



## ***Geology and hydrocarbon resource potential of Cretaceous strata in the Jornada del Muerto, Sierra and Socorro counties, New Mexico***

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# GEOLOGY AND HYDROCARBON RESOURCE POTENTIAL OF CRETACEOUS STRATA IN THE JORNADA DEL MUERTO, SIERRA AND SOCORRO COUNTIES, NEW MEXICO

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**ABSTRACT**—The Jornada del Muerto is a sparsely drilled intermontane valley in south-central New Mexico with real but limited hydrocarbon potential in Cretaceous rocks. Cretaceous strata were deposited on a southwest-downcutting unconformity related to the Mogollon rift shoulder. Thin (15-30m) “Dakota” sandstones are overlain by a thicker (90-115m) marine succession; the lower part includes black organic shale, limestone and heterolithic sandstone that are Greenhorn (Eagle Ford) equivalents. The overlying Tres Hermanos Formation is consistent in thickness (75-90 m) and character across the area, possibly indicating a forced regression, and contains thin coaly layers. The Gallup sandstone consists of multiple shorefaces that slowly and episodically prograded northeastward over a thickening D-Cross Shale tongue. The immediately overlying Crevasse Canyon Formation contains thin coals. Correlation of outcrop data to subsurface well data enhances our understanding of facies relationships. All the above strata were buried by latest Cretaceous McRae and early Paleogene Love Ranch formations. Coeval Laramide folding and faulting occurred along the Rio Grande axis on the east flank of the Sierra uplift. Fold and fault patterns indicate a right-lateral transpression related to northeast-directed compressive stresses, which raised the Rio Grande uplift to the south. Strata were also buried by middle Eocene to Oligocene volcanic and volcanoclastic rocks (Datil Group and equivalents), which are now mostly removed. Burial has matured source rocks well into the gas window and past oil stability. All conventional hydrocarbon accumulations were disturbed or destroyed by Neogene extensional faulting related to the Rio Grande rift. The San Andres Mountains to the east and the Caballos and Fra Cristobal Mountains to the west rose as Neogene rift-flank highs, creating the Jornada del Muerto syncline between them. Unconventional accumulations may have a better chance of survival. The gas-prone nature of the preserved source rocks and the lack of infrastructure for producing and transporting natural gas are serious impediments to further exploration in the area.

## INTRODUCTION

This report discusses the post-Paleozoic geology and summarizes the hydrocarbon potential of the Jornada del Muerto, focusing particularly on the northern Jornada that underlies part of the Pedro Armendaris Grant (Fig. 1). It is based on numerous published sources, theses, public-sector gravity and magnetic data, and examination of well logs. Several days of field work have also been undertaken in the area by the author and R.M. Colpitts; Baseline Resolution and Entrada Geosciences analyzed samples for organic content (see Ewing and Colpitts, this guidebook).

The Pedro Armendaris Grant is the largest Spanish land grant entirely in New Mexico. It extends from the area east of Truth or Consequences northward nearly to San Antonio, New Mexico, including lands from T4S-T14S and R1E to R4W (Fig. 1). The property extends from NM-52 (including the townsite of Engle, now the main ranch headquarters) northwards across the Rio Grande at San Marcial to the southern slopes of the Magdalena Mountains. It includes the Fra Cristobal Mountains, much of the northern Jornada del Muerto, parts of the Rio Grande Valley, and the southern and western outliers of the Chupadera Hills. Access is through NM-52 in the southern area, and from I-25 in the Rio Grande valley and northern area. A branch rail line of the Burlington Northern Santa Fe passes through the grant from San Marcial south to Engle and points south (Belen – El Paso route).

The first grant was given to Pedro Armendariz (or Armendaris) in 1819, covering 397,235 acres (160,755 ha) east of the Rio Grande (Grant No. 33). It was supplemented in 1820 by a grant (No. 34) covering 95,031 acres (38,458 ha) west of the Rio Grande (Fig. 1). The size of these grants was only appreciated

following a U.S. Army survey in 1872; the grant was patented in 1878. After a complex and colorful history, Ted Turner purchased the property in 1994 for a reported \$14 million (Harden, 2009).

The grant includes many topographic and geologic features, including the southern Chupadera Hills, the San Marcial segment of the Rio Grande Valley, the northern Jornada del Muerto, the Fra Cristobal Mountains, the Cutter Sag, and part of the “Engle basin” of the Rio Grande rift. Only two wells penetrate the subsurface in the Jornada portion of the grant, but interpretations can be made using the dozen or so wells drilled on federal and state lands immediately south of the land grant.

## STRATIGRAPHY

### Pre-Cretaceous Unconformity

Over most or all of the study area, Cretaceous rocks overlie the Paleozoic with regional unconformity. The Triassic Chinle Group strata may be present in the northernmost parts of the area. They are reported from the Carthage area (152 m thick in Wilpolt and Wanek, 1951) and east of Socorro. The southernmost report of Chinle is from the northernmost San Andres Mountains in sec. 11, T11S, R2E (Kottlowski et al., 1956), where 16 m of variegated claystone and siltstone rests on San Andres limestone. The mudlog from wells 1 and 2 in T10S, R1W indicate 30-55 m of redbeds referred to the ‘Dockum’ (=Chinle), but after looking at the cuttings from this interval, this assignment appears incorrect.

The pre-Cretaceous unconformity bevels the Paleozoic, removing progressively older Permian units to the southwest (Fig. 2). Artesia Group(?) and San Andres rocks are successively

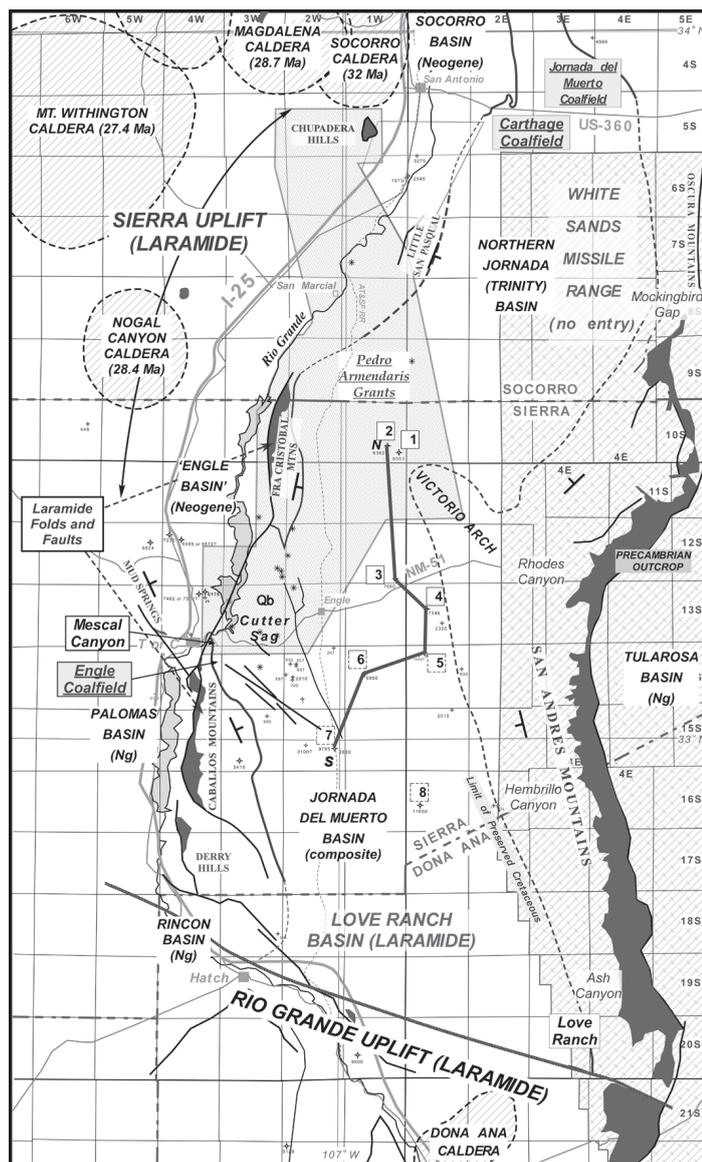


FIGURE 1. Location map of the Jornada del Muerto Basin and the Pedro Armendaris Grant in south-central New Mexico. Also shown are major mountain ranges and physiography, streams and highways, and key geo- logical localities. S-N: line of subsurface section shown in Figure 2.

truncated from northeast to southwest. The erosion that produced this unconformity is probably Early Cretaceous in age, and was caused by uplift along the Mogollon arch, the northwest-southeast oriented rift shoulder of the Bisbee Basin in southwestern New Mexico and southeastern Arizona. The unconformity reaches down to the Precambrian southwest of Silver City and to the Abo and Pennsylvanian on the Cookes Range (83 km southwest of the northern Caballos Mountains).

### Cretaceous and Paleogene Units

Rocks of Cretaceous age occur beneath most of the Jornada del Muerto; the known or inferred limits are shown as the green

line on Figure 1. Outcrops occur in the eastern foothills of the Caballos Mountains, in the Cutter Sag area, and at the south end of the San Andres Mountains. These strata were removed from areas west of the Rio Grande due to Laramide uplift and erosion before deposition of volcanic and volcanoclastic rocks of Eocene and Oligocene age.

The rocks form three major, unconformity-bounded sequences. The first consists of deposits laid down on the western margin of the Western Interior Seaway from Cenomanian to Coniacian (or later) time. This sequence includes the basal Dakota sandstones, overlying marine shale, sandstone and limestone of the Mancos, a transgressive-regressive wedge of shoreline and nonmarine sediment called the Tres Hermanos Formation, and the regressive Mesaverde Group nonmarine sediments with the shoreline Gallup Sandstone at the base (Figs. 2 and 3). Lower Cretaceous sediments underlie the Dakota in the farthest southern part of the Jornada and to the south and southwest, but they do not occur in the main part of the study area.

The second sequence consists of volcanoclastic sediments of the McRae Formation, laid down in latest Cretaceous time in the area of the Cutter Sag. The original limits of deposition of the McRae are unknown.

The third sequence consists of volcanoclastic rocks and lavas of the Love Ranch and Palm Park Formations (Eocene), overlain by ash-flow tuffs and volcanic rocks of latest Eocene and Oligocene age. Several volcanic cauldrons, which sourced the ash-flow tuffs, occur 50 km north and west of the study area.

### Sequence 1. Marine and nonmarine sediments of the Western Interior Seaway

#### Dakota Sandstone

The base of Sequence 1 in the project area is referred to as the Dakota Sandstone. This name has historically been applied to the basal sandstone-rich unit of this sequence throughout the Western Interior; it has been raised to group rank or abandoned entirely over much of its former extent. In this area, the unit is inferred to be middle to late Cenomanian in age, based on fossils from the overlying Mancos; however, older nonmarine Cretaceous strata similar to those exposed to the south (Lucas and Estep, 1998) may be preserved locally.

In the Caballos Range, key exposures are in Mescal Canyon at the north end (sec. 36, 13S-4W), Putnam Draw (sec. 22, T15S, R3W) and to the south at Hidden Tank (sec. 5, 17S-3W). There the Dakota averages 30 m in thickness (ranging from 1.8-60 m). The unit consists of a basal conglomerate, 7.6 m of medium-grained crossbedded sandstone, gray shale with thin sandstones, local oyster shell and bioturbated zones, and an upper yellowish gray, bioturbated medium-grained sandstone with *Ophiomorpha* and ripple cross-lamination. The top is marked by a granule lag passing into the overlying Mancos (Fig. 4). Thickness variations are due to variations in fluvial deposits, suggesting paleovalleys cut into the sub-Cretaceous unconformity. The upper part of the section is reported to contain some sandstones that are locally

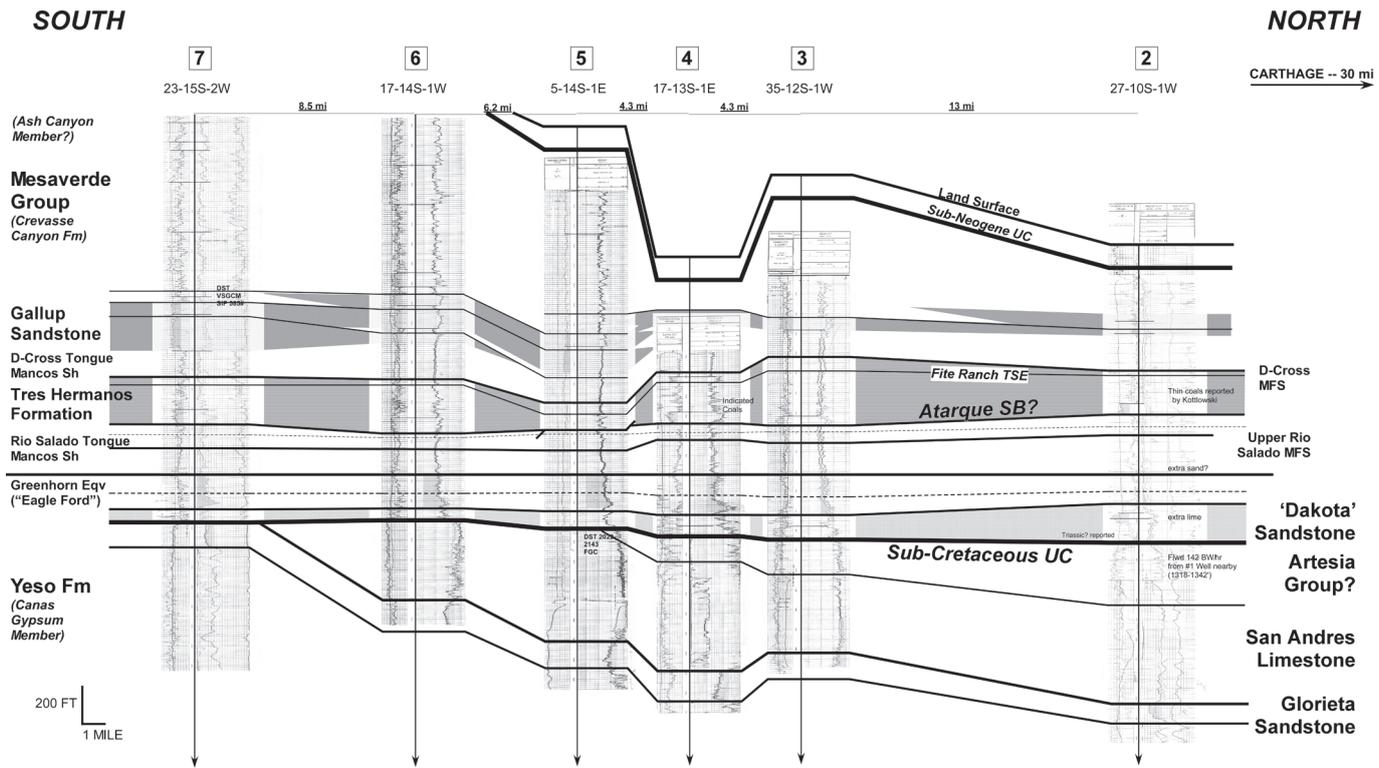


FIGURE 2. Stratigraphic log cross-section S-N, datum on top of "Eagle Ford" facies, showing truncation of Permian units and lithologic details of the marine Upper Cretaceous.

impregnated with bituminous matter (Kelley and Silver, 1952; in Tabet, 1979b).

At Love Ranch at the south end of the San Andres (T20S, R3/4E), 56.7 m of Dakota overlie a Lower Cretaceous clastic section (Lucas and Estep, 1998). The Dakota here includes three thick quartzitic sandstones interbedded with less resistant sandstone.

At Cain Ranch at the north end of the San Andres, 12 m of Dakota (?) sandstone were found overlying the "Dockum" redbeds (Kottlowski et al., 1956).

In the Jornada wells the Dakota sequence is thin (15 m in the south, thickening northward) and lithologically variable. The top is picked at the topmost sandstone visible in the log. There is also interbedded limestone or calcite-cemented sandstone in some wells.

**Rio Salado Tongue of the Mancos**

Marine shale of the Rio Salado tongue of the Mancos overlies the Dakota. At Mescal Canyon it is about 119 m thick, but may include structural complications. In exposures there, the tongue consists of three members: (1) a lower member of dark shale, bentonites (one 12 cm thick) and several beds of gray fetid limestone (Fig. 5A); (2) a middle member (approx. 15m) of finely interstratified sand, silt and limestone (the 'heterolithic member', Fig. 5B); and (3) an upper member of gray to black shale, with sand layers increasing upward in thickness and number towards

the base of the Atarque (Fig. 5C). The flow direction from a gutter cast in the upper Rio Salado is N29°E, indicating a strandline orientation of about 299° (N61°W). Samples from the lower and upper members yielded organic carbon contents of 0.83% and 1.09%, respectively (see Ewing and Colpitts, this guidebook).

The middle "Heterolithic" member is unusual. It contains a high percentage of sand, but finely interstratified with shale, silt

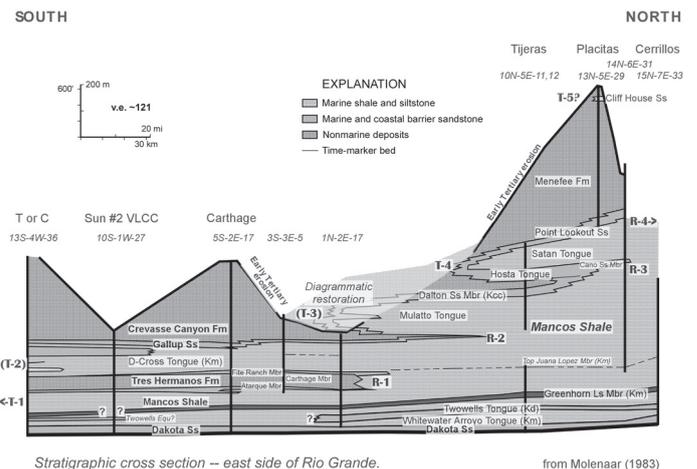


FIGURE 3. South to north regional correlation of Cretaceous units with T-R (transgressive-regressive) cycle designations, from Molenaar (1983).

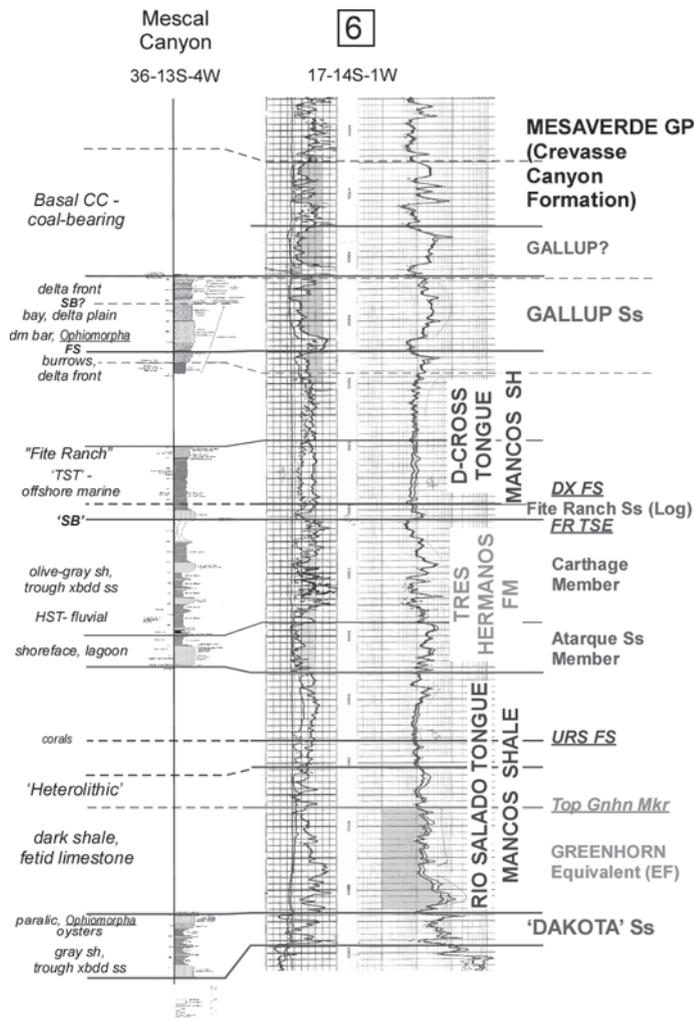


FIGURE 4. Cretaceous log signatures in well 6, compared with surface geologic sections in Mescal Canyon (Seager and Mack, 2003). Ss – Sandstone; sh – shale; xbdd – cross-bedded; SB – sequence boundary; FS – flooding surface; TST – transgressive systems tract; hst – highstand systems tract.

and a few thin limestone layers. The unit is lightly burrowed with possible flaser bedding indicative of a tidal flat environment, and climbing ripples. The indicated current flow from a ripple trough is toward  $351^\circ$  ( $N9^\circ W$ ). This unit may sustain fracturing and have permeability sufficient for gas production.

In the Love Ranch area, Kottowski et al. (1956) referred to an equivalent section as “Eagle Ford Formation,” and correlated it with the Colorado Shale of the Silver City and Cookes Peak area, and the Benton interval of the Mancos. They describe the lithologies at Love Ranch as arenaceous limestone, black shale, silty sandstone, silty limestone concretions, carbonaceous shale with plant imprints, and a lens of coal. Lucas and Estep (1998) indicate only 13 m of Rio Salado strata.

In the Jornada subsurface, a very distinctive log pattern overlies the Dakota and underlies typical low-resistivity Mancos Shale. The top of this distinctive high-gamma ray and high-resistivity pattern provides the datum for Figure 2. The interval from the datum to top of Dakota includes thin limestones and

black shales, and is taken to correspond to the “Eagle Ford” of Kottowski and to be approximately correlative to the Eagle Ford of Texas and the Greenhorn of northern New Mexico. It appears to correlate to the lower and middle members of the Rio Salado in Mescal Canyon. Overlying the middle Rio Salado marker is a low-resistivity unit, coarsening upward into the overlying Atarque shoreface sandstone. Total thickness is 91-116 m.

### Tres Hermanos Formation

The Tres Hermanos Formation (middle Turonian) is a significant tongue of marginal-marine and nonmarine sediment in south-central New Mexico (Hook et al., 1983). At the base is the Atarque Sandstone Member, a marginal-marine prograding shoreface, followed by the nonmarine Carthage Member and the transgressive Fite Ranch Sandstone. In the Mescal Canyon section (Fig. 4), the formation as described by Seager and Mack (2003) is 104 m thick, including 10 m of Atarque sandstone, 90 m of Carthage Member and 5 m of the Fite Ranch Member. The Atarque coarsens upward and shows the internal characteristics typical of a prograding shoreface. The main sandstone of the Atarque in Mescal Canyon contains hummocky cross-stratification and shell lags, with trough crossbeds and lateral accretion foresets indicating a strandline trending  $334^\circ$  ( $N26^\circ W$ ,  $n=2$ ). The base of the Carthage consists of 3 m of bioturbated gray shale with thin sandstones and root traces, followed by an impure coal seam (10”). About 12 m above this is a white, very well sorted, medium-grained eolian sandstone with abundant trough and tabular cross-beds. Foresets from two locations in this bed trend  $SW$ , averaging  $215^\circ$  ( $S35^\circ W$ ), about normal to the inferred strandline ( $n=22$ ). The remainder of the Carthage consists of thin (1-5 m) sandstones and olive mudstones. Crossbed paleocurrent directions measured by Wallin (1983) in this unit indicate flow to the northeast, consistent with small streams normal to the shoreline trend.

Comparison of the Mescal Canyon section to the subsurface indicates that the measured section is too thick, and that the “Fite Ranch” as described by Seager and Mack (2003) in fact correlates to a progradational silty sandstone within the D-Cross Tongue. The shale underlying the “Fite Ranch” is bioturbated and contains ammonites (Seager and Mack, 2003), and should be included in the D-Cross Tongue of the Mancos, and the sandstone below that shale should properly represent the Fite Ranch member.

In the Jornada wells, the Tres Hermanos is usually easily recognizable between two low-resistivity shales. The Atarque Member shoreface is well developed in southern wells, but the northern wells show a sharp-based sandstone that may represent a channel, possibly a sequence boundary. The Carthage Member is variable, generally sandier to the south and shalier to the north, with coals indicated in well 4 and reported from well 2. The Fite Ranch Member is a thin, generally sandy transgressive unit at the top. Total thickness is 60-90 m. The overall constant thickness and aspect of the Tres Hermanos Formation in south-central New Mexico suggests a rapid forced regression that moved the shoreline 100 km northeast (Fig. 3).

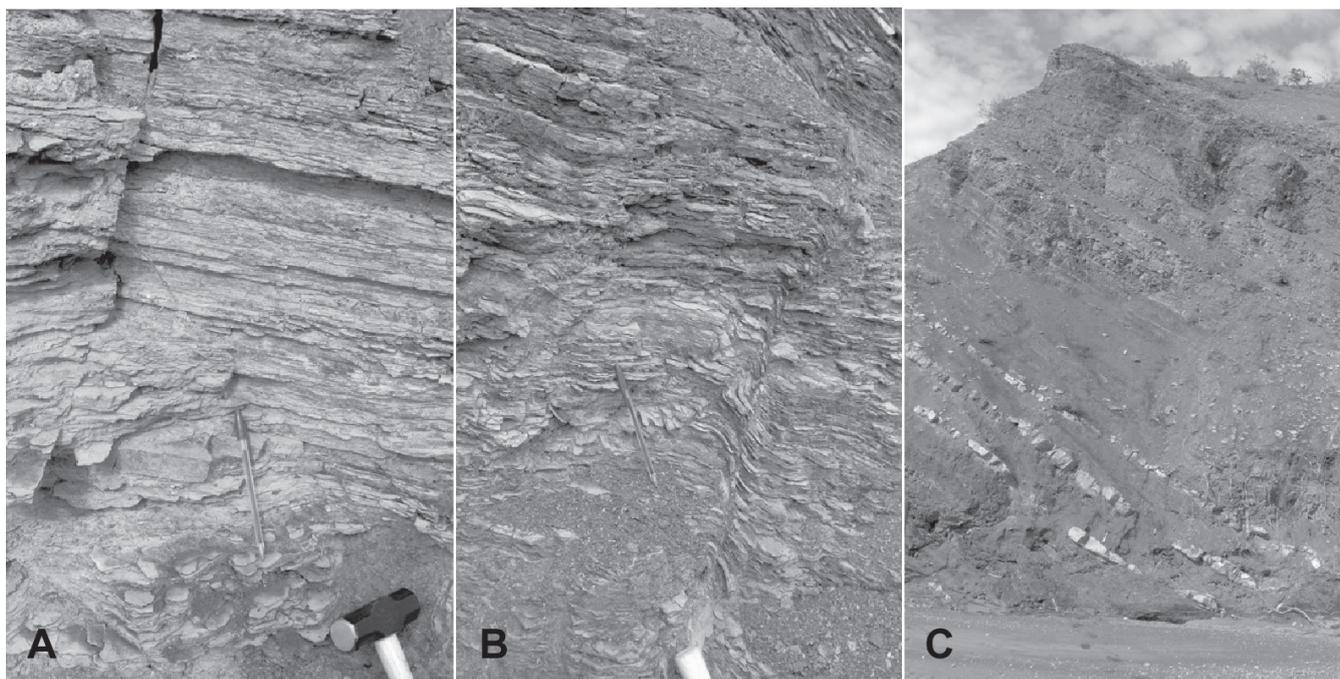


FIGURE 5. Rio Salado Tongue (Greenhorn equivalent) in Mescal Canyon. A—Lower member with fetid limestones; B – Heterolithic member; C—Upper shale underlying the Atarque sandstone at crest of hill.

#### D-Cross Tongue of the Mancos

Above the Tres Hermanos lies the marine D-Cross Tongue of the Mancos Shale (Molenaar, 1983; Seager and Mack, 2003). This late Turonian shale is 50 m thick as described by Seager and Mack (2003) at Mescal Canyon, but only 20 m at Putnam Draw to the southeast. The shale grades upward into the Gallup Sandstone. In the Jornada wells, the unit is generally present, about 73-91 m thick, but quite variable, largely due to the complexity of the overlying Gallup; much of the shale appears to be distal shoreface and shelf deposits related to Gallup progradation. In Mescal Canyon and elsewhere, the unit has a less distinct geomorphic expression than the Rio Salado.

The sandstone described by Seager and Mack (2003) as the “Fite Ranch” is fine-grained with hummocky cross-bedding and *Ophiomorpha*; it also contains transgressive granular calcareous sandstone with shell fragments and sharks teeth. As mentioned above, it appears to correlate with a progradational silty sandstone in the D-Cross, probably a distal edge of a Gallup sandstone more fully developed to the southwest.

#### Gallup Sandstone

The Gallup Sandstone marks the final progradation of the Late Cretaceous shoreline across the project area in latest Turonian time. At Mescal Canyon (Fig. 4), the Gallup is at least 40 m thick (Seager and Mack, 2003), with a gradational base. The first “main Gallup” unit is a thick parasequence set with bioturbation and plant fragment impressions, coarsening and thickening up-section, culminating in sandstone with some plant debris and an *Ophiomorpha*-burrowed upper surface (the “pouloff ledge” at Mescal Canyon). The second unit contains lagoonal shale and

very oyster-rich sandstone, followed by a brownish massive sandstone with abundant plant debris and a petroliferous odor. Overlying this sand is carbonaceous sand and silt, laminated sandstone suggestive of a crevasse splay, and carbonaceous shale of the basal Crevasse Canyon. This sequence as observed in the field is not easily related to Seager and Mack’s (2003) measured section. They interpret the “Main Gallup” as a prograding deltaic sequence, which is consistent with field observations.

In the Jornada wells, the Gallup is surprisingly variable in thickness and log character (Fig. 2). The southernmost well (sec. 7, T15S, R2W) is similar in appearance to the surface description at Mescal Canyon with three fairly thick, blocky sand bodies. But in well 5 to the northeast, the lower sand appears as a shoreface sandstone, with two blocky sands overlying. In the Exxon well, only one blocky sand body is seen with two silty packages beneath. In the northern wells, only one sand body is seen, with a coarsening-upward base; this sand is often thin, especially in wells 1 and 2 at the north end of the section. The impression is one of a relatively slow northward progradation that led to stacking of discrete shorefaces in the southern part of the area, then perhaps more rapid progradation or bypass of the area of the northern wells before stacking of shorefaces resumed, perhaps in the Carthage area. This area of thin Gallup Sandstone may explain the lack of outcrop expression in the northern Jornada.

#### Mesaverde Group – Crevasse Canyon Formation

The Crevasse Canyon Formation is the nonmarine Cretaceous section overlying the Gallup and lying beneath the McRae Formation or younger units. In the Mescal Canyon section, the basal Crevasse Canyon (perhaps 60 m total thickness) contains a persistent coal seam and related carbonaceous shale, generally less

than 61 cm thick (Tabet, 1979b). Boreholes in the vicinity indicate up to 91 cm of coal. In Mescal Canyon, the coal is 33 cm thick, overlain by 15 cm of carbonaceous shale and 15 cm of gray shale; the coal has moderate cleat and is probably sheared. The coal overlies a brown to brownish-green, fine-grained sandstone with root traces, rare *Skolithos* and scattered oyster shells. Trough cross-beds just above the coal indicate flow directions of N65-80°E from several measurements. At Engle mine, about 30 cm of coal is exposed, overlain by 2.4 m of carbonaceous gray shale.

Overlying the coaly basal member is a lower member of mudstone and thin sandstones with a few thin coals (13 cm of coal is exposed along the upper road leading into Mescal Canyon, NE sec. 20, T14S R3W), and an upper, sandstone-rich Ash Canyon Member. Seager and Mack (2003) report an approximate thickness of 670 m, including 366 m of the Ash Canyon Member. The Ash Canyon Member may represent the deposits of a northeastward-flowing trunk river that intersected the present outcrop belt in the Elephant Butte area.

In the Jornada wells, the basal coals are not visible in the logs available (although coals are reported from older shallow tests in the Cutter foldbelt area). The overlying Mesaverde Group is thick and studded with channel sandstones. There is no clear definition of an Ash Canyon Member in the logs.

### Sequence 2. Early Laramide basin fill – McRae Formation

The McRae Formation is a unique lithologic unit in south-central New Mexico. Its main outcrop area lies in the Cutter Sag and northeast foothills of the Caballos Mountains; scattered low outcrops have been reported in the Jornada del Muerto northeast of Engle. The formation has been divided into two mappable members, the Jose Creek and the upper Hall Lake members. A Lancian dinosaur fauna in both members indicates that the McRae is Maastrichtian in age (see Lozinsky, 1985; Seager and Mack, 2003). According to Seager and Mack (2003), the McRae in the Elephant Butte area includes 170 m of Jose Creek (tightly cemented dark brown to green-gray feldspathic coarse-grained sandstones, and conglomeratic sandstone with volcanic fragments, mudstone, and siliceous tuff) and perhaps 400 m of Hall Lake (deep purple-red mudstone, sandstone, and quartzite conglomerate with andesite clasts). Both members thin southeastward to a feather edge in T16S. Volcanic clasts in the unit suggest a connection with the Copper Flat volcano west of Truth or Consequences, or similar concealed volcanic centers of Cretaceous age (see McMillan, 2004 for a detailed discussion).

### Sequence 3. Late Laramide basin fill and Paleogene volcanic aprons

The Love Ranch Formation occurs in the southern Jornada del Muerto and overlies the McRae Formation in T13-16S. The unit thickens southward into an asymmetric basin, the “Love Ranch Basin;” the southern margin of the basin is faulted against the Rio Grande uplift in T19-20S (Fig. 1). The maximum thickness of Love Ranch exceeds 900 m in the southern Jornada (as penetrated by well 8, T16S, R1E), but the unit is much thinner to the

north. In the Jornada, it consists of a basal boulder conglomerate (up to 40 m thick) followed by friable conglomerate, sandstone, mudstone and gypsiferous mudstone; most of the outcrop near Engle consists of pink gypsiferous mudstone (Seager and Mack, 2003). The Love Ranch is probably mostly lower and middle Eocene, equivalent to the Baca Formation of the Socorro and Carthage area (Cather, 2004). At Carthage, 190-305 m of Baca overlies Mesverde. This formation extends southward but is probably not present south of Little San Pasqual Mountain (Fig. 1).

Overlying the Love Ranch and Baca formations are volcanoclastic and volcanic formations related to the vast eruption of andesitic and dacitic volcanic rocks in the late Eocene and Oligocene. The lower portion of the sequence in all areas is a 300-1500 m thick volcanoclastic unit (tuffaceous sandstone and breccia) of andesitic composition (the Palm Park Formation in the Caballos Mountains, the Rubio Peak in southwestern New Mexico, and the Spears Formation in the Socorro area). Andesitic dikes were intruded throughout the region; two 35.4-Ma dikes occur in the Cutter Sag. Afterwards, extensive ash-flow tuff sheets were erupted from large, fault-rimmed cauldrons 50 km or more to the southwest, west and northwest. The outflow sheets of these cauldrons are collectively referred to as Bell Top Formation in the southern Jornada, where they are only 60-150 m thick. The northern part of the Pedro Armendaris Grant lie close to the margins of both the Socorro and Magdalena cauldrons, and the equivalent volcanic rocks are considerably thicker there.

These post-Love Ranch units are not preserved in the central and northern Jornada del Muerto, although they are preserved farther north near Carthage. However, it is likely that they were deposited over the entire area, due to the proximity of the volcanic centers. The area may have been uplifted either during eruptions or before the Neogene rifting episodes, allowing most of the volcanic cover to be eroded before the Jornada surfaces were formed.

### Neogene Units

The Neogene (Miocene-Recent) units are entirely nonmarine, consisting of the fill of rift valleys along the Rio Grande rift axis; sediments deposited by streams during downcutting and excavation of these basins; thinner sediments deposited on large pediments in the Jornada del Muerto basin; and extensive but thin basalt flows of Pliocene to Recent age.

In the Caballo area (Palomas and Rincon basins; Seager and Mack, 2003), the Santa Fe Group is divided into the Rincon Valley Formation (Miocene) and the Palomas and Camp Rice Formations (Pliocene – early Pleistocene). The earlier formation is characterized by conglomerate, sandstone, and red gypsiferous mudstone, indicating internal drainage to playa lakes. The younger Palomas Formation and equivalents are widely exposed in the valleys; they show an axial-fluvial facies indicating an integrated drainage and a piedmont facies of alluvial fan deposits (Seager and Mack, 2003).

Total Santa Fe Group thickness is large and highly variable, as it is controlled by rift valley evolution. In the Hatch-Rincon basin, the Santa Fe Group reaches 1500 m and overlies the Palm Park and related units (Seager and Mack, 2003).

The Jornada del Muerto, by contrast, is a largely unbroken geomorphic surface comparable to the highest surface in the Palomas basin. At least in its southern and central portions, it is covered by a very thin pediment gravel (less than 6 m according to Lozinsky, 1985) and some playa lake deposits. North of the Victorio Arch area, Neogene units probably thicken towards the Trinity Lake or Oscura basin and the Oscura Mountains (Neal et al., 1998; Villalobos and Keller, 2003; Cather, 2009).

Mafic volcanoes produced basalt flows along the entire Rio Grande rift during Pliocene and Pleistocene time (Baldrige, 2004). Over a dozen basaltic cinder cones and tuff rings occur in the Elephant Butte volcanic field. These basalts date to Pliocene time (2-5 Ma; Lozinsky, 1985). In the subsiding Palomas and "Engle" basins, basalts are intercalated with sediments of the Palomas Formation. Out of the basin in the Cutter Sag and Engle area, volcanoes of the same age lie on the preserved Jornada surface and keep their original depositional form. In the northern Jornada, the Jornada del Muerto field consists of three Pleistocene basalt flows (covering 435 km<sup>2</sup>) and a central volcanic vent, all well preserved. These flows are spectacular geomorphic features, but are thin (15-30 m).

Pleistocene and Recent gravels associated with the present Rio Grande and its inset terraces line the present day valley of the river. The river has excavated the older Neogene fill to a depth of 140 m within the last 0.4 million years (Lozinsky, 1985).

## STRUCTURE

Structures within the area range from Precambrian to Recent in age. Setting aside Precambrian features, major structures formed during the Laramide (latest Cretaceous to Eocene) and Neogene.

The Rio Grande axis is a chain of linked structures that extend north by north-northeast through central New Mexico and northwards. The most conspicuous structures are Neogene extensional faults and basins containing Santa Fe Group alluvium. However, they follow closely a line of Laramide contractional and strike-slip features (seen in the Caballo and Fra Cristobal Mountains, and also in Cerros del Amado east of Socorro). The Rio Grande axis could have had pre-Laramide ancestry and have been active during Paleozoic deformation, but this is not yet well documented.

### Laramide Structures

Laramide structures in southern and central New Mexico are largely basement-involved and compressional in nature (thrust faults and folds), with varying amounts of strike-slip movement also known or inferred (Fig. 6; also see Cather and Harrison, 2002). There appear to be two stages of deformation and basin development, an early latest Cretaceous phase (responsible for the McRae basin) and the later Eocene phase (responsible for the Love Ranch basin and most of the larger features).

### Rio Grande Uplift and its Foredeeps

Seager and Mack (2003) defined the Rio Grande uplift as a northwest-trending fault-bounded basement uplift that was thrust

northeastward over the Love Ranch basin. An intermediate structural block or bench at the south end of the Caballo Mountains gave rise to complex structures in the Derry Hills area. The extent of the uplift west of the Derry Hills is not known. Seager and Mack (2003) and Seager (2004) suggest that the deposition of the McRae Formation occurred along the northeastern edge of a broad proto-Rio Grande uplift, and that the unit represents a stripping of Laramide volcanic debris from the dome.

### Sierra Uplift and the Rio Grande transpressional zone

The Sierra uplift encompasses a broad and poorly defined area west of the Rio Grande in Sierra and Socorro Counties (Fig. 6). Marine Cretaceous rocks and underlying Triassic and Permian rocks (over 1500 m of section) were removed by erosion from a wide area. All pre-Tertiary outcrops west of the Rio Grande from Cookes Peak and Silver City northward past Magdalena show that Tertiary strata overlie Permian or older rocks.

The eastern boundary of the Sierra uplift (Armendariz uplift of Seager, 2004) consists of a series of folds and faults of transpressional character along the Rio Grande axis. Folds in the Caballo and Fra Cristobal Mountains (Hellion fold), and in the area east of Socorro are similar in character, consisting of basement-involved overturned to nearly overturned east-verging folds with steeply west-dipping axial planes. Between these folds are inferred strike slip faults, of which the Hot Springs fault at Elephant Butte is the

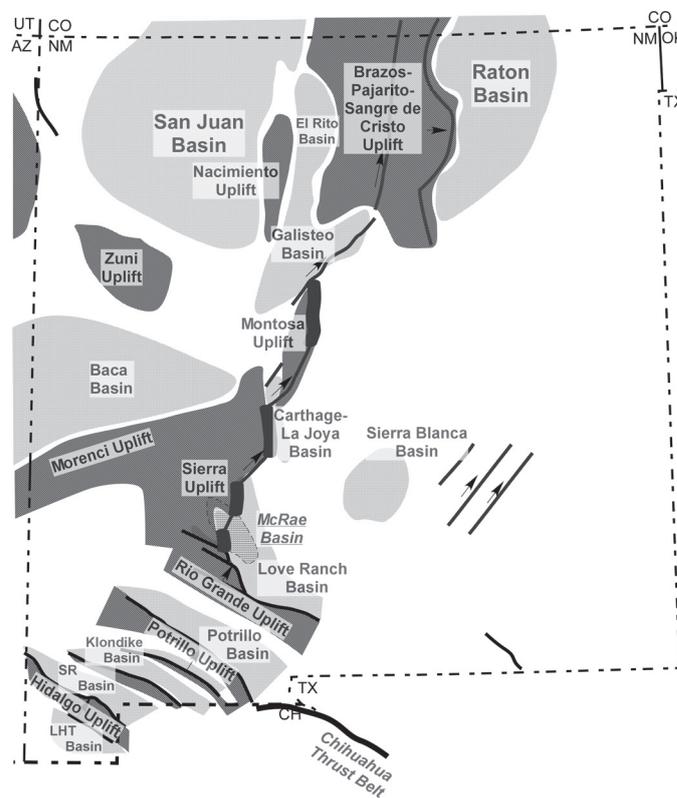


FIGURE 6. Laramide tectonic features in New Mexico; compiled from Cather (2004) and Seager (2004). Black faults are compressional, dark red are strike-slip, green are composite, and red/yellow are transpressional folds. SR = Skunk Ranch basin; LHT = Little Hat Top basin.

best exposed and studied (Cather and Harrison, 2002; Harrison and Cather, 2004). A similar (but concealed) fault probably trends northeast past Little San Pasqual Mountain, to link the deformation in the Fra Cristobal Range to complex deformation in the Socorro area, as shown by Cather and Harrison (2002); Cather (2009) extended the name of Hot Springs fault to this feature.

In younger strata, especially those overlying Yeso gypsum beds, a detached fold style predominates. These upright to box folds are widespread in the Cutter Sag, where the Cutter fold-belt trends northwest-southeast with compression to the northeast (Seager and Mack, 2003).

### Neogene Structures

The Neogene (Miocene to Recent) is a time of extension throughout New Mexico. Major structures include normal faults, transtensional fault complexes, and uplifted and tilted basement blocks at the edges of major extensional grabens. Development of these structures has shaped the physiography and present structural configuration of south-central New Mexico.

#### Rio Grande Rift Basins – Palomas, “Engle,” Socorro and Related Basins

Deep Neogene rift basins lie along the Rio Grande axis – the same trend that had experienced Laramide transpression. From north to south, they are the Socorro basin (extending south past the Chupadera Hills), the “Engle basin” or Elephant Butte basin (west of the Fra Cristobal Mountains and north of the constriction at Truth or Consequences), and the Palomas basin (west of the Caballo Mountains). The Palomas and “Engle” basins are separated by the Mud Springs Mountains, a northwest-trending, north-dipping fault block of Precambrian igneous and Cambrian through Permian sedimentary rocks. The gap between the “Engle” and Socorro basins has not been well studied. The trend from the north end of the Fra Cristobal Mountains to the Bosque del Apache (passing by San Marcial and the Little San Pasqual Mountains) is probably a transtensional accommodation zone within the overall Rio Grande line of weakness.

Both the Palomas and “Engle” basins have the major faults on the east flank, separating them from the Caballos and Fra Cristobal ranges. Between the two mountain ranges is a broad area known as the “Cutter Sag.” This area, roughly coextensive with the McRae depositional basin, appears to represent a zone of transtensional accommodation between the fault bounding the Caballo Range to the south, and the faults that bound the Fra Cristobal Range to the north. The Elephant Butte volcanic field occurs within this intensely faulted accommodation zone (Lozinsky, 1985).

#### Fra Cristobal and Caballos Uplifts and the Jornada Draw Fault

East of the major Palomas and “Engle” rift basins lie two east-tilted basement-cored extensional uplifts, the Fra Cristobal and Caballo ranges.

The Fra Cristobal Range is bounded on the west by the Walnut Canyon fault. A smaller Fra Cristobal fault is also mapped on the east flank (Nelson, 1986). The two fault systems are mapped as meeting at the north end of the range. The uplift decreases in magnitude to the south, where Permian rocks are exposed. The uplift has a low-relief southeast extension, called the “Central horst” by Seager and Mack (2003), which brings up Mesaverde Group rocks against the McRae Formation. The intense faulting of the Cutter Sag accommodation zone occurs west of this horst extension.

The Caballo Range is bounded on the west and south by the Caballo fault; a complex of other faults occur in the southern part of the range. The range dips generally east-northeast into the Jornada del Muerto. Between the two uplifts, a NNE-trending fault may be a transtensional connector.

A significant fault with late Neogene and Quaternary motion, the Jornada Draw fault, extends southeast along the east foot of the Caballo Range (Seager and Mack, 1995; location is purple line just west and south of Engle on Fig. 1). This fault, with down to the east displacement, localizes the trace of the southern part of the Jornada del Muerto syncline; the youngest preserved rocks in the Jornada lie east of this fault.

#### Tularosa Basin, Oscura Basin and the San Andres and Oscura Rift Shoulders

The Tularosa Basin, lying east of the San Andres Mountains, is an active Neogene rift valley. It is an asymmetric full graben, with the largest bounding faults on the west and lesser faulting on the east. West of the basin is the long, west-tilted footwall block of the San Andres Mountains, extending from the Organ Mountains near Las Cruces north to Mockingbird Gap (with a major bend just north of Rhodes Canyon).

At Mockingbird Gap, the polarity of the fault system reverses across an accommodation fault system. To the north, the Oscura Mountains dip eastward, exposing Precambrian on their west flank. The major faults are on the west, and a deep Neogene “Trinity Lake Basin” lies southeast of Carthage and northeast of the Victorio arch (Villalobos and Keller, 2003; Cather, 2009). This basin, which localized Pleistocene Lake Trinity (Neal et al., 1998), lies east of the Pedro Armendaris Grant on the White Sands Missile Range and has not been drilled to depth; gravity information suggests 3 km of fill (Healey et al., 1978; Villalobos and Keller, 2003). Displacement on the Oscura faults dies off to the north, as the entire Tularosa-San Andres trend loses displacement.

The Jornada del Muerto syncline was formed in Neogene time by the west tilt of the San Andres Range meeting the east tilt of the Fra Cristobal and Caballo Mountains. The syncline deepens to the south, largely due to the presence of the Love Ranch basin but also assisted by the Jornada Draw fault. The shallowest part of the syncline is on the north end, where a northwest-trending feature, the Victorio Arch, is inferred from gravity data. North of this point, the tilting due to adjacent footwall blocks dies away, and a broad and featureless undrilled area of the northern Jornada is structurally indeterminate.

### POTENTIAL HYDROCARBON PLAYS

The Jornada del Muerto and the Pedro Armendaris Grant are areas of frontier exploration that lack producing oil and gas reservoirs and have seen only sparse drilling. The entire area has seen only 31 wells drilled for hydrocarbons (Fig. 1). Many of these wells date back to the 1920s, and the most recent wells only to the 1970s. There are few seismic lines in this area. Thus, all of the play ideas considered here are conceptual, and guided by very limited data.

The Cretaceous section hosts significant oil and gas resources in the San Juan Basin in northwestern New Mexico, with production from the basal Dakota, from shoreline sandstones of the Gallup, from sandstones in the nonmarine Mesaverde and Fruitland sections, and coalbed methane from the Fruitland. Coalbed methane is also produced in the Raton Basin of northeastern New Mexico.

The Cretaceous in the Jornada frontier appears to provide the best chance of finding hydrocarbons, as it contains thin marine shales with organic content, thin coals, and numerous sandstone reservoirs. However, all known sources are in the gas window, and Neogene tilting and extensional faulting negatively impact the preservation of traps. The lack of natural gas infrastructure in the area is the chief limitation for exploratory work in the area.

#### Conventional Resources

Source rocks for oil and gas occur within the Mancos section of the marine Upper Cretaceous, as well as gas potential from coals of the Tres Hermanos and Crevasse Canyon formations.

The Turonian shales and limestones overlying the Dakota (Greenhorn or Eagle Ford equivalents in the Rio Salado Tongue) appear to have high organic content; two fairly random samples were analysed with 0.82-1.10% TOC and Ro of 1.45-1.64% (see Ewing and Colpitts, minipaper). The shales could be especially rich in oil-prone source materials (although now generating gas). Coals also occur and generate gas (see below).

Potential reservoirs occur in all of the shoreface sandstones and transgressive sandstones of the section – Dakota, Tres Hermanos and Gallup. As with the Paleozoic plays, any traps filled before the Neogene are subject to leakage due to Neogene faulting, tilting and dip reversal; and flushing due to water influx from the nearby mountain ranges, and to hydrothermal activity related to high thermal gradients during rifting. The best places to look would be in unreversed blocks in areas of low fault density.

#### Unconventional Resources

Coalbed methane – the methane gas adsorbed on the fracture systems in coal seams – is possibly productive in the area. Coals in the area are thin but occur widely:

Small-scale mining took place along a 30-90 cm coal seam at the top of the Gallup Sandstone in the Mescal Canyon area (Tabet, 1979b). As reported in the companion minipaper, a sample of this coal has 19% ash, 0.57% sulfur, and 15,200 BTU/lb (ash and moisture-free) and is considered high-volatile B to

low-volatile B in rank.

In the Carthage area northeast of the property, commercial mining proceeded for many years in coal seams above the Gallup Sandstone. The nearby Jornada del Muerto coal field also had limited production from one mine in a 120 cm seam. The coal at both Carthage and Jornada fields is high-volatile C bituminous coal, with 10-16% ash and 0.6-1.3% sulfur, with BTU values of 14,300-14,530 BTU/lb on an ash and moisture-free basis (Tabet, 1979a).

Thinner, noncommercial coals have been found in the Carthage Member of the Tres Hermanos Formation in both coal areas, and are indicated in the log of well 4.

Between Carthage and Engle there is over 60 km in which all coal-bearing strata are buried beneath the Jornada pediment and younger Cretaceous rocks. Coal conditions there are not known, but there is potential for similar or thicker occurrences in this area. Some of this area lies beneath the White Sands Missile Range (Fig. 1).

Coalbed methane content is a function of rank and burial history, groundwater flow and bacterial processes. High-volatile C coals generally are in the gas window for thermogenic gas generation, and have cleat sufficient to trap such gas. Coalbed methane reservoirs are less susceptible than conventional reservoirs to Neogene tilting, dip reversal and fresh-water flushing. Faulting complicates development and open water-filled fractures can make production uneconomic. One should search for areas with thicker coals that are away from highly faulted areas.

Organic marine shale is present in the Rio Salado Tongue of the Mancos Shale. This unit is equivalent to the Greenhorn and associated formations to the north and the Eagle Ford Formation in Texas. Limited sampling to date does not indicate a low-clay, high-organic target, but more survey work is warranted.

#### Summary and Further Work Needed

To summarize the oil and gas potential for the Pedro Armendaris Grant in Sierra and Socorro Counties, New Mexico:

Areas west of the Rio Grande and north of the Fra Cristobal Mountains have no Cretaceous potential and limited Paleozoic potential. The subsurface configuration of this area is essentially unknown, and a volcanic cover is ubiquitous, which hinders exploration.

The area east of the Rio Grande and north of the Victorio Arch (the northern Jornada del Muerto) has some Paleozoic potential and better potential for Cretaceous conventional and coalbed methane traps. The structural configuration of this area is unknown, and substantial geophysical and/or core hole work would be required. Much of the surface in the area is covered by a recent basalt flow, impairing operations and geophysical imaging. About half this area is off-limits to exploration due to the White Sands Missile Range.

The area west of the Fra Cristobal Mountains and the Cutter Sag has limited potential for oil and gas, due to complex Neogene faulting and thick Neogene rift fill.

The southern Jornada del Muerto area has the highest oil and gas potential. Paleozoic and Cretaceous conventional oil and gas

reservoirs are possible, particularly on the west side of the syncline. Exploring for traps in these units is somewhat problematic, given the sparse well control and geophysics. Coalbed methane potential is good through this area, especially in areas away from the complex faulting of the Cutter Sag. The lack of outcrops in much of this area will require core drilling to determine coal conditions.

As mentioned, the sparse drilling and geophysical database make additional work imperative.

We need to understand the basin configuration better, particularly in the area of the "Victorio arch" and its northern boundary, but also in the areas adjoining the Fra Cristobal Mountains.

The thickness and distribution of coal and organic shale is poorly understood, being based only on two outcrops over 60 km apart. A series of core holes spudded in the Mesaverde would be required to determine unit thickness and get suitable samples for analysis. Logging through the Gallup and Tres Hermanos units will also allow a much better understanding of sandbody architecture, which may lead to concepts for conventional trapping.

The northern outcrop of the basal Mesaverde and older Cretaceous formations (at the south end of the Fra Cristobal Mountains) needs to be remapped. A quick auto traverse across the outcrop area coupled with aerial photography shows that the old mapping failed to identify the Tres Hermanos and D-Cross units, and mischaracterized the overall structure of the area.

A better understanding of the axis of the Jornada del Muerto syncline and its relationship to the Fra Cristobal Mountains would be useful, not only for the coalbed work but also for conventional reservoir exploration. This should be obtained by a modest seismic reflection program guided by aeromagnetic data and coreholes.

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## APPENDIX: WELLS MENTIONED IN TEXT

<b>No.</b>	<b>Name</b>	<b>Location</b>	<b>KB</b>	<b>TD</b>	<b>Date</b>
1	Sun #1 Victorio Land and Cattle Co	25-10S-1W	4809'	6053'	1/52
2	Sun #2 Victorio Land and Cattle Co.	27-10S-1W	4789'	6352'	5/52
3	Gulf #1 Sierra 'K' State	35-12S-1W	5123'	7860'	8/70
4	Shell #1 Leeman Federal	17-13S-1E	5261'	7283'	3/65
5	Exxon #1 Beard Federal	5-14S-1E	5179'	8850'	2/74
6	Beard #1 Jornada del Muerto Unit	17-14S-1W	4806'	9800'	4/73
7	Sunray Midcont. #1 New Mexico Fed. 'M'	23-15S-2W	4689'	9775'	4/59
8	Exxon #1 Prisor	20-16S-1E	4640'	11,650'	3/77

PENNSYLVANIAN	Late	<b>Bursum Formation</b>		
		Bar B Formation	Atrasado Formation	Moya Member
				Del Cuerto Member
				Story Member
				Burrego Member
				Council Spring Member
				Tinajas Member
		Middle	Gray Mesa Formation	Amado Member
				Adobe Member
				Garcia Member
				Whiskey Canyon Member
				Elephant Butte Member
Red House Formation				
Miss.	Lake Valley Formation			
Dev.	Percha Formation			
Sil.	Fusselman Formation			
Ordovician	Montoya Fm.	Cutter Member		
		Aleman Member		
		Upham Member		
		Cable Canyon Member		
	El Paso Group	Bat Cave Formation	McKelligon Limestone	
Hitt Canyon Formation				
	Sierrite Limestone			
Є	Bliss Formation			

CRETACEOUS	Late	McRae Formation	Hall Lake Mbr.	
			Jose Creek Mbr.	
		Crevasse Canyon Formation	Ash Canyon Mbr.	
			barren member	
			coal-bearing member	
		<b>Gallup Sandstone</b>		
		Mancos Shale (D-Cross Tongue)		
		<b>Tres Hermanos Formation</b>		
		Mancos Shale (Rio Salado Tongue)		
		<b>Dakota Sandstone</b>		
		Triassic-Early Cretaceous		
PERMIAN	Early	San Andres Formation		
		Glorieta Sandstone		
		Yeso Group	Los Vallos Formation	Joyita Member
				Cañas Member
				Torres Member
		Arroyo de Alamillo Formation		
		Abo Formation	Cañon de Espinoso Member	
			Scholle Member	

**Paleozoic-Mesozoic stratigraphy, Sierra County, New Mexico**

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2012