	7
Synclines	7	2	
Monoclines	7	2	1
Inferred Fractures	11	3	
No association	28	16	1
Total	86	28	9

Table 2.- Spatial distribution of thermal anomalies with respect to structural elements and fracture systems shown in figure 8. Twenty-five of the 45 anomalies in the "no association" category are situated on or near major LANDSAT lineaments shown in figure 9.

water wells, identified in this report, are located on the eastern perimeter of the field near Tolchaco anticline (T. 22 N., R. 12 E.); but their association with the HDR prospect, if any, is unknown.

Geothermal data pertaining to this area appears to be limited to a report of the U.S. Geological Survey which was published by the Energy Research and Development Administration (Wolfe and others, 1977). Information contained herein was obtained from this report.

The potential geothermal resources of the San Francisco volcanic field consist of two localities underlain by a pluton or magma chamber. The two sites have been identified through surface mapping, radiometric age dating, and Bouguer gravity and aeromagnetic data.

The younger site, near Sunset Crater, consists of a linear zone aligned between two silicic volcanic peaks. Rhyolite domes and rhyodacite plugs within this zone range between 16,000 and 230,000 years old. In addition, the presence of the Recent basalt vent of Sunset Crater as well as other evidence indicates a youthful age for this portion of the field. A linear magnetic low and a weak gravity low coincide with these vents which is interpreted to record the presence of low density silicic rocks within the shallow crust. These rocks may have a low magnetic susceptibility or high temperature but current data is not conclusive.

A second site is located northwest of Sunset Crater in the Sitgraves-Kendrick Peaks area. The site exhibits a belt of rhyolitic domes which coincide with a distinct gravity low. The domes range in age between 2.8 and 1.1 million years old. Petrographic examination of xenoliths within rhyolite ash units indicates that the pluton is at least one to two kilometers below the surface.

Hydrothermal Waters - St. Johns Area

A potential geothermal resource area is located in the general vicinity between St. Johns and Springerville (T. 9 N., R. 29 E.). Swanberg and others (1977) and Swanberg (1978) consider this region as a "prime prospect." They report chemical geotemperatures in excess of 150°C.

Seven anomalies have been identified in this study within the area containing Townships 12 to 14 North and Ranges 24 to 31 East. Five anomalies are located on or near anticlines; two are aligned between the axial extension of local structures. The three anomalous water wells exhibit an approximate thermal gradient varying from 46 to 60°C/km and are 116 to 122 meters deep (table G). Of the four thermal springs, three issue from travertine deposits. Stinking Spring (T. 14 N., R. 26 E.) was observed to flow from a Quaternary travertine cone at the rate of about 40 gpm (Harrell and Eckel, 1939). The spring is located on the west limb of the Apache Dome (Hunt) anticline, a broad open dome that plunges 6° NW and 3° SE.

The Salado Springs (T. 12 N., R. 28 E.) comprise several springs along the Colorado River that yield water from crevices in travertine. The springs are located on the southwest limb of Cedar Mesa anticline in close proximity to a fault which parallels the structure. Akers (1964) reports that the fault is downthrown on the southwest about 75 feet and has diverted the Little Colorado River for about a mile. The fault is part of a lineament that extends 14 miles southeast to Voight Mesa.

The association of travertine deposits with local structures in the St. Johns-Springerville area is common. An example is the Buttes (St. Johns) anticline, located seven miles southeast of St. Johns. The structure trends N. 20° W. and is asymmetrical with dips of 20° on the west limb and 8° on the east limb. The west limb is modified by a monoclinal flexure. It appears that logitudinal joints, fractures and (or) a subsurface fault may have localized ascending lime-bearing hydrothermal fluids along the monocline. The anticlinal flexure of the monocline is overlain by a row of buttes capped by travertine (Sirrine, 1958). The synclinal bend exhibits small depressions which are attributed to groundwater solution of the Permian San Andres Limestone and collapse of the overlying strata.

The relationship between basement rock structure and surface structures in the St. Johns-Springerville are has not been fully determined. Current geophysical maps lack sufficient detail to clearly define basement structure. However, existing data strongly suggest that, locally, surface structures have been influenced by displacements within basement rocks.

It is significant to note that the structural fabric of the St. Johns-Springerville area is dominated by many subparallel, northwest-trending elements. The alignment of folds, faults, lineaments, travertine outcrops, joints, and subsurface structure contours strongly suggests common structure control of significance to geothermal exploration. Fold axes within the cited area and those also located north and northwest of St. Johns represent the major structural elements. In addition, both the axes and associated faults of the Cedar Mesa and Antelope Valley anticlines are colinear, with an extensive, elongated outcrop of travertine (Voigt Mesa) aligned between the two structures.

The aeromagnetic and geologic basement configuration maps (pls. 5 and 4) indicate a basement fault and positive closure directly below the Antelope Valley anticline (pl. 1). Structure contours on the Permian Coconino Sandstone (Conley and Scurlock, 1976) also strike northwest, parallel to the alignment of the local structural elements.

Numerous late Tertiary and Quaternary travertine outcrops are found in the general vicinity of St. Johns (Akers, 1964, pl. 4). Most of these deposits are apatially associated with anticlines, but small erosional remnants are also prevelant. Most of the deposits form cones or a series of coalesced cones. In places, travertine outcrops cap hills and are known to extend below the surface to considerable depths. Harrell and Eckel (1939) believe the deposits were formed by hot spring activity which began during late Tertiary time. It is probable that current deposition of travertine represents a waning phase of once much more extensive hot spring activity.

The presence of the Quaternary White Mountain volcanic field southwest of the St. Johns-Springerville area is encouraging. A warm to hot pluton may exist below the field in the upper crust. It is possible that the association of extensive travertine deposits with local faults and folds, located on the present perimeter of the volcanic field, is the result of hydrothermal convection of heated groundwaters upwelling along permeable faults or fracture zones within the Phanerozoic cover.

Although surface thermal activity has apparently decreased, it is conceivable that significant geothermal resources could be found below the general perimeter of the field, southeast of St. Johns or surrounding Springerville. Geothermal heat could potentially be found in hot dry rock or as hydrothermal fluids, localized along structure controlled conduits.

Considerable additional subsurface data is needed, however, to determine if a significant resource exists and to delineate the subsurface structure and hydrologic regimen of the area.

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APPENDIX

EXPLANATION FOR TABLES A, B, AND C

Table A.- Oil and gas test holes used for control on structure and isopach maps

Columns, left to right

1. Map number and Oil and Gas Conservation Commission identification number
2. The geographic base used for well location is the appropriate Public Land Survey, Township (T)-Range (R)-Section (S)
3. Operator. The name of the company responsible for the drilling operation at the time the well reached total depth

   Number. Well number designated by original operator

   Lease. Normally the name of the owner of the mineral rights is listed. In some instances the name of the owner of the surface rights and (or) the original leasee is also listed.
4. Elevation. Land surface altitude (feet above mean sea level) Ground level elevations indicated by letters "GL." All other elevations are referenced to the kelly bushing or derrick floor.
5. Sea level datum. Top of undifferentiated Permian Coconino Sandstone (Pco) or De Chelly Sandstone (Pdc). All datums above sea level.
6. Sea level datum. Top of Mississippian Redwall Formation (Mrw) Minus sign (-) shown for datums below sea level
7. Drilled thickness. Mississippian Redwall Formation (Mrw)
8. Drilled thickness. Undifferentiated Devonian rocks (Du)
9. Drilled thickness. Cambrian rocks (Є)
10. Sea level datum. Precambrian rocks (PЄ) Lithology suffix: Ia, igneous acidic; Ib, igneous basic; I, igneous undifferentiated; Ir, igneous residue; Gw, granite wash; M, metamorphic undifferentiated; and Q, quartzite undifferentiated but with a few questionable exceptions of Precambrian age

Table B.- Stratigraphic test holes used for control on Permian Coconino-De Chelly structure map

Data presented in this table restricted to Permian Coconino-De Chelly structural control

Table C.- Water wells used for control on Permian Coconino-De Chelly structure map

Data presented in this table restricted to Permian Coconino-De Chelly structural control. Projected datums of wells not penetrating Coconino or De Chelly sandstones are indicated by the letter suffix "P."

Table A.— Oil and gas test holes used for control on structure and isopach maps

MAP NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	ELEV. (ft.)	Pco/Pdc DATUM	Mrw DATUM	Mrw TH.	Du TH.	Є TH.	PЄ DATUM
APACHE	COUNTY ...	Townships North, Ranges East							
66	9-31-20	Belcher 1 State	7274	6204					4366 M?
370	10-24- 4	Tenneco 1 Federal-B	6865	5843	2467	92	140		2235 Q
207	10-30-27	Eastern 1-A Coyote Creek	6962 GL	6486					4641 Ia
375	11-28-22	Tenneco 1 Federal-C	6064	5553					
159	11-31-29	Ram 1 State	7090 GL	6490?					
100	12-31- 9	Townsend 1 Federal	6258 GL	5681					
98	13-25-12	Pan American 1 NM&AL-A	5888	5685					2254 M
1-3	13-27-28	Greer 1 State	5970 GL	5378					
1-6	14-26-14	Franco-Arizona 1 Govt	5672 GL	5472					3117 Ia
655	15-25-30	Webb 30-1 NM&AL	5416	5742					1698 Ia
339	15-26-31	Grimm 1 Platt	5472 GL	4984					
1-11	15-29-22	Argo 1 State	5738 GL	5303					3388 M?
1-13	15-30-33	Hinkson 3	6090 GL	4791					
365	16-25- 5	Eastern 1 NM&AL	5595 GL	4980					
373	- 9	Eastern 3 NM&AL	5550 GL	4984					
442	17-26- 3	Crest 1 Spurlock	5971	4927					2371 Ia
57	18-25-23	Kerr-McGee 1 Hortenstine	5597	4979					2173 Ia
180	18-29-16	Martin 1 State	6491 GL	4321E					
120	19-25- 2	Sierra 1 State	5608	4635					
190	-36	Busby 2 State	5510 GL	4780					
78	19-26- 6	Eastern 1-6 State	5663	4713					
80	-10	Eastern 1-10 State	5743	4769					
262	-20	McCaughey 1 Sunland-State	5595 GL	4742					
449	-36	Hallett 1 State	6048 GL	4698					
206	19-27- 5	Eastern 14 Santa Fe	5801 GL	4771					
109	- 9	Eastern 3 Santa Fe	5898	4732					
229	-12	Eastern 19 Santa Fe	5985 GL	4585					
150	19-28- 9	Eastern 5 Santa Fe	5930 GL	4160					
586	19-29-29	Eastern 1 Santa Fe-Surprise Creek	6380 GL	4393					
99	20-25-22	Texas American 2 Fitzgerald	5763 GL	4442					
147	20-26- 9	Linehan & Stoltenberg 1 Spurlock-Wetzler	5750 GL	4551					
88	-28	Eastern 1-28 State	5705	4771					
36	-34	Apache O&H 3 Macie-State	5779 GL	4778					
276	20-27- 3	Eastern 28 Santa Fe	5732 GL	4709					
108	- 7	Eastern 2 Santa Fe	5776	4646					
237	-13	Eastern 18 Santa Fe	5833 GL	4498					
255	-29	Eastern 31 Santa Fe	5690 GL	4698					
140	-34	James Brown 1 Santa Fe	5857	4647					
601	20-28-11	Eastern 1-11 Santa Fe	6172 GL	5153					
282	-29	Eastern 30 Santa Fe	5903 GL	4393					
505	21-25-25	Thoureen (Eastern) 1 Navajo	5866 GL	4616					
504	21-26-27	Thoureen (Eastern) 1 Santa Fe	5871 GL	4661					
567	21-28-21	Eastern 1 Santa Fe-Chambers	5796 GL	4957					
74	-27	Brown & Assoc 2 Chambers-Sanders	5816	5256					3711 Ia
218	21-29-31	Eastern 16 Santa Fe	6085 GL	5315					
1-76	23-30-24	Hogback 1 Tufts	7210 GL	7060					5700 Ia
510	29-24-21	Gulf 1 Navajo-CZ	6175	4295			125		1675 Ia
1-77	31-23- 3	Amerada-Stanolind 1 Black Mtn-Navajo	6333	3973	1161	99	282	194	586 Ia
438	34-28- 4	Gulf 1 Navajo-4	6509	6363	4515	156	455	25	3878 M
308	35-22- 2	Tenneco 1 Navajo-8939	6111	3244	293	229	513	194+	
526	35-27-31	Buttes 1-31 Navajo-1576	5880	5880	4087	207	424	24	3432 Ia
354	35-28- 5	Buttes 1 Navajo-8850	5835	5835?	3450	180	405	23	2842 M
461	-25	Buttes 1-25 Navajo	6359	6159	4006	202	415	12	3377 M
463	35-29- 1	Pan American 1 Navajo-AE	8576	5540	2867				
594	-15	Eastern 1 Chuska-Mtn Fuel	6791	5751	3426				
478	-25	Little & Richardson 1 Tohotso Navajo	7076	5951	3688	211	232	8	3237?Ib
395	35-30- 3	Anadarko 1-135 Navajo	8143	7011	4579	209	327	15	4028 Ia
385	- 5	Kerr-McGee 2 Navajo-B	8509		4452	101	374	8	3969 Ia
381	- 5	Kerr-McGee 1 Navajo-B	8503	6879	4473				
388	- 6	Humble (Kerr-McGee) 1 Navajo-138	8278	6925	4525	139	378		4008 Ia
400	- 6	Humble 2 Navajo-138	8374	6481	3838				
393	- 8	Humble 1 Navajo-140	8635	6993	4403	165	333		3905 Ib
501	-10	Odessa 1 Aircodessa-Navajo	9310	7143	4734	184			
426	35-30-14	Kerr-McGee 1 Navajo-H	9044	6620	4294	121	362	97	3714 M
452	-15	Humble 1 Navajo-146	8775		5313	198	378		4737 Ia?
454	-35	Humble 1 Navajo-151	8793	7611	5371	124	365		4926 Ia
325	36-22-14	Cactus 1 Navajo	5923	3019	180	207	560		- 708 Ia
345	36-24-23	Cactus 1 Navajo	5604	3529	534	160	366	121	6 M
494	36-27-30	Riddle & Gottlieb 1 Navajo	5363	4825	1935				
435	-30	Simmons 1 Navajo	5403	5053	2803	180			
612	36-28- 3	American Fuels 1 Navajo-O	6320	4870	2440				
300	- 6	Blackburn 6-1 Navajo	5993	5023	2389	200		35	1693 Q

Table A.— Oil and gas test holes used for control on structure and isopach maps — Continued

MAP NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	ELEV. (ft.)	Pco/Pdc DATUM	Mrw DATUM	Mrw TH.	Du TH.	Є TH.	PЄ DATUM
APACHE COUNTY ...		Townships North, Ranges East (continued)							
549	36-29- 4	Union Oil 1-P-4X Navajo	6584	6030	3636				
519	-11	Union Oil 1-N11 Navajo-Lukachukai	7197	6257	3900	101	442	21?	3357 Ia
522	-17	Union Oil 1-M17 Navajo	7705	5106	2667				
401	-23	Humble 1 Navajo-87	8980	6412	4071	109		24	3513 Ia
427	-24	Kerr-McGee 1 Navajo-F	8499		4087				
431	-25	Humble (Kerr-McGee) 2 Navajo-88	8512		4206	54	435	22	3695 Ia
447	-25	Humble (Kerr-McGee) 4 Navajo-88	8670	6608	4216				
421	-25	Humble (Kerr-McGee) 1 Navajo-88	8175	6765	4377				
595	-32	Eastern 2 Chuska-Mtn Fuel Navajo-122	6530	5454					
443	-36	Humble (Kerr-McGee) 3 Navajo-88	8334	6890	4505				
545	36-30- 6	Union Texas 1-6 Navajo	6620	5650?	3055				
571	-19	Republic Mineral 2X Navajo-E	8633	6432					
398	-20	Kerr-McGee 1 Navajo-E	7027	6393	3776	149	394	69	3164 Ia
391	-29	Kerr-McGee 8 Navajo	7177		4084	121	365	68	3530 Ia
446	-30	Kerr-McGee 10 Navajo	7370		4090	108	382	81	3519 Ia
396	-30	Kerr-McGee 9 Navajo	7894	6688	4229				
420	-31	Kerr-McGee 13 Navajo	8919		4533				
392	-31	Kerr-McGee 5 Navajo	8534		4456	135	336	57	3928 Ia
303	-32	Kerr-McGee 1 Navajo	7573	6973	4403	101	373	46	3883?
422	-33	Kerr-McGee 2 Navajo-C	7981	6973	4171	116	366	76	3613 Ia
455	37-25- 4	Champlin 1 Navajo	5205	3475	475	168			25 Q
311	37-27- 8	Blackburn 8-1 Navajo	5539	4389	1199	165	445	36+	
476	-23	Buttes 1-23 Navajo	5791	4623	2058				
520	37-28-24	Buttes 1-24 Navajo	6677	5291	2823				
538	-32	Little 1 Aircodessa-Petes Nose-Navajo	6205	4762	2275				
491	37-29-12	Gulf 1 Navajo-BS	5985	5121	2455	160	165		2130 Ia
544	-14	Union Texas 1-14 Lukachukai-Navajo	6220	5150	2582				
575	-16	Little 1-16 Navajo	6356	5056					
563	-22	Little 1-22 Navajo	6451	5131	2696				
489	-33	Odessa 1 Aircodessa-Cove-Navajo	6440	5866	3430	100	425	52	2850 Ia
298	-35	Blackburn 35-1 Navajo	6257	5832?	3249	195	397	32	2625 Ia
507	-34	Gulf 1 Navajo-CS	6057	4851	2121	161	433	15	1467 Ia
433	38-22- 1	McCulloch 1-1 Navajo	5654	2974					
593	38-23-13	Tesoro 1 Navajo-Davis	5278	3138	30				
280	38-27-20	Pan American 1 Navajo-T	6258	4393	1094	232	400		462 Ia
415	38-29-16	Pan American 1 Navajo-V	6595	5668					
497	38-30- 2	Depco 4-2 Navajo	6324	4991	1814	200			
468	-12	Pan American 1 Navajo-AF	5881	5030	1231				
423	-18	Skelly 1 Navajo-Q	6713	5083	2060	222			
316	-32	Pure 1 Pure-Sun-Tidewater-Navajo 103	5922	5017	231				1572 Ia
292	39-23-12	Superior 22-12 Navajo-V	5228	3104	- 115	306	572	24	-1017 M
265	-12	Superior 33-12 Navajo-V	5232	3100	- 78	360	523	67	-1028 M
412	-24	Horizon 1-24 Navajo-Mobil	5237	3237	- 107	331	590	178	-1206 M
297	39-24- 7	Amerada 1 Navajo	5195	3182	- 197	401	584		
382	39-25-16	JCM Drlg 1 Navajo-Mobil	5043		8	261	64	138?	- 455 M
272	-28	Socony-Mobil 1 Navajo	4982	3352	38	291	285	60	- 598 M
305	39-26-19	Cactus 1 Navajo-Rock Point	5375	3422	43	238	520?	32?	- 715
503	39-29- 1	Monsanto 1 Carrizo-Navajo	8914	5824	774	230	60+		
247	40-24- 8	Pan American 1 Navajo-Q	5116	3136	- 496	348	625	32+	
271	40-25- 6	Texaco 1 Navajo-AK	5016	2916	- 644	340	599	151+	
60	-11	Pan American 1 Tohlacon-Navajo	5308	3408?	- 142	358	542	190	-1232 M
95	40-26-20	Texas Pacific 1 Navajo-190	5322	3367	- 118	335	530	119+	
145	-30	Bonanza 1 Navajo	5346	3291?	- 84	374	514		-1167 M
261	40-27- 6	Occidental 1 Texaco-Navajo	5294	3174	- 587	286	578	50+	
213	40-28- 1	Pure 5 Navajo-138	5926	3556?	486				
115	- 2	Texas Pacific (Monsanto) 3 Navajo-138	5688		508				
179	- 6	Pan American 1 Navajo-F	6595	3212	- 404	255	64		- 723 Q
513	- 9	Little 1 West Dry Mesa-Navajo	5849	3359	185	291	59		- 136 Q
77	-11	Texas Pacific (Monsanto) 1 Navajo-138	5953	3603	518	273	58		215 M
116	-11	Texas Pacific 4 Navajo-138	5960	3593	448	253	23		172 Q
106	-12	Texas Pacific (Monsanto) 2 Navajo-138	5980		513	250	33		230 Q
628	-16	Fee O&G 1 Navajo	5776	3413	116	262	178	64	- 388 Q
138	-17	Western States 2 Navajo	5762	3352	- 28	228	297	15	- 568 Q
94	-18	LaRue 1 Navajo	5592	3212	- 553	275	445		-1273 Q
610	40-29- 6	American Fuels 1 Navajo-C	5583 GL	3473	- 161	260	483	23	- 927 Q
146	- 7	Atlantic Refining 7-1 Navajo	6029	3659	563	244	60		259 Q
176	-15	Pan American 1 Moko-Navajo	6076	3586	485	222	44		219 Q
598	-15	Universal Resources 1-15 Navajo	6148	3616	539	166			
581	-16	Cities Service 1 Monsanto-Navajo-C	6104	3666	534				
615	-17	American Fuels 1 Navajo-AC	6150	3650	525	265	230		32 Q
274	-18	Marathon 1 Navajo	6604	3534	490				
559	-21	Cities Service 1 Monsanto-Navajo-A	6396	3649	524				
566	-27	Cities Service 1 Monsanto-Navajo-B	7289	3623	451	192	19		173 Q
546	40-30- 2	Depco 1-2 Navajo	5383	2623	- 914	363	478	87	-1842 Ia
105	- 5	British American 1 Navajo-C	5545	3045	- 323	285	222		- 840 M

Table A.— Oil and gas test holes used for control on structure and isopach maps — Continued

MAP NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	ELEV. (ft.)	Pco/Pdc DATUM	Mrw DATUM	Mrw TH.	Du TH.	Є TH.	PЄ DATUM
APACHE COUNTY ... Townships North, Ranges East (continued)									
290	41-22-12	Occidental 1 Monument-Navajo	4844		3268	481	603	369+	1784 P
1-78	41-23- 7	San Juan (Midwest) 1 Navajo	4881		3201	401+			
248	41-24-16	Gulf 1 Garnet Ridge-Navajo	5176	3216	- 559	386	648+		
226	41-25-16	Texaco 1 Navajo-AG	4870	2972	- 734	326	595?	40	-1655 M
295	-17	Great Western 2 El Paso-Navajo	4860		- 797	371	402?	27+	
245	-20	Great Western-Moncrief 1 El Paso-Navajo	4874		- 808	378	630	347	-2163 M
266	-21	Texaco 2 Navajo-AG	4868	2924	- 785	351	632	96	-1864 M
165	41-26-23	LaRue 1 Navajo	5505	2977					
50	-28	Gulf-British American 1 Walker Creek	5204	3425	- 373	315	529+		
260	-31	McDonald 1 Navajo	5125	3350	- 472	363	540+		
304	-33	Tenneco 1 Navajo-4332	5258	3442	- 277	351	546	168?	-1342?I
166	41-27-22	LaRue 2 Navajo	5454	2984					
31	-29	Hancock 29-1 Navajo	5666	3236	- 504	310	20+		
528	41-28- 1	Consolidated 1-1 Navajo-226	5710		- 412				
481	- 2	Consolidated 2-13 Navajo	5375	3285	- 296				
22	- 3	Shell 2 Navajo	5307	3414	- 198	282	538	14+	
490	- 3	Consolidated 3-4 Navajo	5343	3439	- 184				
28	- 4	Humble 1 Navajo	5375	3438	- 135	305	538	29+	
118	- 5	Humble 2 Navajo	5442	3434	- 666				
65	- 9	Humble 2 Navajo-E	5537	3201	- 461	320?			
32	-22	Franco Western 1 Navajo	5446		- 446				
205	-27	Franco Western 2 Navajo	5494	3194	- 436	280	49+		
613	-31	American Fuels 1 Navajo-E	6598	3198	- 969				
434	41-29- 4	Champlin 1 Navajo-335	5218		- 704				
18	- 6	Shell 1 Navajo	5248	3232	- 287	311	526	118+	
168	-22	LaRue 1 Toh Atin	5336	2806	- 734				
139	-29	Davis 1 Navajo-C	5445	2785	- 455	293	556+		
44	41-30-10	Superior 1 Navajo-H	4885		-1211	221+			
46	-16	Superior 2 Navajo-H	5126	2763	- 744	295			-1514?Q
128	-21	Superior 23-21 Navajo-M	5155	2600	- 805				
232	-23	Pan American 1 Navajo-O	5088	2698	- 927	280	461	36	-1704 M
425	-30	Miami 1 Navajo-41-54	5353		- 504	240			
637	-30	Northwest Pipeline 1 Navajo-Judy Lee	5477	2932	- 499	254	522+		
113	-36	Texaco 1 Navajo-Z	5286	2544	- 837	529			-1632 Ib
256	41-31- 7	Zoller & Danneberg 1 Navajo-161	5016	2285					
191	42-29-33	Davis 1 Navajo	5146	2913					
APACHE COUNTY ... Navajo Survey - Townships North, Ranges West									
1-87	2- 6-20?	Wilson-Cramer 1	7630?GL						6861
1-88	2- 9-15?	Wilson-Cramer 2	6450?GL						5655
499	4- 7-11	Gulf 1 Texaco-Navajo	7444	7389?	5641	92	281	104	5164 Ia
500	-36	Gulf 1 Navajo-BW	7568	7541	5898	63	269		5569 M
477	6- 6-20	Union 1 Navajo	7571	7029	5264	87	359		4818 M
429	6- 7-12	Gulf 1 Defiance-Navajo	7310		5269	104	407		4757 M?
448	-26	Texaco 1 Navajo-BF	7699	7207	5409	57	392		4963 M
496	-32	Gulf 1 Anadarko-Navajo	7421	6836	5130	109	322	18	4681 I
453	6- 8-26	Little 1 Bear Springs-Navajo	7414	7134	5437	58	251	4	5124 Ia
534	6-10-14	Union Texas 1-14 Navajo	5774	5558	3224	75	410	55	2684 Ia
432	7- 7- 7	Depco 1 Navajo	6783		4605	157	392	41	4015 I?
480	-15	Doherty 1-15 Navajo	7085	6670	4641	146	393		4102 I
430	-26	Texaco 1 Navajo-BC	7139	6672	4759	161	384		4214 Ib
428	-32	Pan American 1 Navajo-AB	7312		4937	140	448?		
437	7- 8- 4	Gulf 1 Agua Sal-Navajo	6562	6317	4533	121	462	44+	
439	-11	Gulf 1-11 Navajo	6709	6415	4630	109?	423?	40?	4058 Ia
440	-22	Gulf 1-22 Navajo	6875		4702	149	450?	15?	4089 Ia
466	7- 9-14	Buttes 1-14 Navajo	6307		4271	108	478	66	3617 Ia
531	7-10- 1	Union Texas 1-1 Navajo	5672		2750	108	375+		
529	-17	Union Texas 1-17 Navajo	5363	5133	2137	192		54	1443 Ia
COCONINO COUNTY ... Townships North, Ranges East									
71	14-14-30	Monsanto 1 Cabin Wash-Federal	6857	6563			348		3197 Ia
667	17- 9-11	Wichita Industries 1-11 Federal	7652		3834	106	264+		
436	19- 6-17	Oil Discovery 1 Federal	7012				85?		
661	19- 7- 1	Wichita Industries 1 Federal	7186	6796	4212	99	425?		3688?I
376	19-10-24	Steinberg 1A Flowalt-Babbitt	6271		3136	?	?		2658 Ia
313	20- 5-24	Willett 1 SDD State	7199 GL		4445	30	71+	?	4344 Q*
240	20-10-26	Pickett 1 Padre Canyon-State	6261	5942	3126	65	391		2670 Q
186	20-11-12	Owens 1 Diablo-Amarillo	5735	5452	2665	110	380		2175 Q
3-2	22-10- 3	Flagstaff Assoc 1 Joe Kellam	5588 GL	5310	3327?				
3-4	27- 9-21	Lockhart Bros 1 Babbitt Ranch	5096	4806	2381	215?	402?	190?	1573?Q*
474	29-14-11	Pennzoil 1-11 Hopi	5650	2401	- 290	217	458	253	-1218 I
321	29-15- 6	Moore Moore & Miller 1 Hopi	5648	2253	- 437	197	441	249	-1324 M
3-5	33- 8- 2	Collins-Cobb 1-X Natoine-Navajo	5781 GL	5558	?	?	40?	927?	2354 I
3-6	37-14-28	Sinclair 1 Navajo	6620	3670	977	539	321	707+	
275	39- 2-32	Underwood 1-32 Jacob Lake-Federal	7680	3868	1630	684	146	808+	

* Precambrian or Cambrian quartzite

Table A.— Oil and gas test holes used for control on structure and isopach maps — Continued

MAP NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	ELEV. (ft.)	Pco/Pdc DATUM	Mrw DATUM	Mrw TH.	Du TH.	Є TH.	PЄ DATUM
NAVAJO COUNTY ... Townships North, Ranges East									
369	10-19-15	Tenneco 1 Federal	6992	6342					
368	10-21-31	Tenneco 1-X Fort Apache	6638	6294	3121	108	205	173	2635 Ia
374	12-17-18	Tenneco 1 Federal-A	6696	6438					
76	12-23-25	Pan American 1 NM&AL-B	6253	6089	2163?	67?	247		1849 M
654	13-18- 8	Morton Bros 8-1 Federal	6165	5925	2875	27	76	162	2610 GW
291	14-19-35	Taubert & Steed 1 Babbitt Bros	6040	5862	2352?	6?	106?		2240 Ia
659	14-20- 8	Webb Resources 8-1 NM&AL	5937	5929			65?		2337 Ia
660	-29	Webb Resources 29-1 Rocking Chair Ranch	5808				87		2454 Ia
61	-33	Lydia Johnson 1 Aztec Land & Cattle	5998	5998			98		2265 Q
9-3	-33	Lockhart 1 Aztec Land & Cattle	6028	6012	2371	7	58	12	2301 Ia
662	14-21-30	Webb Resources 30-1 NM&AL	5803	5796	2159	72	46		2041 Ia
658	14-22- 6	Webb Resources 6-1 NM&AL	5514	5507	2032?	23?	52?		1957 Ia
9-5	15-18-19	Union-Continental 1 Aztec Land & Cattle	6127	6102	2355	40	28+		
9-6	-23	Holbrook 1	6020 GL	5970					
9-8	15-19-34	Union-Continental 1 NM&AL	6049	5999					2456 Ia
20	16-16- 1	Eisele 1 McCauley	5558	5468	2158	70	260		1828 Ia
9-9	16-17-20	Black Canyon 1 Fee	5675 GL	5627?					
86	16-18- 9	Pan American Pet 1 Aztec L&C-B	5691		2114	49	209		1856 Ia
85	16-20- 5	Pan American Pet 1 Aztec L&C-A	5442		1853	71	250		1518 Ia
9-23	17-20-21	Great Basin-Taylor 1 Fuller	5270 GL		1596?	11?			1570?
83	18-20-28	Arrowhead-Besoyan Bros 1 State	5352	4969					
221	18-23-35	Franklin Aston & Fair 2 NM&AL-A	5340 GL	5010					
657	19-17-36	Webb Resources 36-1 State	5139	4714	1694	35?	295?		1366 M
26	19-22- 1	Hager Mills & Landrum 1 Santa Fe	5670 GL	4625					
181	-13	Fohs 1-13 Santa Fe	5605	4640					
9-28	19-23- 6	General 14-6 Creager-State	5720	4593					2375 Ia
656	20-15-25	Webb Resources 25-1 NM&AL	4863	4591	1544?	24?	348		1166 M
211	20-21- 4	Linehan & Stoltenberg 1 Matthews-State	5460 GL	4500					
158	-11	Linehan & Stoltenberg 1 Jeffers	5360 GL	4470					
307	26-16-15	Texaco 1 Hopi-A	5547	2909	- 134	36	281	126	- 309 Ia
312	28-15- 9	Atlantic 9-1 Hopi	5820	2625	- 42	171	426	149	- 788 Ia
310	29-19- 8	Amerada 1 Hopi	6183	2139	- 658	197	502	154	-1511 Ia
309	30-17-35	Skelly 1 Hopi-A	6119	1889	- 867	174	462	138	-1641 Ia
283	38-19-24	Tenneco 1 Navajo-8351	5865	3060	- 135	450	583	349	-1517 Ia
281	38-21-29	Superior 21-29 Navajo-W	5561	2931	- 241	389	592	369	-1591 Ia
270	39-21-36	Texaco 1 Navajo-AM	5516	2679	- 529	378	588		-1496 Ir
13	42-18-34	Texas-Skelly-Sinclair 1 Navajo-A	6662	6306	3061	449	373	79+	

Table B.— Stratigraphic test holes used for control on Permian Coconino-De Chelly structure map

MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM	MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM	MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM	MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM
APACHE COUNTY			1-22	17-24-13	4898	1-58	18-27-35	4580	NAVAJO COUNTY		
Townships North			1-25	17-25-22	4889	1-59	18-28-15	4435	Townships North		
Ranges East			1-26	-29	4936	1-60	-19	4450	Ranges East		
200/2	10-25- 2	6117	1-29	17-26-16	4820	1-68	19-27-19	4673	9-4	14-23-12	5128
1-4	14-25-18	5052	1-32	17-27-15	4655	1-69	-22	4646	343	15-22- 3	5165
1-5	-28	5184	1-33	17-28-34	4760	1-70	-28	4640	243	-24	5710
1-7	15-24-23	5061	1-34	17-29-27	4488	404	19-28-34	4485	323	15-23-10	4963
1-8	-29	4986	1-35	18-24- 2	4892	408	19-29- 9	4867	329	16-22-16	5150
1-9	15-27-18	4946	1-37	-17	5009	414	20-27-22	4489	530	17-21- 6	4945
1-10	15-28- 4	4636	1-38	-20	4990	1-75	20-29-31	4989	340	18-23-18	4700
324	16-24-32	4908	1-40	18-25-10	4921	107	21-26-35	4665	9-30	19-23-36	4700
1-18	16-25-27	4900	1-43	-20	5039	COCONINO COUNTY			231	21-18-35	4639?
1-19	16-26- 2	4818	1-46	18-26- 4	4761	Townships North					
1-20	-20	4807	1-52	-22	4898	Ranges East					
1-21	16-29-34	4772	1-53	-24	4877						
			1-57	18-27-10	4537	3-7	18-15-28	5030			

Table C.— Water wells used for control on Permian Coconino-De Chelly structure map

MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM
APACHE COUNTY		
Townships North Ranges East		
221	8-29- 7	5835
5	11-25- 5	6038
290	11-29-27	5975
291	11-30-20	6235
8	12-25-14	6003
11	12-27-19	5500
12	12-28- 7	5385
14	12-29-35	6372
280	13-28-12	5030
267	13-30-21	5235
268	14-25-12	5060
22	14-30-24	5148
284	14-31-29	4966
234	22-25- 4: 9	4537
239	22-27-11	6020
28	22-28-34?	5810
170	22-29- 9:16	6285
171	-13	5926
30	22-30-12	6030
176	23-27- 8	5830
39	24-26- 4: 9	5645
241	24-30-22	5850
42	25-25-24	4345
46	25-28- 3	7290
186	25-30-11	6601
242	26-26-18?	5140
232	-35	6384
161	26-27-23	6855
243	26-30- 1	6425
220	-34	6695
190	26-31- 7	6620
60	27-22-11	3300 P
162	27-24- 3	3550 P
244	27-26-20:21	5978
199	27-27-19	6420
200	27-28-27	7148
67	27-31-18	6040
226	28-24-23	4520?
245	28-25-27:34	4560?
163	30-24- 2	3900
164	-23	4200 P
209	31-23-29	3625
165	31-25-14	4402 P
166	32-22-34	3600 P
95	33-23-21	3150 P
96	33-25-29?	4127
167	34-24- 8	3500 P
110	35-23-28	3000 P
113	35-24- 1	3650 P
249	35-27-11	5601
120	35-28-27	6095
123	35-29-20	5820
Navajo Survey		
Townships North Ranges West		
204	2- 9-17	6100
169	2-10-15	5390
206	3-10- 9:10	5500
210	4- 9-18?	6260
89	5-10-15	5287
100	6- 6-16	6675
99	6- 7- 8	6980
256	6- 9-12?	6420
257	7- 7-30	6660
258	7- 8-33	6358
260	7- 9-35	6240
261	7-10-13	5622
107	7-11-12	4500

MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM
COCONINO COUNTY		
Townships North Ranges East		
1	12-13½- 1	7145
7	15-13-25	6206
214	15-14- 3	5712
216	18-14-13	5020
218	19-12½-15	5255
142	19-13- 5	5044
219	-23	5055
143	-29	5285
220	19-14- 2	4810
147	20- 8-18	6467?
221	20- 9-22	6368?
148	20-12-29	5312
18	21- 6-11	6270
177	-35	6475
178	21- 7-16	6390
151	21- 9-14	6000
152	21-10-16	5710
224	21-11-19	5555
239	-24	5255
238	21-12½-14	4910
235	21-13-22	4600
29	21-14-10	4430
32	22- 5-26	6327
163	22- 6-26	6590
165	22- 8-16	6135
39	22- 9-29	6075
226	22-10-15	5540
255	22-11-35	5100
43	22-12-11	4870
241	-36	4870
232	22-13-14	4525?
227	-18	4575
242	22-14-14	4086
209	23- 8-16	6200
156	23-11-28	4800
170	25- 9- 6	5075
55	25-10-30	4535
176	26- 8- 1	4870
171	26- 9-15	4838
172	-33	5035
192	28- 8-25	4555
243	33- 8- 7	4780
247	37- 7- 9	4710
104	37-11-11	2900 P
105	37-12-23	2800 P
213	37-13-35	3500 P

MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM
NAVAJO COUNTY		
Townships North Ranges East		
2	8-23- 4	6245
9	10-21-10	5950
277	10-22- 9	6049
12	-32	5975
380	11-18-36	6300
341	11-20-32	6310
16	11-22-19	5970
18	11-23- 3	5715
17	-23	5935
278	12-15-36	6952
22	12-21- 2	5503
80	- 6	5602
24	12-22-19	5551
289	-33	5605
25	13-15-14	6565
26	13-17- 5	6159
83	13-19-18	6027
226	13-20-22	5807
84	13-21-13	5429
228	-15	5537
85	-23	5386
87	-34	5513
299	13-23- 9	5502
40	14-17-18	5875
230	14-19- 7	5713
42	14-22-34	5640
43	14-23- 2	5100
233	-32	5420
234	15-16- 6	5716
45	16-15-24	5528
306	16-17-27	5569
307	16-19- 4	5278
46	16-20-16	5388
245	17-16-25	5407
246	17-18-16	5150
249	17-19- 9	5051
257	18-16-35	5112
56	18-17-12	4761
58	18-18-10	4715
59	18-19- 8	4737
335	18-21-12	4610
71	19-15-36	4820
268	19-16-20	4735
77	19-17- 5	4510
269	20-16-24	4421
373	21-17-32	4180
94	21-18- 1	4040
96	22-15-34	4200
203	22-17-11	3800 P
204	23-21-12	3700 P
102	24-16-23	3550 P
103	24-18-19	3700 P
205	25-19-13	3100 P
108	26-18- 7	3100 P
206	27-14-35	2700 P
63	27-15-13	2400 P
207	27-18-10	3000 P
208	27-19- 2	3100 P
118	27-21-32	3100 P
53	28-16-16	2100 P
209	28-17-22	2500 P
210	28-18-12	2800 P
129	28-20-22	2650 P
130	28-21-15	3000 P

MAP NO.	LOCATION T-R-S	Pco/Pdc DATUM
211	29-17-24	2500 P
140	29-21- 8	3300 P
140A	30-16-24	2050 P
212	30-18-15	1700 P
143	30-20- 8	2600 P
151	31-21-30	2500 P
152	-36	3600 P
213	32-17-29	1900 P
214	32-19- 1	2000 P
177	36-18-20	1430
182	36-21-16	2600 P

OIL SHOW TABLES D, E, AND F

Discussion

A "show" is considered to be any indication of oil occurring naturally in rocks. The description of the types of shows found in the rocks of northeast Arizona are highly variable. Descriptions noted on the graphic lithologic logs of American Stratigraphic Company, Denver Sample Laboratory, and Permian Basin Sample Laboratory; consulting geologists; hydrocarbon logs; manuscript logs accompanying operators' completion reports submitted to the Oil and Gas Conservation Commission; scout tickets; and Petroleum Information completion cards vary considerably. Commonly noted descriptions include: asphaltic residue or bitumen; dead oil staining; trace, poor, faint, slight, light, fair, medium, good, heavy, even, and spotty oil staining; varying degrees of discolorations in solvent; poor, fair, good, or spotty oil fluorescence discernible on cuttings and cores or in solvent; and oil odor. The recovery of free oil, oil-cut mud, or oil-cut water on drill-stem or production tests furnish positive evidence of an "oil show" in the interval tested.

The best available source of oil staining on drill-bit cuttings in compiling the oil show tables was the excellent graphic lithologic logs produced by the American Stratigraphic Co. The grading of the oil stain data presented in the tables is patterned after the method used by this company.

The lowest grade of oil shows is not indicated on the tables in areas where numerous shows of this grade occur. With a few exceptions, no shows are listed for pool wells or wells near pools.

Shows of gas have not been listed in the tables although many of the drill-stem and production tests made in the study area recovered free gas, gas-cut mud, or gas-cut water. The gases recovered in many tests were largely or wholly non-flammable.

Arrangement and Organization of Tables

ID No. Oil and Gas Conservation Commission permit number or number assigned to wells drilled prior to the creation of the Commission

Location. The geographic base used for well location is the appropriate Public Land Survey, Township (T)-Range (R)-Section (S). Wells are in townships north of the Gila and Salt River Base Line and east of the Gila and Salt River Meridian except for the few wells in north townships and west ranges in the Navajo Survey of northern Apache County.

Well. Operator. The name of the company or person responsible for the drilling operation at the time the well reach total depth

Number. Well number designated by original operator

Lease. Name of the owner of the mineral rights

Type of Show. Cuttings - Oil stain

Grade 1. Even, good, heavy staining

Type of Show.

Cuttings - Oil Stain.

Grade 1. Even, good, heavy staining

2. Fair, medium, or spotted staining

3. Light, questionable, or positive test

DST. Drill-stem tests. Fluid recovery contained free oil, oil-cut mud, or oil-cut water, or a combination of these fluids

Prod. Test. Production test. Oil recovered on flowing, pumping, or swabbing tests

Interval. Depth of interval in which show occurred

Strat. Unit. Stratigraphic unit in which show occurred

Abbreviations used:

Pennsylvanian

- Pn Naco Formation
  - Hermosa Group
    - Phu Undifferentiated
    - Ph Upper
    - Phl Lower
    - Phd Desert Creek Unit
    - Pha Akah Unit
    - Phb Barker Creek Unit
- Pm Molas Formation

Mississippian

- Mu Undifferentiated
- Mrw Redwall Formation
  - Mhm Horseshoe Mesa Member
  - Mmf Marble Falls Member
  - Mts Thunder Springs Member
  - Mww Whitmore Wash Member

Devonian

- Du Undifferentiated
- Do Ouray Formation
- De Elbert Formation
  - Dem McCracken Sandstone Member
- Da Aneth Formation
- Dm Martin Formation

Table D.— Oil shows in Pennsylvanian rocks in northeast Arizona

ID NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	CUTTINGS OIL STAIN 1	2	3	DST	PROD. TEST	STRAT. UNIT	INTERVAL (Depth in feet)	REMARKS
APACHE COUNTY										
435	36-27-30	Simmons 1 Navajo					x	Phu	2404-25, initial pump rate 3-4 bbls fluid (15-20% oil), total fluid decreased to almost zero at end of 17-day test	
311	37-27- 8	Blackburn 8-1 Navajo		x				Phu	4140-60	
491	37-29-12	Gulf 1 Navajo-BS			x			Phu	3270-3300, 3650-80, 3720-30	
544	-14	Union Texas 1-14 Navajo				x		Phl	3423-64	
575	-16	Little 1-16 Navajo		x				Phl	3730-40	
			x					Phl	3740-50	
590	-16	St Mary Parish 2-16 Navajo		x				Phl	3690-3700	
563	-22	Little 1-22 Navajo				x		Phl	3536-3601	
591	37-30-30	St Mary Parish 1-30 Navajo			x			Ph-Phl	2450-80, 3130-50	
			x					Phl	3100-10	
424	38-24-28	American Mng 1 Navajo			x			Ph	5140-80, 5220-40, 5290-5320	
				x				Ph	5180-5220	
280	38-27-20	Pan American 1 Navajo-T			x			Phu	4840-50	
468	38-30-12	Pan American 1 Navajo-AF			x			Phu	3520-30 (Numerous minor shows of oil noted in Tertiary igneous sill 3900-4560)	
145	40-26-30	Bonanza 1 Navajo		x				Phd	4970-90	
261	40-27- 6	Occidental 1 Texaco-Navajo		x				Pha	5380-5400	
					x			Pha	5400-30	
					x			Phl	5450-70, 5510-20, 5940-50	
179	40-28- 6	Pan American 1 Navajo-F					x	Pa	6422-67	
513	- 9	Little 1 Navajo				x		Phd-Phl	5110-63	
176	40-29-15	Pan American 1 Navajo				x		Phi-Phd -Phl	Flammable gas several zones 4700-5360	
274	-18	Marathon 1 Navajo			x			Phd	5630-50	
					x			Phl	5730-40, 5990-6000	
566	-27	Cities Service 1 Monsanto-Navajo-B			x			Phu	6070-90, 6680-90	
				x				Phu	6350-80	
546	40-30- 2	Depco 1-2 Navajo		x				Phi	5240-50	
105	- 5	British American 1 Navajo-C			x			Phl	5380-90	
290	41-22-12	Occidental 1 Navajo		x				Phu	950-70, 980-1030	
295	41-25-17	Great Western 2 El Paso-Navajo			x			Pha	5010-40	
266	-21	Texaco 2 Navajo-AG			x			Phl	5410-30	
50	41-26-28	Gulf-British American 1 Walker Creek			x			Phi	4710-20	
				x				Phi	4720-30	
				x				Phd	4850-60	
					x			Phd	4880-90	
			x					Phd	5030-32	
					x			Phl	5230-40	
260	-31	McDonald 1 Navajo			x			Phd	4880-90	
					x			Phl	Numerous in gross interval 5060-5380	
304	-33	Tenneco 1 Navajo-4332				x		Phi	Flammable gas 4722-41	
						x		Pha	4883-5070	
139	41-29-29	Davis 1 Navajo-C				x		Phd	5216-31	
44	41-30-10	Superior 1 Navajo-H		x				Phi	5120-50	
					x			Phi	5150-60	
				x				Phd	5200-10	
					x			Phd	5210-20, 5260-80	
					x			Phl	5590-5600	
			x					Phl	5600-10	
299	-13	Duncan 1 El Paso-Navajo					x	Phi	5185-5203	
128	-21	Superior 23-21 Navajo-M	x					Phi	5020-32	
637	-30	Northwest Pipeline 1 Navajo-Judy Lee				x		Phi-Phd	5078-5167	
				x				Phd	5130-70	
COCONINO COUNTY										
667	17- 9-11	Wichita 1-11 Federal			x			Pn	3790-3800	
321	29-15- 6	Moore-Moore-Miller 1 Hopi						Pn	Dead oil stain 6016-38	

Table D. — Oil shows in Pennsylvanian rocks in northeast Arizona — Continued

ID NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	CUTTINGS OIL STAIN 1	2	3	DST	PROD. TEST	STRAT. UNIT	INTERVAL (Depth in feet)	REMARKS
NAVAJO COUNTY										
9-3	14-20-33	Lockhart 1 Aztec			x			Pn		No oil stains logged on cuttings or cores. Very minor oil shows noted in core analyses. See figure
9-5	15-18-19	Union-Continental 1 Aztec			x			Pn		Numerous thin zones with slight spotty staining, slight oil odor, occasional few gas bubbles, and asphaltic residue reported in cores of gross interval 3289-3767.
13	42-18-34	Texas-Skelly-Sinclair 1 Nav-A	x					Phu	2770-80	
					x			Phu	2780-90, 2800-10, 2820-30	
				x				Phu	2810-20	
					x			Phu	3430-50	

Table E. — Oil shows in Mississippian rocks in northeast Arizona

ID NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	CUTTINGS OIL STAIN 1	2	3	DST	PROD. TEST	STRAT. UNIT	INTERVAL (Depth in feet)	REMARKS
APACHE COUNTY										
311	37-27- 8	Blackburn 8-1 Navajo			x			Mww	4480-90	
382	39-25-16	J C M Drlg 1 Navajo-Mobil			x			Mts	5180-5200	
					x			Mww	5270-80	
60	40-25-11	Pan American 1 Navajo			x			Mh	5510-30	
					x			Mmf	5670-80	
			x					Mww	5760-70, 5790-5800	
145	40-26-30	Bonanza 1 Navajo	x					Mmf	5560-70	
261	40-27- 6	Occidental 1 Texaco-Navajo			x			Mu	6040-70	
179	40-28- 6	Pan American 1 Navajo-F			x			Mts	7150-60, 7190-7200	
				x				Mts	7170-90	
					x			Mww	7210-20, 7230-40	
				x				Mww	7220-30	
598	40-29-15	Universal 1-15 Navajo	x					Mts	5750-60	
				x				Mts	5760-70	
581	-16	Cities Service 1 Monsanto-Nav-C				x		Mu	Flammable gas 5650-5710	
566	-27	Cities Service 1 Monsanto-Nav-B			x			Mmf	7040-80	
266	41-25-21	Texaco 2 Navajo-AG		x				Mww	5990-6000	
					x			Mww	6520-50	
260	41-26-31	McDonald 1 Navajo			x			Mmf	5750-95	
					x			Mts	5795-5850, 5880-5900, 5910-20	
				x				Mts	5900-10	
205	41-28-27	Franco Western 2 Navajo				x		Mu	6010-6150	
168	41-29-22	LaRue 1 Toh Atin		x				Mhm	6130-50	
					x			Mhm	6180-6210	
44	41-30-10	Superior 1 Navajo-H			x			Mhm	6300-06	
COCONINO COUNTY										
464	14-11-10	Eastern 1 Federal-Moqui Bardo						Mrw	Dead oil stain 3340-60	
376	19-10-24	Steinberg 1A Flowalt-Babbitt	x					Mrw	3190-3210	
NAVAJO COUNTY										
654	13-18- 8	Morton Bros 8-1 Federal	x					Mrw	3090-3120	
9-3	14-20-33	Lockhart 1 Aztec			x			Mrw		No oil staining logged on cuttings or cores. Very minor oil shows noted in core analyses.
662	14-21-30	Webb 30-1 NM&AL		x				Mrw	3700-10	
86	16-18- 9	Pan American 1 Aztec-B		x				Mrw	3620-30	
270	39-21-36	Texaco 1 Navajo-AM		x				Mts	6310-30	
					x			Mts	6330-70	
					x			Mww	6420-30	

Table F.— Oil shows in Devonian rocks in northeast Arizona

ID NO.	LOCATION T-R-S	OPERATOR-NUMBER-LEASE	CUTTINGS OIL STAIN 1	2	3	DST	PROD. TEST	STRAT. UNIT	INTERVAL (Depth in feet)	REMARKS
APACHE COUNTY										
308	35-22- 2	Tenneco 1 Navajo-8939		x				Dem	6348-80	
461	35-28-25	Buttes Gas & Oil 1-25 Navajo	x					De-Dem	2740-60	
			x					Dem-Da	2780-2800	
						x		De-Dem	2748-2810	
454	35-30-35	Humble 1 Navajo-151	x					De	3725-40	
519	36-29-11	Union 1-N11 Navajo		x				Dem	3540-70	
			x					Dem	3710-20	
401	-23	Humble 1 Navajo-87	x					Dem	5230-50, 5270-80	
			x					Da	5430-40	
422	36-30-33	Kerr-McGee 2 Navajo-C	x					Dem	4132-60	
				x				Dem	4170-90, 4210-20	
489	37-29-33	Odessa 1 Arcodessa-Cove-Navajo		x				Do	3110-30	
				x				De	3250-70	
298	-35	Blackburn 35-1 Navajo		x				Da	3580-3600	
			x					Da	3596-3600	
280	38-27-20	Pan American 1 Navajo-T		x				Da	5700-20	
			x					Da	5760-70	
						x		De-Dem -Da	5590-5690	
292	39-23-12	Superior 22-12 Navajo-V		x				Da	6170-94	
			x					Da	6190-6200	
265	-12	Superior 33-13 Navajo-V		x				Do	5680-90	
						x		Dem	5992-6009	
247	40-24- 8	Pan American 1 Navajo-Q				x		Dem-Da	6428-6525	
271	40-25- 6	Texaco 1 Navajo-AK		x				De	6374-78	
						x		Dem	6423-91	
60	-11	Pan American 1 Navajo				x		Da	6230-86	
95	40-26-20	Texas Pacific 1 Navajo-190		x				De	5940-50	
				x				Da	6220-30	
145	-30	Bonanza 1 Navajo		x				Da	6300-14	
138	40-28-17	Western States 2 Navajo	x					Dem	6110-20	
290	41-22-12	Occidental 1 Navajo		x				Da	2600-30, 2650-60	
226	41-25-16	Texaco 1 Navajo-AG					x	Dem-Da	Productive zone 6370-84	
22	41-28- 3	Shell 2 Navajo		x				Dem	5970-90	
18	41-29- 6	Shell 1 Navajo				x		Du	6014-80	
425	41-30-30	Miami 1 Navajo				x		Du	6422-32, 6600-35	
637	-30	Northwest Pipeline 1 Navajo-Judy Lee		x				Dem	6340-50	
						x		De-Dem	6480-6555	
113	-36	Texaco 1 Navajo-Z					x	Dem	6758-93	
Navajo Survey										
477	6- 6-20	Union 1 Navajo	x					Du	2410-20	
COCONINO COUNTY										
667	17- 9-11	Wichita 1-11 Federal			x			Dm	4020-40, 4110-30	
			x					Dm	4040-50, 4060-90	
240	20-10-26	Pickett 1 Padre Canyon-State						Dm	Dead oil stain 3410-20	
NAVAJO COUNTY										
9-3	14-20-33	Lockhart 1 Aztec			x			Dm	No oil staining logged on cuttings or cores. Very minor oil shows noted in core analyses. See figure	
9-5	15-18-19	Union-Continental 1 Aztec			x			Dm	3795-3812, slight to fair spotty staining reported in cores	
307	26-16-15	Texaco 1 Hopi-A			x			De	5610-20	
312	28-15- 9	Atlantic 9-1 Hopi			x			Da	6430-50	
310	29-19- 8	Amerada 1 Hopi						Dem	Dead oil stain 7330-50	
283	38-19-24	Tenneco 1 Navajo-8351						Da	Dead oil stain 6970-7033	

EXPLANATION FOR TABLES G, H, AND I

Location. Appropriate Public Land Survey, Township (T)-Range (R)-Section (S)

MAT. Mean annual temperature (Druitt, 1976)

°C. Degrees Celsius

Temp. Reported temperature (Principal sources: Davis and others, 1963; McGavock, 1968; and McGavock and others, 1966)

Depth (m). Depth in meters at which temperature was measured, if known; otherwise generally depth of deepest water-productive zone

TG (°C/km). Thermal gradient, degrees Celsius per kilometer

TD. Temperature differential. Number of Celsius degrees in excess of maximum temperature profile

Factors used in converting data reported in degrees Fahrenheit and feet:

$°C = 5/9(°F-32°)$

$m = \text{feet} \times 0.305$

Table G.— Thermally anomalous water wells in northeast Arizona

LOCATION T-R-S	MAT (°C)	TEMP. (°C)	DEPTH (m)	TG (°C/km)	TD (°C)
APACHE COUNTY ... Townships North, Ranges East					
10-25- 7	8.9	18.3	148	64	0
12-24-14	10.6	18.3	116	66	0
13-27-21	11.7	18.3	122	54	0
14-27-18	12.2	17.8	122	46	0
21-29- 6	10.0	22.2	39.7	307	0.5
21-30-26	9.4	18.3	183	49	0
22-29-21	9.4	22.2	62.2	206	1.0
-23	9.4	19.4	116	86	1.0
-24	9.4	22.8	91.5	146	5.0
22-30-12	9.4	22.8	56.4	238	1.0
-12	9.4	22.2	39.7	322	0.5
23-29- 8	9.4	18.3	90.6	98	0
26-26-18	10.0	23.3	441	30	0
26-31-18	8.9	17.2	90.9	91	0
27-26-25	8.9	21.1	36.0	339	0
30-23- 9	9.4	17.2	176	44	0
31-24-10	10.0	20.6	64.1	165	0
35-28-17	10.0	17.8	177	44	0
35-29-32	10.0	17.8	92.7	83	0
36-27-19	10.0	22.8	229	56	3.0
-19	10.0	21.1	38.4	289	0
37-22- 7	10.0	17.8	186	42	0
37-27-24	10.0	24.4	420	34	0
38-30-13	9.4	17.8	124	68	0
40-28-32	11.7	18.3	210	31	0
40-30- 3	12.8	21.7	58.0	153	0
- 3	12.8	19.4	191	35	1.5
41-28- 5	12.8	21.7	40.3	221	0
41-29-16	12.8	17.8	90.0	56	0
APACHE COUNTY ... Navajo Survey Townships North, Ranges West					
2-10-27	10.6	17.8	213	34	0
3-10- 9:10	10.0	17.2	94.9	76	0
5-10-16	11.1	17.2	178	34	0
COCONINO COUNTY ... Townships North, Ranges East					
18-13 -13	11.1	17.0	145	41	0
18-14 -36	11.7	17.0	145	37	0
19-12½-15	11.7	19.0	232	31	0
21-12½-14	12.2	17.2	118	42	0
21-13 -34	12.2	20.6	130	65	2.5
22-12 -36	11.7	18.3	157	42	0
23-12 -26	12.2	18.9	116	58	1.0
25-14 -14	12.8	20.6	36.3	215	0
27-14 -36	13.3	20.6	83.9	87	2.5
29- 9 -22	13.9	18.9	113	44	1.0
29-14 - 1	10.6	17.2	102	65	0
30-14 -21	12.8	20.0	197	37	1.0
31-14 - 6	10.0	17.8	161	48	0
32- 9 -20	13.3	19.4	74.7	82	0.5
37- 9 - 7	12.8	24.4	360	32	1.0

LOCATION T-R-S	MAT (°C)	TEMP. (°C)	DEPTH (m)	TG (°C/km)	TD (°C)
NAVAJO COUNTY ... Townships North, Ranges East					
11-23- 3	10.0	17.8	142	55	0
14-23- 2	11.7	17.2	160	34	0
15-16-15	10.3	25.5	275	55	4
15-21-32	11.4	17.0	131	43	0
-36	11.7	18.0	104	61	0
15-22-10	12.2	18.0	91.5	63	0
15-23- 3	12.5	17.0	82.4	55	0
-34	12.2	17.0	131	37	0
16-18-28	11.7	19.0	229	32	0
16-22-14	12.2	19.0	92.4	74	1
16-23-15	12.8	19.5	153	44	1
17-19- 2	12.8	18.0	151	34	0
-12	12.5	18.0	137	40	0
17-20- 3	12.8	17.0	153	27	0
- 5	12.8	17.0	137	31	0
- 6	12.8	17.0	123	42	0
-10	12.8	17.0	91.5	57	0
-11	12.8	17.0	122	43	0
18-19- 8	13.3	17.0	143	26	0
-16	13.3	17.0	153	24	0
-16	13.3	18.0	142	33	0
-16	13.3	17.0	122	30	0
-16	13.3	17.0	150	25	0
-16	13.3	18.5	99.1	52	0
-17	13.3	18.0	153	31	0
-17	13.3	17.5	130	32	0
-28	12.8	17.0	137	31	0
22-17-10	13.3	21.1	61.0	128	0
23-20-15	12.8	17.8	159	31	0
24-21-15	11.7	22.8	114	97	5.0
25-20-22	12.2	17.2	80.5	62	0
26-19- 7	11.7	17.8	107	57	0
27-16-12	12.8	17.2	110	40	0
27-18-10	11.7	17.2	136	40	0
28-21-31	10.0	21.7	54.9	213	0
29-16-11	10.0	19.4	262	36	0
30-17- 3	10.0	22.2	61.0	200	0.5
30-18-15	10.0	23.3	76.3	174	4.5
30-19-11	10.0	21.1	41.2	269	0
31-18-19	10.0	22.8	44.2	290	1.0
32-17-19	10.0	26.1	86.0	187	8.0
32-21- 7	9.4	20.0	233	45	0
36-22- 6	10.0	17.2	122	59	0
38-18- 3	10.6	20.6	76.3	131	2.0

Table H.— Water wells with thermal gradients greater than 98° Celsius per kilometer at depths less than 70 meters in northeast Arizona

LOCATION T-R-S	MAT (°C)	TEMP. (°C)	DEPTH (m)	TG (°C/km)
APACHE COUNTY				
Townships North, Ranges East				
20-26-12	10.6	16.7	33.6	182
23-26-21	10.0	16.7	43.6	154
23-27-19	10.0	15.6	40.0	140
24-23-22	10.6	17.8	34.5	209
25-23-19	10.0	15.0	40.3	124
26-31-13	8.9	12.8	39.3	99
27-27-14	8.9	16.7	65.9	118
30-23-24	9.4	15.6	43.9	141
35-27- 5	9.4	16.1	61.6	109
36-28-19	10.0	15.6	56.1	100
36-30- 3	9.4	16.1	58.0	116
37-22-21	10.0	16.7	64.7	104
37-23-15	10.6	16.7	49.7	123
37-26- 7	10.0	16.7	50.3	133

LOCATION T-R-S	MAT (°C)	TEMP. (°C)	DEPTH (m)	TG (°C/km)
APACHE COUNTY (Continued)				
Townships North, Ranges East				
38-23- 9	11.7	18.9	32.6	221
41-25-14	11.1	20.0	39.7	224
APACHE COUNTY ... Navajo Survey				
Townships North, Ranges West				
1-11-12	10.0	16.7	39.0	172
3- 5-12	9.4	13.3	37.5	104
COCONINO COUNTY				
Townships North, Ranges East				
22- 4-26	7.2	11.0	38.0	100
22-13-19	12.2	18.9	61.0	110
24-14-36	13.3	19.4	60.7	100
32-11-30	12.8	17.8	41.0	122

LOCATION T-R-S	MAT (°C)	TEMP. (°C)	DEPTH (m)	TG (°C/km)
NAVAJO COUNTY				
Townships North, Ranges East				
9-22-22	9.4	13.5	36.6	112
-24	9.4	14.0	31.4	146
9-23-32	8.9	12.0	21.4	145
13-21-34	10.6	15.6	49.0	102
22-23-18	11.7	15.0	33.2	99
29-15-13	10.0	16.1	52.5	116
-13	10.0	16.1	50.0	122
41-20-18	10.0	15.6	37.5	149

Table I. — Thermally anomalous springs with temperatures greater than 6.1 Celsius degrees above mean annual temperatures in northeast Arizona

NAME	LOCATION T-R-S	MAT (°C)	TEMP. (°C)
APACHE COUNTY			
Townships North, Ranges East			
Salado	12-28-17	11.1	21.7
Salado	-17	11.1	17.2
Salado	-21	11.1	23.0
	13-27-13	11.7	22.0
Stinking	14-26-10	12.2	16.7
	20-27-29	10.6	25.0

NAME	LOCATION T-R-S	MAT (°C)	TEMP. (°C)
COCONINO COUNTY			
Townships North, Ranges East			
	33- 4- 9	10.0	21.0
	39- 6-12	14.4	26.0
	40- 8-18	15.6	22.5

NAME	LOCATION T-R-S	MAT (°C)	TEMP. (°C)
NAVAJO COUNTY			
Townships North, Ranges East			
Gomez	8-23-25	7.8	21.0
Paige	9-23-18	9.4	17.8
	12-21-25	10.6	18.3