CHESAPEAKE

Summary of Samson Literature Contradicting its Geologic Testimony

BEFORE THE
OIL CONSERVATION DIVISION
Case No. 13493 Exhibit No. B-1
Submitted By: Rebuttal
Chesapeake Operating
Hearing Date: December 14, 2006

CHESAPEAKE

Summary of Samson Literature Contradicting its Geologic Testimony

Mr. Johnson has ignored Mr. Mazzullo's cautions in mapping the Morrow and in fact ignored his entire outline for exploration and development strategies for evaluating the Morrow.

- **Mazzullo states that** ***"using simplified models or gross isopach maps is not going to tell the whole story certainly not to the level of detail required to accurately predict reservoir orientations…" "If you treat the entire section as a single geologic/engineering unit, presumptions made regarding depositional environments and reservoir trends can be misleading and can result in either missed opportunities or dry holes."*** **Refer to:**
  - **Samson Exhibit 7 - p59** Slide: Lit Rebut 2 – **p 2**

- **Mazzullo also states that** ***"the first practices that must be abandoned are the treatment of the Morrow section as a single unit".*** **Refer to:**
  - **Samson Exhibit 7 – p60** Slide: Lit Rebut 3 – **p 3**

- **Mr. Johnson has followed none of the techniques outlined by Mazzullo. Mazzullo states that** ***"the Morrow should be divided into smaller sequences… based initially upon "first pass" correlations using large scale logs".*** **Followed by** ***"detailed sample analysis".*** **Refer to:**
  - **Samson Exhibit 7 – p60** Slide: Lit Rebut 3 – **p 3**

- **Then** ***"isopach maps of each small sequence drawn to determine (1) the precise geometry and orientation of each reservoir, and (2) any potential terminations of reservoirs…".*** **Then** ***"production histories and bottom hole pressure data … may be useful in determining pressure separation…".*** **Refer to:**
  - **Samson Exhibit 7 – p61** Slide: Lit Rebut 4 – **p 4**

- **Mr. Johnson has done exactly what Mazzullo has stated should <u>not</u> be done and has not attempted any of the geologic or engineering work that Mazzullo has outlined.**

- **Mr. Johnson has ignored Mr. Mazzullo's reference that in Eastern portions of the Delaware Basin the Central Basin Platform was a local sediment source for the Morrow. Refer to:**
  - **Samson Exhibit 7 - p55, 56 –** p 5,6

- **The Central Basin Platform and the Delaware Basin began forming in late Mississippian into the early Pennsylvanian. Morrowan sediments were derived from the Pedernal Uplift to the NW and locally from the CBP to the East. The Midland Basin was not yet formed and was an emergent area of non-deposition and minor erosion. This is consistent throughout the literature. Refer to:**
  - **Samson Exhibit 7 - p55, 56** p 5,6
  - **Samson Exhibit 12 - p38, 39, 42** p 7,8,9
  - **Samson Exhibit 15** p 10
  - **Samson Exhibit 15A - p77, 78** p 11, 12
  - **Samson Exhibit 16 – p159, 163** p 13,14
  - **Samson Exhibit 18 – p159, 160** p 15,16,17,18,19
  - **Samson Exhibit 9 – p107** p 20
  - **Samson Exhibit 10 – p417** p 23
  - **CHK Exhibit GEO 13** Slide: Lit Rebut 9 - p 24

- **The Central Basin Platform was an exposed landmass during Morrowan time and shed sediments into the Delaware Basin in an East to West direction. Consensus of the literature is evident in the various paleogeographic maps for the Morrow. Review these sources:**
  - **<u>SAMSON EXHIBIT 7 p. 55</u>** Slide: Lit Rebut 5 – p 5
    Purpose: Shows Paleogeographic map of the Delaware Basin in Morrow time with the CBP as a sediment source.
  - **<u>SAMSON EXHIBIT 12 p. 39 also CHK Exhibit GEO 12</u>**
    Slide: Lit Rebut 6 – p 8
    Purpose: Shows Paleogeographic map of Penn. with Morrow sediment source from CBP.
    States the Penn clastic input was from Pedernal and the CBP.

- SAMSON EXHIBIT 12 p. 42
  Slide: Lit Rebut 7 – p 9
  Purpose: Shows Paleogeographic map of Morrow with sediment source from CBP.
  Shows East-Westerly sediment transport direction
  Shows the outline of the Delaware Basin.
  Note the changing sediment transport direction arrows as you follow the curvature of basin.
- SAMSON EXHIBIT 18 p. 160 ZOOMED bottom right page Slide: Lit Rebut 8 – p 19
  Purpose: Shows paleogeographic map of SE New Mexico for Morrow.
  Shows CBP highlands to East and depositional systems from East-Westerly direction.
  Shows sediment depositional patterns rimming basin, trending towards the axis of the Delaware Basin.
- CHK EXHIBIT GEO 13 p 56 Slide: Lit Rebut 9 – p 24
  Source: Geologic Wonders of West Texas 2004
  Authors: McGookey, Hanson
  Purpose: Shows paleogeographic map of Morrow.
  Shows CBP highlands to East and area of non-deposition.
  Shows sediment source of CBP.
  Shows major Morrow river systems with 2 coming off of CBP in vicinity of KF trending East to Westerly towards the Delaware Basin.
  States Morrow sediment is multi-sourced including CBP.

- **Mississippian rocks were eroded from the surrounding exposed land masses and were viable sediment sources for Morrow sand deposition. Erosion of the Barnett and Chester sands and the lower Mississippian cherts contributed sediment. Refer to:**
  - **Samson Exhibit 6 – p75** p 25
  - **Samson Exhibit 10 – p414, 415, 417** p 21,22,23
  - **Samson Exhibit 12 – p38** p 7
  - **Samson Exhibit 15** p 10
  - **Samson Exhibit 15A – p77** p 11

- **The axis of the Delaware Basin lies to the West of the KF 4 St. #1 area, near the Lea/Eddy county line and trends in a NNW-SSE lineation. Refer to:**
  - **Samson Exhibit 40 – Fig 1-7** p 27
  - **Samson Exhibit 12 - p39, 42** p 7,9
  - **Samson Exhibit 18 – p160** p 18,19
  - **CHK Exhibit GEO 13** Slide: Lit Rebut 9 - p 24

- **In the vicinity of the KF 4 St. #1, sediments originally eroded from the Pedernal and deposited during Transgression and High Stand along the flanks of the CBP were then eroded again from the CBP and re-deposited by dip trending incised fluvial systems during Regression and Lowstand. Supplemental sediments were derived from erosion of the Mississippian section off the exposed CBP itself. This resulted in an overall East-West deposition direction by dip oriented fluvial and fluvio-deltaic systems in the vicinity of the KF 4 State #1. Refer to:**
  - **Samson Exhibit 40 – p2** p 26
  - **Samson Exhibit 40 – Fig 3-29 and CHK Exhibit GEO 17** p28
  - **Samson Exhibit 18 – p159, 160** p 15,16,17,18,19

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isting paleo-topographic highs (Figure 4). These changes are not always obvious when correlating logs, but are often suggested by anomalous changes in thickness of the entire Morrow section (Figure 5) and repeated correlation busts. In other areas, such as eastern Lea County, structures were sporadically reactivated throughout the Pennsylvanian (and through the early Permian), in some places inhibiting deposition and in others, resulting in removal of large portions of the Morrow section (Figure 6).

IMPLICATIONS FOR MORROW EXPLORATION AND DEVELOPMENT

The net result of the tectonic and exposure history of the Morrow Formation was a series of subtle to more recognizable intraformational unconformities throughout the Morrow clastics. These unconformities and re-activation surfaces are easily missed with conventional mapping and may be very important when tracing a sandstone reservoir across a field area or in regional reservoir trend analysis. It is clear, therefore, that evaluating the Morrow using simplified models or gross isopach maps is not going to tell the whole story, certainly not to the level of detail required to accurately predict reservoir orientations and new well locations.

When mapping the Morrow, many operators will either choose specific mapping intervals based on what are assumed to be correlative shale markers, or treat the entire section as a single geologic/engineering unit. In either case, presumptions made regarding depositional environments and reservoir trends can be misleading, and can result in either missed opportunities or dry holes. For example, what may appear to be correlative shale

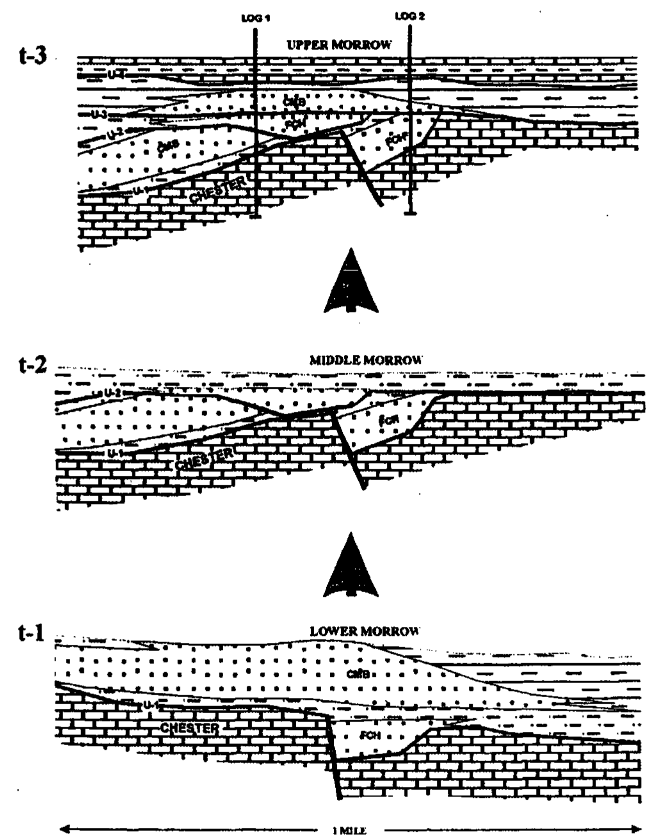

Figure 7. Schematic developmental history of the Morrow clastics representative of conditions observed throughout Eddy and Lea Counties, New Mexico. FCH= fluvial channels, CMB= channel mouth (or deltaic)bars. Intraformational unconformities are labeled U-1 through U-4. Log sections are referenced in Figure 8.

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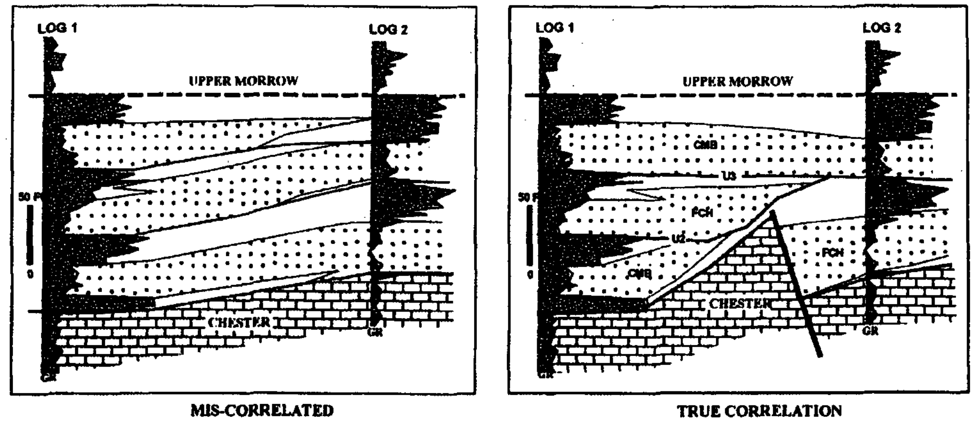

Figure 8. Two interpreted gamma ray log sections from the previous figure. The true correlation accurately reflects conditions shown in Figure 7.

markers may in fact be two entirely different time units, despite similarities in electric log signatures that are used for correlations. To illustrate this point, Figure 7 shows development of a hypothetical Morrow clastics section in present-day Eddy County, New Mexico that is a scenario common to the Morrow throughout the region. Pre-existing Late Mississippian faults in places may have influenced deposition of south-trending fluvial channels in the basal Morrow, during an initial lowstand event. These fluvial sands were superceded by deposition of an east-trending channel mouth bar or deltaic sand during a subsequent highstand. Prior to the end of the lower Morrow, the deep fault was reactivated, and movement along it caused tilting of pre-existing beds. Part of the channel mouth bar sand was eroded by an incised fluvial channel during another lowstand. Sometime in the middle Morrow, another highstand channel mouth bar unit built up and was partially reworked by wave energy as the sea advanced further shoreward.

Figure 8 shows gamma ray log sections through the Morrow illustrated in Figure 7, taken less than one mile apart. This figure illustrates how the Morrow section in closely-spaced wells can be easily mis-correlated based upon log signatures. The mis-correlated interpretation differs dramatically from the true correlation as depicted in figure 7. Reservoir mapping based on the mis-correlation would incorrectly project the orientations of the individual sand bodies that make up the section. For example, south-trending fluvial sands might be correlated to east-trending channel mouth bar sands in adjacent wells, resulting in a map interpretation with erroneous reservoir morphologies. New or offset wells based on such a map may not be optimally located.

EXPLORATION/DEVELOPMENT STRATEGIES

Log correlations alone are not a reliable means by which to map sequences in the Morrow clastics because in many instances, the mapper will inadvertently cross time lines and not correlate time-equivalent units. Biostratigraphic zonation of sandstone sequences is not possible because of the lack of diagnostic fossils. Although it may seem an impossible task to effectively map and correlate the Morrow, there is a vast database of well logs and well cuttings in southeastern New Mexico that, when used together, may help delineate correlative units much better.

The first practices that must be abandoned are the treatment of the Morrow section as a single unit and attempting to map too large an area at a time. Treatment of the whole section as a single geologic unit has two major drawbacks: (1) it blends different depositional environments that can exist in a single well bore or field area, and (2) it fails to recognize any missing section that can arise from intraformational unconformities. Mapping a large area increases the odds of correlation busts, especially in tectonically complex areas. In either case, the explorationist may either underestimate the potentials for multiple reservoir trends or project trends into areas where sands may be missing. The Morrow should be divided into smaller sequences, ideally no thicker than about 25 feet apiece, based initially upon "first pass" correlations using large-scale electric logs. These correlations may not all hold up under further analysis. The next step is to try and identify key time correlative markers with detailed sample analyses, looking for such features as soil horizons, unique and locally continuous marker beds, or laterally persistent lithologic as-

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sociations. The aim here is to place each general sequence into its proper depositional facies context. Sandstones should be related both laterally and vertically to the facies in which they are encased (Mazzullo, 1999). Once gross depositional sequences are isolated, the log correlations can be adjusted if needed, and isopach maps of each small sequence drawn to determine (1) the precise geometry and orientation of each reservoir, and (2) any potential terminations of reservoirs due to intraformational unconformities. In field extension studies, production histories and bottom hole pressure data (if available) of each Morrow well may be useful in determining pressure separation between zones in adjacent wells that were thought to be correlative. They can also be used to identify suspected permeability barriers that exist between closely-spaced sand bodies that may actually reflect mis-correlated, pressure-separated sand bodies.

CONCLUSIONS

The Morrow Formation of southeastern New Mexico is a complicated depositional system that had been subjected to syn- and post-depositional tectonically-induced changes that are not always recognized or obvious to the exploration or development geologist. Many dry holes or poor producers have been drilled in the Morrow when it seemed a sure bet that "the thickest sand is going off in that direction". Whereas loss of reservoir sands can be related to such phenomena as clay plugging in the case of a fluvial channel, it can also be attributed to re-activation and at times, complete removal at an intraformational unconformity. It is important to know where these surfaces are in a section, and also important to realize that abrupt changes in section can happen within very short lateral distances and more than once within a single well. Consequently, it may be an exercise in futility to try and map too large an area of the Morrow at a time; efforts should focus on smaller mapping areas and vertical sequences.

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"The Permian Basin: Providing Energy For America", D. T. Grace, G. D. Hinterlong, eds.,
West Texas Geological Society Publ. # 99-106

Significance of Intraformational Unconformities in the Morrow Formation of the Permian Basin

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ABSTRACT

The tectonic history of the Morrow Formation in the Permian Basin involved numerous syngenetic and post-depositional uplift and exposure events which locally profoundly modified its siliciclastic reservoir section. These multiple events created numerous internal stratigraphic truncations or discontinuities. Consequently, *stratigraphic correlations* of pay sandstones and reservoir trends in the Morrow are often difficult, even between closely-spaced wells. Intraformational unconformities or re-activation surfaces are easily missed with conventional mapping and may be very important when tracing a sandstone reservoir across a field area or in regional reservoir trend analysis. Presumptions made regarding depositional environments and reservoir trends based on log correlations alone can be misleading, and can result in either missed opportunities or dry holes.

INTRODUCTION

Natural gas reservoirs of the Lower Pennsylvanian Morrow Formation are once again in the spotlight as one of the hottest plays in the Permian Basin because of the recent drop in oil prices. Renewed interest in the play has recently resulted in an acceleration of exploration and infill drilling of Morrow sandstone targets in Eddy, Lea and Chaves Counties, New Mexico, and in the Delaware Basin of far west Texas (Figure 1). The Morrow, as with other deep gas plays in the same region, has always been an attractive target in times like this *because of its potential for substantial gas reserves,* but finding good Morrow wells has often been elusive. Diagenetic factors affect reservoir performance in the Morrow and have been discussed elsewhere (Mazzullo, 1999a; Mazzullo and Mazzullo, 1984; 1985). The purpose of this geologic note is to show how the geologic development of the Morrow section was more complex than previously thought, and how the tectonic development of the formation affected reservoir trends and continuity. An understanding of these mechanisms is fundamental to the success of any exploration or exploitation program *for these reservoirs.*

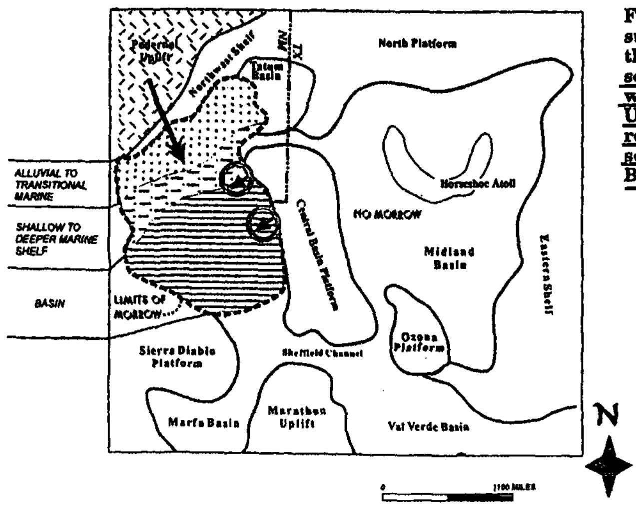

Figure 1. Location of the subsurface Morrow Formation in the Permian Basin. The major source for Morrow sediments was the ancestral Pedernal Uplift (large arrow). Small arrows denote limited source of sediments from the Central Basin Platform.

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GEOLOGIC DEVELOPMENT

General

The Morrow Formation in southeastern New Mexico and west Texas produces from sandstone reservoirs that were deposited in environments ranging from fluvial through and including deeper water marine (Mazzullo and Mazzullo, 1985; Mazzullo, 1999a). The general patterns of major facies tracts in the Morrow reflect basinward (generally north to south) transitions from alluvial to deep water sedimentation along any given time line (Figure 1). The developmental history of the Morrow also involved numerous local to regional syngenetic and early post-depositional tectonic uplifts and glacio-eustatic exposure events that overprinted depositional facies. These modifications to the section, if not recognized, could create problems in correlating pay sands and tracing reservoir trends. It is not always obvious from subsurface mapping to what extent these factors affected the section in any given area.

The Morrow Formation in southeastern New Mexico has been subdivided by many workers into informal lower, middle (both siliciclastic-rich) and upper (carbonate-rich) units (Figure 2), separated by what are assumed to be regional transgressive shale markers. Most of the significant natural gas reserves from the Morrow come out of sandstones in the lower and middle units, which together form the so-called "Morrow clastics" that are referred to in this paper. For the most part, the division between the lower and middle units holds up across large mapping areas, and is marked by a major highstand event followed by a drop in sea level in earliest middle Morrow time (Mazzullo, 1999a). The top of the middle Morrow unit, however, is not as easy to correlate and is often ambiguous, as are other shale markers that occur throughout the clastics section. These other shale units are also used by many workers as markers to correlate wells across fields or over larger mapping areas.

Paleozoic Tectonic History

The geologic record of the Permian Basin includes several major high-order Paleozoic tectonic episodes that have always been assumed to be the major events that shaped the basin outlines and structures. But a number of lower-order, episodic events were also important to the development and/or preservation of reservoirs, particularly throughout the Lower Pennsylvanian. Figure 3 is a schematic diagram that shows the relative magnitudes of tectonic events that were important to development of the Permian Basin. Tectonically influenced lithologic development and sporadic moderate-duration exposure events have been documented in Ordovician, Silurian, and Devonian carbonates (e.g., Holtz and Kerans, 1992; Troschinetz, 1992; Mazzullo, 1990), where they had profound influences on reservoir preservation and porosity development.

A major tectonic event occurred at the end of the Mississippian (Wright, 1979) at which time the outlines of the major features of the present-day Permian Basin began to take shape. The Central Basin Platform, for example, was a low-relief feature at this time. In some places, the initial structuring event was followed by large-scale tilting and erosion of part of the Upper to Lower Mississippian section (e.g., Mazzullo, 1999b). The next high-order basin-shaping event occurred in the Late Atoka, prior to deposition of the Strawn carbonate. Significant lower-order episodic tectonism and erosion, however, occurred throughout the Morrow and into the Early Atoka, culminating locally with

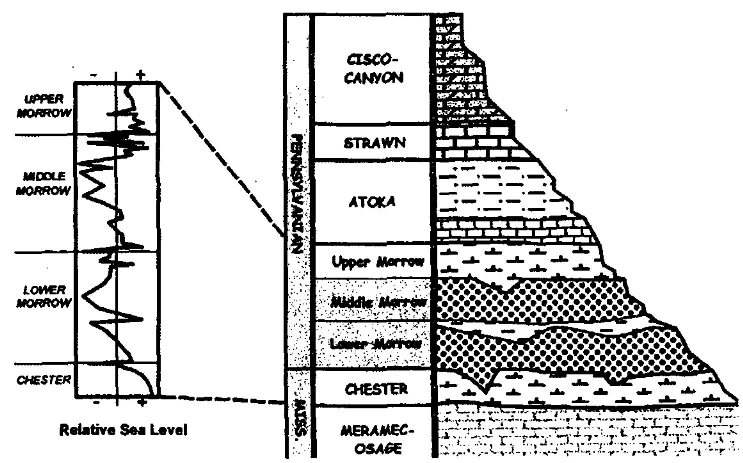

Figure 2. The major gas reservoirs in the Morrow are in sandstones of the lower and middle units. Depositional environments shifted laterally across a low-gradient shelf through time in response to repeated glacio-eustatic sea level changes. During low stands, exposure reactivated parts of the section, and concurrent uplifts contributed to localized truncation of reservoir sands (after Mazzullo, 1999a).

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The top and base of the Mississippian limestone is usually easily recognizable in well samples and mechanical logs (Grant and Foster, 1989).

The Mississippian in Kalinga Corporation's Margaret no. 1 well, along the Hovey anticline in the Glass Mountains area, is predominantly a black shale with minor amounts of limestone. The shale is gray to black, hard, platy, pyritic, organic and very siliceous. The limestone is brown to dark-brown, microcrystalline to very finely crystalline, generally clean, commonly sandy, and dolomitic (Bloom, 1988). In Dodson Texas American Syndicate no. 1, the unit is 52 m thick (Stevens, 1957).

The Mississippian limestone in Gaines and Andres Counties reaches 335 m thick. In Humble's Antelope Draw no. 1 it consists of over 76 m of crinoidal limestone, but in Kalinga Corporation's Margaret no. 1, 9.6 km southeast of the Antelope Draw well, it is only 15 m thick. Thus, overall, Mississippian limestone thins southward over the study area.

Barnett Shale

Overlying the Mississippian limestone is an upper unit, called the Barnett Shale, consisting of partly silty, brown shale and containing very fine-grained sandstone and siltstone (Hayes, 1964; Wilshire et al., 1972; Grant and Foster, 1989). The Barnett Shale is on the order of 60-140 m, thickening somewhat to the west of the Pecos River. In some places the total thickness of Mississippian strata can reach 250-335 m (Netherland et al., 1974). In Kalinga Corporation's Margaret no. 1 well, the Barnett consists of 60 m of shale with minor units of sandstone and limestone. The shale is gray to dark-gray towards the top, becoming dark-gray or black with depth; the shale is hard, siliceous, subfissile, organic, and very pyritic (Bloom, 1988).

In the area of Carlsbad, the top of the Mississippian below the "last" or lowest Pennsylvanian sand is called the Chester member, an informal unit which is composed of fine-grained sandstone, siltstone, argillaceous limestone, and shale (Andersen, 1976). The Chester interval is usually considered to be of Mississippian age, but may actually be the lowest part of the Pennsylvanian sequence. The Chester represents the first progradation of clastics from the Pedernal landmass and entrance into pre-delta deposition, and it signals the beginning of Pennsylvanian sedimentation in the basin.

The Barnett Shale was the result of tectonic movement at the onset of the Ouachita orogeny (Gardiner, 1990). Sedimentation continued unabated in the Tobosa Basin until the Late Mississippian, but beginning at that time there was a tectonic upheaval that would, in the Pennsylvanian, divide the Tobosa Basin up into the Midland Basin, Central Basin Platform, and Delaware Basin (Fig. 11C). This ended the existence of the Tobasa Basin, but during the 200 my or so from the Ordovician to Late Mississippian, this ancient basin accumulated as much as 2000 m of dolomite, limestone, shale, and sandstone — a continuous sedimentary record interrupted only by relatively brief periods of exposure at the end of Early, Middle, and Late Ordovician time, and again at the end of the Silurian, Early Devonian, and Mississippian periods.

Pennsylvanian

The history of the Delaware Basin as a separate entity began with the rise of an Early Pennsylvanian medial ridge in the Tobosa Basin, brought about by the Marathon-Ouachita orogeny which was the dominant structural event that determined the nature of Pennsylvanian sedimentation (Galley, 1984). Movement along zones of weakness inherited from Precambrian faulting (Fig. 9) induced the emergence of a complex series of fault blocks near the center of the Tobosa Basin (collectively known as the Central Basin Platform), which divided the Tobosa Basin into the Midland Basin on the east and the Delaware Basin on the west (Figs. 10B and 11C). In the southwestern part of the Central Basin Platform (near Fort Stockton, Texas), coarse, arkosic sandstone, vari-colored shale, and subordinate carbonates of Pennsylvanian age cover a large area of the shelf and directly overlie the Precambrian basement, the intervening Paleozoic rocks having been eroded away from the uplifted fault block (Mazzullo, 1986). Also during this time tectonic activity increased on the Diablo Platform to the west of the Delaware Basin (Fig. 13), and these rocks were folded, faulted, and deeply eroded prior to the transgression of the Permian sea. The highlands which occupied the Apache Mountain area subsequent to uplift were stripped down to Ordovician rock, as can be seen in Humble's Reynolds Cattle Company "B" no. 1 well in the Apache Mountains where Permian Wolfcampian beds rest unconformably on the Ordovician Bliss Sandstone. In the Sierra Diablo west of the Apache Mountains, Wolfcampian beds rest on Precambrian rocks.

The Delaware Basin subsided rapidly during Pennsylvanian time. Material was eroded from the Pedernal uplift ("Ancestral Rockies"), Diablo Platform, Marathon-Ouchita fold belt (Fig. 13), and other highland areas, and was deposited as thin sequences of sand and shale with interbedded carbonates on and along the edges of the shelves. A deep, starved, shale basin occupied the central and southern parts of the broad Delaware depression throughout the Pennsylvanian, and during this period of geologic time approximately 600 m of sediment accumulated in the basin. Within the area of the Northwest Shelf, intrashelf basins (such as the Tatum Basin; Fig. 18) formed in the Late Pennsylvanian as a result of regional tectonism, and these persisted until the earliest Permian when the basins became filled (Grover, 1993).

Provincial series names for Pennsylvanian rock in the study area are: the Morrowan, Atokan, Des Moinesian, Missourian, and Virgilian. Equivalent formations (groups) are the Morrow, Atoka, Strawn, Canyon, and Cisco, respectively. From a petroleum standpoint these names are somewhat arbitrary, being based on a number of log tops and facies changes which are difficult to correlate from well to well (Grant and Foster, 1989). Meyer (1966) indicated a

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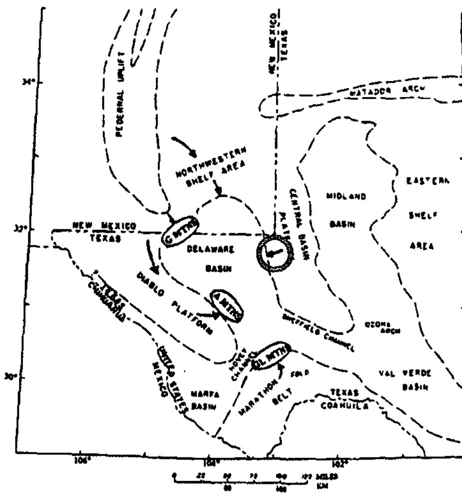

FIGURE 13—Paleogeography of Pennsylvanian time showing approximate location (dashed lines) of land masses and submerged areas. The Pedernal uplift, Diablo Platform, Marathon-Ouachita fold belt, and Central Basin Platform supplied sediment to the Delaware Basin during the Pennsylvanian and also later, in the Permian. After Hayes (1964).

maximum of 900 m of Pennsylvanian rock in the Delaware Basin area, but in an Eddy County reference well, it is only 810 m thick. Pennsylvanian rocks thin to the east and are absent as a result of erosion on fault blocks associated with the uplift of the Central Basin Platform, or as the result of onlap.

The record of Pennsylvanian rock has been recovered mostly from oil and gas wells in subsurface units (Morrow, Atoka, Strawn, Cisco and Canyon), but in the Glass Mountains Pennsylvanian rocks do crop out (the Gaptank Formation). These outcrops make up less than 5% of Pennsylvanian rock strata in the Delaware Basin and cover only the Late Pennsylvanian, but they constitute important field evidence for sedimentary conditions during this time.

Morrowan Series

Morrow Formation

The Morrow Formation of Lower Pennsylvanian age lies unconformably over Mississippian rocks (Fig. 8). A rapid subsidence of the Delaware Basin portion of the old Tobosa Basin began in Early Pennsylvanian time and clastics and carbonates were deposited in this new basin (Fig. 11C). The Morrow varies considerably over its range, consisting of limestones, sandstones, shales, and siltstones (James, 1985). Over much of the area it is a fine- to coarse-grained and conglomeratic sandstone and gray shale with some interbedded limestone and, in the west, it is a red shale and limestone pebble conglomerate. In the Delaware Basin reference well located in Eddy County, the bulk of the Pennsylvanian has been assigned to the Morrow; here, the Morrow interval is 508 m thick and 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, oolitic limestone in the lower part (Grant and Foster, 1989).

James (1985) divided the Morrow Formation into the lower, middle, and upper members (also designated the "A", "B", "C" zones, respectively; Fig. 14). The lower Morrow rests unconformably on the underlying Mississippian Chester member or Barnett Shale. The middle Morrow is marked by a prominent basal shale, called the "Morrow shale" by James (1985, p. 1044) which consists of shales and sandstones. The upper Morrow consists of limestone with interbedded shales and sands, and the top of the Morrow is commonly referred to as the "top of the Morrow clastics."

From the Chester member (last of the Mississippian beds) to the Morrow "C" zone (youngest of the Morrow beds), four pulses of prograding clastics, separated by transgressive (and radioactive) marine shales, record Morrow fluctuations from a marine to primarily deltaic environment (Andersen, 1976; Fig. 15). Sand bodies within the Morrow are primarily of fluvial-deltaic origin; sands represent channels and point bars (James, 1985). The sand bodies are multiple, stacked, and overlap each other. The composite thickness of the lower and middle Morrow intervals can reach as much as 510 m in the deeper parts of the basin and reflects the maximum progradational episode of Pennsylvanian clastic input into the basin from the surrounding Pedernal highlands to the north and west and Central Basin highlands to the east (Fig. 16). Subsequent upper Morrow sediments record a major marine inundation of this clastic wedge prior to Atokan time wherein areas on, or immediately adjacent to, the source areas received little to no Morrow sedimentation.

Atokan Series

Atoka Formation

The Delaware Basin continued to receive an uninterrupted input of sediment in Atoka time. The basal contact of the Atoka Formation appears to be conformable with the below-lying Morrow. The Atoka is a brown, fossiliferous limestone with interbedded shale in its lower portion and primarily shale with occasional limestone in its upper portion (Netherland et al., 1974). The unit also contains light- to dark-gray chert and intervals of poorly-sorted sandstone (commonly conglomeratic) which continue into the easternmost part of the study area. In the Delaware Basin reference

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Lindsay, Garber, James, Speer

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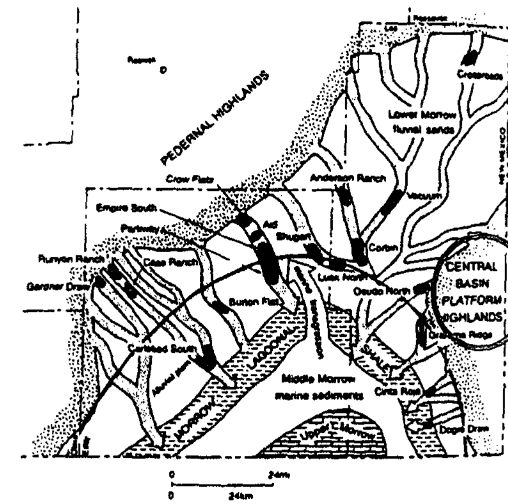


FIGURE 16—Schematic paleogeographic map of southeastern New Mexico with clastic depositional axes and related facies patterns during early Morrowan time. Several Morrow reservoirs have been superimposed. The Delaware Basin study area is shown in outline. From James (1985) and Speer (1993e).

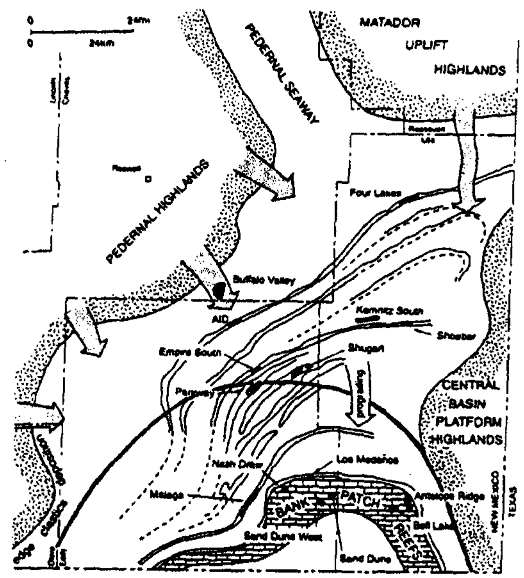


FIGURE 17—Schematic paleogeographic map of southeastern New Mexico during Atokan time with various progradational strandlines and their resultant sand trends. Several significant gas reservoirs are superimposed. The Delaware Basin study area is shown in outline. From James (1985) and Speer (1993d).

upper contact with the Wolfcamp Formation is also unconformable (King, 1937). In places the Gaptank Formation is separated from the Wolfcamp by a strong angular unconformity, a relationship that is clearly shown in many places in the southwestern part of the Glass Mountains.

King (1930) chose the *Chaetetes*-bearing limestone bed as the base of the Gaptank; however, Ross (1967) later restricted the type Gaptank to shallow-water shelfal clastics and carbonates deposited on the surface of the Marathon allochthon after a time of tectonic movement, and as such, transferred the *Chaetetes*-bearing limestone member to the underlying Haymond Formation and placed the Gaptank over faulted and folded strata of Des Moinesian and older rock (Fig. 19). The Gaptank is unconformably overlain by the Neal Ranch Formation of Permian Wolfcampian age. King (1942) defined the break between the top of the Pennsylvanian Gaptank and base of the Permian Wolfcamp as occurring at the bottom of a *Pseudoschwagerina*-bearing limestone (Wolfcamp) which lies directly on the *Uddenites*-bearing shale member. However, Ross (1959) was of the opinion that King's "*Uddenites* zone" did not represent the boundary between the Pennsylvanian and Permian; instead, Ross thought that the overlying "gray limestone member" of King was Pennsylvanian in age based on Pennsylvanian (Cisco) faunas. Therefore, according to Ross, the Pennsylvanian Gaptank includes both the *Uddenites* zone and "gray limestone member" thought by King to be part of the Permian Wolfcamp Series (Ross, 1963a, 1987a). Cys (1975) and Davis (1984) thought that the base of the gray limestone member seemed like the most logical place for the Pennsylvanian-Permian boundary.

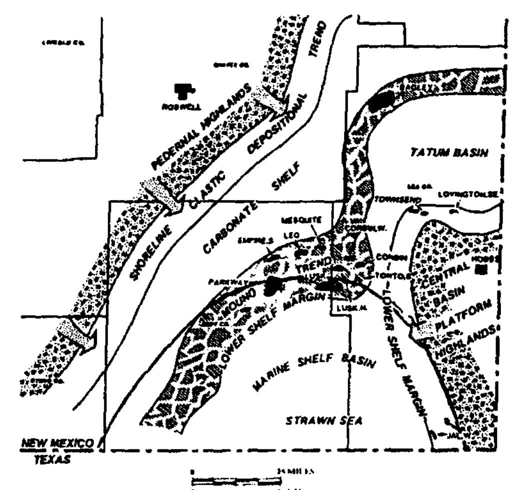


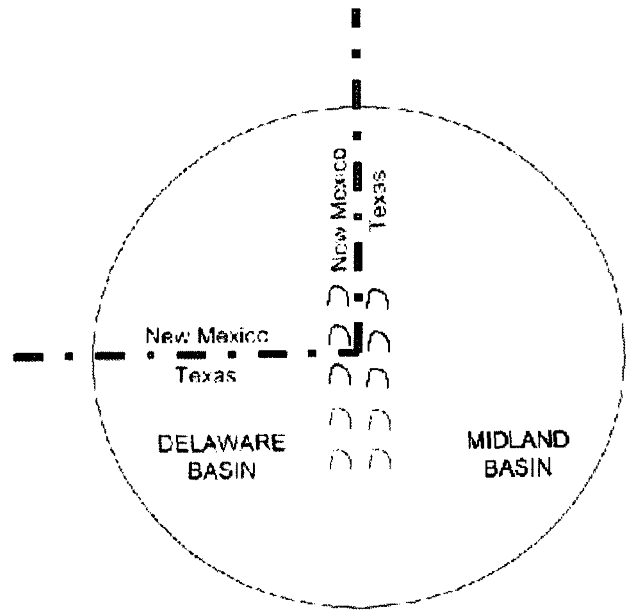
FIGURE 18—Depositional environments during Strawn time and oil reservoirs hosted by the Strawn Formation. The Delaware Basin study area is shown in outline. From James (1985).

LATE MISSISSIPPIAN
EARLY PENNSYLVANIAN

Stress caused en echelon folds

Low relief structures

* Erode Barnett Shale & Mississippian Limestone



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where the sandstone wedges out updip on the flanks of a reef; Page field, Schleicher County, where zones of porosity in limestone disappear updip on a broad terrace; and the Arledge field, Coke County, where porosity decreases updip on a structural nose.

Examples of isolated reef limestone build-ups are the Salt Creek field, Kent County; Reinecke field, Borden County; Vealmoor field, Howard County; and Todd field, Crockett County. Most reef build-ups are overlain by confining beds of compacted shale.

OUTCROPS

Pennsylvanian strata discussed in this report outcrop in the Llano Uplift of Central Texas; Marathon region, Solitario Uplift, Marfa Basin, Sierra Diablo, Hueco Mountains and Franklin Mountains in West Texas; and, in the Sacramento Mountains and San Andres Mountains in New Mexico.

THICKNESS

Rocks of the Pennsylvanian system of West Texas and Southeast New Mexico range from a feather edge along truncation lines and near areas of non-deposition to over 2,000 feet in the Midland, Delaware and Palo Duro basins; 2,500 feet on the Eastern Shelf; to aggregate thicknesses of more than 3,600 feet in the Orogrande Basin of New Mexico; and 12,000 feet in the Marathon Basin.

DISTRIBUTION

Pennsylvanian strata overlie rocks ranging in age from Pre-Cambrian to Mississippian. In most areas they are overlain by beds of lower Permian age. Except in restricted areas of truncation or non-deposition, Pennsylvanian rocks cover the entire West Texas and Southeast New Mexico province.

GEOLOGICAL HISTORY

From the beginning of the Cambrian period to late Mississippian time, West Texas and Southeast New Mexico had been a region of mild structural relief and uniform sedimentation. Broad regional arches modified relatively flat, expansive landmasses and shallow depositional basins and troughs.

Near the close of the Mississippian period, tectonic readjustment produced regional warping which destroyed the Tobosa Basin as a distinct structural entity, giving rise to several new regional structural subdivisions which were accentuated into high relief structural provinces during Pennsylvanian time. The broad, low-relief upwarps were the Pedernal Arch, which extended south to north from Trans-Pecos Texas to North Central New Mexico; the Central Basin Platform, which extended northwest to southeast from Southeast New Mexico to eastern Pecos County, Texas; the Matador-Red River Uplift, oriented west to east from Easten New Mexico to North Texas. The Texas Peninsula, which was the exposed crest of the Texas Arch, sank slightly below sea-level.

Compressive orogenic forces from the southeast uplifted the Llanoria Landmass progressively in lower Mississippian and early Pennsylvanian time, raising the west to east Ouachita-Maralon mountain ranges along the cratonic border. Contemporaneous with these positive movements, cratonic-edge downbending depressed an extensive geosyncline which lay in front of and parallel to the north rim of the mobile belt, embracing the whole Marathon region. Clastic debris, stripped from the uplifted blocks of the mountain ranges, was deposited into the newly formed Llanoria Geosyncline, being the source material of the Tesnus formation, which evidently crosses the late Mississippian and early Pennsylvanian time boundary. The lowermost member of the Tesnus formation is considered to be of upper Mississippian age. The middle and uppermost members of the formation have been classified as Springer and Morrow, which are of lower Pennsylvanian age. Strata of Springer age are not known in the region beyond the boundaries of the Llanoria Geosyncline.

The pronounced late Mississippian - early Pennsylvanian uplift caused a general withdrawal of the sea, which subjected the exhumed region previously occupied by the Tobosa Basin to erosion. Subsidence at the close of Springer time permitted the sea to encroach northward from the Llanoria Geosyncline. Landward expansion of the sea, initiated by regional subsidence, continued throughout most of the Pennsylvanian period, gradually filling a broad regional embayment which extends east to west from the Texas Arch to the Pedernal Arch and which extended from south to north from the Ouachita - Marathon mobile belt to the Amarillo Uplift. Crests of the intra-embayment upwarps such as the Central Basin Platform and the Matador-Red River Uplift were exposed as chains of islands.

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Broad, shallow structural depressions separating upwarps occupied regional positions which evolved eventually into the Delaware, Midland, Marfa and Palo Duro basins. The Midland Basin and the north part of the Delaware Basin sagged rapidly during the Morrow and Bend epochs.

The expanding early Pennsylvanian sea advanced northward from the Llanoria Geosyncline during the Morrow epoch, entering into and filling the northern part of the Delaware Basin. Clastics derived from the rising New Mexico highlands, rejuvenated by early Pennsylvanian orogenies, were deposited in and near the basin north of thicker shale and limestone deposits.

The expanding sea entered the northern part of the Midland Basin by way of a depression at the north edge of the Central Basin Platform, thence through structural lows of the Matador Uplift into the southern part of the Palo Duro Basin.

Principal elevation of the Matador Uplift occurred at the close of Morrow time. Emerging peaks contributed sand, arkose and gravel which mixed with detritus swept from the New Mexico highlands and deposited on the north flanks of the Midland Basin and the south flank of the Palo Duro Basin. The sea continued to encroach during Bend time until it had filled most of the Delaware Basin and all of the Midland Basin except the eastern flank. Bend strata in the Delaware Basin consist principally of shale and sandstone in its lower part, grading upward into limestone. Sandstone at the base of the section thickens northward into southeast New Mexico. The Bend section is predominantly limestone on its western and eastern margins. In the Midland Basin shale is less common than limestone, which is cleanest over local highs in the basin and on the east flank of the Central Basin Platform.

Deposition of the Dimple limestone in the Llanoria Geosyncline represents a period of quiescence in the adjacent Ouachita-Marathon orogenic belt during the Bend epoch.

Uplift and structural deformation occurred in late Bend time. The Ouachita-Marathon region was re-elevated, pushing its northern rim and the Llanoria Geosyncline northwestward toward the foreland. Strong compressive forces from the south and west mildly downwarped the asymetrical Delaware and Midland basins, uplifted and deformed the elongate Central Basin Platform, and flexed trends of local structures between the Midland Basin and the Lanoria Geosyncline known as the Regan Uplift.

The Fort Stockton High in northern Pecos County stood at the south end of the Central Basin Platform as the highest and most pronounced element of the structural province. Milder upwarps in the basins lay as an echelon trend studded with local tectonic displacements, some of which projected above sea-level as fault blocks that formed isolated islands. Axes of the trends generally paralleled regional structural grain. Erosion stripped sedimentary covers from the crests of exposed high-relief fold and fault blocks. Residual detrital sediments accumulated on the flanks of structure.

Regional subsidence spread early Strawn seas beyond the boundaries of structural basins of the embayment. Thin beds of limestone covered shallow embayment shelves and basin floors except where water was too deep for limestone deposition, such as in the southern sectors of the Delaware and Midland basins.

During the mid-Strawn epoch, structural deformation with renewed vigor rejuvenated local and regional tectonic elements. Intensity of deformation was greatest in the southern part of the embayment. Compressive forces thrust the Ouachita-Marathon mobile belt farther northwest. The Llanoria Geosyncline migrated further toward the foreland. The Central Basin Platform, Matador Uplift, and possibly the Pedernal Arch, were compressed, re-elevated and modified with trends of high-relief localized structures. Enchelon structural trends flanking major positive and negative tectonic provinces were reaccentuated by higher vertical relief and interrupted by well-defined local anomalies. The intricate pattern of the Reagan Uplift was modified by re-elevation of local structures which were sharply folded and faulted.

These positive regional and local tectonic events were accompanied by contemporaneous deepening of the structural basins.

The close of the mid-Strawn epoch initiated a period of stability and gentle subsidence which characterized West Texas and Southeast New Mexico until near the close of the Pennsylvanian period.

During late Strawn time, the expanding sea encroached upon the eroded flanks of regional and local structures, depositing carbonates over detrital sediments which accumulated along shoreward margins as the waste products of denudation.

Widespread deposits of bedded and biostromal limestones were distributed over the floors of shallow shelves and along the flanks of positive

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INTRODUCTION

The CBP (CBP) is a positive tectonic feature of the Permian Basin in the subsurface of West Texas and southeastern New Mexico (Figure 1). It is a NNW-SSE trending basement uplift that is bounded by complex, high-angle fault zones. The CBP trends at high angle to the Marathon fold-and-thrust belt to the south and separates the Delaware Basin to the west and the Midland Basin to the east (Figure 1). The CBP started to form inboard of and at about the same time as crustal shortening in the Marathon-Ouachita fold-and-thrust belt to the south and east during late Mississippian time (Hills, 1970; Wuellner et al., 1986; Ewing, 1991; Yang and Dorobek, 1995a). Uplift of the CBP peaked in late Pennsylvanian-late Wolfcampian time and was largely over by early Leonardian time (Ewing, 1991; Yang and Dorobek, 1995a). Since Late Permian time, the CBP has not been subjected to significant deformation, and its present structural configurations are basically the same as those that existed during late Paleozoic time (Frenzel et al., 1988).

The complex structural features, together with their associated pre-, syn-, and post-orogenic stratigraphic relationships, provide many important hydrocarbon traps across the CBP. In the past few decades of hydrocarbon exploration and production, however, most previous studies have focused on individual oil and gas fields across the CBP. Few studies have attempted to summarize these data and address the relationships between local structures and regional, basin-scale tectonic features.

One long-standing question regarding the CBP is the tectonic model responsible for its origin. Various tectonic models, involving either regional extension (Elam, 1984), compression (Galley, 1958; Ye et al., 1996), or strike-slip deformation (Harrington, 1963; Hills, 1970; Walper, 1977; Goetz and Dickerson, 1985; Gardiner, 1990a, Ewing, 1991; Shumaker, 1992; Yang and Dorobek, 1995a), have been proposed to explain the deformation that produced the CBP, the structural features associated with the CBP, the stress fields responsible for its formation, and the significance of the CBP to regional deformation across the Marathon-Ouachita foreland (Kluth and Coney, 1981; Ye et al., 1996).

Despite debates on the tectonic origin of the CBP, right-lateral strike-slip deformation due to SW-NE directed compressive stress appears to best explain most of the structural features along the margins of the CBP (Harrington, 1963; Hills, 1970; Ewing, 1991; Yang and Dorobek, 1995a). There are many observed structural features, however, that cannot be explained by right-lateral strike-slip deformation. For example, clockwise rotation of crustal blocks resulting from right-lateral shear couple (cf. Yang and Dorobek, 1995a) does not adequately explain either regional uplift of the CBP or the broader pattern of en echelon folding that developed across the eastern Delaware Basin, CBP, and western Midland Basin prior to major deformation and uplift of the CBP.

Reasonably detailed descriptions of the boundary fault zones of the CBP are given by Shumaker (1992) and Yang and Dorobek (1995a). To date, however, no study has been conducted on the slip motion along the boundary faults of the CBP. The amount of lateral displacement along the CBP's boundary faults is difficult to estimate because of uncertainties in establishing piercing points across either the eastern or western boundary fault zones of the CBP (Shumaker, 1992). By largely focusing on the late Paleozoic structural features along the margins of the CBP, most previous studies (Hills, 1970; Gardiner, 1990a; Shumaker, 1992; Yang and Dorobek, 1995a; Ye et al., 1996) have generally overlooked the comparatively low-relief late Paleozoic structures within the sub-basins that are adjacent to the CBP (e.g., the Pegasus-Amacker structural trend in the southwestern Midland Basin; Figures 1, 2; Tai and Dorobek, 1999). Thus, the kinematic relationships between these subtle structures within the basins and the CBP have not been examined, even though they may provide important constraints on the tectonic evolution of the Permian Basin region (Tai and Dorobek, 1999).

A better understanding of the structural features of the CBP and adjacent areas is important for unraveling the complex tectonic history of the Permian Basin. In this study, we utilized a data set that was donated to Texas A&M University by Chevron USA. This data set, which covers the southwestern Midland Basin and eastern CBP regions, includes five 3-D seismic surveys (covering over 800 km^2), numerous 2-D seismic profiles, over 200 digital well-logs, and production data. We first examined the various structural features across the southwestern Midland Basin and eastern CBP using seismic data, structural contour maps, and well-log cross sections. The timing of deformation was inferred from variations in the thickness of stratigraphic units on cross sections and recognition of unconformities on seismic profiles and well-log cross sections. We also integrated our observations with previously published information from the eastern Delaware Basin and other parts of the CBP in order to put these structural features into a regional tectonic framework. Finally, we used a simple geometric method to determine the nature of slip motion and the displacement vector along the boundary faults of the CBP, which in turn, lead to a new tectonic model for the formation of the CBP and adjacent areas. A better understanding of the tectonic history of the CBP and adjacent sub-basins may provide an important analog for understanding other basement uplifts (e.g., Diablo Platform, Ozona Arch) that developed across distal parts of the Marathon-Ouachita foreland region during late Paleozoic time.

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the southwestern Midland Basin, these anticlines are important petroleum traps and also display an en echelon pattern relative to the boundary fault zones of the CBP (Figure 1; Harrington, 1966; Hills, 1970; Frenzel et al., 1988). The average trend of fold axes is N30°W. Compared to the en echelon folds within the eastern Delaware and western Midland Basin, the crest of folds from interior parts of the CBP are more deeply eroded, with a major post-Pennsylvanian unconformity that generally separates Permian rocks from underlying lower Paleozoic rocks. Cross faults that cut the asymmetric anticlines and terminate into the main boundary fault have been reported in the Andector, Dollarhide, Eunice, Martin, Embar, Andector, Fullerton, Halley, and TXL fields, and they are right-lateral strike-slip faults or normal faults with small displacement (Gardiner, 1990a; Ewing, 1991; Algeo, 1992; Shumaker, 1992; Montgomery, 1998).

The Sand Hills Fault is an intra-block fault located within the Fort Stockton Block (Figure 1; Gardiner, 1990a). This fault has a sigmoidal trace in map view and has been described as a scissor fault with changing sense of throw along the fault's strike. At its northern end, the Sand Hills Fault dips westward and Wolfcampian strata lie unconformably on the Ordovician Ellenburger Formation, whereas at its southern end, the fault dips eastward and Wolfcampian strata directly overlie the Precambrian basement rocks (Figure 1; Gardiner, 1990a).

Steeply dipping fault zones characterize the boundaries of the CBP (Figures 1, 4, 5, and 6; Hills, 1970; Bebout and Meador, 1985; Yang and Dorobek, 1995a). The eastern margins of the CBP are characterized by NNW-SSE trending (N16°W) high-angle reverse faults that dip 50°-60° westward toward the interior of the CBP (Figures 2a, 4, and 5; Yang and Dorobek, 1995a). Deformed pre-Permian rocks along the boundary fault zone commonly display asymmetrical positive flower structures (Figures 4, 5; Gardiner, 1990a; Turmelle, 1992). In map view, the eastern boundary faults of the CBP are not as laterally continuous as the western boundary faults. Instead, the traces of individual fault segments tend to display a jagged pattern (Figures 1, 2a). The greatest amount of vertical displacement along the eastern side of the CBP is found at the NE corners of the Andector and Fort Stockton blocks (Yang and Dorobek, 1995a). Vertical displacement progressively decreases from north to south along the eastern margins of Andector and Fort Stockton blocks. Calculated amounts of basement shortening also decrease southward along the eastern boundary of the Andector and Fort Stockton blocks, away from their NE corners. Normal faults at the SE corner of the Andector Block dip eastward into the Midland Basin (Yang and Dorobek, 1995a).

The western boundary of the CBP is an approximately 10-mile wide fault zone that separates the uplifted CBP from the Delaware Basin to the west (Figure 1, Hills, 1970). In general, the western boundary of the CBP has greater structural relief, vertical separation, and basement shortening than its eastern boundary (Yang and Dorobek, 1995a). The western boundary fault zone consists of several closely spaced and steeply dipping faults that bound narrow, elongate slices of basement, which rapidly step down to the west (Figures 1, 6; Hills, 1970; Bebout and Meador, 1985). The SW corners and western margins of the Andector and Fort Stockton blocks are characterized by NW-SE trending (N10°W-N45°W) steeply-dipping, basement-involved reverse faults that dip 50°-60° eastward toward the interior of the CBP (Figure 1, 6; Yang and Dorobek, 1995a). The greatest amount of vertical displacement is found at the SW corners of the Andector and Fort Stockton blocks; vertical displacement progressively decreases from south to north along the western margins of the Andector and Fort Stockton blocks (Ewing, 1991; Yang and Dorobek, 1995a), with maximum vertical separation of 10,000 to 25,000 feet at the SW block corners (Hills, 1985; Shumaker, 1992). Calculated amounts of basement shortening also decreases northward along the western boundary of the Andector and Fort Stockton blocks, away from their SW corners (Yang and Dorobek, 1995a). Some steeply dipping faults at the SW corner of the Fort Stockton Block are traceable along the western margin to NW corner of the block, where they become high-angle normal faults that dip westward toward the Delaware Basin (Yang and Dorobek, 1995a).

The boundary between the Andector and the Fort Stockton blocks is an ENE-WSW cross fault zone (Figure 1). This fault zone is characterized by flower structures, pop-ups, and near vertical faults (Yang and Dorobek, 1995a).

Another important structural feature along the western boundary of the CBP is the Puckett-Grey Ranch fault zone, which extends southward from the CBP to the Marathon fold-and-thrust belt (Figure 1). This high relief, steeply dipping fault zone extends southward from the western boundary fault zone of the CBP and disappears southward beneath the Marathon thrust sheets (Ewing, 1991). The Puckett-Grey Ranch fault zone separates the Val Verde Basin to the east from the southern Delaware Basin to the west (Figure 1). Several NW-SE trending faulted anticlines are distributed along this fault zone and are arranged in an en echelon pattern with the average fold axis trending at N34°W (e.g., Puckett, Grey Ranch, and Hokit fields; Figure 1).

INTERPRETATION OF STRUCTURAL FEATURES

In terms of the dominance of contractional structures (folds and reverse faults) across the study area

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New Mexico Bureau of Mines and Minerals

Speer, James, Mazzullo

PP-4. MORROW

Stephen W. Speer

The Morrow Formation has produced more than 3 TCF of nonassociated gas from 1,700+ wells in more than 220 designated reservoirs in southeast New Mexico. Of this total, 2.929 TCF comes from the 85 reservoirs (containing 1,374 wells) that have produced at least 5 BCF of gas (Table PP-4.1; Fig. PP-4.1). Field development has consolidated many reservoirs into several large contiguous areas of development. More than 20 MMB of 45° to 60°+ condensate have also been produced from this play even though the Morrow is generally considered a dry gas play having BTU values generally less than 1100 and gas-oil ratios ranging into the hundreds of thousands. The quality and abundance of this large gas reserve base led many operators to actively explore and exploit it during the boom times of the 1970s and early 1980s when peak production reached more than 15 BCF/month (Fig. PP-4.2). However, because of the inherent high risk and high costs of developing this deep play (typically from 8,500 to more than 15,000 ft deep), the dramatic decrease in oil and gas prices that befell the industry in 1986 significantly curtailed continued play development.

Stratigraphically, the Morrow Formation in southeast New Mexico unconformably overlies Mississippian limestones and can be subdivided into three distinct intervals commonly designated as either the lower, middle, and upper Morrow, or the "A," "B," and "C" Morrow zones (Fig. PP-4.3). The lower and middle Morrow intervals are primarily clastic in composition and are by far the dominant Morrow producing horizons, whereas the upper Morrow is principally composed of transgressive, oolitic limestones interbedded with thin shales and minor sandstones (Anderson, 1976; James, 1985; Mazzullo and Mazzullo, 1984). The composite thickness of the lower and middle Morrow intervals reaches as much as 1,700 ft in deeper parts of the basin and reflects the maximum progradational episode of Pennsylvanian clastic input into the basin from the surrounding Pedernal highlands to the north and west and the Central Basin highlands to the east (Figs. PP-4.4, PP-4.5). Subsequent upper Morrow sediments record a major marine inundation of this clastic wedge prior to Atokan time (James, 1985; Mazzullo and Mazzullo,1985) wherein areas on or immediately adjacent to the source areas received little to no Morrow sedimentation. Depositionally, the lower and middle Morrow intervals represent a diachronous, cyclically interbedded, fluvial-deltaic to basinal marine facies tract (Figs. PP-4.4, 4.5; Anderson, 1976; James, 1985; Mazzullo and Mazzullo, 1984). Production is found in depositional environments ranging from proximal distributary channel and point bar deposits to mid-tract channel mouth bar, beach, and delta front shelf sands *(Fig. PP-4.6), on out to distal submarine fan deposits found* off the edge of the delta platform in prodelta slope settings (Martin et al, 1986).

Productive lower Morrow reservoirs are typically characterized as straight and elongate, very coarse to medium-grained, angular to subangular quartzose sands oriented perpendicular to Morrow sediment source areas (Figs. PP-4.5, PP-4.7, PP-4.8, PP-4.9). They can be as much as 60 to 80+ ft thick with porosity ranging from 8 to 14% and are broadly interpreted as distributary channels that were the source of fluvially dominated lower Morrow deltas. These channel sands, together with their associated point bar and channel mouth bar deposits, can be extremely prolific and many times produce upwards of 10 to 20 BCF/well. Trapping is generally achieved through a combination of depositional, structural, and/or diagenetic factors, with cementation by either silica, carbonate, or clay commonly playing a significant role by occluding all porosity in these otherwise continuous, elongate sands (Anderson, 1976; James, 1985; Mazzullo and Mazzullo, 1985; Lambert and Berg, 1986). Authigenic and detrital clay (primarily kaolinite, chlorite, and lesser amounts of illite) are present in both lower and middle Morrow sands and can pose serious problems regarding well productivity if not addressed during drilling and completion programs (Mazzullo and Mazzullo, 1985).

As a whole, middle Morrow sands are individually thinner and more numerous than those found in the lower Morrow and map out not only as occasional dip-elongate distributary channels, but more often as broadly lobate delta front and strike-elongate beach accumulations (Figs. PP-4.8, PP-4.9). This pattern of deposition suggests multiple alternating periods of middle Morrow transgression and regression (Mazzullo and Mazzullo, 1984) and possibly a more wave-dominated delta setting affecting the sand distribution and deposition. Although porosity also ranges from 8 to 14% in these reservoirs, they are commonly finer grained and more glauconitic than those in the lower Morrow (James, 1985). Trapping, and hence gas production, is primarily controlled by a combination of both depositional and cementation patterns, with structure not playing nearly as significant a role as it does in the lower Morrow (Anderson, 1976; James, 1985).

Several areas in southeast New Mexico have been delineated by the FERC as tight formation for Morrow production (Fig. PP-4.1). This designation qualifies affected Morrow gas for economic incentives and is due to the formation's combination of extreme depth and relatively low average reservoir permeability (and hence deliverability). Although standard Morrow completions generally require only a small acid cleanup job, many wells need additional fracture stimulation treatments to achieve acceptable economic production rates. Consequently, it is imperative for prudent operators to give serious and realistic consideration to economic factors when developing Morrow gas reserves. Although prices and demand have been relatively weak and/or unstable as of late, it is certain that when they become firmer, more Morrow gas will be developed.

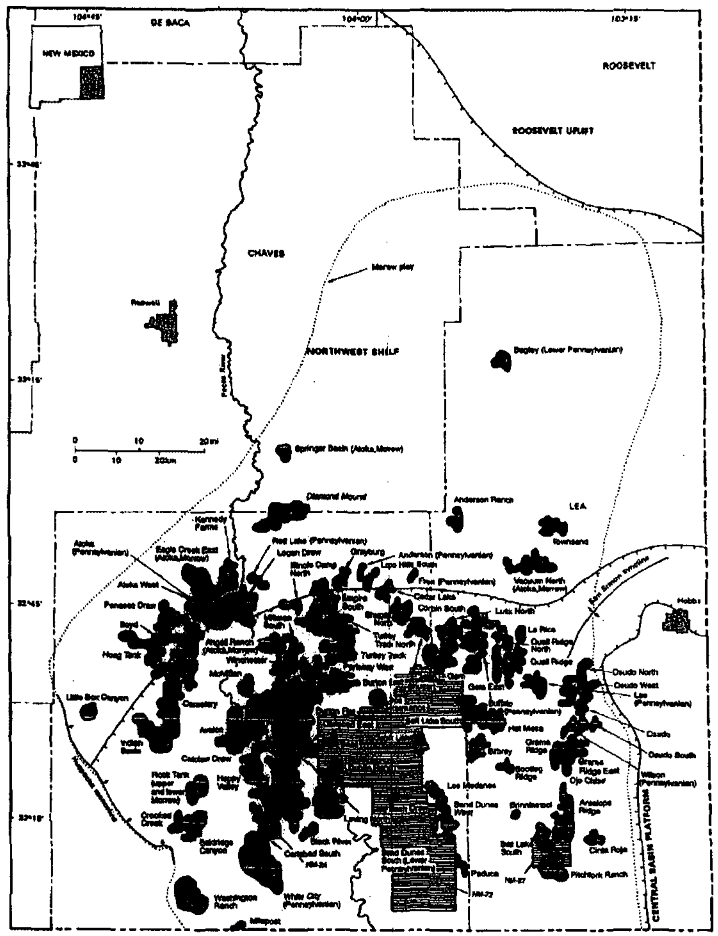

FIGURE PP-4.1—Reservoirs in the Morrow play and FERC-designated tight formation areas. All reservoirs produce from the Morrow only unless otherwise indicated.

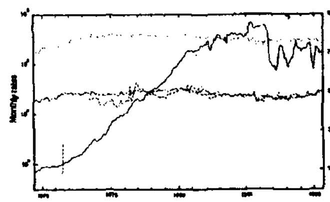
FIGURE PP-4.2—Historical production from the Morrow play. ···, gas (MCF); — - —, oil (BBLS); --, water (BBLS); —, wells. From INTERA Bergeson; data source, Dwight's Energydata, Inc.

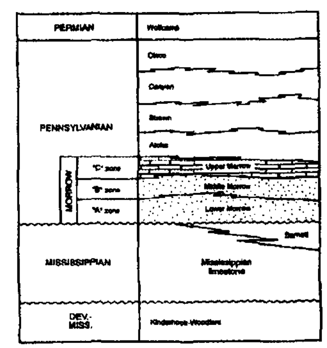

FIGURE PP-4.3—Generalized stratigraphic column of southeast New Mexico with commonly recognized Morrow subdivisions and nomenclature. Modified from Mazzullo and Mazzullo, 1985.

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p. 159 (zoomed in)

New Mexico Bureau of Mines and Minerals

Speer, James, Mazzullo

Mazzullo, 1984). The composite thickness of the lower and middle Morrow intervals reaches as much as 1,700 ft in deeper parts of the basin and reflects the maximum progradational episode of Pennsylvanian clastic input into the basin from the surrounding Pedernal highlands to the north and west and the Central Basin highlands to the east (Figs. PP-4.4, PP-4.5). Subsequent upper Morrow sediments record a major marine inundation of this clastic wedge prior to Atokan time (James, 1985; Mazzullo and Mazzullo, 1985) wherein areas on or immediately adjacent to the source areas received little to no Morrow sedimentation. Depositionally, the lower and middle Morrow intervals represent a diachronous, cyclically interbedded, fluvial-deltaic to basinal marine facies tract (Figs. PP-4.4, 4.5; Anderson, 1976; James, 1985; Mazzullo and Mazzullo, 1984). Production is found in depositional environments ranging from proximal distributary channel and point bar deposits to mid-tract channel mouth bar, beach, and delta front shelf sands (Fig. PP-4.6), on out to distal submarine fan deposits found off the edge of the delta platform in prodelta slope settings (Martin et al, 1986).

Productive lower Morrow reservoirs are typically characterized as straight and elongate, very coarse to medium-grained, angular to subangular quartzose sands oriented perpendicular to Morrow sediment source areas (Figs. PP-4.5, PP-4.7, PP-4.8, PP-4.9). They can be as much as 60 to 80+ ft thick with porosity ranging from 8 to 14% and are broadly interpreted as distributary channels that were the source of fluvially dominated lower Morrow deltas. These channel sands, together with their associated point bar and channel mouth bar deposits, can be extremely prolific and many times produce upwards of 10 to 20 BCF/well. Trapping is generally achieved through a combination of depositional, structural, and/or diagenetic factors, with cementation by either silica, carbonate, or clay commonly playing a significant role by occluding all porosity in these otherwise continuous, elongate sands (Anderson, 1976; James, 1985; Mazzullo and Mazzullo, 1985; Lambert and Berg, 1986). Authigenic and detrital clay (primarily kaolinite, chlorite, and lesser amounts of illite) are present in both lower and middle Morrow sands and can pose serious problems regarding well productivity if not addressed during drilling and completion programs (Mazzullo and Mazzullo, 1985).

As a whole, middle Morrow sands are individually thinner and more numerous than those found in the lower Morrow

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p. 159 (zoomed in) continued

New Mexico Bureau of Mines and Minerals

Speer, James, Mazzullo

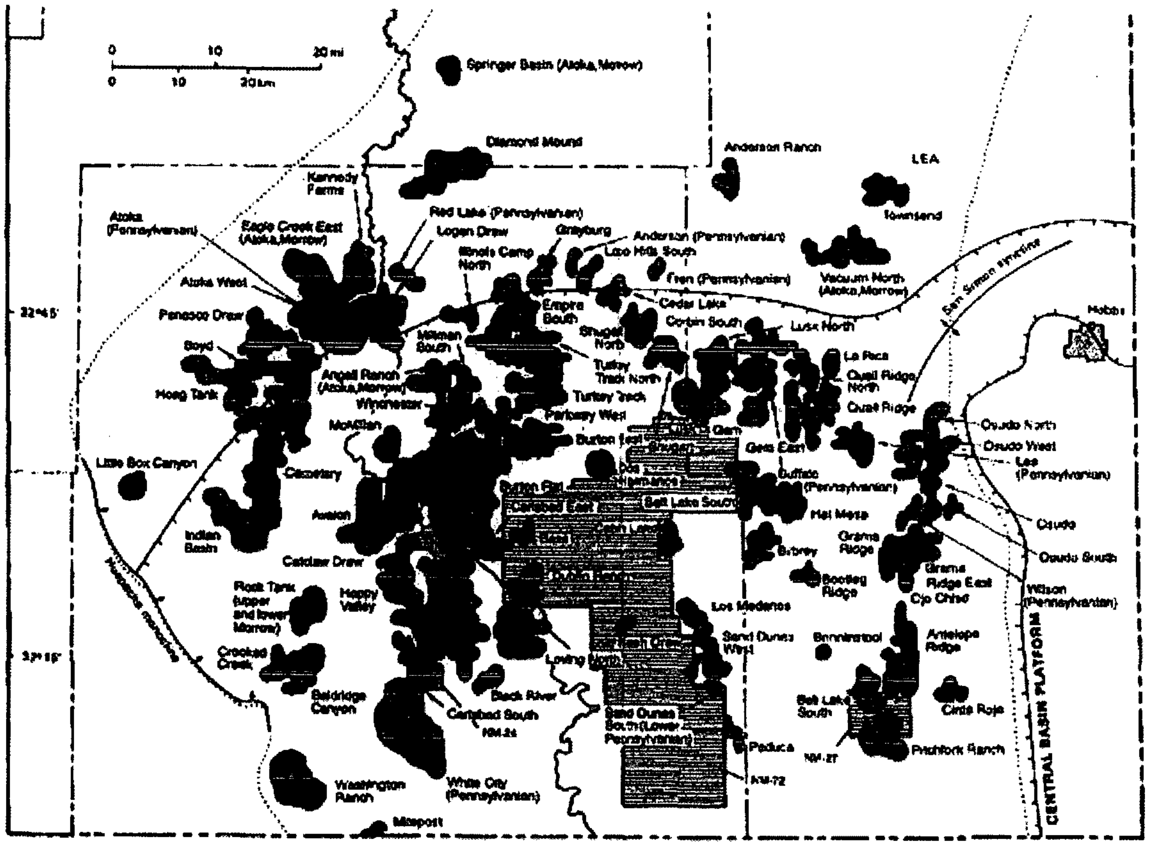

FIGURE PP-4.1—Reservoirs in the Morrow play and FERC-designated tight formation areas. All reservoirs produce from the Morrow only unless otherwise indicated.

and map out not only as occasional dip-elongate distributary channels, but more often as broadly lobate delta front and strike-elongate beach accumulations (Figs. PP-4.8, PP-4.9). This pattern of deposition suggests multiple alternating periods of middle Morrow transgression and regression (Mazzullo and Mazzullo, 1984) and possibly a more wave-dominated delta setting affecting the sand distribution and deposition. Although porosity also ranges from 8 to 14% in these reservoirs, they are commonly finer grained and more glauconitic than those in the lower Morrow (James, 1985). Trapping, and hence gas production, is primarily controlled by a combination of both depositional and cementation patterns, with structure not playing nearly as significant a role as it does in the lower Morrow (Anderson, 1976; James, 1985).

Several areas in southeast New Mexico have been delineated by the FERC as tight formation for Morrow production (Fig. PP-4.1). This designation qualifies affected Morrow gas for economic incentives and is due to the formation's combination of extreme depth and relatively low average reservoir permeability (and hence deliverability). Although standard Morrow completions generally require only a small acid cleanup job, many wells need additional fracture stimulation treatments to achieve acceptable economic production rates. Consequently, it is imperative for prudent operators to give serious and realistic consideration to economic factors when developing Morrow gas reserves. Although prices and demand have been relatively weak and/or unstable as of late, it is certain that when they become firmer, more Morrow gas will be developed.

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New Mexico Bureau of Mines and Minerals

Speer, James

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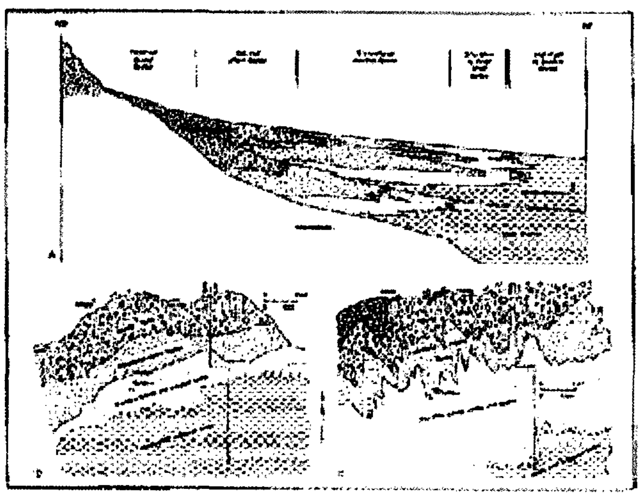

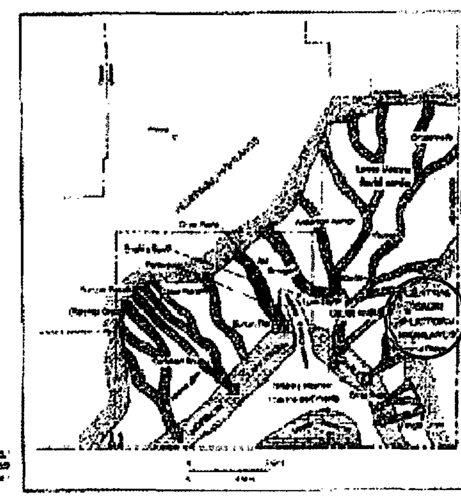

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Figure PP-4.5

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Speer, James

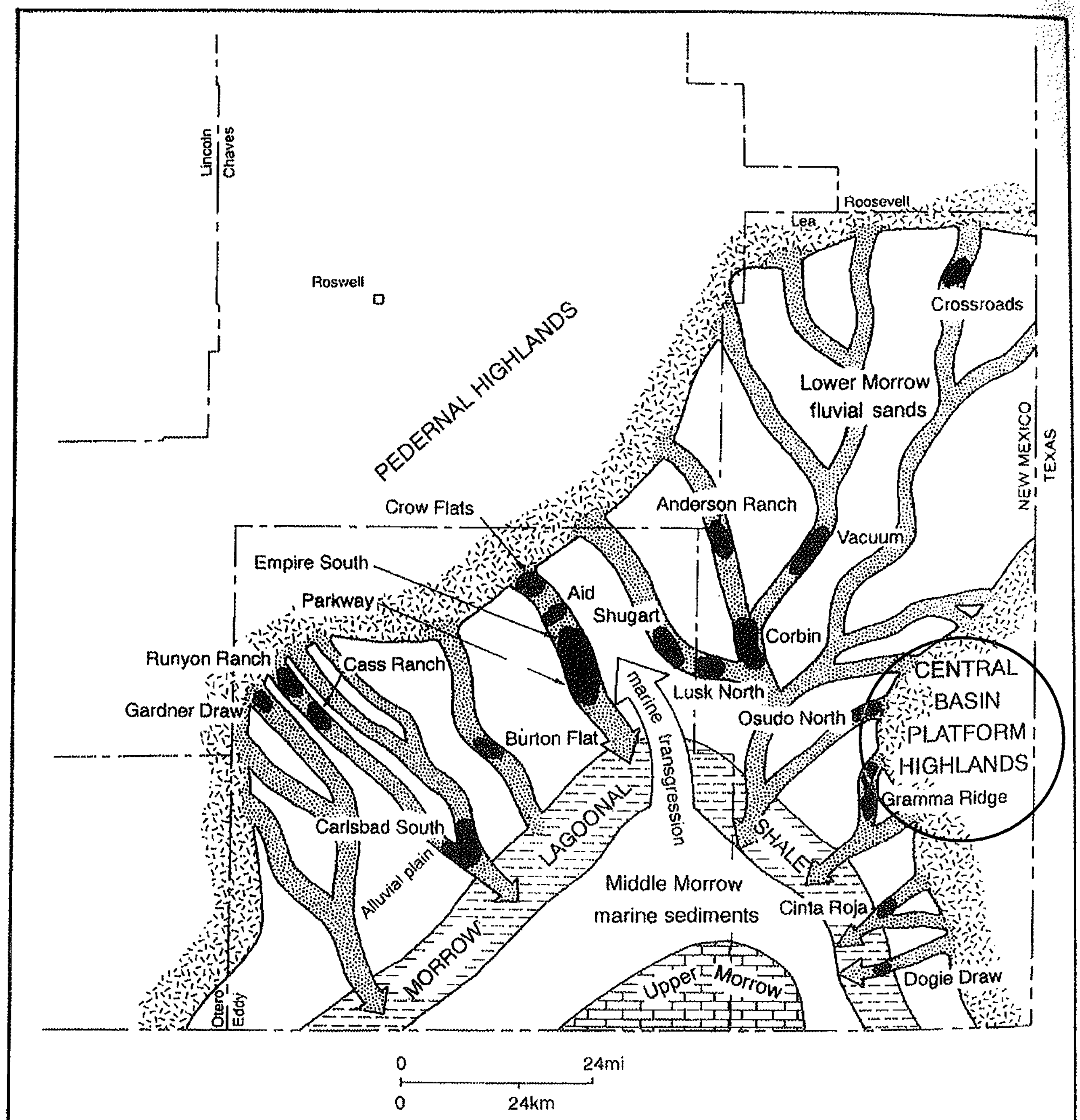

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FIGURE PP-4.5—Schematic paleogeographic map of southeast New Mexico with interpreted clastic depositional axes and related facies patterns during early Morrowan time. Several Morrow reservoirs have been superimposed. Modified from James, 1985.

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Bureau of Economic Geology,

Frenzel, Heckel

the play are Todd, Deep (Crinoidal), which produced 37.3 MMbbl (5.93×10^6 m^3) of oil through 2000, and Clairemont (Penn., Lower), which produced 15.9 MMbbl (2.53×10^6 m^3). Total cumulative production from the 10 fields in the Permian Basin part of the play is 92.1 MMbbl (1.46×10^7 m^3) (table 12).

Similarly, the Upper Pennsylvanian Shelf Sandstone play is located mainly in North-Central Texas and thus is not described in this report. Five reservoirs in this play occur in the Permian Basin (table 13). These five reservoirs had cumulative production of 7.3 MMbbl (1.16×10^6 m^3) through 2000 (table 13).

Present structural features of the Permian Basin, including the Central Basin Platform and Midland and Delaware Basins (fig. 2), began forming in Early Pennsylvanian time (Frenzel and others, 1988). The thickness and distribution of Pennsylvanian rocks in the Permian Basin are quite variable owing to nondeposition and erosion over positive areas such as the Central Basin Platform. Pennsylvanian faulting formed many of the oil-producing anticlines in the area. Pennsylvanian rocks in the Permian Basin are commonly cyclic because they formed during a time of high-amplitude, high-frequency eustatic sea-level fluctuations caused by glaciation and deglaciation in the Southern Hemisphere (Heckel, 1986).

Table 13. Upper Pennsylvanian Shelf Sandstone play[1].

RRC RESN	RRC	FLDNAME	RESNAME	STATE	COUNTY	DISCYR	DEPTHTOP	2000 PROD	CUMPROD
2711001	8A	ANDREW NOODLE CREEK		TX	KENT	1969	4010	0	1,063,283
21959500	8A	CROTON CREEK, E.	TANNEHILL	TX	DICKENS	1969	4574	0	1,285,206
64626380	8A	NAVIGATOR	TANNEHILL B	TX	DICKENS	1996	4418	323,280	1,273,061
78525500	8A	ROUGH DRAW, N.	NOODLE CREEK	TX	KENT	1963	4140	4,050	1,620,751
91784700	8A	TUMBLEWEED, NW.	TANNEHILL	TX	DICKENS	1986	4108	99,226	2,021,841
				TX					
		Totals						426,556	7,264,141

[1] This play is not included in the play portfolio because most of the play is in the North-Central Texas geologic province. Production listed here represents only the five reservoirs in the Permian Basin, as defined in figure 1.

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Weeks, Galley

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The source of the oil is somewhat difficult to determine from considerations of gross lithology and stratigraphic relations. In areas where the entire unit is dolomite, and oil occurs in the highest porous zone below the uppermost unconformity, sources in the overlying Woodford shale and perhaps also in the Simpson group which underlies the entire Montoya-Silurian-Devonian carbonate sequence are suggested. Where separate reservoirs exist, three possible sources are present.

1. Small amounts of shale and argillaceous material associated with the lower carbonate beds in southern areas suggest conditions favoring conversion of organic matter to hydrocarbons during deposition of these older sediments.

2. Gray-green shale, questionably of upper Ordovician age (Sylvan?), occurs locally in thicknesses generally less than 50 feet over an area of about a dozen counties on the east flank of the Tobosa basin, lying between Montoya and Siluro-Devonian strata.

3. There may have been channels of migration from Woodford and Simpson strata *via* the uniform dolomite sequence in the basin areas. Oil arriving by this route would displace formation water in different amounts in different reservoir strata, depending on the volume of flow through different parts of the dolomite facies.

Finally, as in the case of the Ellenburger group, there remains the conjecture that oil in Silurian and Devonian carbonate reservoirs, if not indigenous or derived from immediately adjacent argillaceous strata, migrated from source beds in a postulated clastic basin to the south before the occurrence of the Marathon orogeny.

Gravity of the oil in the Silurian-Devonian reservoirs extends through a wide range from about 32° to 60°, and the sulfur content is low; however, the pattern of distribution of various grades is irregular and offers no obvious clue to the source.

The total volume of oil found to the present date in Silurian and Devonian strata is close to ¾ billion barrels, although the volume of rock in these systems is only about 5,500 cubic miles, making the Silurian-Devonian strata appear to be more prolific than the Ellenburger dolomite in terms of unit volumes (Fig. 1). Local accumulations are found mainly in anticlinal traps, more than half of the total production being obtained from fields on the Central Basin platform, and the remainder chiefly in the Midland basin and north end of the Delaware basin.

PRE-MISSISSIPPIAN UNCONFORMITY

In late Devonian time widespread uplift and erosion created a surface of unconformity across the Permian Basin area, and the areal geology of that surface (Fig. 16) clearly reveals the position of the Concho arch, at the northwest end of which Precambrian rocks were exposed; Ordovician, Silurian, and Devonian strata cropped out on the northeast and southwest flanks. The Tobosa basin also is evident in the pattern of pre-Woodford outcrops.

MISSISSIPPIAN

Over the late Devonian erosion surface the next marine invasion spread a sequence of dark shale and limestone of rich organic content. As in Cambrian and lower Ordovician time, the transgressing sea deposited first a clastic unit and then carbonate sediments. The first is a body of black shale, commonly described as "bituminous," which has been correlated with the Woodford chert of Oklahoma; it contains disseminated pyrite crystals and detrital grains of various materials, and, locally at its base, a thin and patchy zone of sandstone. In northern areas it contains

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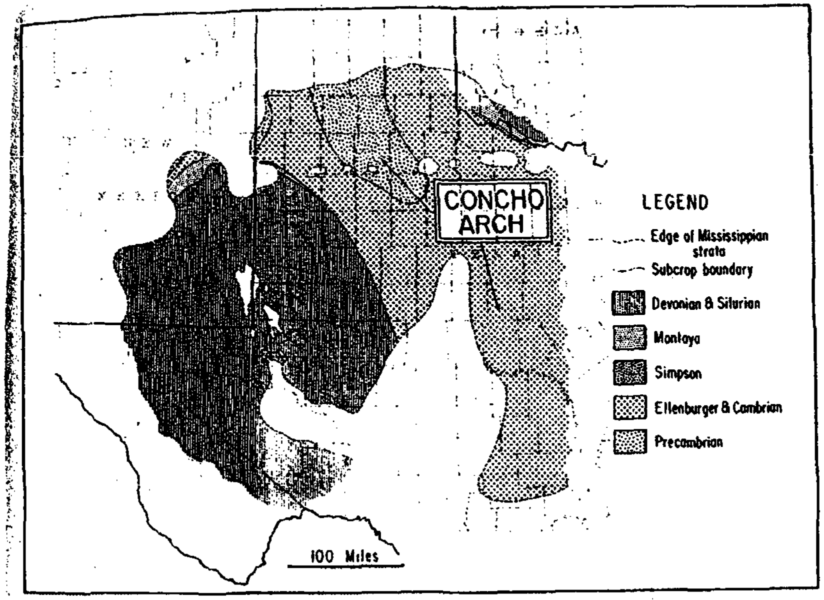

FIG. 16.—Pre-Woodford paleogeology. The map shows the age and distribution of strata immediately underlying Woodford shale and Mississippian limestone. The Concho arch is a prominent pre-Mississippian uplift.

thin interbedded siltstone and sandstone members, and at the edges it grades into a fine-grained sandstone facies of irregular distribution which the author considers *to be the nearshore facies of the Woodford shale (Fig. 17). This is the earliest* Paleozoic shore line which has not been removed by subsequent erosion, within the area of the Permian Basin, and its semicircular or embayment-like shape indicates the submergence of the Tobosa basin prior to later deposition across the Concho arch. However, there was contemporaneous deposition of Woodford shale northeast of the Concho arch, and probably around its southeast end as well. Deposition began in late Devonian time and, as the sea transgressed across the area, probably continued into early Mississippian. The Woodford shale, which is the product of a stagnant marine basin (Ellison, 1950, p. 15) and has an estimated present volume of about 1,300 cubic miles in the Permian Basin, is considered by many geologists, including the present author, to be a good source bed.

The remainder of the Mississippian System consists of generally finely crystalline nonporous limestone ranging from pure calcitic limestone to argillaceous and silty or to siliceous and cherty limestone in various places, interbedded with and overlain by dark-gray or brown shale. The clastic content increases generally southward, toward the clastic basin which apparently continued to exist in front of the hypothetical landmass of Llanoria.

In north-central Texas, high on the east flank of the Midland basin, the lime-

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stone in places is crinoidal, coarsely crystalline, and porous, and is an oil reservoir of local importance; irregularly distributed porous beds produce also in a few places in the Midland basin and on the Central Basin platform. Generally, however, despite the organic richness of its dark shale and argillaceous limestone which gives them the outward aspects of source beds, the Mississipian System produces little oil or gas. Its minor role in oil production must be attributed to low permeability, for it generally yields little water when tested. Like the oil in pre-Mississippian reservoirs, the Mississippian oil is generally sweet; that is, it contains relatively small amounts of sulfur. Recorded gravities range from 34° to 44° in most fields; a few are higher.

The dark shale which overlies the Mississippian limestone has a lithologic character so nearly like that of lower Pennsylvanian shale that the position of the time boundary is obscure.

The stratigraphic interval mapped in Figure 18 extends from the base of the Woodford shale to the approximate position of the Mississippian-Pennsylvanian boundary. It is an eroded interval, within which lithologic correlations provide some evidence that original thicknesses were greatest in the center of the Tobosa basin, but minor uplift of portions of the later Central Basin platform in late Mississippian or early Pennsylvanian time is indicated by present thin areas in the center of the basin. The total volume of rocks in this interval is estimated to be about 6,000 cubic miles. The shore lines of the Mississippian sea were beyond the present limits of distribution of Mississippian beds in the Permian Basin.

PRE-PENNSYLVANIAN UNCONFORMITY

Toward the close of Mississippian time some orogenies which were the principal environmental controls of the Permian Basin area throughout the Pennsylvanian Period were initiated, and widespread withdrawals of the sea produced a broad surface of erosion in which can be seen some of the principal orogenic elements and upwarps (Fig. 19). To the south and east the mountainous lands of the Marathon and Ouachita folded belts were rising, most of their erosional debris being trapped in adjacent sinking troughs which were beyond the limits of the area with which we now are concerned. It is the writer's belief that the pear-shaped area in the southeast part of the Permian Basin from which Mississippian strata have been removed (Figs. 18 and 19) is a portion of the Concho arch which was tilted northward at the initiation of the Marathon orogeny, thus becoming exposed to denudation.

Extending eastward across the south edge of the map is an area of pre-Mississippian subcrops outlining a large anticlinal structure which merges with the north-plunging pear-shaped area of erosion on the Concho arch. The eastward-trending anticline was uplifted at some time after Mississippian limestone deposition and prior to deposition of Atoka sediments, and is the structure to which the author has applied the name *Pecos arch*.

In some portions of the later Central Basin platform from which Pennsylvanian strata have not been completely removed, thinning of the Mississippian System by

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New Mexico Bureau of Mines and Mineral Resources,

Grant, Foster

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).

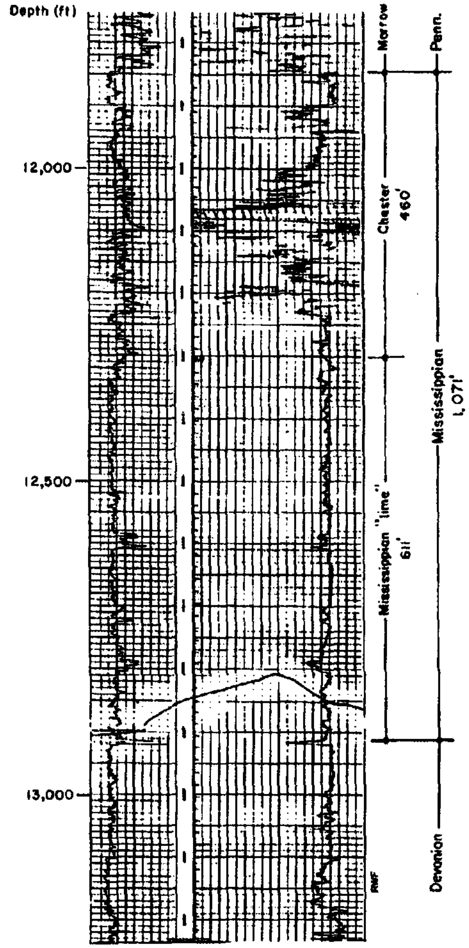

FIGURE 94—Sample gamma ray/sonic log of Mississippian and Upper Devonian on Northwest shelf. Gulf No. 1 Caprock, sec. 34, T14S, R31E, Chaves County.

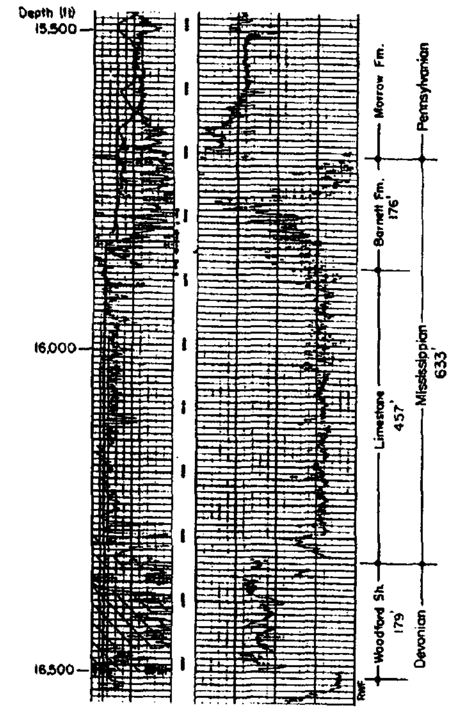

FIGURE 95—Sample gamma ray/sonic log of Mississippian and Upper Devonian in Delaware Basin. Texas American No. 1 Todd, sec. 14, T23S, R31E, Eddy County.

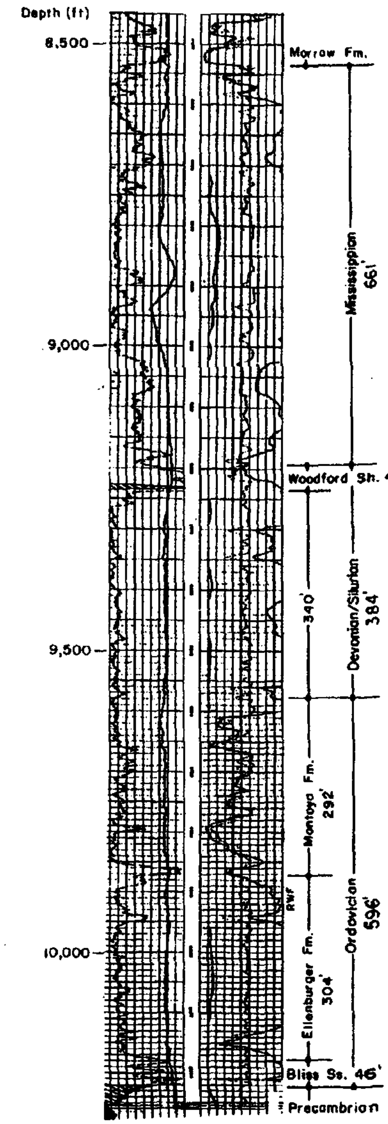

FIGURE 96—Sample gamma ray/resistivity log of Mississippian through Precambrian on Northwest shelf. Honolulu No. 1 Malco, sec. 15, T14S, R28E, Chaves County.

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GEO13

Permian Basin Formation and Filling

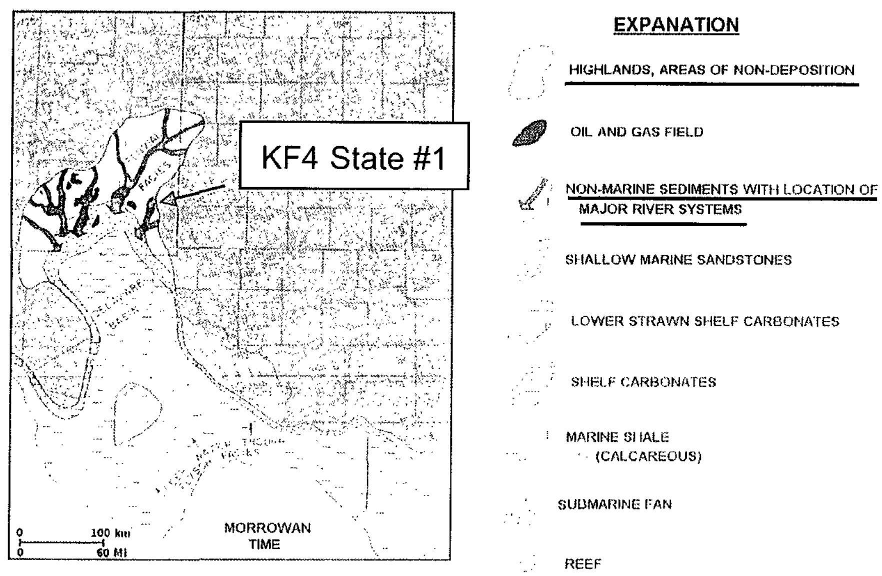
The structures of the Permian Basin, including basins, uplifts, faults, and anticlines developed in a series of tectonic pulses. The major pulses were: Middle Mississippian, early Morrowan, early Atokan, middle Desmoinesian, and early Wolfcampian. Most of these tectonic pulses also occur in nearby Late Paleozoic basins.

Paleogeographic reconstructions place the Permian Basin about 20 degrees south of the equator in the late Mississippian and gradually moving south. The basin was on the equator in mid-Pennsylvanian time and the region was about 15 degrees north by the end of the Permian.

Mississippian. The formation of the Permian Basin started in late Mississippian time. The first deposits were widespread marine muds of the **Barnett Shale**. The Barnett overlies lower Mississippian through Ellenburger rocks on a low relief angular unconformity.

Pennsylvanian

The sediments of the Pennsylvanian age **Morrow Formation** (PB Figure 3) are fine-grained sandstone and shales eroded from areas north, east, and northwest of the Delaware Basin. Down warp of the Delaware Basin is obvious. The rest of the Permian Basin was exposed to erosion and were most likely low rolling hills at this time.



PB Figure 3. Morrowan paleogeographic map showing early downwarp of the Delaware Basin and Morrow sediments fed from the north. After Hanson and others, 1991. Explanation covers PB Figures 3 to 7.

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p. 2

Integrated Solutions,

Core Lab

overlain by heterolithic estuarine and bay-fill successions. They are capped by flooding surfaces, or their up-dip correlatives, and interfinger down-dip into shoreface and shelf facies composed of coarsening upward parasequences. These valleys appear to have been separated by interfluves that may have been subaerially exposed.

- The Lower Morrow third-order sequence is capped by a basin-wide maximum flooding surface and highstand shale, recording a major rise in sea level that h as been documented in Morrowan-aged rocks around the world. The shale thins northward, and in several weeks appears to be cut out. This thinning is probably a combination of depositional pinch-out and erosion by the Middle Morrow fluvial system.

- Following deposition of the Lower Morrow sequence, a major, third-order drop in sea level resulted in the creation of a basin-wide unconformity across the top of the Lower Morrow. Over this unconformity, a network of early Middle Morrow, bed-load-dominated fluvial systems flowed southward across a coastal plain characterized by paleosols and *Lepidodendron* swamps. The cross sections reveal that the Middle Morrow rivers did not erode as deeply as the Lower Morrow streams, possibly reflecting a lower gradient across the basin.

- During middle to late Middle Morrow time the basin appears to have been a large, persistent, highstand embayment that was repeatedly crossed by incised fluvial systems during fourth – and – fith-order sea level lowstands. The deposition and architechture of these valley fill successions was controlled by these low-amplitude base level fluctuations that resulted in The creation of limited amounts of accommodation space. Tides reworked fluvial sands in estuaries across the basin. A coarsening upward, southwest to northeast-trending, shoreface to beach parasequence developed across the northern part of the study area, and may be locally incised by fluvial stream systems along the eastern edge of the basin.

Samson Exhibit 40

Fig. 1-7

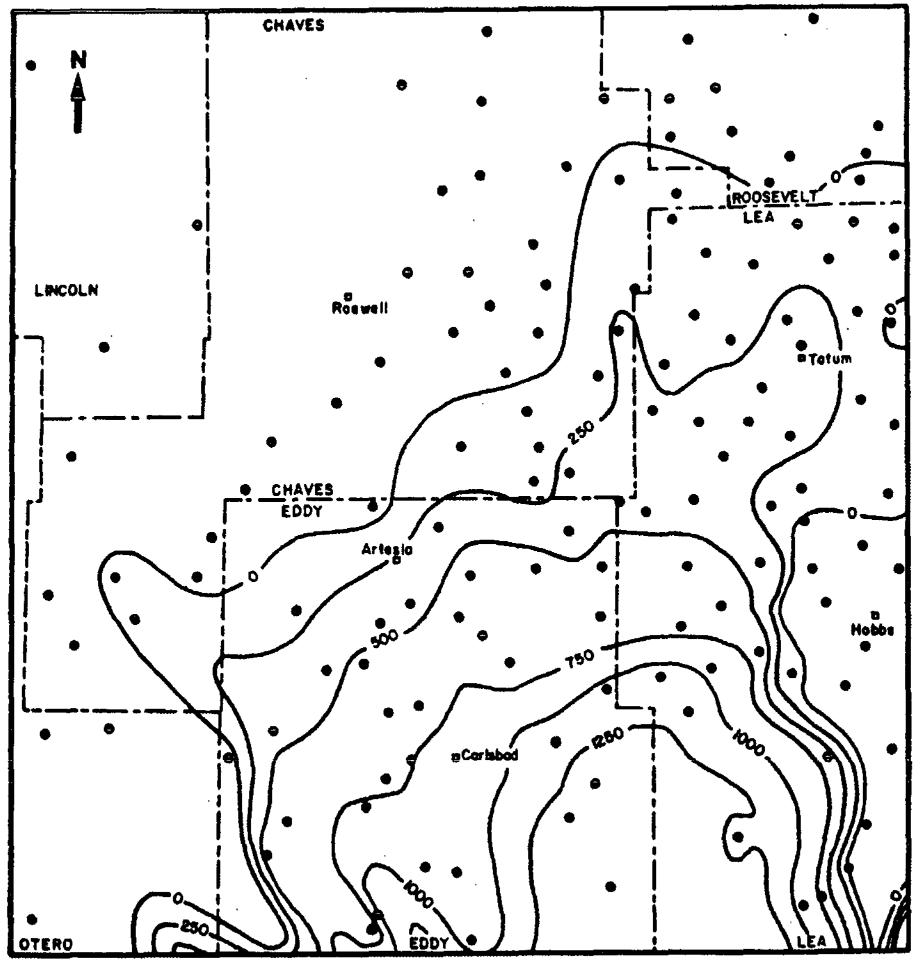
Also CHK Exhibit GEO AD 13

Meyer,

Integrated Reservoir Solutions,
Core Lab

FIGURE 1-7

ISOPACH MAP OF THE MORROW FORMATION



From Meyer 1966

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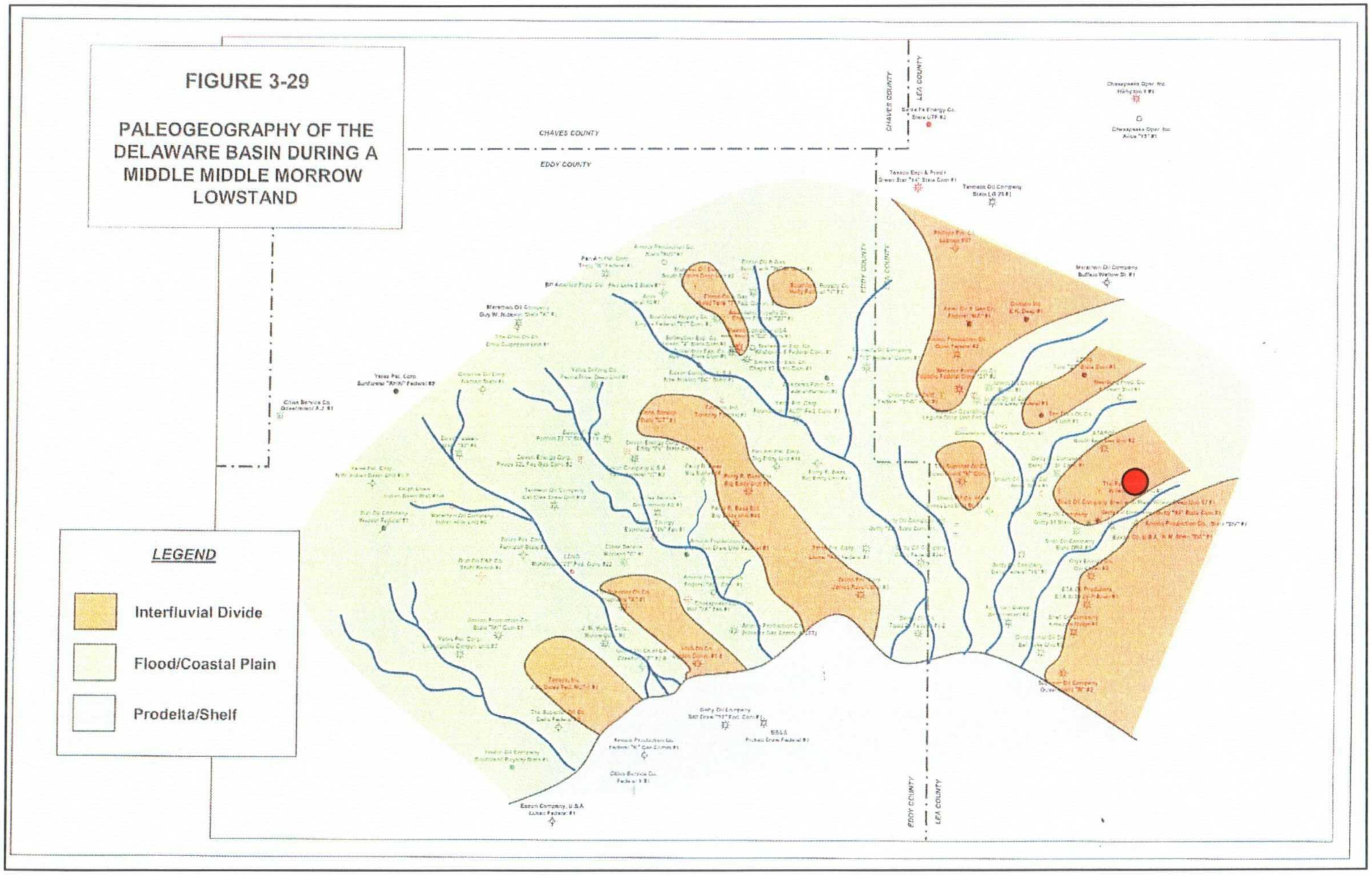
GEO17



2004, Sequence Stratigraphy and Petrophysical Study of the Morrow Sandstones Delaware Basin, Integrated Reservoir Solutions and Core Lab

Recent Morrow study shows East to West depositional pattern

LITERATURE SUMMARY

- A cross-section of literature from 1955 to present, from 25 authors.
- The Delaware Basin began forming in late Mississippian into the early Pennsylvanian.
- Morrowan sediments were derived from the Pedernales Uplift to the NW and locally from the CBP to the East.
- In the vicinity of the KF 4 St. #1, this included sediments originally eroded from the Pedernales, deposited during Transgressions and High Stands along the flanks of the CBP then eroded again from the CBP and re-deposited.
- Supplemental sediments were derived from erosion of the Mississippian section off the exposed CBP itself.
- The Midland Basin was not yet formed during Morrowan time and was an area of non-deposition.
- This resulted in an overall East-West deposition direction by dip oriented incised fluvial and fluvio-deltaic systems in the vicinity of the KF 4 State #1.
- The axis of the Delaware Basin lies to the West of the KF 4 St. #1 area and trends in a North-South lineation.
- To the west of the KF 4 St. #1 vicinity, dip-oriented fluvial sand depositional systems merged in the deeper Delaware Basin with sands derived directly from the Pedernales.
- Mapping of the Middle Morrow sands as one unit must be followed by detailed stratigraphic correlations and sample analysis to differentiate individual sand units.
- Individual sand bodies should then be mapped separately to differentiate reservoir separation.
- Reservoir Engineering data, production decline histories and pressure data analysis should be utilized to confirm geologic interpretation.