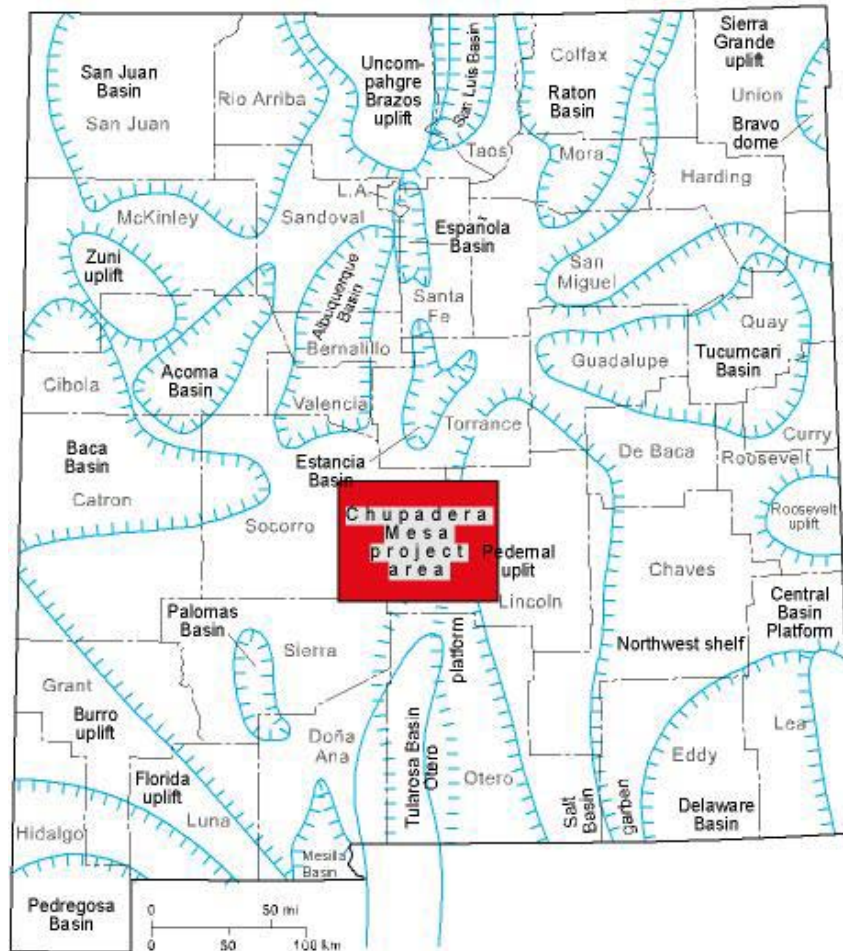


Oil, natural gas and helium potential of the Chupadera Mesa area, Lincoln and Socorro Counties, New Mexico

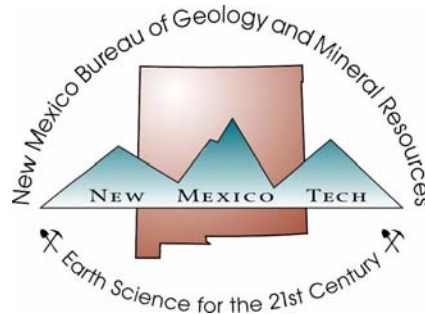


by

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Oil, natural gas and helium potential of the Chupadera Mesa area, Lincoln and Socorro Counties, New Mexico

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ABSTRACT

The Chupadera Mesa region encompasses 3900 mi² in eastern Socorro and western Lincoln Counties, central New Mexico. The area includes varied geological elements including the broad Jornada del Muerto Basin in the west, and the Oscura Mountains and Chupadera Mesa in the medial area. The Laramide-age Sierra Blanca Basin and several isolated mountain ranges formed principally by Tertiary-age igneous intrusive bodies occupy the eastern third of the region.

The Chupadera Mesa area has been sparsely drilled. A total of 45 wells have been drilled within the project area. This is a density of approximately one well for every 85 mi². Many of the wells are shallow and reached total depth in Permian strata. Only 20 wells have been drilled to Precambrian basement. This is a density of one well per 200 mi², or 6.4 townships. Neither oil, natural gas nor helium production have been established. Nevertheless, several of the wells have encountered promising shows of oil, natural gas, and helium.

The geology of the Chupadera Mesa area indicates favorable potential for oil and natural gas. Petroleum source rock facies are concentrated in marine Pennsylvanian strata that blanket the western two-thirds of the project area and attain a maximum thickness of 2200 ft. Dark-gray to black Pennsylvanian shales contain both gas-prone and oil-prone kerogen populations and are thermally mature to the east and west, but marginally mature in the medial area. Maturation into the oil window is caused primarily by heating associated with igneous events during the Tertiary. Favorable reservoirs are Pennsylvanian marine to marginal marine sandstones, continental sandstones of the Abo Formation (Permian: Wolfcampian), and marine to marginal marine sandstones of the

Yeso Formation (Permian: Leonardian). Untested plays include speculated but undrilled late Paleozoic basins that underlie Laramide-age synclines, truncation traps in Pennsylvanian sandstones under a basal Permian unconformity at the eastern pinchout of Pennsylvanian strata, and northward pinchout of Ordovician carbonate rocks in the southern part of the project area. There is also limited coalbed methane potential in Cretaceous strata in the Jornada del Muerto and Sierra Blanca Basins.

The Chupadera Mesa project area also has favorable potential for helium. Uranium-bearing rock types favorable for the formation of radiogenic helium are present. In addition, high-angle fracture and fault systems and Tertiary-age igneous thermal events characterize the area and are favorable to the release of radiogenic helium from the Precambrian basement into the overlying Paleozoic sedimentary column. Pennsylvanian and Permian shales and Permian anhydrites and salt beds are favorable seals for helium. Analyses of gases recovered from one well on Chupadera Mesa indicate the presence of helium in substantial amounts. Nonburnable gases recovered from other wells may also contain helium.

INTRODUCTION

The Chupadera Mesa area lies in central New Mexico in eastern Socorro and western Lincoln Counties (Fig. 1). Areal extent is approximately 3900 mi². The project area encompasses several diverse geomorphic elements including the broad Jornada del Muerto Basin in the west, the Oscura Mountains and Chupadera Mesa in the medial area, and several isolated mountain ranges formed principally by Tertiary-age igneous intrusive bodies in the eastern third of the area (Fig. 2). The area is sparsely populated. There are two major towns in the area, Carrizozo (population approximately 1200) and Capitan (population approximately 760). Land ownership is interspersed state (Fig. 3), federal and private. Federal lands in the western two-thirds of the area are managed mostly by the U.S. Bureau of Land Management. And are managed mostly by the U.S. Forest Service in the eastern third of the project area. Most of the area west of the east flank of the Oscura Mountains and south of U.S. Highway 380 is within the boundaries of White Sands Missile Range and access for surface travel as well as oil and gas leasing is restricted. Several natural gas pipelines traverse the area, including two northwest-

southeast interstate pipelines in the northeastern part of the region. There are smaller pipelines that supply the towns of Capitan and Carrizozo.

No oil or natural gas production has been established in the Chupadera Mesa project area. Forty-five wells have been drilled within the area. These have targeted mainly oil or natural gas prospects based on mapping of anticlines at the surface. In recent years helium gas has also become an attractive target. Paleozoic strata in the

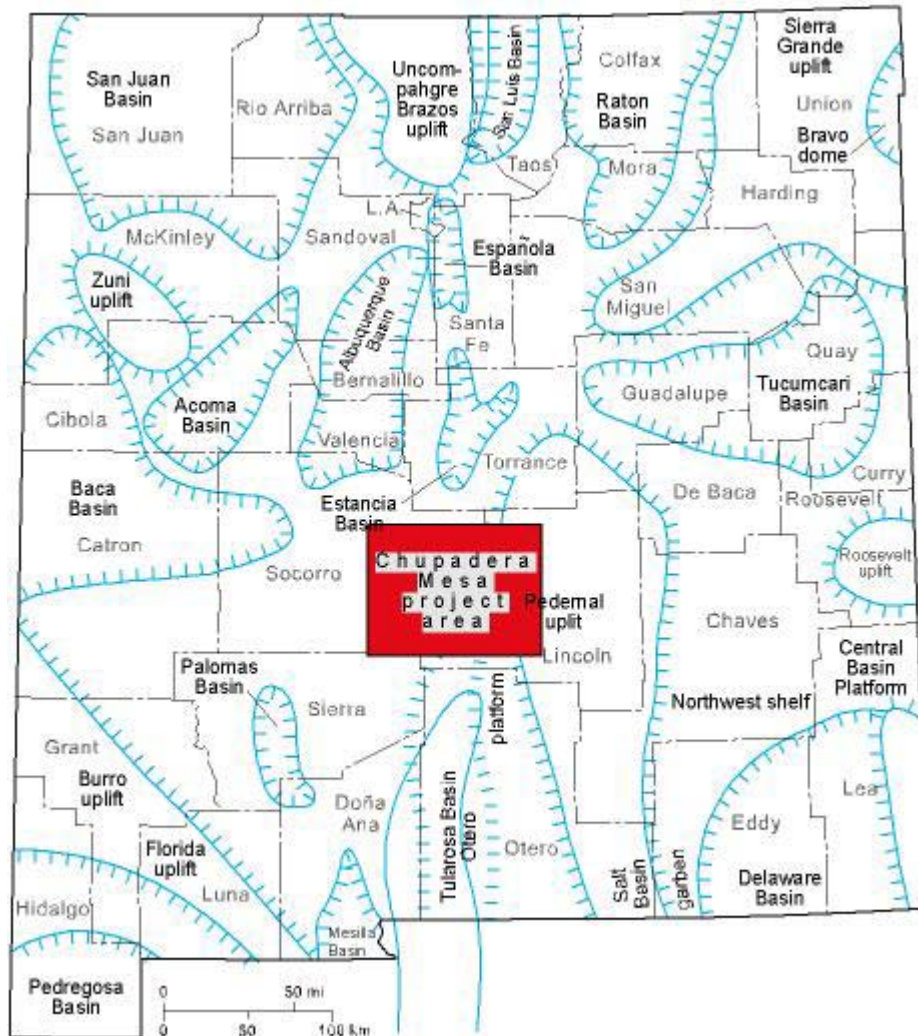


Figure 1. Location of the Chupadera Mesa project area and major basins and other tectonic elements in New Mexico.

region range in age from Cambrian to Permian (Figs. 4, 5). Mesozoic strata include Triassic red beds and Cretaceous shales, sandstones, and coals. Principal stratigraphic

units of interest to oil, gas and helium explorationists include Ordovician dolostones, Pennsylvanian sandstones and limestones, and Lower Permian sandstones and carbonates.

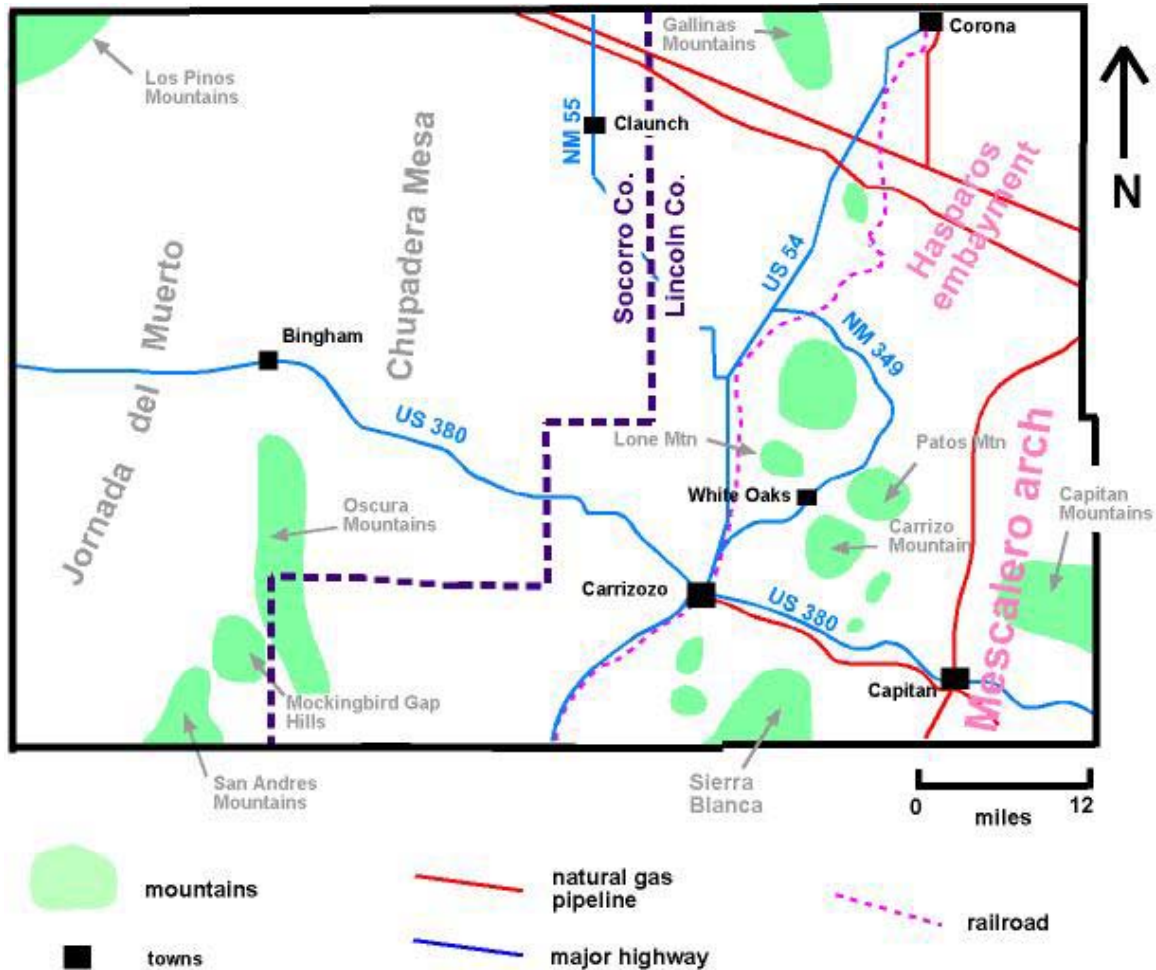


Figure 2. Major geomorphic elements, towns, highways, natural gas pipelines and railroads in the Chupadera Mesa project area.

The purpose of this report is to document past oil and gas drilling and exploration activity and to provide an overview of the petroleum geology and petroleum and helium potential of the Chupadera Mesa area. The report is meant to provide a useful source of data for those involved in the exploration for oil, natural hydrocarbon gas, and helium and is also designed to provide an introduction to the petroleum geology of the area. Data presented in this report were obtained mostly from the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. Supplementary data were obtained from the New Mexico Oil Conservation Division.

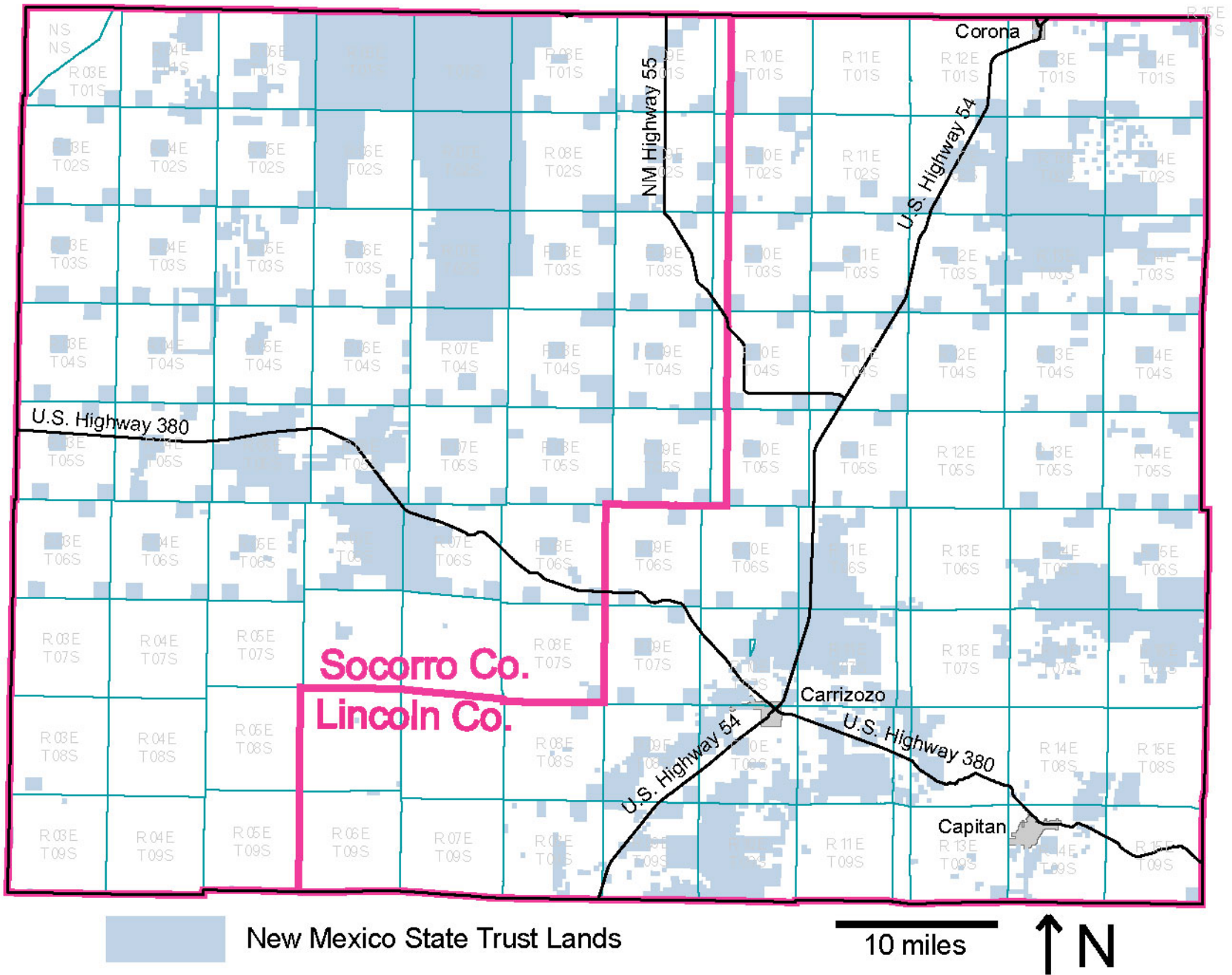


Figure 3. Distribution of New Mexico State Trust Lands in Chupadera Mesa project area.

AGE		STRATIGRAPHY	THICKNESS (feet)
Quaternary		unconsolidated sediments	0-thin
Tertiary		intrusives, volcanics, continental sediments	0-2000
Cretaceous		Mesaverde	0-800
		Mancos	0-1000
		Dakota	0-200
Triassic		Chinle	0-1000
		Santa Rosa	
Permian	Ochoan	absent	0
	Guadalupian	Artesia	0-325
	Leonardian	San Andres	0-975
		Glorieta	0-400
		Yeso	1000-4300
		Abo	230-1700
	Wolfcampian	Bursum	0-390
Pennsylvanian	Virgilian	Madera	0-2200
	Missourian		
	Des Moinesian		
	Atokan	Sandia	
	Morrowan	absent	0
Mississippian		Lake Valley	0-15
Devonian		undivided	0-30
Silurian		absent	0
Ordovician		Montoya	0-43
		El Paso	0-128
Cambrian		Bliss	0-19
Precambrian		granodiorite, diabase, monzonite, meatquartzite	

Figure 4. Stratigraphic column of Phanerozoic sedimentary units in the Chupadera Mesa project area.

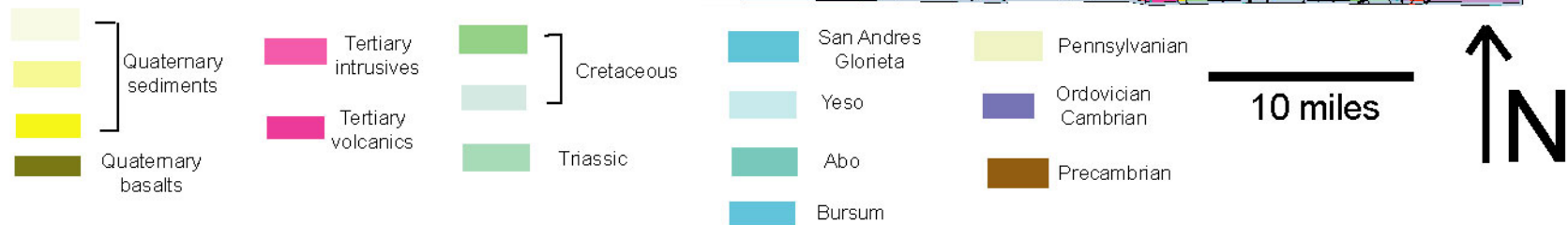
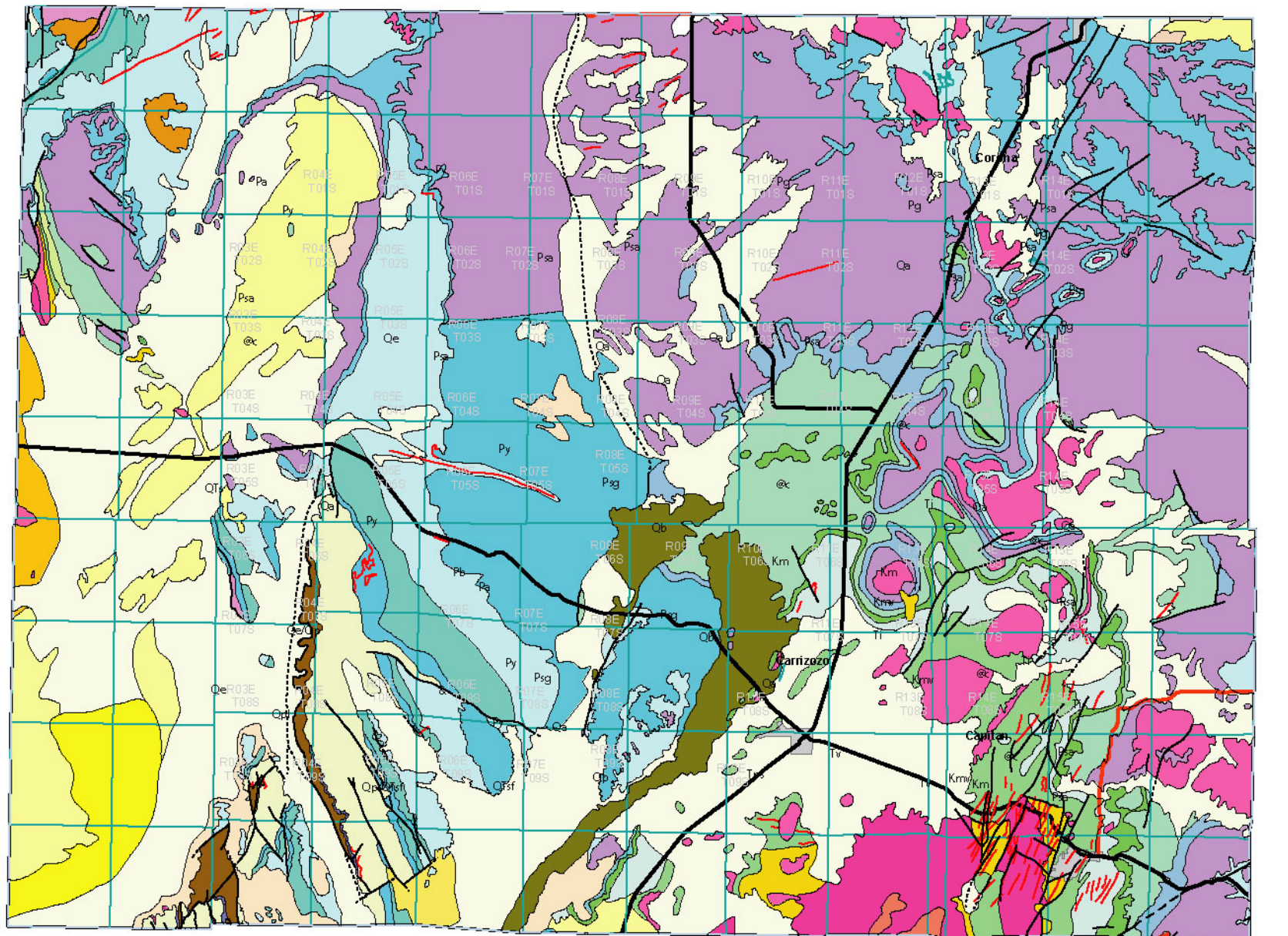


Figure 5. Surface geologic map of Chupadera Mesa project area.

Bouguer gravity anomaly data was graciously supplied by Dr. G. Randy Keller and Raed Aldouri of the University of Texas at El Paso. The maps included in this report were developed explicitly for this report using data obtained from the sources mentioned above.

This report contains four major parts. **The first part of this report** is this pdf document which presents key geologic data, maps and analyses for the Chupadera Mesa area and presents a summary of the petroleum geology. **The second part of this report** is a database of oil and gas exploratory wells (*Chupadera wells.xls*). the database contains key well data for each well including location (expressed in both the section-township-range cadastral system of the U.S. Bureau of Land Management and as latitude-longitude coordinates), well depths, depths to top of stratigraphic units, and well test and show data. The well database is more fully described in Appendix I of this report. **The third part of this report** contains data on petroleum source rock data (*Chupadera source rocks.xls*) including well location, sample depth, and a variety of parameters related to organic richness, kerogen type, and maturation level. **The fourth part of this report** is a series of geographic information systems (GIS) maps of key parameters useful in oil and gas assessments. The GIS maps are presented in *ArcReader* and *ArcMap* format. These maps are also presented statically as part of this pdf document, but the GIS portrayal allows the user to overlay the maps on top of each other. *ArcReader* is a free program made available by ESRI Corp. that allows the user to view the maps after software is downloaded from this CD-ROM but does not allow modification of the maps with new data that the user may have. For this reason, all maps are also presented as an *ArcMap* project. If the user has *ArcMap* software, then the maps may be modified to fit additional data or additional map types may be created from either the well database or the source rock database, or from databases that the user may supply. All GIS maps utilize the data presented in the well and source rock databases. In order to use *ArcReader*, you must have one of the following three operating systems installed on your computer: 1) *Windows 2000*; 2) *Windows XP*; or 3) *Windows NT 4.0 with Service Pack 6a or later*.

ACKNOWLEDGMENTS

This contract was funded by the New Mexico State Land Office (The Honorable Patrick H. Lyons, Commissioner of Public Lands) through contract 03-18. Larry Kehoe, formerly Assistant Commissioner for Mineral Resources of the State Land Office, and Jami Bailey, Deputy Director of the Oil, Gas & Minerals Division of the State Land Office, were instrumental in acquiring funding for this work. Joe Mraz of the State Land Office provided helpful input into the design and purpose of this project. Tom Kaus of the New Mexico Bureau of Geology and Mineral Resources drafted the cross sections. Lynsey Rutherford, an undergraduate student at New Mexico Tech, helped prepare the well samples for source rock analyses. Irene Roselli, an undergraduate student at New Mexico Tech, entered much of the data into the databases. As always, the staff of the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources, Amy Trivitt Kracke and Annabelle Lopez, contributed through their meticulous organization of data. Dr. Geoffery S. Bayliss of Geochem Laboratories, Inc. performed most of the source rock analyses listed in Appendix II (*Chupadera source rocks.xls*). Ben Donegan, instrumental in much of the recent exploration in the region, shared his information on the recent wells drilled by Manzano Oil Corp. and Primero Operating and willingly discussed his ideas on oil, natural gas, and helium in the region. Ben arranged for funding for several source rock analyses. The data and ideas expressed in this report are the responsibility of the senior author.

GEOLOGIC STRUCTURE

Three structure maps were prepared for this project: a map of structure on top of the Precambrian basement (Fig. 6), a map of structure on the upper surface of the Abo Formation (Fig. 7), and a map of structures at the land surface (Fig. 8). The Precambrian and Abo structure maps are contour maps based primarily on subsurface data. Contouring techniques are discussed below. Two east-west structural cross sections (Figs. 9, 10) were also constructed.

Contouring techniques

Primary data used in map preparation are from petroleum exploration wells (see accompanying Microsoft Excel database *Chupadera wells.xls*). In most of the wells, depth to top of the Abo Formation and top of the Precambrian were identified by examining and correlating wireline borehole logs, sample logs, and drill cuttings on file at the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. For wells that had no logs available, stratigraphic data were obtained from scout cards and other drilling records. Because of the lack of consistency between tops obtained from scout cards and tops obtained from borehole logs and drill cuttings, more credence was given to the latter information when constructing the contour maps. For selected wells, drill cuttings were examined in order to determine the depth range of stratigraphic units within the wells.

Contouring was aided by surface geologic maps and regional tectonic maps (Osburn, 1984; Bachman, 1968; Griswold, 1959; Kelley, 1971, 1972). These maps were used to obtain structural strike and dip directions of strata as mapped at the surface and also to locate faults and folds that have been mapped at the surface. In combination with topographic maps, surface geologic maps were used to obtain structural elevation of the upper contacts of Precambrian basement and the Abo Formation where they crop out. Unpublished structure maps by Ed Beaumont that are based on aerial photography and remote sensing were also employed in mapping the exact locations of structures at the surface.

Contouring was also aided by gravity and aeromagnetic data. The statewide Bouguer gravity anomaly and aeromagnetic intensity maps (Keller and Cordell, 1983; Cordell, 1983) were used as well as local Bouguer gravity anomaly data provided by Dr. G. Randy Keller of the University of Texas at El Paso. The data obtained from Keller

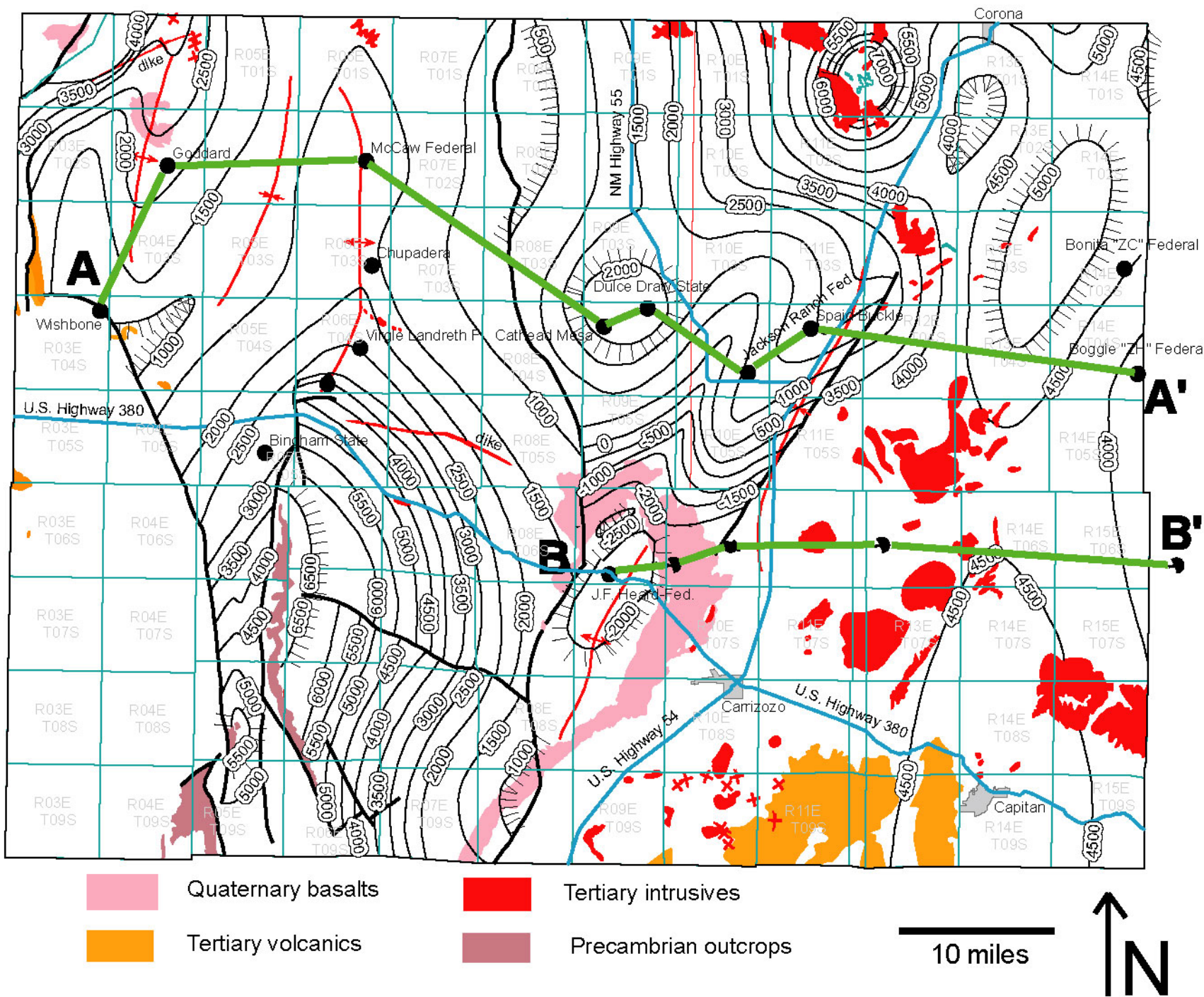


Figure 6. Precambrian structure contour map and outcrops of Quaternary basalts, Tertiary intrusive rocks, Tertiary volcanic rocks and Precambrian basement rocks. Contour interval equals 500 ft. datum is sea level.

Gallinas Mountains

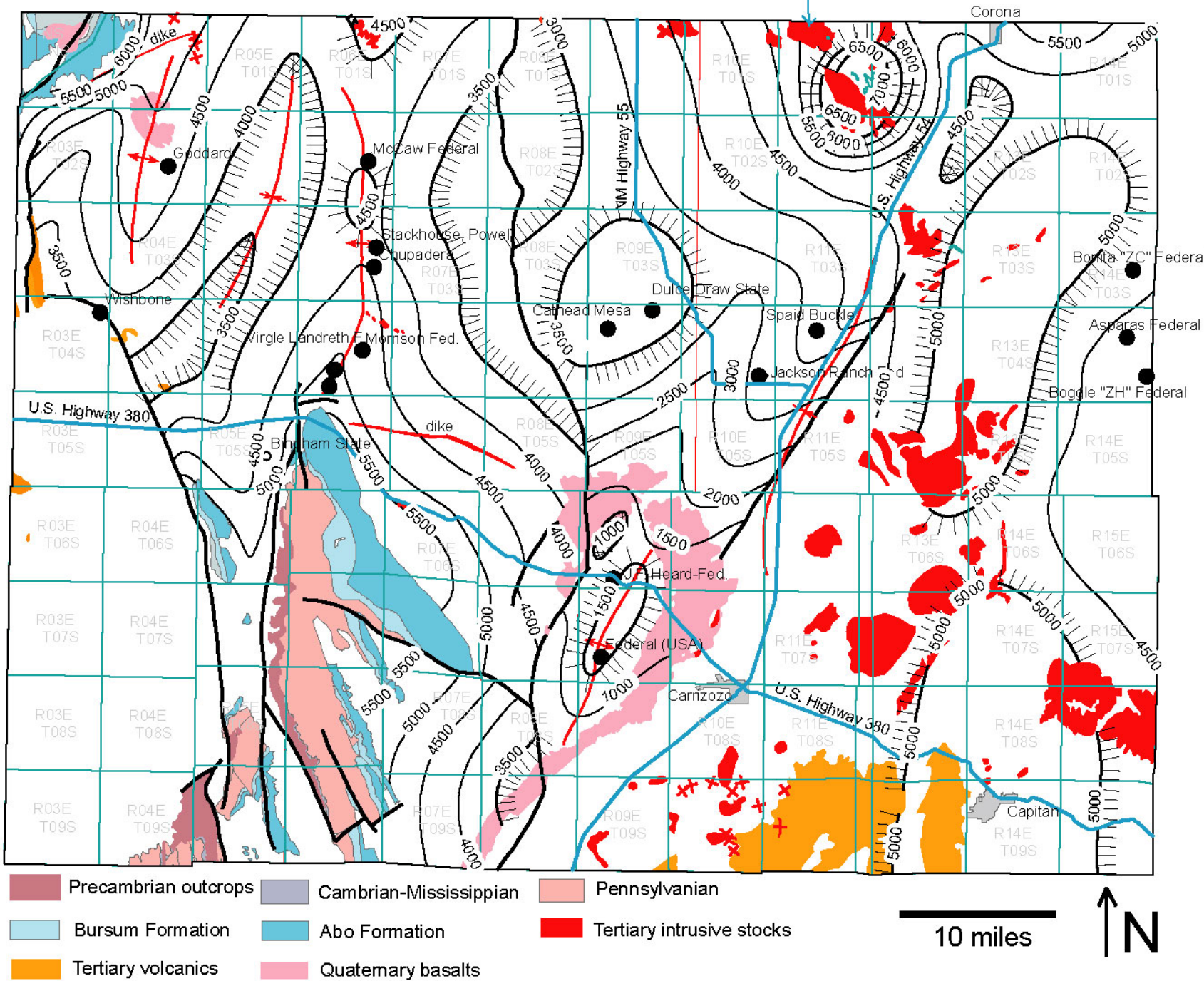


Figure 7. Structure contour map on top of Abo Formation. Contours in feet above sea level. Contour interval equals 500 ft.

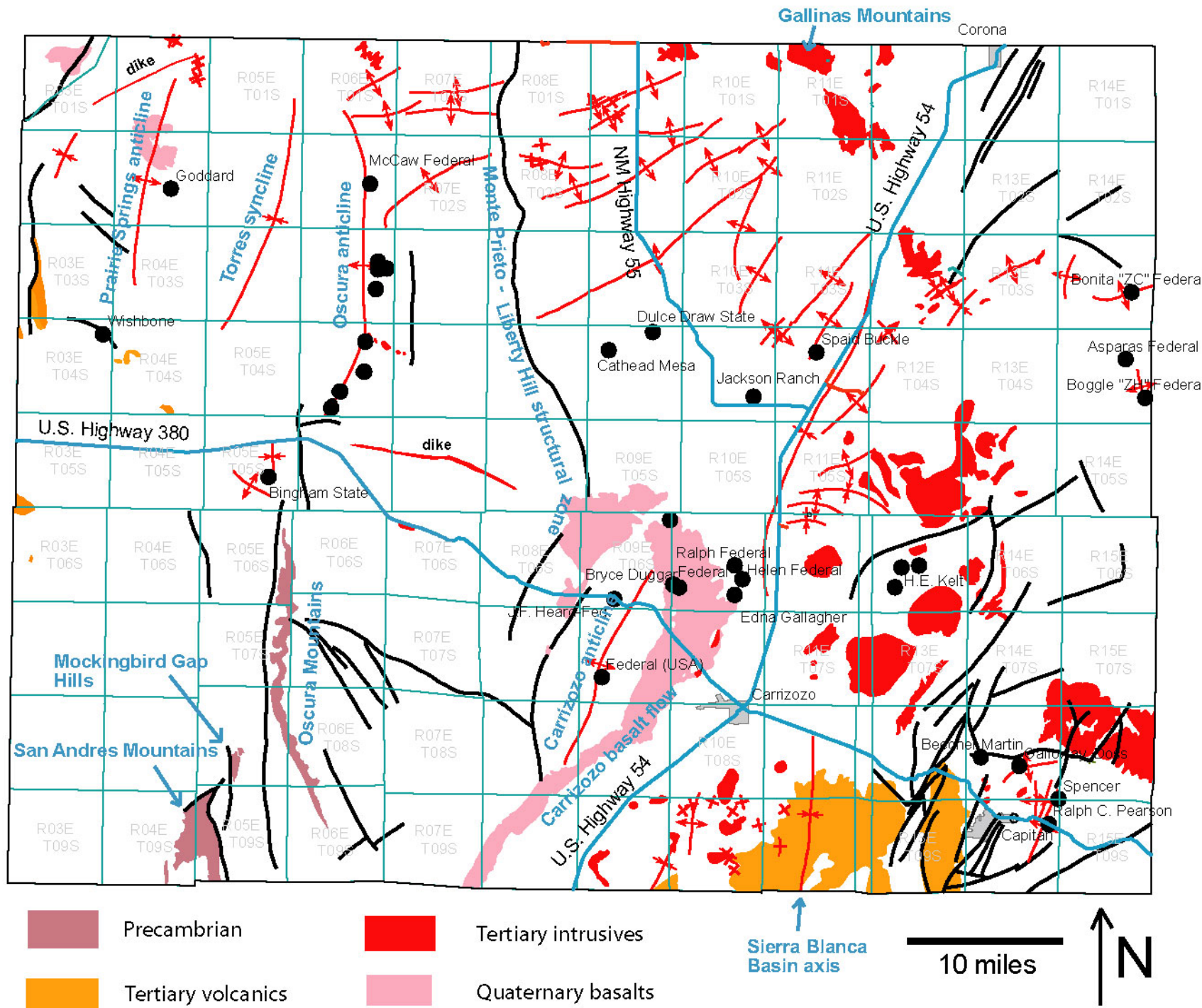


Figure 8. Structures mapped at the land surface. Structures from Osburn (1984), Griswold (1959), Kelley (1971, 1972) or as discussed in text.

Jornada del Muerto Basin

Chupadera Mesa

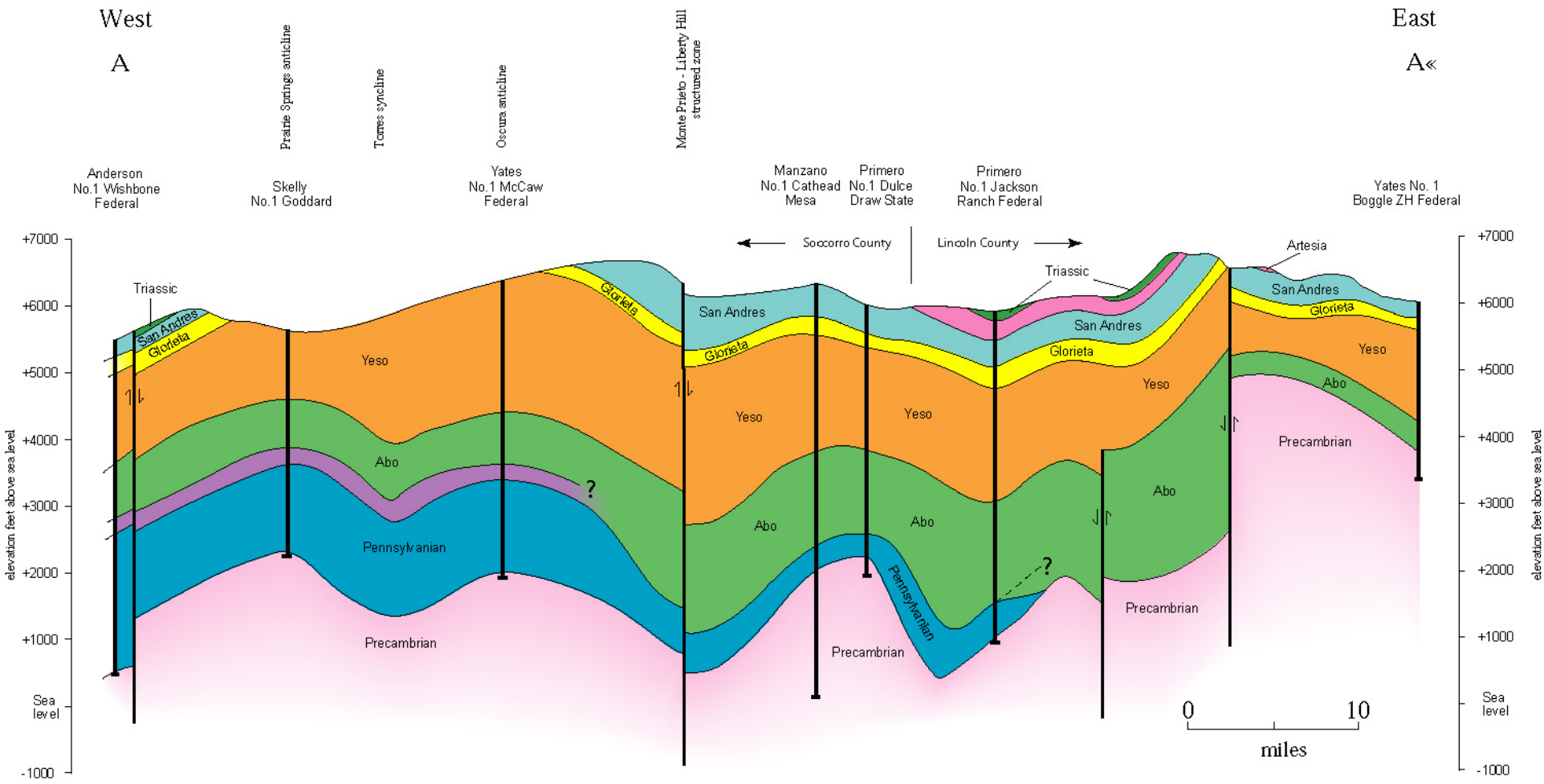


Figure 9. Structural cross section A-A'. See Figure 6 for location.

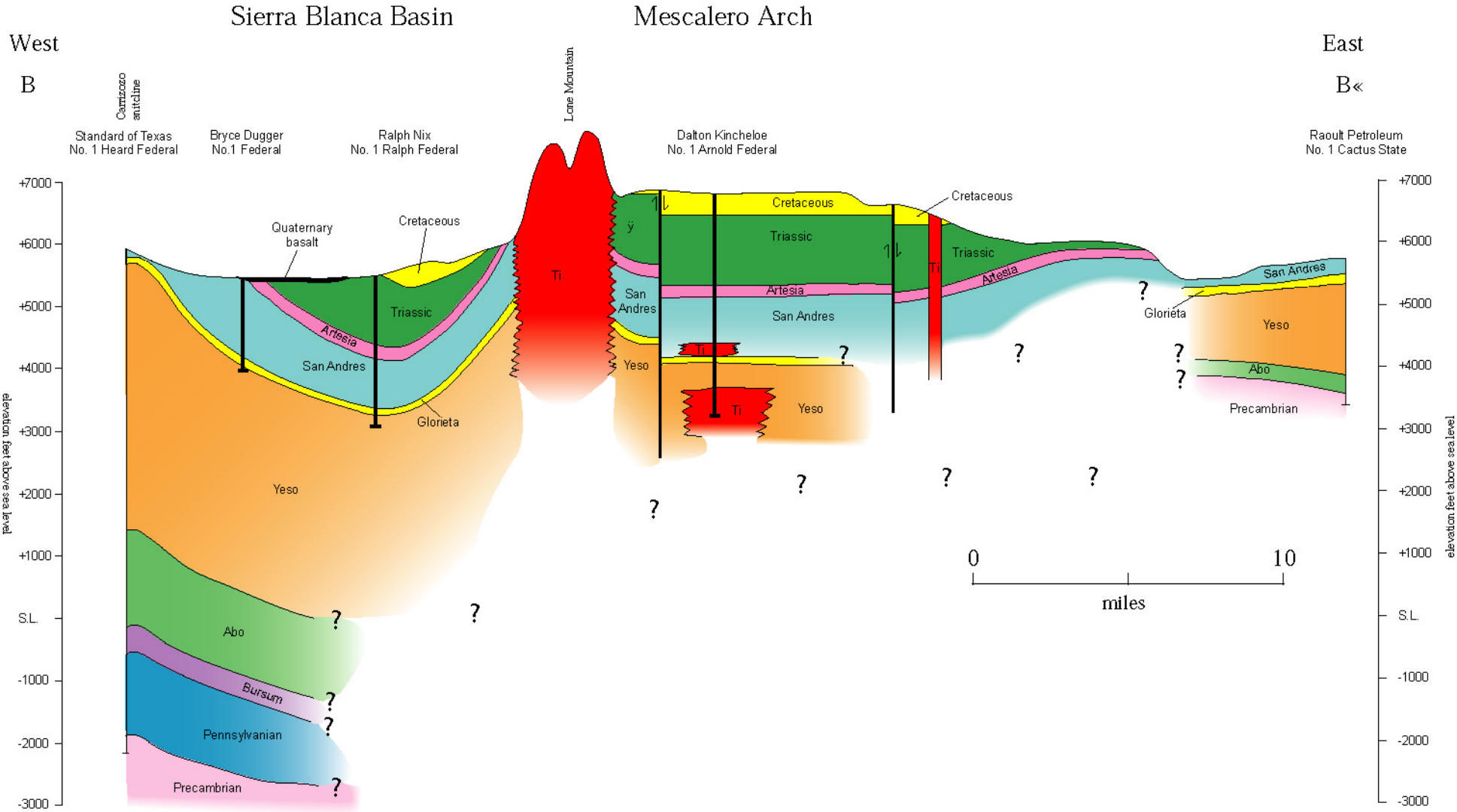


Figure 10. Structural cross section B-B' See Figure 6 for location.

were contoured using *Surfer version 8.0* (*Surfer version 8.0* is a registered trademark of Golden Software, Inc.) with the default kriging method (Fig. 11).

Major mapped surface structures and depth to Precambrian basement, as observed in wells, are roughly discernable from the Bouguer gravity anomaly maps in the western half of the project area. Gravity data appear to be partially obscured by variations in the rock types that constitute the basement (mainly granite, diorite, gabbro, metasediments) as well as by intrusive bodies of Tertiary age. Therefore, Bouguer gravity anomaly data were used as a rough guide to contouring in the western half of the project area.

In the eastern half of the project area, the Bouguer gravity map appears to indicate trends of the large Tertiary-age igneous intrusive bodies that inhabit the region. The gravity signal from these bodies appears to mask the gravity signal associated with structural relief of the Precambrian basement. In addition the Precambrian does not have uniform composition in this region and is comprised of granitic rocks, diorite, gabbro, and metasediments, all of which have different densities and therefore different gravity signatures, further complicating the gravity signature.

The available regional aeromagnetic anomaly map was not useful for mapping basement structure. A number of igneous dikes that crop out at the surface or were encountered in wells contain magnetic minerals. These undoubtedly help mask the magnetic signatures associated with structural relief of the Precambrian basement. Larger igneous bodies that were the source of the magmas that formed the dikes may also bear magnetic minerals and further mask the structural signature. More closely spaced aeromagnetic survey lines would almost certainly help locate and map additional dikes and sills that have intruded the Phanerozoic section along joints and faults but lie at sufficient depth that they have not been exposed by erosion. Aeromagnetic anomaly maps with dense data spacing were not available for this project.

Reflection seismic lines would also help to define subsurface structure. Reflection seismic lines were not available for this project. Apart from two short, proprietary lines that were recorded in the area near the Cathead Mesa and Dulce Draw wells, it is not believed that any reflection seismic lines have been recorded within the project area.

Precambrian structure contour map

Precambrian structure (Fig. 6) is dominated by the large tectonic elements that command the structure of the region. Most apparent in the central part of the region are

Chupadera Bouguer Gravity Anomaly

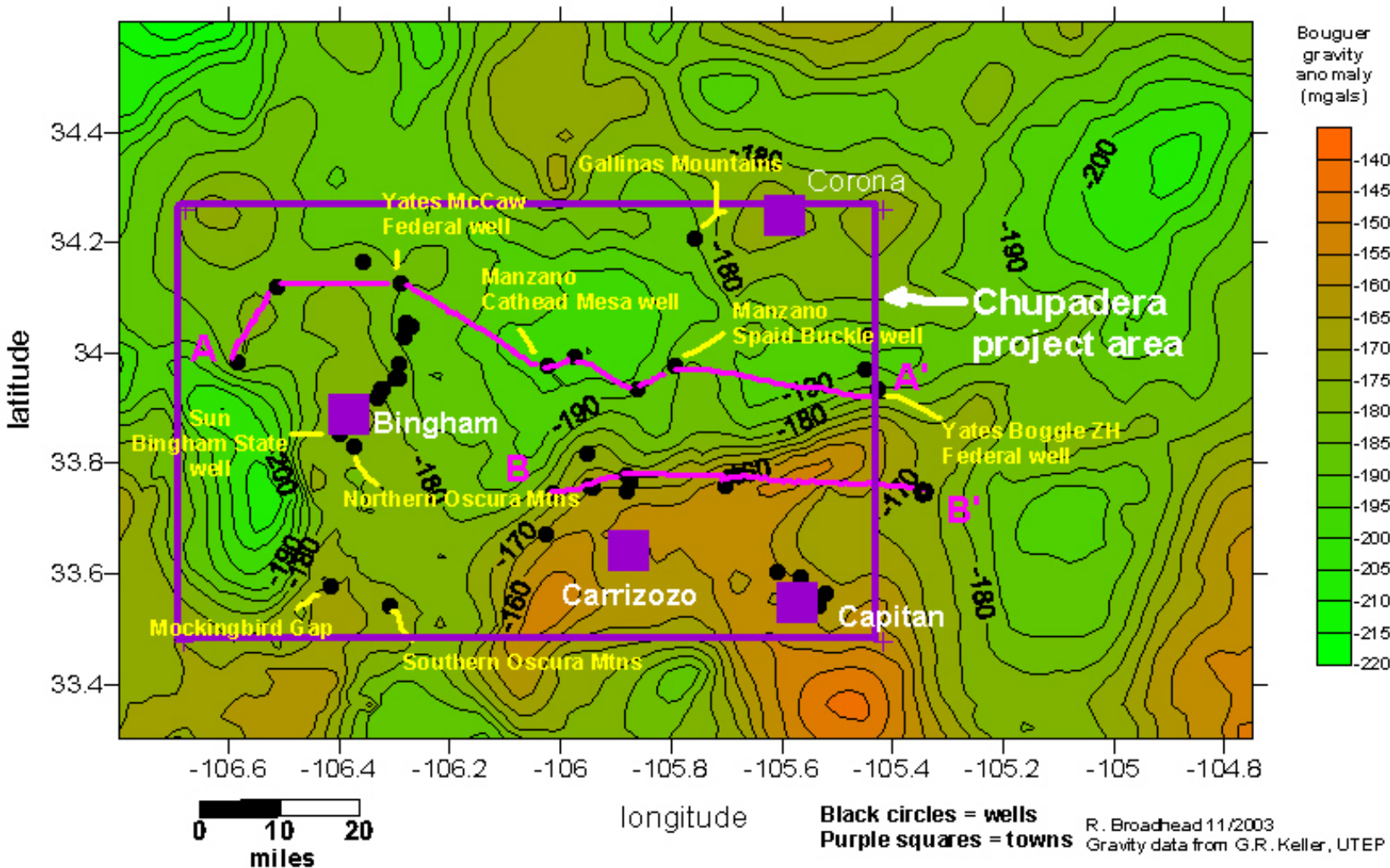


Figure 11. Bouguer gravity anomaly map of Chupadera Mesa project area and surrounding region. Contoured from gravity anomaly data supplied by G.R. Keller of the University of Texas at El Paso. Contours in milligals.

the fault block that forms the Oscura Mountains and its northern extension, the Oscura anticline. The Gallinas Mountains and the Mescalero arch form a north-south oriented structural highland in the eastern third of the project area. The eastern dip slope of the Los Pinos Mountains forms a prominent structural and topographic highland at the northwestern margin of the Chupadera Mesa project area.

The Precambrian structure of the north-central and northwestern parts of the project area are dominated by the north-south trending anticlines and synclines that have been mapped at the surface: the Prairie Springs and Oscura anticlines and the Torres syncline as well as a synclinal area east of the Oscura anticline (Figs. 6, 8). The folds all exhibit significant plunge in either a northerly or southerly direction. The structural configuration of the anticlines has been reasonably well established by surface maps and by exploratory wells that have targeted prospects on the anticlines. Depth to Precambrian basement is known from the wells. However, the intervening synclinal areas have not been drilled so depth to Precambrian basement and configuration of the basement has not been established in these areas.

These anticlines and synclines are almost certainly Laramide in age because Mesozoic strata are involved (see map by Osburn, 1984). Regional Laramide compression produced these folds, which are parallel to major Laramide structures in New Mexico (see Cather, 2002). The Precambrian is composed of brittle igneous lithologies in this region and it is unlikely that this brittle basement deformed plastically under Laramide compression. If this is the case, then the brittle basement must have deformed by faulting. Stratified Phanerozoic cover rocks were folded over the fault-bounded basement blocks, resulting in the system of anticlines and synclines we see at the surface. Direct evidence for this form of structural deformation can be seen in the central part of the project area where the fault-bounded Oscura uplift grades northward into the Oscura anticline, which in turn plunges north into the subsurface. Vertical displacement along the faults that bound the western side of the Oscura uplift was sufficiently large to rupture the stratified cover rocks and the faults penetrated to the surface. Without additional subsurface control it is not possible to determine the locations of faults that bound the Torres syncline and the Prairie Springs and Oscura anticlines at the Precambrian level. Therefore, these features are contoured without faults on the Precambrian structure map.

Many Laramide structural features in New Mexico are thought to have developed by reactivation of late Paleozoic Ancestral Rocky Mountains structures (Cather, 2002; Broadhead et al., 2002; Broadhead, 2000). Although there is no direct evidence from either seismic lines or drill holes, it is possible that the anticlines and synclines mapped at the surface overlie Pennsylvanian to Permian-age fault-bounded blocks of the Ancestral Rockies that were reactivated during Laramide compression. The anticlines would have developed over Ancestral Rocky Mountain horst blocks and the intervening synclines would have developed over Ancestral Rocky Mountain grabens or elevator basins. If this is the case, then thickened sections of Pennsylvanian and Lower Permian strata are present under the synclines (Fig. 12A). Alternatively, the flanks of the anticlines and synclines may be underlain by a series of step faults of Laramide age and no thickened late Paleozoic section is present under the synclines (Fig. 12B).

There is some evidence at the surface that supports the first hypothesis (reactivation of Ancestral Rocky Mountain horsts and grabens) on the Oscura anticline. On the anticline, strata at the surface dip off the flanks in most places at angles of less than 10 degrees (see Osburn, 1984). However, local areas of dip up to 30 degrees have been identified and mapped. These areas of locally greater dip may represent local folding of cover strata over deep faults. If this is the case, and again there is no direct evidence to support it, then it is possible that the gentle north-south oriented folds overlie a far more complex structural regime of north-south aligned fault block uplifts and intervening elevator basins, with thickened Pennsylvanian and Lower Permian sections present within the elevator basins. Furthermore, the Pennsylvanian section thins over the Oscura Mountains (Fig. 13), indicating that the Oscuras may have been a positive tectonic feature during the Pennsylvanian.

The Monte Prieto – Liberty Hill structural zone of Hawley (1986) extends from the Estancia Basin southward into the north-central part of the Chupadera Mesa project area. This north-south trending feature manifests itself at the surface as the east-facing Monte Prieto Bluff of Bates et al. (1946). This topographic feature attains a maximum relief of more than 250 ft. Hawley (1986) concluded that the Monte Prieto – Liberty Hill structural zone is a high-angle fault zone with down-to-the-east vertical throw. Vertical displacement at the ground surface must be less than 300 ft because the San Andres Formation (Permian: Leonardian) crops out on both sides of the bluff. Cather (1999) and

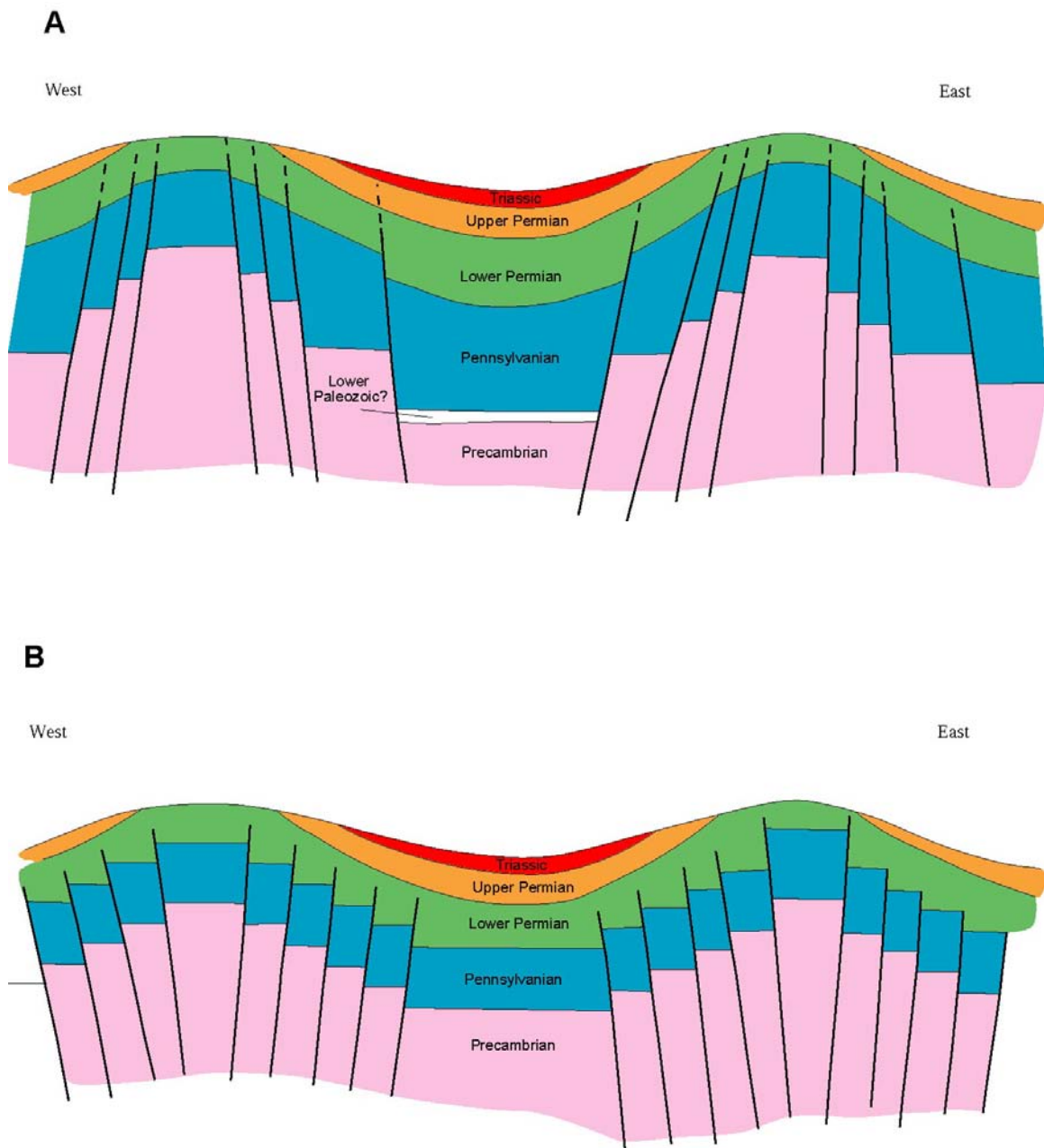


Figure 12. Possible structural and stratigraphic configuration of Precambrian basement and Pennsylvanian strata underneath the synclines and anticlines in the western part of the Chupadera Mesa project area, assuming brittle failure of the basement during Laramide compression. **A.** Assumes Laramide reactivation of Ancestral Rocky Mountain faults was responsible for formation of drap folds in sedimentary cover rocks. **B.** Assumes no Ancestral Rocky Mountain tectonic ancestry.

Cather and Harrison (2002) labeled this feature as the Chupadera fault and mapped it as a Laramide-age strike slip fault with dextral movement.

The Precambrian structure in areas adjacent to the Monte Prieto – Liberty Hill structural zone is poorly known and understood because of a paucity of exploratory wells. At the Manzano Oil Company N. 1 Cathead Mesa well located in Sec. 8 T4S R9E, the top of the Precambrian sits at an elevation of +2018 ft MSL. Its relationship to the Precambrian elevation in the Primero No. 1 Dulce Draw State well located in Sec. 2 T4S R9E indicates that the top of the Precambrian dips generally westward into the Monte Prieto – Liberty Hill structural zone. However, surface structure of the Oscura anticline and wells drilled on the Oscura anticline indicate that the Precambrian surface on the west side of the Monte Prieto – Liberty Hill structural zone dips eastward into the structural zone. Therefore, there is a poorly defined north-south trending synclinorium aligned generally along the Monte Prieto – Liberty Hill structural zone. A reversal of dip takes place along the axis of the synclinorium. Because the Monte Prieto – Liberty Hill structural zone is the sole north-south trending structural discontinuity identifiable from surface geology, this structural zone is mapped on the Precambrian contour map as a fault with down-to-the-east vertical throw. Steep dips of 25° to 52° east in the San Andres Formation just west of the structural zone (see surface map by Osburn, 1984) support the presence of a down-to-the east fault or fault zone in the subsurface with folded San Andres draped over deeper faults. Vertical displacement across the fault zone is unknown because of a lack of closely spaced control points so the map was contoured to reflect even spacing of contour lines and a Precambrian offset that somewhat exceeds inferred offset seen at the surface. If the Monte Prieto – Liberty Hill structural zone had a late Paleozoic Ancestral Rocky Mountains ancestry, then it is likely that offset of the Precambrian across the fault zone exceeds what is shown on Figure .

The Precambrian structure east of the Monte Prieto – Liberty Hill structural zone has been demonstrated by drilling to be complex. Four exploratory wells (Primero No. 1 Dulce Draw State, Manzano No. 1 Cathead Mesa, Primero No. 1 Jackson Ranch Federal, Manzano No. 1 Spaid Buckle; see database *Chupadera wells.xls*) were drilled in the area between 1996 and 2001. The Precambrian surface has a structural relief of at least 1200 ft across the 70 mi² covered by these four wells (Figs. 6, 9). As is the case with the Precambrian in the northwest part of the project area, it is likely that the brittle

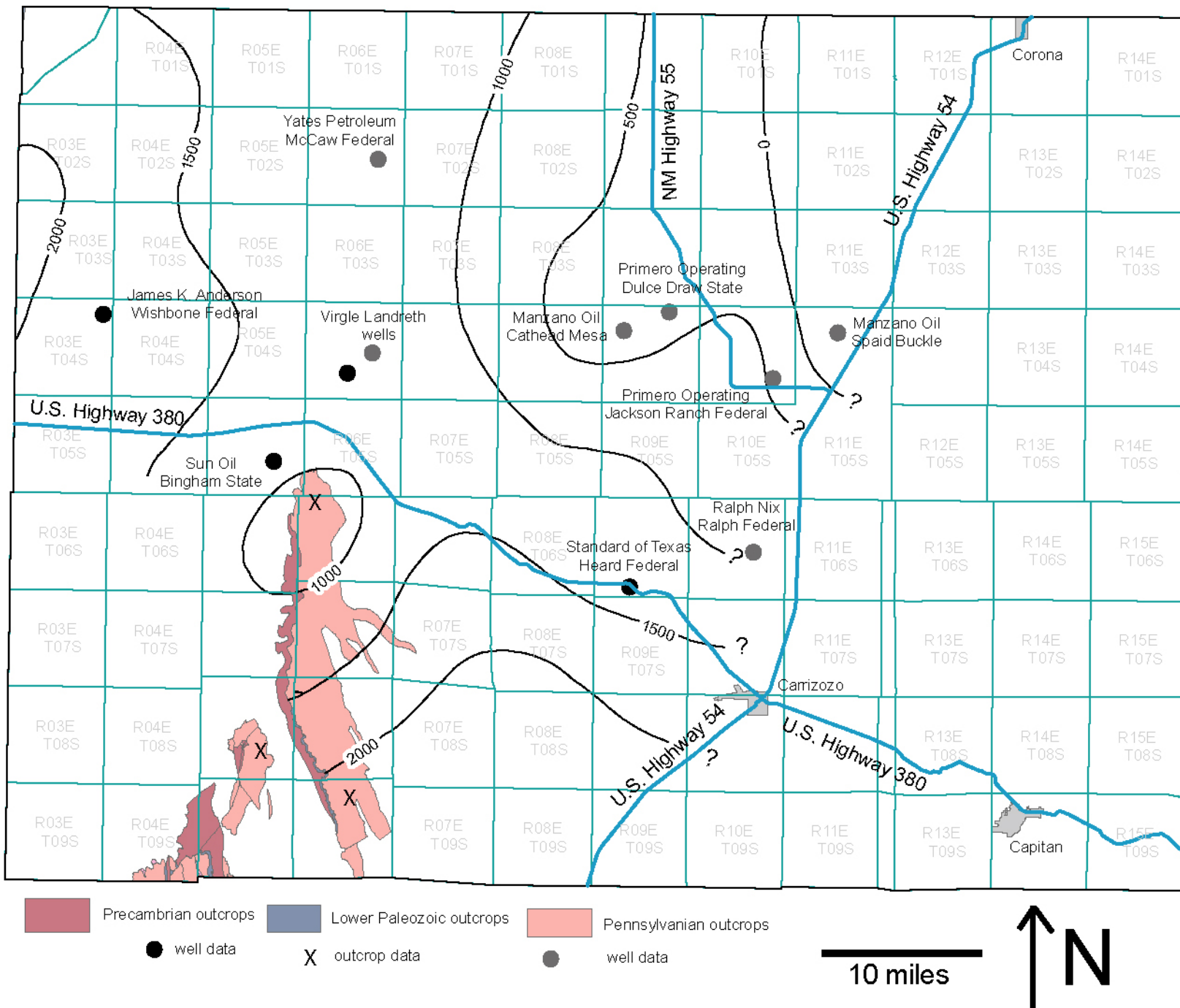


Figure 13. Isopach map map of Pennsylvanian strata. Contour interval equals 500 ft.

Precambrian in this area was deformed through brittle failure (faulting) rather than by ductile folding. The dominant structures that form the high and low areas shown on the Precambrian contour map (Fig. 6) are not anticlines and synclines, but rather downdropped, upthrown and tilted fault blocks bounded by high-angle faults in the subsurface; subsurface control is inadequate to portray the exact locations of the faults. The northeast-southwest trending surface anticlines that appear to have Tertiary-age igneous dikes as cores provide evidence that deep-seated faults trend northeast-southwest in this area. On Figure 6, contour lines have been drawn with a northeast-southwest structural grain.

Further to the northeast in an area just south and east of Corona, Kelley (1972) mapped a system of northeast-southwest trending faults at the surface. The structural low in the area of the Primero No. 1 Jackson Ranch Federal well (Sec 26 T4S R10E) is projected to extend northeast into the area southeast of the Gallinas Mountains and Corona. East of this region, the Precambrian rises to an elevation of more than +4500 ft MSL on the crest of the Pennsylvanian – Early Permian Pedernal uplift.

A deep graben (the Carrizozo Basin of Ben Donegan) lies to the west of the town of Carrizozo under the Carrizozo anticline. The Carrizozo Basin has been penetrated at depth by two wells, the Standard of Texas No. 1 Heard (Sec. 33 T6S R9E) and the Texaco No. 1D Federal well (Sec. 29 T7S R9E). Structural elevation of the Precambrian surface is below –2000 ft MSL in the deepest parts of the basin. The Texaco No. 1D Federal well was drilled to a total depth of 7616 ft and may have been in Precambrian at total depth, although neither logs nor samples are available for the lowermost 30 ft of the well; Pennsylvanian strata are present just above this lowermost 30 ft. There is at least 4000 ft of structural relief between this basin and structurally higher areas to the north, west, and east (Fig. 6). Fill in the basin consists primarily of pre-San Andres Permian strata. The Carrizozo Basin is contoured to be consistent with the identified northeast-southwest structural grain and is identified as a southwest extension of the structurally low area in the vicinity of the Primero No. 1 Jackson Ranch Federal well (Sec. 26 T4S R10E).

The eastern boundary of the Carrizozo Basin is ambiguous. It must lie between the Texaco No. 1D Federal well in T2S R9E and the Yates No. 1 Munoz Canyon well in T10S R15E where the elevation of the Precambrian is +4423 ft MSL on the Pedernal uplift. No deep wells have penetrated the Precambrian or the pre-Permian section in the

intervening area. The western boundary of the Pedernal uplift may coincide with the eastern boundary of the Carrizozo Basin. Cather (2002) indicates that the western margin of the Pedernal uplift coincides with the eastern margin of the Sierra Blanca Basin (a Laramide tectonic feature) and that the two were formed initially by Ancestral Rocky Mountain structures that were reactivated during the Laramide.

Cross section B-B' (Fig. 10) provides some clues as to the nature of the Precambrian structure between the Texaco No. 1D Federal well and the Yates Munoz Canyon well. At the eastern end of the cross section, the Rault Petroleum No. 1 Cactus State well was drilled on the crest of the Pedernal uplift where it encountered Precambrian at +3542 ft MSL. In this well, the Precambrian is overlain by only 292 ft of nonmarine Abo red beds (Permian: Wolfcampian) and 1488 ft of marine to marginal marine strata of the Yeso Formation (Permian: Leonardian). At the western end of the cross section, the Standard of Texas No. 1 Heard well was drilled in the Carrizozo Basin where it encountered Precambrian basement at -1861 ft MSL. In the Heard well, the Precambrian is overlain by 1344 ft of Pennsylvanian limestones, shales and sandstones, 390 ft of lowermost Wolfcampian (Permian) limestones, red shales and sandstones of the Bursum Formation, 1540 ft of nonmarine Abo red beds, and 4265 ft of marine to marginal marine strata of the Yeso Formation. This is clearly an anomalous Yeso thickness and dipmeter logs in the Texaco No. 1D Federal well (see discussion of Yeso stratigraphy) suggest that at least some of the excess Yeso thickness in the Carrizozo Basin may be caused by chaotic folding of evaporites. However, as discussed later in this report, the presence of a significant section of evaporites suggests that the area was topographically or bathymetrically low during the Leonardian. East of the Standard of Texas No. 1 Heard well lies the Laramide-age Sierra Blanca Basin where Paleozoic and Mesozoic strata have been folded into a syncline; more than 1100 ft of Triassic red beds have been drilled on the western limb of the Sierra Blanca Basin in the Ralph Nix No. 1 Ralph Federal well (Sec. 23 T6S R10E). Cretaceous strata are preserved within the axial area of the Sierra Blanca Basin.

The Dalton Kincheloe No. 1 Arnold Federal well (Fig. 10) provides the evidence for the location of the hidden eastern boundary of the Carrizozo Basin. The Yeso Formation lies at lower elevations in the Kincheloe well than wells to the east and the San Andres Formation is thicker in the Kincheloe well than it appears to be in outcrops farther east. These two observations suggest that the axis of the Pedernal uplift lies east of

the Kincheloe well. The eastern boundary of the Carrizozo Basin may also lie to the east of the Kincheloe well. If this is true, then the eastern margin of the Sierra Blanca Basin may indeed coincide with the western margin of the Pedernal uplift and the Carrizozo Basin may extend eastward under Lone Mountain and terminate somewhere between the Kincheloe well and the Rault Petroleum No. 1 Cactus State well.

Abo structure contour map

The Abo structure contour map (Fig. 7) portrays the same faults, folds, and trends as the Precambrian structure contour map. However, the structural relief from one point to the next is generally less on the Abo map compared to the Precambrian map. This subdued relief on the Abo is a function of the age of structural movement. Structural movement that occurred during Laramide (latest Cretaceous to Early Tertiary) or basin and range (post-Laramide Tertiary) deformation will have resulted in equal structural relief on top of the Abo and the Precambrian. Structural movement that occurred during Ancestral Rocky Mountain (Pennsylvanian to Early Permian) deformation has resulted in greater relief on the Precambrian surface as compared to the upper surface of the Abo because sediments of Pennsylvanian and Early Permian age were derived from emergent highlands and filled in low areas created during Ancestral Rocky Mountain deformation. This is evident in the wells drilled east of the Monte Prieto – Liberty Hill structural zone, especially in the Manzano Oil No. 1 Cathead Mesa well, the Primero No. 1 Dulce Draw well, the Primero No. 1 Jackson Ranch well, and the Manzano Oil No. 1 Spaid Buckle well (Fig. 9). Relief on top of the Abo is one-half to two-thirds the relief on top of the Precambrian, indicating that structures in this area have a late Paleozoic ancestry. The structures were reactivated, perhaps during the Laramide, and relief was enhanced. The structural relief on top of the Abo may largely be considered to be Laramide whereas relief on the Precambrian is a result of both Ancestral Rocky Mountain tectonics and Laramide tectonics. It is quite possible that the anticlines and synclines west of the Monte Prieto – Liberty Hill structural zone have a similar tectonic history.

Surface structures (Figures 2, 8)

Oscura Mountains uplift

The Chupadera Mesa project area is dominated by a number of large tectonic features that subdivide it into regional geomorphic regions. The central part is dominated

by the Oscura Mountains. The Oscura Mountains are formed by a series of north-south trending, east-dipping asymmetrical fault blocks (Bachman, 1968) that rise from an elevation of approximately 5000 ft on the east side to more than 8500 ft at the summit of the mountain range. The western boundary of the mountain range is formed by a high-angle fault that extends north-south for approximately 22 miles and offsets Precambrian basement rocks at altitudes of more than 8500 ft on the summit of the range against Pennsylvanian and Permian strata at altitudes of less than 6000 ft to the west of the fault. The western boundary fault dies out northward as the crest of the Oscura Mountains plunges into the subsurface and forms the north-south trending Oscura anticline.

Oscura anticline

The Oscura anticline is a broad, gentle, north-plunging structure more than five miles wide and fifteen miles long. Strata of the Yeso Formation (Permian: Leonardian) are exposed along its crest. Younger strata of the Glorieta Sandstone and San Andres Formation (Permian: Leonardian) are exposed on the flanks. Osburn (1984) indicates that strata dip away from the crest of the anticline at angles of generally less than 10° on its eastern and western flanks.

San Andres Mountains and Mockingbird Gap Hills

The northernmost part of the San Andres Mountains and Mockingbird Gap Hills lie to the southwest of the Oscura Mountains. These prominent topographic features are formed by uplifted fault blocks of Precambrian basement and Ordovician, Pennsylvanian, and Lower Permian strata. The Mockingbird Gap Hills are bounded on the west by high-angle faults that are exposed at the surface. The faults separate the Oscura Mountains uplift on the east from the Jornada del Muerto Basin on the east.

Jornada del Muerto Basin

The Jornada del Muerto Basin forms the wide valley that occupies the region from the Oscura Mountains and Oscura anticline on the east to the western boundary of the project area. South of U.S. Highway 380, bedrock in the Jornada del Muerto basin is covered by eolian, alluvial and playa deposits of Quaternary age. The Quaternary sediments obscure basin structure. North of Highway 380, the bedrock rises upward out of the subsurface and forms the northern, eastern and western flanks of the basin. West of

the Oscura Mountains and Mockingbird Gap Hills, the Bouguer Gravity anomaly map shows a large, negative gravity anomaly. This anomaly could represent an undrilled deep basin of either Tertiary age or Pennsylvanian and Permian age. If the anomaly represents a tertiary basin, then a substantial section of Cretaceous strata could be present within its areal extent. If it represents an undrilled Pennsylvanian to Early Permian Basin, then substantial sections of Pennsylvanian basinal sediments could be present. Alternatively, this gravity minimum could represent variations in the composition of the Precambrian basement.

There are two principal structures within the Jornada del Muerto Basin, the Torres syncline and the Prairie Springs anticline (Wilpolt and Wanek, 1951; Osburn, 1984). Both structures plunge to the south. The Yeso Formation is exposed along the crest of the Prairie Springs anticline and younger strata crop out on its flanks. Scattered, small exposures of Triassic and Cretaceous strata are exposed along the axial part of the Torres syncline, which is covered mostly by unconsolidated Quaternary sediments. Elevation of the land surface in the Jornada del Muerto Basin is determined by basin structure and ranges from 5400 ft in the south where a blanket of Quaternary sediments is present to 6200 ft in the north where bedrock is exposed.

Los Pinos Mountains

The eastern slope of the Los Pinos Mountains occupies the very northwestern part of the project area. Elevation of the crest of this mountain range exceeds 7000 ft. That portion of the Los Pinos Mountains covered by the project area is formed by Pennsylvanian, Bursum, and Abo strata with a gentle southeast dip of 1° to 3° (see Wilpolt and Wanek, 1951).

Chupadera Mesa

Chupadera Mesa lies east of the Oscura anticline. The mesa is a wide uplifted area whose surface is formed by limestones of the San Andres Formation. Topography consists of rolling hummocky hills and mesas cut by canyons and arroyos. Elevation of the land surface varies from 6000 to 7000 ft. A number of northeast-southwest trending anticlines cut across Chupadera Mesa. These were mapped with aerial photographs, first by Kelley (1972) and more recently by Ed Beaumont (unpublished work). These anticlines are generally less than a few hundred feet wide. Length is typically 5 to 10

miles. They are thought to have been formed by Tertiary-age igneous dikes that have intruded Paleozoic strata along faults but have not penetrated to the surface, arching overlying beds that remain unpierced (Ben Donegan, personal communication 2003). Similar folds with northeast-southwest orientation and their cores of igneous dikes are exposed in the Gran Quivira quadrangle in T1N R5-6E immediately north of the project area (Bates et al., 1947).

Monte Prieto – Liberty Hill structural zone

The Monte Prieto – Liberty Hill structural zone of Hawley (1986) lies within the western part of Chupadera Mesa. This regional tectonic feature is described elsewhere in this report under the section *Precambrian structure map*.

Carrizozo anticline

East of the Oscura Mountains strata dip gently east toward Carrizozo. The eastward slope is punctuated by several southeast-trending high-angle faults. East of the Carrizozo basalt flow, Triassic and Cretaceous strata form an eastward-dipping sequence at the surface. Just west of the lava flow, Kelley and Thompson (1964) mapped the Carrizozo anticline at the surface. This feature trends northeast-southwest and is doubly plunging. The Yeso Formation is exposed along its axis and The San Andres Formation and Glorieta sandstone are exposed along the flanks. Kelley and Thompson mapped an estimated 400 ft of structural closure at the surface.

Sierra Blanca Basin

East of the Carrizozo anticline, strata dip into the Sierra Blanca Basin. The Sierra Blanca Basin (Cather, 2002) is an elliptical structural depression that extends from Carrizozo on the west to Capitan on the east. Its northern limit is approximately 12 miles north of Carrizozo in T6S R10-11E and it stretches 40 miles to the south to T12S R10-11E. The basin is defined by Triassic and Cretaceous strata that dip inward on all sides. The Cretaceous section has been removed by erosion outside of the basin boundaries. The basin is asymmetrical about its northerly trending axis with a gently dipping western limb and a steeply dipping eastern limb. The Sierra Blanca Basin is late Laramide in age (Cather, 2002), having formed from easterly directed regional compression.

Numerous late Eocene to early Miocene (Tertiary) intrusive stocks and associated volcanic rocks are present in the Sierra Blanca Basin. These intrusive bodies form prominent mountains.

Mescalero arch

The Mescalero arch lies to the east of the Sierra Blanca Basin (Kelley and Thompson, 1964; Kelley, 1971). The Mescalero arch is a broad, uplifted structural divide that separates the Sierra Blanca Basin on the west from the Pecos Slope on the east. As the surface structure map (Fig. 8) indicates, it is complexly folded and faulted. Folds and faults have a dominant northeast-southwest trend. The Mescalero arch plunges northward and is terminated by the east-west trending Tertiary stock that forms the Capitan Mountains. North of the Capitan Mountains, the arch is a vague feature that appears to be offset to the west. Outcrops on the arch are formed mostly by San Andres limestones with the underlying Yeso Formation exposed in the more deeply incised stream valleys. Cather (2002) stated that the Mescalero arch is late Laramide in age. However, it appears to overlie the spine of the Pedernal uplift and therefore has a late Paleozoic ancestry.

Pecos Slope

The Pecos slope (Kelley, 1971) lies to the east of the Mescalero arch. Strata on the Pecos slope dip gently eastward into the Permian Basin. The boundary with the Mescalero arch is gradational. The Pecos slope lies entirely to the east of the area covered by this report.

Hasparos embayment

The Hasparos embayment (Kelley, 1971) lies to the north of the Capitan Mountains. This tectonic feature is a regional east-plunging synclinal downwarp that merges eastward with the Pecos slope. Within the project area, the western boundary of the Hasparos embayment is defined by the Tertiary igneous intrusions that form the Gallinas Mountains.

STRATIGRAPHY

Precambrian

Precambrian rocks of the Chupadera Mesa region are granites, granodiorites, diorites, and metasediments. Granitic igneous rocks are present in the Los Pinos, Oscura, and San Andres Mountains (Bachman, 1968; Beers, 1976; Condie and Budding, 1979) as well as in most of the deep exploratory wells that have penetrated the Precambrian. Diorites are present in the Oscura Mountains and at Mockingbird Gap (Bachman, 1968), in the Precambrian at the bottom of the Standard of Texas No. 1 Heard well in T6S R9E (Foster, in Griswold, 1959), and in the Primero Operating No. 1 Jackson Ranch Federal well in T4S R10E. An 850 ft section of diabase overlain and underlain by granodiorite was encountered in the Manzano Oil No. 1 Cathead Mesa well in T4S R9E; this body of mafic rock is interpreted to be a laccolith because of its thickness. The upper granodiorite was dated at 1018 Ma by the New Mexico Bureau of Geology and Mineral Resources Geochronology lab and the lower granodiorite was dated at 942 to 1426 Ma. The diabase was found to be not datable. The presence of sills and/or dikes of diabase in the Abo and Yeso Formations (Permian) in the well suggests, but does not prove, that the thick laccolith within the Precambrian may be an intrusive body of Tertiary age. However, the diabase at total depth in the Standard of Texas No. 1 Heard well has been dated at 1231 Ma. Diabases interspersed with granodiorites were also drilled in the Manzano No. 1 Spaid Buckle well in T4S R11E. In the Los Pinos Mountains at the northwestern margin of the project area, meta-rhyolites, meta-arkoses, hornblende schists, and meta-quartzites are present within the Precambrian (Beers, 1976).

Metasedimentary rocks have been encountered in the Precambrian in two wells in the Chupadera Mesa project area. In the Primero Operating No. 1 Dulce Draw State well, located in T4S R9E, 150 ft of metasediments form the upper part of the Precambrian and overlie granitic igneous rocks. The metasediments are mostly white quartzites but some of the well cuttings have a schistose fabric and contain amphiboles in addition to quartz. In the Skelly Oil No. 1 Goddard well, located in T2S R4E, the uppermost 10 ft of Precambrian were penetrated and consist of metaquartzite.

Precambrian rocks in the Chupadera Mesa project area are Proterozoic in age. As discussed above, the granodiorites in the Manzano No. 1 Cathead Mesa well have been dated at 942 to 1426 Ma and the diabase at total depth in the Standard of Texas No. 1

Heard well is 1231 Ma. These ages are similar to those obtained from outcrops of Precambrian basement rocks in the region (see Wilks and Chapin, 1997).

The composition of the Precambrian basement is a major variable that must be considered when using aeromagnetic and gravity anomaly maps to help construct structure maps of the Precambrian surface. Thick bodies of mafic igneous rocks may affect both Bouguer gravity anomaly maps and aeromagnetic anomaly maps. Most wells in the region that have been drilled to a sufficient depth to penetrate the Precambrian have only drilled the uppermost 100 ft of the Precambrian. The Manzano No. 1 Cathead Mesa well drilled 1930 ft of Precambrian and demonstrated that the uppermost part of the basement may consist of low-density granitic rocks with a low magnetic signature but that high-density mafic rocks with a highly magnetic signature may be present at depth. Therefore, the contour patterns on the gravity and aeromagnetic anomaly maps may represent the loci of buried mafic bodies as well as positive structural elements.

Cambrian and Ordovician Systems

Strata of Cambrian and Ordovician age consist of the Bliss, El Paso, and Montoya Formations (Fig. 4). These strata are not present in the wells drilled within the project area. However, Bachman (1968) has mapped and described Bliss, El Paso, and Montoya strata in the Mockingbird Gap Hills and in the southern part of the Oscura Mountains. These strata are erosionally truncated in a northward direction and are not present in the northernmost parts of the Oscura Mountains. The regional pinchout of Cambrian and Ordovician rocks is shown in Figure 14. This pinchout is consistent with the regional isopach maps of Kottlowski (1963). Cather and Harrison (2002) concluded that the Liberty Hill – Monte Prieto structural zone is a right-lateral strike-slip fault of Ancestral Rocky Mountains age. Cather and Harrison conclude that Cambro-Ordovician strata may not be present east of the structure within the project area. However, insufficient data are available to determine the pinchout of the Cambro-Ordovician in the subsurface east of the Monte Prieto-Liberty Hill structural zone and it is quite possible that these strata are present east of this tectonic feature within the subsurface of the project area. If so, the northern pinchout lies somewhere to the south of the Texaco No. 1 Federal well in Sec. 29 T7S R9E, although the rocks at total depth in the Texaco well remained undetermined and it is possible that a lower Paleozoic section was penetrated but not reported. Because the eastern boundary of the Carrizozo Basin is not well defined in the subsurface, the

eastern limit of Cambro-Ordovician strata is not known. The Cambro-Ordovician pinchout must be located west of the Yates No. 1 Munoz Canyon well in T10S R15E where Permian sediments rest unconformably on the Precambrian.

Bliss Sandstone (Cambrian-Ordovician)

The Bliss Sandstone is thought to be Late Cambrian to Early Ordovician in age (Bachman, 1968). It is present in outcrops in the Mockingbird Gap Hills and in the southern Oscura Mountains where it is 0 to 19 ft thick (Bachman, 1968). The Bliss sandstone is not present north of the lower Paleozoic pinchout (Fig. 14).

Bachman (1968) described the Bliss of the Oscura Mountains and Mockingbird Gap as composed of a lower unit and an upper unit. The lower unit has an average thickness of 3 ft and consists of medium-gray, medium-grained, subangular to subrounded, glauconitic, hematitic, quartzose sandstone with clay, calcite and silica cements. The upper unit has an average thickness of approximately 10 ft and consists of sandstone with minor granule conglomerates, shale, and limestone. It is thinly bedded. Sandstones and conglomerates are dark brown to dark reddish brown and crossbedded. They are composed dominantly of detrital quartz but contain significant amounts of detrital carbonate and minor glauconite, hematite, limonite and carbonate cement. Bliss shales are dark greenish gray to dark brown. Limestones are yellowish to reddish brown to dark gray.

The lower contact of the Bliss with the Precambrian is unconformable and erosional (Bachman, 1968). Local relief on this surface is as great as 5 ft. The upper contact with the El Paso Formation (Ordovician) is gradational.

El Paso Formation (Lower Ordovician)

The El Paso Formation is Early Ordovician in age. Within the Chupadera Mesa project area, it is present in outcrops of the Mockingbird Gap Hills and southern Oscura Mountains where it is 0 to 128 ft thick (Bachman, 1968). The El Paso pinches out northward and is beveled by the overlying Montoya Formation (Middle Ordovician). At the northernmost extent of the El Paso the Montoya is not present. There it is beveled and truncated at the base of the Pennsylvanian.

Bachman (1968) described the El Paso as composed of light- to medium-gray, finely crystalline, sandy dolostone. Sand content decreases upward. Beds are 2 to 18

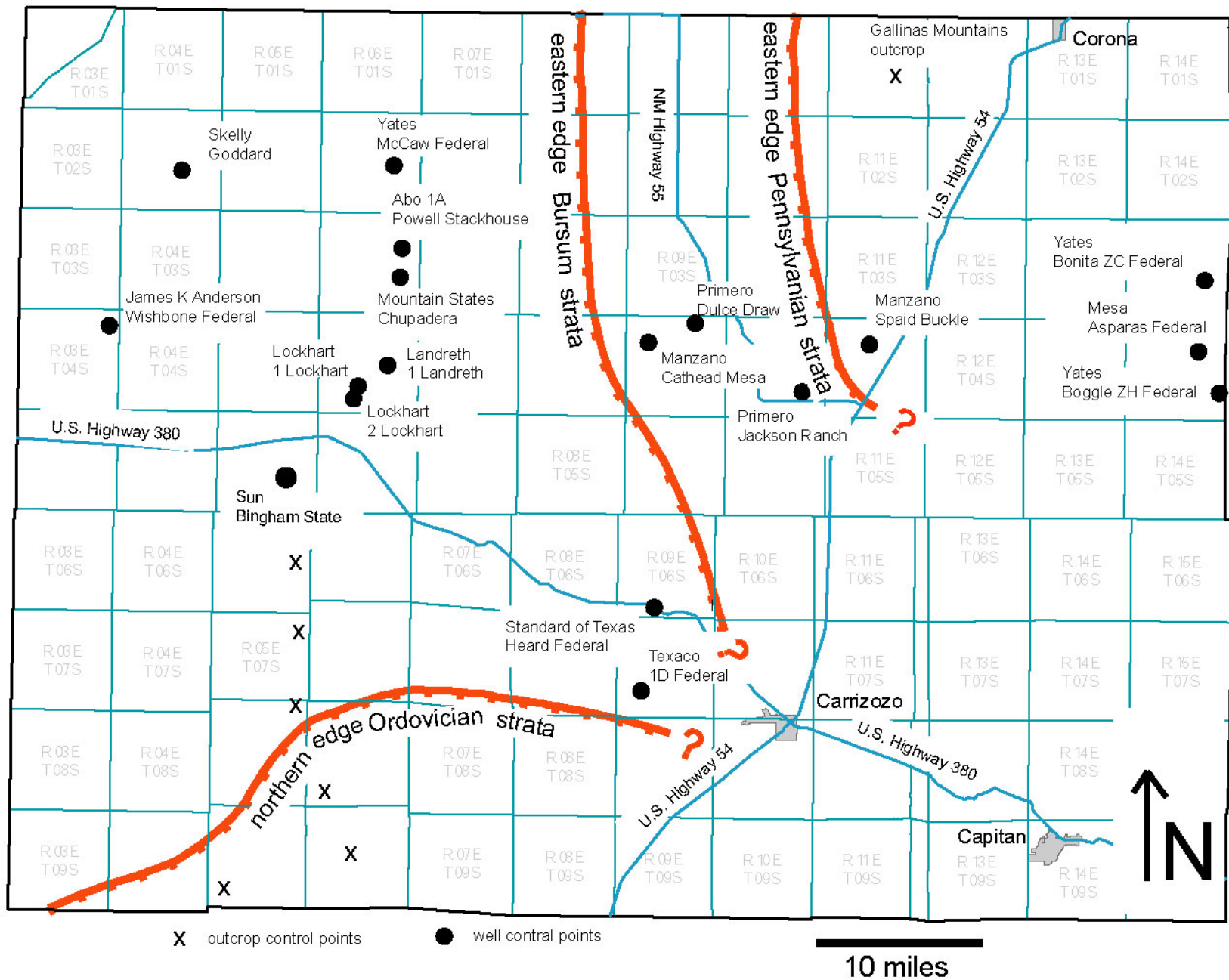


Figure 14. Zero isopach lines of Ordovician and Pennsylvanian strata and the Bursum Formation.

inches thick and bed thickness increases upward within the formation. Intraformational conglomerates are present in the lowermost 10 ft. Some glauconite is present within the lower part of the formation.

The lower contact with the Bliss Sandstone is gradational (Bachman, 1968). The upper contact with the Montoya Formation is sharp and unconformable. Where the Montoya has been removed by erosion at the base of the Pennsylvanian, the El Paso is overlain unconformably by the Sandia Formation and basal Sandia sandstones fill channels cut into the El Paso. The Cable Canyon Sandstone (Ordovician) lies between the El Paso Formation and the Montoya Formation in southern New Mexico. It is absent in the Chupadera Mesa project area and is represented by the unconformity that separates the El Paso Formation from the Montoya Formation.

Montoya Formation (Middle Ordovician)

The Montoya Formation is represented in the Chupadera Mesa project area by its lowermost unit, the Upham Dolomite Member of Middle Ordovician age (Bachman, 1968). Younger members of the Montoya had been removed by erosion prior to deposition of Devonian strata. Where it is present in outcrops in the Mockingbird Gap Hills and southern Oscura Mountains, the Upham Member is 0 to 43 ft thick (Bachman, 1968). From the southern boundary of the project area, it thins northward and is truncated underneath the Sandia Formation south of the lower Paleozoic pinchout (Fig. 14).

Bachman (1968) described the Upham Member as a medium-dark-gray to olive-gray, microcrystalline to cryptocrystalline dolostone. Beds are 1 to 6 ft thick.

The lower contact with the El Paso Formation is sharp and unconformable. Where present within the project area, the Upham Member is overlain unconformably and erosionally by the Sandia Formation (Pennsylvanian) in most places. However, in the Oscura Mountains within 5 miles of the southern boundary of the project area the Upham is overlain unconformably by Devonian strata.

Devonian System

Devonian strata have been preserved over a limited area in the southernmost part of the project area where they crop out in the southern Oscura Mountains. At Johnson Park Canyon in Sec. 31 T9S R5E, just north of the southern project area boundary in the northernmost San Andres Mountains, the Devonian is approximately 30 ft thick

(Bachman, 1968). It consists mostly of yellowish-brown mudstone and fine-grained sandstone. Devonian strata are truncated to the north by erosion at the base of the Pennsylvanian System. These Devonian strata are Middle to Late Devonian in age (Sorauf, 1984). The lower and upper surfaces of the Devonian are unconformities.

Mississippian System

A dark-gray, thin-bedded cherty limestone is present beneath the Sandia Formation (Pennsylvanian) at Johnson Park Canyon and other nearby areas of the northernmost San Andres Mountains. Bachman (1968) correlated this limestone with the Alamogordo Limestone Member of the Lake Valley Formation (Lower Mississippian). It is truncated just north of Johnson Park Canyon by the unconformity at the base of the Pennsylvanian System. The lower and upper surfaces of the Mississippian are unconformities.

Pennsylvanian System

Pennsylvanian strata are composed of 0 to 2200 ft of interbedded marine limestones, sandstones, and shales (Fig. 13). Most of the sandstones are arkosic or lithic arenites, although some quartz arenites are present. Within outcrops in the Oscura Mountains, the Pennsylvanian has been divided into two formations: the lower Sandia Formation and the upper Madera Formation (Bachman, 1968). For this report, the Pennsylvanian section is mapped in the subsurface as a single unit. Pennsylvanian strata are absent from the Pedernal uplift in the eastern part of the project area. Pedernal was an emergent highland during a significant part of Pennsylvanian time and detritus eroded from its exposed Precambrian core was transported into adjacent basinal areas and deposited as fluvial, alluvial, and marine sands and shales. Within the project area, Pennsylvanian strata attain a maximum thickness of 2200 ft in the southern Oscura Mountains (see Bachman, 1968).

The Pennsylvanian section is 1300 to 1400 ft thick throughout most of the central part of the project area and also to the south in the Standard of Texas No. 1 Heard well (Fig. 13). From these central areas, the section thins eastward to zero on the flank of the Pedernal uplift. Pennsylvanian strata thicken southward to 2200 ft in the Oscura Mountains at the southern boundary of the project area and thicken westward to more than 1500 ft at the western boundary of the project area. Further west, Wilpolt and

Wanek (1951) reported 2150 ft of Pennsylvanian strata in T2S R1E, less than 10 miles west of the western boundary of the project area.

The Pennsylvanian section has an apparent thickness of 2150 ft in the Anderson No. 1 Wishbone Federal well in T4S R3E. Surface geology at the well location (Osburn, 1984) indicates a 30° southwest dip; true thickness of the Pennsylvanian is 1870 ft after correction for structural dip is made. Sue Reid examined cuttings of the Wishbone Federal well for fusulinids. She identified *Triticites* of Missourian or Virgilian age at a depth of 3140 ft, 310 ft below the top of the Madera Formation, indicating that Upper Pennsylvanian strata are present in the western part of the project area.

The Pennsylvanian section thins to only 920 ft in the northern Oscura Mountains (Fig 13; Thompson, 1942). Thompson indicates that lower Virgilian strata are present in the northern Oscuras. Thinning of the Pennsylvanian section is erosional rather than depositional in this area. The upper part of the Virgilian has been removed by pre-Bursum erosion. Therefore it is likely that the northern Oscura Mountains were an emergent highland during the latest Pennsylvanian and the Oscura Mountains uplift has an Ancestral Rocky Mountains precursor.

Although data are sparse, there do not appear to be thickness trends within the Pennsylvanian section associated with the Carrizozo Basin (Fig. 13). Data indicate that the section thickens southward from 1344 ft in the Standard of Texas No. 1 Heard well to at least 1800 ft in the Texaco No. 1 D Federal well. The dipmeter log indicates that Pennsylvanian strata dip less than 10° east in the Texaco well, so measured thickness is approximately true and is not exaggerated significantly by structural dip. It is possible that the northward thinning is caused by erosional truncation at the top of the Pennsylvanian, similar to the situation in the northern Oscura Mountains. Meyer (1966) indicated that Virgilian strata are present in the Heard well, so any erosional truncation must have only involved the upper part of the Virgilian, again similar to the situation in the northern Oscuras. Further to the north, Pennsylvanian strata thin to less than 500 ft in the Manzano No. 1 Cathead Mesa well, the Primero Operating No. 1 Dulce Draw State well, and the Primero Operating No. 1 Jackson Ranch Federal well. In these three northern wells, Pennsylvanian strata are overlain by the Abo Formation (Permian: Wolfcampian). Unpublished fusulinid determinations by the late Garner Wilde indicate that the Pennsylvanian in the Cathead Mesa well is early Atokan in age. The Des

Moinesian (Middle Pennsylvanian) and Missourian and Virgilian (Upper Pennsylvanian) sections are missing.

This same truncation of the Middle and Upper Pennsylvanian also occurs in an east-west direction (Fig. 9). Meyer (1966) indicates that the Virgilian is present in the Skelly No. 1 Goddard well in the western part of cross section A-A'. Unpublished work by Dick Norman indicates that the Upper Pennsylvanian is present as far east as the wells on the Oscura anticline, although it is uncertain if Norman's correlations were based on fusulinid identifications or lithostratigraphic correlations. At the eastern limit of cross section A-A', only the lower part of the Atokan is present.

The earliest Pennsylvanian strata present within the project area are Atokan in age. This is indicated by Wilde's fusulinid determinations in the Manzano Oil No. 1 Cathead Mesa well and by Meyer's (1966) regional cross section (which is based in part on fusulinid determinations). Morrowan (Lower Pennsylvanian) strata appear to be absent although it is possible that some are present in structurally low areas of the subsurface, as they are to the north in the Estancia Basin (Broadhead, 1997).

The Pennsylvanian section can be divided into two informal lithostratigraphic units within the north-central and western parts of the Chupadera Mesa project area: a lower sandstone-rich unit and an upper limestone-rich unit. Both units contain substantial thickness of shale. The lower unit appears to be roughly correlatable with the Sandia Formation and the upper unit appears to be roughly correlatable with the Madera Formation. The sparse available fusulinid determinations in wells indicate the lower unit is Atokan in age and the upper unit is Des Moinesian through Virgilian in age. Bachman (1968) used fusulinid determinations to conclude that the lowermost part of the Madera in the Oscura Mountains is Atokan. Therefore, it appears that the Atokan-Desmoinesian boundary lies somewhere above the base of the upper limestone-rich unit.

Permian System

Strata of Permian age consist of the following lithostratigraphic units (Fig. 4; ascending): Bursum Formation, Abo Formation, Yeso Formation, Glorieta sandstone, San Andres Formation, and Artesia Group. The Bursum and Abo are Wolfcampian in age, although some workers believe that the upper Abo may be Leonardian. The Yeso Formation, Glorieta Sandstone, and San Andres Formation are Leonardian. The Artesia Group is Guadalupian.

Bursum Formation (Permian: Wolfcampian)

The Bursum Formation is the lowermost Permian unit within the project area. It is composed of marine limestones, red shales, and fine- to coarse-grained arkosic sandstones and conglomerates. The Bursum is lower Wolfcampian in age. The Bursum has long been regarded as a transitional facies between the dominantly marine limestones, shales and sandstones of the Madera Formation and the overlying dominantly nonmarine red beds of the Abo Formation. The type section of the Bursum Formation is located within the project area in Sec. 1 T6S R4E (Wilpolt et al., 1946).

The upper and lower contacts of the Bursum are gradational. Basal Bursum beds interfinger with beds of the Madera Formation. Upper Bursum beds interfinger with the overlying Abo Formation (Bachman, 1968). Therefore, the upper and lower contacts are indistinct and difficult to trace in outcrop (Bachman, 1968), much less in the subsurface where distances between adjacent wells exceeds 10 miles in places. For this project, the base of the Bursum is placed at the top of the uppermost thick marine limestone beds within the Pennsylvanian-Wolfcampian stratigraphic sequence. Although this criterion identifies neither a chronostratigraphic marker nor a single lithostratigraphic unit, it is a criterion that can be identified with gamma ray and resistivity logs (modern wells) or with samples and sample descriptions (older wells). Wilpolt and Wanek (1951) and Bachman (1968) used a similar method in outcrops in the Oscura Mountains where the contact separates largely gray shales, limestones and sandstones of the Madera Formation from red shales, sandstones and limestones of the Bursum. Furthermore, examination of scout card tops indicates that most industry geologists have used this criterion to separate the Bursum from the Madera.

The top of the Bursum is placed at the top of the highest identifiable marine limestone in the Abo-Bursum sequence. This agrees with the criterion used by Bachman (1968) in the Oscura Mountains.

The thickness of the Bursum varies between 185 and 390 ft in wells where sufficient data were available for reliable correlation. This variation in thickness is less than what Bachman (1968) observed in the Mockingbird Gap quadrangle where the Bursum is 65 to 480 ft thick. The Bursum is absent over the Pedernal uplift in the eastern third of the project area (see regional zero isopach line, Fig. 14) and covers most of the remainder of the project area without apparent trends in regional thickness.

The Bursum is also absent in the area around the Manzano Oil No. 1 Cathead Mesa well where the Abo Formation rests directly on Atokan (Lower Pennsylvanian) strata (Fig. 9). The absence of the Bursum in this area may be ascribed to the following causes: 1) it was not deposited because the area was an emergent highland during early Wolfcampian; 2) the Bursum is temporally equivalent to nonmarine red beds of the lower Abo in this area (Ben Donegan, personal communication, 2003); 3) the Bursum was deposited but subsequently removed by erosion along with Upper and Middle Pennsylvanian strata prior to Abo deposition. The first two possibilities are satisfied by most available geologic data, but can be neither proved nor disproved because there are no biostratigraphic data to indicate whether basal Abo strata in this area are temporally equivalent to the Bursum or post-date the Bursum. Explanation No. 3 would require the existence of a clastic wedge derived from erosion of Bursum and Middle to Upper Pennsylvanian strata; this clastic wedge would need to lie west and south of the Cathead Mesa area and would be stratigraphically located between the Bursum and Abo Formations. A thick band of Abo trends north-south through the Cathead Mesa – Spaid Buckle – Heard well area. Perhaps the increased thickness of Abo along this trend is in part caused by a separate clastic wedge in its lower part. Again, proof is elusive. However, the coarse-grained nature of many of the Pennsylvanian, Bursum, and Abo sandstones and conglomerates and the presence of Precambrian lithoclasts in these clastic sediments indicates that the core of the Pedernal uplift was exposed during significant portions of the Pennsylvanian and Early Permian and was not covered by Bursum sediments.

Abo Formation (Permian: Wolfcampian to Leonardian)

The Abo Formation rests conformably on the Bursum Formation in the western half of the project area and in the Carrizozo Basin. It is composed of red fluvial sandstones, red nonmarine shales, and minor limestones and dark-gray to black shales. Where exposed in outcrop, local cut-and-fill fluvial channels are present where lower Abo channels eroded into the underlying Bursum beds before being filled with Abo sandstones and conglomerates (Bachman, 1968). These scour features are local unconformities and have the same geographic and stratigraphic extent as intraformational channel scours within the Abo. To the east of the Bursum zero isopach line (Fig. 14), the

Abo rests unconformably on Atokan strata. Further to the east, the Abo rests on Precambrian basement over the Pedernal uplift.

The Abo Formation is 230 to 1700 ft thick within the project area. It is thinnest where it rests unconformably on Precambrian basement over the Pedernal uplift (Fig. 9). It thickens westward to between 1200 and 1700 ft off the west flank of the Pedernal uplift. From there, the Abo thins westward to between 600 and 750 ft on the Oscura anticline and thins further westward to less than 550 ft in the Skelly No. 1 Goddard well in T3S R4E and to less than 500 ft in the Sun Oil Company No. 1 Bingham State well in T5S R5E. There does not appear to any increase in thickness associated with the Carrizozo Basin.

The Abo Formation is composed of interbedded fine- to coarse-grained red sandstones, red conglomerates, and red shales. Minor thin beds of limestone are locally present. Lithic fragments in the coarser clastics are mostly granite but also include other Precambrian basement lithologies. Although no attempt was made to systematically map Abo lithofacies or grain size for this project, examination of well samples, sample logs, and gamma ray-resistivity logs indicates that percentage of sandstone increases generally from less than 40 percent of the Abo on the west to perhaps 50 percent of the Abo in R9-11E where the formation attains maximum thickness. Over the Pedernal uplift in the Yates No. 1 Bogle ZH Federal well in T4S R14E, the Abo is perhaps 30 percent sandstone and conglomerate and has perhaps 70 percent shale. The Abo has even a smaller percentage of sandstone in the Mesa Petroleum No. 1 Asparas Federal well, also located in T4S R14E, which is in a similar structural position as the Bogle well. The thick sandy trend of Abo in R9-11E is a thick clastic wedge of sediments eroded from the exposed Precambrian core of the Pedernal uplift and deposited along the western flank of this uplift. As such, the bulk of the Abo strata within the thick trend must be older than the Abo strata that cover the top of the uplift.

Abo sandstones are fine to coarse grained and rounded to angular. A minor amount are conglomeratic. Examination of gamma-ray borehole logs indicates that most beds are 2 to 10 ft thick and are separated by red shales. Outcrops of the Abo within the project area indicate that sandstones are lenticular. The sandstones are composed primarily of quartz and feldspar grains. Lithic fragments are common in both conglomerates and the more coarsely grained sandstones. Lithic fragments consist of a variety of Precambrian lithologies, including granite, diabase, gabbro, quartzite, and

rhyolite. The presence of easily weathered lithologies such as gabbro and rhyolite indicates deposition close to the sedimentary source area. In general, grain size of sandstones decreases upward within the Abo. Conglomerates are present mostly in the lower parts of the formation.

Abo shales are dominantly red in color. A minor amount (<10 percent) are light to medium gray or greenish gray. The shales are generally silty and are calcareous to non-calcareous. Microscopic calcareous nodules are present. Some Abo shales swell when placed in fresh water.

Thin beds of dark limestones and shales are locally present within the Abo. In the James K. Anderson No. 1 Wishbone Federal well, thin dark-brown limestones are present in the lower half of the Abo. They are lime mudstones. When present, they are less than 10 percent of the well cuttings in any 10 ft sample interval and are present in only a few 10 ft sample intervals. Limestones present from depths of 2260 to 2280 ft are dark gray to very dark gray lime mudstones that contain sparse fragments of bioclasts, including brachiopods. Also present in the cuttings from these depths are trace amounts of very dark-gray silty shales. A few thin black shales are present from 3850 to 3870 ft within the Abo in the Manzano Oil No. 1 Spaid Buckle well in T4S R11E; well cuttings of these black shales have a shiny luster. Perhaps these thin and presumably local occurrences of black shales represent limited development of anaerobic swamps on the Abo alluvial plain. The limestones could have been deposited in freshwater lakes. Alternatively, they may be temporal equivalents of Bursum strata deposited during far-reaching, short-lived, marine incursions on a very low-relief coastal plain.

In other wells, minor limestones have been noted on sample logs. These appear to be gray to red, microcrystalline to cryptocrystalline limestones that may be either thin lime mudstones or calcareous concretions in shale (cornstones).

Yeso Formation (Permian: Leonardian)

The Yeso Formation rests on the Abo Formation throughout the project area except where it has been removed by Tertiary or Recent erosion from topographically high areas. The Yeso Formation is composed of marginal marine to marine orange to white sandstone, orange shale, limestone, dolostone, anhydrite, and salt. The anhydrites have been hydrated to gypsum where they are at or near the surface. The lower contact

with the Abo appears sharp on well logs. In outcrop, the contact between the Abo Formation and the Yeso Formation is gradational and conformable in the Mockingbird gap area (Bachman, 1968). Elsewhere, the sharp nature of the contact and the transition from nonmarine Abo facies to marine Yeso facies suggests that a disconformity may be present, a conclusion also reached by Needham and Bates (1943).

The Yeso Formation is 1000 to 4300 ft thick in the Chupadera Mesa project area. It is thinnest on top of the Pedernal uplift in the eastern part of the project area. From the spine of the Pedernal uplift, the Yeso thickens to the east and to the west. Depositional thickness increases westward to more than 2000 ft over the Oscura anticline. On the southern part of the Oscura anticline, the Yeso is substantially less than 2000 ft thick because it is exposed at the surface and the upper parts have been removed by Tertiary and Recent erosion. Further west, the Yeso is only 1030 ft thick in the Skelly No. 1 Goddard well in T2S R4E where it is exposed at the surface and the upper parts have been removed by erosion (Fig. 9). Yet further west in the Anderson No. 1 Wishbone Federal well, the Yeso is 1348 ft thick where it is overlain by the Glorieta Sandstone. When corrected for the 30° dip measured at the surface (see Osburn, 1984), the Yeso is 1172 ft thick in the Wishbone Federal well. Because both the San Andres Formation and Glorieta Sandstone are present in the Wishbone Federal well and there is no evidence that a part of the Yeso has been removed by a normal fault, it appears that the Yeso thins westward from the Oscura anticline. Wilpolt and Wanek (1951) measured 1650 ft of Yeso in outcrops just west of the Oscura Mountains. They also demonstrate that the Yeso thins westward across the Jornada del Muerto and is only 800 ft thick in the southern part of T1S R3E.

The Yeso attains a maximum thickness of 4200 ft in the Standard of Texas No. 1 Heard Federal and Texaco No. 1D Federal wells within the Carrizozo Basin. This thickness may be associated with steep structural dips within the Yeso Formation. The dipmeter log in the Heard well indicates that the underlying Abo Formation dips a relatively gentle and uniform 6 to 12° southwest. The dipmeter survey did not extend above the Abo in that well. In the Texaco No. 1D Federal well, the upper Abo has a uniform dip of 3 to 8° east. The Yeso Formation in the Texaco well is characterized by chaotic dips ranging from near horizontal to more than 80° within vertical distances of only 20 ft. Dip directions are also mostly chaotic. The steep, random dips appear to be associated with thick evaporite-rich sections, although other rock types such as

sandstones are involved. The steep dips may have several origins, including ductile deformation in response to Laramide compression or intraformational collapse due to salt solution. The association of thick evaporites in the Yeso in the Carrizozo basin suggests that the basin may have existed as a restricted bathymetric depression during the Leonardian. If so, then not all of the excess thickness of the Yeso is due to salt deformation; some the extra thickness is depositional.

The Yeso Formation has been subdivided into four members (ascending; Wilpolt and Wanek, 1951): Meseta Blanca Sandstone Member, Torres Member, Canas Gypsum Member, and Joyita Sandstone Member. The Meseta Blanca Member is composed of evenly bedded, orange-red sandstone and sandy shale. In outcrops on Chupadera Mesa, the Meseta Blanca Member is 190 to 355 ft thick (Wilpolt and Wanek, 1951). Sandstones predominate. The sandstones are fine to very fine grained, well to moderately sorted, and quartzose to arkosic in composition. In outcrops the Meseta Blanca is readily differentiated from the underlying Abo Formation by the sharp transition from red lenticular sandstones and red shales of the Abo to the orange, evenly bedded Meseta Blanca sandstones and shales. More than one-half of the Abo section is shale whereas most of the Meseta Blanca is sandstone. Most Abo sandstones appear to be channelized and depositional relief is on the base of the sandstone beds. Meseta Blanca sandstones are not generally channelized and depositional relief is on the top of the sandstone beds.

The Torres Member is composed of interbedded sandstone, dolostone, limestone, anhydrite and, in some areas, salt. The anhydrite has been hydrated to gypsum in outcrop. The Torres member is 310 to 1000 ft thick in outcrops on Chupadera Mesa (Wilpolt and Wanek, 1951). It attains a maximum thickness of 3500 ft in the Standard of Texas No. 1 Heard well in the Carrizozo Basin. Torres sandstones are similar to those found in the Meseta Blanca, but the color ranges from orange-red to white. Although most Torres sandstones are very fine to fine grained, some are very fine to medium grained or very fine to coarse grained. The coarser grained sandstones may be angular or well rounded; quartz grains in the rounded sandstones are often frosted. Many of the sandstones are poorly indurated; this is particularly true of the coarse-grained sandstones. The poor induration is a result of poor cementation and the sandstone are disaggregated into individual sand grains in the samples; they are permeable. Other sandstones are well cemented by anhydrite and have poor permeability. Sandstones typically have traces

amounts to 10 percent porosity when examined in well cuttings with a binocular microscope.

Torres dolostones are medium to dark gray or light to dark brown in color. They have sucrosic to compact microcrystalline textures. The sucrosic dolostones are generally brown and have trace amounts of visual intercrystalline porosity. Compact microcrystalline dolostones are gray and most have no visual porosity when examined under a binocular microscope. Small vugular pores are present in some of the compact crystalline dolostones.

Torres anhydrites are gray. They typically are present in beds less than 20 ft thick.

Salt is not present in most places in the Torres Member. The Standard of Texas No. 1 Heard Federal well, located in T6S R9E in the Carrizozo Basin, encountered approximately 900 ft of salt in the Torres Member. Salt dominates intervals 100 to 300 ft thick that separated by intervals of dolostone-rich or sandstone-rich units. It is not possible to know the true thickness of the salt beds because of steep dips and chaotic nature of the Yeso bedding, as described above.

Salt is also present within the Torres Member in the Manzano Oil No. 1 Cathead Mesa well, located in Sec. 8 T4S R9E. Salt beds are present mostly between depths of 1740 and 2310 ft. This section of the well is dominated by salt beds interlayered with 2 to 10 ft thick orange-red shales and red to white, friable, fine- to very fine-grained sandstones.

It is possible that salt was once more extensive in the Torres Member than it now is. The chaotic nature of Yeso bedding in many outcrops throughout the region suggests the possibility that salt has been dissolved where it is close to the surface.

The Canas Gypsum Member is composed of anhydrite in the subsurface. The anhydrite has been hydrated to gypsum near the surface and in outcrops. The Canas Member consists of thick beds of anhydrite/gypsum and minor thin beds of fine- to very fine-grained sandstone and siltstone as well as thin beds of anhydritic dolostone. The Canas Gypsum Member has a maximum thickness of 190 ft in outcrops on Chupadera Mesa. Unlike the underlying Torres Member, the Canas does not vary in thickness by more than 100 ft across the project area and does not exhibit any increase in thickness in the Carrizozo Basin.

The Joyita Sandstone Member of the Yeso Formation is composed of sandstone, siltstone, and minor thin-bedded shale, dolostone and anhydrite. The sandstones are

orange red to white, silty, fine to very fine grained, moderately sorted, and arkosic. Trace percentages of porosity are typically visible in well cuttings. Shales are thinly bedded and orange red. The Joyita Sandstone Member is 30 to 150 ft thick in outcrops on Chupadera Mesa (Wilpolt and Wanek, 1951). Wilpolt and Wanek (1951) indicate an intertonguing relationship between the Joyita Member and the overlying Glorieta Sandstone.

Glorieta Sandstone (Permian: Leonardian)

The Glorieta Sandstone is comprised of 35 to 200 ft of white to light-gray quartzose sandstone in outcrops of the Chupadera Mesa region (Wilpolt and Wanek, 1951). Where encountered in wells, it is 28 to 400 ft thick. The limited data indicate thickness distribution is irregular across the project area, possibly because of an intertonguing relationship with the San Andres Formation. The Glorieta has been eroded from topographically higher areas including the Oscura Mountains and the Oscura and Pinon Springs anticlines.

Glorieta sandstones are white to light-gray, very fine- to coarse-grained quartz arenites. They are typically crossbedded (Wilpolt and Wanek, 1951). Trace amounts of visual porosity are usually evident in well cuttings. The lower part of the Glorieta intertongues with the Joyita Sandstone Member of the Yeso Formation. The upper contact with the San Andres Formation is gradational and also appears to be intertonguing.

Exact correlation of the Glorieta in the subsurface is tenuous because of the presence of Glorieta-like sandstones in the lower San Andres. In some wells there is a sharp and sudden transition from white Glorieta sandstones to San Andres carbonates. In other wells, the contact is gradational with thin sandstones in the lower San Andres giving way downward into the thick sandstones of the Glorieta. In these wells, the top of the San Andres is placed at the top of highest thick sandstone with Glorieta characteristics; this correlation generally places 10 to 20 ft thick carbonate units within the upper part of the Glorieta.

San Andres Formation (Leonardian)

The San Andres Formation is comprised of 240 to 975 ft of limestone, dolostone, and anhydrite. The San Andres has been removed by erosion from many of the topographically higher areas, including the Oscura Mountains and the Oscura and Prairie

Springs anticlines. It crops out over large parts of Chupadera Mesa as well as the region north of Sierra Blanca.

The San Andres Formation covers large portions of New Mexico and west Texas. Only the lower part of the San Andres is present within the project area (Kottlowski, 1969). The upper part of Guadalupian age, so prolifically productive of oil and gas in southeast New Mexico is absent, and is represented temporally by an unconformity in central New Mexico.

Kottlowski (1969) described the San Andres Formation at its type section near Rhodes Pass in the San Andres Mountains, approximately 20 miles southwest of the Chupadera Mesa project area. There, it is subdivided into three units: a lower unit of light-gray limestones 95 ft thick, a middle unit of dark-gray massive limestones 220 ft thick, and an upper unit of light-gray dolomitic limestones 255 ft thick. The lower unit contains some dolomitic limestones as well as some sandy calcarenites. Bituminous material stains intraclasts of micrite in some places. The middle unit is composed mostly of massively bedded high-calcium limestones that are petroliferous and smell of hydrocarbons when broken open. The upper unit consists mostly of light-gray dolomitic limestone. The San Andres bears a wide variety of marine fauna at the type section (Kottlowski et al., 1956).

From the type section, the San Andres grades northward into a clastic facies consisting of interbedded limestones and sandstones near Capitan in the southeast part of the Chupadera Mesa project area (Kottlowski, 1969). Sandstones constitute approximately 25 percent of the vertical section where the clastic facies is present.

From the Capitan area, the San Andres grades north and west into an evaporite facies (Kottlowski, 1969). This facies consists of a lower gypsum-rich unit and an upper unit of thinly bedded to massive limestone. The evaporite facies covers most of the Chupadera Mesa project area.

In outcrops of the Chupadera Mesa area, Wilpolt and Wanek (1951) described the San Andres as consisting of 270 to 400 ft of limestone interbedded with gypsum and gray sandstone. The limestones are thin to medium bedded, dark gray, and slightly petroliferous.

In the subsurface, significant sections of the San Andres have been penetrated by several wells east of the Oscura anticline. Where the formation is present west of the

Oscura anticline, it is usually at the surface and thin or has been removed by erosion altogether.

The San Andres is 470 ft thick in the Manzano No. 1 Spaid Buckle well in T4S R11E and consists of interbedded dolostone, gypsum, anhydrite, and minor sandstone and siltstone. The dolostones are light to dark gray and compact microcrystalline. Some are cherty. The sandstones are very fine grained, silty and red to fine grained and white. Some of the sandstones are disaggregated in the samples and obviously permeable as lost-circulation materials were seen in the samples. Dolostones dominate the lower 200 ft of the san Andres in the Spaid Buckle well. The evaporites, dolostones, sandstones and evaporites of the upper part are thinly interbedded with each other.

From the Spaid Buckle well, the San Andres grades west into a unit of thinly interbedded dolostone, limestone, and sandstone in the Manzano No. 1 Cathead Mesa well in T4S R9E where only the lower 400 ft have been preserved. Dolostones dominate the section and are light brown to dark gray. Depositional textures are evident in many of the dolostones in the Cathead Mesa well; bioclastic dolomudstones, dolowackestones, and dolopackstones are present. Lime mud has been recrystallized to a sucrosic matrix in many of the samples. The sucrosic matrix has visual porosity when examined under the binocular microscope. The limestones in the Cathead Mesa well are medium-brownish-gray to dark-gray lime mudstones. Sandstones are fine- to medium-grained, rounded quartz arenites; many are poorly cemented and have been disaggregated into individual sand grains in the samples.

To the southeast, the San Andres becomes more evaporitic in the Dalton Kincheloe No. 1 Arnold Federal well in T6S R13E. In that well, the formation is 945 ft thick although true thickness may be only 775 ft because 170 ft of intrusive igneous felsite is present in the lower part of the San Andres section. In the Kincheloe well, the San Andres is composed mostly of gray to brownish-gray, anhydritic microcrystalline dolostone and dolomitic anhydrite. Beds of anhydrite are also present. Ten to twenty thick intervals of fine- to very fine-grained, well-sorted quartzose sandstone are present in the lower 300 ft.

The San Andres in the Ralph Nix No. 1 Ralph Nix well in T6S R10E is 808 ft thick. It has less sandstone than in the Kincheloe well. Dolostones are brownish gray to dark gray with compact microcrystalline to sucrosic textures; vugular and intercrystalline porosity is present.

Artesia Group (Permian: Guadalupian)

The Artesia Group is composed of 0 to 325 ft of fine- to very fine-grained sandstones with minor thin beds of dark-gray limestone. It is present south and west of T3S R9E where it unconformably overlies the San Andres Formation and is unconformably overlain by Triassic red beds. The Artesia Group has also been referred to as the upper member of the San Andres Formation (Wilpolt and Wanek, 1951), and the Bernal Formation. Both of these terms are obsolete.

Artesia sandstones are red to orange to light gray, fine to very fine grained, and silty. Within the Artesia section in the Ralph Nix No. 1 Ralph Federal well in T6S R10E, trace amounts of quartz mica schist are present in well cuttings from 1230 to 1234 ft. These detrital fragments may be second-cycle clasts derived from erosion of older sandstones and conglomerates. Alternatively, they could indicate that small, remnant high parts of the Pedernal uplift were still exposed in the region during Guadalupian time.

Triassic System

Triassic strata attain a maximum thickness of approximately 500 ft in outcrops (Wilpolt and Wanek, 1951; Griswold, 1959). They have a maximum thickness of approximately 1000 ft where penetrated by wells on the flanks of the Sierra Blanca Basin. They consist of maroon shales and maroon sandstone. The Triassic section has been eroded from large parts of the project area and is generally present within structurally or topographically low areas.

The Triassic section in the region has been subdivided into lithostratigraphic units different ways by different workers. Traditionally the Triassic section has been considered to be the Dockum Group, consisting of the basal Santa Rosa Sandstone and the overlying Chinle Formation (Wilpolt and Wanek, 1951; Griswold, 1959; Kelley, 1971, 1972). Lucas (1991) revised the Triassic lithostratigraphic nomenclature. He subdivides the Triassic into the basal Moenkopi Formation and overlying Chinle Group. Strata that form the Moenkopi were previously included in the lower part of the Santa Rosa Sandstone. Lucas Chinle Group is subdivided into the basal Santa Rosa Formation (mostly sandstones) and the overlying San Pedro Arroyo Formation (mostly maroon shales).

Within the subsurface, Triassic strata attain a maximum thickness of approximately 1000 ft. They are 976 ft in the Dalton Kincheloe No. 1 Arnold Federal well located in T6S R13E on the northeast limb of the Sierra Blanca Basin. The Triassic is 1080 ft thick in the Ralph Nix No. 1 Federal well located in T6S R10E on the northwest limb of the Sierra Blanca Basin. In both wells, the Triassic section consists mostly of silty maroon shales and a lesser amount of fine- to medium-grained, maroon to orange-red sandstone. In general, Triassic strata within the west Texas and eastern New Mexico region are fluvial and fresh-water lake deposits (McGowen et al., 1979).

Cretaceous System

Cretaceous strata unconformably overlie Triassic strata. Jurassic strata are absent. Cretaceous strata are present only in structurally low areas: the Sierra Blanca Basin and the Jornada del Muerto Basin. Cretaceous strata consist of sandstones, tan to gray to black shales, and coal. The Cretaceous sections of the Sierra Blanca and Jornada del Muerto Basins are discussed separately.

Sierra Blanca Basin

The Cretaceous section in the Sierra Blanca Basin consists of six lithostratigraphic units (ascending; Arkell, 1986): Dakota Sandstone, lower Mancos Shale, Tres Hermanos Sandstone, D-Cross Tongue of Mancos Shale, Gallup Sandstone, and Crevasse Canyon Formation. All are Upper Cretaceous. Arkell (1986) provided a good summary of Cretaceous strata in the Sierra Blanca Basin. The following descriptions are taken from his work except where otherwise noted.

The Dakota Sandstone rests unconformably on Triassic strata and is approximately 180 ft thick. The Dakota consists of basal nonmarine sandstones and conglomerates that grade upward into fining-upward sequences of lenticular sandstones, siltstones and shales deposited by meandering stream systems. This succession of stream deposits grades upward into fine- to medium-grained, well-rounded, well-sorted, quartzose sandstones of coastal marine origin.

The lower Mancos Shale overlies and intertongues with the Dakota Sandstone. The lower Mancos is approximately 260 ft thick and consists of gray to black marine shale with minor thin beds of sandstone and siltstone.

The Tres Hermanos Sandstone conformably overlies and intertongues with the lower Mancos Shale. The Tres Hermanos consists of 300 ft of sandstones and minor siltstones and gray to black shales. The lower part of the formation consists of a series of regressive coastal-marine sandstones with minor siltstones and sandstones. The sandstones are very fine grained, well sorted, and quartzose. The middle part of the Tres Hermanos Sandstone consists of lenticular sandstones, siltstones, and gray to black carbonaceous shales of coastal plain origin. The sandstones are very fine grained, arkosic to lithic, and not as well sorted as the underlying coastal marine sandstones. The upper part of the Tres Hermanos Sandstone consists of laterally continuous coastal-marine sandstones with minor siltstones and shales. The sandstones are fine grained, well sorted, and quartzose.

The D-Cross Tongue of the Mancos Shale conformably overlies and intertongues with the Tres Hermanos Sandstone. It is composed of 450 to 500 ft of gray to tan shales and siltstones.

The Gallup Sandstone conformably overlies and intertongues with the D-Cross Tongue. It consists of 150 to 180 ft of coastal-marine sandstones. Sandstone are fine to medium grained. Thin beds of gray shale and siltstone are present within the lower part of the Gallup.

The Crevasse Canyon Formation conformably overlies and intertongues with the Gallup Sandstone. The Crevasse Canyon Formation consists of 600 to 800 ft of interbedded lenticular sandstones, siltstones, shales, and coals. The sandstones are fine grained, not well sorted, and arkosic to lithic in composition. The siltstones and shales are also lenticular and are complexly interbedded with the sandstones. A large percentage of finer grained rocks are carbonaceous and contain plant debris.

Coal beds are present within two zones in the Crevasse Canyon Formation. One zone is near the base of the formation and the other zone is approximately 80 ft below the top of the formation. Most of the coal beds are less than 2 ft thick but a few exceed 4 ft in thickness. The coals have been mined on a relatively small-scale basis (Hoffman, 2002). The mines are presently inactive. Extensive faulting and associated intrusions of Tertiary-age igneous rocks have rendered the area structurally complex and has made mining difficult. Bodine (1956) mapped and described Cretaceous coal-bearing strata near Capitan.

Jornada del Muerto Basin

The Cretaceous section in the Jornada del Muerto Basin consists of three Late Cretaceous stratigraphic units (ascending; Tabet, 1979): Dakota Sandstone, Mancos Shale, and Mesaverde Group. These strata have not been penetrated by petroleum exploration wells so subsurface information is limited to descriptions made from shallow wells drilled for coal exploration. Tabet (1979) provided a good summary of Cretaceous strata in the Jornada del Muerto Basin. The following description is taken from his work, unless otherwise noted.

The Dakota Sandstone consists of 70 to 200 ft of orange-brown, medium-grained quartzose sandstones (Gardner, 1910; Tabet, 1979). The Mancos Shale conformably overlies the Dakota. The Mancos Shale consists of a lower shale unit, the middle Tres Hermanos Sandstone, and an upper shale unit. The upper shale unit is the D-Cross Tongue of the Mancos Shale. The lower and upper shale units are composed of gray to black shales with minor thin beds of tan-colored quartzose sandstones and limestones. Poor exposures and local faulting render thickness uncertain, but the lower shale is estimated to have a maximum thickness of approximately 680 ft and the upper shale has a maximum thickness of approximately 360 ft.

The Tres Hermanos Sandstone separates the lower and upper shale units in a regional intertonguing relationship (Hook, 1984). In the Jornada del Muerto Basin, the Tres Hermanos consists of approximately 240 ft of medium-bedded, fine- to medium-grained, tan-colored quartzose sandstones, gray shales, and bioturbated silty sandstones.

The Mesaverde Group overlies the Mancos Shale. It is composed of gray and tan shales, minor thin sandstones, and lenticular coal beds. The Mesaverde Group is known to vary in thickness between 230 and 650 ft. Thickness varies because the upper surface is erosional. Where not exposed at the surface, the Mesaverde is unconformably overlain by Tertiary-age sedimentary rocks or by Quaternary sediments.

Mesaverde coals have been mined in the Jornada del Muerto coal field in T4S R3E and in the Carthage coal field in T5S R2E, which is located just west of the project area. Coals are thin and lenticular. Maximum coal thickness is approximately 4 ft but most coals are less than 2 ft thick. The last coal mining in the area took place in 1975 from a small underground mine in the Carthage field (Hoffman, 1996). A mine in the Jornada del Muerto coal field closed in 1927 (Hoffman, 1996).

Tertiary System

Tertiary rocks within the Chupadera Mesa project area include continental sedimentary units, extrusive volcanic rocks and associated volcanoclastic sediments, and intrusive stocks, dikes, and sills. Sedimentary and volcanic rocks are present in the Jornada del Muerto and Sierra Blanca Basins. Intrusive rocks are present mainly in the eastern half of the project area.

Continental conglomerates, sandstones and mudstones of Tertiary age are present in the Jornada del Muerto basin where they unconformably overlie Cretaceous strata. They have been assigned to the Baca Formation (Tabet, 1979) and attain a maximum thickness of approximately 1000 ft (Gardner, 1910). Andesitic, rhyolitic and associated volcanoclastic sediments are also present locally within the Jornada del Muerto basin (Tabet, 1979) with a maximum thickness of 2000 ft (Wilpolt and Wanek, 1951).

Sedimentary rocks within the Sierra Blanca Basin are assigned to the Cub Mountain Formation and the Sanders Formation (Cather, 2002). The Cub Mountain Formation, of Eocene age, unconformably overlies Cretaceous strata. It consists of 2500 ft of red bed sandstones, mudstones and conglomerates. The Sanders Canyon Formation gradationally overlies the Cub Mountain Formation and consists of volcanoclastic sandstone and mudstone. Flows, tuffs and volcanoclastic breccias, sandstones and conglomerates of the Sierra Blanca volcanics gradationally overlie the Sanders Canyon Formation. They range in age from 26 to 38 Ma (Moore et al., 1991)

Tertiary igneous intrusive rocks form numerous stocks, dikes, and sills in the eastern half of the project area (Fig. 5). The stocks form prominent mountains in the region. East to northeast-trending dikes and sills have been mapped at the surface on Chupadera Mesa and areas to the east of Chupadera Mesa and also have been cut by exploratory wells drilled in the region. Composition of the igneous intrusive rocks is varied includes diabases, monzonites, and rhyolites (Kelley, 1971; Bachman, 1968).

PETROLEUM SOURCE ROCKS

Introduction

A *petroleum source rock* can be defined as any unit of rock that has generated and expelled oil and/or gas in commercial quantities (Hunt, 1996). When assessing source-rock potential, four questions must be answered (Dow, 1978; Barker, 1980; Brooks et al., 1987; Hunt, 1996). First, does the rock have sufficient organic matter? Second, is the organic matter capable of generating petroleum and, if so, is the organic matter oil prone or gas prone? Third, is the organic matter thermally mature? Fourth, have generated hydrocarbons been expelled from the rock?

The question of whether or not the rock has sufficient organic matter to be a source rock can be answered on the basis of *total organic carbon* (TOC) measurements. Rocks that have insufficient TOC content can be ruled out as possible source rocks. Jarvie (1991) has summarized TOC ratings systems for screening potential source rocks (Table 1). The TOC content needed for petroleum generation is thought to be greater in siliciclastic shales than in carbonate source rocks.

The second question asks what type of organic matter is present within the rock. The type of organic matter, if present in sufficient quantity, will determine if a source rock will produce principally oil or principally gas upon maturation (Table 2). For this project, identification of organic-matter type was based mainly on petrographic analyses of kerogen concentrate. Algal, herbaceous, and many amorphous kerogens (kerogen types I and II) will generate oil and associated gas upon maturation (Hunt, 1996; Brooks et al., 1987; Tyson, 1987). Woody kerogens (kerogen type III) and some amorphous kerogens will generate gas and possibly a minor amount of oil or condensate upon maturation. Inertinites are type IV kerogens that have extremely low hydrogen contents and are incapable of generating significant amounts of hydrocarbons. Although it is possible to differentiate kerogen types I, II, and III using Rock-Eval pyrolysis (e.g. Tissot and Welte, 1978; Peters, 1986), some type III kerogens may be confused with other types of kerogens and result in misleading characterization of kerogen types when using pyrolysis (Tyson, 1987). Oxidation of kerogen may also alter its Rock-Eval character. Also, pyrolysis can not discern the different varieties of kerogens present in samples with mixed kerogen assemblages. For these reasons, Rock-Eval pyrolysis was used only as reinforcement for petrographically determined kerogen identification.

The level of thermal maturity was evaluated primarily using visual kerogen analyses. For the Petroleum Source Rock Project and for the analyses made specifically for this project, the color of the kerogen concentrate was analyzed. Kerogen color changes from yellow to orange to brown to black with increasing maturation (Staplin, 1969). Based on calibrated color charts, the sample is assigned a numerical value (*Thermal Alteration Index* or TAI) which ranges from 1.0 (immature) to 5.0 (metamorphosed; Table 3).

Vitrinite reflectance (R_o) is a measure of the percentage of incident light that is reflected from the surface of vitrain, a type of woody kerogen. It can be used to assess thermal maturity of a source rock and is a standard measurement of maturity. Essentially, vitrinite reflectance increases with thermal maturity and can be used to assess whether or not a source rock has attained a sufficient level of maturation for petroleum generation. For this project, vitrinite reflectance data were not available.

Table 1. Generation potential of petroleum source rocks based on TOC content. From Jarvie (1991).

Generation potential	TOC in shales (weight percent)	TOC in carbonates (weight percent)
Poor	0.0 - 0.5	0.0 - 0.2
Fair	0.5 - 1.0	0.2 - 0.5
Good	1.0 - 2.0	0.5 - 1.0
Very good	2.0 - 5.0	1.0 - 2.0
Excellent	> 5.0	> 2.0

Rock-Eval pyrolysis can also be used to evaluate thermal maturity. The temperature at which the maximum amount of hydrocarbons is generated from the S_2 peak (TMAX, °C) has been correlated to the thermal maturity of the source rock (Peters, 1986; Table 3). This method, although quantitative, does not give as complete an evaluation of maturity as TAI and only places a sample as being within, above, or below the oil window. Also, the measured value of TMAX is partially dependent upon the type of organic matter present as well as several other factors (Peters, 1986). Most workers recommend that TMAX values be confirmed with either R_o or TAI determinations. Because R_o values were not available, thermal maturity was determined primarily from TAI values. For this project Rock-Eval TMAX and PI values were used to support TAI data or were used in wells for which no TAI data were available.

Table 2. Kerogen types and petroleum products produced upon thermal maturation. Based on summary works of Merrill (1991) and Tyson (1987).

General kerogen type	Kerogen type	Petrographic form	Coal maceral group	Hydrocarbons generated
sapropelic (oil prone)	I	algal	exinite or liptinite	oil, gas
		amorphous		
	II	herbaceous		
humic (gas prone)	III	woody	vitritinite or huminite	gas, possibly minor oil
	IV	coaly (inertinite)	inertinite	none

The fourth question concerns the expulsion of generated hydrocarbons from the source rock. This question is more difficult to answer than the other three questions. For the most part, studies of thermal maturity of a source rock are empirically correlated with the presence of oil or gas in associated reservoirs. It is generally assumed that once a sufficient volume of hydrocarbons have been generated in a source rock, they will be expelled and migrate into reservoirs. Reservoirs that are thinly interbedded with reservoirs will expel hydrocarbons at lower levels of thermal maturity than thick source rocks that contain few or no interbedded reservoirs (Leythauser et al., 1980; Cornford et al., 1983; Lewan, 1987).

Three gross stratigraphic intervals, the Pennsylvanian section, the San Andres Formation (Permian), and the Upper Cretaceous section are generally been considered to contain significant organic-rich source facies within the Chupadera Mesa project area. Source rock data presented in the accompanying Source Rock Database (*Chupadera source rock data.xls*) indicate that other stratigraphic units generally have insufficient levels of organic carbon to have generated significant volumes of hydrocarbons, although

Table 3. Correlation of maturation parameters with zones of hydrocarbon production. Based on Geochem Laboratories, Inc. (1980), Sentfle and Landis (1991), Peters (1986), and Hunt (1996).

Maturation level (products generated)	Visual kerogen Thermal Alteration Index (TAI)	Rock-Eval PI	Rock-Eval TMAX (°C)
Immature (biogenic gas)	1.0 - 1.7		
Moderately immature (biogenic gas and immature oil)	1.8 - 2.1		<435
Moderately mature (immature heavy oil)	2.2 - 2.5	< 0.1	
Mature (mature oil, wet gas)	2.6 - 3.5	0.1 – 0.4	435 - 470
Very mature (condensate, wet gas, petrogenic dry gas)	3.6 - 4.1	> 0.4	
Severely altered (petrogenic dry gas)	4.2 - 4.9		>470
Metamorphosed	5.0		

thin, local source beds are present within Yeso (Permian: Leonardian) strata.

Pennsylvanian strata, with their thick sections of black, organic-rich shales, are present over a large part of the project area at depth and source rock analysis and mapping concentrated on these units. The San Andres Formation crops out at the surface, is present only at shallow depths, or has been eroded altogether from most of the project area and therefore was not analyzed or mapped in detail. Potential Cretaceous source rocks are present only in the Sierra Blanca Basin and the Jornada del Muerto Basin and are summarized, but source rock data are very limited. Therefore, mapping and analysis were concentrated on the Pennsylvanian section although a summary of the source potential of all major stratigraphic units is presented.

Two source rock maps were prepared for the Pennsylvanian. One map shows regions of TOC content within the lower part of the Pennsylvanian section (Fig. 15). The lower part of the Pennsylvanian was chosen for mapping because it has wide geographic occurrence within the project area and is thick; as discussed previously, the upper part of

the Pennsylvanian section has been eroded from significant portions of the north-central part of the project area. The other map type shows levels of thermal maturity (Fig. 16). The data used in map production are presented in the Petroleum Source Rock Database. Analytical and sampling procedures are discussed in Appendix III. Maps that show regions of TOC content were prepared from the total organic carbon measurements. Mapped regions indicate generative potential of source facies. When more than one TOC analysis was available from a well, the one with the maximum TOC content was used in map preparation unless it was considered to be an anomalous value caused by local maturation associated with an intrusive dike or sill of Tertiary age. Cuttings were “picked” before analysis to exclude non-source lithologies such as sandstones. Most of the analyses were performed on drill cuttings from composite 100 ft intervals because of limited volumes of cuttings available for analytical work. The TOC analyses should therefore generally be considered as the average TOC of source facies within the sampled depth interval with actual TOC contents bracketing the average value. If the measured TOC content is, for example 3.2 percent, actual TOC values within source strata in the sample interval probably exceed 3.2 percent in some source beds and are less than 3.2 percent in other source beds.

Lower Paleozoic Source Rocks

As discussed in the section on stratigraphy, Cambrian, Ordovician, Devonian, possibly Mississippian strata are present as a thin erosional wedge in the southern part of the project area. These stratal units are composed mostly of light- to dark-gray carbonates, sandstones, and minor light-colored shales. The units are not present in wells drilled within the project area; where present in outcrop they are located on military reservations with restricted access. Their lithologic characteristics indicate that they are mostly poor source facies and they are not considered to have significant source potential within the Chupadera Mesa project area. The dark-gray Montoya dolostones may have favorable source characteristics. Source rock analyses of Ordovician strata in the Houston Oil and Minerals No. 1 Lewelling well (Broadhead et al., 1998), located 15 miles south of the project area in T12S R9E, are indicative of a poor source character with TOC values less than 0.1 percent.

Pennsylvanian Source Rocks

The Pennsylvanian section contains numerous, thick dark-gray to black shales throughout its vertical and aerial extent in the Chupadera Mesa region. In most places, shales from the lower part of the Pennsylvanian section contain 1 to 2 percent Total Organic Carbon (Fig. 15), ranking them as good source rocks in terms of organic richness. Maximum TOC content shows no regional trend, but exceeds 2 percent in the James K. Anderson No. 1 Wishbone Federal well located in T4S R3E at the western edge of the project area. These rich measurements were obtained despite inadequate sampling procedures for the well; cuttings were not selectively picked before analysis and contain substantial amounts of sandstones and limestones that will skew the TOC measurements toward the low end. Most analyzed samples in this well exceeded 0.5 percent TOC and several exceeded 1 percent with one sample exceeding 2 percent TOC. It can be readily surmised that many, if not most, lower Pennsylvanian shales in the Anderson well contain at least 1 percent TOC and that several shales probably contain more than 2 percent TOC. Organic content of Pennsylvanian shales decreases to the south in the Sun Oil No. 1 Bingham State well, located in T5S R5E. In that well, which has a relatively thin Pennsylvanian section of 1144 ft, maximum TOC measured in shales is 0.79 percent, still adequate for petroleum generation but not as rich as elsewhere.

Organic matter type in the Pennsylvanian section is more or less equally divided among kerogens that are mostly oil prone (amorphous and herbaceous types), gas-prone kerogens (woody types), and nongenerative types (inertinite). All four types of kerogens (amorphous, herbaceous, woody, inertinite) are present in most samples but no single type constitutes more than 40 percent of the kerogen population. Therefore, most Pennsylvanian shales contain both oil-prone and gas-prone kerogens. However, the presence of significant amount of inertinite in some samples reduces the amount of TOC available for petroleum generation.

Most of the Pennsylvanian samples in the project area have low values of the Rock-Eval Hydrogen Index (HI). In most samples, it is less than 50. This is at least partly a function of the mixed kerogen populations with significant amounts of woody kerogens and inertinite in most samples. In most samples with little or no inertinite and woody kerogens, the HI is significantly higher.

Thermal maturity patterns in the lower part of the Pennsylvanian section show a relationship to Tertiary heating events. Although data are somewhat sparse, there is a

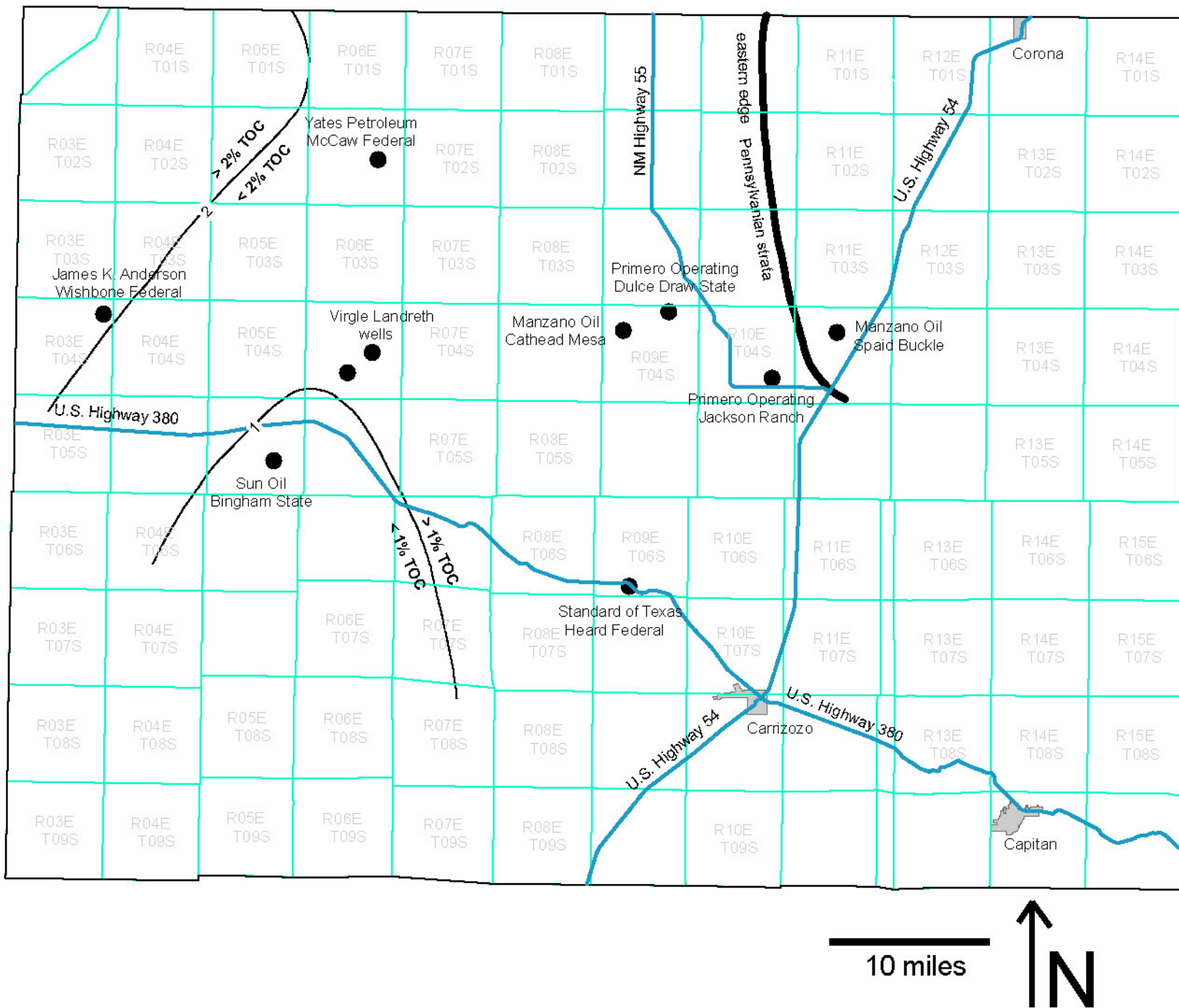


Figure 15. Contour map of Total Organic Carbon (TOC) in lower Pennsylvanian shales. Conour values are weight percent TOC. Black dots are wells with TOC analyses.

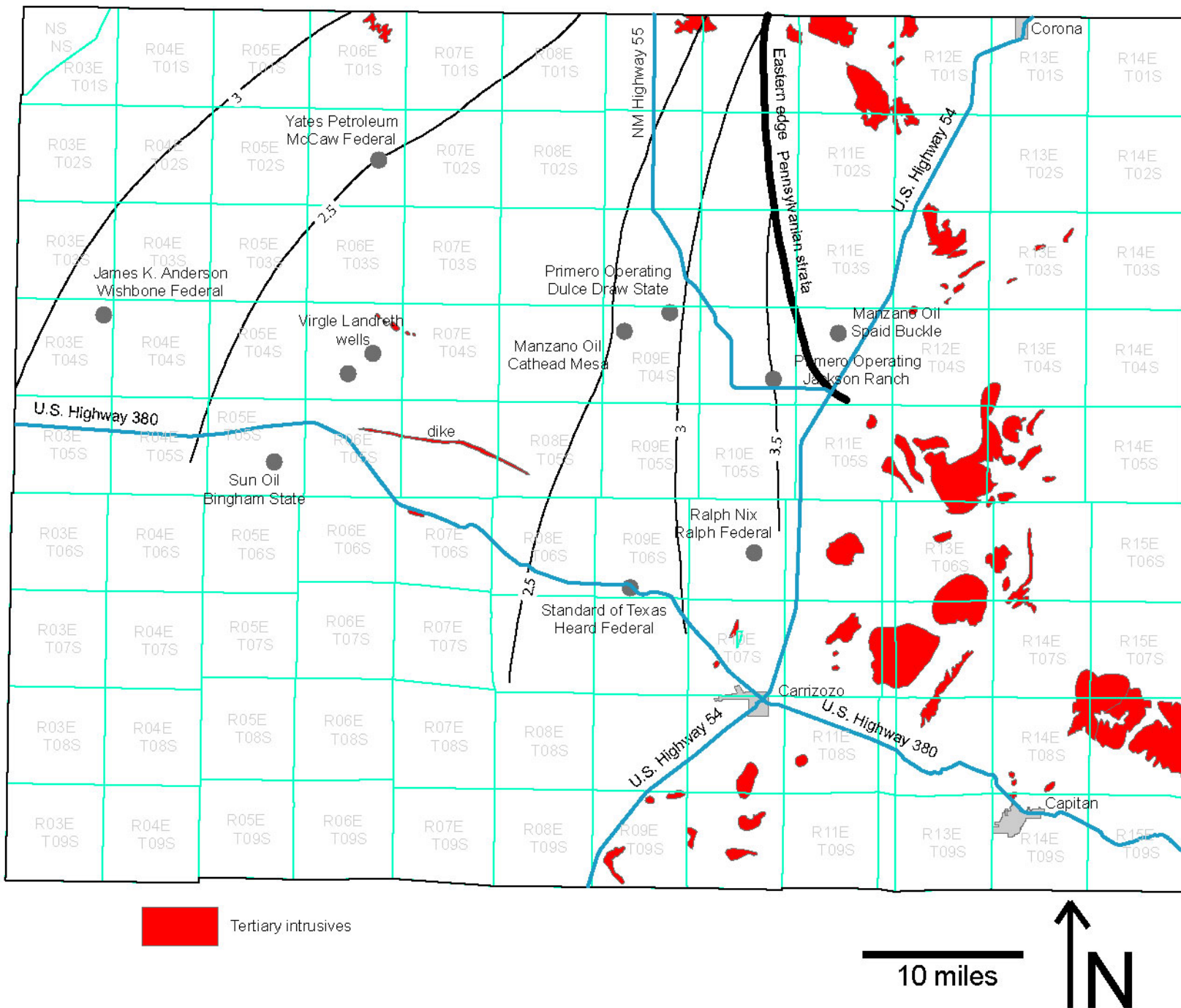


Figure 16. Contours of the Thermal Alteration Index (TAI) of kerogen in lower Pennsylvanian shales. TAI is an indicator of thermal maturity of a source rock. Black dots are wells with TAI analyses.

north-south aligned trend of lower thermal maturity on an axis approximately centered about the Oscura Mountains and the Oscura anticline (Fig. 16). Along this trend, shales in the lower part of the Pennsylvanian are moderately mature with TAI values ranging from 2.2 to 2.5. These maturity levels indicate generation of some heavier, immature oils and perhaps some associated gas as well.

Maturity increases both west and east from this central trend. To the west, TAI reached a maximum of 2.8 in the lower 1000 ft of the Anderson No. 1 Wishbone Federal well in T4S R3E. This maturity level places these strata in the upper part of the oil window. The same west-increasing trend in maturity was seen to the north in the Estancia Basin (Broadhead, 1997) where it is independent of burial depth. This westward increase in thermal maturity is ascribed to a Tertiary-age heating event associated with the Rio Grande rift (Broadhead, 1997). Oligocene and Miocene (Early Tertiary) volcanism associated with early phase rifting (Chapin and Seager, 1975; Kelley et al., 1992) may have elevated temperatures in areas adjacent to the rift, resulting in enhanced thermal maturity in north-south trending bands adjacent and parallel to the rift.

Thermal maturity of Pennsylvanian strata also increases eastward from the central “cool” area. From the minimum TAI of 2.3 in the Sun No. 1 Bingham State well in T5S R5E, thermal maturity of the Pennsylvanian section increases eastward to a maximum TAI of 3.5 in the Primero No. 1 Jackson Ranch Federal well located in T4S R10E. This places the Pennsylvanian in the Jackson Ranch well at the base of the oil window, well past the stage of maximum oil generation and at the point where light oils and associated gas should have been formed. Rock-Eval TMAX values and Rock-Eval PI values confirm the levels of thermal maturity that the TAI indicates.

The eastward increase in thermal maturity is independent of burial depth within the project area. Source units have similar maturity in shallow areas to the north as well as in the deep Carrizozo basin to the south. There is no similar eastward increase in maturation to the north in the Estancia Basin (Broadhead, 1997). This thermal maturity trend can be explained by higher paleo-heatflow (and perhaps modern heatflow?) associated with the large igneous intrusive bodies of Tertiary age that occur throughout western Lincoln County (see Fig. 16). If this is the case, then Pennsylvanian strata along this north-south aligned trend of enhanced maturity were rendered thermally mature during the Early Tertiary (as they were also in the western part of the project area). Lack

of major Tertiary-age intrusive bodies along the west flank of the Estancia Basin explains why this maturation trend does not extend north of the project area.

Early Tertiary thermal maturation of Pennsylvanian source rocks has important implications for petroleum migration and accumulation. First, regions of optimal thermal maturity are concentrated within a zone two townships wide centered on approximately R10E with an eastern boundary at the eastern eroded edge of the Pennsylvanian (Fig. 16). Second, structures established prior to Early Tertiary heating would have determined migration routes and entrapment for oil and gas. Oil generated within Pennsylvanian strata in the area around the Jackson Ranch well would have migrated updip, including to the northeast and east, until it either accumulated in favorable areas along the eastern limit of the Pennsylvanian or escaped upward into coarser clastics of the basal part of the Abo Formation.

One sample from the Pennsylvanian in the Manzano No. 1 Cathead Mesa well, located in T4S R9E, has a TAI value of 3.5, placing that sample in the lower part of the oil window. That sample was taken near a Tertiary-age igneous sill that the well penetrated. The high level of maturity may well be associated with locally elevated paleotemperatures associated with the sill. If this is the case, it raises an interesting possibility concerning maturity distributions in otherwise marginally mature areas. Oil and/or gas could be locally generated in local areas associated with dike or sill swarms and local hydrocarbons kitchens could be scattered throughout an area that would otherwise be considered marginal for oil and gas generation.

Permian Source Rocks

Permian strata within the Chupadera Mesa project area consist of the following stratigraphic units (ascending): Bursum Formation, Abo Formation, Yeso Formation, Glorieta Sandstone, San Andres Formation, and Artesia Group. None are considered to have potential as major source units, but analyses indicate that there may be source beds of limited extent within the Yeso and San Andres Formations. A short summary of the source potential of Permian units follows.

Bursum Formation (Wolfcampian)

The Bursum Formation is not considered to have significant source potential. It is composed of red shales, mostly red sandstones, and a few thin limestones. Although no source rock analyses are available for the Bursum Formation, lithologic similarity to the overlying Abo Formation suggests that the source character of Bursum strata is poor. The oxidized nature of the shales indicates they contain little kerogen and what kerogen is present has probably been oxidized. The limestones appear light gray and, in addition to being thin, probably have minimal organic content.

Abo Formation (Wolfcampian to Leonardian)

Twelve samples of well cuttings have been analyzed for TOC. TOC values for all samples are less than 0.25 percent and are less than 0.15 percent in nine of the samples. The analyzed values are what is expected for the oxidized red shales that constitute most of the Abo. As noted in the section under stratigraphy, the Abo contains minor, thin beds of black shales and dark-gray limestones. Sampling for source rock analyses was not possible because of an insufficient volume present in the archived well cuttings. Although these dark and presumably organic-rich strata may act as local source facies, they are not regionally significant. They can be expected to have lower thermal maturity than underlying, deeper source rocks.

One dark-gray to black Abo shale was analyzed for source rock character. The sample came from well cuttings at depths of 2430 to 2450 ft in the Manzano No. 1 Spaid Buckle well. The sample was mature with a TAI of 3.3. kerogens are mostly amorphous and herbaceous types. However, TOC is low, 0.22 percent, so this shale has a poor source character.

Yeso Formation (Leonardian)

The Yeso Formation has modest possibilities as a petroleum source unit. Overall, the formation contains few lithofacies favorable as oil and gas source rocks. The sandstones, red to orange shales, anhydrites, and salts will contain only small percentages of organic matter, and much of that will be heavily oxidized. However, the dark-gray to brown dolostones present within the Yeso have modest source possibilities. Although individual thin dolostone beds may not have sufficient volume to constitute significant source beds, the aggregate thickness of several organic-rich dolostones could conceivably

produce locally significant source rocks. Three samples of Yeso dolostones were analyzed for source rock character.

Dark-gray dolostones from depths of 2140 to 2150 ft in the Manzano No 1 Spaid Buckle well were analyzed. The well is located in T4S R11E. TOC is 0.49 percent, sufficient for hydrocarbon generation in a carbonate. The TAI is 3.3, indicating a level of thermal maturation within the lower part of the oil window. Rock-Eval maturity indicators are mixed with a mature PI of 0.25 but an immature TMAX of only 379° C. The kerogen population is mixed with 25 percent amorphous material, 33 percent herbaceous material, 33 percent woody material, and 8 percent inertinite.

The second Yeso sample was taken from brown dolostones at depths of 1440 to 1490 ft in the Primero No. 1 Dulce Draw well, located in T4S R9E. TOC is 1.07 percent, again good for a carbonate rock. TAI is 2.8, putting the sample within the upper part of the oil window. The maturity level is confirmed by a Rock-Eval TMAX of 442° C. Kerogens are dominantly herbaceous and amorphous types. The Rock-Eval PI of 0.28 also indicates thermal maturity of the sample.

The third sample was from dark-brown dolostones at depths of 1859 to 1868 ft in the Standard of Texas No. 1 Heard well, located in T6S R9E. TOC is 1.10 percent, good for a carbonate rock. The kerogen population is comprised entirely of amorphous and herbaceous types so oil should be generated upon maturation. However, TAI is only 2.3, indicating moderate maturity. Rock-Eval TMAX is 434° C, supporting the maturity level obtained from TAI. The Rock-Eval PI is 0.28, indicative of thermal maturity. However, the high value of PI may also result from the presence of heavy oil in the source rock. A strong shoulder on the S₂ peak of the pyrogram may also result from the presence of heavy immature oil in the source rock.

Glorieta Sandstone (Permian: Leonardian)

The Glorieta Sandstone, composed mostly of quartzose sandstone and minor intertonguing carbonates from the San Andres Formation as well as the Joyita Sandstone Member of the Yeso Formation. These rock types are unlikely to be petroleum source rocks.

San Andres Formation (Permian: Leonardian)

The San Andres Formation crops out over large parts of the project area. In most other places, it has been completely removed by erosion. Therefore, it is of little interest as a petroleum source unit in most places within the Chupadera Mesa project area. However, it is present to significant depths in the Sierra Blanca Basin where it is overlain by Triassic and Cretaceous strata but has been penetrated by only two wells.

For this project, one sample was analyzed from the San Andres in the Sierra Blanca Basin. The sample consisted of cuttings of brown to dark gray dolostones from depths of 1440 to 1450 ft in the Ralph Nix No. 1 Ralph Federal well, located on the western flank of the Sierra Blanca Basin. The samples contain 1.00 percent TOC, more than sufficient for petroleum generation in a carbonate source rock. The TAI of 2.6 indicates thermal maturation in the uppermost part of the oil window. The maturity interpretation is confirmed by the Rock-Eval TMAX of 434° C and the Rock-Eval PI of 0.17. Amorphous and herbaceous materials dominate the kerogen population with no woody types and only 13 percent inertinite.

The San Andres should be more mature to the east where it is buried beneath Mesozoic strata in the Sierra Blanca Basin and where it will also be closer to the large Tertiary-age igneous intrusions within the Sierra Blanca Basin. It is quite possible that the San Andres dolostones are within the thermogenic gas window within the deeper parts of the Sierra Blanca Basin.

Artesia Group (Guadalupian)

The Artesia Group is present only as thin erosional remnants in the eastern third of the project area. The fine-grained sandstones that constitute most of the Artesia Group are unlikely petroleum source rocks. Therefore, it is of little interest as a source unit.

Triassic Source Rocks

Triassic lithostratigraphic units are not regarded as having significant potential as petroleum source rocks. The oxidized, maroon shales and interbedded sandstones are unlikely to contain sufficient organic matter for petroleum generation.

Cretaceous Source Rocks

Cretaceous stratigraphic units contain thick, laterally extensive, dark-gray to black shales and thin, lenticular coals that are generally regarded as favorable source facies.

These units are present within the Jornada del Muerto Basin and within the Sierra Blanca Basin. Source rock analyses were not performed on these sample for this project, but some idea of their suitability as source rocks can be obtained from published information from coal fields in these basins.

Sierra Blanca Basin: Most coal seams in the Sierra Blanca coal fields are high-volatile C bituminous in rank (Hoffman, 1996). This indicates that the coals, and the associated Cretaceous shales, are thermally immature. Sidwell (1946) maintained that coal rank increased locally with proximity to igneous intrusions. The immature nature of the coals suggests that significant hydrocarbons generated by either the coals or the shales will be biogenic gas.

Jornada del Muerto Basin: Coals in the Jornada del Muerto coal field are high-volatile C bituminous (Tabet, 1979). As is the case with the Sierra Blanca field, this indicates the coal is thermally immature. Cretaceous shales in the area are also probably thermally immature. The immature nature of the coals suggests that significant hydrocarbons generated by either the coals or the shales will be biogenic gas.

OIL AND GAS SHOWS

The Chupadera Mesa project area is a frontier area for oil and natural gas exploration. It has been sparsely drilled and production has not been established. A total of 45 wells have been drilled in the area. Several of these wells have encountered oil and gas shows (Figs. 17-21; database *Chupadera wells.xls*). Shows are important indicators that at least some oil and gas is present within the region. Oil and gas shows are discussed by stratigraphic occurrence. This section and accompanying maps discuss shows of oil and gas and also drill-stem tests that either recovered oil or gas, formation water, drilling mud, or were failed tests. Failed drill-stem tests or drill-stem tests that recovered water or mud may indicate that shows were observed in samples or in mud gas.

Precambrian basement rocks

A show of gas in Precambrian basement has been reported from one well drilled in the project area (Fig. 17). This show appears to have originated within a fracture system in igneous rocks. An additional well along the eastern boundary of the project area had a drill-stem test run in the Precambrian during drilling operations, indicating that a show may have been encountered during drilling.

The Manzano Oil No. 1 Cathead Mesa well, located in T4S R9E, was drilled in 1996. The well drilled 1930 ft of Precambrian granite and encountered a diabase laccolith and diabase sills that had intruded the granodiorite. A substantial show of gas was detected by the mudlogging unit while drilling the Precambrian section. The gas curve on the mudlog indicates it contains C₂ as well as C₁. Two drill-stem tests run over the show interval recovered saline formation water but no gas. The lowest string of casing in the well was set in the Paleozoic section with the base of casing in the lowermost part of the Abo Formation approximately 350 ft above the top of Precambrian.

The Cathead Mesa well was reentered during October 2003. Upon reentry, a gas sample was collected from inside the casing. Presumably this was gas that had accumulated in the casing between 1996 and October 2003. The gas had to have seeped into the casing from the lower 30 ft of the Abo, the Pennsylvanian section, or from the Precambrian. The gas would not burn. Analyses run by the Amarillo helium facility of the U.S. Bureau of Land Management indicate a helium content of 2.56 mole percent.

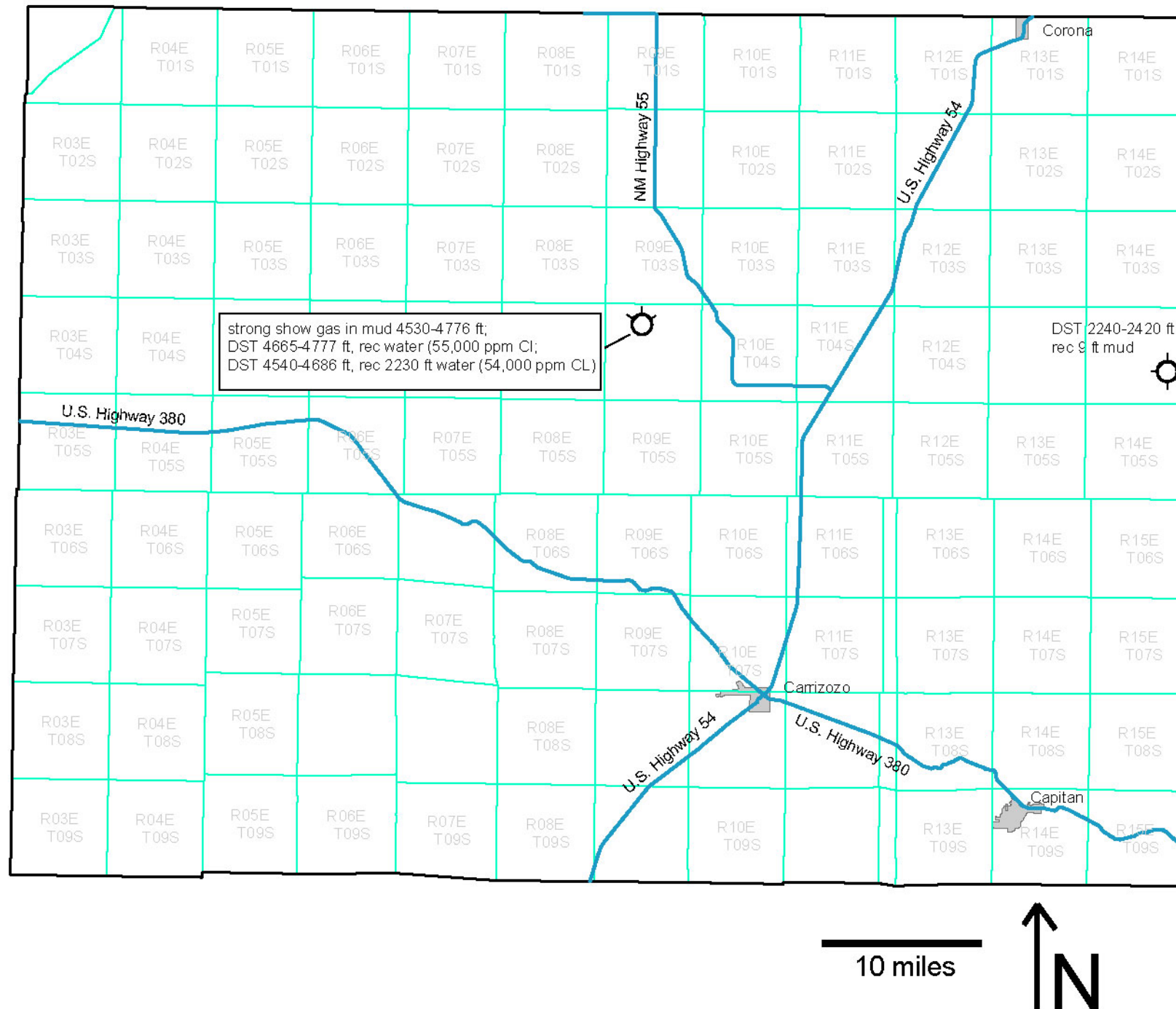


Figure 17. Wells with oil and gas shows, water recovery, or drill-stem tests in Precambrian rocks.

Pressure inside the casing was very low and attempts to stimulate gas flow by swabbing the well were unsuccessful.

The Yates Petroleum No. 1 Boggle ZH Federal well was drilled at the eastern edge of the project area in T4S R14E. A drill-stem test of the uppermost Precambrian recovered drilling mud and a shut-in pressure less than one-fifth of hydrostatic mud pressure in the well. Drill-stem tests were also run in the upper part of the Precambrian in several other wells drilled just a few miles east of the eastern boundary of the project area; these drill-stem tests also recovered drilling mud. Although mudlogs were not available for the Boggle well or for the other wells just east of the project boundary, the use of drill-stem tests suggests that shows may have been encountered in the Precambrian.

Pennsylvanian System

Shows of oil and gas have been reported from Pennsylvanian strata in several wells (Fig. 18; database *Chupadera wells.xls*). Most of the shows have been in wells drilled on the Oscura anticline. Although data are sketchy, the shows appear to have been from Pennsylvanian sandstones within the Atokan, Des Moinesian, and Morrowan sections.

The Pennsylvanian was perforated, acidized, and fractured at depths of 4216 to 4226 ft in the Mountain States Petroleum No. 1 Chupadera well, located in T3S R6E. Gas was reportedly recovered at a flow rate of 50 MCFD. The composition of the gas is unreported, so it is unknown whether it is composed of hydrocarbons, nonvolatile gases, or a combination of hydrocarbon and nonvolatile gases.

To the east, a slight slight show of gas in lower Atokan sandstones was recorded on the mudlog in the Manzano No. 1 Cathead Mesa well, located in T4S R9E.

Abo Formation

Several wells within the project area have tested the Abo Formation (Permian: Wolfcampian to Leonardian) for oil and gas with either drill-stem tests or casing perforations or have mudlogs with shows (Fig.19; database *Chupadera wells.xls*). Two wells drilled on the Oscura anticline in T4S R5E had oil shows in Abo sandstones. A third well drilled on the Oscura anticline in T3S R6E encountered a substantial flow of

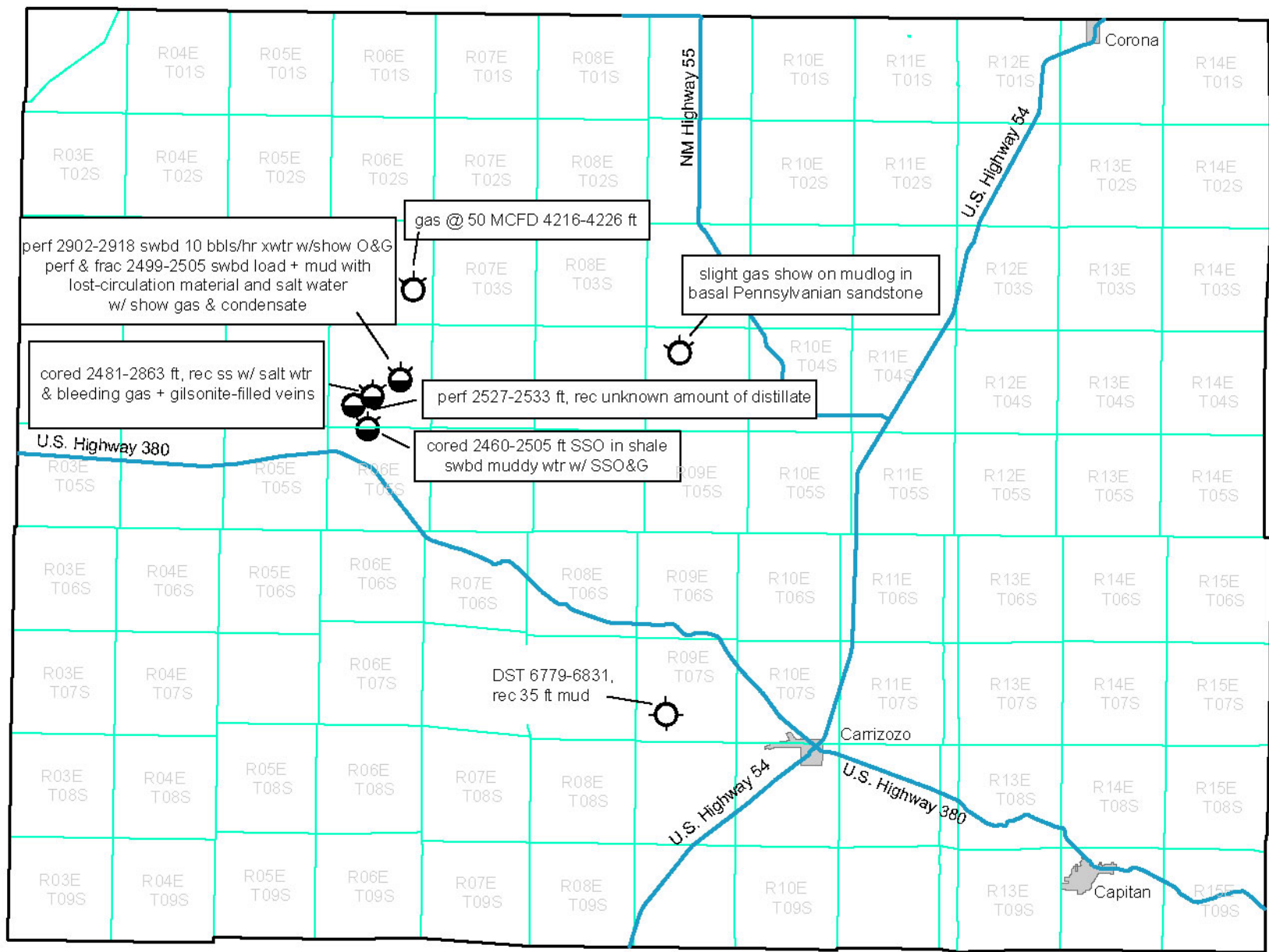


Figure 18. Wells with oil and gas shows, water recovery or drill-stem tests in Pennsylvania strata.

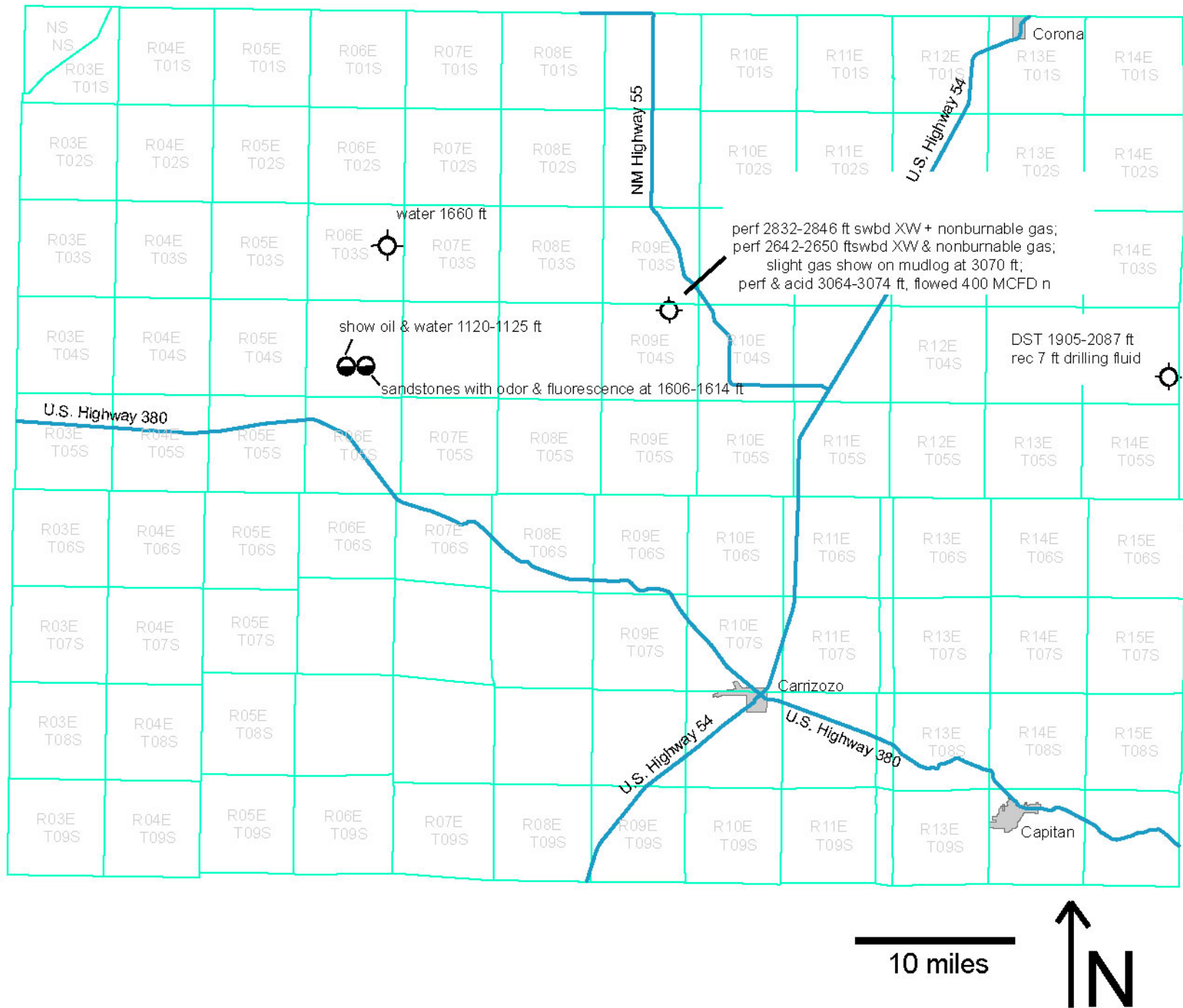


Figure 19. Wells with oil and gas shows, water recovery or drill-stem tests in the Abo Formation.

water in sandstone at a depth of 1660 ft; the sand yielded a water column of 1100 ft in this hole, which was drilled with a cable tool rig.

The Primero Operating No. 1 Dulce Draw well was drilled in Sec. 2 T4S R9E. A slight mudlog gas show in an Abo sandstone from 3064 to 3072 ft was tested through casing perforations. The perforated sandstone yielded nonburnable gas that flowed at an average rate of 400 MCFD over a four-day period. Unfortunately, no analyses were made for helium content. Two other Abo sandstones were perforated through casing and yielded salt water and nonburnable gas after swabbing.

Yeso Formation

The Yeso Formation (Permian: Leonardian) has yielded shows in two wells (Fig. 20; database *Chupadera wells.xls*). Water was encountered in four other wells. In the Virgle Landreth No. 1 Panhandle A well, located in T4S R6E, slight fluorescence and cut was reported in sandstone from the Meseta Blanca Member. In the Manzano No. 1 Cathead Mesa well located in T4S R9E, fluorescence and cut in a brown dolostone at 1720 ft was noted on the mudlog.

San Andres Formation

One well had oil and gas shows from the San Andres Formation (Permian: Leonardian; Fig. 21; database *Chupadera wells.xls*). That well is the Ralph Nix No. 1 Ralph Federal well, located on the western flank of the Sierra Blanca Basin in T6S R10E. The San Andres was perforated from 1410 to 1690 ft and a slight show of oil and gas was reported after swabbing the well. The mudlog indicates a gas show from 1380 to 1490 ft. The well also yielded other shows within the San Andres. A dolostone at 1250 ft had fluorescence and stain and a dolostone at 1575 ft was oil stained. A dolostone at 1980 ft had fluorescence and cut.

A smell of gas from the San Andres was reported in the Layne Texas Company Capitan water well, located in T9S R14E. The smell originated from a dark limestone at 1257 ft.

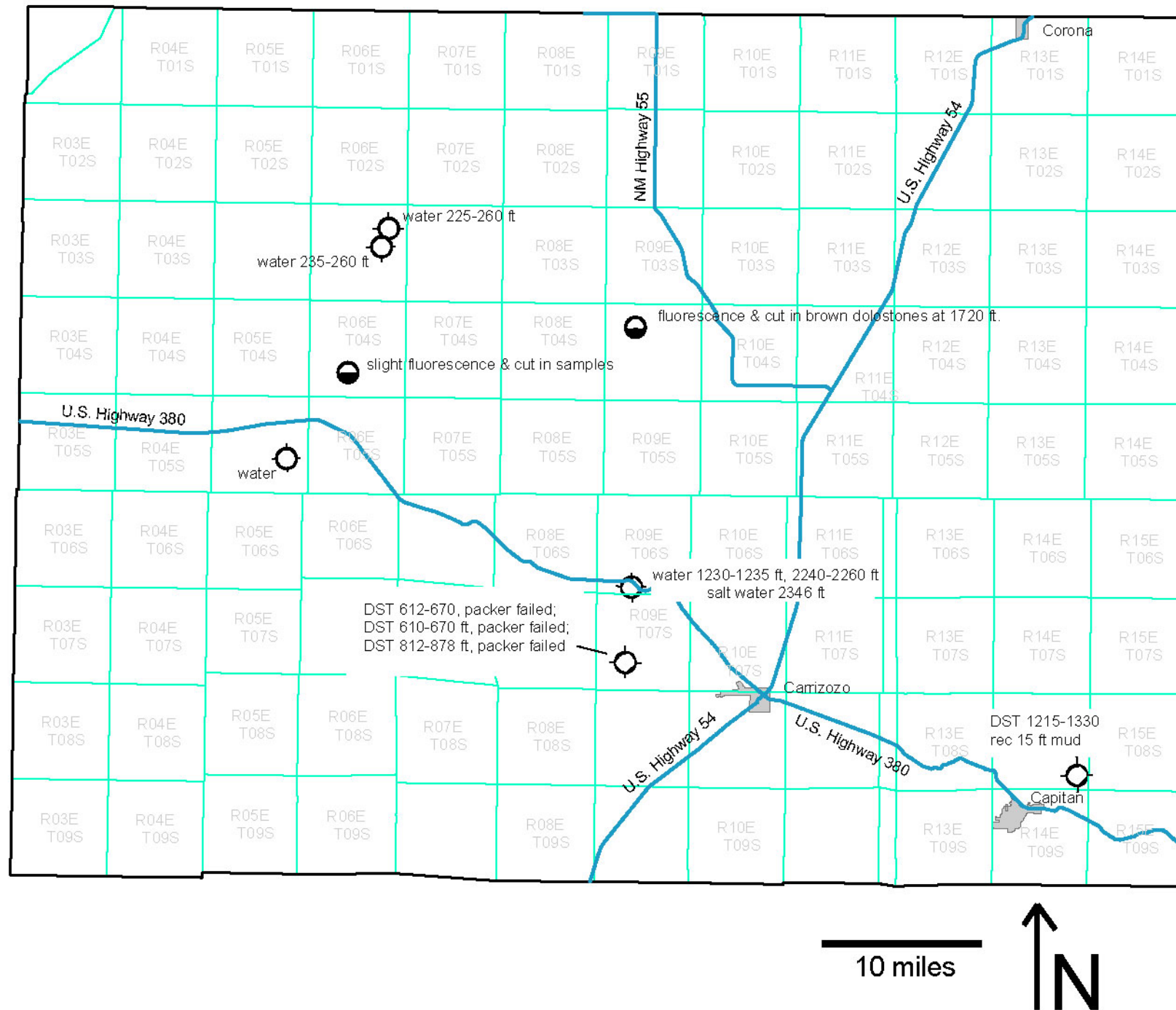


Figure 20. Wells with oil and gas shows, water recovery or drill-stem tests in the Yeso Formation.

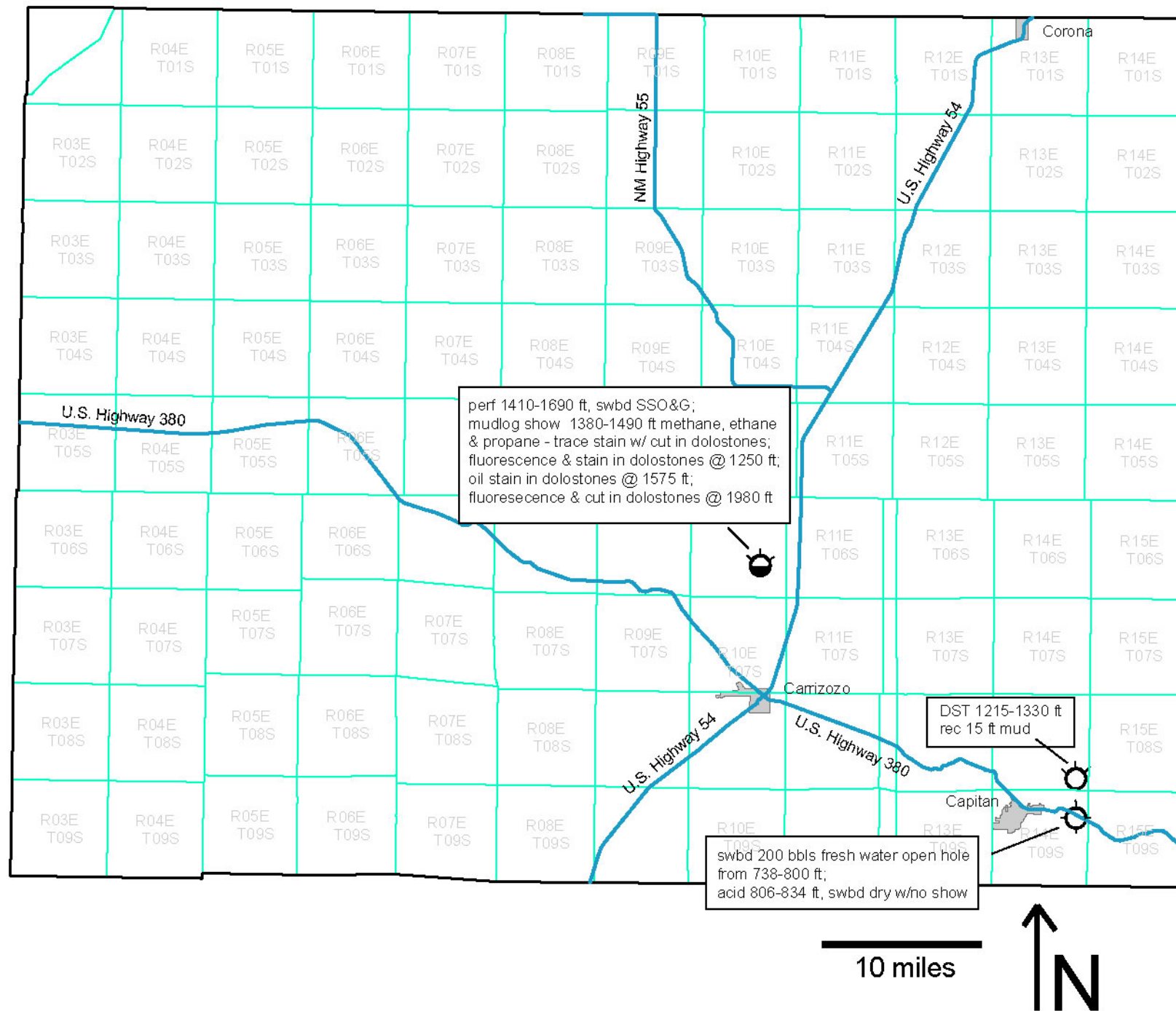


Figure 21. Wells with oil and gas shows, water recovery or drill-stem tests in the San Andres Formation.

OIL AND GAS POTENTIAL

Exploratory wells drilled within the Chupadera Mesa project area have targeted mainly anticlines that have been mapped at the surface. No commercial discoveries have been made using this prospecting philosophy. A total of 45 wells have been drilled within the project area. This is a density of approximately one well for every 85 mi². Many of the wells are shallow and reached total depth in Permian strata. Only 20 wells have been drilled to Precambrian basement. This is a density of one well per 200 mi², or 6.4 townships.

The densest concentration of wells has been drilled on the Oscura anticline (Fig. surface structure map). Wells drilled on the anticline have mostly been drilled to Precambrian. Although intriguing shows have been encountered, commercial production has not been established. This structure plunges northward and Paleozoic strata penetrated by wells on the anticline are exposed along structurally higher areas to the south. As any traps that may be present on the Oscura anticline must involve a stratigraphic component formed by southward permeability pinchouts or stratal truncations. Pennsylvanian source facies in this area have insufficient thermal maturity for generation of major volumes of hydrocarbons.

Within the last decade, four wells have been drilled on Chupadera Mesa to the east of the Oscura anticline. All four wells reached Precambrian. These well did not encounter substantial shows of oil or hydrocarbon gases.

Despite the lack of success to date, the structural, stratigraphic, and source rock maps generated in this report indicate significant oil and gas potential. In addition to exploration concepts that have been tested and still hold potential, the data and maps generated by this project indicate that there are at least exploration concepts or plays that have been poorly tested or untested within the project area. These plays cover substantial areas: 1) the synclinal basin play; 2) the eastern Pennsylvanian boundary play; and 3) the lower Paleozoic pinchout play. In addition, the presence of coals in Cretaceous strata of the Jornada del Muerto Basin and the Sierra Blanca Basin indicates some potential for coalbed methane. The three above-mentioned plays as well as coalbed methane potential are discussed below.

Synclinal Basin Play

This play covers the Torres synclines and the synclinorium that straddles the Monte Prieto – Liberty Hill structural zone. This play is in large part predicated on the possibility that these structurally low areas have an Ancestral Rocky Mountains ancestry (Fig. 12A). If this hypothesis is true, then thickened sections of Pennsylvanian strata underlie the synclinal areas and are separated from the adjacent anticlinal areas by late Paleozoic faults that die out upward. The thickened Pennsylvanian will not only have additional reservoirs in possible basinal facies, but also thicker sections of source rocks and shale seals. Having been buried more deeply than the adjacent anticlinal areas, thermal maturity will be enhanced under the synclines as compared to the marginal mature areas of the adjacent anticlines. The kerogen populations within the Pennsylvanian indicate that this play has the potential for oil as well as gas.

This play may extend southward into the Jornada del Muerto Basin. The area of the basin west of the Oscura Mountains is characterized by a minimum Bouguer gravity anomaly that indicates a deep basin may possibly be present.

Eastern Pennsylvanian Boundary Play

The zero isopach line of the Pennsylvanian System trends roughly north-south in R10-11E (Fig. 13). The location of the zero isopach line in the southern half of the project area is uncertain and could lie anywhere from R10E to R13E. As previously discussed, the location of the zero isopach line has several possible explanations based on presently available data. However, the most viable explanation is erosional truncation of lower Pennsylvanian strata under an unconformity at the base of the Permian.

The eastward thinning of the Pennsylvanian underneath Chupadera Mesa is accompanied by increasing thermal maturity of source rocks. The Pennsylvanian section in R10-11E is thermally mature and within the oil window, whereas Pennsylvanian strata to the west are only marginally mature. Hydrocarbons generated within the mature area would have migrated updip. Because maturation (and therefore petroleum generation) was associated with Tertiary-age igneous activity, migration pathways would have followed structural trends in existence at the time the igneous bodies were emplaced and these pathways would closely approximate the current structure of the area.

Hydrocarbons would have migrated from the hydrocarbon kitchen updip, to the east.

Potential traps include Pennsylvanian sandstones truncated under the basal Permian unconformity.

Lower Paleozoic Pinchout Play

It has been well demonstrated from outcrop mapping that lower Paleozoic strata are truncated northward under the unconformity at the base of the Pennsylvanian section (Fig. 14). This truncation raises the possibility that hydrocarbons could be trapped in favorable updip locations under the unconformity. Although the sparse available information does not provide firm evidence for good reservoir quality within the Ordovician dolostones and sandstones, it is possible that fracturing and karsting of Ordovician dolostones could have occurred during formation of the major unconformity at the top of the lower Paleozoic section.

The Oscura Mountains bisect the northward pinchout into a western part and an eastern part. Potential areas for trap formation and petroleum accumulation include the southern part of the Jornada del Muerto Basin west of the Oscura Mountains. Limited areas east of the Oscura Mountains may also be favorable for hydrocarbon entrapment. The general structure dips east from outcrops in the Oscura Mountains. This geometry would have led to updip leakage of hydrocarbons to the outcrop. However, if lower Paleozoic strata are present within the Carrizozo Basin, then the western boundary fault of the basin may have acted in concert with the northern pinchout to form a trap.

Coalbed Methane Potential

The presence of coals in Cretaceous strata of the Jornada del Muerto and the Sierra Blanca Basin raises the possibility of coalbed methane potential in these areas. In general, the coalbed methane potential is low to possibly moderate. The thin discontinuous nature of the coals limits the coalbed methane potential. The low rank of the coals also limits potential as well and suggests that any coal gas that may be present in the region may have been generated primarily through biogenic processes. Sidwell (1946) thought that coal rank, and therefore thermal maturity, increased near igneous intrusive bodies in the Capitan coal field. It is possible that areas of thermogenic gas generation may be present in the subsurface near the larger intrusive bodies. If this is the case, then there may be some opportunity for a thermogenic coalbed methane play.

HELIUM

Introduction

Helium is a common constituent of natural gases. It is believed to occur trace amounts in all natural gases (Tongish, 1980) More than one-half of all natural gases contain less than 0.1 mole percent helium (Table 4). Only 17.6 percent of all natural gases in the U.S. contain more than 0.3 mole percent helium.

Table 4. Distribution of helium-bearing natural gas reservoirs in United State by helium content of gases. Data from Tongish (1980).

Helium content of reservoir gas, mole percent	Percent of U.S. reservoirs in helium-content range
< 0.1%	55.6%
0.1 – 0.3%	26.8%
> 0.3%	17.6%

A very few reservoir have gases with more than 7 percent helium. In New Mexico, these are confined to the Four Corners platform in the extreme northwest part of the state (summarized in Broadhead, 1993). These New Mexico helium-rich fields include the rattlesnake Mississippian reservoir (7.49% He), Tocito Dome North Mississippian reservoir (7.19% He), Hogback Pennsylvanian reservoir (7.17% He), and the Beautiful Mountain Mississippian reservoir (7.14% He). The content of hydrocarbon gases in most of these reservoirs is less than 20 percent; most of the non-helium fraction of the reservoir gas is nitrogen. Although gas has been produced from these reservoirs for the helium they contain, most of the helium produced in the United States is obtained from reservoirs with less than 1 percent helium in their gases. Six natural gas reservoirs contain an estimated 97 percent of all identified helium reserves in the United States (Pacheco, 2002; Table 5). The reservoirs listed in Table 5 are also produced for their hydrocarbons, which constitute the largest component of the reservoir gas.

Table 5. The six natural gas reservoirs that contain 97 percent of identified helium reserves in the United States. Data from Pacheco (2002) and Parham and Campbell (1993).

<u>Reservoir</u>	State	Helium content of gas Mole percent
Hugoton	Kansas, Oklahoma, Texas	0.2-1.18
Panoma	Kansas	0.4-0.6
Keyes	Oklahoma	Not available
Panhandle West	Texas	Not available
Riley Ridge area	Wyoming	Not available
Cliffside	TX	He-storage reservoir

Helium uses, demand and economics

Helium has a number of uses (Pacheco, 2002). Major uses in the United States include cryogenics, pressurizing and purging, welding, and controlled atmospheres. Leak detection, synthetic breathing mixtures, chromatography, lifting, and heat transfer are other uses. The major cryogenic use is in magnetic resonance imaging (MRI) instruments. There is no substitute for helium in cryogenic applications where temperatures less than -429°C are required (Pacheco, 2004).

Sales of Grade A refined helium have been increasing in recent years (Pacheco, 2002). Total helium sales in the United States increased 112 million m^3 during 1998 to 127 million m^3 during 2002, an increase of 13 percent. As sales have increased, domestic production has fallen by 22 percent from 112 million m^3 during 1998 to 87 million m^3 during 2002 (Peterson, 2001; Pacheco, 2004). The shortfall in production in recent years has been filled by withdrawing helium from the U.S. Bureau of land Management storage facility in the Cliffside gas field near Amarillo, Texas. The trends of increasing demand and decreasing production indicate a need to identify and develop new sources of helium.

Helium prices have increased as production has fallen below demand. The private industry price for Grade A helium was estimated to be \$60 to \$65 per thousand ft^3 in 2003 (Pacheco, 2004), up from \$42 to \$50 per thousand ft^3 in 2000 (Peterson, 2001). Some producers added a surcharge to these prices.

Geology of Helium

Helium has two isotopes, He^3 and He^4 . He^3 is derived from the mantle; mantle derived helium is rare in reservoir gases (Hunt, 1996). He^4 , on the other hand, is derived from the radioactive decay of uranium, thorium and radium in the earth's crust (Hunt, 1996; Selley, 1998; Maione, 2004). It is thought that the common sources of helium are the uranium, thorium and radium-bearing minerals in granitic basement rocks and in sedimentary uranium ore deposits. High helium flux in the crust is associated with faults, lineaments and natural springs (Hunt, 1996; Maione, 2004) and helium-enriched gases are associated with areas of crustal tension (Selley, 1998). Thermal activity or tectonic events that create or enhance fracture permeability facilitate release of helium gas from granitic basement into overlying sedimentary rocks (Selley, 1998; Maione, 2004). Periodic release of helium from the crust is associated with strong earthquakes (Maione, 2004).

Helium diffuses upward through the sedimentary section more rapidly and readily than other natural gases. The helium atom has an effective diameter of 0.2 nm, significantly less than CO_2 (0.33 nm), CH_4 (0.38 nm), and N_2 (0.34 nm; Hunt, 1996), allowing helium to diffuse through seals that are effective barriers to larger molecules. Sedimentary rocks of high density such as salt, anhydrite or Paleozoic shales make the best seals for helium and slow its upward diffusion through the crust (Maione, 2004).

Helium Potential of the Chupadera Mesa Project Area

The geology of the Chupadera Mesa project area is favorable to helium generation, migration, and entrapment. The region is underlain by Precambrian granitic rocks in most places that gamma-ray log indicate are significantly more radioactive than the overlying sedimentary section. Deep, high-angle faults penetrate the basement in many places. Although many of these may have a late Paleozoic ancestry, they were reactivated during Laramide and post-Laramide Basin and Range tectonism. The latter event was characterized by extension that would enhance fracture permeability in the Precambrian. In addition, Tertiary igneous activity was apparently accompanied by widespread heating that would have facilitated the release of helium into the Paleozoic sedimentary sequence. Pennsylvanian stratal units immediately overlie the Precambrian and contain shales that may act as effective seals for helium. In addition, basal

Pennsylvanian sandstones overlie basement in most places would make ideal migration pathways through which helium, liberated from the basement, could migrate updip until trapped. In addition, the overlying Abo Formation contains abundant thick shales and the Yeso Formation contains widespread anhydrite beds that would make good seals. In the area extending from the Carrizozo Basin northward to the Manzano Cathead Mesa well, the Yeso Formation contains salt beds that make ideal seals for helium. Therefore, there are abundant seals within Permian stratal units that would act to trap any helium that diffused upward from the Pennsylvanian into the Permian.

Other favorable targets include basal Pennsylvanian sandstones located updip of major basement involved structures where in trap configuration. A structure of primary interest is the Monte Prieto – Liberty Hill structural zone.

Sedimentary units enriched in uranium may also be present at depth. In the Primero Operating No. 1 Dulce Draw State well, located in Sec. 2 T4S R9E (Fig. 22), the gamma ray log went off scale below 2600 ft, reading more than 400 API units gamma radiation from 2700 ft in the Abo Formation to total depth of 4030 ft in Precambrian granite. The Spectroscopy gamma ray log indicates that the high radioactivity is caused mostly by uranium. If the gamma ray log provided an accurate analysis of radioactivity, the Precambrian, Pennsylvanian, and Abo have been mineralized by uranium in this area, and may be a local rich source of radiogenic helium.

There are also direct indications of elevated helium levels in the area. The casing gas recovered from the Manzano Oil No. 1 Cathead Mesa well, located in Sec. 4S R9E, had 2.56 percent helium. This is the only recovered gas within the project area that was analyzed for helium. Attempts to coax the well into yielding measurable and sustainable gas flow rates were unsuccessful. However, sustainable flow rates of 400 MCFGD were obtained from an Abo sandstone in the Primero No. 1 Dulce Draw State well, located in Sec. 2 T4S R9E, just 3 miles northeast of the Cathead Mesa well. As is the case with the gas recovered from the Cathead Mesa well, this gas was nonburnable and therefore may also contain elevated amounts of helium. The sustained flow rates indicate the viability of Abo sandstones as reservoirs.

In summary, there is significant potential for helium accumulations under Chupadera Mesa. Sources of radiogenic helium are present as are reservoirs through which generated helium could migrate and accumulate. Seals appropriate for helium entrapment are present. Thermal events associated with Tertiary igneous activity and

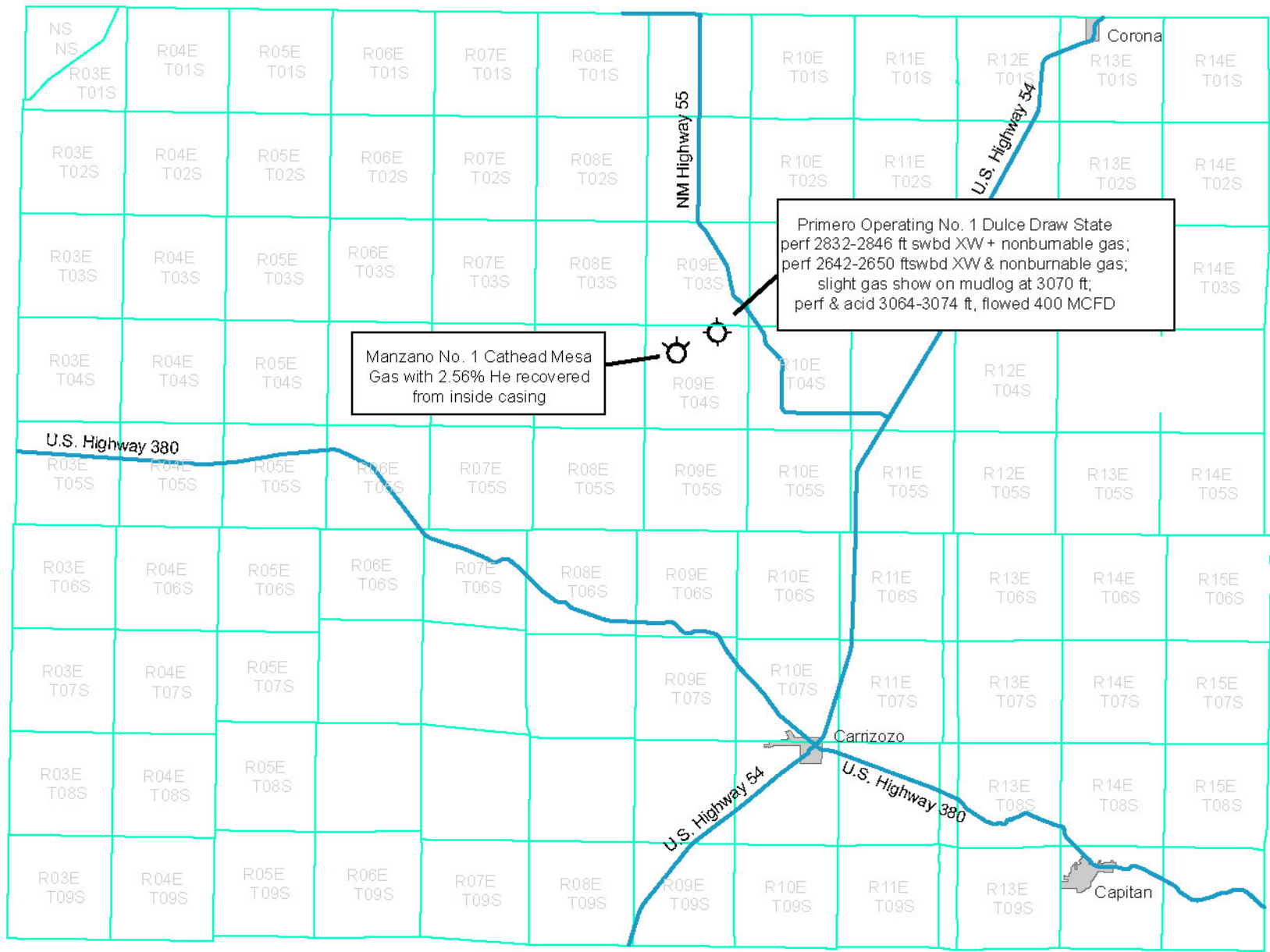


Figure 22. Wells discussed in helium potential section of this report..



extensional tectonics may have facilitated release of helium from the crust. Finally, gas analyses indicate the presence of gas with enriched helium content.

SUMMARY

This report utilized surface and subsurface structure maps, stratigraphic maps and analysis, petroleum source rock analysis, and analysis of oil and gas shows in wells to evaluate the petroleum, natural gas, and helium potential of the Chupadera Mesa region of central New Mexico. This region encompasses 3900 mi² in eastern Socorro and western Lincoln Counties and includes varied geological elements including the broad Jornada del Muerto Basin in the west, and the Oscura Mountains and Chupadera Mesa in the medial area. Several isolated mountain ranges formed principally by Tertiary-age igneous intrusive bodies and the Laramide-age Sierra Blanca Basin occupy the eastern third of the area.

The Chupadera Mesa area has been sparsely drilled. A total of 45 wells have been drilled within the project area. This is a density of approximately one well for every 85 mi². Many of the wells are shallow and reached total depth in Permian strata. Only 20 wells have been drilled to Precambrian basement. This is a density of one well per 200 mi², or 6.4 townships. Neither oil, natural gas nor helium production have been established. Nevertheless, several of the wells have encountered promising shows of oil, natural gas, and helium.

The geology of the Chupadera Mesa area indicates favorable potential for oil and natural gas. Petroleum source rock facies are concentrated in marine Pennsylvanian strata that blanket the western two-thirds of the project area and attain a maximum thickness of 2200 ft. Dark-gray to black Pennsylvanian shales contain both gas-prone and oil-prone kerogen populations are thermally mature to the east and west. Maturation into the oil window is caused primarily by heating associated with igneous events during the Tertiary. Favorable reservoirs are marine Pennsylvanian sandstones, continental sandstones of the Abo Formation (Permian: Wolfcampian), and marine to marginal marine sandstones of the Yeso Formation (Permian: Leonardian). Untested plays include speculated but undrilled late Paleozoic basins that underlie Laramide-age synclines, truncation traps in Pennsylvanian sandstones under a basal Permian unconformity at the

eastern pinchout of Pennsylvanian strata, and northward pinchout of Ordovician carbonate rocks in the southern part of the project area. There is also limited coalbed methane potential in Cretaceous strata in the Jornada del Muerto and Sierra Blanca Basins.

The Chupadera Mesa project area also has favorable potential for helium. Uranium-bearing rock types favorable for the formation of radiogenic helium are present. In addition, high-angle fracture and fault systems and Tertiary-age igneous thermal events characterize the area and are favorable to the release of radiogenic helium from the Precambrian basement into the overlying Paleozoic sedimentary column. Pennsylvanian and Permian shales and Permian anhydrites and salt beds are favorable seals for helium. Analyses of gases recovered from one well on Chupadera Mesa indicate the presence of helium in substantial amounts. Nonburnable gases recovered from other wells may also contain helium.

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APPENDIX I

Structure Database Part 1 -

Wells, Well Structural Data, and Production and Shows in Wells

A database of oil and gas wells, subsurface structure data, and oil and gas shows and production in Microsoft Excel format (*Chupadera wells.xls*) accompanies this report. This database contains data on well location, total depth, dates of drilling, surface elevation, structural elevation of the top surface of the Abo Formation and Precambrian surface, as well as data on oil and gas shows and production encountered in the wells. The following data fields are present for each well.

API Number: The unique API well number. Some wells in the New Mexico Bureau of Geology databases have no API number. For these wells, an identifying number was constructed from the section- township-range location data, for example 14N32E16, which indicates a location in sec. 16 T14N R32E. If an API number becomes available, the user may wish to substitute it for our synthetic number.)

Operator: name of the company or individual that operated the well during drilling

Lease name: name of the lease the well was drilled on.

Well number: lease number of the well.

County

Location: section-township-range.

Footage: location of well in feet from section boundaries

Longitude: in decimal degrees

Latitude: in decimal degrees

Spud date: month/year

Completion date: month/year

Total depth: of the well, in feet

Surface elevation: the elevation of the surface of the surface in feet above sea level

Surface datum: KB = Kelly Bushing; DF = derrick floor; GL = ground level

Depth to top of stratigraphic units: in feet

Subsea depth top of stratigraphic units: in feet above (+) or below (-) sea level

Completed status of well: **D&A** = dry and abandoned; water well = completed as water supply well.

All data were derived from files and records in the Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources Library of Subsurface Data. Longitude and latitude for most wells were with the Geographix Exploration System Landgrid Module and the Whitestar Corp. digital land grid

Depths to the top of the stratigraphic units were correlated by the senior author. The primary tools used for correlation were geophysical wireline logs in the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. For many wells, depth to the top of the Precambrian and the Abo were confirmed with additional examination of sample logs or mud logs. Where needed, drill cuttings were examined to identify or verify depth to formation tops. For many older wells (pre-1960) and some more modern wells, sample logs and drill cuttings are the only source of stratigraphic data because the wells lack wireline logs. In a few wells for which logs were not available, stratigraphic tops from scout cards were used. It was noted, however, that scout card tops are inconsistent in this area.

Oil and Gas Shows

The well database contains substantial information on oil and gas shows compiled from records on file at the New Mexico Bureau of Mines and Mineral Resources. Oil and gas shows are identified by the stratigraphic unit they occur in. The following Data examined for shows included completion reports and scout cards. Particular attention was paid to drill stem tests, mudlogs (where available), and attempted well completions.

For **drill stem tests**, the fluid recovery from the test was considered as evidence for a show. If a drill stem test recovered either oil or gas, the test was considered to have an oil show or a gas show. Also reported were negative tests that recovered water with no oil or gas. If the drill stem test recovered only drilling mud, then it was also reported in this database but the mud could have either entered the test tool through an unsealed

packer or it could have invaded the zone of interest during drilling and subsequently flowed back into the borehole during the test. In this report, the depth of the test interval is reported as is the type of fluid or fluids recovered (oil, gas, or water)

Completion tests are defined in this report as an attempt to produce oil or gas by perforating casing and a subsequent attempt to recover fluid. After perforation, the target reservoir may have been stimulated by acid treatment or artificial fracturing. In this report, the depth of the perforated interval is reported as is the type of fluid or fluids recovered. Also reported is the result of either no show (NS) or no production (NP), which are sometimes the only results available.

APPENDIX II

Petroleum Source Rock Database

This database (*Chupadera source rocks.xls*) is a companion to the maps and discussion of petroleum source rock data presented on this CD. Analytical data are presented for key exploration wells drilled in the Tucumcari Basin. Most analyses were performed on composite samples of drill cuttings from 100 ft intervals. Several attributes are given for each sample, including:

API number of the well

Operator

Lease name

Well number

County

Location (section-township-range)

Footage from section boundaries

Longitude

Latitude

Top of sampled interval (recorded as depth in well, in feet)

Bottom of sampled interval (recorded as depth in well, in feet)

Geologic system (e.g. Permian, Pennsylvanian, etc.)

Geologic series (e.g. Wolfcampian, Desmoinesian, etc.)

Lithostratigraphic group (e.g. Artesia, Canyon, etc.)

Lithostratigraphic formation (e.g. San Andres, Abo, etc.)

TOC - total organic carbon (weight percent)

Algal - percentage of kerogen that is algal material, by visual estimate

Amorphous - percentage of kerogen that is amorphous material, by visual estimate

Herbaceous - percentage of kerogen that is herbaceous material, by visual estimate

Woody - percentage of kerogen that is woody material, by visual estimate

Inertinite - percentage of kerogen that is inertinite, by visual estimate

Maturation - level of thermal maturity as interpreted from TAI, R_o , or TMAX

TAI - the Thermal Alteration Index as provided on analyses performed by Geochem Laboratories, Inc. A measure of thermal maturity.

TMAX - the temperature, in degrees centigrade, of the S_2 peak derived from Rock-Eval pyrolysis in degrees Celsius. A measure of thermal maturity.

S₁ – Rock Eval S₁ peak, measured in milligrams evolved hydrocarbons per gram of rock.

S₂ – Rock Eval S₂ peak, measured in milligrams evolved hydrocarbons per gram of rock.

S₁ – Rock Eval S₁ peak, measured in milligrams evolved carbon dioxide per gram of rock.

PI – Rock Eval Productivity Index

HI – Rock Eval Hydrogen Index, measured in milligrams evolved hydrocarbons per gram of organic carbon.

OI – Rock Eval Oxygen Index, measured in milligrams evolved carbon dioxide per gram of organic carbon.

Sample type – all cuttings for this project.

Data sources

Some source rock data used in this report were obtained from a published digital database (Broadhead et al., 1998). Most data are analyses performed explicitly for this project. All of the source rock data used in this report were obtained from analyses and cuttings curated at the New Mexico Library of Subsurface Data at the New Mexico Bureau of Geology and Mineral Resources. There are three sources for the analyses:

1. New Mexico Petroleum Source Rock Project. This project ran from the late 1980's until the mid 1990's. It was a joint effort between private industry and the New Mexico Bureau of Mines (now Geology) and Mineral Resources. Well cuttings from key exploration wells throughout New Mexico were analyzed for petroleum source rock attributes. Geochem Laboratories, Inc. was selected by competitive bid to perform the analyses. The following standard set of analyses were performed on each sample:

- Total organic carbon (TOC) measurement
- Visual kerogen assessment for kerogen type
- Visual kerogen assessment for thermal maturity using the Thermal Alteration Index (TAI)
- Rock-Eval pyrolysis

Most of the analyses presented in this report were performed as part of the New Mexico Petroleum Source Rock Project. For all samples of drill cuttings analyzed as part of this project, the cuttings were selectively picked under a binocular microscope in order to

exclude non-source lithologies (e.g. sandstone) from the sample. This procedure, although time consuming, helps insure analyses that are representative of source facies encountered in the borehole.

- 2. Donated data.** These are source rock data donated to the New Mexico Bureau of Geology and Mineral Resources by private industry. The analyses were made by private industry on samples in the collections of the New Mexico Bureau of Geology and Mineral Resources. In return for allowing the samples to undergo destructive source rock analysis, the analytical results were given to the Bureau and were made public. Cuttings samples from donated data have generally not been sorted to exclude non-source lithologies and obvious cavings from the samples. As a result, the analyzed sample may have contained a large percentage of non-source lithologies that are either caved or interbedded with the source rocks. Although unsorted samples probably yield good values of thermal maturity, the presence of non-source lithologies such as sandstones will result in artificially low values of total organic carbon (TOC). Therefore, the analyzed TOC values for the donated samples should be considered minimum values not necessarily representative of what may actually be in the source facies. Some of the donated data was performed on sample selected and picked by the senior author on the more recent wells drilled within the project area.
- 3. Analyses performed explicitly for this project.** A few samples of cores and cuttings from the Pennsylvanian section and the San Andres Formation were analyzed as part of this project in order to fill in gaps of existing source rock coverage. Analyses were performed by Geochem Laboratories and the same types of analyses were performed as for the New Mexico Petroleum Source Rock Project. Cuttings samples were picked to exclude non-source lithologies.