Petroleum Geology of the McGregor Range Otero County, New Mexico*

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Abstract

The McGregor Bombing and Artillery Range is a U.S. Army training and testing facility in Otero County, New Mexico. It encompasses several tectonic elements including the Otero platform, the Hueco Mountains, the Tularosa Basin, and the Sacramento Mountains. Only nine exploratory wells have been drilled within the Range. The most recent well was drilled in 1954. Oil and gas production has not been established. Gas was discovered during 1997 in the Harvey E. Yates No. 1Y Bennett Ranch well, drilled 10 miles east of the Range. This well marks the first commercially viable gas discovery in an otherwise unproductive frontier region. Petroleum source rocks are Devonian shales, Mississippian shales and limestones, and Pennsylvanian shales and limestones. Source rocks are generally thermally mature in the southern part of the range and are immature to marginally mature in the northern part of the Range. Thermal maturity increases with proximity to Tertiary-age intrusive complexes and also probably increases within Pennsylvanian grabens due to increased burial depth. Reservoir rocks are present within the Ordovician, Silurian, Mississippian, and Pennsylvanian sections. Ordovician and Silurian reservoirs are dolostones with well-developed vugular porosity. The Mississippian section may contain some carbonate reefal reservoirs. Pennsylvanian strata are dominantly basinal deposits and potential reservoirs include carbonate debris flow deposits; shallow water reservoir facies may be present on intrabasinal uplifts. Tertiary igneous sills may also be reservoirs where they have intruded Mississippian or Pennsylvanian source rocks.

Introduction

The U.S. Army McGregor Bombing and Artillery Range is located in central and southwestern Otero County, New Mexico (Figure 1). The McGregor Range occupies an area of approximately 3000 km^2 and is militarily restricted. It encompasses several tectonic elements including the Otero platform, the Hueco Mountains uplift, the Tularosa Basin, and the Sacramento Mountains uplift.

Commercial volumes of oil and natural gas have not been discovered by the nine wells drilled within the boundaries of the McGregor Range (Figure 1; Table 1). The last of these wells was drilled in 1954. The nearest discovery of commercial hydrocarbons is ten miles east of the Range at the Heyco No. 1Y Bennett Ranch well (Figure 1) which was drilled in 1997. The main reservoir in that well appears to be a Tertiary age igneous sill that intruded the Mississippian section. Exploration in this play has subsequently been extended southward into Texas where several wells have been drilled. Nearest other production is more than 40 miles east in the Permian Basin.

This paper is derived from a larger report prepared by the New Mexico Bureau of Geology (formerly Mines) and Mineral Resources and TRC-Mariah Associates, Inc. for the U.S. Army as part of the process to enable continued use of federal lands within the McGregor Range by the U.S. Army (New Mexico Bureau of Mines and Mineral Resources, et al., 1998).

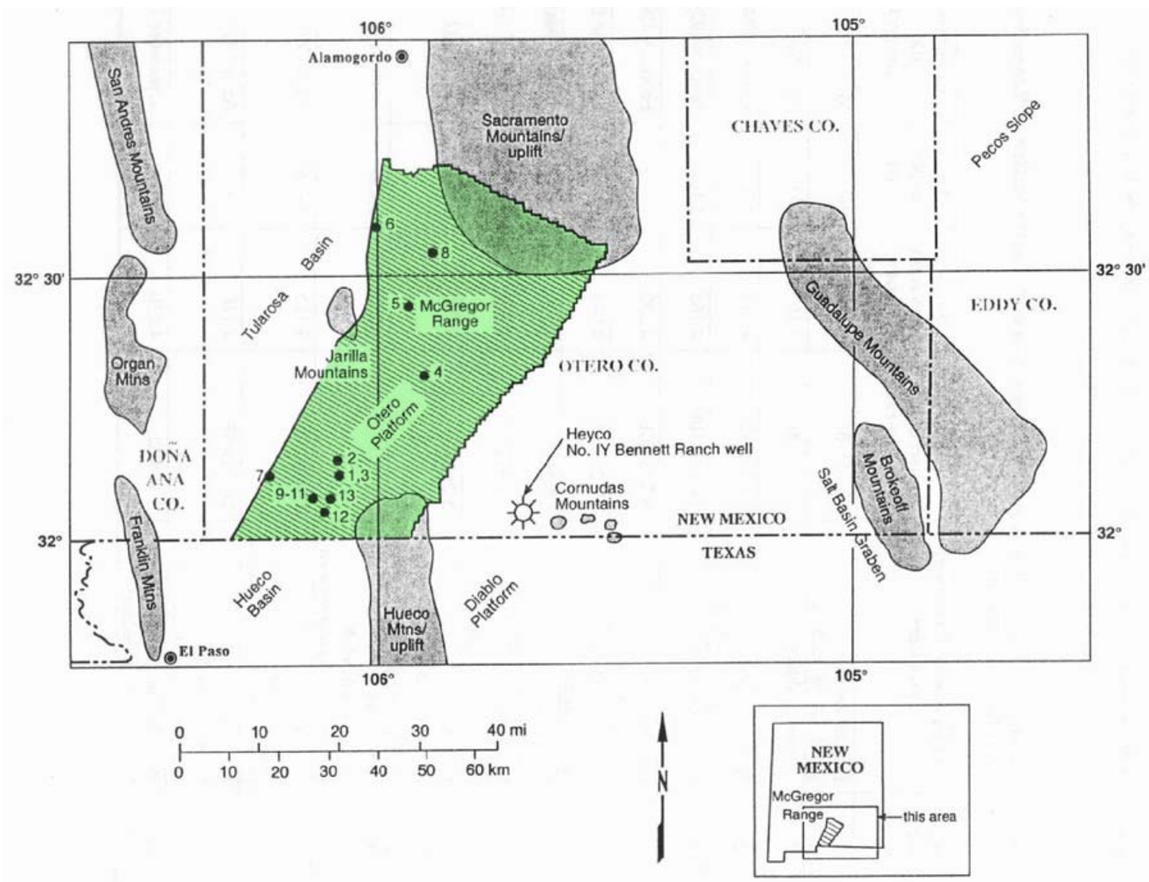

Figure 1. The McGregor Range, the five tectonic elements that are present within its boundaries (Otero platform, Hueco Mountains uplift, Sacramento Mountains uplift, Jarilla Mountains uplift, and Tularosa basin), and deep test wells drilled within the Range. See Table 1 for well data.

Number on Fig. 1	Operator, well number, and lease	Location (section-township-range)	Surface elevation (ft above sea level)	Total depth (ft)	Completion date (mo/yr)
1	Bechtel Brothers No. 1 J.A. Maris State	23-25S-8E	4,192	986	May 1950
2	George Muldery No. 1 State	11-25S-8E	4,165	263	July 1937
3	Holland Page Jr. No. 1 J.A. Maris State	23-25S-8E	4,217	731	October 1949
4	Kinney Oil & Gas No. 1 State	14-23S-10E	4,768	2,168	January 1926
5	Otero Oil Co. No. 1 McGregor	5-22S-10E	4,230	1,730	February 1943
6	Plymouth Oil Co. No. 1 Federal	15-20S-9E	4,044	7,585	November 1954
7	R.H. Ernest No. 1 Located Land	20-25S-7E	4,099	3,941	January 1942
8	Sun Oil Co. No. 1 T.J. Pearson	35-20S-10E	4,408	4,468	December 1954
9	U.S. Army Ft. Bliss core 45-5 (geothermal evaluation well)	5-26S-8E	4,107	3,961	April 1997
10	U.S. Army Ft. Bliss core 46-6 (geothermal evaluation well)	6-26S-8E	4,105	2,258	April 1997
11	U.S. Army Ft. Bliss core 61-6 (geothermal evaluation well)	6-26S-8E	4,115	2,018	April 1997
12	U.S. Army Ft. Bliss core 51-8 (geothermal evaluation well)	16-26S-8E	4,110	2,573	April 1997
13	W.G. Wilmoth No. 1 Wilmoth Federal	3-26S-8E	4,130	206	September 1949

Table 1. Petroleum exploration and deep geothermal test wells drilled in the McGregor Range. See Figure 1 for well locations.

Stratigraphy

Rocks that crop out within the boundaries of the McGregor Range are Precambrian through Tertiary in age (Figure 2). Precambrian rocks are basement lithologies: granite, gabbro, diabase, rhyolite porphyry, and metasedimentary rocks. The Precambrian is exposed along the west face of the Sacramento Mountains. Ordovician and Silurian rocks are mostly dolostones that are present throughout the subsurface of the McGregor Range and crop out in uplifted blocks in the Sacramento Mountains as well as in the Texas part of the Hueco Mountains. Devonian strata are black shales and black cherts. Mississippian strata are black shales and thinly bedded basinal limestones. Pennsylvanian strata are present within the extent of the late Paleozoic Orogrande Basin (Pray, 1959; Kottlowski, 1960) but are not present on uplifted fault blocks of the late Paleozoic Ancestral Rocky Mountains or are thin on those uplifted blocks. Pennsylvanian limestones, shales, and sandstones crop out extensively in the Sacramento and Hueco Mountains and on isolated outcrops in the southern part of the McGregor Range. Permian carbonates, shales, and sandstones blanket the area and crop out over large parts of the Otero platform as well as the Hueco and Sacramento Mountains. Tertiary intrusive stocks, dikes, and sills have been intersected by several petroleum exploration wells and crop out in the Hueco, Jarilla, Cornudas, and Sacramento Mountains. Tertiary igneous stocks form the cores of the Hueco, Jarilla, and Cornudas Mountains.

Era	Period	Stratigraphic units	Lithology	Thickness (feet)	Description
CENEZOIC		Quaternary		0-2000	Alluvial conglomerate and gravel in Tularosa basin and along flanks of Hueco and Sacramento Mountains. Well-sorted aeolian sands in northern and southeastern part of McGregor Range.
CENEZOIC		Tertiary			Monzonite, diorite, syenite. Occurs as sills, dikes, and stocks intruding Paleozoic strata.
PALEOZOIC	Permian	San Andres Fm.		0-750	Brown to olive gray limestone with minor olive gray dolostone; fine-to medium-grained white sandstone in lower part.
PALEOZOIC	Permian	Yeso Fm.		0-1800	Tan to brown finely crystalline dolostone and limestone with subsidiary red to gray, fine-grained sandstone.
PALEOZOIC	Permian	Abo Fm.		0-300	Red shale; minor fine-to very fine-grained sandstone and dolomitic siltstone.
PALEOZOIC	Permian	Hueco Fm.		400-1500	Light-to dark gray limestone with minor interbedded gray shale and white fine-to coarse-grained sandstone.
PALEOZOIC	Permian	lower Abo or Pow Wow Cg1.		0-600	Red shale, dolomitic fine-to coarse-grained sandstone, arkosic conglomerate. Minor dolostone and limestone.
PALEOZOIC	Pennsylvanian	Panther Seep Fm.: Holder Fm., Beeman Fm.; Lead Camp Fm.: Gobbler Fm.		0-3300	Holder, Beeman and Gobbler Formations in Sacramento Mountains; Panther Seep Fm. and Lead Camp Fm. elsewhere. Panther Seep Fm. comprised of black lime mudstones and wackestones. Holder, Beeman, and Gobbler Fms. consist of light-to dark gray limestone interbedded with light-to dark gray shale and minor quartzose sandstone.
PALEOZOIC	Mississippian	undivided (Helms, Rancherio Lake Valley, and Caballero Fms.)		0-500	Gray to dark gray limestone interbedded with dark gray to black shale. Divided into Helms Rancheria, Las Cruces, Lake Valley, and Caballero Formations in the Sacramento Mountains; undivided in subsurface.
PALEOZOIC	Devonian	upper Shale		10-100	Black shale
PALEOZOIC	Devonian	Canutillo Fm.			Black chert, bedded to brecciated
PALEOZOIC	Devonian	lower Shale			Black shale
PALEOZOIC	Silurian	Fusselman Formation (including Valmont Dolomite)		130-500	Dolostone, dark gray, cherty
PALEOZOIC	Ordovician	Montoya Group		150-500	Dolostone, light gray, cherty in places
PALEOZOIC	Ordovician	El Paso Group		400-700	Thin bedded dark gray dolostone with minor quartzose sandstone.
PALEOZOIC	Ordovician	Bliss Sandstone		100-250	Quartzose sandstone, minor thin-bedded dolostone.
PRECAMBRIAN		Proterozoic			Granitic rock, rhyolite porphyry, diabase to gabbro, metasedimentary rocks.

Figure 2. Stratigraphic column of rocks within McGregor Range and surrounding areas.

Structure

The McGregor Range and surrounding areas exhibit a complex interplay of structures of late Paleozoic Ancestral Rocky Mountain age (Pennsylvanian to Permian), Laramide age (Late Cretaceous to earliest Tertiary), and basin-and-range (Tertiary) age. The Tularosa Basin, present along the west side of the McGregor Range, is formed by a north-south-trending system of downdropped fault blocks (Figure 1; King and Harder, 1985; Seager et al., 1987). Individual fault blocks are asymmetric, west-tilted grabens related to the Tertiary-age Rio Grande rift (Mattick, 1967; Seager, 1980; Adams and Keller, 1994; Collins and Raney, 1994). The faults that form the boundaries of the Tularosa Basin are Tertiary in age. Tertiary and Quaternary sands and gravels fill the basin and are thought to attain a maximum thickness of 9000 ft in the deepest parts of the basin (Mattick, 1967; Healy et al., 1978).

The Otero platform occupies most of the area encompassed by the McGregor Range (Figure 1). The Otero platform is a broad, uplifted area bordered on the west by the Tularosa Basin, on the southwest by the Hueco Mountains uplift, on the east by the Salt Basin graben, and on the north by the Sacramento Mountains uplift. To the south, in Texas, the Otero platform is known as the Diablo platform.

The most prominent structural features at the surface of the Otero platform are en echelon systems of north to northwest trending anticlines and synclines (Black, 1973, 1976). Axial length averages approximately 5 to 15 miles but may be as short as 5 miles and as long as 20 mi. These folds are thought to have formed during Laramide compression in the region but may also have seen post-Laramide movement (Black, 1973, 1976).

The subsurface of the Otero platform is structurally more complex than the gently folded Permian strata at the surface. For this work, subsurface structures were interpreted from well data, regional gravity and aeromagnetic data (Keller and Cordell, 1983; Cordell, 1983), surface outcrop maps (Seager et al., 1987; Pray, 1961) which indicate locations of folds and faults as well as strata1 dip at the ground surface, and regional geophysical studies (Healy et al., 1978; Mattick, 1967). Laramide folds and northeast-vergent Laramide thrust faults have been superimposed upon large scale faulting of Ancestral Rocky Mountain age (Pennsylvanian - Early Permian). The Ancestral Rocky Mountain structures are dominated by horst and graben blocks bounded by high-angle normal faults with northerly to northwesterly trends. These are buried beneath Early to Middle Permian strata (Figures 3 and 4). The grabens trend southeasterly and can be considered as southeastward extensions of the Orogrande Basin. In the southern Sacramento Mountains, Ancestral Rocky Mountain structures also include anticlines and synclines in which erosionally truncated Pennsylvanian strata are overlain unconformably by the Abo Formation (Wolfcampian; Pray, 1961).

The age of formation of these fault blocks is constrained by distribution of strata between the horsts and the grabens. Ordovician strata are present in all of the grabens and on all of the horsts. Silurian, Devonian and Mississippian strata are present in all of the grabens and on some of the horsts. Pennsylvanian and Lower Permian strata of the Hueco Group are present within the grabens but are not present on all of the horsts. Where present on horst blocks, the Pennsylvanian occurs as relatively thin erosional remnants unconformably overlain by the Pow Wow Conglomerate (Lower Permian). The Pow

Wow is correlative with the lower tongue of the Abo Formation of the Sacramento Mountains. Elsewhere on the horsts the Pennsylvanian was either never deposited or has been removed by erosion and Precambrian, Ordovician, Silurian, Devonian, or Mississippian rocks may be overlain unconformably by the Pow Wow Conglomerate (Figure 4). Pow Wow strata thicken markedly into the grabens, indicating syndepositional tectonic movement or perhaps post-tectonic deposition of a molasse-type deposit into a pre-existing structurally defined basin. Where overlain by Pennsylvanian strata, the Mississippian section shows no discernable thickness variation across fault boundaries and is therefore pre-tectonic. Post-Wolfcampian strata also show no discernible thickness variations across horst and graben boundaries and are therefore post-tectonic.

The extensive systems of en echelon folds mapped by Black (1973, 1976) are thought to be Laramide structures. They are concentrated over major Ancestral Rocky Mountain fault trends and are subparallel to those fault trends. They probably represent Laramide deformation of stratified cover rocks during reactivation of the Ancestral Rocky Mountain faults.

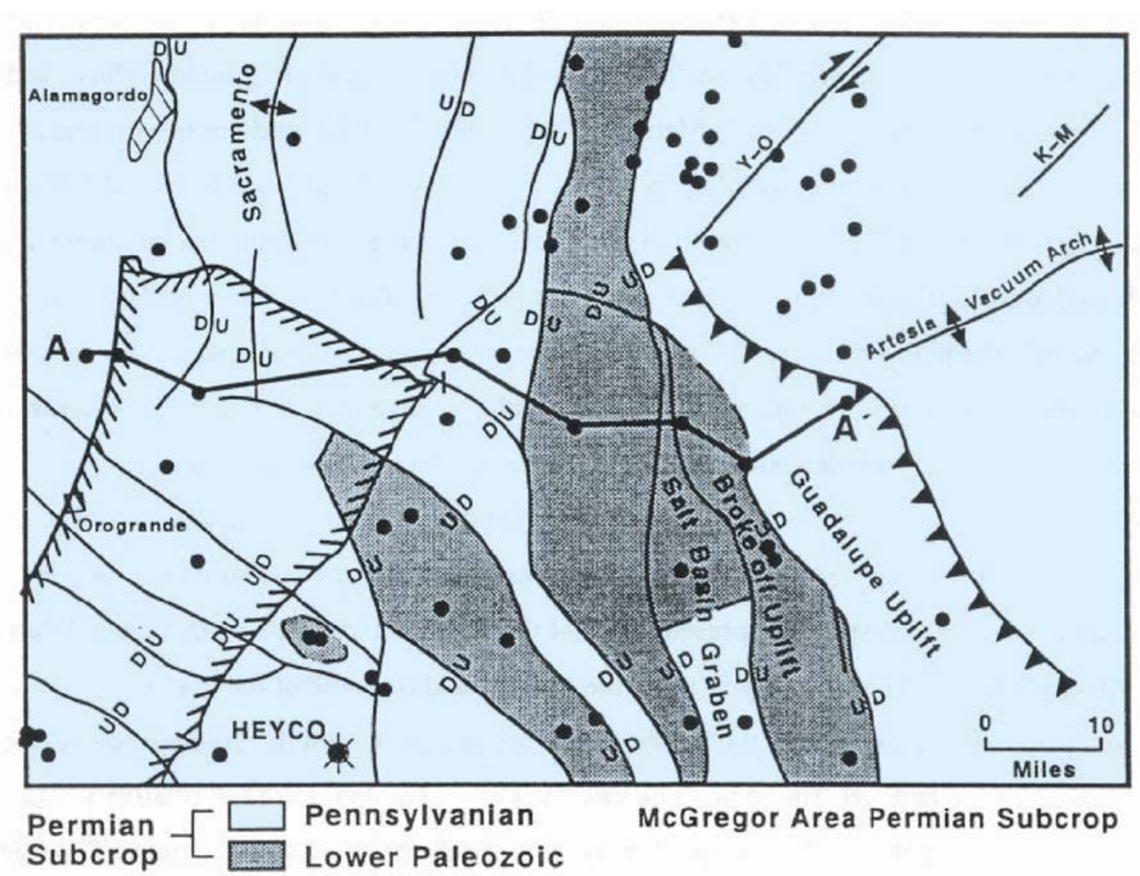

Figure 3. Subsurface tectonic and Permian subcrop map. Boundary of McGregor Range is hachured.

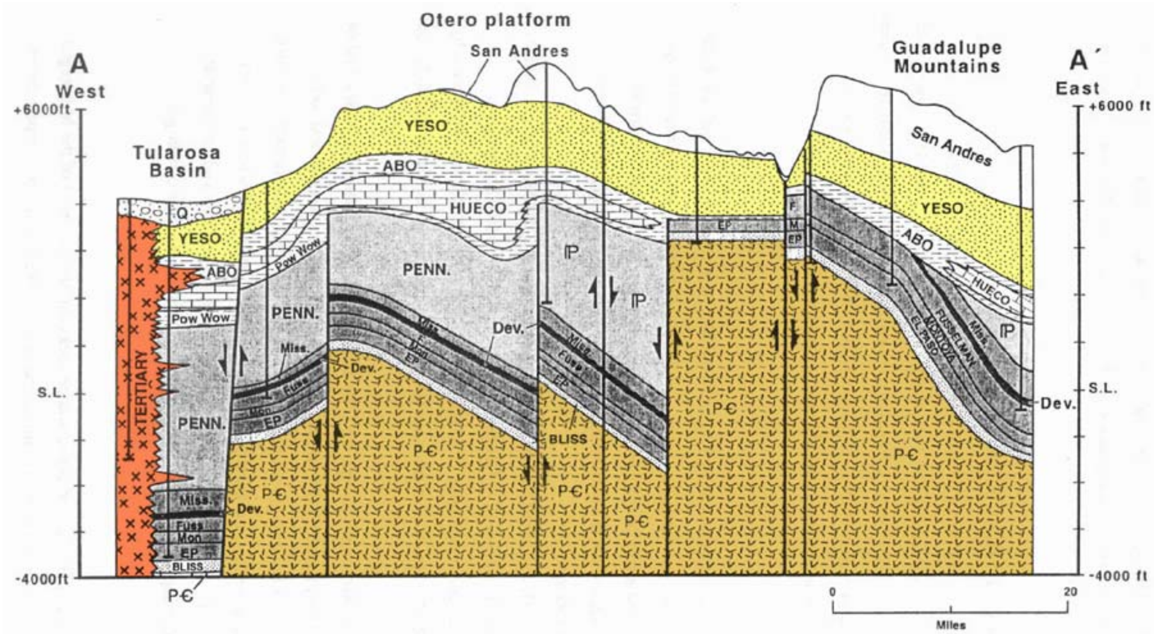

Figure 4. Cross section A-A' indicating complexity of subsurface Ancestral Rocky Mountains structure beneath the Otero platform. See Figure 3 for location.

A northwest-trending reverse fault in the southwest part of the McGregor Range (Figure 3) is well defined by U.S. Army Corps of Engineers core holes (Table 1, wells 9 through 12). This fault offsets Paleozoic strata from Silurian to Pennsylvanian age and is of probable Laramide age. It is parallel to other Laramide reverse faults in southwestern New Mexico and northern Chihuahua and represents northeast compression during the Laramide (Mack and Clemons, 1988; Corbitt, 1988). Other reverse faults with similar orientation may be present beneath the Recent aeolian and alluvial sediments that cover Otero Mesa. A well-defined northwest-southeast surface drainage pattern present at the surface may be related to underlying structure.

The predominant post-Laramide Tertiary structures in the region are the normal faults that bound the Tularosa Basin and form the west face of the Sacramento Mountains. These were formed during extensional basin and range faulting (Healy et al., 1978; Pray, 1961). In the Jarilla and Hueco Mountains, upward doming of Paleozoic strata by Tertiary-age igneous stocks resulted in radial dips away from major igneous bodies.

Petroleum Source Rocks

Petroleum source rocks in the region are Devonian shales and cherts, Mississippian shales and limestones, and Pennsylvanian limestones and shales. Petroleum source rock data (New Mexico Bureau of Mines and Mineral Resources et al., 1998) obtained from outcrops and wells drilled both within the grabens and on top of horst blocks indicate that other stratigraphic units have insufficient total organic carbon (TOC) to be considered significant source rocks or are thermally immature (Figure 5).

PERIOD	LITHOSTRATIGRAPHIC UNIT	TOC (percent)	THERMAL MATURITY
Quaternary	sands & gravels	super low	immature
Tertiary	sands & gravels igneous intrusives	super low	immature
Permian	San Andres		immature
	Yeso	0.3 - 1.08%	immature
	Abo		
	Hueco	0.15 - 0.96%	immature
Pennsylvanian	Panther Seep	0.23 - 0.96%	immature to mature (see Fig. 8)
Mississippian	undifferentiated	0.14 - 2.92%	mature (south) moderately mature (north)
Devonian	upper shale	3.67%	immature to mature (see text)
	middle chert	0.18 - 1.17%	
	lower shale	0.7 - 3.68%	
Silurian	Fusselman	< 0.2%	
Ordovician	Montoya El Paso Bliss	< 0.2%	
Precambrian		super low	

Figure 5. Summary of petroleum source rock analyses in McGregor Range and adjacent areas.

Devonian

Devonian strata are thermally mature, oil-prone source rocks in the McGregor Range. TOC values of the black shales range from 0.7 to 3.9 percent. Kerogens are predominantly amorphous and herbaceous types. Although data are very limited because of a paucity of outcrops and because few wells have drilled sufficiently deep to penetrate the Devonian, the section appears to be mature and within the oil window throughout most of the McGregor Range.

In the northern part of the Range in the Sacramento Mountains (Figure l), the Devonian is immature to marginally mature. On an uplifted fault block in Grapevine Canyon, the

Devonian is immature to marginally mature with a Thermal Alteration Index (TAI) of only 1.5. This fault block was interpreted by Pray (1961) to be an Ancestral Rocky Mountains structure. It was never buried to a sufficient depth for oil generation.

In the southern part of the McGregor Range, the Devonian is moderately immature with a TAI of 2.0 to mature with a TAI of 3.4 at depths of 1500 ft in the U.S. Army Ft. Bliss geothermal test wells. Thermal maturity varies vertically within a single well. Data are too limited to explain maturity variations.

The Devonian in the Tularosa Basin is buried to depths of more than 6500 ft where it is very mature. TAI values are 3.8 to 3.9. These strata are in the condensate-wet gas window and any generated petroleum that still resides at these depths has probably been converted to condensate or wet gas.

Mississippian

Mississippian strata contain thermally mature, oil-prone source rocks throughout most of the McGregor Range and surrounding areas. TOC in both shales and limestones is more than sufficient for petroleum generation, ranging from 0.22 percent to 2.92 percent, exceeding 1.0 percent in most places. In the southern part of the Range, Mississippian rocks are mature and within the oil window with TAI values in the 2.4 to 3.1 range. In the northern part of the McGregor Range, Mississippian strata are moderately mature with TAI values in the 2.2 to 2.5 range, sufficient for generation of immature or heavy oils. Kerogens in Mississippian source rocks are algal, amorphous, and herbaceous types that will mostly generate oil and associated gas upon maturation.

Pennsylvanian

Pennsylvanian strata are mature, oil-prone source rocks throughout most of the McGregor Range. Pennsylvanian strata are mostly basinal black lime mudstones that form good to excellent source rocks. TOC values vary from 0.23 to 1.62 percent, more than sufficient for petroleum generation in carbonates. Unlike older strata, sufficient data exists from outcrops, cores, and drill cuttings to map thermal maturity patterns in the Pennsylvanian (Figure 6). The Pennsylvanian is immature over a northwest-trending horst block in the central part of the Range. Stratigraphic relationships reveal that the horst block is an Ancestral Rocky Mountains structure (Figure 3). In deeper areas to the north and south of this fault block, the basinal limestones are more mature and within the oil window. Further to the south, maturity appears to increase near the large Tertiary-age igneous intrusions that form the core of the Hueco and Cornudas Mountains. It is postulated that heat derived from the Tertiary intrusions enhanced thermal maturity of source facies. In the Tularosa Basin to the northwest, higher temperatures associated with deeper burial have matured the Pennsylvanian into the condensate and gas windows.

Kerogens within the Pennsylvanian source rocks are mixed amorphous, herbaceous, woody, and inertinitic types. Amorphous and herbaceous types appear to be dominant in most places. Therefore, oil and associated gas are the most likely hydrocarbons to have been generated upon maturation.

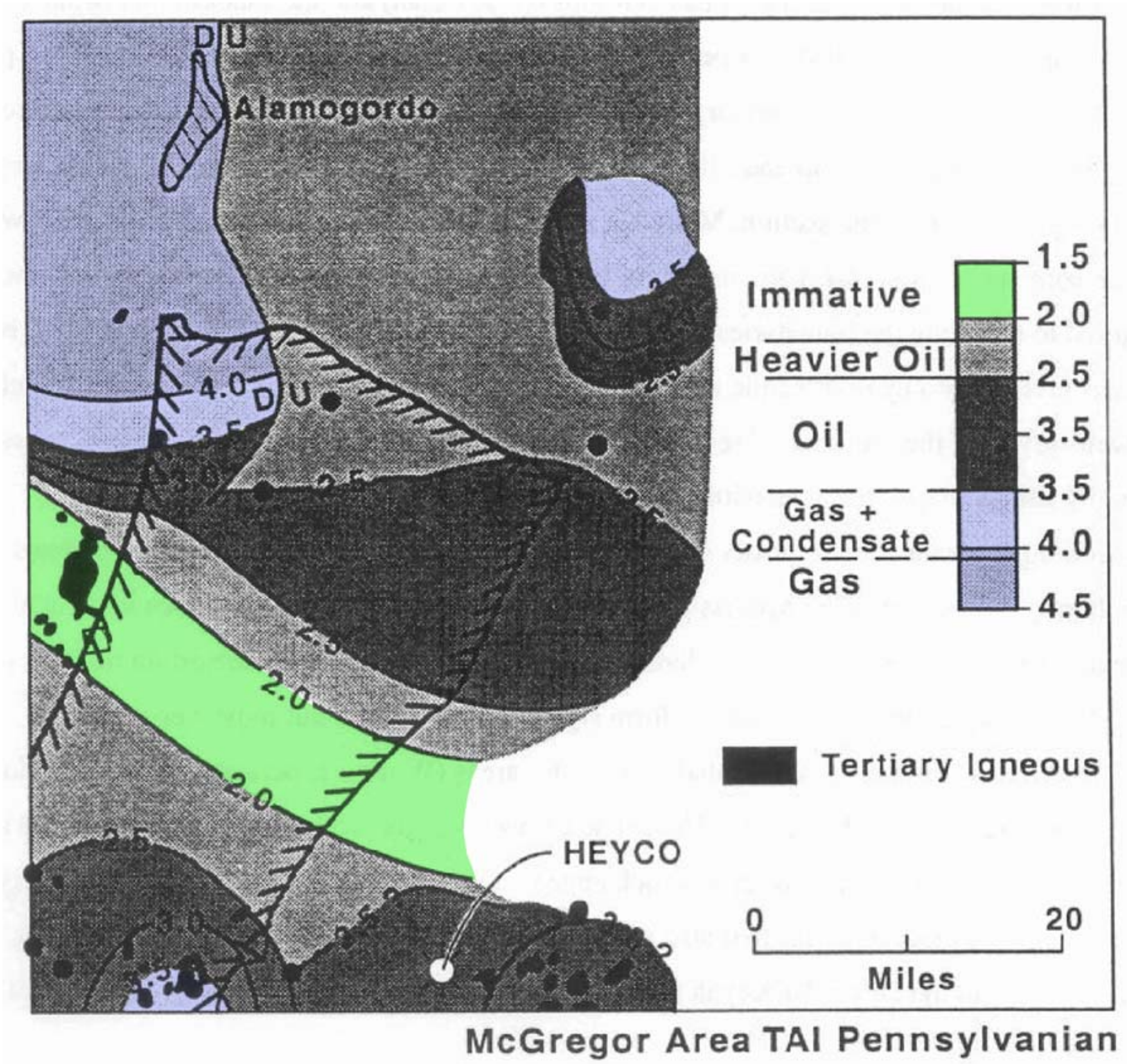

Figure 6. Thermal maturity of Pennsylvanian source rocks in McGregor Range and adjacent areas.

Hueco Group

Limestones of the Hueco Group have TOC values ranging from 0.15 to 0.96 percent. However, the kerogens in many samples contain substantial amounts of nongenerative inertinite. Generative types of kerogen are present in insufficient amounts for significant hydrocarbon generation and expulsion. Moreover, the Hueco is mature and within the oil window only near intrusive igneous bodies in the Hueco Mountains and in the deeper parts of the Tularosa Basin. The sparse data available indicate it is immature elsewhere, even within the grabens. Therefore, it appears that the Hueco Group is not a major source unit in the region.

Post-Hueco strata

Samples from Permian strata shallower than the Hueco Group were not analyzed for source rock character. Within the McGregor Range, these strata have either been eroded, crop out at the surface, or are not present at any great depth within the subsurface. Post-

Hueco strata should be thermally immature because underlying strata of the Hueco Group are thermally immature. Therefore, the role of post-Hueco strata as source rocks in a petroleum system is inconsequential.

Petroleum Reservoir Rocks

The main petroleum reservoir targets are Ordovician and Silurian dolostones, Mississippian limestones, Pennsylvanian limestones, and Tertiary-age igneous sills. Other stratigraphic units have either insufficient matrix porosity to be considered as primary reservoir targets (unless fractured) or crop out over large areas and are likely to have been flushed by influent surface waters.

Dolostones of the Montoya and El Paso Groups (Ordovician) and the Fusselman Formation (Silurian) are characterized by well-developed vugular porosity. Several wells drilled on the Otero platform and in the Tularosa Basin have recovered large volumes of water on drill-stem tests or have lost circulation while drilling through the Ordovician and Silurian dolostones, indicating good permeability is widely distributed through this part of the section. Many but not all of the drill-stem tests recovered fresh water, indicating that some petroleum reservoirs may have been flushed by influent surface waters. Additional work is required to delineate the boundaries of flushed and unflushed areas that could conceivably be related to areas favorable to hydrodynamic trapping. Examination of cores from the Fort Bliss geothermal evaluation wells revealed the presence of several exposure surfaces and underlying permeable zones characterized by karst collapse breccias within the Fusselman.

Mississippian strata consist mostly of interbedded shales and thin, fine-grained limestones. Although bioherms are present in the Mississippian of the Sacramento Mountains, Greenwood et al. (1977) concluded that most are too small to be considered major exploratory targets. Waulsortian mounds in the Sacramento Mountains are sufficiently large to form significant reservoirs but most were probably deposited north of the McGregor Range in shallower water areas (W. Raatz, personal communication, 2002). The gas discovered in the Heyco No. IY Bennett Ranch well is produced from an interval within the Mississippian section but the primary reservoir rock appears to be a fractured igneous sill of Tertiary age; seals are probably Mississippian shales that also acted as the source rocks for the gas accumulation. A similar situation exists in the Dineh-Bi-Keyah field of Apache County, Arizona (Danie, 1978). That field has produced oil since 1967.

Pennsylvanian strata in the Sacramento Mountains in the northern part of the McGregor Range consist mostly of limestones and dark-gray to black shales with minor thin sandstones. They are predominantly shelf deposits. Bowsher (1986) documented the presence of numerous shelf and shelf-margin bioherms that, if present in the subsurface, could be reservoir targets.

In the central and southern parts of the McGregor Range, the Pennsylvanian consists primarily of basinal deposits, mostly dark-gray lime mudstones and minor arkosic sandstones. Thin beds of carbonate grainstone were described by Jim Witcher in core from the Fort Bliss geothermal test wells but these form a minor facies. Soreghan and

Giles (2001) documented well-developed algal bioherms in the Panther Seep Formation (Pennsylvanian) in the San Andres Mountains. Factors controlling localization of algal mound growth in the Panther Seep have not been established but are likely to include paleostructural position with intrabasinal positive elements providing more favorable mound nucleation sites. Other possible opportunities for reservoir development are debris flows on the flanks of intrabasinal structures.

Pennsylvanian limestones are permeable in the McGregor Range and adjacent areas. Exploratory wells drilled with rotary rigs have encountered oil and gas shows and have recovered water with drill-stem tests. Cores indicate that permeability is provided by dissolution enhanced vertical to near-vertical fractures and not to matrix porosity.

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