Future petroleum provinces in New Mexico — discovering new reserves

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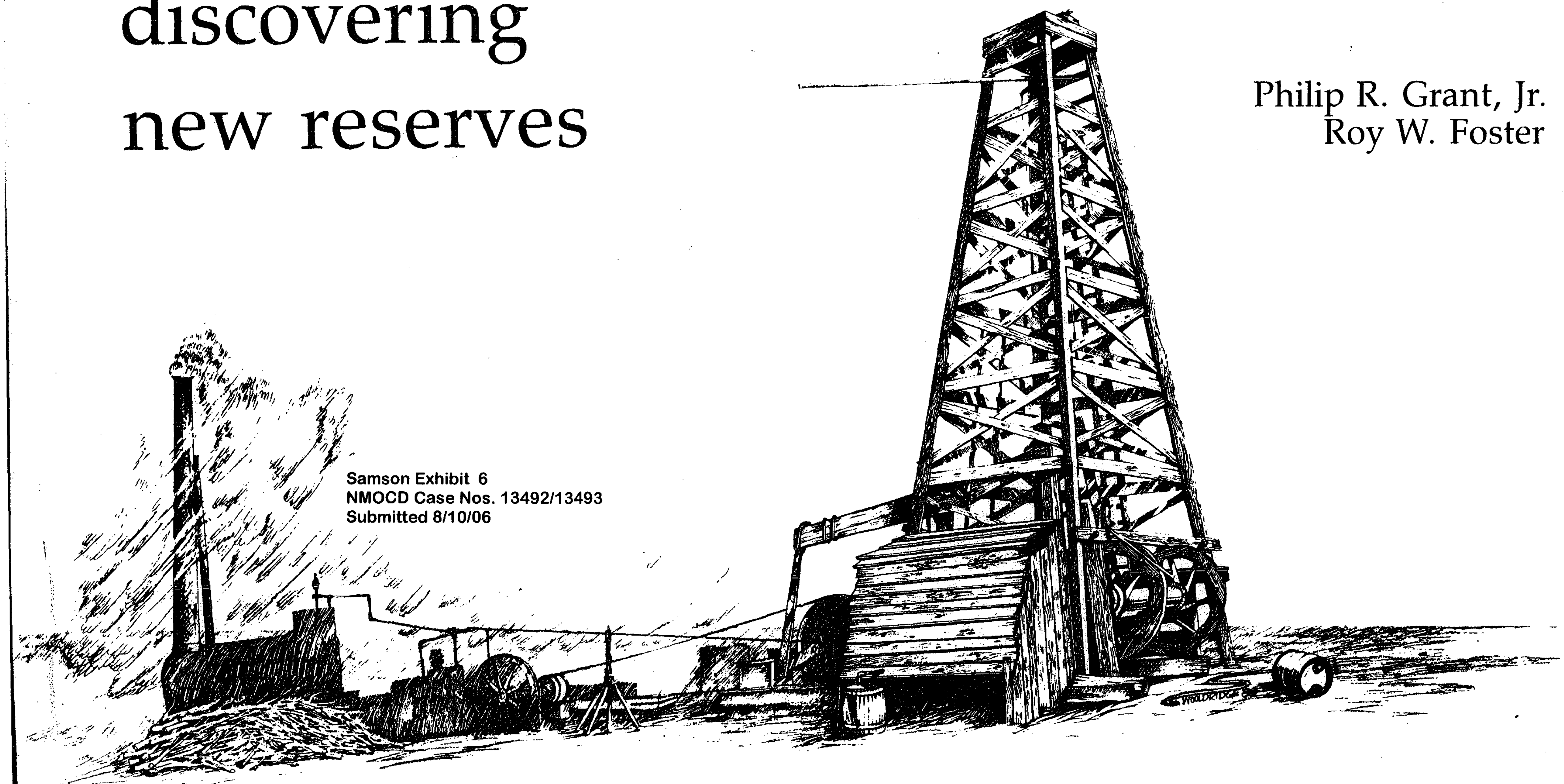

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Pennsylvanian—Pennsylvanian stratigraphic nomenclature is a perplexing melange of parochial detail that resists simplification and widespread correlation of units. Many outcrops are narrow bands separated by large gaps of covered or eroded areas. The tendency of some investigators to treat exposures in different parts of the state and adjoining regions as disconnected and unrelated sections has resulted in a proliferation of local names and detail. A general inability to reduce these to common denominators contributes to unfavorable results in correlating Pennsylvanian strata regionally and often creates confusion in dealing with them as subsurface units.

Early Pennsylvanian seas encroached upon a mature, subdued topography and quickly inundated the emergent land areas. Sediment distribution reflected rapid responses to cyclic tectonism that affected the area in and around New Mexico at this time. Profound tectonism during middle Desmoinesian time rearranged the preexisting structural fabric resulting in the rapid emergence and prominence of the Uncompahgre, Pedernal, Sierra Grande, Zuni, Defiance, and Burro–Florida uplifts.

The magnitude of Pennsylvanian orogeny was probably greater than that of the Late Cretaceous–early Tertiary Laramide. Intense movements generated a complex topography that resulted in the accumulation of a varied suite of rocks. It is not surprising that one of the major Pennsylvanian depositional basins, a part of which is located in extreme northwestern New Mexico, is called "Paradox." Despite the puzzles this system presents, or perhaps because of them, Lower and Middle Pennsylvanian rocks offer great promise for the discovery of significant reserves by explorationists willing to abandon conventional concepts in favor of alternative ideas.

Because of difficulty in relating diverse facies suites from one region to another the New Mexico Pennsylvanian, more than any other System, relies on fossil data to determine equivalence of units. This sometimes results in correlations that don't seem to make sense. An example that illustrates the difficulty of maintaining regional continuity in nomenclature within equivalent units is that created by Miller et al. (1963) to make the Lower Pennsylvanian La Pasada and Flechado Formations of the Sangre de Cristo Mountains equivalent to each other and to the Sandia and Molas Formations nearby, substantially on the basis of faunal evidence. In a recent attempt to address this problem Baltz and Myers (1984) commendably assign value to facies–stratigraphic equivalences as well as fossil evidence. However, they may have added confusion by rejecting regionally recognized nomenclature and renaming the lower gray limestone and arkosic limestone members of the Madera Formation the Porvenir and Alamitos Formations, respectively. In the process, they contradict themselves: "In recommending these revisions, we believe it is desirable to retain, where possible and useful, the terminology of previous published literature that reflects the regional unity of extensively mapped bodies of rocks of generally similar lithology and age," (p. 13), and effectively perpetuate the Pennsylvanian nomenclature predicament.

Another conclusion that may be erroneously influenced by fossil evidence is that most Pennsylvanian uplifts were present during all of Pennsylvanian time and that thickening, thinning, and "0" lines are predominantly a function of deposition. However, if these features are primarily the result of postdepositional erosion, interformational and intraformational unconformities in marine units become principal targets of opportunity for hydrocarbon exploration.

The significance of Middle Pennsylvanian cyclic deposition is discussed by Szabo (1968, pp. 129–130) in his analysis of the genesis of the Pennsylvanian Paradox depositional basin:

> The Paradox Basin is the larger southwestern segment of a regional Pennsylvanian sag which was transected by the Uncompahgre uplift during the latter part of Desmoinesian time. The Maroon Basin of northwestern Colorado is the other segment of the original sag.
>
> Deposition in the sag was cyclic, and each cycle represents a mappable unit identifiable on well logs. Both horizontal and vertical lithologic gradation are shown by each cycle. Clastic sediments are proximal to emergent areas along the eastern margin, and shallow-water carbonates are characteristic of the marine environment extant along the western margin at that time.
>
> Lithologic sequences of the Paradox shelf, previously called "zones," are mappable units separated by interformational unconformities. The zones qualify as units of formational rank, and the Paradox Formation of earlier usage is in reality a group.
>
> Subsidence of the Paradox Basin appears to be the result of episodic subcrustal withdrawal, and lateral transfer of subcrustal material is proposed as the mechanism for growth of the mobile rim. Episodic pulses of the rim may be the result of uplift related to this lateral transfer. This uplift, terminating depositional cycles in the basin, resulted in erosion of shelf deposits, as indicated by the numerous interformational unconformities.
>
> The Uncompahgre became an emergent feature during the latter part of Desmoinesian time, when uplift was followed by faulting along the flank. . . .
>
> The dominant tectonic elements of the Paradox region are apparently the result of Late Desmoinesian or younger uplift. The major unconformities along the basin margin are in agreement with this dating. The present-day tectonic patterns in the area are, in part, the result of rejuvenation along these older lines of movement.

In summarizing his work, Szabo further states (1968, p. v):

> Subsidence of the Paradox shelf at the end of Atokan time, and contemporaneous uplift of the margin, created a sag which became the site of evaporite deposition. Bordered by a carbonate-covered, submerged welt on the seaward side and the clastic-fringed Front Range uplift on the landward side, the pan-shaped sag is now divided into two basin segments by the Uncompahgre uplift.
>
> Several unconformities are recognized in the Lower Pennsylvanian sequence, none of which extend into the middle of the basin. Successively younger erosion surfaces migrate shelfward, suggesting concentric expansion of the peripheral shelf. Each cyclic sequence, or formation, terminates with peripheral uplift and erosion, suggesting that cyclic deposition was tectonically controlled.

Extending these concepts over a broader region of contemporaneous Pennsylvanian deposition makes it possible to correlate marine units of this system between the present-day Paradox and San Juan structural basins. It becomes feasible to demonstrate the existence of interformational unconformities in tectonically active areas and show equivalence of events and units in widely separated areas. Well logs generally provide more recognizable markers for regional correlations, and the absence of subsurface units is more easily recognized in a cyclic sequence. Tracing unconformities is greatly facilitated with the use of log markers.

The relationship between Pennsylvanian production and these subtle unconformities has been observed in northwestern New Mexico. On the San Juan Basin's Four Corners platform, Tocito dome is partially controlled by an unconformity in the lower part of the Barker Creek formation. The more precise location of unconformities in the San Juan Basin is possible with careful utilization of the sparse well control available. Detailed and thorough analysis of seismic data should contribute significantly to the search for unconformities in this region.

The Pre-Akah erosion surfaces map (Fig. 15) and three accompanying cross sections (Pennsylvanian cross section, Four Corners platform, Fig. 16; Pennsylvanian cross section, northeast–southwest, San Juan Basin, Fig. 17; and Pennsylvanian cross section, northwest–southeast, San Juan Basin, Fig. 18) use limited subsurface data to show these relationships. It is important that the reader understands that these are not intended to be absolute correlations and precise locations of stratigraphic boundaries and eroded surfaces. In gross perspective they project depositional relationships, timing of uplifts, and the premise of formational and interformational unconformities that are different from those to which some explorationists are accustomed. Additional refinement should provide the necessary accuracy for locating traps.

The Pennsylvanian isopach map (Fig. 19) is undoubtedly influenced by the Middle and Upper Pennsylvanian uplifts that continued into the Permian. Some of the greater thicknesses do not represent the sites of preeminent marine deposition; but, particularly in northern New Mexico, they are regions where large volumes of detritus that eroded from Upper Pennsylvanian mountain masses filled intervening troughs. The thick areas located in the Tularosa (Orogrande), Pedregosa, and Delaware Basins, as well as the Lucero uplift and parts of the San Juan and Las Vegas Basins, are exceptions that contain thick marine suites.

An anomalous zone represented by an isopach thin is apparent extending from the Nacimiento Mountains through the center of the Albuquerque Basin of the Rio Grande rift to the Joyita Hills north of Socorro. From here it swings southeast to connect with the north–south Pedernal axis in the vicinity of Carrizozo. If this feature was a ridge that was present throughout Early Pennsylvanian time, it has implications for facies suites suitable for hydrocarbon accumulation in nearby areas. Baars (1982) has drawn regional tectonic inferences of interest from this feature, suggesting that the Rio Grande rift in the Albuquerque Basin is an Early Pennsylvanian feature connected to a major fracture lineament that extends northwest across the length of the Colorado Plateau.

Finally, in the context of posing a nontraditional solution to some perplexing Pennsylvanian dynamics, a "What If?" scenario is presented in Figure 20. It is often appropriate to break with tradition in order to gain new insight to an old problem. Preparation of this map represents a different approach to generate patterns that provoke thought and controversy, often a necessary ingredient for progress.

When a different contouring approach is proposed, an isopach map of the Pennsylvanian System can be the basis for some intriguing interpretations. For instance, there is an apparent lithologic pattern break on a line that follows a gentle northwest-to-east arc across the northern third of the state. The arc trends eastward from the Chacra Mesa region of the San Juan Basin, crosses the gap between the southern Nacimiento and northern Sandia Mountains, passes through the Glorieta fold and fault belt, and skirts the south end of the Sierra Grande arch as it trends into the Texas panhandle. The linearity of this feature suggests a fault.

In the Chacra Mesa area the Pennsylvanian isopach shows a spur-like feature that indicates drag on a strike-slip fault. Just north of this spur the Pennsylvanian thickens into the San Juan Basin across the region where anomalous fracturing of the Niobrara part of the Upper Cretaceous Mancos Formation has developed porosity and permeability. This results in significant hydrocarbon production in a normally tight section. Recent oil discoveries and strong shows in fractured Cretaceous shale in the Galisteo area of the Albuquerque–Hagan Basin are also on this trend.

Shear faults and fracturing related to regional left-lateral shifting on this trend should be an important influence upon exploration in east-central New Mexico's Palo Duro–Tucumcari Basins. Drag folds truncated by relief faults should form important traps in this area. Complex faulting like that illustrated in Figure 21 will make geophysical exploration an important tool when applied with detailed stratigraphic mapping.

South of the east–west anomaly the features of the Rio Grande rift and Orogrande Basin may be contoured into arcs that appear genetically related to the Pedernal axis. The mid-Pennsylvanian paleogeographic map (Fig. 22) is an effort to show how the isopachous thicks and thins can be worked into a series of highs and lows reflecting structure as it may have been.

A segmented ridge extends southward from the Pedernal uplift into Texas. Twisting of this ridge can be explained as sliding along a series of fracture zones parallel to the Huapachi structure. The forces for such movement could have been generated by eastward drift of the Zuni–Florida massive or by gliding of the Pedernal. In either case, the ancestral Rio Grande "rift" would have originated as a compressional trough between converging crustal elements.

Evidence suggests that some time in Early Pennsylvanian time the backbone of New Mexico was probably the Uncompahgre uplift, an arcuate compressional ridge extending from north-central Utah across western Colorado to the Santa Fe area of New Mexico. The structure continued southward as a shallow submarine ridge. This ridge reached maximum development during Middle Pennsylvanian time. At that time arching extended to include the Pedernal and its southward-projecting "tail."

Uplift of the Zuni massive and northeastward-directed compression from Mexico resulted in a "twisting" of the Pedernal with accentuation of folding and concurrent erosion. The tail of the Pedernal axis became a prominent, deeply eroded fold that continued into Texas. Shearing across the axis at regular intervals provided gliding planes for stress relief.

The apparently complex Rio Grande trough may be explained as the focus of the convergent forces of the Zuni and Pedernal uplifts. The trough was initially the site of a series of southeastward-trending folds. The forces responsible for bending the southern Pedernal also twisted and faulted the structures in the trough. Uplift of the Zuni region generated compressive forces that caused thrust faulting in the trough.

It is suggested, then, that the ancestral Rio Grande rift was a broad syncline, asymmetrical to the west, with an axis of north–south folds occupying the length of its eastern flank. Continued stress generated a series of en echelon folds that eventually became diagonal torsional shears.

A transverse shear developed to separate the Uncompahgre from the Pedernal uplift. Drag in this zone caused by eastward movement offset structural features. Post-Cretaceous rejuvenation not only offset the Sandia–Nacimiento faults but also created fracture systems in the San Juan Basin, Puerco and Glorieta fold and fault belts, and the Tucumcari Basin and probably generated important fracture zones paralleling the trend. Fracture-enhanced production similar to that encountered in the Verde Gallup and Puerto Chiquito regions of the San Juan Basin should be encountered along this trend.

The Lower Pennsylvanian shoreline of the Delaware Basin trended northeast–southwest until it was disrupted by uplift during Middle Pennsylvanian time. On the south side of the Huapachi monocline, uplift resulted in erosion of older sediments posing the potential to discover unconformity traps in this area.

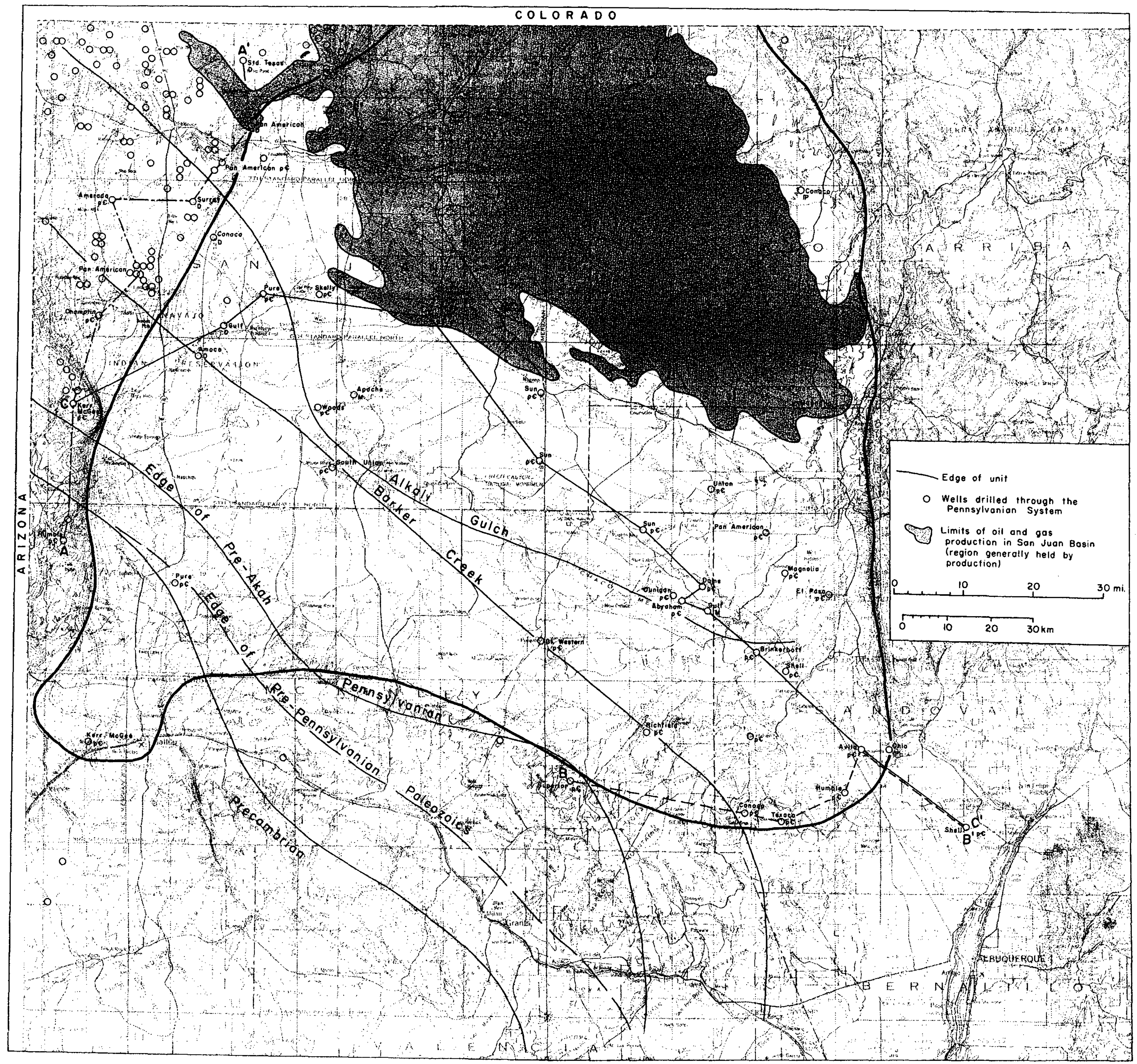
Tectonic timing is probably the most critical problem in any interpretation. It is unlikely that all events occurred at once or as an unbroken chain-like sequence of events. Unfortunately, there is little stratigraphic data with sufficient detail to develop facies-controlled paleogeographic patterns. Absence of this information means exploration for hydrocarbon accumulations will continue to be somewhat random. If, however, Pennsylvanian exploration is related to crustal movements, there is an opportunity for it to become focused.

Assuming that the major Pennsylvanian uplifts were accompanied by more than up-and-down movement, a vast network of thrusting, lateral sliding, and normal faulting appears throughout the state. Some of these could be useful in explaining anomalies such as large gravity "lows" beneath Precambrian and Paleozoic exposures in several areas and "out-of-place" thicknesses of Pennsylvanian strata. Further refinement might suggest rationales for identifying the concentration of Cretaceous Mancos fractured-shale production like that west of Cuba and the recent discoveries in the southeast part of the Albuquerque–Hagan Basin near Galisteo and lead to discoveries in other areas.

As the number of target areas decreases, testing of new ideas must increase. It may be that extending a fracture zone hundreds of miles is unreasonable. Structural disruption on a gigantic scale may or may not exert a favorable influence on trapping conditions. How will lateral crustal movements affect the location of productive trends? Is it significant that the configuration of the Central Basin platform may be related to left-lateral gliding? Was the Pedernal a southwest-trending eroded ridge in Pennsylvanian time that was later twisted north–south?

It is emphasized that the map is not precise, and many of the features shown are subject to alternate interpretation. Determining its accuracy and validity and answers to the questions surrounding the origin and development of Pennsylvanian structure and facies could prove to be extremely rewarding.

(Text continued on page 21.)


COLORADO
ARIZONA
Edge of Pre-Akah
Edge of Pre-Pennsylvanian
Pennsylvanian
Paleozoics
Precambrian
Alkali Gulch
Barker Creek
A
A'
B
B'
C
C'
ALBUQUERQUE
Edge of unit
Wells drilled through the Pennsylvanian System
Limits of oil and gas production in San Juan Basin (region generally held by production)
0 10 20 30 mi.
0 10 20 30km

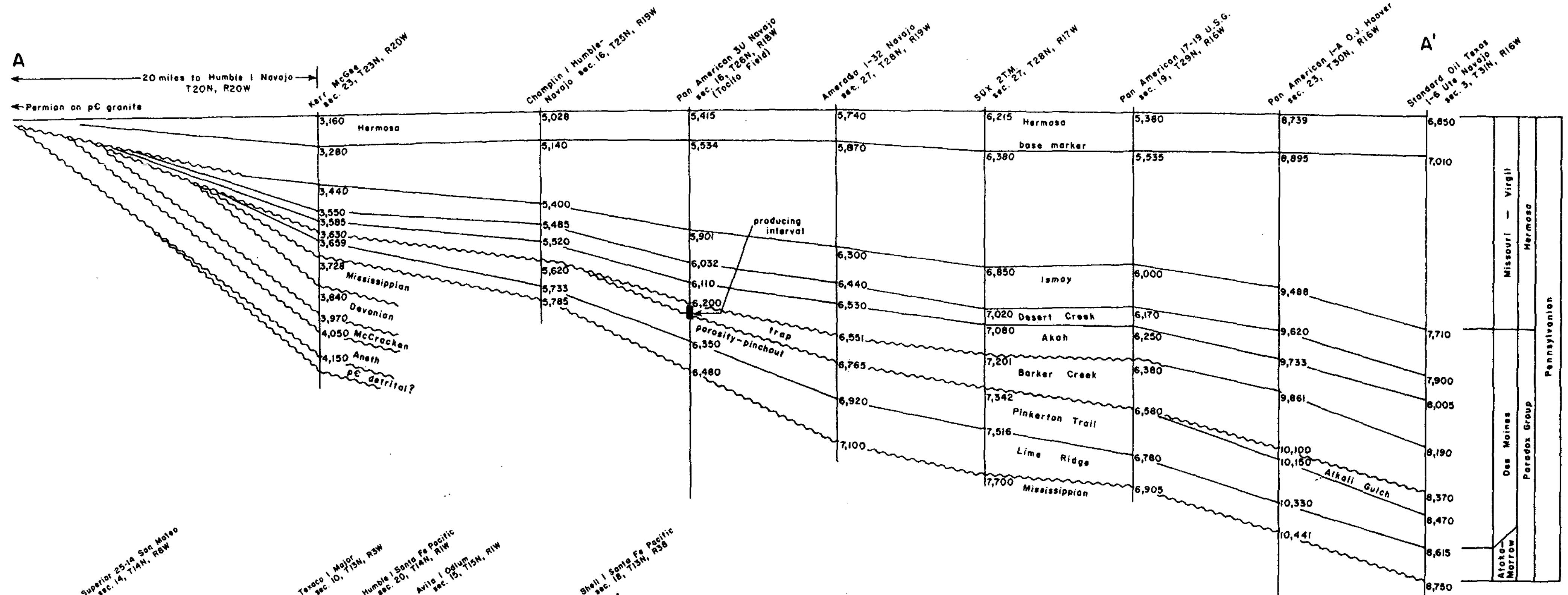


FIGURE 16—Pennsylvanian cross section A–A', north–south, Four Corners platform (see Fig. 15 for location).

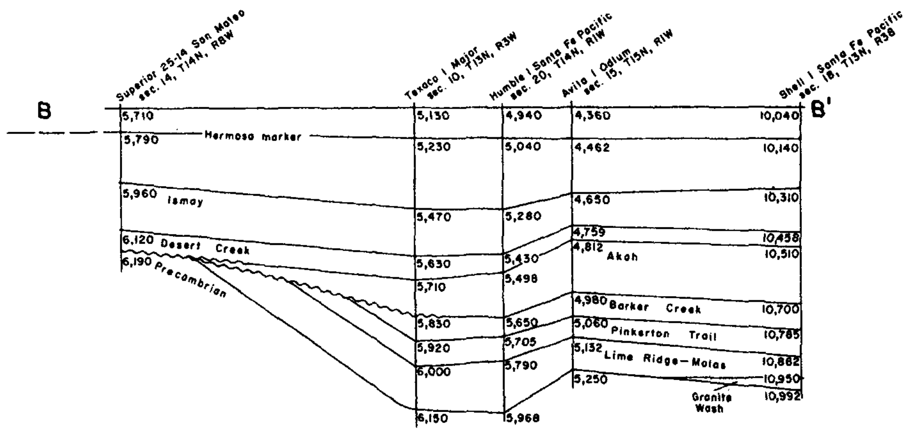


FIGURE 17—Pennsylvanian cross section B–B', northeast–southwest, San Juan Basin (see Fig. 15 for location).

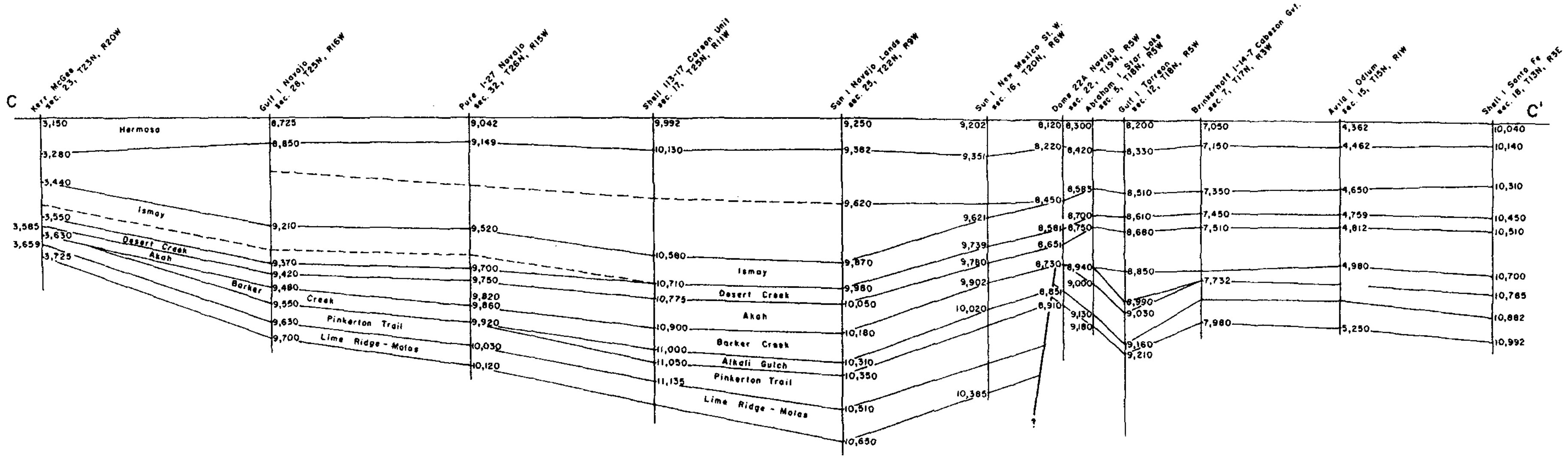


FIGURE 18—Pennsylvanian cross section C–C', northwest–southeast, San Juan Basin (see Fig. 15 for location).

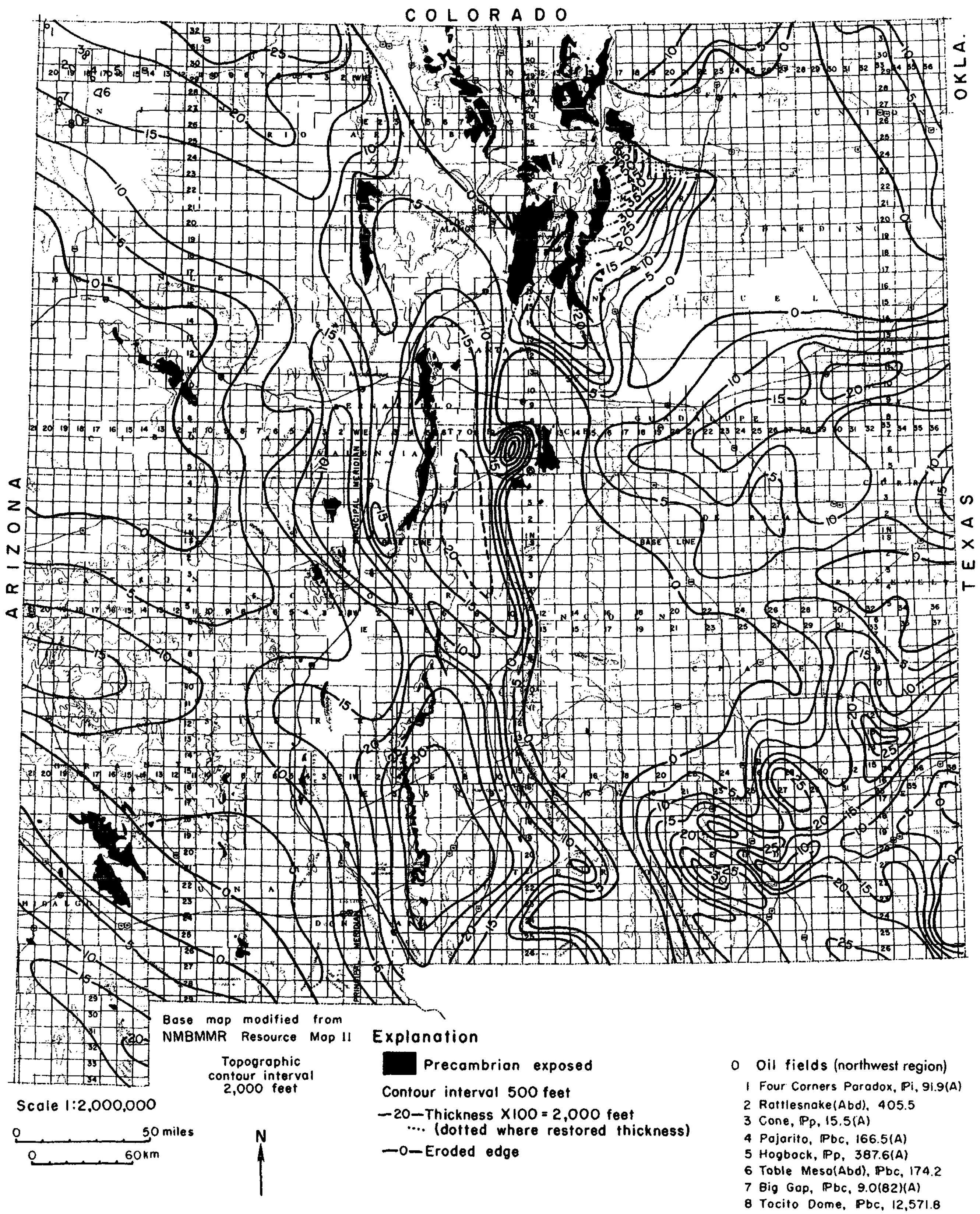


FIGURE 19—Pennsylvanian System isopach map (adapted from Baltz, 1965; Foster, 1978; Mallory, 1972; McKee et al., 1975; Roberts et al., 1976; Szabo, 1968; and well data).

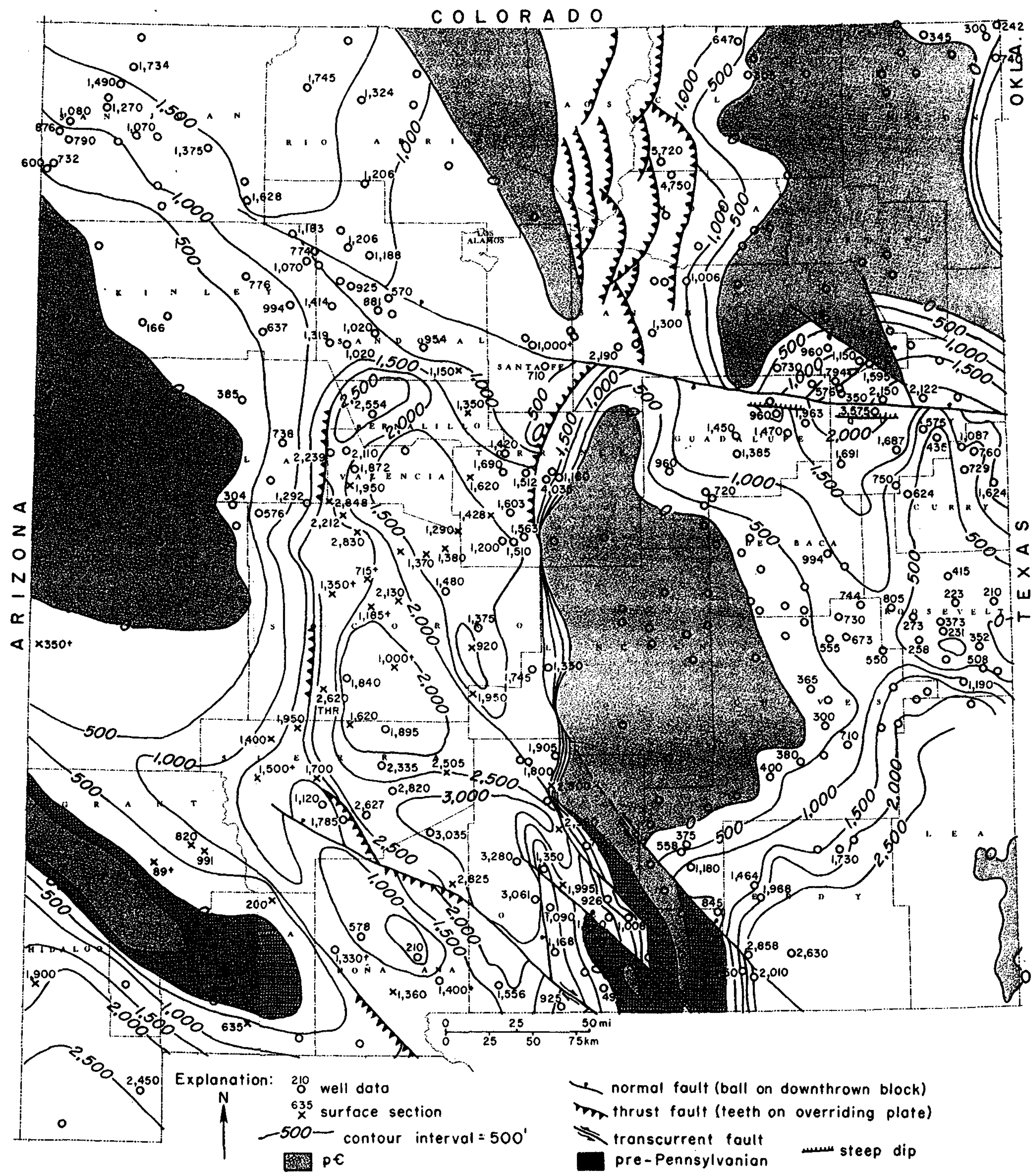


FIGURE 20—Pennsylvanian System isopach map and major tectonic features.

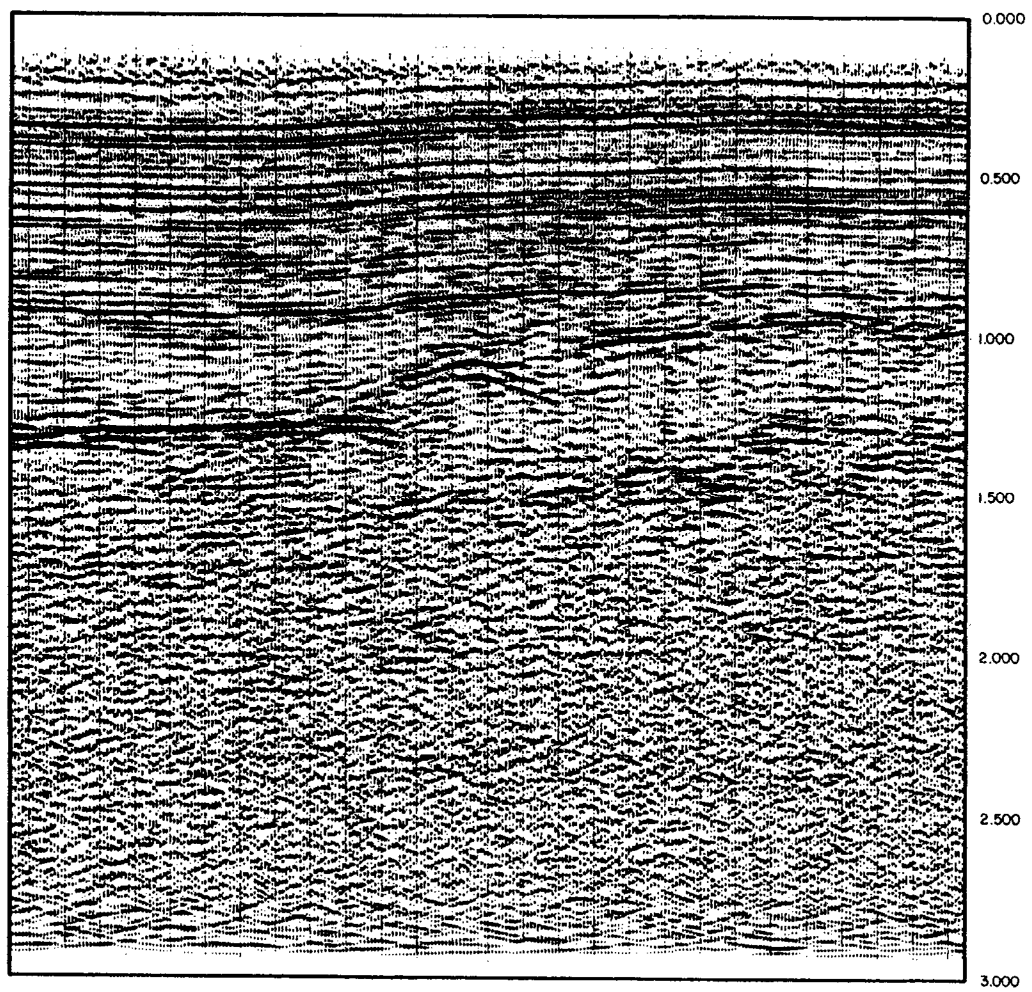


FIGURE 21—Seismic profile, Bravo dome area (published with permission of Permian Exploration Corporation, Roswell, New Mexico).

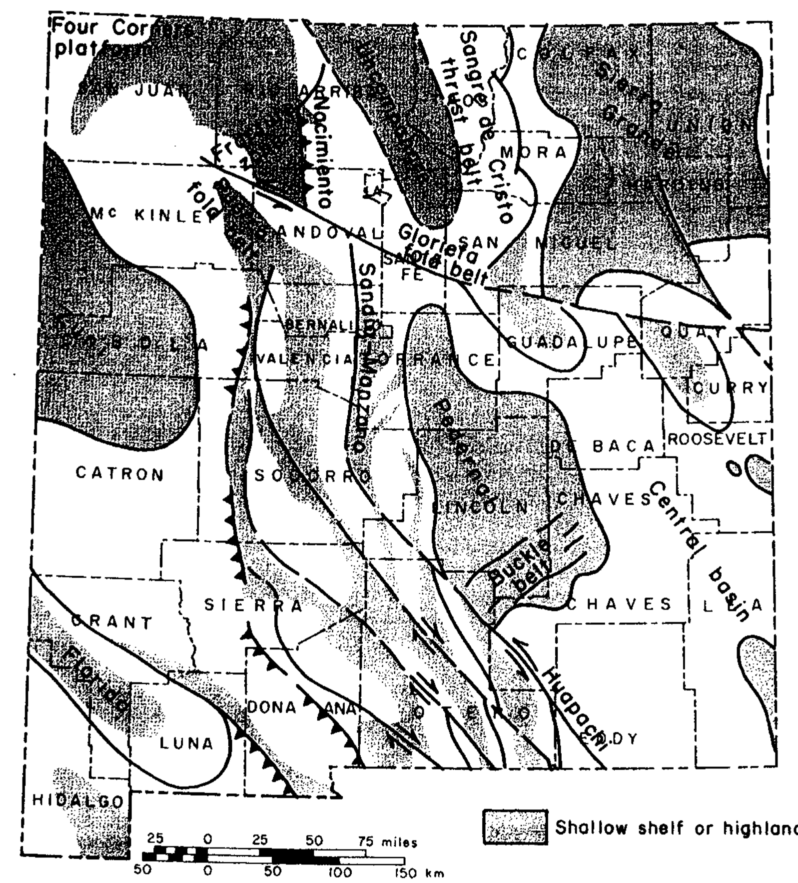


FIGURE 22—Mid-Pennsylvanian paleogeographic map.

In southeastern New Mexico the Abo pay zone is considered to be the dolomite above the Hueco Limestone. Oil and gas fields producing from the limestone part of the section are generally referred to the Wolfcamp.

Oil and gas field maps show the distribution of Abo and Wolfcamp production (Figs. 85 and 86). Included on the Abo maps are a wide variety of reservoir rocks and types of traps. In the northwest is the large Pecos Slope (Abo) gas field where gas is recovered from sandstones in the red-bed section of the Abo. The fields are closely associated with the Y-O, Border, and Six Mile faults. It would appear that the gas migrated into the Abo along these faults from accumulations in the underlying Ordovician, Devonian, and/or Pennsylvanian. To the east are a few scattered stratigraphic and combination traps in Abo dolomite. To the south is a narrow east–west belt of production associated with dolomites of the Abo reef and some back-reef production such as at north Vacuum. On the Central Basin platform there are a number of usually small anticlinal fields producing from dolomite. It seems as though there should be more occurrences of oil and gas in the dolomitic section of the Abo north of the reef zone. This absence may be the result of limited exploration although a fair number of tests have penetrated the section in the search for hydrocarbons in the underlying Pennsylvanian. Another possible explanation is the lack of suitable traps, reservoir rocks, or source rocks. Additional exploration of this nonproductive area is warranted.

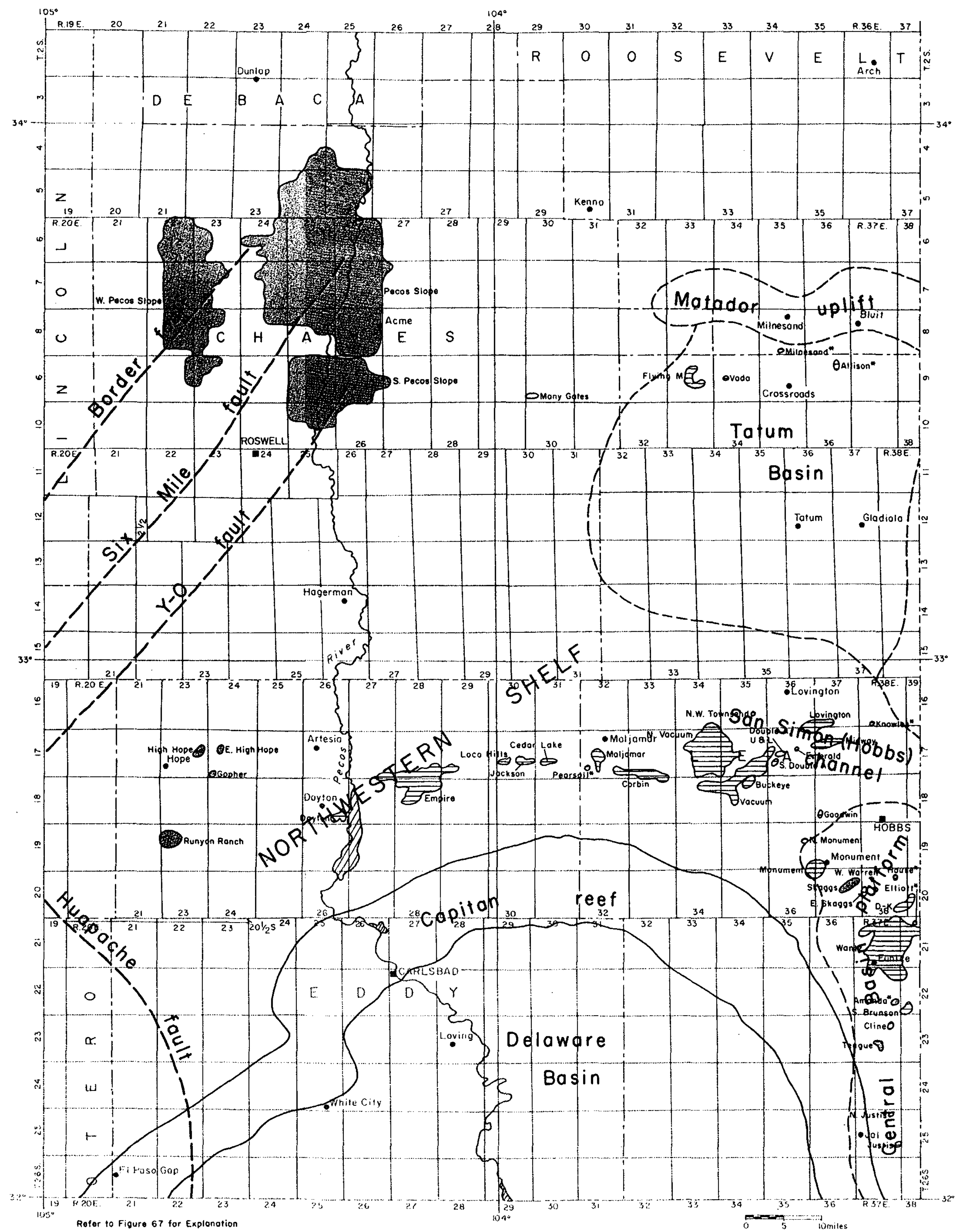


FIGURE 85—Oil and gas fields producing from the Permian Abo Formation.

Limestone constitutes the reservoir rock for most Wolfcamp oil and gas fields. Most traps are anticlines, with some porosity variations partially controlling entrapment of the hydrocarbons. There are also a few reservoirs thought to be small bioherms. Of interest on the Wolfcamp field map is the distribution of oil and gas. A line separating oil and gas production in the Wolfcamp is shown on Figure 86. Gas fields are confined almost entirely to the western area and deeper parts of the Delaware Basin. Oil production in the basin is associated with structurally higher parts of the Wolfcamp that reflect Late Pennsylvanian–Early Permian faulting. A rather well defined separation of oil- and gas-producing areas also is present in underlying formations. It is important to note that this is not always related to depth. Rock type and other factors, probably source material, are involved. The widespread distribution of hydrocarbons in the Wolfcamp is an incentive for further exploration of this interval even though most reservoirs are not very large.

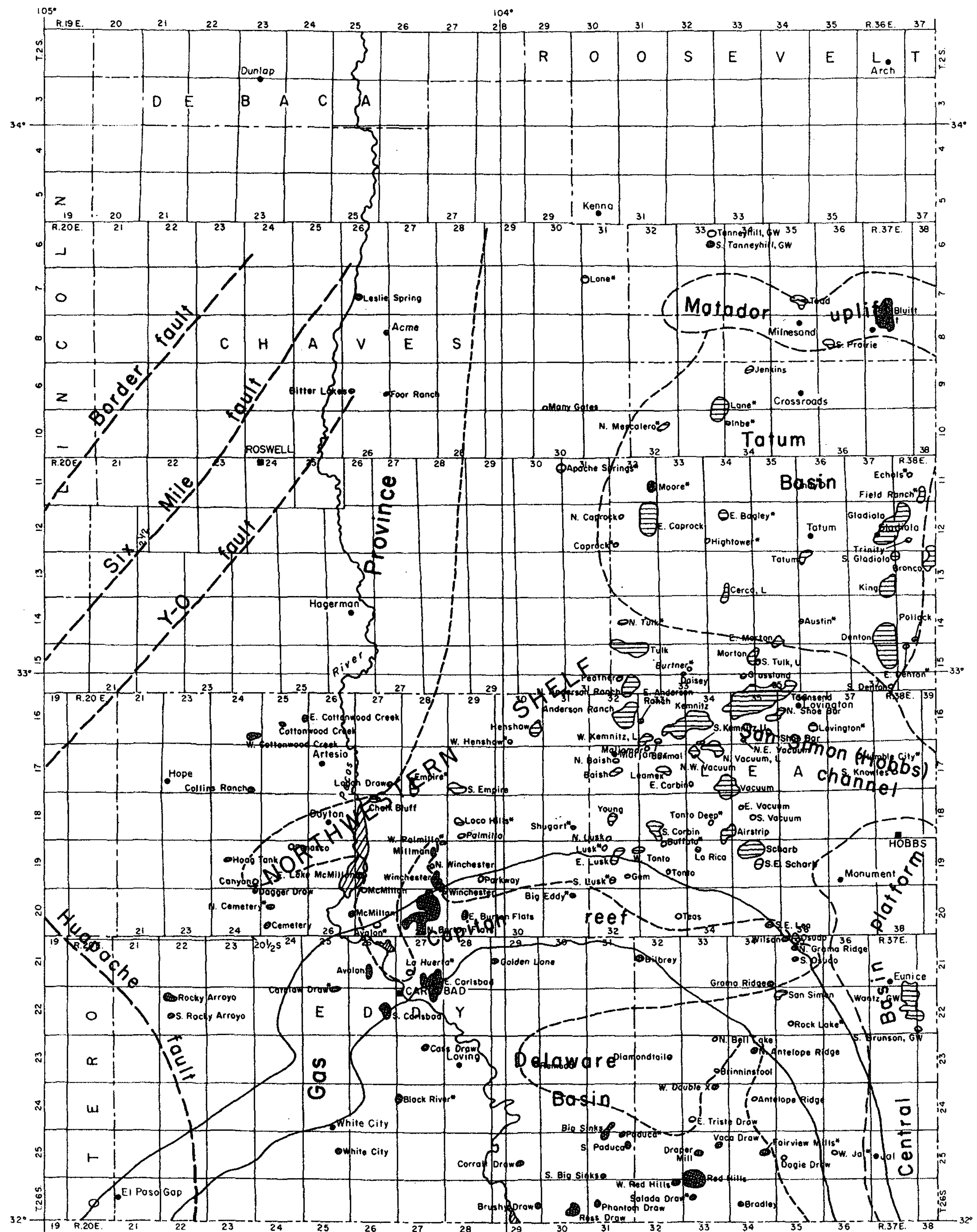


FIGURE 86—Oil and gas fields producing from the Wolfcamp Formation.

Pennsylvanian stratigraphy and oil and gas fields—Meyer (1966) and others have used time-stratigraphic units for the Pennsylvanian System in southeastern New Mexico. From youngest to oldest these are Virgilian, Missourian, Desmoinesian, Derryan (Atokan), and Morrowan. These names with the exception of Derryan represent the provisional series classification accepted for use by the U.S. Geological Survey. This classification is not used here except for the lower two terms because the other names are uncommon in the literature pertaining to oil and gas in southeastern New Mexico. The standard nomenclature for this area is Cisco, Canyon, Strawn, Atoka, and Morrow. From a petroleum standpoint these terms are used as formations. The reference gamma ray/sonic logs of the Gulf Caprock well (Figs. 87 and 88) show the log characteristics for these formations on the Northwest shelf. The formation tops are somewhat arbitrary but are based on an examination of a number of log tops and seem to be representative of what is used by most operators. Facies changes can lead to difficulty in correlating from well to well.

The Cisco in the Northwest shelf area consists of limestone with some medium- to dark-gray and red shale and minor light-gray, generally fine grained sandstone. The amount of red shale decreases from west to east, but some is still present in the easternmost part of the area. Sandstone also decreases to the east and is not present in some areas. The Canyon interval is mostly brown limestone and gray shale with some white sandstone and conglomerate near the base. Sandstone decreases to the east and the carbonate section is mostly dolomite. Chert is more abundant in the east. The Strawn consists mostly of brown limestone and gray shale. In the west it contains abundant fine to coarse sandstone and some red shale and limestone pebble conglomerate. The Atoka is generally gray to white, fine- to coarse-grained, quartz sandstone, commonly conglomeratic. Included is some brown fossiliferous limestone and gray shale. The conglomeratic sandstones continue to the easternmost part of the area. The Morrow varies considerably. Over much of the area it consists of fine- to coarse-grained and conglomeratic sandstone and gray shale with some interbedded limestone, and in the west some red shale and limestone pebble conglomerate. Limestone increases to the east.

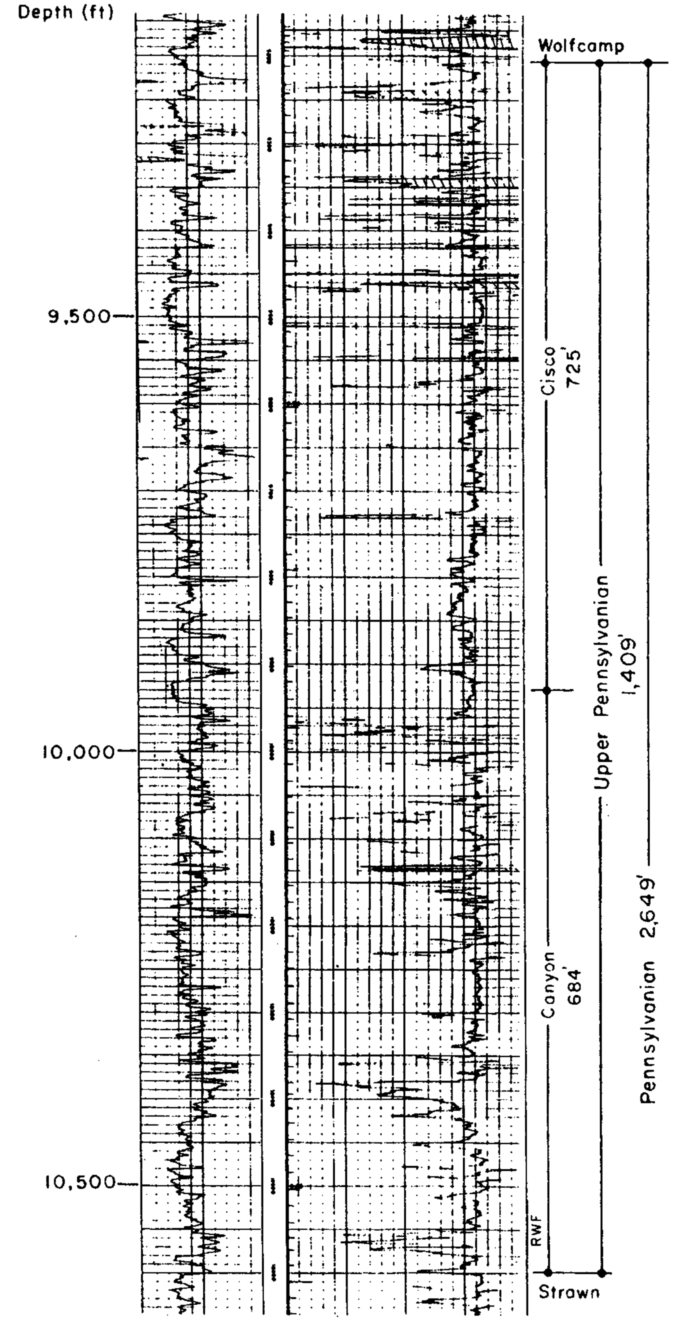


FIGURE 87—Sample gamma ray/sonic log of Upper Pennsylvanian on Northwest shelf. Gulf No. 1 Caprock, sec. 34, T14S, R31E, Chaves County.

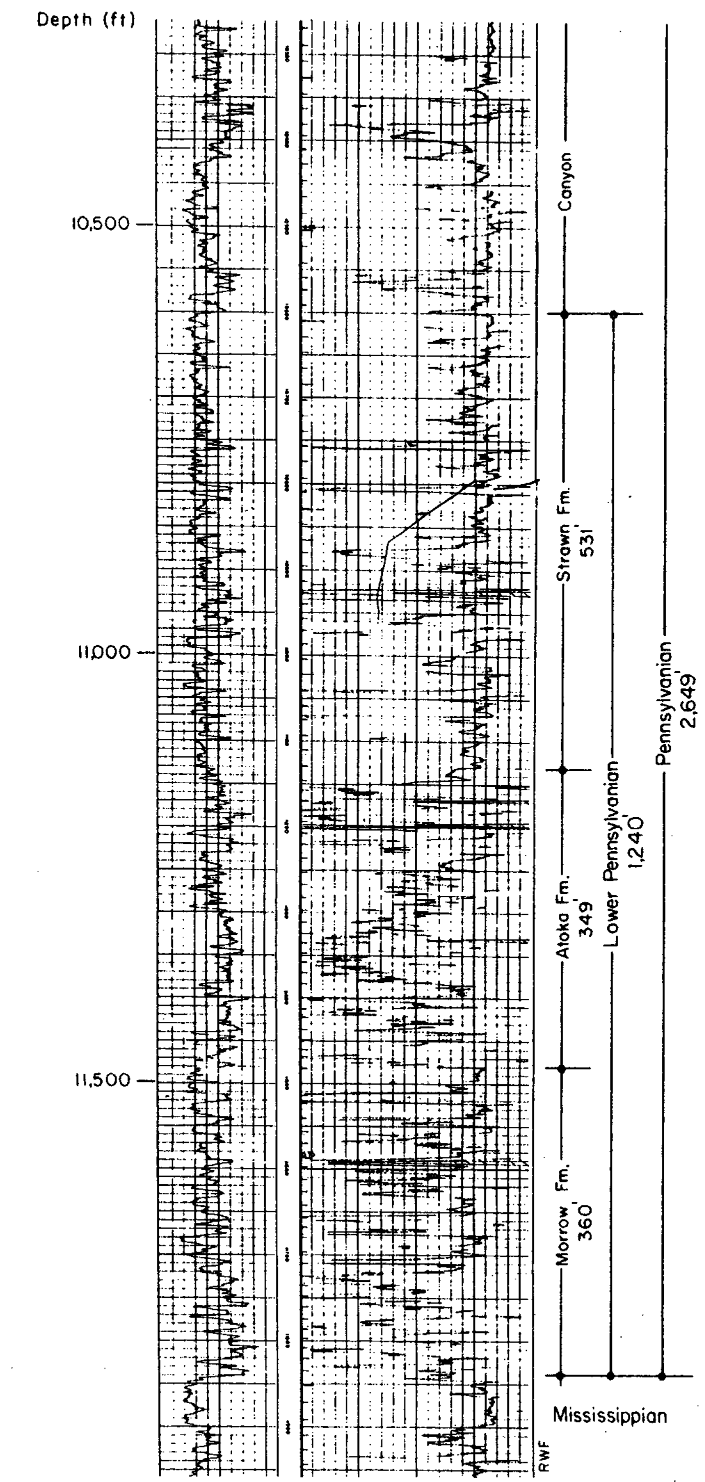


FIGURE 88—Sample gamma ray/sonic log of Lower Pennsylvanian on Northwest shelf. Gulf No. 1 Caprock, sec. 34, T14S, R31E, Chaves County.

Meyer (1966) shows the Pennsylvanian thickening to the east from a "0" line in the vicinity of Roswell to 2,750 feet in the Northwest shelf. In the Gulf Caprock well the Pennsylvanian is 2,649 feet thick with 725 feet of Cisco, 684 feet of Canyon, 531 feet of Strawn, 349 feet of Atoka, and 360 feet of Morrow. In the area of the Delaware Basin, Meyer indicates from 750 to 1,000 feet of Virgilian (Cisco) and Missourian (Canyon) strata. Hills (1963) indicates Strawn underlying Wolfcamp in the Delaware Basin of New Mexico. In 1974 a series of Pennsylvanian stratigraphic cross sections were published by the New Mexico Oil Conservation Commission. Logs from wells in Eddy County were studied by an Industry Advisory Committee and, based on a consensus of that committee, a stratigraphic nomenclature was established to be used in designating the producing formations of Pennsylvanian oil and gas fields in Eddy County. They concluded that the Cisco–Canyon interval thinned from the north to the south and that in southern Eddy County there was only about 350 feet of Pennsylvanian left above the Atoka in the area of the Texas American Todd well (Figs. 84 and 89). What is indicated as Strawn on the reference log is the upper part of their Atoka. Their interpretation for this well is given on the left side of the reference well. Although the Commission's classification is used for designating fields, the most common oil-field usage seems to be that applied here.

The upper part of the Pennsylvanian in the Delaware Basin reference well consists of 368 feet of red and dark-gray shale. It is not known what part of the Pennsylvanian section is represented. The Strawn interval is 176 feet thick and limited to a yellowish-brown to dark-gray argillaceous, cherty limestone with a minor amount of dark-gray shale. The Atoka consists of light-gray to light yellowish-brown and dark-gray shale with some gray, medium- to coarse-grained sandstone. About 460 feet of Atoka are present. The bulk of the Pennsylvanian present in this area is assigned to the Morrow. It contains brownish limestone interbedded with gray shale in the upper part and gray to brown, coarse-grained to conglomeratic sandstone interbedded with dark gray shale and some brownish, oölitic limestone in the lower part. The interval is 1,668 feet thick in this well.

Meyer (1966) indicates a maximum of 3,000 feet of Pennsylvanian in the Delaware Basin area. In the reference well it is almost 2,700 feet thick. It thins to the east and is absent as a result of erosion on fault blocks associated with the uplift of the Central Basin platform. It is overlapped by Permian on the higher parts of this uplift. Similar highs with partially truncated sections are present elsewhere in the Delaware Basin area.

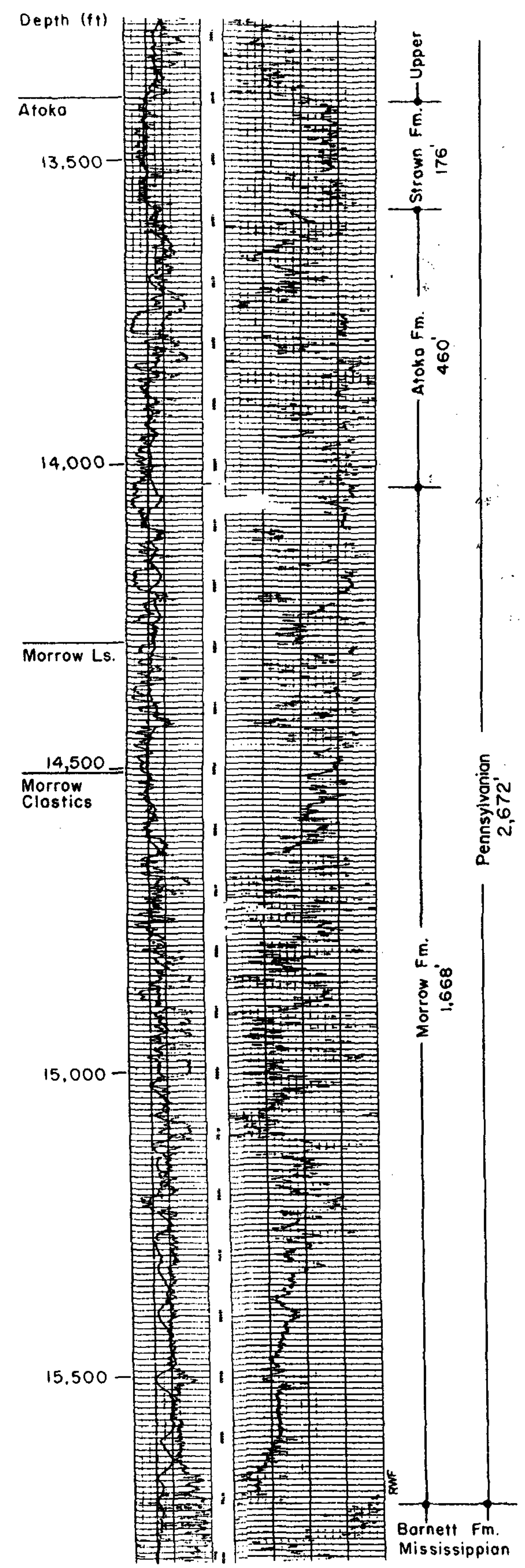


FIGURE 89—Sample gamma ray/sonic log of Pennsylvanian in Delaware Basin. Texas American No. 1 Todd, sec. 14, T23S, R31E, Eddy County.

Four producing-zone maps have been prepared for the Pennsylvanian (Figs. 90 through 93). The first includes Cisco and Canyon production and those fields that produce both from the Upper Pennsylvanian and Wolfcamp. These fields also are shown on the Wolfcamp map (Fig. 86). Figures 91 through 93 are for the Strawn, Atoka, and Morrow intervals. As noted in the discussion of the Wolfcamp there is a fairly well defined pattern of oil and gas production. This also is true for the Pennsylvanian and the approximate boundary is shown on each map. Almost all of the oil fields have limestone as the reservoir rock and the majority of the gas fields have sandstone. This seems to be a more significant factor than depth except in the deeper parts of the Delaware Basin. The occurrence of oil is more restricted in the Atoka and Morrow intervals than in the Strawn or Upper Pennsylvanian.

Areas for exploration are fairly well defined by established production. A wide variety of trap conditions exists. Most important are stratigraphic and combination stratigraphic-structural traps. Reefs, phylloid algal mats, and anticlines are locally important. Pennsylvanian rocks are absent on the Central Basin platform and in the northwestern part of the area on the Pedernal and Lower Pennsylvanian uplifts.

A broad east–west uplift occurred across central and parts of northern New Mexico in Late Mississippian–Early Pennsylvanian time. This resulted in the removal mostly of Mississippian strata that had overlapped Devonian and older sediments. This uplift may have extended somewhat farther south between Roswell and Carrizozo. South of this line it appears that a fairly complete section of Pennsylvanian was deposited. To the north on the early uplift successively younger rocks of Pennsylvanian age overlap onto the eroded Precambrian. It is this area to the north and northwest that served as a source for the clastic deltaic deposits in the Atoka and Morrow. In Late Pennsylvanian–Early Permian time, the main period of north–south faulting occurred that resulted in the Pedernal uplift and removal of the Pennsylvanian and in most cases older Paleozoic rocks from the southern part of this uplift. The potential for unconformity traps exists in the Pennsylvanian where it overlaps older rocks. In the southern part of the Pedernal uplift and on the Central Basin platform additional unconformity traps could be present in the Pennsylvanian beneath the Permian.

(Text continued on page 75.)

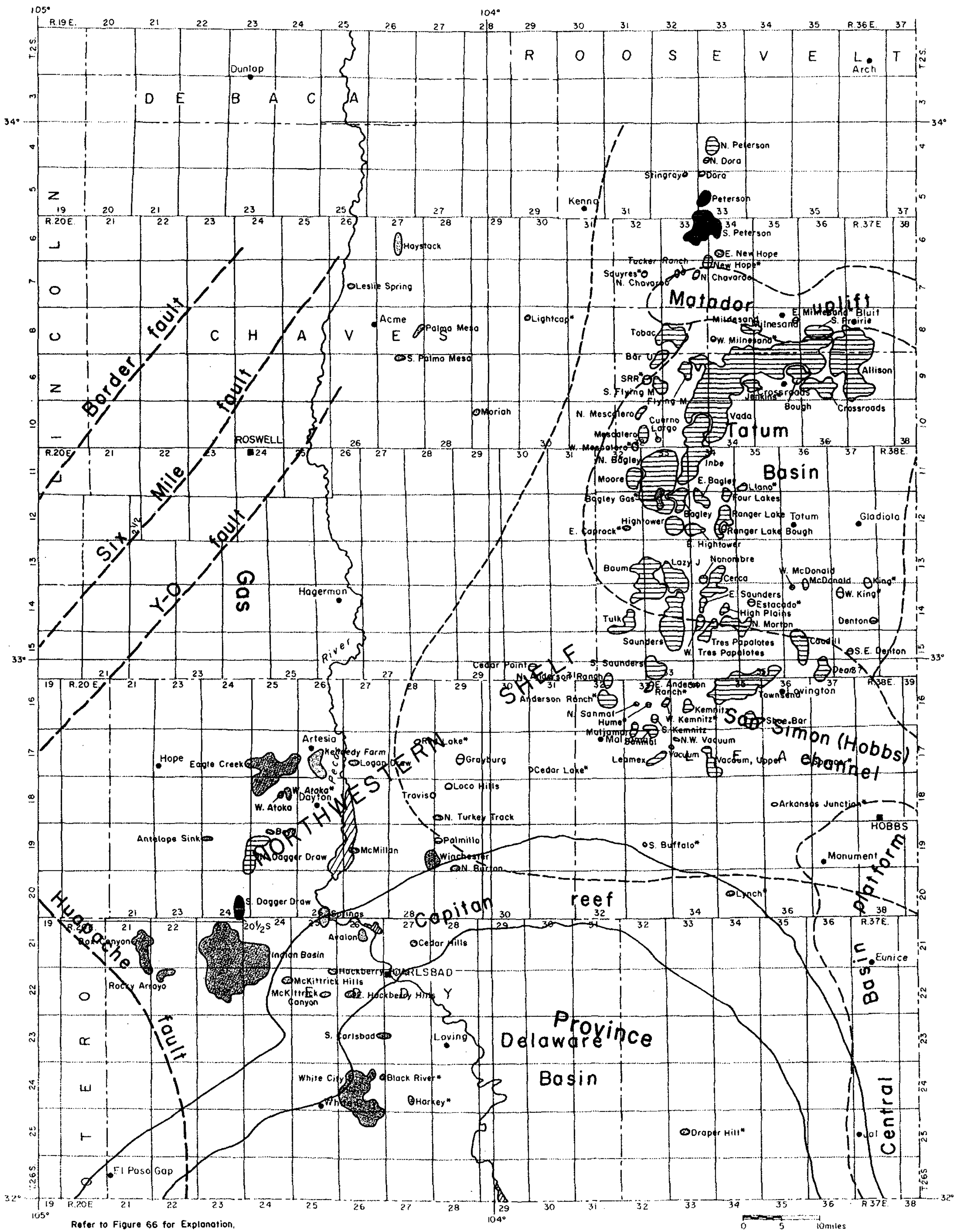


FIGURE 90—Oil and gas fields producing from the Permian-Pennsylvanian and Upper Pennsylvanian rocks.

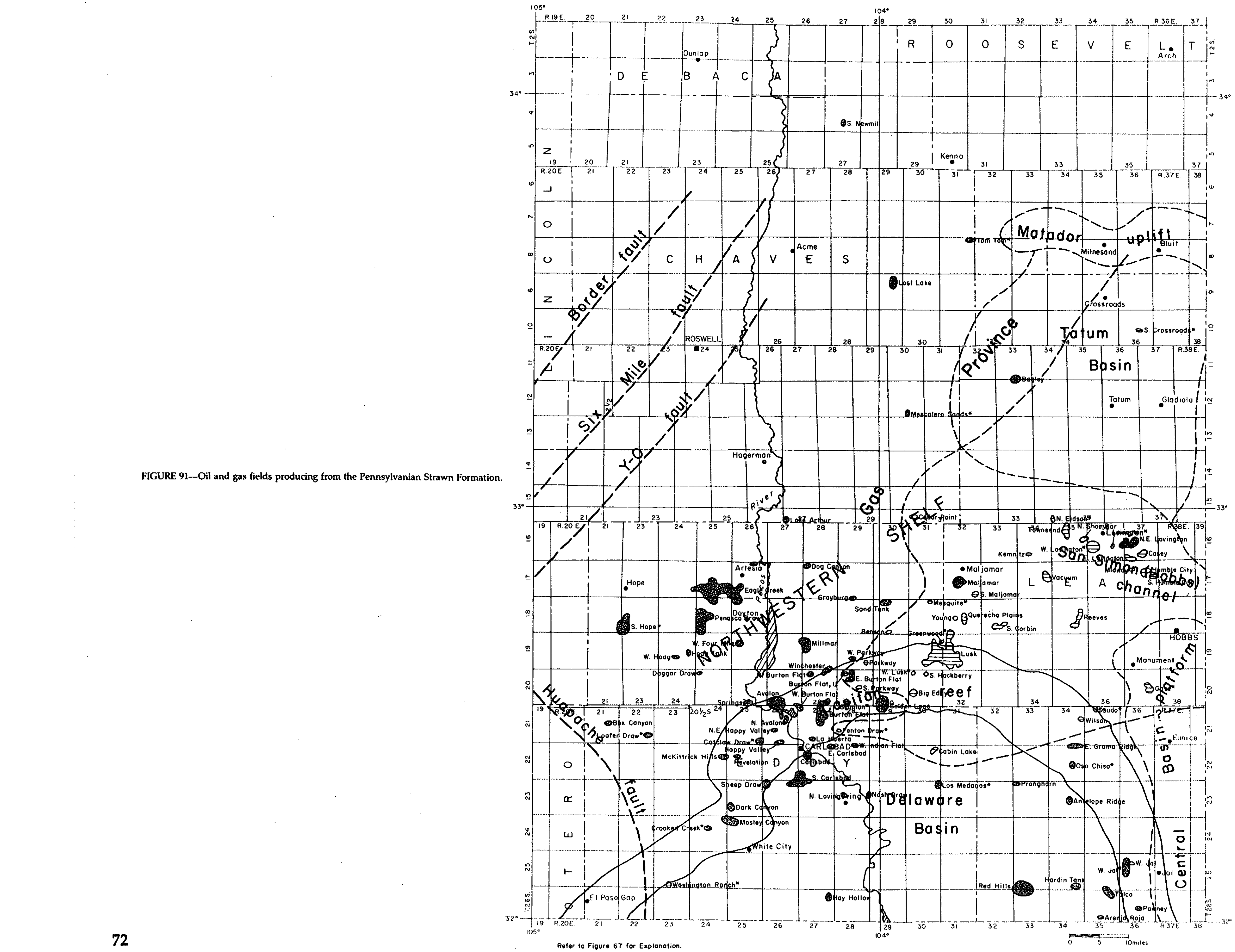
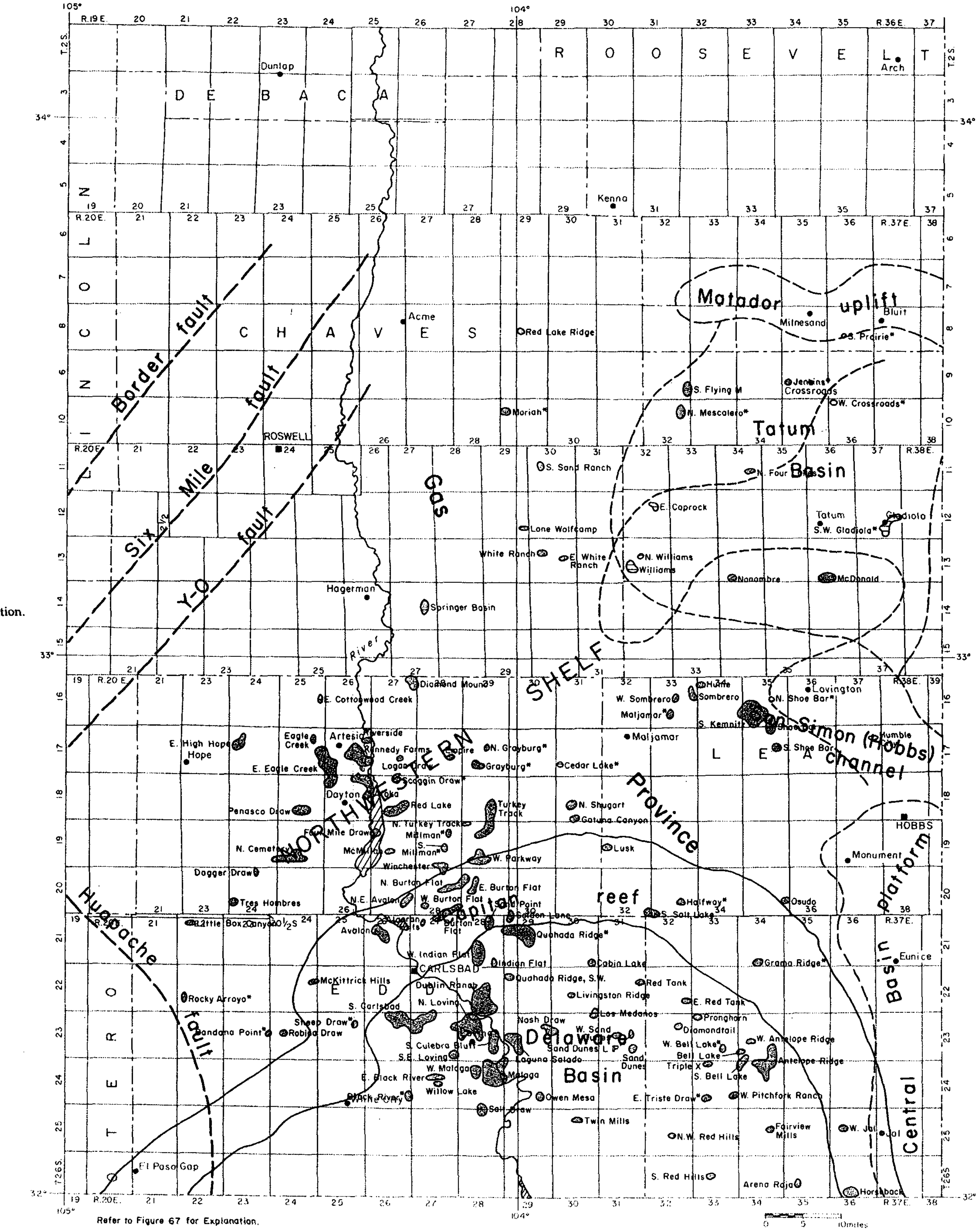


FIGURE 91—Oil and gas fields producing from the Pennsylvanian Strawn Formation.

FIGURE 92—Oil and gas fields producing from the Pennsylvanian Atoka Formation.



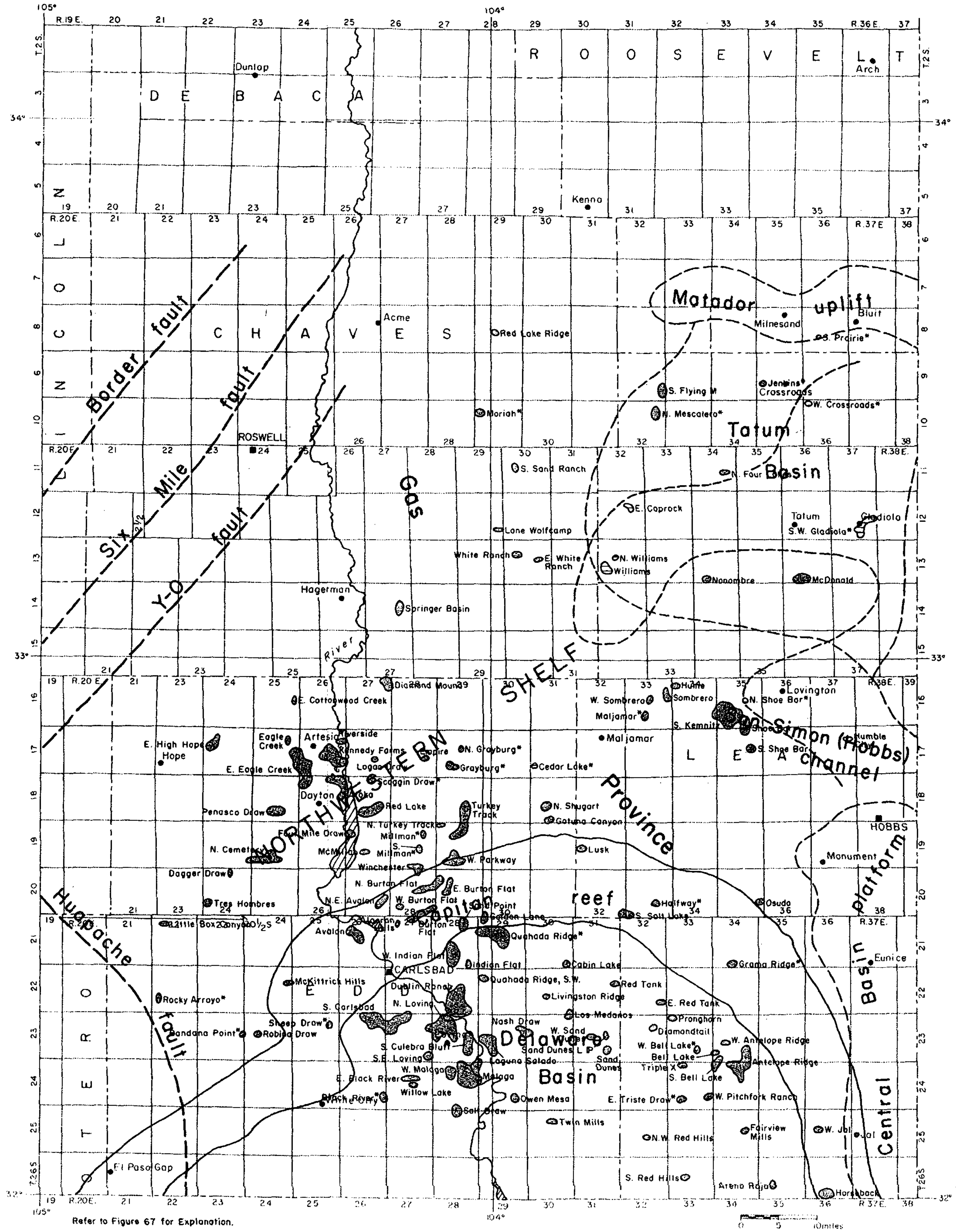


FIGURE 92—Oil and gas fields producing from the Pennsylvanian Atoka Formation.

Pre-Pennsylvanian stratigraphy and oil and gas fields—Rocks assigned to the Mississippian include a sequence of limestones referred to simply as Mississippian limestone and an overlying shaly interval called the Barnett shale. This follows the general oil-field usage in southeastern New Mexico. The top and base of the Mississippian limestone can be easily recognized, in most cases, in well samples and from mechanical logs. The contact between the Barnett shale and overlying Pennsylvanian rocks is less reliable. Chester is sometimes used for the Barnett section.

No attempt has been made to project into southeastern New Mexico the formations established by Laudon and Bowsher (1941, 1949) or Pray (1961) in the Sacramento Mountains to the west. It appears that the Barnett is equivalent to some degree with the Rancheria and Helms Formations of Meramec and Chester age, and the underlying limestone is equivalent with the Lake Valley Formation of Osage age (Armstrong et al., 1980).

The Barnett consists of brown, partly silty shale. It does not appear to be present in the Gulf Caprock well (T14S, R31E) but in part the limestones are considered Chester (Fig. 94). In the Texas American Todd test (Fig. 95), 176 feet have been assigned to this interval. It is on the order of 150 to 300 feet thick in the southern part of the area and may thicken somewhat to the west of the Pecos River. The Mississippian limestone sequence consists of brown cherty limestone with some interbedded gray shale. The interval is 1,071 feet thick in the Gulf Caprock well and 457 feet thick in the Texas American Todd well reflecting the regional southward thinning. In the Honolulu Malco well in T14S, R28E the Barnett is not present and the limestone interval has thinned to 661 feet (Fig. 96).

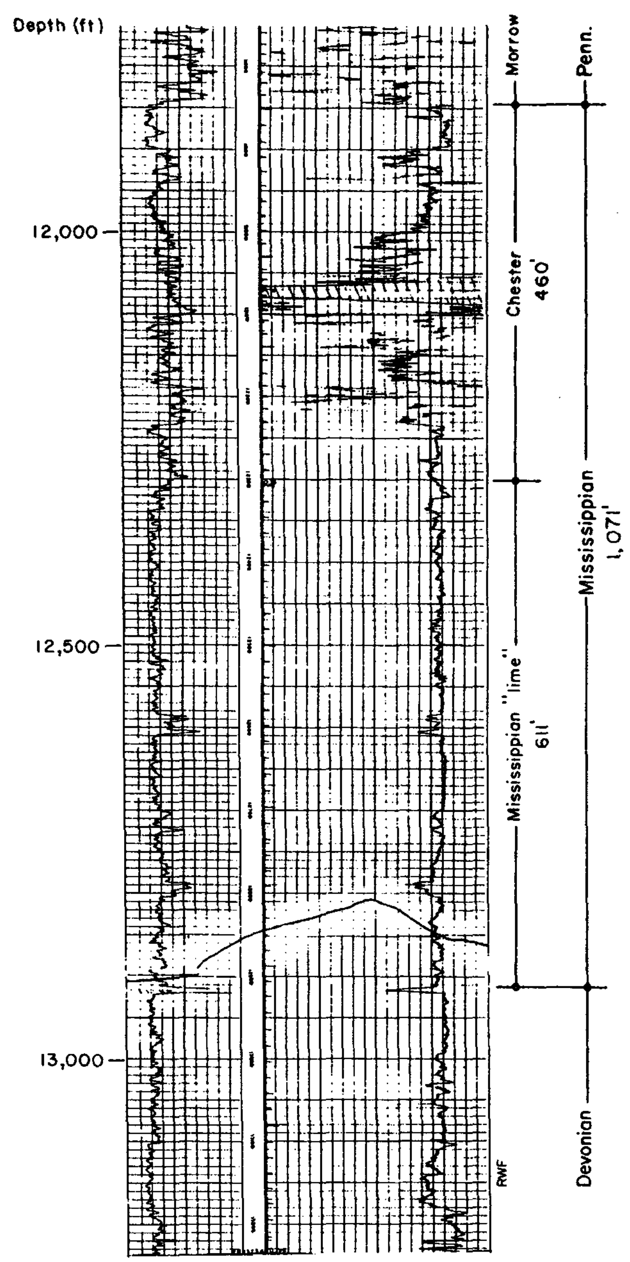


FIGURE 94—Sample gamma ray/sonic log of Mississippian and Upper Devonian on Northwest shelf. Gulf No. 1 Caprock, sec. 34, T14S, R31E, Chaves County.

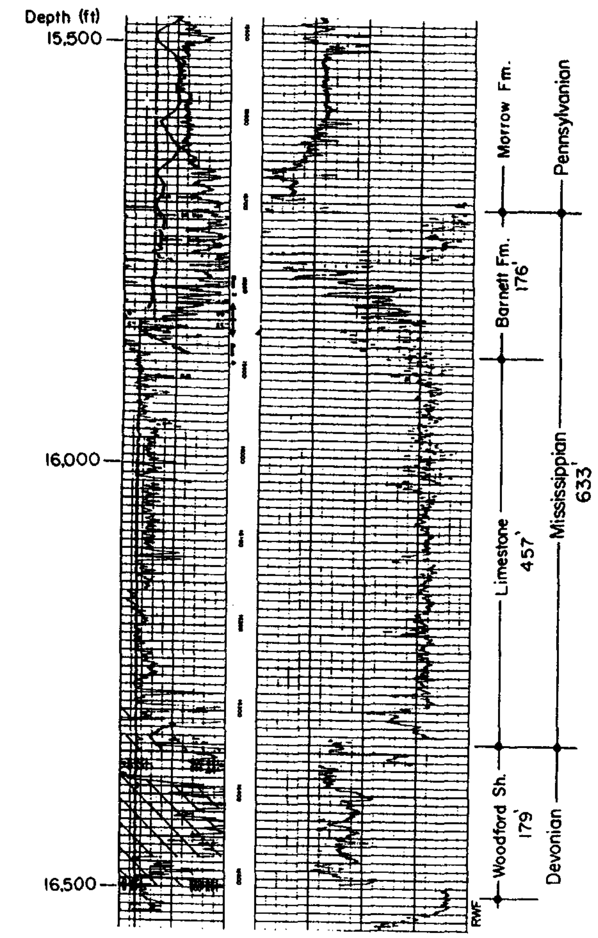


FIGURE 95—Sample gamma ray/sonic log of Mississippian and Upper Devonian in Delaware Basin. Texas American No. 1 Todd, sec. 14, T23S, R31E, Eddy County.

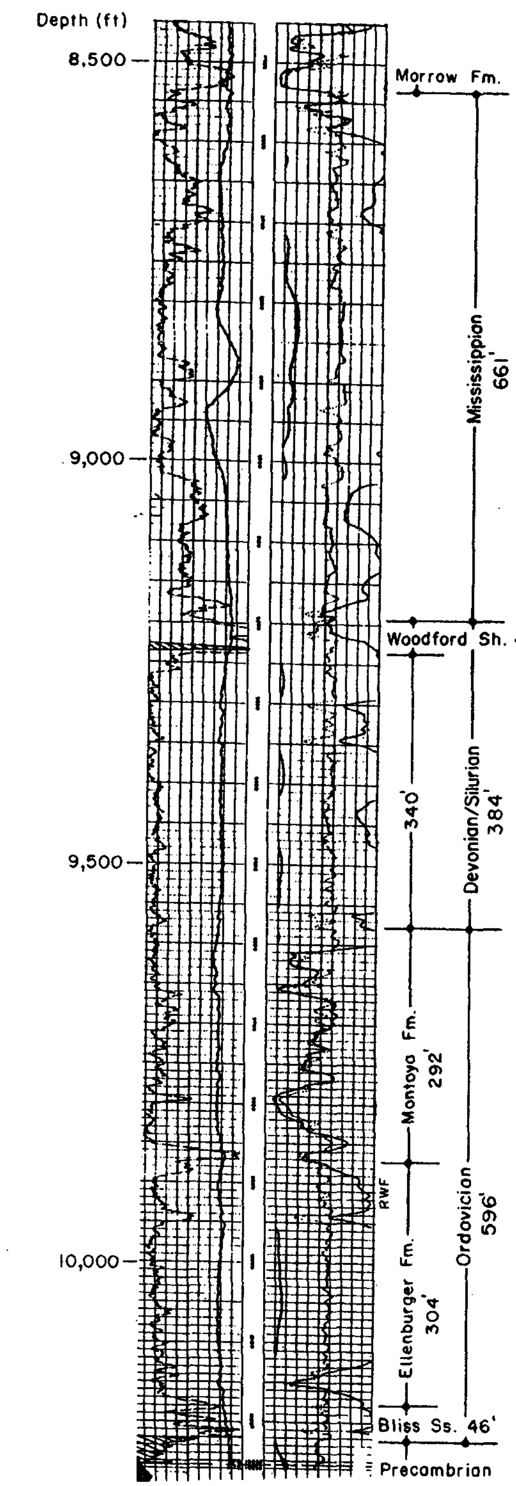


FIGURE 96—Sample gamma ray/resistivity log of Mississippian through Precambrian on Northwest shelf. Honolulu No. 1 Malco, sec. 15, T14S, R28E, Chaves County.

Only a few oil and gas fields have been discovered in rocks of Mississippian age and none have proven to be very significant. All production is on the Northwest shelf and most of it is in the eastern part of this area (Fig. 97). Here there is also a distribution of gas and oil with gas occurring to the south and west. Although many wells have penetrated the Mississippian and have tested the Devonian on the Northwest shelf, large areas remain unevaluated particularly to the south where most wells are Pennsylvanian or shallower tests. Mississippian and other lower Paleozoic production is associated with faulted anticlinal structures.

The Devonian consists of an upper, dark-brown to black, bituminous shale called the Woodford and an underlying carbonate sequence consisting mostly of dolomite but generally having some limestone just beneath the Woodford (Figs. 96 and 98). Included with the lower carbonate sequence are more dolomites that generally are considered of Silurian age and often are correlated with the Fusselman Dolomite. The difficulty in separating the carbonate sequence has been discussed by numerous geologists. Gibson (1965) used the term Hunton terrane for the carbonate sequence because of the varied terminology in the Permian Basin. McGlasson (1967) suggested that the carbonate rocks in the Delaware Basin of New Mexico are restricted to Fusselman with rocks of Devonian age found only at the southern end of the Central Basin platform in Lea County. Many geologists restrict the Devonian to the Woodford interval.

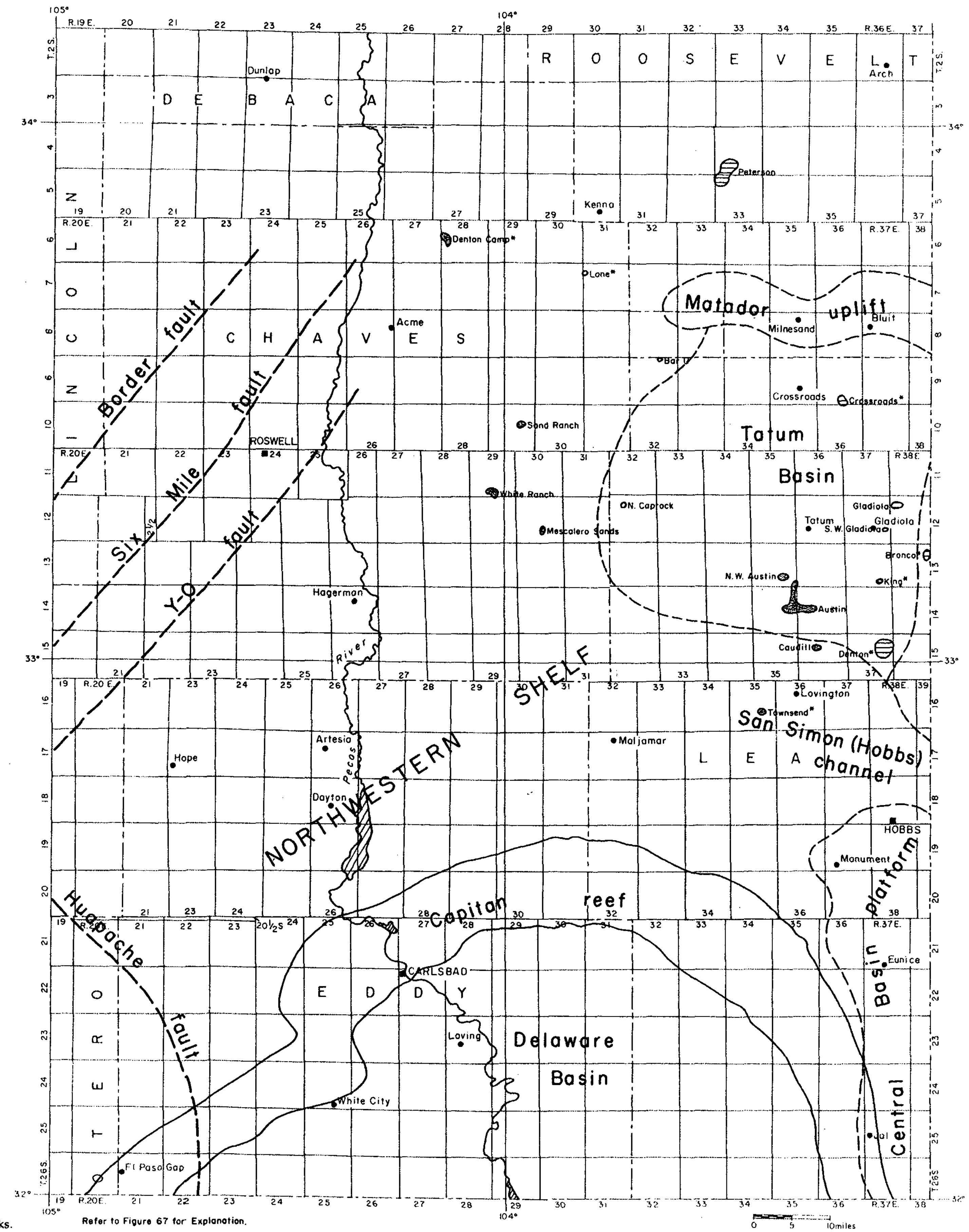


FIGURE 97—Oil and gas fields producing from Mississippian rocks.

Oil is found in the Devonian and Silurian on the Northwest shelf, particularly the Tatum Basin area, and the Central Basin platform (Fig. 99). Gas is found in these beds in the deeper parts of the Delaware Basin and in a few other areas at shallower depths. The typical field has an anticlinal or faulted anticlinal trap, the reservoir rock is dolomite with porosity and permeability controlled by fracturing and vugs, and the pay zone is immediately below the pre-Woodford unconformity or a thin limestone caprock. Exceptions to this are fault traps and unconformity traps where Silurian–Devonian rocks are truncated updip beneath a seal of Permian rocks. The pay zone may be as much as 200 feet below the Woodford shale, or a second pay zone may be present in the lower part of the interval. The necessity of an anticlinal trap has been noted by Salisbury (1968), Gibson (1965), Holmquest (1965), and Wright (1963) although Wright suggested the possibility of stratigraphic traps where there is a facies change from dolomite to limestone. Most of the productive anticlines in southeast New Mexico have steeply dipping limbs and exhibit considerable closure. A large area remains for exploration of Silurian–Devonian rocks, particularly for gas, in the southern part of the southeast region.

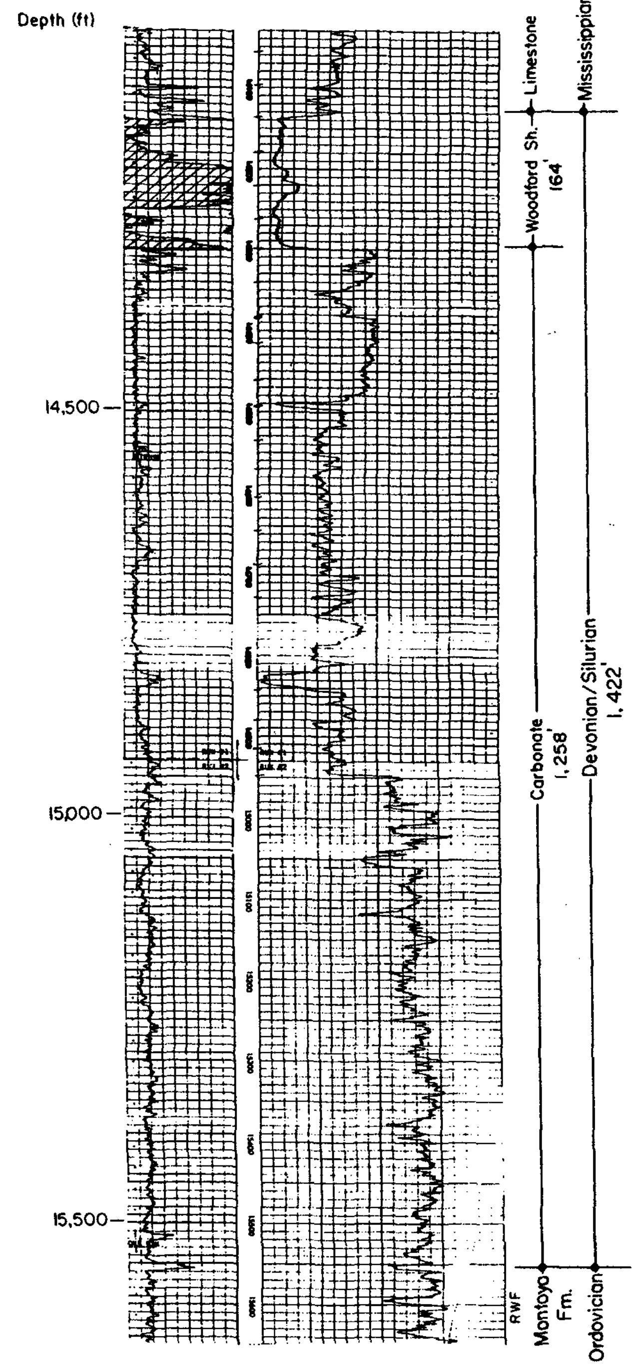


FIGURE 98—Sample gamma ray/neutron log of Devonian in Delaware Basin. Texas No. 1 Richards, sec. 25, T20S, R32E, Lea County.

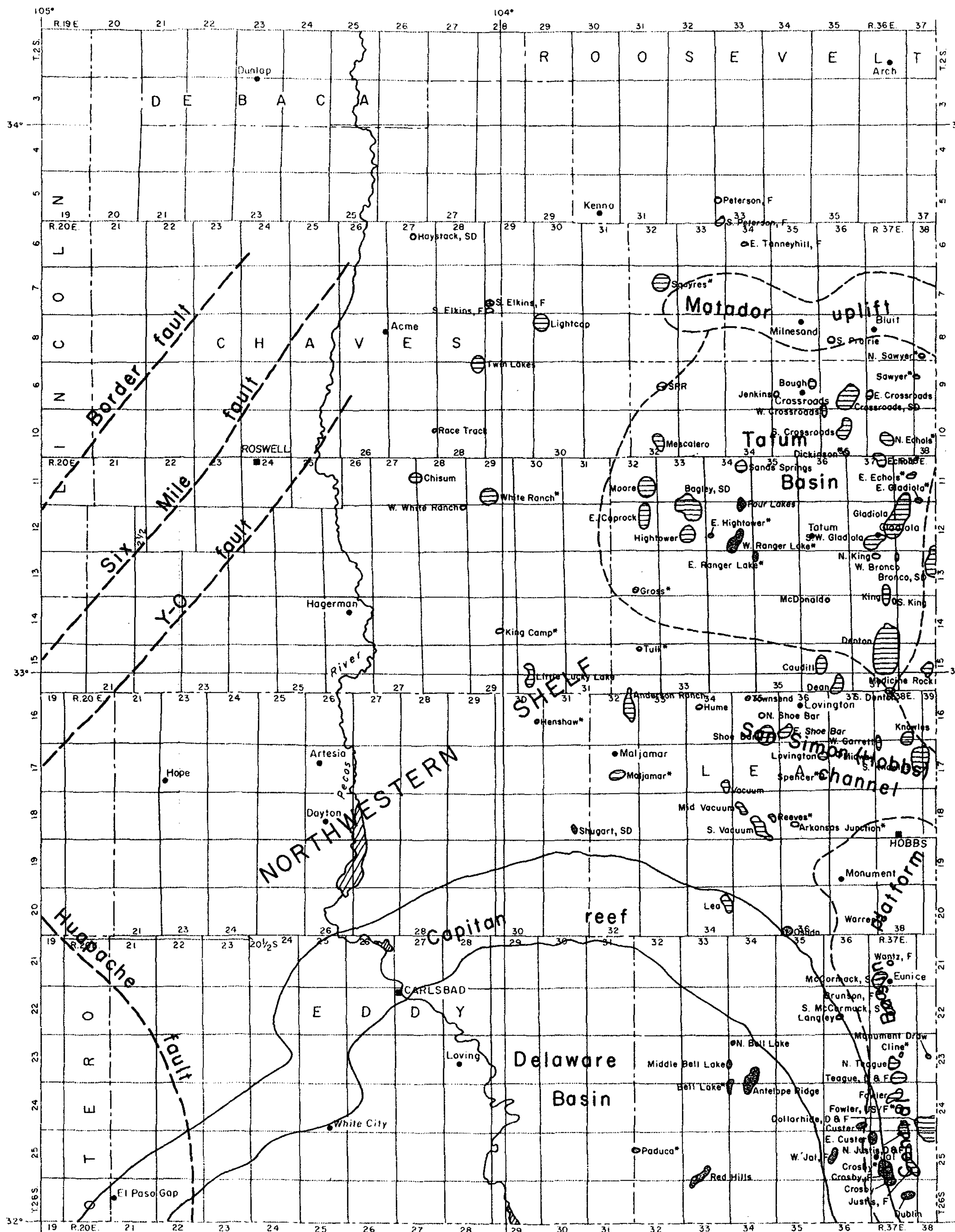


FIGURE 99—Oil and gas fields producing from Silurian and Devonian rocks. S, Silurian; D, Devonian; F, Fusselman.

Ordovician rocks are divided into the Montoya, Simpson, and Ellenburger Groups (Figs. 96 and 100). Where it crops out west of the southeast region, the Montoya has been subdivided from youngest to oldest into the Cutter, Aleman, and Upham Formations and Cable Canyon Sandstone. Normally these names are not used in the subsurface although an examination of the section penetrated in wells suggests possibilities of suitable correlations with outcrop sections. With the exception of the Cable Canyon, the Montoya consists mostly of dolomite with locally abundant chert. In the southernmost part of the area it is commonly limestone suggesting a facies change similar to that observed in the Franklin and San Andres Mountains. The Montoya is 349 feet thick in the Texas Richards well (T20S, R32E) and thins to 292 feet in the Honolulu Malco well (T14S, R28E).

The Simpson Group unconformably overlies the Ellenburger and in turn is unconformably overlain by the Montoya. It consists of alternating beds of limestone, sandstone, and green to gray shale. It is 323 feet thick in the Texas Richards well and is absent in the Honolulu Malco well in T14S, R28E. Most of the oil found in the Simpson Group occurs in the McKee Sandstone Member of the Tulip Creek Formation. Some oil has been produced from the Waddell Member of the McLish Formation and from the Connell Sandstone of the Oil Creek Formation.

According to Gibson (1965) Simpson reservoirs are of two types: sandstones confined by shales, and truncated sand bodies unconformably overlain by a suitable caprock. In both cases traps are the result of anticlinal folding. All currently known fields are anticlinal, commonly faulted or truncated, and in the latter case unconformably overlain by rocks of Permian age. The blanket-type sandstones of the Simpson would seem to require prominent structures to provide adequate traps. West of the Central Basin platform and at the northern limit of the Simpson the interval thins beneath the pre-Montoya unconformity, and where unfractured the Montoya could be an effective caprock.

The Ellenburger Group consists of dolomite with some chert and locally sandy dolomite. The Ellenburger is correlative with the El Paso Group of southern New Mexico and the Franklin Mountains of Texas. It is unconformably overlain by the Simpson in the south and the Montoya in the north. Successively older beds of the Ellenburger underlie this unconformity from south to north. In some areas there is an interval of sandstone and a conglomerate at the base of the Ellenburger that is considered correlative with the Bliss Sandstone of south-central New Mexico.

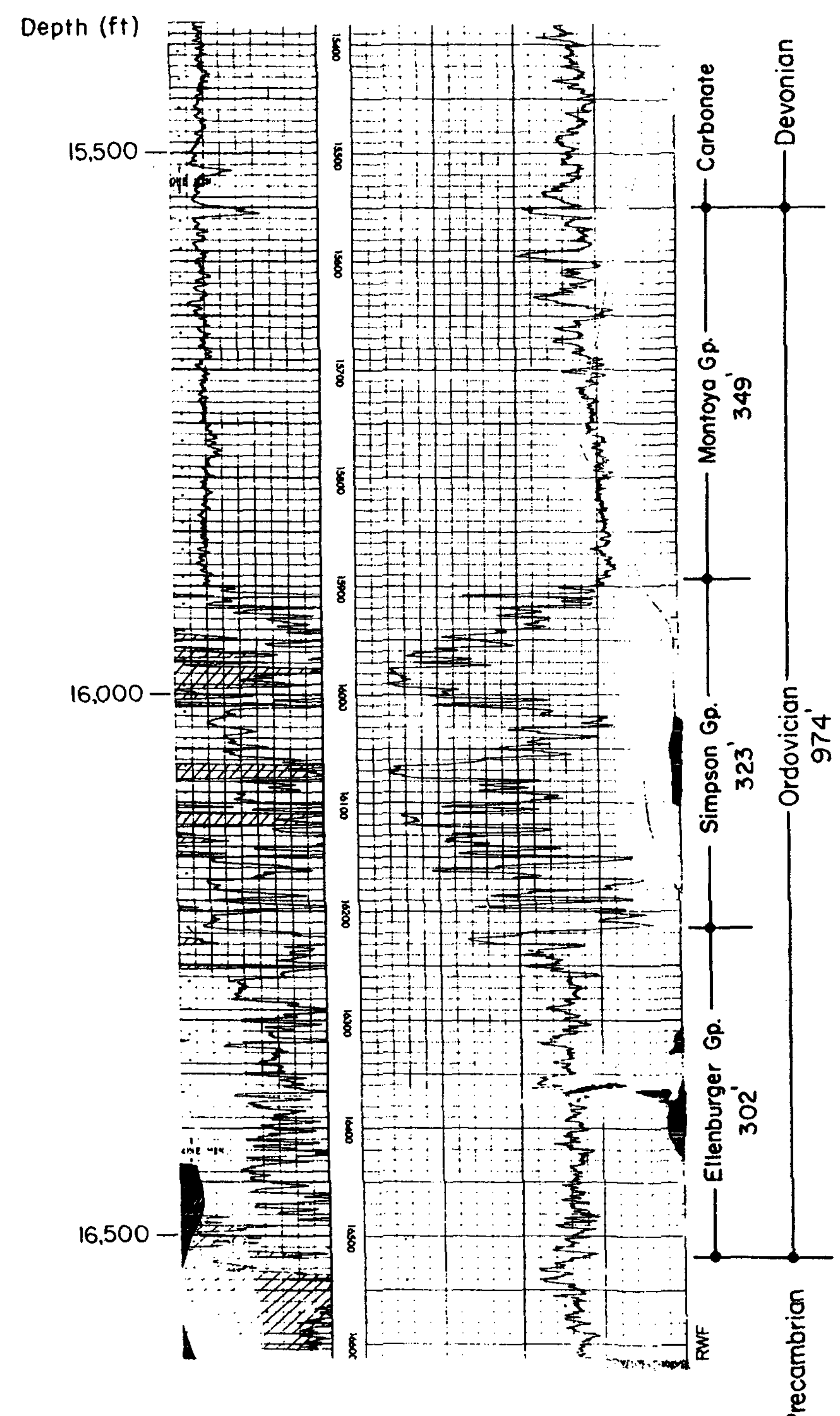


FIGURE 100—Sample gamma ray/neutron log of Ordovician and Precambrian in Delaware Basin. Texas No. 1 Richards, sec. 25, T20S, R32E, Lea County.

Almost all Ordovician oil and gas fields are located on or adjacent to the Central Basin platform (Fig. 101). There are, however, three fields to the north that give some hope for additional discoveries away from established production. Deep exploration for gas west of the platform has been done in only a few wells.

Based on its exploration history the Montoya would seem to have the least potential of Ordovician reservoirs. Existing fields are truncated anticlines, and permeability appears to be closely related to fracturing. Most seals consist of Permian rocks overlying truncated Montoya beds. There may be some potential for stratigraphic traps where dolomite interfingers with limestone.

Like the Montoya and Simpson, Ellenburger production is encountered in dolomite reservoirs on anticlines or erosionally truncated anticlines. Porosity is primarily controlled by fractures with vugs and intergranular porosity contributing to the overall pay zone.

Gibson (1965) believes that there is a common paleoaquifer in the upper part of the Ellenburger that was developed by ground-water solution during the long period of subaerial erosion that preceded the deposition of the Simpson. He further suggests that any indigenous oil escaped during the period of erosion and that the oil and gas in Ellenburger reservoirs entered after formation of the reservoir and deposition of the overlying sediments. If some fields are associated with a post-Ellenburger–pre-Simpson unconformity, and structures are in part of middle Ordovician age, the potential for discovering accumulations that are not associated with the Central Basin platform would appear attractive.

According to Jones and Smith (1965) it appears that some Ellenburger and Simpson oils have a common origin, and that the source of these oils is present in shales in the Simpson. Other oils appear to be similar to Devonian, Pennsylvanian, and Wolfcamp oils, and on the higher parts of the Central Basin platform oil in the Ellenburger is Simpson oil diluted primarily with oil from the Pennsylvanian and Wolfcamp. From the foregoing, any oil or gas present in the Ellenburger away from the Central Basin platform would either have to be indigenous or derived from the overlying Simpson. Further, the trapping mechanism would seem to require an anticlinal fold or possibly faulting. Although the tightly folded, high-closure structures of the Central Basin platform may not be necessary, some structural displacement may be required to develop suitable fracture porosity. Other possible traps include favorable mound or reef structures surrounding Precambrian highs, selective dolomitization, and local unconformity traps beneath the Simpson.

The similar tectonic and stratigraphic history of the Central Basin platform and the Pedernal uplift makes the area west of the Delaware Basin attractive for exploration of Ordovician rocks.

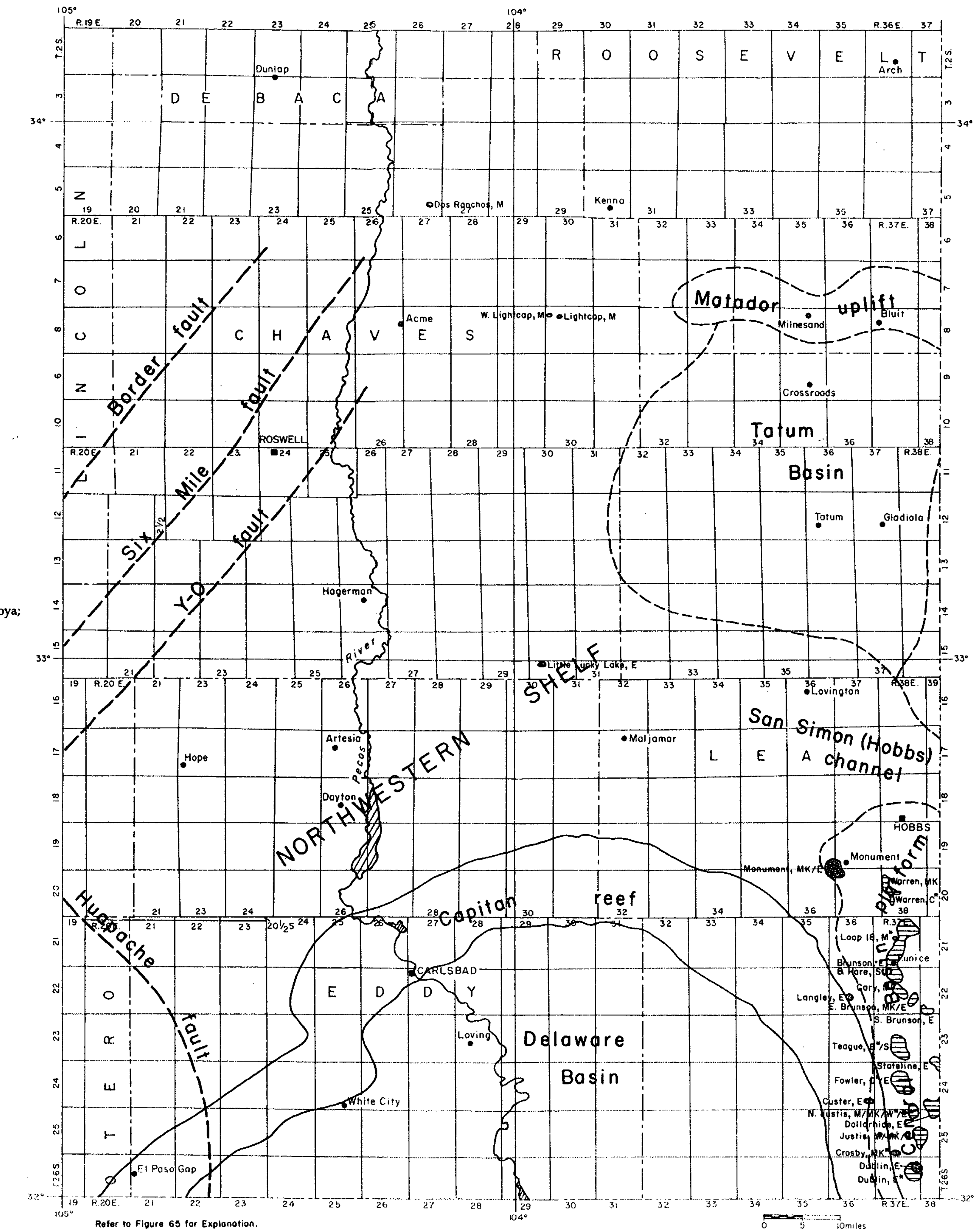


FIGURE 101—Oil and gas fields producing from Ordovician rocks. M, Montoya; S, Simpson; MK, McKee; W, Wadell; C, Connell; E, Ellenburger.

Target exploration area 12, Northwest shelf—The Northwest shelf encompasses a large area north of a line that roughly coincides with US 62–180 between Hobbs and Carlsbad, a line that is the buried front of the Permian Capitan reef. The boundary continues southwest of Carlsbad to the New Mexico–Texas State Line along the exposed front of this reef in the Guadalupe Mountains. The northern limit merges into the Tucumcari–Palo Duro Basins along an east–west trend paralleling US 60–84 between Clovis and Fort Sumner. The eastern limit is the New Mexico–Texas State Line and the west margin of the subsurface Central Basin platform.

Objectives—Rocks ranging from Triassic through Ordovician are present (Hills and Kottlowski, 1983). Strata within the Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Permian produce oil and gas. The most prolific production is from Permian, Pennsylvanian, and Devonian rocks in Lea, Chaves, and the southeast part of Roosevelt Counties. Mississippian production is least valuable. This region contains several of the nation's giant oil fields. One of these, the Empire–Abo field, is a stratigraphic trap with more than 250 million barrels of recoverable oil in a Permian reef with up to 700 feet of porosity (LeMay, 1972). The north-central part of the area is the site of the extensive Early Permian Abo gas field. Together with the adjoining Central Basin platform target exploration area 13, most of New Mexico's oil and large volumes of gas are produced in this region.

Although it is part of a mature producing province occupying a portion of the depositional and structural shelf north of the Delaware Basin, this region presents many opportunities for the discovery of new reserves, particularly in the lower Paleozoics underlying extensive production in Pennsylvanian and Permian beds. Besides the occurrence of porous zones in marine-shelf and transitional units, rocks of Ordovician through Early Pennsylvanian age are truncated in a northerly and westerly direction and dip up toward the Pedernal and Roosevelt–Marathon uplifts. This is a primary area for encountering unevaluated and subtle stratigraphic traps, stratigraphic traps with structural assists, and structural traps.

Discussion—Pennsylvanian seas that entered the state from south of this area encroached on low-relief topography that permitted the development and preservation of deltas and offshore bars on the northern and northwestern margins of the incipient Delaware Basin. This was followed by deposition of shelf carbonates on the basin margin and dense dark-colored shales in the deeper trough as Pennsylvanian seas covered most of the state. This relative depositional stability was interrupted in Middle Pennsylvanian by the uplift of the Pedernal Mountains in central New Mexico and the assertion of the Central Basin platform to the east.

Fortuitous circumstances of water depth, temperature, light, and salinity together with relative equilibrium on the shelves surrounding the horseshoe-shaped basin permitted the flourishing of reef organisms that grew in pace with the slowly subsiding shelf areas during much of Pennsylvanian and most of Permian time. That these conditions were preserved in the stratigraphic column to the present with their hydrocarbon wealth intact is remarkable.

It would also be remarkable and surprising if at least some of these structural and stratigraphic features were not repeated elsewhere in the less explored part of this region. For a structural element as prominent as the Central Basin platform to occur unaccompanied by less profound but depositionally influential features is unlikely.

This so-called "mature" province is in reality a relatively unexplored frontier region. The history of the search for oil is replete with examples of seemingly thoroughly developed petroleum provinces being rejuvenated to another exploration cycle by a serendipitous or systematic discovery. It also provides ample evidence that the best place to look for other big fields is where they are known to occur. If history repeats itself, this region hosts a number of undiscovered large oil fields.

Cross section D–D′ (Fig. 102) is a diagrammatic illustration of the geologic conditions. For an excellent regional overview of Pennsylvanian and Lower Permian deposition, see Meyer (1966).

Target exploration area 13, Central Basin platform—This region is in the extreme southeast corner of New Mexico south of Tatum and US-380. It includes the state's largest concentration of petroleum-dependent communities, Hobbs, Lovington, Eunice, and Jal. About 85 miles long in a north–south direction and about 20 miles wide, its approximately 1,700 square miles contain a large part of New Mexico's petroleum wealth.

Objectives—Up to 6,500 feet of Paleozoic strata from Cambrian through Pennsylvanian are present in the Delaware Basin west of the Central Basin platform. All of these predominantly marine strata are truncated on the flanks of the platform. Permian rocks covering its core of Precambrian and older Paleozoics are responsible for much of New Mexico's cumulative oil production. Eroded porous suites surrounding the platform offer potential for regional hydrocarbon accumulations if lessees holding acreage by production can be persuaded to evaluate their leases vertically.

Discussion—Although it is part of the Permian Basin, the Central Basin platform is a profound structural element that influenced sedimentation on and around it in Pennsylvanian and Permian time and the accumulation of oil and gas on and near it through the present. Adams (1965) offers explanations of regional tectonism that formed the Permian Basin and its appurtenant structural elements. He suggests that the Central Basin platform originated from compressional stresses related to crustal shortening requiring adjustments to compensate for a deeply sagging basin. He assumes an almost catastrophic foundering of the basin during Permian Wolfcamp time that squeezed the Central Basin platform horst upward several thousands of feet to separate the Delaware and Midland Basins and coincidentally stripped from the platform many of the pre-existing Paleozoic rocks.

Figure 103 shows the approximate configuration of the truncated Paleozoic rocks beneath the Permian in target exploration area 13. Cross section D–D′ (Fig. 102) shows simplified geologic relationships.

Target exploration area 14, Delaware Basin—This region encompasses the Permian Basin south and east of Carlsbad in Eddy and Lea Counties except the Central Basin platform area, which was considered separately as target exploration area 13.

Objectives—Rocks from every Paleozoic system are present (Hills and Kottlowski, 1983). All of these are productive on the contiguous Northwest shelf and Central Basin platform. Although significant reserves of natural gas have been developed in recent years in Pennsylvanian strata in the deeper part of the Delaware Basin, operators have had limited success finding production in other horizons.

Discussion—Deep wells drilled to test beds beneath the Permian and Pennsylvanian are scarce. A stratigraphic column of primarily marine rocks in the lower Paleozoic Mississippian, Devonian, Silurian, and Ordovician ranging in thickness from a wedge edge on the west to more than 6,000 feet in the south and east is present in this area. Many of these beds are prolific producers in the Midland Basin segment of the Permian Basin in west Texas. An overlying aggregate thickness of up to 15,000 feet of Permian rocks in the deeper basin is a deterrent to testing these strata. The thick Permian section is itself sparsely drilled in the deeper basin.

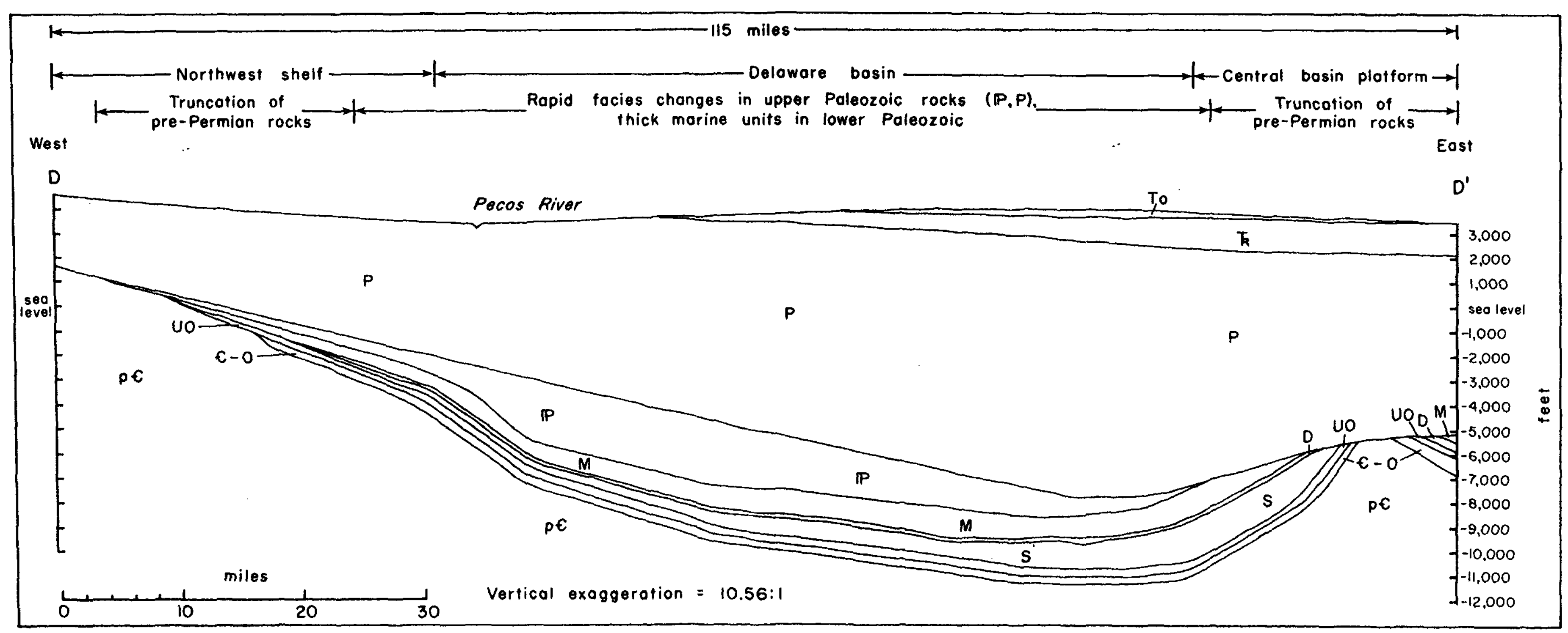


FIGURE 102—Cross section D–D′. Schematic structural–stratigraphic relationships in southeast New Mexico (see Fig. 29 for location). To, Tertiary Ogallala Fm.; Ꞧ, Triassic; P, Permian; IP, Pennsylvanian; M, Mississippian; D, Devonian; S, Silurian; UO, upper Ordovician; €–O, Cambrian–Ordovician; p€, Precambrian.

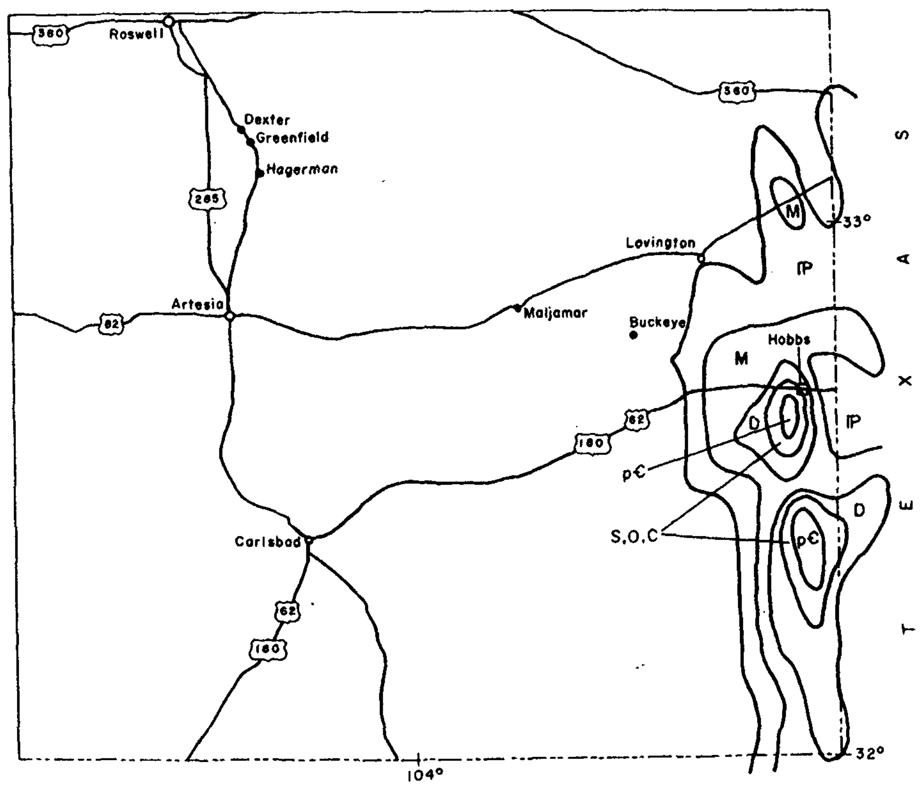


FIGURE 103—Central Basin platform, pre-Permian outcrop map (Oriel et al., 1967). IP, Pennsylvanian; M, Mississippian; D, Devonian; S, Silurian; O, Ordovician; Є, Cambrian; pЄ, Precambrian.

South-central region

Target exploration area 15, Otero Mesa platform—The configuration and location of this area is related primarily to subsurface features. The buried Pedernal uplift on the north and east marks those limits, and an arbitrary line close to a break in the structural platform where it joins the Tularosa Basin forms the west line. The New Mexico–Texas State Line is the south border. There are about 1,100 square miles within these boundaries.

Objectives—Rocks of Pennsylvanian, Mississippian, Devonian, Silurian, Ordovician, and Cambrian are truncated in the east part of the area against the north–south axis of the Pedernal uplift. Two to three thousand feet of Permian sediments cover these strata and the Precambrian core of the uplift.

Discussion—The area is sparsely drilled. It is likely that a number of the wells were located on the basis of surface or subsurface expressions of anticlinal structure. Proximity to the distal end of the Pedernal uplift means that its tectonic influence may have caused the development of subordinate structures of sufficient magnitude to remove all or parts of the sedimentary cover overlying them. If so, these structures reflect the relict Pennsylvanian–Permian Pedernal structure and not the more recent tectonics, and their axis may lack the favorable sedimentary package that will be found flanking them.

Structural assists may be necessary for entrapment of hydrocarbons in this area, but it is suggested that detailed and sophisticated analysis of geophysical data to detect thicker sections away from anticlinal axis and truncation of units on the periphery of these features may be rewarding. Hydrodynamically tilted oil–water contacts may also influence exploration targets in this region.

Schematic cross section E–E′ (Fig. 104) crosses a part of this region. Hayes (1964), King (1945), Kottlowski (1965), and Meyer (1966) offer additional detail on the structure and stratigraphy of this area. Black (1975) presents insight into the oil and gas potential.

Target exploration areas 16, 17, and 18, Tularosa Basin—The Tularosa structural basin occupies a large region extending from a point just south of Carrizozo to the New Mexico–Texas State Line. It is bounded (from north to south) by the Sierra Blanca, Sacramento Mountains, and Otero platform on the east and (from south to north) by the Franklin, Organ, San Andres, and Oscura Mountains on the west, an area of about 3,300 square miles. It is the site of the depositional Orogrande Basin that accumulated thick suites of Pennsylvanian and Permian rocks during those periods.

Although it is divided into three segments (south, central, and north) on the target exploration areas map (Fig. 29) because of structural and stratigraphic differences that are discussed separately, the Tularosa Basin is treated as a single entity below to avoid repetition.

Objectives—The entire Paleozoic era is represented in the rocks of the basin. With the exception of the predominantly dark gray and green shales of the Devonian, all are potential reservoirs. Dark-gray to black shales that may be important source rocks are present in the Devonian, Mississippian, Pennsylvanian, Permian (locally), and Cretaceous (locally).

Discussion—The stratigraphy of the Tularosa Basin has been examined in great detail because of the excellent exposures in the mountains bounding it. These data, supplemented with information from a relatively small number of wells, make the stratigraphic framework fairly well known. Because of the ubiquitous nature of the lower Paleozoics throughout southern New Mexico west of the Pedernal uplift and because of the unique suite of Pennsylvanian and Permian sediments furnished to the Orogrande depositional basin then occupying the region, it is appropriate to supplement the stratigraphic descriptions presented with the System maps.

The following is a summary from an unpublished report by Grant (1983):

Stratigraphy—Mesozoic rocks—In contrast with northern New Mexico where thousands of feet of Mesozoic rocks dominate the stratigraphic column, the Tularosa Basin has no Jurassic rocks and the Triassic is represented by only very thin remnants in the northern part. However, as much as 2,000 feet of Cretaceous may be present in the Carrizozo–Sierra Blanca–Three Rivers region of the northeastern Tularosa Basin.

Permian rocks: Bursum–Hueco–Abo–Yeso–San Andres—The combined thickness of all the Permian rocks exceeds 4,000 feet in the northern part of the Tularosa Basin, west of Carrizozo, thinning rapidly to about 2,000 feet of predominantly Lower Permian Bursum–Hueco at the southern end of the basin.

The Bursum Formation is the transitional unit straddling the Permian–Pennsylvanian boundary. This unit consists of interbedded limestones, red and gray shales, sandstones, and limestone conglomerate, with red shale and sandstone increasing upward. This change reflects the increasing influence of the Pedernal uplift as erosion stripped older Paleozoic strata exposing the Precambrian core. These sediments were transported into the Orogrande Basin and redeposited in the shallow Permian sea that occupied much of what is now the Tularosa Basin. In the northern Sacramento Mountains, this formation undergoes rapid facies changes. Foster (1978) reports that at one site the section changes in a distance of one and half miles from an open-marine environment with fringing carbonate reefs to a terrestrial floodplain.

Above the Bursum is a thick sequence of sandy marine limestones in the south that intertongues with a thick suite of continental red beds composed of shale, siltstone, sandstone, and arkosic conglomerates in the north. These strata, the limestones of the Hueco Formation and the red beds of the Abo Formation, are contemporaneous over most of the Tularosa Basin. The flood of Abo clastics introduced by numerous streams draining the Pedernal region periodically overwhelmed the shallow Hueco sea. The Early Per-

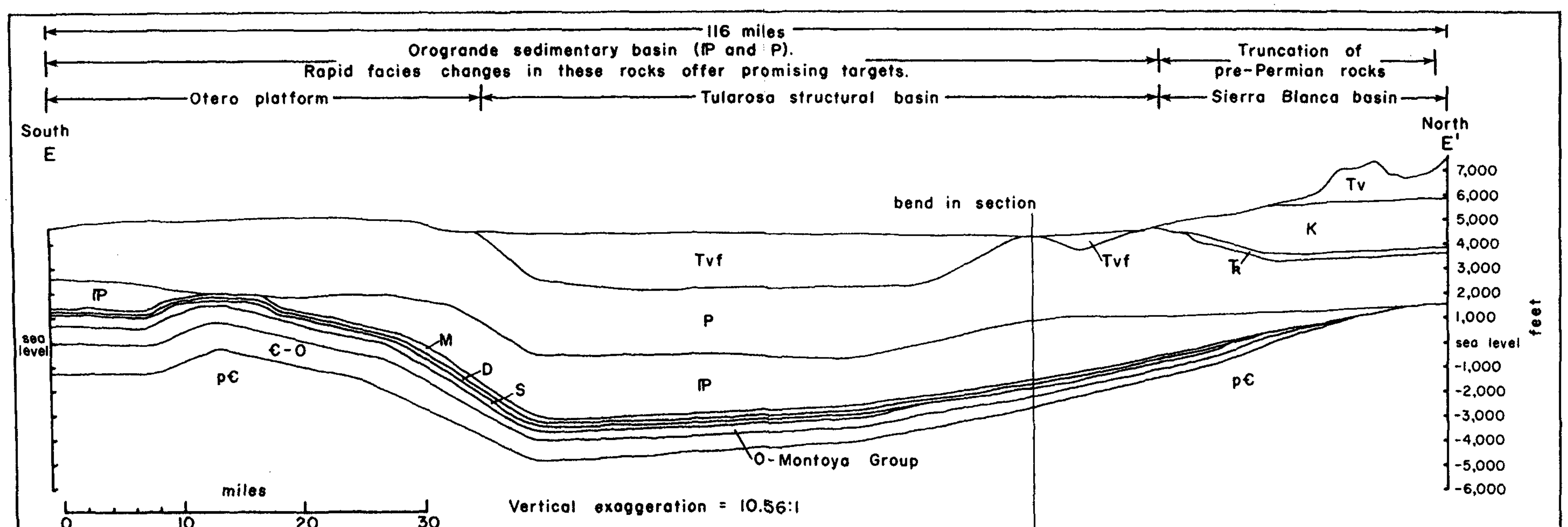


FIGURE 104—Cross section E–E′. Schematic structural–stratigraphic relationships in south-central New Mexico (see Fig. 29 for location). Tv, Tertiary volcanics; Tvf, Tertiary valley fill; K, Cretaceous; Ћ, Triassic; P, Permian; IP, Pennsylvanian; M, Mississippian; D, Devonian; S, Silurian; O, Ordovician; Є–O, Cambrian–Ordovician; pЄ, Precambrian.

mian sea eventually retreated to the vicinity of the Organ Mountains in the extreme southwest part of the basin.

The Yeso Formation of middle Permian age represents the end of the influence of the Pedernal as the sea spread out once again to cover this land mass that by then had been eroded to sea level. In the Tularosa Basin region the Yeso is a complex sequence that includes red and orange sandstone and shale, dolomite, limestone, and gypsum–anhydrite. Salt beds to 50 feet thick with cumulative thicknesses to 418 feet have been encountered in the Yeso in wells drilled by Standard of Texas, Texaco, and Houston Oil and Minerals on the east side of the basin from around Carrizozo to south of Three Rivers. Here, Yeso sediments are characteristic of very shallow marine environments similar to lagoons that have been cut off from open seas. This permits the noncirculating sea water to periodically evaporate precipitating pure salt, gypsum, and anhydrite. From a depositional center in the northeastern Tularosa Basin where more than 3,000 feet of Yeso strata accumulated, the formation thins to less than 500 feet at the south end of the basin.

Following Yeso deposition, a more normal ocean environment was inaugurated. Shallow marine seas of the middle Permian deposited the massive-bedded dolomitic limestone and dolomite of the San Andres Formation. This unit may exceed 1,000 feet in thickness in the northeastern basin but thins rapidly to the south approaching a "0" edge near the southern limits of the basin.

Pennsylvanian rocks—Sediments deposited during Pennsylvanian time consist of a complex sequence of limestone, shale, sandstone, conglomerate, and minor anhydrite and dolomite. Most of the Pennsylvanian is composed of rocks deposited in a marine environment with various shelf, basin, and deltaic features and show rapid facies changes. Bioherms are common in parts of the section (Foster, 1978).

Lower Pennsylvanian beds of the Lead Camp Limestone are massive, thick carbonates. Layers of arkosic clastics in the upper part of the formation suggest the influence of initial stages of the Pedernal uplift.

The Pedernal uplift, the central New Mexico contemporary of the state's other Middle Pennsylvanian to middle Permian uplifts, began major movement in this area in Late Pennsylvanian. The existing Paleozoic rocks were stripped to a Precambrian core along the east margin of the present Tularosa structural basin creating the Orogrande depositional basin and separating this seaway from the rapidly sagging Delaware Basin to the east. As the preexisting sedimentary beds were stripped away, they were reworked and redeposited around this massive island mass. The thick, cyclical limestones, shales, and sands of the Upper Pennsylvanian Panther Seep Formation were deposited in this rapidly subsiding, generally shallow water, and short-lived depression. Reefs are present in the Panther Seep Formation in the Hembrillo Canyon area of the San Andres Mountains (T16S, R3E) and in the Upper Pennsylvanian exposed in the Sacramento Mountains almost 40 miles due east across the Tularosa Basin.

Pennsylvanian rocks exceed 3,000 feet in thickness in outcrops in the central part of the San Andres Mountains, the Sacramento Mountains, and in deep wells drilled in the Tularosa Basin southeast of Alamogordo. They thin to less than 1,000 feet in the Sierra Oscura and in the northern part of the basin west of Carrizozo. They are absent because of erosion in the eastern Sacramentos. In the northern Tularosa and Jornada del Muerto Basins, and the Chupadera Mesa area, Upper Pennsylvanian rocks were deposited on the Precambrian surface.

Mississippian rocks—Lower and middle Mississippian rocks of the Caballero and Lake Valley Formations are accumulations of relatively pure limestone interbedded with shales containing nodular limestone beds. Upper Mississippian rocks of the Rancheria Formation are dense, dark limestones. Massive bioherms are seen in outcrops of the Lake Valley Formation in the Sacramento Mountains southeast of Alamogordo. The Mississippian is not present in the Oscura Mountains and is represented by the Lake Valley Formation in the northern part of the San Andres Mountains where it is less than 100 feet thick. In the southern part of the Tularosa Basin the Mississippian may be 500 feet thick.

Devonian rocks—The Devonian System is represented in the Tularosa Basin region by a dark silty shale interbedded with occasional thin, fossiliferous limestone beds. These units have been eroded away at the north end of the San Andres Mountains and across the northern Tularosa Basin, but they may be as much as 200 feet thick in the subsurface adjacent to the east-central front of the San Andres Mountains between the northern and central segments of the basin.

Silurian rocks—Limited fossil collections suggest a Middle Silurian age for the cherty dolomite of the Fusselman. It unconformably overlies the Montoya Group in the southern part of the Tularosa Basin where it is about 500 feet thick. Because of pre-Devonian uplift and erosion, it probably will not be encountered in the basin north of Tularosa.

Ordovician rocks—The Late Ordovician is represented by a massive dolomite containing some chert beds overlying a thin, light-gray to white sandstone. Collectively, this unit is the Montoya Group and is subdivided into four formations in this area. The lower unit, the Cable Canyon Sandstone, is usually dolomitic and occasionally conglomeratic. It caps the beveled surface of the underlying El Paso Group. Conformably overlying the Cable Canyon Sandstone are, in ascending order, the Upham Dolomite (Second Value Dolomite of Hayes and Cone (1975) in southwestern New Mexico), the Aleman Formation, and the Cutter Dolomite. The Montoya Group was eroded prior to Pennsylvanian deposition and thins to a "0" line at the south end of the Oscura Mountains and across the northern part of the Tularosa Basin. Within the south and central part of the basin it may be 400 to 500 feet thick.

Upper Cambrian and Lower Ordovician rocks—The Bliss Sandstone is a marine transgressive unit, primarily a quartz sandstone, that overlies the Precambrian. Based on fossil evidence, the lower part of the Bliss is Late Cambrian age in the Caballo and San Andres Mountains but may be Ordovician in the Sacramento Mountains. It grades into the overlying El Paso carbonates through a zone of sandy dolomite or limestone.

The El Paso Group is Early Ordovician age. Its thickness ranges from a "0"-line erosional pinch-out in the northern Tularosa Basin to more than 1,500 feet in the Franklin Mountains near El Paso. In the San Andres Mountains the El Paso Group is dolomite. In the nearby Caballo Mountains bordering the west side of the Jornada del Muerto it contains numerous biohermal masses that range from tens to hundreds of feet thick (Kelley and Silver, 1952). About 1,000 feet of this unit should be encountered in the subsurface in the southern part of the basin.

Evaluation—If it were possible to design a region with geologic parameters accepted as conducive to the generation and accumulation of hydrocarbons, the Tularosa Basin would be a very good model. The basin shows substantial potential based on a summary of factors considered important for the discovery of oil and gas in regions without a history of production.

1. There are favorable hydrocarbon source beds in the dark-gray to black shales of the Devonian, Mississippian, Pennsylvanian, and Permian.
2. There are suitable porous and permeable reservoir rocks throughout virtually all of the section.
3. Depth of burial is probably adequate for thermal maturation.
4. Numerous trapping mechanisms are evident. They run the full gamut of geological possibilities.

a. Facies changes are particularly common in the Pennsylvanian and Permian formations.

b. Permeability barriers are an especially striking aspect of the diverse sediments deposited during Pennsylvanian and Permian time.

c. In few areas of sedimentary outcrops are carbonate reefs so well exposed. The Pennsylvanian and Permian bioherms of the Tularosa Basin may be genetically related to the prolific Permian reef complex of the Permian Basin. This facies has an almost phenomenal capacity for storing and releasing enormous volumes of oil, and it contains perhaps the most exaggerated example of reef porosity in the world in the Guadalupe Mountain's Carlsbad Caverns about 75 miles southeast of Alamogordo.

d. Nearshore sandstone barrier bars and blanket beach sands are likely exploration targets where paleogeographic mapping establishes shorelines of Pennsylvanian and Permian seas.

e. Drainage features such as deltas and stream channels are primary objectives especially in the Permian Abo and Yeso Formations and many Pennsylvanian units.

f. Truncation of major units on a massive scale takes place in the subsurface of the north-central part of the Tularosa Basin. That the erosional beveling of hundreds of feet of Cambrian, Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian beds occurs in an updip direction within a narrow zone offers fascinating possibilities for entrapment of very large volumes of hydrocarbons beneath the Upper Pennsylvanian and Permian beds that overlie these major unconformities. Further, the evident fluctuations of the shallow Pennsylvanian and Permian seas and the oscillations of their shorelines introduced hiatuses into the sedimentary sequences. These cycles developed subtle interformational unconformities that provided ideal conditions for the later accumulation of hydrocarbons.

g. Fault traps formed by the placement of permeable beds against impermeable ones are very good possibilities within the tectonic framework of the basin.

h. Similarly, these tectonic events would be expected to produce stresses that formed closed anticlinal structures to trap oil and gas.

5. The Tularosa Basin's large volumes of impermeable shales, salt beds, gypsum, and anhydrite provide excellent seals to prevent the escape of hydrocarbons from reservoir rock. This is an especially attractive possibility in regions that have undergone a great deal of tectonic movement.
6. The analogies that can be made to other producing areas should not be overlooked. It was the evaluation of fore-reef and back-reef or basin and shelf relationships that led to the location of the discovery well in the 250-million-barrel Empire–Abo field on the Delaware Basin shelf near Artesia. Although the present-day structural configuration of the region places it within the Southern Rocky Mountains or the Basin and Range physiographic province where exploration for oil and gas has not been particularly rewarding, past tectonic events and stratigraphy are more closely allied with the prolific Permian Basin and Central Basin platform. Virtually all of the Paleozoic strata present in the Tularosa Basin have stratigraphic-time equivalents in the Permian Basin that have produced billions of barrels of oil from these formations in nearby west Texas and southeastern New Mexico.
7. The hydrodynamic gradient in the Tertiary alluvium of the Tularosa Basin is from the mountains on both sides to the center and from north to south (Weir, 1965; McLean, 1970). It is likely that this flow pattern is also encountered in the deeper Paleozoic beds. Because the major truncations of the lower Paleozoics, large numbers of the Pennsylvanian and Permian shorelines, and the Upper Pennsylvanian bioherms trend east–west, the hydrodynamic gradient is favorable for resisting the flushing of trapped hydrocarbons.
8. One of the better indications of whether hydrocarbons are present in a region is the quality of the "shows" encountered while drilling wells. Several of the wells drilled on the east side of the Tularosa Basin have reported good shows of oil and/or gas. One, the Houston No. 1 Lewelling in sec. 12, T12S, R9E, tested 430 MCF of gas per day from a Middle Pennsylvanian unit encountered at 8,000–8,016 feet (Foster, 1978).
9. The major deterrent to exploration is the structural complexity of the region. Despite the favorable parameters, large oil accumulations could have been modified or lost by recurring structural instability. It is possible that oil and gas accumulated in reservoirs in the region prior to or contemporaneous with the large-scale tectonic events of the Laramide orogeny (Foster, 1978). Even if major traps were destroyed during the uplifts, it seems unlikely that all the hydrocarbons were lost.

The Tularosa Basin is divided into three target exploration areas for several geological reasons and one that is political. The latter relates to the inability to access the U.S. Army's White Sands Missile Range. This vast holding of about 2.1 million acres encompasses all of the San Andres Mountains and most of the Tularosa Basin from about US-380 on the north to the Jarilla Mountains at Orogrande on the south. Only about the eastern third of the northern and central segments can be leased and evaluated. In the southern segment, that region west of US-54 is withdrawn by the military.

Although some of the optimum areas for evaluating the Tularosa Basin's hydrocarbon potential are currently inaccessible, those remaining should be considered prospective.

Target exploration area 16, southern segment—The rocks of the Paleozoic System are present and are thickest in this area. Structural traps will be favorable for oil accumulation in the lower Paleozoics. Careful reconstruction of the paleogeography during certain periods in the Pennsylvanian and Permian may determine trends of favorable reservoir facies.

Target exploration area 17, central segment—The region between the White Sands Missile Range boundary and the front of the Sacramento Mountains south of Alamogordo is prospective because of favorable facies suites in the Permian and Pennsylvanian and rapid thinning of all the lower Paleozoic rocks because of truncation. All of this area is on the Jarilla bench, a flat-lying platform between the Sacramento Mountain uplift and the north–south Jarilla fault that is the eastern boundary of the down-dropped block that forms the Tularosa structural basin. Seismic procedures are a prerequisite to interpreting the complex stratigraphic and structural relationships in this region.

Target exploration area 18, northern segment—Lower Pennsylvanian, Mississippian, Devonian, and Ordovician strata are truncated in the area around Three Rivers. The Silurian Fusselman Formation is beveled to a "0" edge between Alamogordo and Tularosa. Favorable reservoir facies in the Pennsylvanian and Permian should occur in the subsurface in this region. Evaporites present in the Permian Yeso Formation may assist in preserving hydrocarbons in traps affected by recent movement.

Figure 105 shows the status of exploration in the southern part of the south-central region. Figures 106 and 107 are stratigraphic sections of Mesozoic and Permian rocks. Figures 108 through 111 show well-log characteristics in this area. Cross section E–E′ (Fig. 104) demonstrates the larger structural and stratigraphic relationships.

Foster (1978) offers an excellent perspective of the Tularosa Basin and its oil and gas potential. The mineral resources of the region are also summarized by Grant (1983). An exceptional synopsis of the geologic history of this part of New Mexico is presented by Seager (1981). Detail on the stratigraphy of rocks in the San Andres Mountains is offered by Kottlowski et al. (1956). Meyer (1966) has prepared detailed maps of Pennsylvanian and Permian Wolfcamp strata that cover this region and other parts of southeast New Mexico. Otte (1959) and Pray (1961) describe the geology of the Sacramento Mountains.

(Text continued on page 86.)

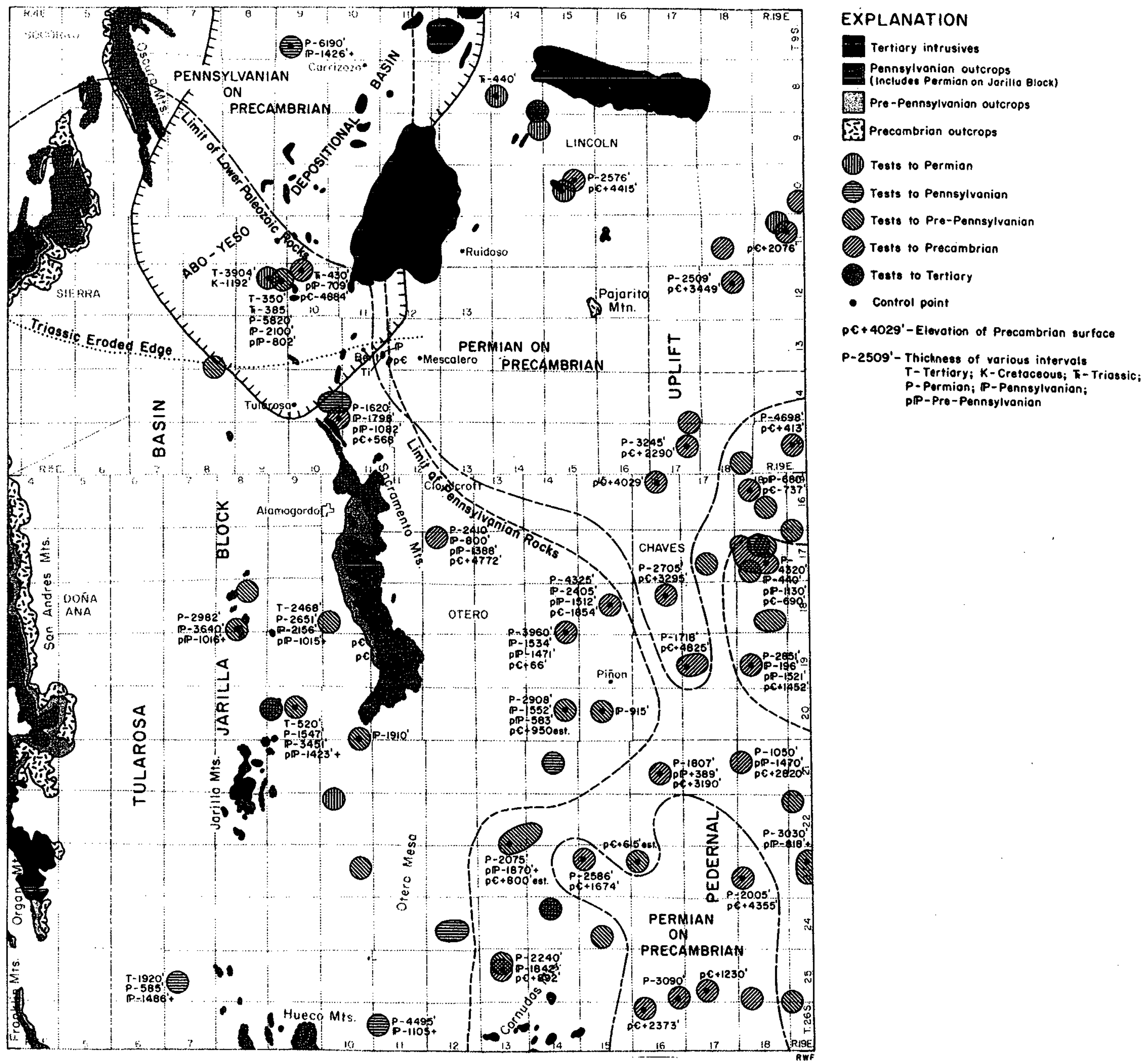


FIGURE 105—Status of exploration in the southern part of the south-central region.

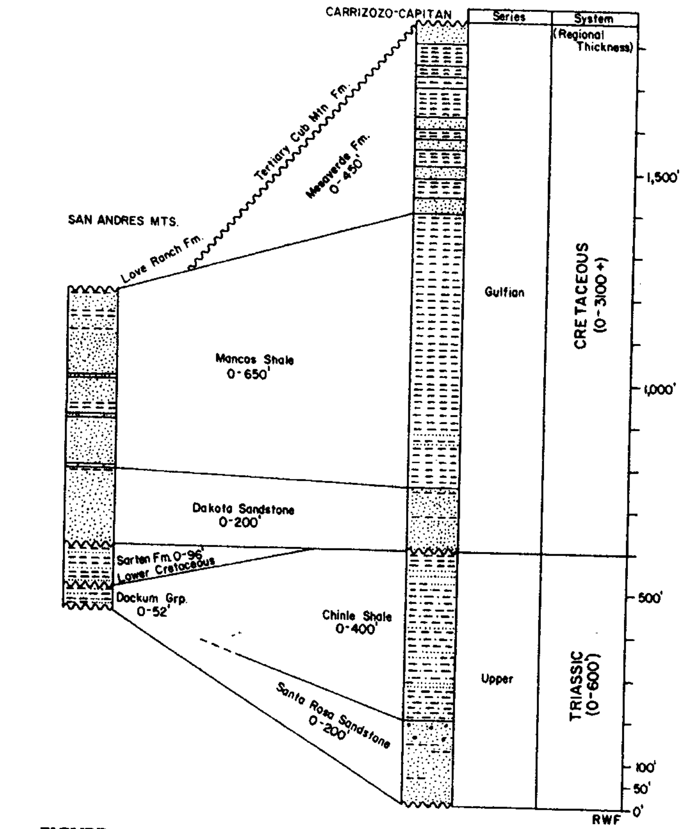


FIGURE 106—Stratigraphic sections of Mesozoic rocks in the Tularosa Basin (Foster, 1978).

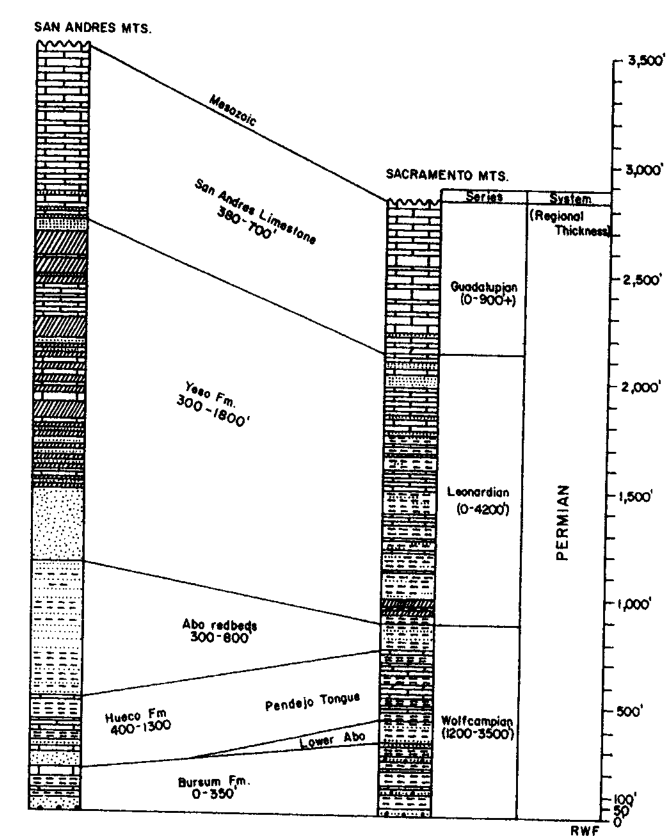


FIGURE 107—Stratigraphic sections of Permian rocks in the Tularosa Basin (Foster, 1978).

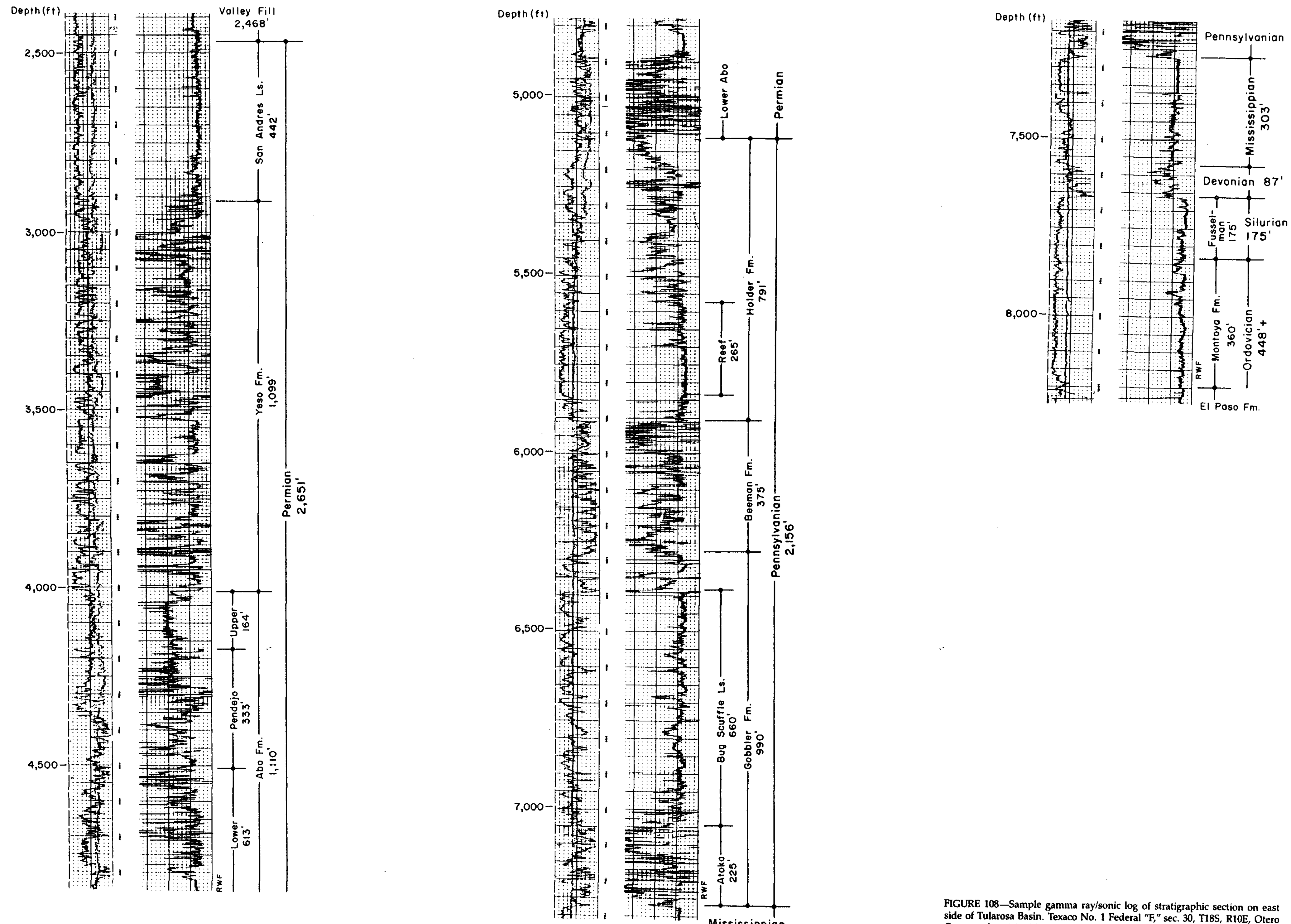


FIGURE 108—Sample gamma ray/sonic log of stratigraphic section on east side of Tularosa Basin. Texaco No. 1 Federal "F," sec. 30, T18S, R10E, Otero County, elev. 4,042'GL, total depth 8,288'.

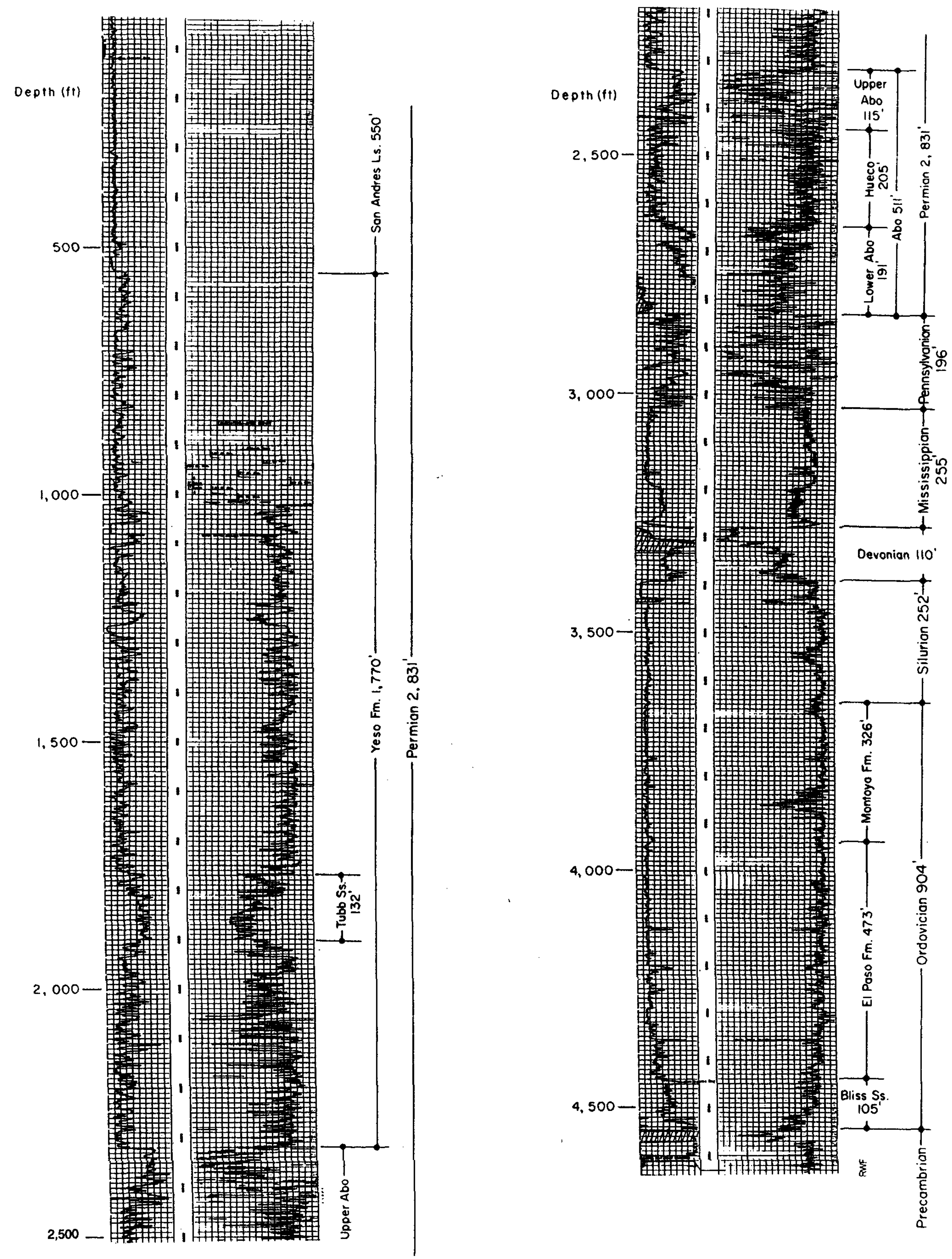


FIGURE 109—Sample gamma ray/sonic log of stratigraphic section on east flank of Pedernal uplift. Gulf No. 1 Munson Federal, sec. 28, T19S, R18W, Chaves County, elev. 5,664'KB, total depth 4,639'.

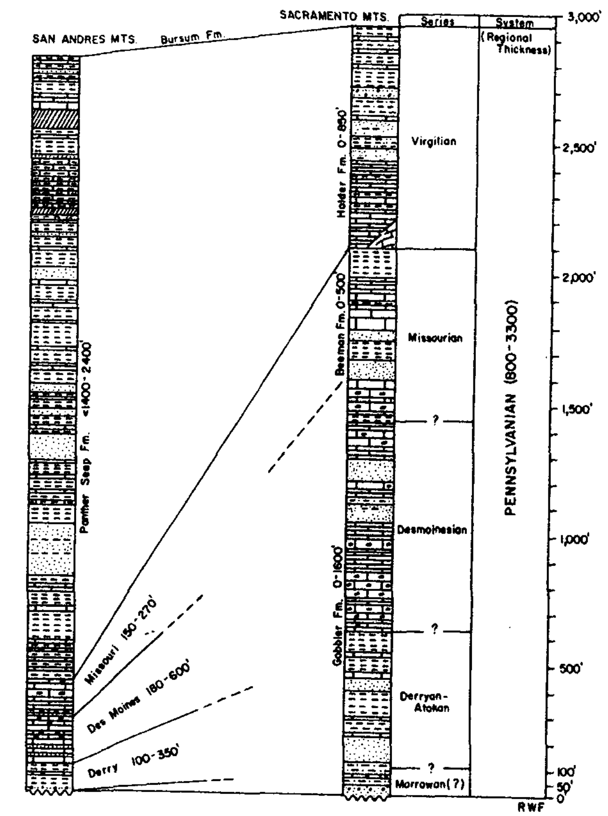


FIGURE 110—Stratigraphic sections of Pennsylvanian rocks in the Tularosa Basin area (Foster, 1978).

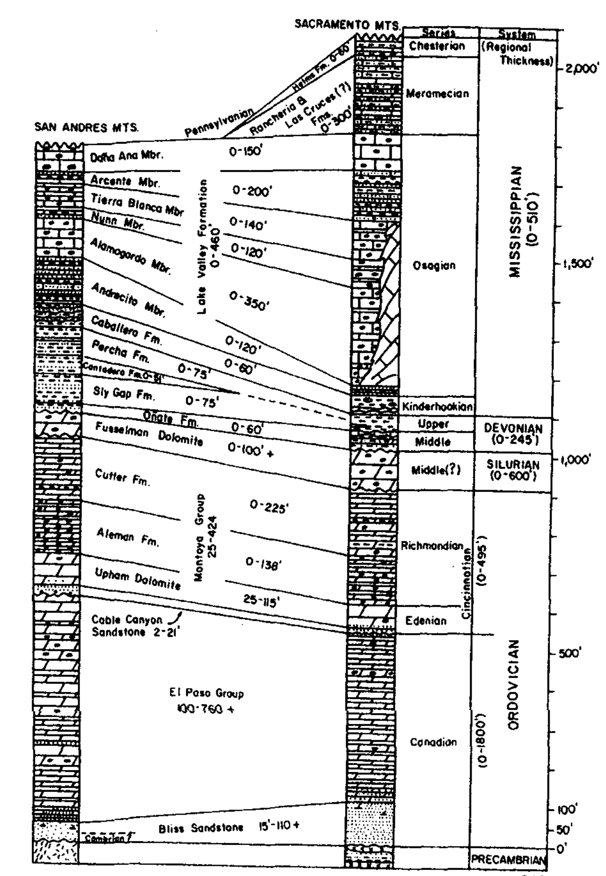


FIGURE 111—Stratigraphic sections of pre-Pennsylvanian rocks in the Tularosa Basin area (Foster, 1978).

Target exploration areas 19, 20, and 21, Jornada del Muerto Basin—The Jornada del Muerto structural basin is a classic synclinal depression with more than 5,000 feet of structural closure (Woodward et al., 1975). It lies between the east-dipping Caballo and Fra Cristobal Mountains on the west and the west-dipping San Andres Mountain block on the east. A northern segment of the east side is faced by the east-dipping Oscura Mountain block. The basin extends north to the southern end of the Manzano Mountains. Its southern limit is not easily defined but physiographically and structurally may be just north of Las Cruces. The Jornada del Muerto Basin encompasses about 2,500 square miles. It is divided into three distinct segments (south, target exploration area 19; central, target exploration area 20; and north, target exploration area 21) because of significant stratigraphic and structural differences that are discussed separately.

Objectives—Rocks of the entire Paleozoic era are present in the central and southern segments of the Jornada del Muerto Basin. Only the Pennsylvanian and Permian are present in the northern part. Cretaceous strata are probably present throughout the basin and attain their maximum thickness of more than 2,000 feet in the structural center. The Triassic is represented by thin remnants of the Chinle Formation in the northern segment. With the exception of the Chinle, all of these are potential source or reservoir rocks.

Discussion—Much of the discussion of the Paleozoic strata in the Tularosa Basin (target exploration areas 16, 17, and 18) applies in this area. Lower Paleozoic marine, predominantly shelf carbonates, shales, and sandstones in the Mississippian, Devonian, Silurian, Ordovician, and Cambrian that are present in the south are absent in the northern segment. Truncated in an east–west direction in the central segment they attain their maximum thicknesses in the southern segment. Pennsylvanian and Permian rocks show great vertical and lateral variability. Depositional and sedimentary relationships between continent and sea in the Orogrande Basin during Early Permian time are presented by Seager et al. (1976). Cretaceous rocks that were probably considerably thicker prior to Laramide uplifts that stripped them away are confined to the lower units of the Upper Cretaceous representing the T–1, R–1, T–2, and R–2 cycles. The southern part of the Jornada del Muerto Basin hosts thin remnants of pre-Dakota Lower Cretaceous rocks.

Although the mountains bounding the west side of the basin exhibit great structural complexity (Kelley and Silver, 1952; Seager et al., 1982; Seager, 1983), there appears to be little tectonic deformation toward the basin center. The southern extremity may be covered by more than 5,000 feet of Tertiary bolson fill.

Kelley and Silver (1952) discuss in considerable detail the structure and stratigraphy of the Jornada del Muerto Basin and Rio Grande rift east and west of the Caballo Mountains. Their presentation includes an assessment of the oil and gas possibilities and an evaluation of the wells that had been drilled at that time.

Target exploration area 19, southern segment—This region contains the thickest suite of Paleozoic and Mesozoic (Cretaceous) rocks. Seager (1983) suggests the reason is that southwestern New Mexico was subjected to northeast-directed Laramide (Late Cretaceous–early Tertiary) stresses that resulted in northwest–southeast-trending uplifts and basins. In many areas late Tertiary movement accentuated or rejuvenated these structural trends, but most of the later uplifts are along north–south lineaments that indiscriminately cut across the Laramide structural grain. The older Laramide features are bordered by narrow zones of steep to moderate southwest-dipping, reverse- and thrust-faulted margins facing northeast with relatively gentle southwest dip off the opposite flank. The exploration significance is that most if not all of the pre-Tertiary sedimentary rocks will be missing from the tops and near flanks of these uplifts, and relatively complete sections will be encountered in the remnants of Laramide structural basins where they are preserved in the subsurface. The southern part of the Caballo Mountains to the south end of the Organ Mountains together with the intervening San Diego and Doña Ana Mountains are such a Laramide structural element with some late Tertiary rejuvenation. The southern Jornada del Muerto Basin northeast of it will, therefore, contain the thickest and perhaps least deformed stratigraphic sections.

Target exploration area 20, central segment—Paleozoic rocks from Cambrian through Lower Pennsylvanian are truncated in a generally southwest–northeast to east–west direction across this segment. Artesian flows of water encountered in some of the wells drilled in this part of the basin suggest strong hydrodynamic gradients that could influence trapping situations.

Target exploration area 21, northern segment—In addition to a thin surface veneer of Cretaceous and Triassic rocks, Permian and Pennsylvanian strata cover a Precambrian basement in this area. Of possible interest from an exploration standpoint is an anomalously "thin" section of Pennsylvanian trending northwest from the vicinity of Carrizozo through the northern Jornada del Muerto Basin to the Joyita Hills region at the south end of the Albuquerque Basin. This feature, described in the discussion of target exploration area 7 (Albuquerque Basin) may be a regional structural element that continues north to connect with the Nacimiento uplift.

Target exploration area 22, Estancia Basin–Chupadera Mesa—The northern part of this area, the Estancia Basin segment, extends from the San Pedro–Ortiz Tertiary intrusive uplifts in southern Santa Fe County south about 60 miles to the vicinity of Gran Quivera National Monument in southwestern Torrance County. Here a broad, low, structural arch separates it from Chupadera Mesa and the Jornada del Muerto Basin. The western margin merges with the eastward-dipping slope of the Sandia and Manzano Mountains. The eastern boundary is a low range of hills within which Precambrian exposures mark the north–south Pedernal uplift.

Chupadera Mesa includes a northern extension of the Tularosa Basin that merges north and west into the broad, north-plunging extension of the Oscura Mountain uplift. It is connected to the Estancia Basin to the north and is bounded by a series of Tertiary intrusives and Precambrian-cored uplifts that trace the Pedernal uplift on the east.

Overview—The exploration-status map of the northern part of the south-central region (Fig. 112) includes the Estancia Basin and Chupadera Mesa as well as contiguous parts of the Sangre de Cristo Mountains, Glorieta Mesa, Sandia–Manzano Mountains, Pedernal Hills, and the Hagan–Galisteo Basins.

Much of the Estancia Basin is covered by a relatively thin veneer of Quaternary alluvium and eolian sands. The Mesozoic is represented by sediments of Cretaceous, Jurassic, and Triassic age that are encountered in the northern limits of the Estancia Basin and some parts of Chupadera Mesa. As shown in Figure 112, Cretaceous rocks have been eroded in the rest of the region.

Upper Jurassic rocks include the Morrison and Todilto Formations and the Entrada Sandstone. The section is similar to that found in the southern San Juan Basin and is 270 to slightly more than 1,000 feet thick.

Triassic rocks underlie a much larger area including much of the western part of Glorieta Mesa. Here, the Triassic consists of the Chinle Formation and Santa Rosa Sandstone with thicknesses ranging from almost 300 to slightly more than 1,500 feet. Jurassic and Triassic rocks have been eroded in most of the rest of this area.

Permian rocks are at the surface over much of the eastern and southern part of the area. The uppermost interval, the orange siltstones and sandstones of the Bernal Formation, are presumed to be present where the Triassic is preserved. Elsewhere the Bernal, except for a few small remnants, has been removed by erosion. Similarly, with the exception of Chupadera Mesa, the San Andres has been eroded from much of the area including most of the Estancia Basin. Elsewhere the San Andres is generally thin with as few as five feet remaining on parts of Glorieta Mesa beneath the Bernal. It also is probably thin in the Galisteo and Hagan Basins. The Glorieta Sandstone underlies a much larger area, particularly in the east, but has also been removed from much of the Estancia Basin. Complete sections are on the order of 400 feet thick (Fig. 113).

The Yeso Formation ranges from 420 feet in the northern part of Glorieta Mesa to almost 1,300 feet beneath Chupadera Mesa. In the south the various members of the Yeso Formation can be recognized. These include the red fine-grained sandstone of the Joyita; anhydrite, dolomite, and red fine-grained sandstone of the Cañas and Torres Members; and the orange fine- to medium-grained sandstone of the basal Meseta Blanca.

Exposures of basal Permian rocks consist of red to orange arkosic conglomerate, mudstone, arkosic sandstone, and limestone pebble conglomerate. These rocks are referred to as the Abo Formation where they are preserved on the southeast dip slope of the Manzano Mountains and the east side of the Sandia Mountains. Equivalent rocks along the base of Glorieta Mesa are generally called the Sangre de Cristo Formation. The thickness of the Abo–Sangre de Cristo varies considerably as a result of being deposited directly on the Precambrian over much of the area. The maximum drilled thickness on Glorieta Mesa is almost 1,200 feet and a similar thickness is present beneath Chupadera Mesa. In the Estancia Basin the interval thins from a maximum of about 1,300 feet to less than 500 feet near the eastern edge of the basin. The Abo is absent over a large area surrounding the Pedernal Hills. Here it is overlapped on the Precambrian surface by sediments of the Yeso Formation. In some areas, particularly beneath the Chupadera Mesa, there is a Lower Permian interval consisting of interbedded limestone, red shale, and arkosic conglomerate that is called the Bursum Formation. This interval is considered to be Wolfcampian in age.

Pennsylvanian rocks are exposed on the east dip slope of the Sandia–Manzano chain and around the southern end of the Sangre de Cristo Mountains. Pennsylvanian exposures and the extent of this interval in the subsurface are shown in Figure 112. The limit of the Pennsylvanian essentially outlines the late Paleozoic Pedernal uplift. Initial upward movement probably took place in Early Pennsylvanian time and was part of an east–west epeirogenic uplift that involved most of central New Mexico. It resulted in the removal of older Paleozoic strata that in this area consisted of rocks of Mississippian age. Available data suggest that the uplift was overlapped by successively younger Pennsylvanian rocks with Virgilian-age sediments extending farthest onto the uplift. Near the end of Pennsylvanian time only low hills of Precambrian rocks remained as islands surrounded by Late Pennsylvanian seas.

Near the end of Pennsylvanian time or in the Early Permian north–south-trending faults developed in the vicinity of the present Pedernal Hills to form what is now referred to as the Pedernal uplift. This uplift, generally buried beneath younger sediments, continues south into Texas. Greatest displacement occurred along the western part of the uplift, and Pennsylvanian rocks were stripped from this area. To the east there was a fairly gentle dip slope from which only minor amounts of Virgilian rocks that had onlapped the earlier uplift were removed. The Lower Pennsylvanian uplift supplied only small amounts of coarse material to the adjacent basins as evidenced by the general absence of arkosic material in the lower part of the Pennsylvanian. This supports the concept of an area of fairly low relief from which the major clastic material being transported consisted of resistant quartz grains.

In interpreting the subsurface of this area, particularly from geophysical data, it is important to realize the wide variety of Precambrian rock types that is present. This includes quartzite, granite, gneiss, and schist in the Pedernal Hills. In the Manzano Mountains there are also metarhyolites; mottled red and green, finely schistose arkosic quartzites; gray, greenish-gray, and red phyllite and slate; and dark-red siltstone (Reiche, 1949). Much of this thick sequence of metaclastic rocks has been subjected to only low-grade metamorphism. From subsurface cuttings, Foster and Stipp (1961) identified a variety of schists, granite, gneiss, conglomeratic quartzite, quartzite, and arkose.

The upper part of the Pennsylvanian, the Madera Formation, consists of interbedded red shale and arkosic conglomerate with gray shale and minor limestone. Below, the section is mostly limestone with some light- to dark-gray shale, and light-gray to white arkosic sandstone. The basal Sandia Formation consists of light-gray to white quartz sandstone with interbedded dark-gray carbonaceous shale, minor limestone, and quartz pebble conglomerate. In the eastern part of the area the Pennsylvanian thins as the Pedernal uplift is approached. Near the uplift thicknesses are on the order of 300 feet. Away from the uplift to the east and north the interval thickens from more than 500 to almost 1,500 feet, and in the Galisteo Basin more than 2,000 feet are present. Beneath Chupadera Mesa the maximum thickness appears to vary from 1,400 to 1,500 feet.

The Estancia Basin presents problems in interpreting the Pennsylvanian section. In most of the basin the thickness appears to be normal with from 900 to 1,400 feet present. The section thickens from west to east toward the Pedernal uplift. The problem arises from three wells drilled in close proximity to each other in T6N, R10E. The first well drilled in this township was the San Juan No. 2 Randall completed in 1928. Limestone, probably from the Bursum Formation, was encountered at 1,690 feet. The well was abandoned at 5,321 feet with a combined thickness of Bursum Formation and Pennsylvanian strata of more than 3,631 feet.

The second well was the Gardner No. 1 Kidwell completed in 1954. The top of the Pennsylvanian was at a depth of 2,365 feet and the well was drilled to a total depth of 5,918 feet. The Pennsylvanian section seemed to have lithologic equivalents of the Madera and Sandia Formations. Foster and Stipp (1961) picked the top of the Precambrian at a depth of 5,680 feet resulting in a thickness for the Pennsylvanian of 3,315 feet.

The third well was the Houston 14–28 Federal completed in 1976. Based on the gamma-ray curve, the top of the Pennsylvanian is at 2,222 feet. The well was drilled to a depth of 8,759 feet. Based on the presence of granite the top of the Precambrian was reported to be at a depth of 8,660 feet for a thickness of Pennsylvanian of 6,438 feet. About four miles to the east the Superior 28–31 Blackwell had only 1,180 feet of Pennsylvanian above a gneissic granite like the Precambrian exposures in the Pedernal Hills a short distance farther to the east.

Thus there is a small area with a potential Pennsylvanian section that varies from 3,300 to more than 6,000 feet thick surrounded by wells with only 1,200 to 1,400 feet of this interval. It would seem unlikely that this can be attributed to depositional processes. The only other explanations are repetition of section by faulting, steep dips, or misinterpretation of the contact with the Precambrian. Late Pennsylvanian–Early Permian faults are known to be present on the west side of the Pedernal uplift. The top of the Abo shows little structural discordance, and it is assumed that later faulting is not present. An examination of the sample and electrical log of the Gardner well does not suggest repetition of section. Beneath what seems a rather normal Pennsylvanian sequence the well encountered principally red arkosic conglomerate, arkosic sandstone, and shale. Much of the red shale may be cuttings from Permian red beds up the hole. Although the section could be Abo with the overlying Pennsylvanian being part of a thrust, this is difficult to explain for such a small area. In addition the nature of the lithologies as interpreted from the cuttings is not representative of the Abo. Based on the gamma-ray curve and other information, it is suggested that the top of the Precambrian in the Houston well is at a depth of approximately 4,250 feet and from the sample and electrical logs, at 4,480 feet in the Gardner well. The Precambrian rocks are considered to be similar to the metaclastic section described by Reiche (1949) in the Manzano Mountains and possibly in part to the Sais Quartzite in the southern part of the range. The thickness of the Pennsylvanian at 2,115 feet in the Gardner well and 2,028 feet in the Houston well is still greater than normal but might be explained by dips related to the

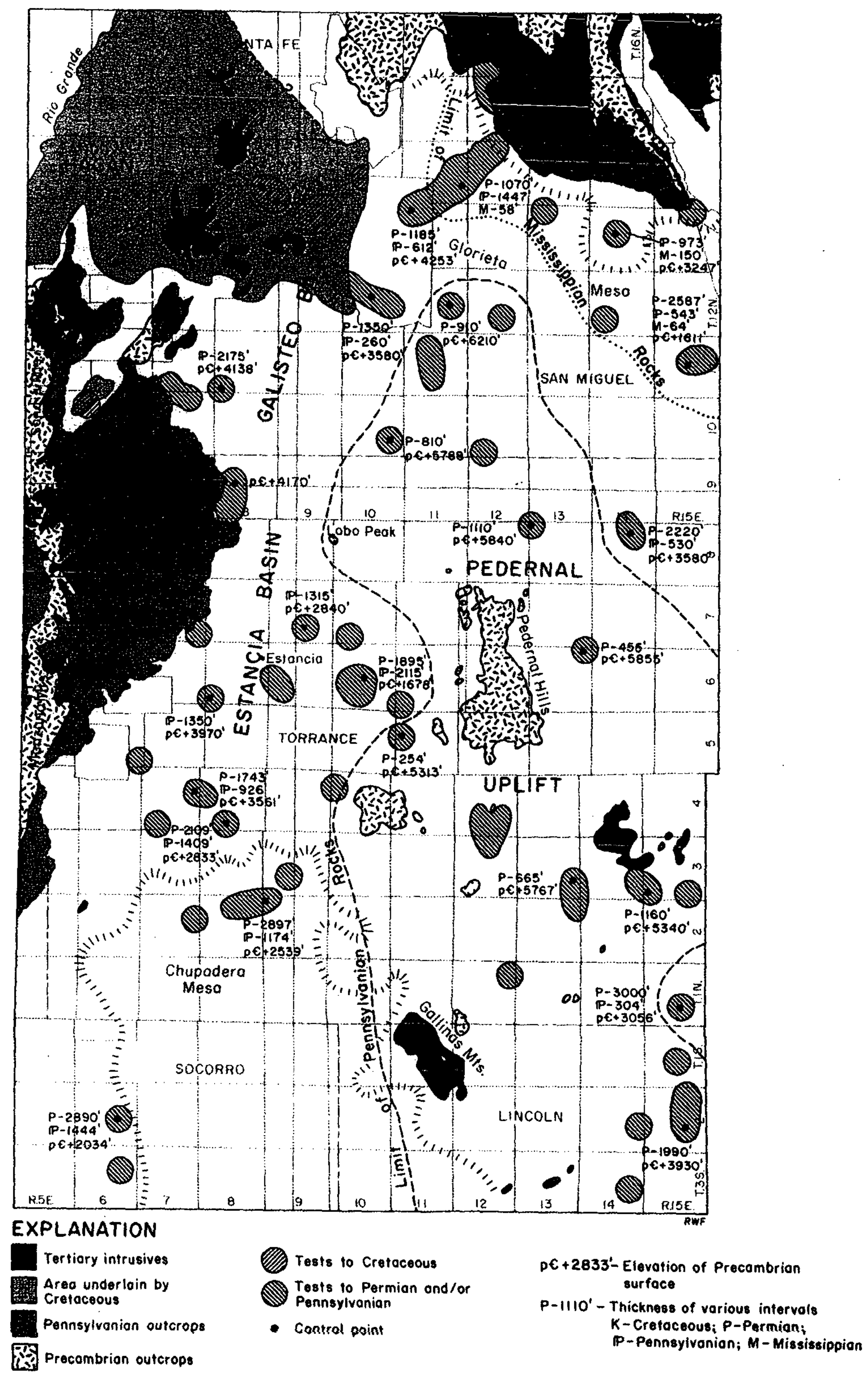


FIGURE 112—Status of exploration in the northern part of the south-central region.

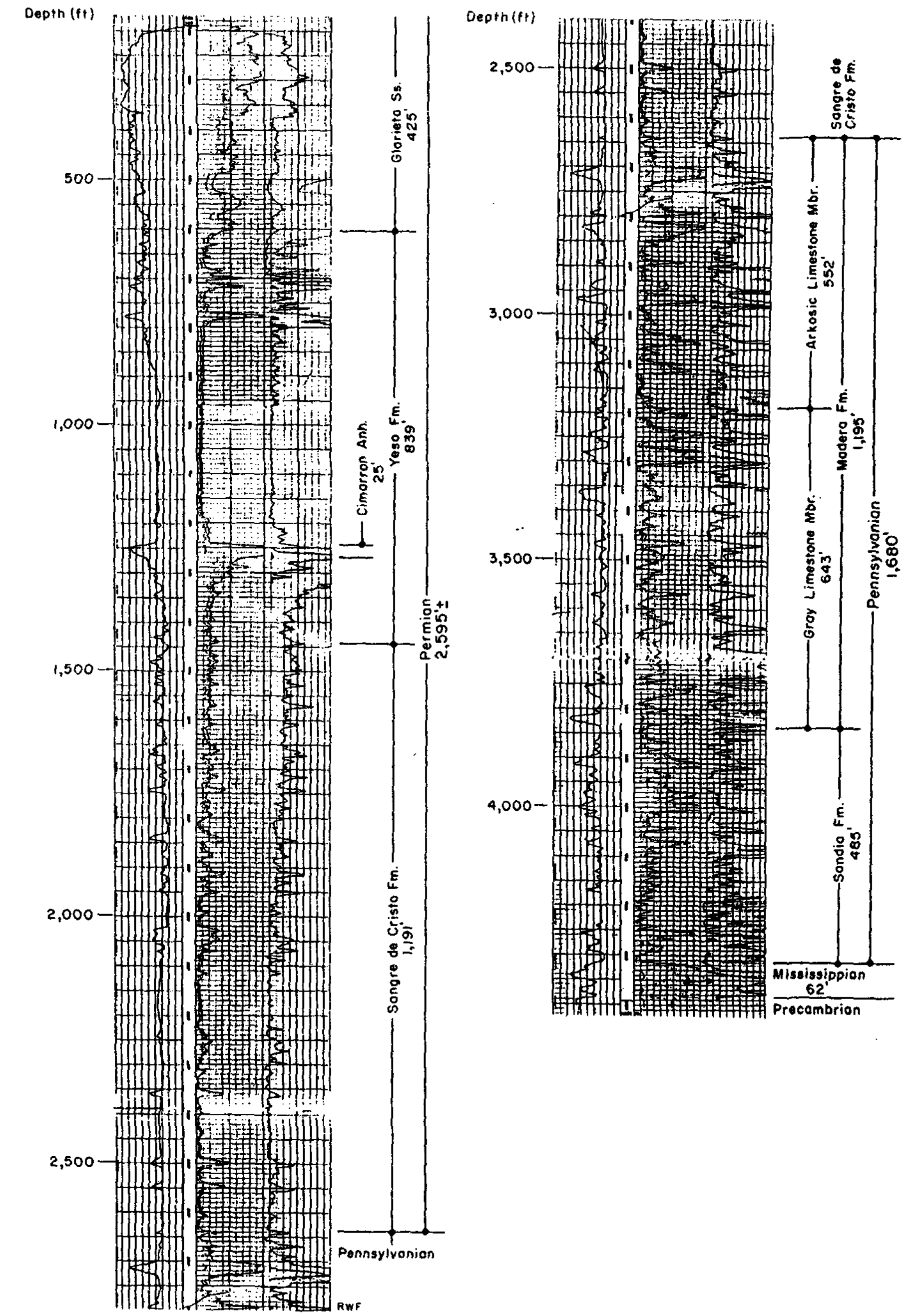


FIGURE 113—Self potential/resistivity log showing Permian, Pennsylvanian, and Mississippian rocks in the northern part of the south-central region. Roberts No. 1 Lucero, sec. 14, T11N, R15E, San Miguel County, elev. 5,890'GL, total depth 4,395'.

west-bounding fault of the Pedernal Uplift. It is also possible that the contact with the Precambrian is higher than interpreted.

The potential for significant discoveries of hydrocarbons is considered marginal. Sandstone intervals in the Yeso Formation may be prospective in Chupadera Mesa. Evaluation of the sandstones and carbonates in the Pennsylvanian is also warranted in the Chupadera Mesa area and southern Estancia Basin. Although suitable traps exist in the Pennsylvanian section in the northern Estancia Basin as evidenced by the presence of carbon dioxide gas, the general structure is a dip slope off the Manzano Mountains suggesting escape routes for hydrocarbons. Exploration along the faulted west margin of the Pedernal uplift may be rewarded.

Although outside target exploration area 22, Pennsylvanian targets may be present beneath the Glorieta Mesa along the northwest edge of the Pedernal uplift.

The Pedernal uplift has had a number of tests. These have established a limited section above Precambrian consisting mostly of a thin veneer of Yeso sediments and, along the margin, Abo red beds. Further exploration of this area does not appear to be justified.

Objectives—Potential reservoir rocks are limited to those in the Pennsylvanian and Permian. Permian rocks are generally on the surface or beneath a veneer of Quaternary sediments. The Pennsylvanian strata are deposited directly over the Precambrian basement.

Discussion—Deposition of upper Paleozoic rocks of Pennsylvanian and Permian age was profoundly influenced by the nearby Pedernal uplift. A series of geologically violent pulses coupled with severe crustal shortening (see discussion of Pennsylvanian System maps) in the Estancia Basin might have left anomalous thicknesses of clastics and marginally marine sediments preserved locally. (See "overview," above, for another explanation of the thick Pennsylvanian clastics.) Interformational unconformities in the Pennsylvanian and places where these rocks are truncated and unconformably overlain by Permian strata may be attractive exploration targets.

Farther south in the Chupadera Mesa segment, prospects are probably limited to defining porosity in Pennsylvanian strata in areas where favorable structural conditions occur. However, strong hydrodynamic gradients may exert a significant influence on hydrocarbon accumulations in this region. Broadhead (1984a) suggests with cross sections that the upper part of the Permian Abo Formation in this area may be depositionally equivalent to the gas-yielding Abo sediments on the east side of the Pedernal.

Detailed information on the Pennsylvanian System in this area, derived from outcrops and well samples, is presented by Kottlowski (1960).

Southwest region

Target exploration area 23, Rio Grande rift, Palomas Basin—This area encompasses 600 square miles bounded on the east by the Caballo Mountains and on the west by the Animas uplift. The latter is a low-lying, faulted, structural, and topographic platform lying between the Black Range–Emory uplift and the Rio Grande rift's west marginal fault. To the north are the Precambrian-cored Mud Springs Mountains that trend northwest across the rift from the north end of the Caballo Mountains. The southern boundary is more obscure and is presumed to coincide with a northwest-southeast-trending bedrock high in the subsurface. Definitive subsurface data are lacking in this area.

Objectives—Paleozoic rocks from Cambrian through Permian should be present. They are the reservoir and source beds discussed with the Tularosa and Jornada del Muerto Basins (target exploration areas 16 through 21). The northeastern part of the area may contain a relatively thick suite of Upper Cretaceous rocks faulted against the upthrown Caballo Mountain block.

Discussion—Although there may be more than 5,000 feet of basin fill covering the Paleozoics and Mesozoics, the stratigraphic and structural integrity of these suites should be comparatively intact. The Palomas Basin lies between major Laramide and late Tertiary uplifts and should, therefore, have the thick sedimentary section that was present prior to these orogenies preserved uneroded in the subsurface. (See previous discussion, Jornada del Muerto Basin, southern segment, target exploration area 16, and Seager, 1983.)

Elements of the Orogrande depositional basin of Pennsylvanian and Permian time were present southeast of this area. Seager et al. (1976) discuss its effect on the Lower Permian sediments exposed in the Doña Ana Mountains southeast of the area. Important regional facies implications for relating the continental and marginal marine clastics of the Abo Formation with its lateral marine Hueco Formation equivalent may be concealed in this area.

Kottlowski (1960) and Meyer (1966) provide discussions and illustrations of Pennsylvanian stratigraphy; Kelley and Silver (1952) detail the Cambrian, Ordovician, Silurian, Devonian, and Mississippian strata and speculate on oil and gas possibilities; and Seager et al. (1982) detail the surface geology of most of the area. Cross section F–F' (Fig. 114) shows the larger geologic features of the area.

North of the Mud Springs Mountains is the Engle Basin segment of the Rio Grande rift. Outcrop patterns suggest that the rift's west-bounding fault may be very close to I-25, restricting this structural basin to a limited area 8 to 10 miles wide between the Caballo Mountains and the highway, from Truth or Consequences north about 35 miles to NM-107. Although much of this rift segment has many of the same characteristics as the Palomas Basin and includes areas where most of the lower Paleozoic rocks were removed by erosion and although major facies changes can be expected in Pennsylvanian and Permian rocks, much of the segment lies beneath Elephant Butte Reservoir. Despite these disadvantages, this area warrants further examination.

Target exploration area 24, Rio Grande rift, Mesilla and Mimbres Basins—This long, narrow, northwest-trending area encompasses about 1,200 square miles. It stretches from the Franklin Mountains on the southeast to the Little Burro Mountains on the west. It lies between the major Laramide Burro–Florida uplift on the south and the mostly concealed late Tertiary Robledo, Sierra de las Uvas, and Sierra uplifts on the north.

Objectives—With the exception of the Triassic, rocks of every geologic period are present. In the southeast part of the area Cambrian through Cretaceous sediments exceed 10,000 feet and should provide good to excellent reservoir and source rocks.

Discussion—This area is also defined on the basis of being most likely to have complete, undisturbed, pre-Laramide stratigraphic sections preserved. The primary area of interest lies east of the Cooke's Range and Deming where the thickest sedimentary units are present.

A deterrent to exploration is the presence of thick suites of Tertiary rocks including unconsolidated valley fill, volcanics, and deposits of material eroded from nearby Laramide uplifts that mask the structure and older stratigraphy. These younger deposits are locally as thick as 10,000 feet in the area south of Las Cruces and may be more than 5,000 feet thick in the Mesilla Basin west of the Franklin Mountains. Although the greater depths discourage exploration, careful analysis of geophysical data may permit the selection of locations with predictable potential that have considerably less Tertiary cover.

Seager (1983) and Seager and Morgan (1979) offer structural explanations for this area. Thompson and Bieberman (1975) have evaluated the wells drilled in Doña Ana County. Cross section F–F' (Fig. 114) is a schematic representation of the larger geological features in this area.

Target exploration areas 25 and 26, Playas–Animas Basins—This area of about 3,000 square miles is essentially the southwestern peninsula of New Mexico from Lordsburg to the New Mexico–Mexico border between Arizona on the west and Mexico on the east.

Objectives—Paleozoic strata more than 10,000 feet thick consisting of marine sandstones, limestones, dolomites, and shales dominate the area. All are potential reservoir and source rocks. In addition, as much as 15,000 feet of Lower Cretaceous rocks may be present including about 3,500 feet of reefoid shelf carbonates (Greenwood et al., 1977). Woodward and Duchene (1982) provide an excellent summary of the stratigraphy and reservoir characteristics of the rocks in this area.

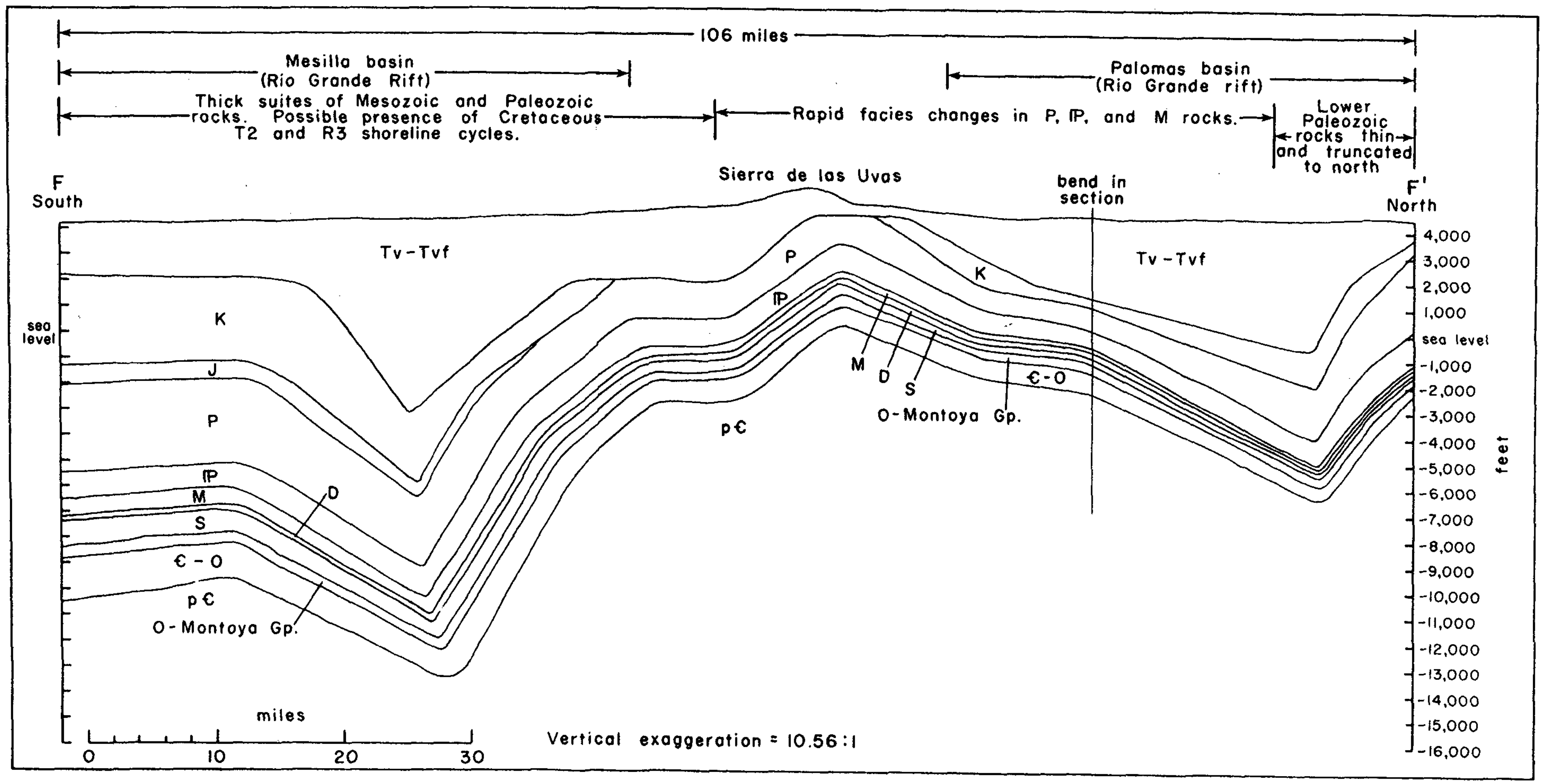


FIGURE 114—Cross section F–F'. Schematic structural–stratigraphic relationships in the Rio Grande rift of south-central New Mexico (see Fig. 29 for location). **Tv**, Tertiary volcanics; **Tvf**, Tertiary valley fill; **K**, Cretaceous; **J**, Jurassic; **P**, Permian; **IP**, Pennsylvanian; **M**, Mississippian; **D**, Devonian; **O**, Ordovician; **€–O**, Cambrian–Ordovician; **p€**, Precambrian.

Discussion—The dominant structural grain for the late Tertiary uplifts in the region is north–south. From west to east the major uplifts are the Peloncillo Mountains along the Arizona border, the Animas–Pyramid Mountains in the central part, and the Alamo Hueco, Big Hatchet, and Little Hatchet Mountains near the border with Mexico. Between the first two ranges is the Animas structural depression, and separating the latter two uplifts is the Playas Valley. The geology of the area has been studied in great detail (see references accompanying Woodward and Duchene, 1982; and Seager, 1983), but resolution of the complex structure is inconclusive. Several deep tests have encountered oil and gas shows (Thompson et al., 1978), but results of exploration have so far been disappointing.

Because of reverse and thrust faulting evident in many of the mountain ranges and its relationship to the Cordilleran geosyncline, the area has been described as analogous to or an extension of the overthrust belt of the western Cordillera. Drewes (1981) and Drewes and Thorman (1978) show a vast network of thrust faulting in a regional structural overview of southeastern Arizona and adjoining southwest New Mexico. Drewes (1978) and Woodward and Duchene (1982) provide a compelling case for northeast-directed compression during Laramide time with accompanying thrust faulting of regional extent. These are persuasive and credible rationales for flat-lying sole faults of regional extent with frontal compressed folds. Several deep wells have been drilled in southeastern Arizona predicated on younger, potentially oil-bearing sediments underlying surface rocks of Precambrian age thrust over them (Hansen et al., 1980). None of these wells penetrated a sole fault into younger sediments.

The area more closely resembles the results of traditional basement-cored "Rocky Mountain-type" uplifts and Basin and Range tectonism with uplift and tilting of large basement fault blocks and subsidence of nearby basins. Steep normal faults were rotated to become reverse faults along many mountain and uplift fronts, and compressional relief created local thrusting, much of it along bedding planes. But Late Cretaceous and Tertiary thrusting on the profound scale of the northern Rockies in southwestern Wyoming through western Alberta is not evident.

As with the discussions of target exploration areas 19, 23, and 24 (southern Jornada del Muerto, Palomas, and Mimbres–Mesilla Basins), it is suggested that those areas between the northwest–southeast-trending Laramide uplifts not involved with uplifts of the more recent north–south Tertiary fault blocks will contain remnants of pre-Laramide basins with thicker sedimentary sections. These are presumed to exist in target exploration areas 24 and 25 within the down-faulted Playas and Animas structural basins.

Wardlaw and Harris (1984) examined conodont color alteration in the Paleozoic rocks of Arizona and concluded that those strata in the Colorado Plateau province approximately north of latitude 32°30′ had thermal maturation values indicative of oil generation. To the south, including southwestern New Mexico, thermal values obtained indicate that these rocks have gas potential. Thompson (1981) reached substantially the same conclusion based on a detailed evaluation of organic chemical, porosity and permeability, and petrographic analyses of samples from outcrops and many of the deep wells in Hidalgo and Grant Counties. Hayes and Cone (1975) determined that Lower Ordovician carbonates may be considered good source rocks in this area.

Elston (1978, 1983) points out that this area is the site of numerous mid-Tertiary cauldron complexes and that the Peloncillo, Animas, and Pyramid Mountains seem likely to be underlain by plutons. Prominent structures in the area may also be influenced by these volcanic features. As a result of drilling into one of these surface features it was determined that the structure was the result of a Tertiary igneous intrusion that had thoroughly metamorphosed the lower part of the sedimentary section. However, analysis of the samples and other data from this well (KCM No. 1 Forest Federal, sec. 3, T31S, R18W, Hidalgo County) provided important information that the influence of heat and hydrothermal fluids associated with the igneous intrusion is limited to just a few thousands of feet, beyond which the sedimentary package is not affected (Thompson, 1977).

Cross section G–G′ (Fig. 115) illustrates schematically some of the structural and stratigraphic relationships described above.

Target exploration areas 27 and 28, San Agustin Basin—These two large areas, about 10,000 square miles, are essentially all of west-central New Mexico from the Zuni Mountains in the north to the Gila Mountains in the south. The New Mexico–Arizona State Line is the west boundary, and an arbitrary line from the Sierra Ladrone to the west side of the Fra Cristobal Mountains forms the east side.

Overview—Figure 116 includes parts of Socorro, Catron, Bernalillo, Valencia, and Cibola Counties and incorporates parts of target exploration areas 1 and 7. Within this part of the southwest region is a wide range of structural and stratigraphic complexities affecting exploration for oil and gas, commodities which have, so far, eluded the drill. The Rio Grande trough near the east edge of the area is flanked on the east in the Socorro area by low hills where Precambrian, Pennsylvanian, Permian, Triassic, Cretaceous, and Tertiary rocks are exposed. On the west are some moderately high ranges and mesas (6,500 to almost 10,000 feet) with Precambrian, Pennsylvanian, and Permian outcrops and locally thin erosional remnants of Mississippian. To the west in the northern one-half to two-thirds of the map area are extensive exposures of generally flat-lying sediments of Cretaceous, Triassic, Permian, and Pennsylvanian age. And in the northernmost part of the area there are small outcrops of Jurassic sediments. Early Tertiary sedimentary deposits unconformably overlie the Triassic and Cretaceous, thicken to the south, and include and are overlain by volcanics of andesitic to rhyolitic composition. In the south half of the area extensive basalt flows of Quaternary age are scattered from the Rio Grande valley to Arizona. Farther to the south are the thick Tertiary volcanics and associated sediments of the Mogollon Plateau.

In general, Paleozoic and Mesozoic rocks can be expected in the subsurface. Exceptions include the probable absence of Triassic rocks in the extreme southern part of the area and the absence of Pennsylvanian sediments over a large part of the northwest. Mississippian, Devonian, and Ordovician rocks may be present in the subsurface along the southwest edge of the area.

The stratigraphic intervals of primary interest for oil and gas exploration are the sandstone beds of Cretaceous age and the carbonate and sandstone intervals in the Permian and Pennsylvanian. Potential for the discovery of hydrocarbons in the area is considered only fair. This is based on a limited stratigraphic section from the standpoint of thickness and possible reservoir rocks. In addition, some areas would involve high-cost exploration efforts because of thick Tertiary sedimentary and volcanic cover, steep thermal gradients, difficult access, and remoteness from drilling supply centers. The possibility remains for the discovery of small- to moderate-size oil or gas pools, and there are areas where exploration costs can be maintained within reason for the smaller operator.

To the west of the Rio Grande valley and adjacent ranges a sequence of pre-Tertiary Paleozoic and Mesozoic rocks like those in the southern San Juan Basin can be expected. Whereas most intervals maintain identifiable lithologic characteristics, there is a marked thinning of Cretaceous and Triassic rocks to the south. In addition, the Pennsylvanian thins to the west and is absent over a large area (Fig. 116), which is the southern extension of the ancestral Zuni–Defiance uplift of probable Early Pennsylvanian age.

A number of oil tests have been drilled to the north of the thick cover of Tertiary volcanics. As in most exploration areas these wells tend to be concentrated either on the crests of surface structures or as additional tests of reported shows. In Figure 116 it can be seen that the majority of wells were drilled to the Precambrian and thus can be to some extent considered as adequate tests of the available stratigraphic section.

Certain areas have been defined in Figure 116 as suitable for exploration. Included is the area where potential reservoir rocks of the Cretaceous are buried. Targets include the transgressive and regressive sandstone bodies of the Dakota, Tres Hermanos, and Gallup and the deltaic sands of the Crevasse Canyon Formation. The maximum thickness is on the order of 2,000 feet.

An exploration area is not defined for the Permian. Rocks of this age should underlie almost all of west-central New Mexico and are fairly uniform in thickness ranging from about 2,000 to 2,500 feet. Within this section favorable reservoir rocks are present in carbonates of the San Andres, sandstones of the Glorieta, and sandstones and

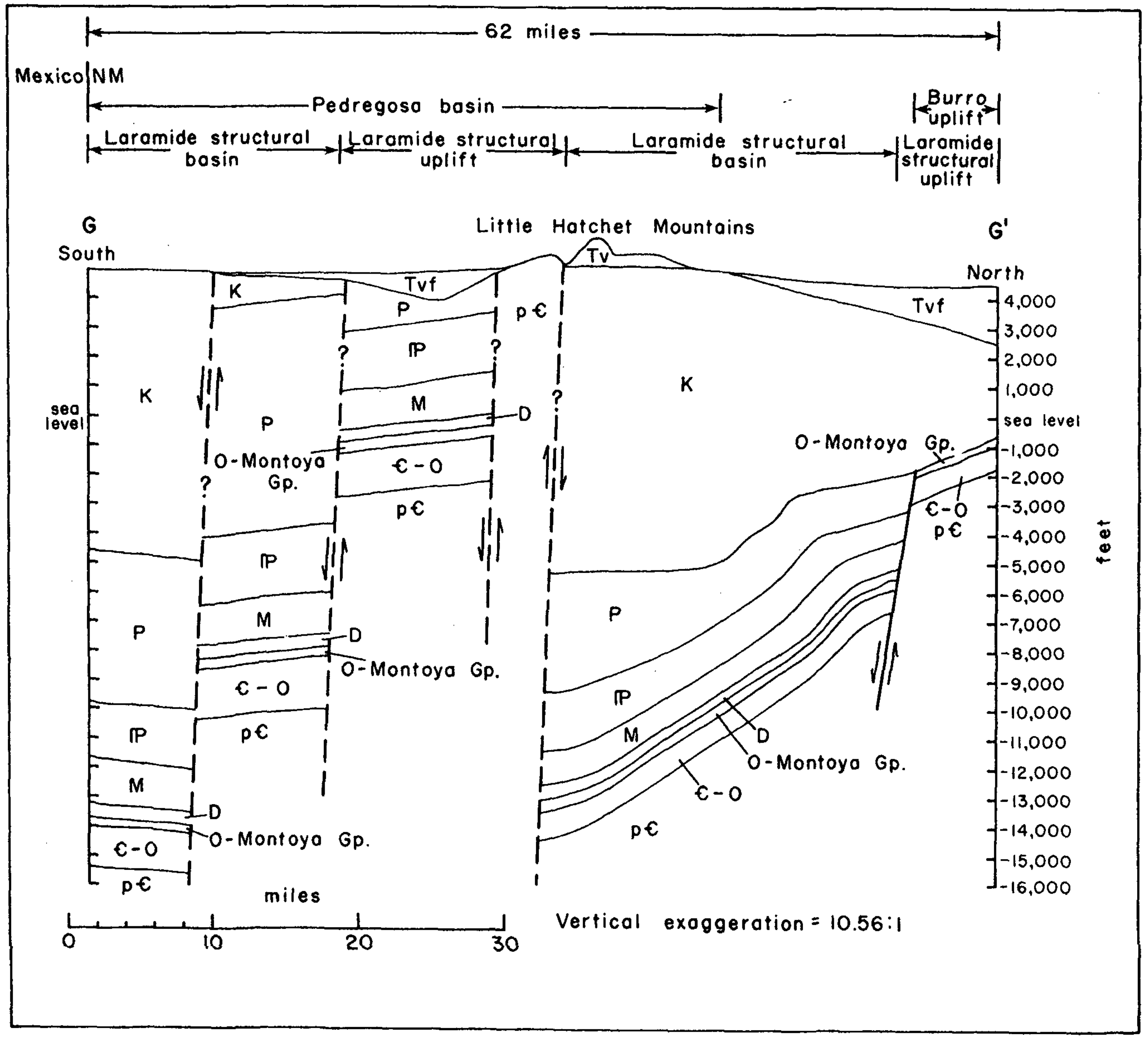


FIGURE 115—Cross section G–G′. Schematic structural–stratigraphic relationships in southwestern New Mexico from the Pedregosa Basin to the Burro uplift (see Fig. 29 for location). Tv, Tertiary volcanics; Tvf, Tertiary valley fill; K, Cretaceous; P, Permian; IP, Pennsylvanian; M, Mississippian; D, Devonian; O, Ordovician; Є-O, Cambrian–Ordovician; pЄ, Precambrian.

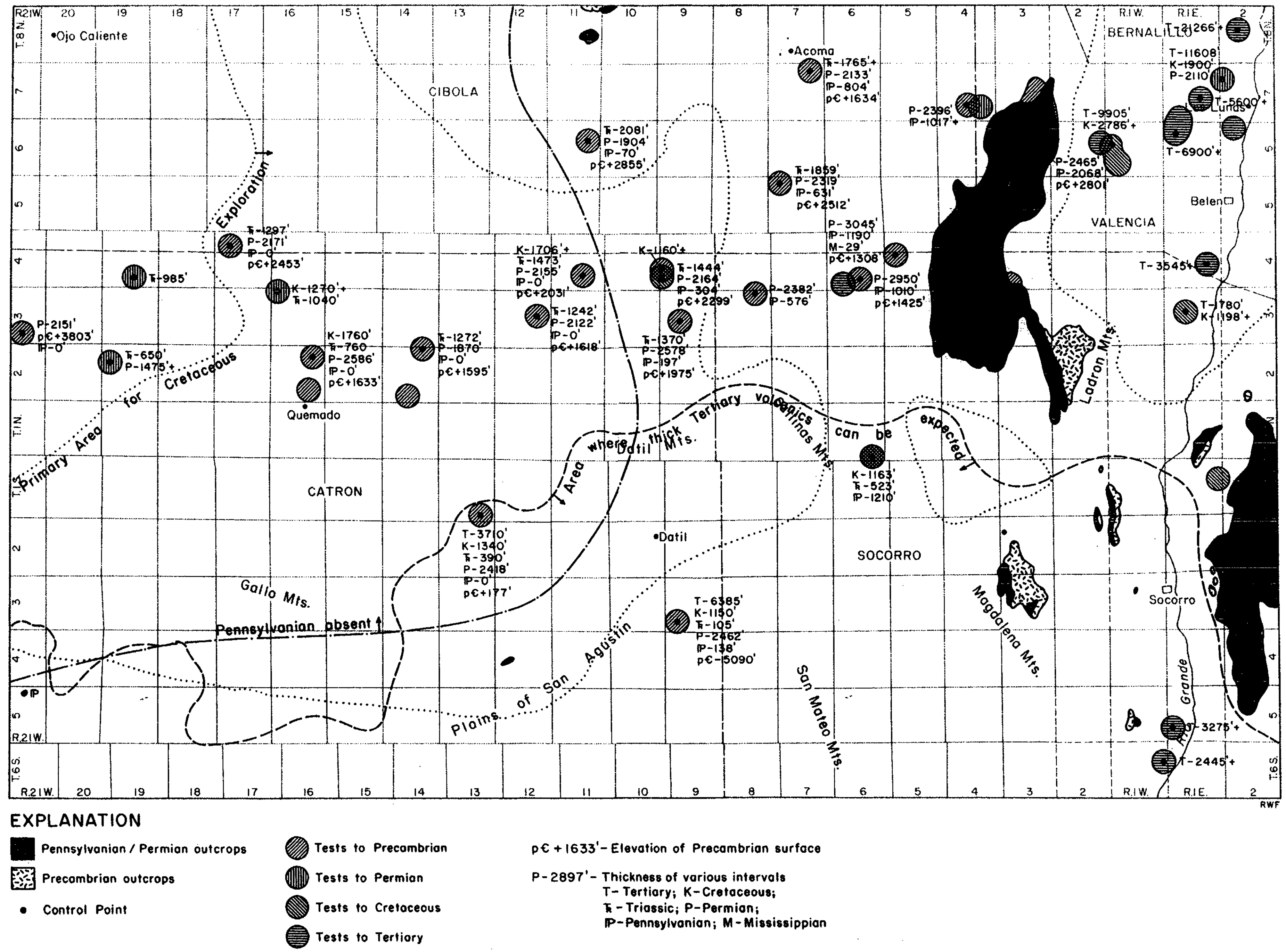


FIGURE 116—Status of exploration in the northern part of the southwest region.

carbonates of the Yeso. Figure 117 shows the stratigraphic section encountered in western Catron County.

Potential for the discovery of hydrocarbons in the Pennsylvanian lies between the outcrops on the east and the "0" line in western Catron and Cibola Counties. On Lucero Mesa the average thickness of Pennsylvanian penetrated is slightly more than 2,000 feet. A short distance west of Lucero Mesa the interval is less than 1,200 feet. This thinning seems to be the result of a combination of onlap of the Zuni–Defiance uplift with successively younger beds extending further to the west and of various periods of minor uplift and erosion within the Pennsylvanian.

Although data are limited, there appears to be a significant unconformity within rocks of Desmoinesian age. In the Spanel well (T4N, R5W), drilled on the Lawson anticline, the top of the Pennsylvanian is at a depth of approximately 3,530 feet (Fig. 118). From here to a depth of 4,040 feet the section is considered to be equivalent to the Virgil, Missouri, and upper part of the Desmoines Series. This is based on correlation with other wells. Fusulinid determinations for the lower part of the section are given on the log. This includes lower Desmoinesian to a depth of 4,435 feet and Atokan to a depth of 4,720 feet. The lowest fusulinid found was at a depth of 4,530 feet and it is possible that Morrowan beds are represented below this depth. It is interpreted that the Madera Formation includes the section from 3,530 to 4,505 feet and the Sandia Formation from there to the base of the Pennsylvanian.

The locations of most of the Pennsylvanian tests are on structural highs. A number of anticlines have been tested and others are present (Wengerd, 1959). These tests have been drilled on the crests of anticlines, and the structures may reflect later uplifts associated with the Zuni–Defiance positive. This could result in unconformity traps on the east flanks of the structures. Similar traps without surface expression might be present between the outcrop and the depositional edge of the Pennsylvanian. The most favorable area for exploration of the Pennsylvanian is a rather narrow north–south strip from the north edge of thick volcanic deposits to the north boundary of Figure 116 and just west of Lucero Mesa.

An area of thick volcanic deposits is defined in Figure 116. Within this area little is known regarding the total thickness of the Tertiary volcanic cover or the thickness and extent of Paleozoic and Mesozoic sedimentary rocks. An outcrop of Permian and Triassic rocks is present on Horse Mountain on the north side of the San Agustin Plains (T4S, R12W). Farther west (T5S, R21W) there is a small exposure of Pennsylvanian limestone that is thought to be a float block in the volcanics. Two wells have been drilled to Precambrian within the area of thick volcanic cover. In the Tenneco well (T1S, R13W) Tertiary volcanics and associated sediments are 3,710 feet thick. In the Sun well in T3S, R9W, this interval is 6,385 feet thick. Between these two wells the Cretaceous thins to the south from 1,340 to 1,150 feet and the Triassic from 390 to 105 feet. This thinning is expected to continue and it is possible that Triassic rocks are absent along the southern edge of the area. The Permian section is uniform while the Pennsylvanian thins to the northwest from 138 feet to absent in the Tenneco well. Based on regional studies (Foster, 1957; Kottlowski and Foster, 1959) the Pennsylvanian could be as much as 1,000 feet thick beneath the Mogollon Plateau. Older Paleozoic rocks including Mississippian, Devonian, and Ordovician may underlie the extreme southwestern part of the area.

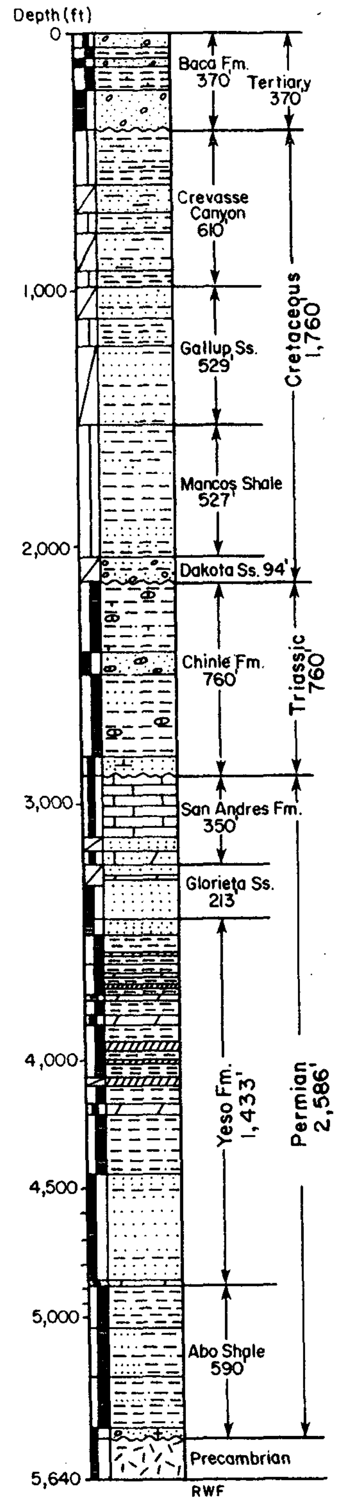


FIGURE 117—Stratigraphic section of western Catron County. Huckleberry No. 1 Federal, sec. 11, T2N, R16W, elev. 7,109'DF, total depth 5,642'. Color and lithologic symbols described in Figure 37 on page 33.

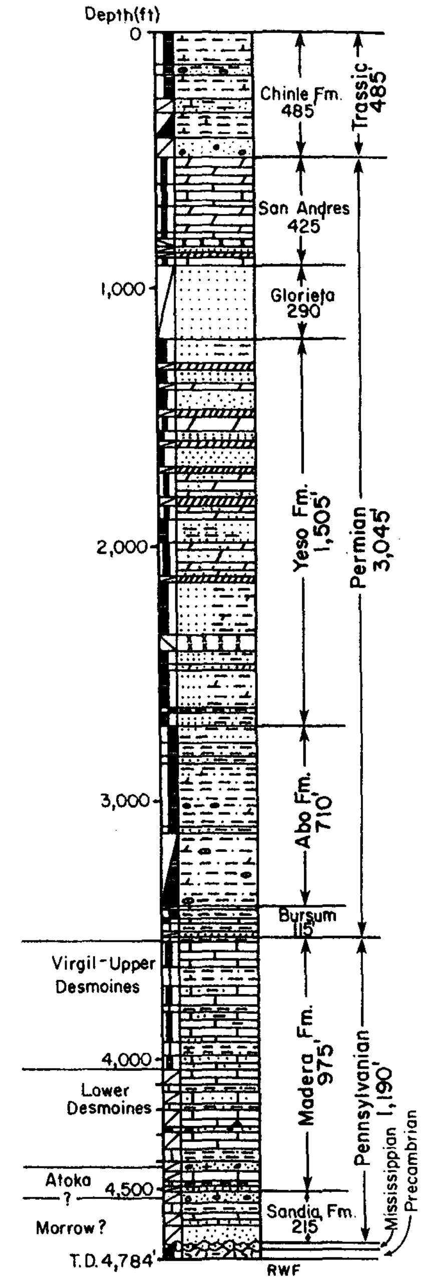


FIGURE 118—Stratigraphic section of northwestern Socorro County. Spanel and Heinze No. 1 Santa Fe Pacific R.R., sec. 17, T4N, R5W, elev. 6,057'GL, total depth 4,784'. Color and lithologic symbols described in Figure 37 on page 33.

In general the area of thick volcanic cover is not considered favorable for exploration. In addition to drilling thick sections of volcanic rocks, Tertiary intrusives can be expected in the underlying Paleozoic and Mesozoic sections. High temperatures, difficulty of locating potential traps, and the largely unknown nature of the pre-Tertiary section further complicate exploration in this area.

Objectives—Essentially, the distinction between target exploration areas 27 and 28 is that target exploration area 27, the southern part, has a volcanic cover of indeterminate thickness and has had no wells drilled in it west of the Rio Grande rift. However, data strongly indicate that it contains thick suites of Paleozoic rocks in the subsurface including sediments older than Pennsylvanian.

The northern part, target exploration area 28, has less volcanic cover and is more amenable to conventional exploration methods. It has had several wells drilled to Precambrian basement rocks. Data indicate an absence of rocks older than Pennsylvanian and, as the Zuni Mountains to the north are approached, the Pennsylvanian is absent and the Permian thins significantly.

The presence of reservoir rocks as well as their potential to contain producible hydrocarbons is speculative in both of these target exploration areas, especially in the southern part. However, extrapolation of limited gravity data obtained by Birch (1981) suggests that the lower part of the Upper Cretaceous (T-1, R-1, T-2, R-2 cycles) may be present in much of the region immediately beneath the cover of Tertiary volcanics and clastics. Cather and Johnson (1984) submit information implying that Laramide graben or structural synclines may contain Upper Cretaceous rocks. Jurassic and Triassic rocks thin to "0" lines from north to south.

Permian rocks are thin regionally around the Zuni Mountains as a result of exposure of this uplift during deposition. However, Heylmun (1981) describes a closed marine evaporite basin with a thick suite of lower Permian evaporites in the Holbrook Basin of east-central Arizona, which extends into west-central New Mexico. Peterson (1980) poses the existence of a thick Permian section in target exploration area 27 with a transition from red beds and evaporites found in wells and outcrops to the north to carbonate rocks in the south beneath the volcanic cover. His data indicate similarities to Permian depositional environments and lateral transitions in the Permian Basin of southeastern New Mexico and west Texas. It is not unlikely that these and other proprietary data are responsible for significant exploratory interest being focused on this area by the petroleum industry during the mid-1980's.

Pennsylvanian thicknesses were also affected by the Zuni and Defiance uplifts of New Mexico and Arizona lying northwest of target exploration area 28. Although almost 2,000 feet of Pennsylvanian rocks are found in the northeast part of this target area where the Rio Grande rift is approached, equivalent units are thin or absent in the northwestern part of the area because of nondeposition and postdepositional erosion. Sparse data and extrapolation convey the impression that Pennsylvanian units also thicken through the southeastern part of target exploration area 27 as the depositional Orogrande Basin is approached. The erosional–depositional wedge edges of Mississippian, Devonian, Silurian, Ordovician, and Cambrian rocks occur in or near the southern part of target exploration area 27.

Discussion—Little is known about the sedimentary package below the Tertiary volcanic cover. Where exposures of Paleozoics are present in the northern Black Range, they are often mineralized. Elston (1978) describes numerous Tertiary ash-flow-tuff cauldrons within an inferred Mogollon Plateau composite pluton covering much of this region. These volcanics are a deterrent to exploration because their thickness and what they cover cannot easily be predicted. However, they do not preclude the generation, accumulation, and preservation of hydrocarbons in any suite of sediments occurring beneath them.

The vast region encompassing target exploration area 27 and parts of target exploration area 28 cannot be discounted as a petroliferous province until a number of definitive wells have been drilled. Simple extrapolation from outcrops and wells in nearby New Mexico and Arizona strongly suggests that perhaps 2,000 to 3,000 feet of Cretaceous rocks and more than 6,000 feet of Paleozoic sediments could be present beneath the masking blanket of Tertiary material. Innovative seismic procedures and careful interpretation of the results may be imperative to the selection of locations that avoid thick Tertiary cover and structures influenced by intrusives.

See Kottlowski (1960) and Siemers (1983) for discussions of Pennsylvanian strata and Foster (1964) for evaluation of the structure, stratigraphy, and oil and gas possibilities in Catron County. Gries (1985) offers objective summaries utilizing seismic data in volcanic terrains.

Data sources

There are a number of places within New Mexico that provide information and expertise to the oil and gas industry. In the interest of making some of them more accessible to those unfamiliar with their location and services, the following listings are provided.

New Mexico State Government

New Mexico Research and Development Institute—Dr. Larry Icerman, Director. 1220 South St. Francis Drive, Piñon Building, Room 358, Santa Fe 87501, (505) 827-5886. Provides funding for a number of research investigations and development projects for New Mexico individuals and firms. Puts primary emphasis on entrepreneurial projects with spinoff economic benefits of creating in-state jobs and income. Offers professional advice on the status of "state of the art" technology, guidance to investigators in specialty fields, and access to an extensive library of energy research and development reports.

New Mexico Bureau of Mines and Mineral Resources—Dr. Frank E. Kottlowski, Director. Campus Station, Socorro 87801, (505) 835-5420. Is a repository for well samples, logs, and completion cards. Produces well spot maps. Maintains a professional staff of geological specialists familiar with the state's mineral resources. Publishes results of geological investigations that are directly and indirectly involved with oil and gas exploration.

Petroleum Recovery Research Center—Mr. David F. Martin, Director. Campus Station, Socorro 87801, (505) 835-5142. Conducts research and publishes results of investigations on hydrocarbon reservoirs and secondary and tertiary methods of oil recovery. Provides expertise on these and related production matters.

New Mexico State Land Office—William Humphries, Commissioner of Public Lands; Floyd Prando, Director, Oil and Gas Division. P.O. Box 1148 (State Land Office Building), Santa Fe 87504-1148, (505) 827-5760. Maintains records on all state mineral acreage. Establishes minimum bonus bids and royalty payments on state oil and gas leases. Conducts monthly sales (public auction) of state oil and gas leases. Interacts with lessees and other interested parties on rules and regulations relating to state-owned minerals. Has professional geological and engineering staff.

New Mexico Energy, Minerals, and Natural Resources Department—Dr. Thomas G. Bahr, Secretary. 408 Galisteo Street, Santa Fe 87503, (505) 827-7835. Regulates oil and gas and other mineral activities within New Mexico. Has an extensive library of energy-related publications and periodicals. Among its divisions are two that relate directly to the petroleum industry: (1) Mining and Minerals Division, 525 Camino de los Marquez, Santa Fe 87501, (505) 827-5970. Publishes annual statistics on oil and gas; provides professional geological-staff expertise on oil, gas, and other minerals. (2) Oil Conservation Division, William LeMay, Director. State Land Office Building, Santa Fe 87503, (505) 827-5800. Regulates the oil and gas industry; promulgates and enforces operating, development, and field rules and regulations; maintains a permanent file on all wells drilled in New Mexico with completion records and well logs; publishes annual statistical reports containing information on well status and production by category, location, and operator.

New Mexico Oil and Gas Accounting Division—Michael A. Cunningham, Director. P.O. Box 2308 (State Land Office Building), Santa Fe 87504-2308, (505) 827-5851. Is a division of the Taxation and Revenue Department that collects all special taxes levied on the oil and gas industry. Publishes monthly reports and annual summary of oil and gas production and tax receipts by category and location. Maintains permanent file of producing wells, monthly production, sale prices, and taxes levied. Maintains summaries of oil and gas production by operator and pool.

New Mexico State Library—Virginia Downing, Director. State Library Building, 325 Don Gaspar, Santa Fe 87503, (505) 827-3804. Is a division of the Office of Cultural Affairs that acts as a repository for all documents generated by state agencies as well as for other publications and periodicals containing information about New Mexico.

Universities

University of New Mexico—Dr. Gerald W. May, President. Scholes Hall, Room 160, Albuquerque 87131, (505) 277-2626. Has an excellent geological library and subscribes to a number of oil and gas industry publications. Department of Geology can provide thesis lists and interaction with professional geologist staff members, many of whom conduct research and publish in areas of interest to explorationists.

New Mexico State University—Dr. James E. Halligan, President. P.O. Box 3Z, Las Cruces 88003, (505) 646-2035. Department of Geology can provide thesis lists and interaction with professional geologist staff members, many of whom conduct research and publish in areas of interest to explorationists.

New Mexico Institute of Mining and Technology—Dr. Laurence H. Lattman, President. Socorro 87801, (505) 835-5508. Has an extensive geological library. Department of Geology can provide thesis lists and interaction with professional geologist and geophysicist staff members, many of whom conduct research and publish in areas of interest to explorationists.

United States Government

Bureau of Land Management—The regional office that includes New Mexico is located in the Joseph M. Montoya Federal Building (U.S. Post Office), Santa Fe 87501. Its Lands and Minerals Division, phone (505) 988-6211, maintains all records on federal oil and gas leases in New Mexico. Topographic maps with land status and mineral ownership at a scale of 1:100,000 are available here and also at district BLM offices in New Mexico. The Minerals Management Division at 435 Montaño Road NE, Albuquerque, 87107, (505) 761-4504 maintains files on all producing oil and gas wells, regulates operations, and collects royalties on federal and Indian leases in New Mexico. Most well files have electric logs and completion data. The BLM's Division of Operations at the Albuquerque Montaño Road address maintains well spot maps for the San Juan and Permian Basins.

U.S. Geological Survey—The water-resources division at 4501 Indian School Road NE, Albuquerque 87110, (505) 262-6654 has an excellent library of USGS and other geological book and map publications.

Los Alamos National Laboratory—Los Alamos 87445. Maintains an excellent scientific library of books and periodicals that is the most extensive available to the public in New Mexico. Scientific personnel include geologists whose investigations include tight gas sands research, and engineers with expertise in drilling in very high temperature environments.

Sandia National Laboratories—P.O. Box 5800, Albuquerque 87185. Scientific personnel include geologists with expertise in waste management, oil shale, volcanic regimes, and tight gas sands.

Private

New Mexico Oil and Gas Association—Darwin Van de Graaff, Executive Director. 1227 Paseo de Peralta, Santa Fe 87501, (505) 982-2568. Provides monthly newsletter to members and annual summary of oil and gas production, value of production, and taxes on production. Provides statistical data about the petroleum industry in New Mexico. Maintains legislative contacts and provides assessments of pending legislation.

Independent Petroleum Association of New Mexico—Alvin Baca, Executive Director. 440 Cerrillos Road, Santa Fe 87501, (505) 982-2500. Represents independent petroleum operators in governmental matters.

New Mexico Oil and Gas Engineering Committee—P.O. Box 127, Hobbs 88241, (505) 393-3411. Prepares monthly oil and gas production reports and annual summaries by pool, operator, and individual well. Membership required.

Permian Association, Inc.—200 West First Street, Roswell 88201, (505) 622-1711. Maintains extensive library of well logs, completion cards, spot maps, and oil and gas lease-ownership maps with primary emphasis on the Permian Basin and southern New Mexico. Membership required.

Geological Societies—Several geological societies provide weekly or monthly meetings with programs of interest to explorationists. Some offer annual meetings with field trips and accompanying guide books covering the geology of the field trip area. (1) Albuquerque Geological Society, P.O. Box 26884, Albuquerque 87125. (2) New Mexico Geological Society, Inc., Campus Station, Socorro 87801. (3) Roswell Geological Society, Inc., P.O. Box 1171, Roswell 88201. (4) Four Corners Geological Society, P.O. Box 1501, Durango, Colorado 81301. (5) El Paso Geological Society, Department of Geological Sciences, University of Texas at El Paso, El Paso, Texas 79968. (6) West Texas Geological Society, P.O. Box 1595, Midland, Texas 79702.

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