SEQUENCE STRATIGRAPHY AND PETROPHYSICAL STUDY OF THE MORROW SANDSTONES DELAWARE BASIN

FINAL REPORT

Volume 1

Text

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INTRODUCTION

This Final Report synthesizes the results of a two-phase study of the Morrow-aged sandstones in the northern Delaware Basin in Eddy and Lea Counties, New Mexico. The first phase was a sequence stratigraphic analysis of the Morrow clastic section, and the second phase was a petrophysical analysis of the Morrow sandstones. Included in this final report is a synthesis of the geologic, petrographic, and petrophysical data acquired during this study.

Integrated Reservoir Solutions initiated the current study to help operators in the area more accurately locate and subsequently exploit Morrow sandstones. The following companies participated in the study:

Chevron/Texaco
Marathon
EOG
LDNG (Dominion)
Devon
Matador (Tom Brown/EnCana)
Mack
Yates
Mission
BP
Chesapeake
Oxy
Amerada-Hess
Pure Resources
Samson

Both conventional cores and rotary sidewall cores were utilized for the study. The conventional cores from thirty wells were located by Integrated Reservoir Solutions, and many of the participating companies contributed rotary sidewall cores from at least two wells. Operators also provided a complete suite of well logs, core analysis data, and completion or production test data for each of the contributed wells. The two-thirds slabs were available for several of the conventional cores and new plugs were cut from these slabs to augment the petrophysical well list where rotary sidewall cores were unavailable. The wells are listed in Table 1-1 and the locations are shown in Figures 1-1 and 1-2. Logs from at least seventy other wells were located and digitized, where necessary, to provide in-fill coverage for six cross-sections constructed across the study area for the sequence stratigraphic analysis.

Objectives

For four decades, operators exploring in the Morrow of Southeast New Mexico have struggled with the complex geology of the unit. The difficulty in correlating the Morrow sandstones from one section to another, let alone among townships, has frustrated efforts to understand the geometry and distribution of the reservoirs. In addition, the Morrow sandstones have exhibited a lack of predictability in drainage area and volume.

In the early 1980's Reservoirs, Inc. conducted a regional core study of the Morrow of southeast New Mexico. Conventional core, core chips, and drill cuttings from one hundred and twenty-eight wells were described and analyzed in one of the first attempts to analyze the Morrow at a regional scale. The Morrow has been studied on a field-by-field basis over the years (e.g. James 1985, Worthington and Brown 1999) but no attempt has been made at a regionally scaled integration of the sequence stratigraphy and the petrophysical properties.

The advent of new concepts and analytical techniques over the years since that first study has resulted in new tools for use in evaluating the Morrow sandstones. These include sequence stratigraphy with its emphasis on genetic packaging and facies prediction, and nuclear magnetic resonance (NMR) logging tools. New completion fluids have been developed since the original study, and the increasing use of 3-D seismic data requires acoustical properties measurements

TABLE 1-1

MORROW SEQUENCE STRATIGRAPHIC AND PETROPHYSICAL PROJECT STUDY WELLS

SS No.	PS No.	API NUMBER	CTY	CONTRIBUTING COMPANY	OPERATOR/WELL NAME	FIELD	SECTION, TOWNSHIP, RANGE	CORE/SAMPLE INTERVAL	SAMPLE TYPE
1		30015205840000	EDDY		Midwest Oil Corporation South Empire Deep Unit No. 2	Wildcat	6-18S-29E	10,715.0 - 10,886.0	CC
2		30015011230000	EDDY		Union Oil Co.of Calif. Crawford "B" No. 1-9	Wildcat	9-24S-27E	10,668.0 - 12,124.0	CC
3		30015100510000	EDDY		Yates Drilling Company Pecos River Deep Unit No. 1	Wildcat	28-19S-27E	10,255.0 - 10,374.2	CC
4		30025271520000	LEA		Union Oil of California Laguna Deep Federal No. 3	East Gem (Morrow)	35-19S-33E	13,065.5 - 13,483.4	CC
5		30025258240000	LEA		Getty Oil Company Getty 35 State No. 1	Gramma Ridge Morrow	35-21S-34E	13,076.0 - 13,114.0	CC
6		30025272500000	LEA		Getty Oil Company Berry "5" St. Com No. 1	North Berry	5-21S-34E	13,867.0 - 14,216.0	CC
7		30015232250000	EDDY		Arco Federal 10 No. 1	Illinois Camp	10-18S-28E	10,350.0 - 10,469.4	CC
8		30015235650000	EDDY		Southland Royalty Company Empire Federal "21" Com. No. 1	Undesignated (Morrow)	21-18S-29E	11,025.0 - 11,216.6	CC
9		30015235020000	EDDY		Southland Royalty Company Empire Federal "22" No. 1	Empire South	22-18S-29E	11,174.0 - 11,216.6	CC
10		30025277050000	LEA		Union Oil of California Smith No.1	East Gem Morrow	25-19S-33E	13,248.0 - 13,495.5	CC
11		30025213360000	LEA		Shell Oil Company State GRA No. 1	Wildcat (Falcon Area)	3-22S-34E	12,810.0 - 13,124.0	CC
12		30015242450000	EDDY		Southland Royalty Company Holly Federal "4" No. 1	Wildcat	4-18S-20E	11,390.0 - 11,431.5	CC
13		30015243270000	EDDY		Cities Service Co. Federal X No. 1	Wildcat	8-26S-27E	12,305.0 - 12,577.3	CC
14		30015229590000	EDDY		Cities Service Company Government A.J. No. 1	Wildcat	8-20S-21E	7,581.6 - 7,664.5	CC
15	5	30015000340000	EDDY	Marathon	Ralph Lowe Indian Basin Well No. 1-A	Wildcat	22-21S-23E	9,044.0 - 9,360.0	CC
16	6	30015258270000	EDDY	Marathon	Marathon Oil Company Indian Hills Unit No. 6	Indian Basin Field	20-21S-24E	9,498.0 - 9,716.0	CC
17		30025271310000	LEA		Union Oil Company of California Federal "31-G" Well No. 1	Gem Morrow	31-19S-33E	13,246.0 - 13,434.8	CC
18	3	30025282630000	LEA	Chevron/Texaco	Santa Fe Energy Co. State UTP No. 2	Feather	21-15S-32E	12,374.0 - 12,403.6	CC
19		30025204610000	LEA		The Pure Oil Company Wilson Deep Unit No. 1	Wildcat	13-21S-34E	12,236.0 - 12,288.0	CC
20		30015217240000	EDDY		Cities Service Oil Company State "CT" No. 1	Burton Flat	16-20S-28E	11,145.0 - 11,361.0	CC
21		30015207970000	EDDY		Cities Service Oil Company Merland "C" No. 1	South Carlsbad	19-22S-27E	11,342.0 - 11,398.0	CC
22	4	30015236250000	EDDY	Chevron/Texaco	Exxon Company-USA New Mexico "CZ" State No. 1	North Turkey Track	2-19S-29E	11,421.0 - 11,470.0	CC
23	8	30015251230000	EDDY	EOG	Conoco, Inc. Tuesday Federal No. 1	Burton Flat East	34-19S-29E	11,592.0 - 11,638.0	CC
24		30015208210000	EDDY		Texaco, Inc. J.M. Gates Fed. NCT-1 No. 1	White City (Penn)	30-24S-26E	11,373.0 - 11,445.6	CC
25		30015235980000	EDDY		Inexco Oil Company Southland Royalty State No. 1	Wildcat	32-25S-25E	11,259.0 - 11,297.5	CC
26		30025272220000	LEA		Union Oil Company of California Eaves Lea Unit St. No. 1	Wildcat	30-21S-33E	14,502.0 - 14,543.2	CC
27	15	30025275010000	LEA	Mack	Union Oil Company of California Berry State No. 1	Wildcat	13-21S-33E	13,696.0 - 13,799.0	CC
28		30025213420000	LEA		Shell Oil Company Shell et al West Wilson Deep Unit 17 No. 1	Wildcat	17-21S-34E	13,956.0 - 14,083.0	CC
29		30015236240000	EDDY		Perry R. Bass Big Eddy No. 86	Sand Point	9-21S-28E	11,747.0 - 11,764.5	CC
30	2	30015230400000	EDDY	Chevron/Texaco	Gulf Oil E & P Company Truitt Ranch No. 1	Wildcat	26-22S-24E	10,394.0 - 10,820.0	CC
	1	30025346620000	Lea	Chevron/Texaco	Texaco Expl & Prod Inc. Green Star "14" State Com No. 1	Anderson Ranch	14-16S-32E	12,236.0 - 12,246.0	RSWC
	7	30015292890000	Eddy	EOG	Enron Oil & Gas Sand Tank "36" St. Com No. 1	Sand Tank	36-17S-29E	11,195.0 - 11,216.0	RSWC
	9	30025346770000	Lea	Dominion	LDNG Greenstone "19" Federal Com. No. 1	Quail Ridge	19-20S-34E	13,431.0 - 13,666.0	RSWC
	10	30015293510001	Eddy	Dominion	LDNG McKittrick "29" Fed. Com. No. 22	Happy Valley	29-22S-26E	11,097.0 - 11,326.0	RSWC
	11	30015308860000	Eddy	Devon	Devon Energy Corp. Eddy "FV" State Com. No. 4	Burton Flat	25-20S-27E	11,145.0 - 11,283.0	RSWC
	12	30015308550000	Eddy	Devon	Devon Energy Corp. Pecos 32L Fee Gas Com. No. 2	Wildcat	32-20S-27E	10,792.0 - 10,989.0	RSWC
	13	30025348300000	Lea	Tom Brown	Matador Petroleum Co. Topacio Federal Com. "28" No. 2	Gem	28-19S-33E	13,270.0 - 13,626.0	RSWC
	14	30025347490000	Lea	Tom Brown	Matador Operating Co. Laguna Deep Unit Fed No. 5	Wildcat	35-19S-33E	13,127.0 - 13,333.0	RSWC
	16	30015317170000	Eddy	Devon for Mack	Devon Energy Esperanza "3N" Fee No. 1	Carlsbad	3-22S-27E	12,410.0 - 11,749.0	RSWC
	17	30025349910000	Lea	Yates	Yates Pet. Corp. Indigo Unit No. 1	Wildcat	7-12S-35E	12,371.0 - 12,434.0	RSWC
	21	30015324210000	Eddy	BP	BP America Red Lake 3 State No. 1	Artesia	3-18S-28E	10,310.0 - 10,509.0	RSWC
	23	30015320640000	Eddy	Chesapeake	Chesapeake Will "7A" Fee No. 1	Loving North	7-23S-28E	12,025.0 - 12,421.0	RSWC
	24	30025360360000	Lea	Chesapeake	Chesapeake Hampton No. 1	Austin SW	1-15S-35E	13,341.0 - 13,363.0	RSWC

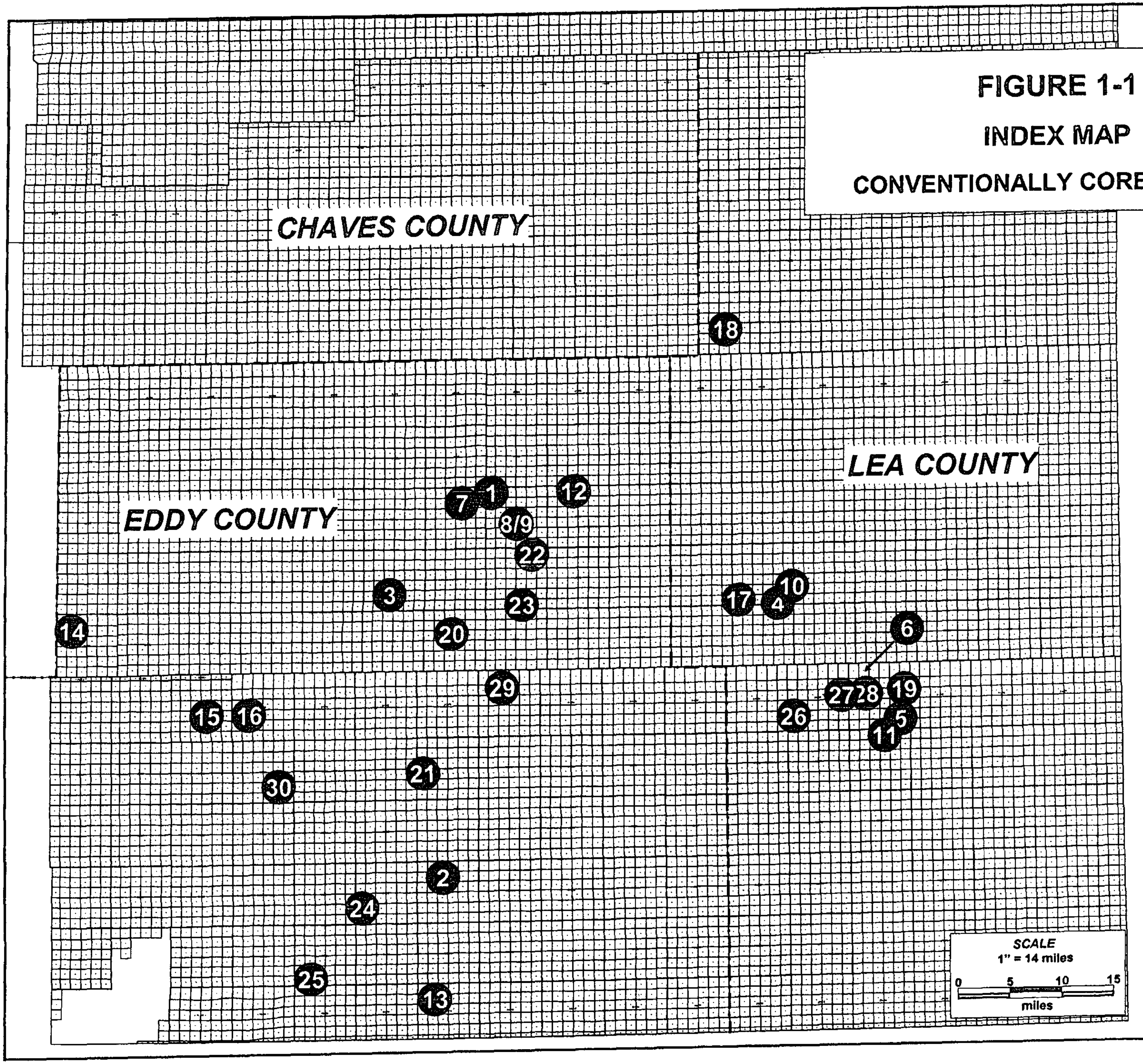


FIGURE 1-1

INDEX MAP

CONVENTIONALLY CORED WELLS

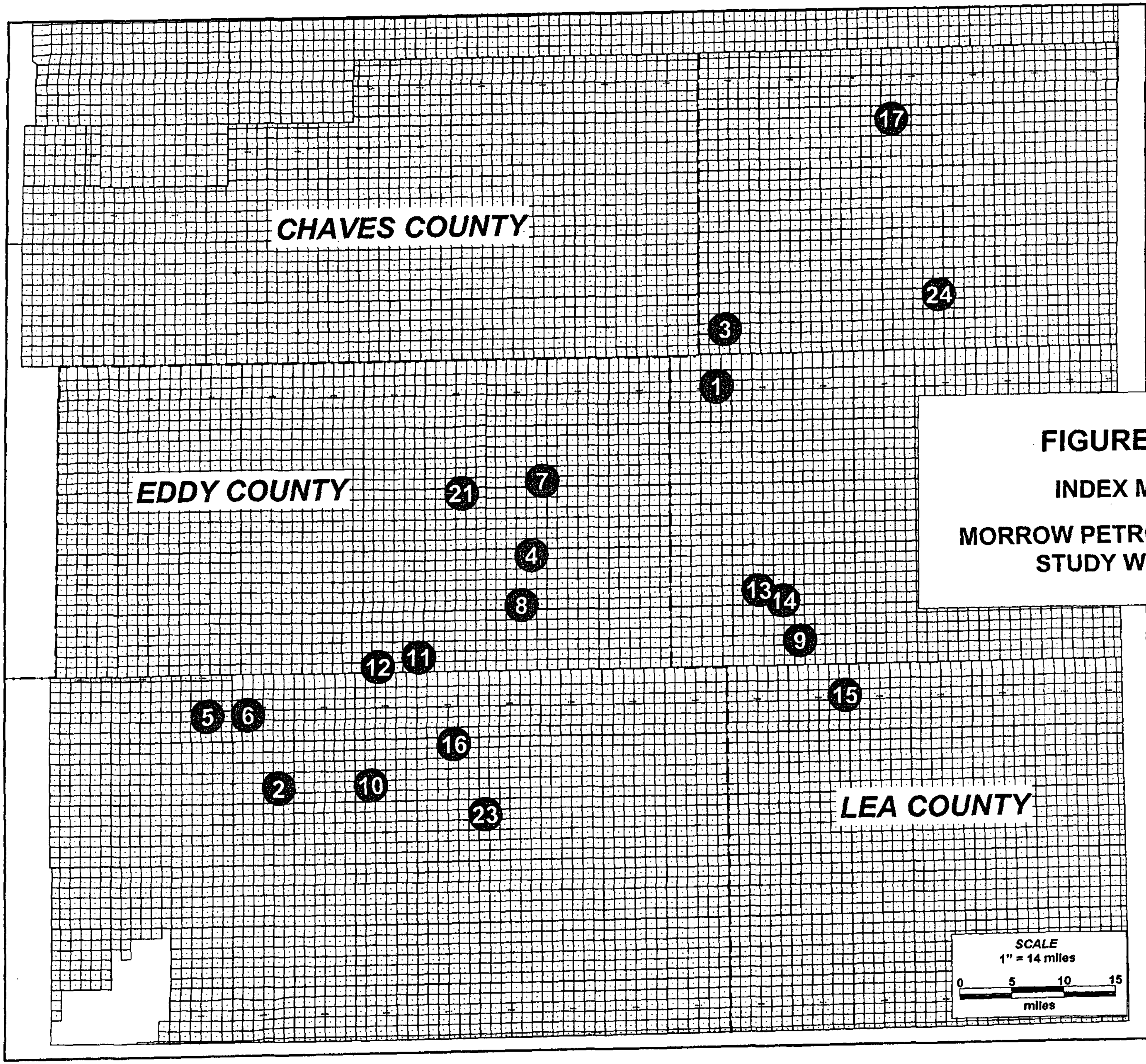


FIGURE 1-2

INDEX MAP

MORROW PETROPHYSICAL STUDY WELLS

conducted directly on rock samples in order to process these data properly. With these considerations the objectives of this study are:

- To develop a sequence stratigraphic model for the Morrow clastic section to improve understanding of the regional distribution of reservoir sandstones.
- Develop a depositional and reservoir architectural model of the Morrow sandstones for an improved success rate of delineation wells.
- Identify the various Morrow reservoir rock types in core and measure the petrophysical properties to improve formation evaluation.
- Integrate the core-measured petrophysical properties, well log data, and well production test data to improve operator's ability to predict the productivity of Morrow sandstones.
- Evaluate current drilling and completion methods and determine the compatibility of common drilling and completion fluids with Morrow sandstones.

Data Set and Analytical Program

In order to achieve these objectives the following analytical program was utilized. A detailed description of the analytical methods is included in Appendix A.

Conventional Core Description: Over two thousand seven hundred and sixty two (2762.7) feet of conventional core were described in detail to determine lithology, vertical facies distribution, and depositional environment. Core description panels directly correlate log response with these geologic parameters and core analysis data.

Sequence Stratigraphy: Six cross sections were constructed in GeoGraphix™ using the conventionally cored wells and additional in-fill wells. Initial correlations were made using the Morrow stratigraphic tops from the *Geological Data Services* Southeast New Mexico Atoka/Morrow database. Using sedimentological and environmental information from the conventional cores, basin-wide surfaces (unconformities and flooding surfaces) were correlated in order to place the Morrow sandstones in their genetic context.

Petrography and Mineralogy: One hundred conventional core plugs and rotary sidewall cores were selected and analyzed using thin section petrographic techniques including modal point count analysis. Thin section petrography and scanning electron microscopy (SEM) documented texture, mineralogy, and porosity development for each sample. Each plug or rotary sidewall core was photographed in plain light, and these images are included on the Petrophysical Summary Panels for each well.

Basic Rock Properties: Basic rock property measurements determined porosity, permeability, grain density, and bulk density for all one hundred samples. Sandstones displaying similar petrographic and petrophysical properties were classified as distinct rock types using Core Laboratories *Worldwide Rock Catalog™* protocols.

Advanced Rock Properties: Forty of the above samples, representing the spectrum of reservoir rock types, were selected for special core analysis testing to determine formation factor (F), cementation exponent (m), resistivity index (RI), saturation exponent (n), effective gas permeability (Keg), and mercury injection capillary pressure characteristics. Thirteen of these Advanced Rock Properties samples were also analyzed using Nuclear Magnetic Resonance (NMR) techniques to provide petrophysical data processing parameters such as T_2 cutoffs and permeability algorithms. These data can be used to calibrate the MRIL or CMR down hole tools resulting in improved formation evaluation. Acoustical properties measurements were conducted on thirteen vertical plugs drilled from the conventional cores to measure Vp, Vs, Poisson's Ratio and Young's Modulus.

Rock-Fluid Compatibility: Thirty-five additional plugs comprising four of the most common reservoir rock types were drilled from the conventional core for Rock-Fluid Compatibility testing. These tests determined the type and extent of formation damage caused by various drilling, completion, and fracture fluids.

To meet the objectives of this study, the Morrow sandstones had to first be placed in their stratigraphic context and reduced to distinct rock types. These rock types, by definition, group together samples displaying similar petrographic and petrophysical properties. Once these have been identified, they can be correlated with production test results and log response, and allow the establishment of log criteria that can be used to distinguish pay from non-pay zones. Depending on the degree of correlation, log shapes and responses could be used to predict a wide variety of petrophysical properties associated with the various rock types. Improved understanding of the shape, size, and architecture of the Morrow sandstones, and their petrophysical properties will: 1) lead to improved accuracy in locating new wells, 2) reduce formation damage during drilling and completion operations, 3) limit the bypassing of productive intervals, 4) minimize unnecessary testing of wet zones, 5) differentiate damaged pay from non-pay, and 6) provide more accurate reserve calculations.

Deliverables for this study include one hard copy of the individual well reports and this Final Report along with their digital files. In addition, the data, maps, tops, and cross-sections will be delivered as a GeoGraphix™ *Discovery™* project.

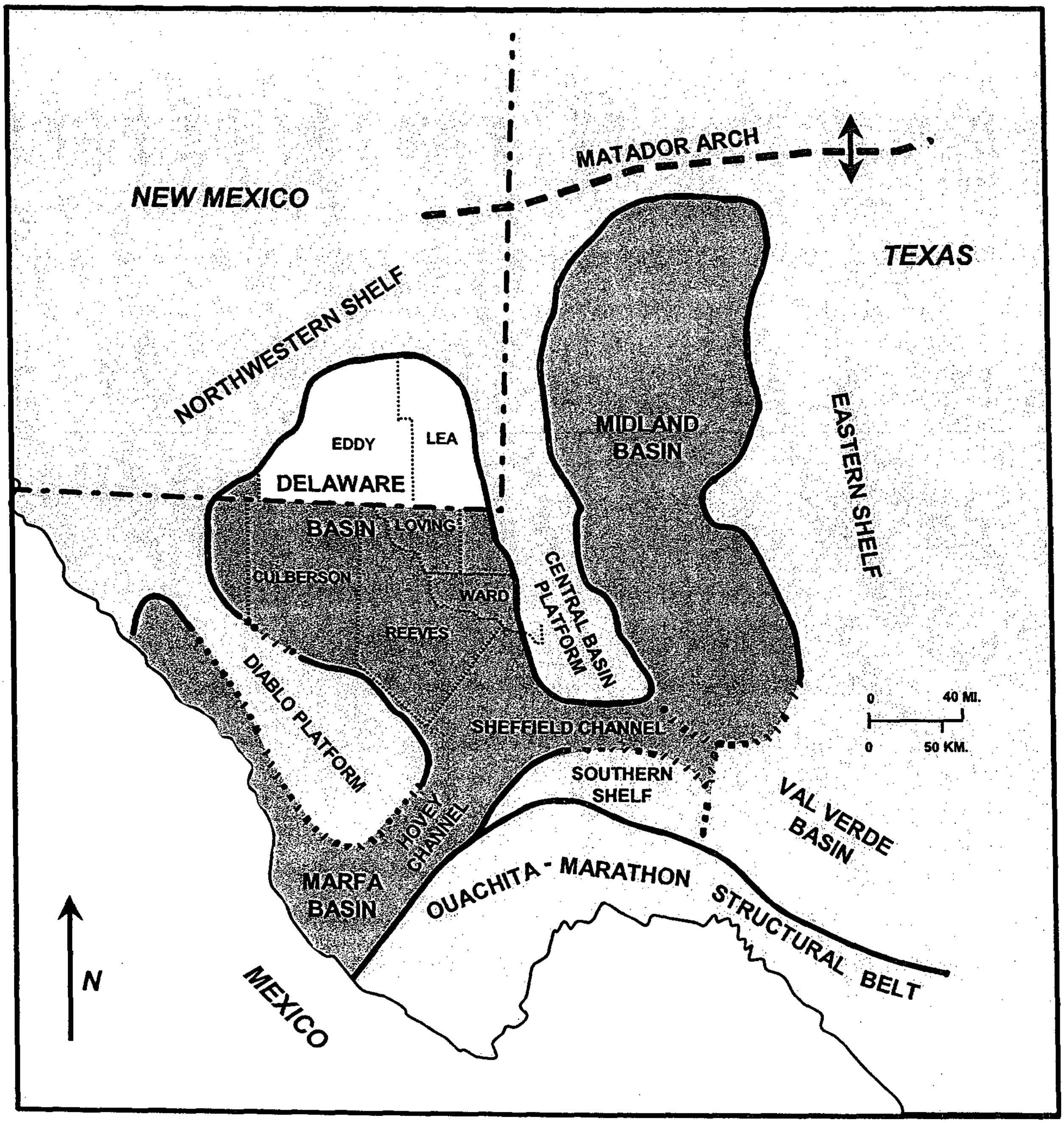
Geologic Setting and Stratigraphy

The Morrow sandstones evaluated in this study constitute the basal Pennsylvanian strata in the Northern Delaware Basin located in Lea and Eddy Counties, New Mexico (Figure 1-3). This basin is a broad, block-faulted, asymmetrical basin approximately 100 miles in diameter, which developed as a distinct structural depression in the Late Paleozoic (Figure 1-4).

The Early Pennsylvanian paleogeography of the western United States was characterized by a series of uplifts and highlands that included the ancestral Rocky Mountains and the Defiance-Zuni Uplift (Figure 1-5). This area extended from central Arizona to southern Wyoming and eastward to the present day Great Plains. Relatively stable basins around the margin of this land mass were flooded by marine waters for much of the Late Mississippian during a period of

FIGURE 1-3

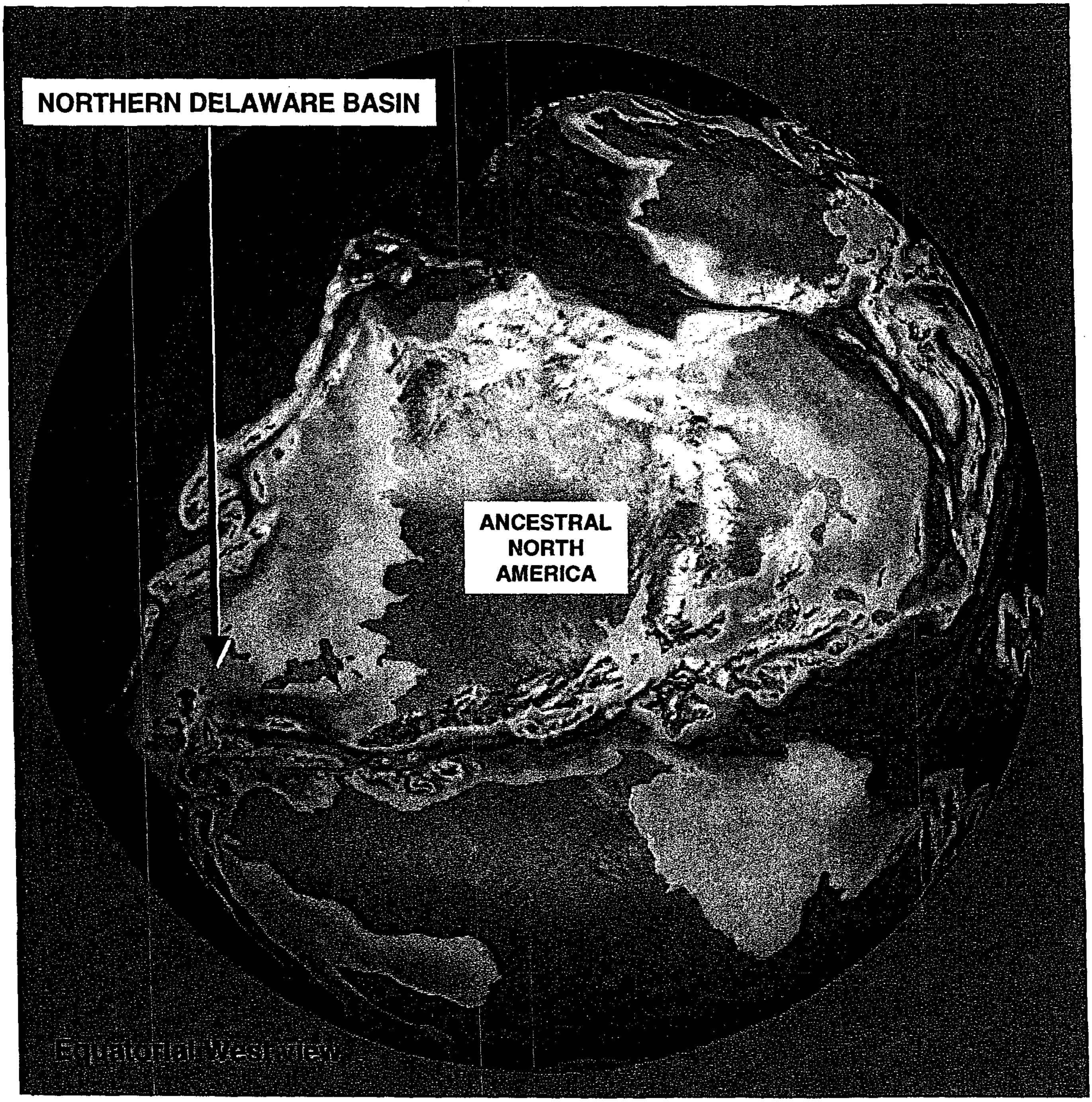
STUDY AREA IN RELATION TO PERMIAN BASIN STRUCTURAL ELEMENTS



(After Williamson, 1979).

FIGURE 1-4

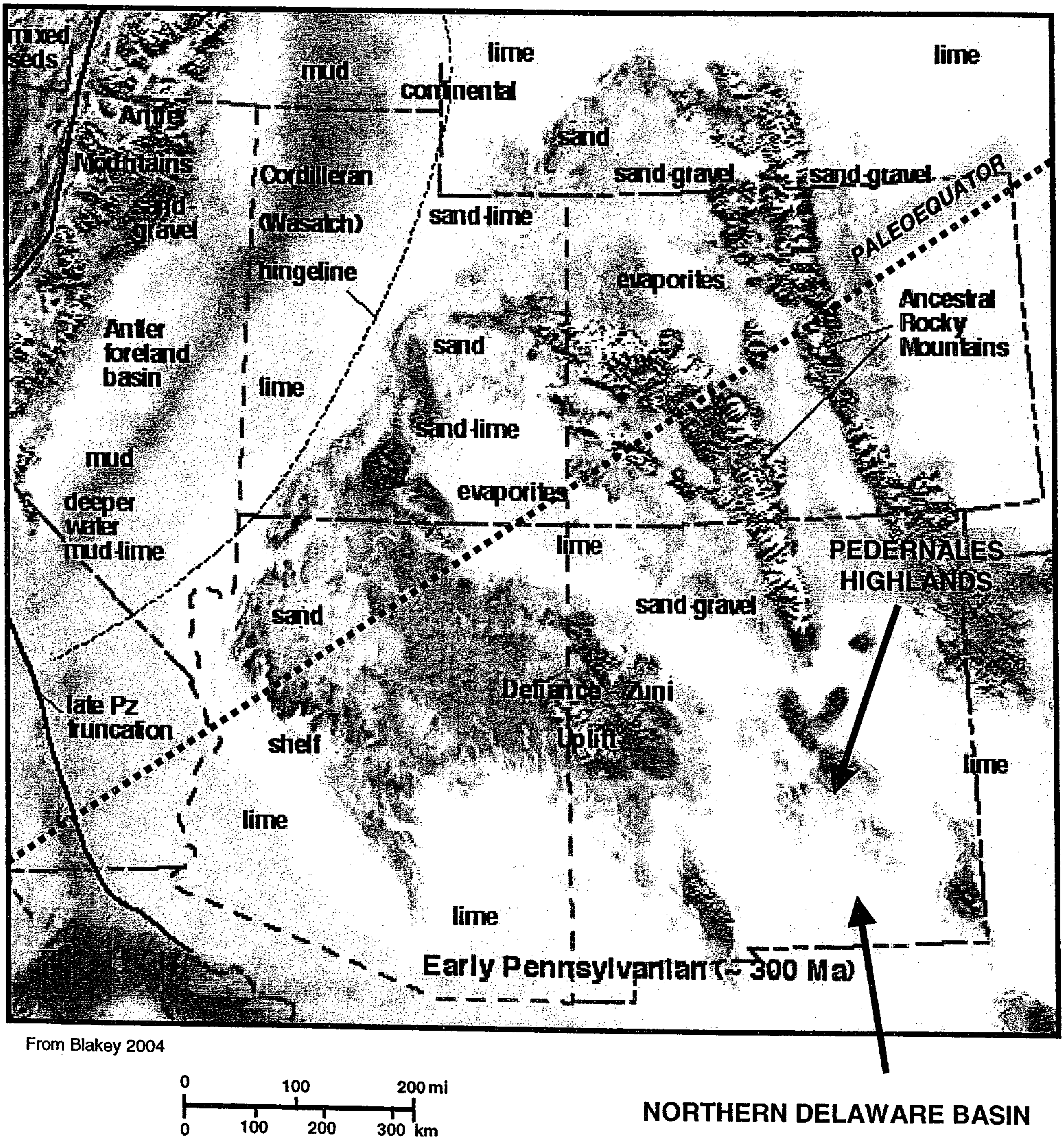
PALEOGEOGRAPHY OF THE WESTERN HEMISPHERE DURING LATE MISSISSIPPIAN TIME



From Blakey 2004

FIGURE 1-5

PALEOGEOGRAPHY OF THE SOUTHWESTERN UNITED STATES DURING EARLY PENNSYLVANIAN TIME



significant sea level highstand. The northern Delaware Basin in southeast New Mexico was one of these broad cratonic basins. It opened southward during Early Pennsylvanian time and lay south of the paleoequator (Figure 1-5).

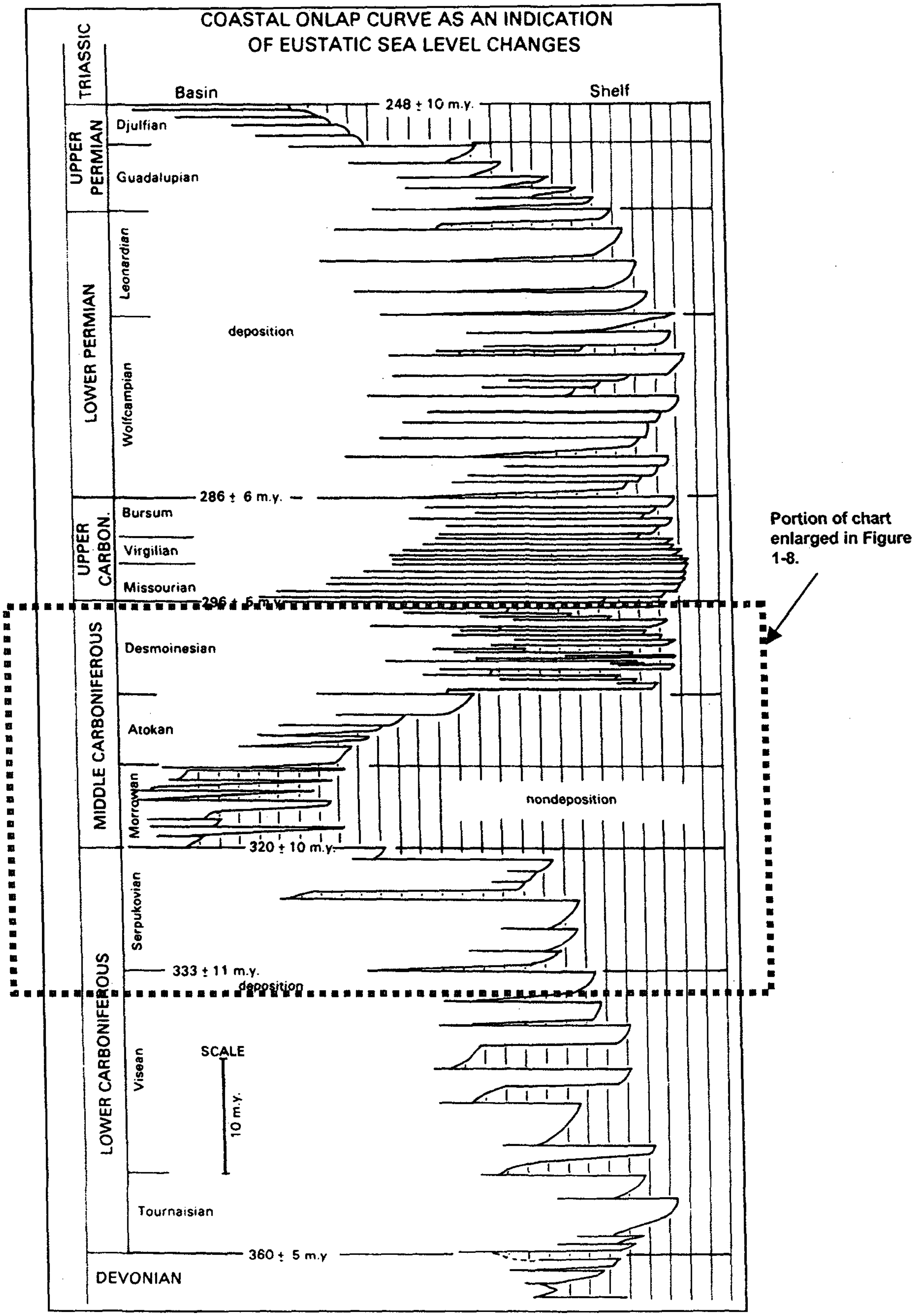
Ross and Ross (1988) have published data indicating that sea levels were globally higher in the Late Mississippian just prior to Morrowan time (Figure 1-6), and the thick, Chesterian-aged limestones, which underlie the Morrow in the Delaware Basin and elsewhere, were deposited during this time.

The northern Delaware Basin was tectonically stable, and due to its intracratonic position, did not experience thermal subsidence, which characterizes trailing edge, passive continental margins. On a passive margin, accommodation space is created by the essentially continuous subsidence of the margin outboard of a hingeline formed at the locus of a transitional crust. This transitional crust is formed during initial rifting and separates silica-rich continental crust and more dense mafic-rich oceanic crust. The basinward slope of the margin is due to differences in buoyancy between continental, transitional and oceanic crust (Sloss 1996) and typically ranges from 0.1° to 0.3°. As a result, the creation of accommodation space on a passive continental margin is measured in thousands of feet per million years, and provides for the deposition of thick packages of sand and mud across a basinward sloping shelf, which terminates in a shelf break and continental slope.

In contrast, the Delaware Basin subsided very slowly, and the subsidence was driven by intraplate stresses. The resulting creation of accommodation space is probably measured in tens of feet per million years rather than the thousands of feet per million years that characterizes trailing-edge margins (Sloss 1996). The rate at which accommodation space is created affects facies distribution and thickness of the sedimentary veneer of the basin floor. As Sloss (1996, pg. 429) states:

FIGURE 1-6

UPPER PALEOZOIC RELATIVE CHANGE OF COASTAL ONLAP CURVES



From Ross and Ross, 1988

> "...*these intracratonic basins* have been repeatedly covered with essentially horizontal sea floors maintained in that state, in spite of minor variations in subsidence, by rates of sedimentation characteristically in excess of the rates of creation of accommodation space. This is an interpretation supported by the relative ease with which individual sedimentary packages (third- to fifth-order cycles of sequence stratigraphy) can be traced for hundreds of kilometers, commonly across basin margins and depocenters...." (italics added)

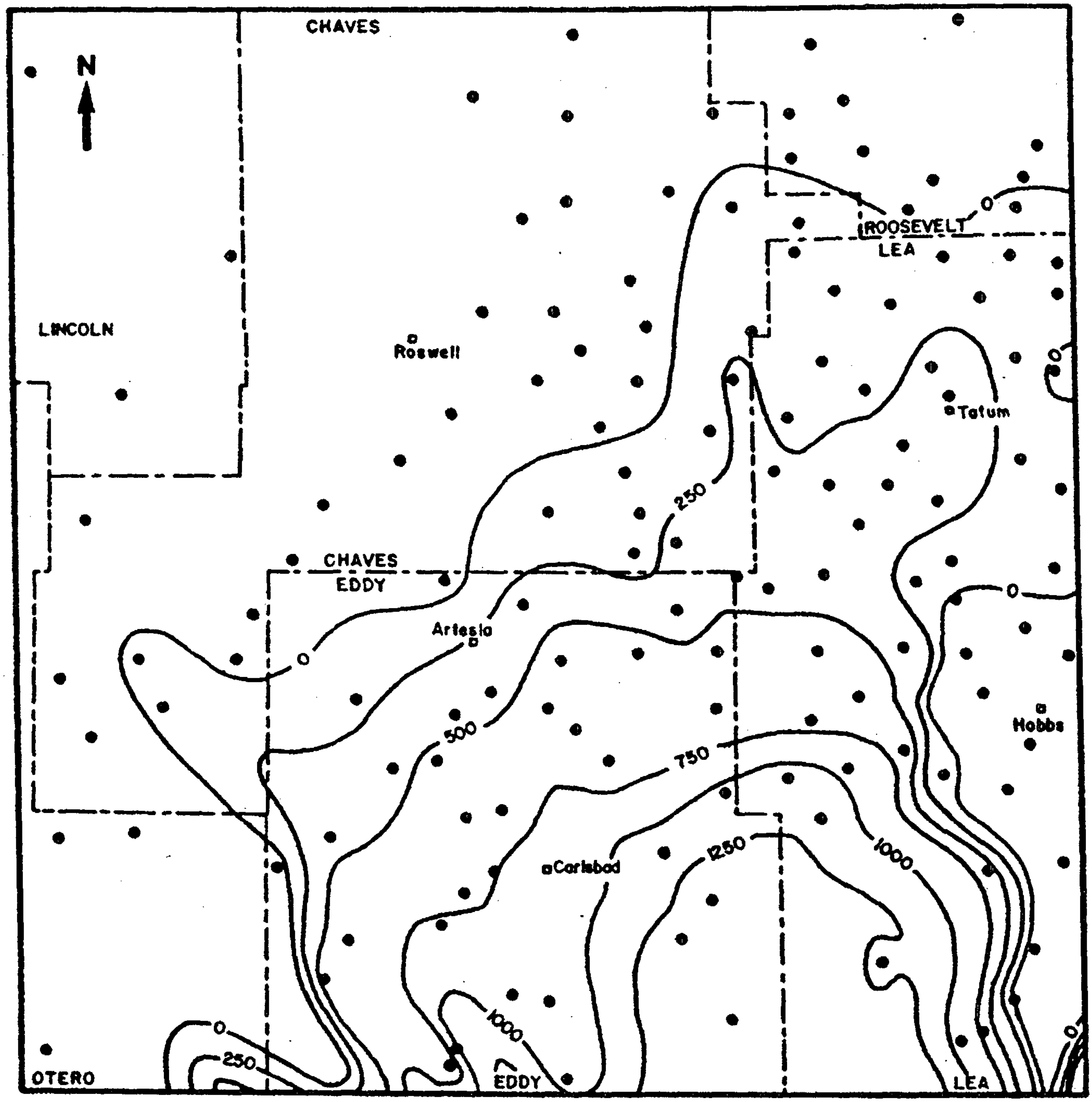
The Northern Delaware Basin during Morrowan time probably exhibited a gentle slope to the present day southeast. Figure 1-7 is an isopach map of the Morrow strata published in the original Reservoirs, Inc. Morrow study, and is taken from Meyer, 1966. It illustrates thickening of the Morrow to the south and southeast, and suggests the basin subsided to the south during deposition of the Morrow. Although thickness changes in the Morrow section indicate a southward slope for the basin floor during deposition of the Morrow, the relatively even spacing of the isopachs suggest that there was no recognizable shelf break within the basin. Assuming that the southeastward expansion in the isopachs is a proxy for the slope of the Morrow shelf, the gradient across the basin may have been 0.01°.

The base of the Pennsylvanian section in the mid-continent and western U.S. is characterized by fluvial to transitional rocks overlying Mississippian carbonates and deeper water deposits. As illustrated in Figure 1-8, a second-order drop in sea level is defined by a dramatic basinward shift in coastal onlap, and is recorded in the stratigraphic record as a significant unconformity at the base of the Morrow section. The base of the Morrow in the western U.S. is also the base of Sloss's Absaroka Sequence (Sloss 1963), and he picked the base of the sequence at the second-order regressional maximum.

Note the higher frequency relative change in coastal onlap curves during Morrow time in Figure 1-8. These are considered to be third-order sea level changes,

FIGURE 1-7

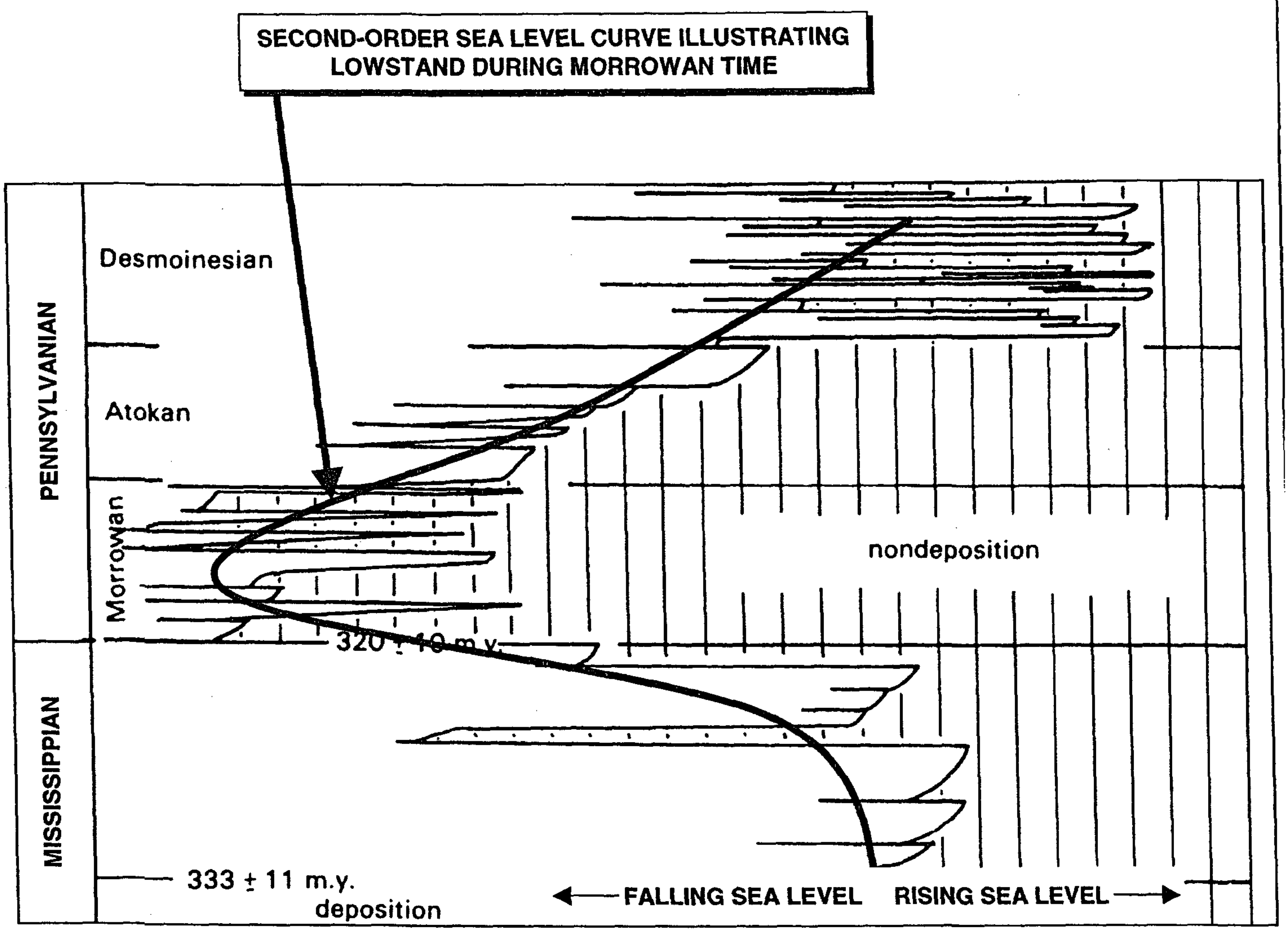
ISOPACH MAP OF THE MORROW FORMATION



From Meyer 1966

FIGURE 1-8

MORROWAN SECOND-ORDER LOWSTAND



Modified from Ross and Ross, 1988

which are superimposed on the second-order curve, and are key to understanding deposition of the Morrow in southeast New Mexico.

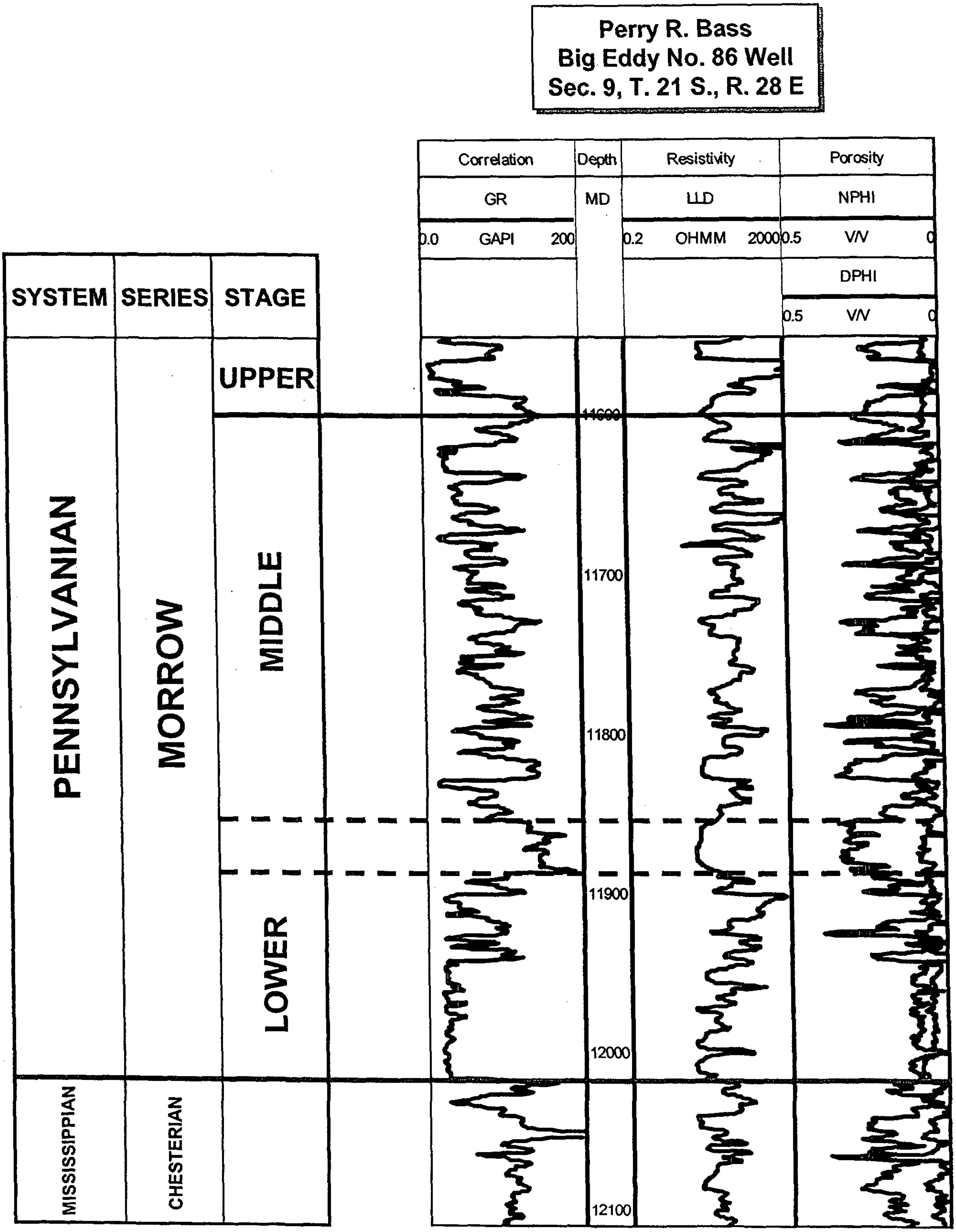
Figure 1-9 illustrates the breakout of the Morrow Series and the stage-level subdivision of the unit. Also shown is a type log for the Morrow rocks in the Northern Delaware Basin in the Perry R. Bass Big Eddy No. 86 Well. The contact between the Lower and Middle Morrow is shown by dashed lines in two positions above and below the well-known "Middle Morrow Shale", which is a good regional marker. The top of the Lower Morrow has been traditionally placed at the highest gamma ray spike above the sandstones of the Lower Morrow. As will be shown by this sequence stratigraphic study however, the "Middle Morrow Shale" is genetically connected to the Lower Morrow and constitutes a third-order highstand facies deposited following a major flooding of the basin. The top of the shale is picked at a basin-wide unconformity at the base of the Middle Morrow sequence.

The top of the Middle Morrow has been difficult to pick consistently on a regional basis. It has been typically picked at the base of the thick carbonate sequences that are characteristic of the Upper Morrow. For the purposes of this study an effort has been made to pick the "top" of the Middle Morrow at a consistent maximum flooding surface below the lowest significant carbonate unit of the Upper Morrow. In some locations, this occurs in a tidal flat to bay facies, and in other places, it has been cut out by a fluvial channel facies.

The climate during the Early Pennsylvanian was the primary driver of sea level changes that alternately created and destroyed accommodation space for accumulation of Morrow strata in the Northern Delaware Basin. Icehouse conditions developed during the Late Paleozoic and glacial ice accumulated in Gondwana (Crowley and Baum 1991). Yasamanov (1981) reports that ocean temperatures during the Morrowan were cooler on the basis of Ca:Mg ratios.

FIGURE 1-9

STRATIGRAPHIC COLUMN FOR SOUTHEAST NEW MEXICO AND TYPE LOG FOR THE MORROW FORMATION, NORTHERN DELAWARE BASIN



The Pennsylvanian Period lasted from 323 mya to 290 mya and the Late Paleozoic Ice Age discussed by Crowell (1999) lasted from 338 mya to 256 mya. Glacially driven transgressive-regressive cycles in the Early Pennsylvanian have been documented by Crowell (1978), Heckel (1986), and Veevers and Powell (1987), and the transition to icehouse conditions is postulated as the mechanism for the second-order lowstand shown in Figures 1-6 and 1-8.

The third-order cycles that are superimposed on the climatically driven, second-order lowstand in Figure 1-8 may be due to fluctuations in the ice sheets. Crowley and Baum (1991) postulate that changes in the Gondwanan ice area may have resulted in eustatic amplitudes ranging from 150 feet to 250 feet between lowstand and highstand. It is interesting to note that a sea level rise of 150 feet to 250 feet from lowstand to highstand would result in a landward shift in a shoreline of approximately 20 miles to 30 miles (i.e. 4 to 5 townships) across a basin floor with a slope of less than 0.08°. The flatter slopes that may have existed across some areas of the basin (0.01°) would have resulted in even greater dislocations of the shoreline.

In addition to climatic mechanisms, tectonism in the Pedernales highlands to the north of the study area probably influenced sediment flux into the Morrow rivers, and affected the stratigraphic architecture of the Morrow. Periods of uplift would have resulted in larger volumes of coarser-grained sediment being delivered to the basin, and enhanced the potential for progradation of deltas and coastal plains. During periods of reduced tectonism, the sediment volume and average grain size would have decreased, resulting in a tendency for the Morrow coastline to retrograde.

Discriminating a tectonic signal from a eustatic signal in the Morrow is complicated by the extensive downcutting and cannibalization of the fluvial channels as discussed in the next chapter. This has made detailed correlation of coeval units across the basin, and analyzing vertical and areal changes in sediment texture and distribution difficult.

Depositional Models

One of the important criteria for interpreting the depositional facies detailed above is their stratigraphic relationships or associations. In conformable successions Walther's Law may be used to reconstruct a depositional environment from a vertical succession of facies, and lead to a predictive model for reservoir distribution. Depositional models for the *Alluvial*, *Transitional/Bay Fill*, *Deltaic*, and *Shoreface/Shelf* environments are discussed below and illustrated in Figures 2-1 through 2-7.

Alluvial Depositional Model

The alluvial facies association is summarized in Figure 2-1. The cored interval included in this figure is from the Marathon Indian Hills Unit No. 6 Well and comprises a succession of coarse-grained fluvial channel facies overlain by marsh, crevasse splay, channel margin and paleosol facies. Note the smooth, blocky shape in the gamma-ray log through the fluvial channel interval.

The upper block diagram illustrates the channel characteristics, and the middle block diagram lays out the temporal relationships of the major depositional units in a fluvial/floodplain setting. The fluvial channel migrates across its floodplain, and channel sands lie in erosional contact against floodplain sediments including levee and crevasse splay deposits.

The effects of base level and base level change are illustrated in the diagram in the lower right of Figure 2-1. Base level changes influence fluvial architecture, causing channels to aggrade and/or alter their patterns, depths, or widths (Schumm 1993; Wright and Marriott 1993). Under conditions of slow base level rise and abundant sediment supply, rivers may aggrade. Crevassing becomes more common, and often leads to avulsion and aggradation of the floodplain (McCarthy et al. 1992). Smith and Smith (1980) indicate that low-sinuosity fluvial systems with well-vegetated floodplains and adequate sediment supply may anastomose as base level rises, producing stacked channels.

In the case of a static base level, rivers will typically meander and migrate laterally. Prolonged migration may yield extensive, laterally amalgamated point bar deposits, which will form laterally stacked sheet sands (Holbrook 1996; Olsen et al. 1995). Under these conditions, fluvial sands will form broad, continuous bodies. These units may be overlain by subaerial fine-grained sediments, which are subject to weathering and the development of paleosols.

In fine-grained, meandering fluvial systems, an increase in accommodation space will lead to vertically and laterally separated point bar sands in a mud-dominated valley fill (Holbrook 1996; and Smith and Smith 1980). These reservoirs tend to be isolated from each other as a result.

Fluvial crevasse splays are typically small-scale and attached to or associated with levee deposits. Mjøs et al (1993) report on the architectural aspects of crevasse splay lobes in the Ravenscar Group of Yorkshire, UK. They report width/thickness ratios for single lobe deposits of less than 1500 and length/thickness ratios of less than 2000. They also found that the units thinned rapidly outward, and that some of the thicker crevasse splay sands were in communication with their feeder fluvial channel.

Fluid communication within fluvial channel deposits is controlled to varying degrees by sedimentology. Depositional processes and the caliber of the supplied sediment influence sedimentary processes within the channel, creating a wide variety of bedforms that may erode, cross-cut or overly one another (Allen 1983). This leads to internal heterogeneities including shale drapes and abrupt textural changes, and may compartmentalize the reservoir (Hooke 2003; Miall 1985, 1988a, 1988b). Taylor and Ritts (2004) analyzed fluvial sandstones in the Uinta Basin of Utah and concluded that within channel and crevasse splay deposits the highest quality reservoirs are associated with amalgamated channels due to their lateral connectivity. Small-scale heterogeneities such as discontinuous shale and siltstone beds, mud-chip lags and large shale clasts may compartmentalize fluvial reservoirs by acting as baffles reducing vertical fluid flow. On a larger scale, Wizevich (1993) found that major channel erosional surfaces in the Lee Formation of Kentucky extended for 100's to 1000's of meters laterally. These contacts are often overlain by lag deposits and may form barriers to flow.

Reynolds (1999) conducted a review of the dimensions of various paralic or transitional sandstone bodies as reported in the published literature. He concluded that fluvial channel deposits (at least near their down-dip limits) range from 187 feet to 4592 feet wide, and average approximately 2475 feet wide, and from 8 feet to 79 feet thick, with an average of almost 30 feet thick. These correspond with an aspect ratio of approximately 1:100. Applying this ratio to the 8-foot-thick fluvial channel in Figure 2-1 yields a channel width of 800 feet.

Leeder (1973) published a rigorous analysis of fluvial systems and concluded that the ratio is closer to 1:10, which would estimate a channel width of approximately 80 feet for the channel in Figure 2-1. The difference between the two ratios is probably due to differences in datasets. Leeder's analysis was of up-dip, fully fluvial deposits and included several dozen data points, whereas Reynolds' examples were from lower portions of the fluvial systems near the alluvial-paralic boundary.

These two, seemingly disparate, estimates may have importance in exploration. In the northern portions of the study area, fluvial channels that are encased in floodplain muds and are associated with paleosols may have channel widths approaching 100 feet. In contrast, down-dip fluvial channels that are associated with marsh sediments, coals, tidal deposits, and bay or estuarine strata may have channel widths on the order of 1000 feet. The detailed core descriptions suggest that most of the Morrow channel facies may be compound, and, as discussed above, may be stacked or laterally amalgamated affecting the volume and distribution of reservoir sandstone.

Transitional/Bay Fill Depositional Model

In general, the transitional facies association includes all of the sub-environments which are neither fully fluvial nor fully marine. These include deposits exhibiting evidence of brackish water conditions, restricted circulation, or tidal action. In the case of the Morrow of the Delaware Basin, these facies can be broadly grouped into a bay fill succession as shown in Figures 2-2 and 2-3.

A portion of the cored interval from the Getty Berry "5" St. Com No. 1 Well is included in Figure 2-2 to illustrate the characteristics of a typical bay and tidal flat sequence in the Morrow. The tidal flats constitute a sandy facies deposited in an intertidal to supratidal zone lateral to the subtidal, mud-dominated portion of the bay. Figure 2-3 includes a cartoon of a bay head delta building into an estuary or bay as was encountered in the Shell State GRA No. 1 Well. These deltas exhibit a coarsening upward pattern on the well logs similar to a marine delta and can be discriminated by the associated facies.

The Morrowan bays were probably broad features, however, sedimentological evidence of wave action is rare to nil suggesting that the fetch was inadequate to develop a wave regime that would leave a stratigraphic record. Storms appear to have flushed sand, possibly from the shoreface or offshore, into the Morrow bays, but the stratigraphic evidence for this process is also rare. Whether this indicates that storms were rare, or that their deposits were limited to the seaward reaches of the bays is unknown.

The Morrowan bays developed during transgression as coastal reentrants were flooded by rising sea level. Estuaries formed in the flooded river valleys around

The gradient was low, and there is no evidence for the hundreds of feet of valley relief that is seen in the Lower Morrow. Because of the low gradient, and limited accommodation space, these fourth-order sequences are thin. They are, however, locally dominated by fluvial sandstones that may exceed 15 to 20 feet thick. These channel sandstones are often coarse-grained and internally heterogeneous due to cut-and-fill processes.

Deposition of this sequence was terminated by a rise in sea level and development of a highstand systems tract over a flooding surface. Subsequently, a series of high-frequency sea level cycles resulted in the stacking of a succession of similar fluvial-dominated lowstand systems tracts capped by estuarine and/or bay-dominated highstand systems tracts. Figure 3-29 illustrates an example of one of the fourth-order lowstands in the upper portion of the Middle Morrow. A drop in sea level caused a basinward shift in the shoreline and incision of river systems on the exposed plain. The interfluvial divides shown in brown are underlain predominantly by highstand facies of underlying sequences. Subsequent highstand facies are dominated by finer grained bay and nearshore deposits, which will possess coarsening upward log signatures and more lobate geometries.

As documented in Table 2-2, **fluvial reservoirs are the most abundant and most important reservoir type in the Middle and Lower Morrow of the Northern Delaware Basin.** Based on this study they may be most commonly recognized in well logs by their sharp-based, fining-upward character. **Fluvial channel reservoirs will be oriented parallel to depositional dip**, and associated reservoir facies include crevasse splays and avulsion channels. These reservoirs, and the fluvial valleys that contain them, broadly trend northwest to southeast in the western half of the basin, and become more north to south in the eastern half.

Where individual channels have meandered and eroded into coeval channels, they may be in communication. Lateral communication will be controlled by 1) the depth of incision and width of the river valley; 2) the extent of lateral migration of the river systems and the frequency with which the migrating channels cut into each other; and 3) the presence or absence of mud drapes or grain size changes along the contact between the two channel sandstones that may form baffles in the reservoir.

Sea level changes during Lower and Middle Morrow time resulted in the deposition of multiple, stacked and "nested" sequences containing fluvial sandstone reservoirs capped by estuarine and bay sediments. These sequences grade from fluvial-dominated successions up-dip to shoreface and deltaic successions down-dip. These down-dip facies are typically thinner bedded, finer grained, and have greater along-strike dimensions than the fluvial reservoirs. All of the non-fluvial channel facies in this core study together constitute less than half of the total facies thickness of the Morrow (Table 2-2).

Based on this stratigraphic analysis and the paleogeographic reconstructions in Figures 3-26 through 2-29, the Lower Morrow river systems tend to be concentrated in the northern two-thirds of the study area (ie., north of T24S). Fluvial channels will be the most significant reservoir type in these areas; whereas south of T24S deltaic and shoreface/shelf sands will be more common. In the case of the Middle Morrow, the fluvial channel sands are typically thinner than the Lower Morrow, and the point at which the reservoirs grade from fluvial to transitional facies (deltaic and shoreface/shelf) is further north, possibly as far north as T22S.

FORMATION EVALUATION

Well logs were obtained from the twenty wells used in the petrophysical study, and a digital database was constructed through each of the cored intervals (conventional and rotary sidewall) to facilitate comparisons between log response and Rock Type. This analysis also examines the relationship between Rock Type, log-derived water saturations, and production data.

Rock Types and Log Response

The log response at each rotary sidewall core depth point, and at each depth-shifted conventional core plug depth point was statistically analyzed by Rock Type and the results are provided in Table 8-1. The conventionally cored wells used for this portion of the study were drilled over a time span of several decades, and therefore, changes in tool sensitivity, calibration, and processing technology may impact the consistency of the log response values. Also, some of the curves from the conventionally cored wells were digitized from small-scale paper logs, which may increase the margin of error in the correlation of the core to the log and, thus, decrease the precision in determining the actual log response value. The recent wells from which the rotary sidewall cores were taken probably offer more precision and consistency in relating rock data to the log response. A consideration in these wells, however, is that most of the rotary cores were taken from prospective sandstone reservoirs, which biases the database to cleaner sandstones.

Nevertheless, some trends are evident in the log responses. As reservoir quality diminishes from Rock Type A to Rock Type F, the following trends were noted: 1) maximum and average gamma-ray values increase to Rock Type E, and then drop back in Rock Type F to values similar to Rock Type D, 2) resistivity decreases to Rock Type C and then increases to Rock Type F, 3) density porosity generally decreases, and 4) the neutron-density cross plot porosity decreases. It is important to note that there is considerable overlap in log response values between rock types. Due to this overlap, Rock Types do not appear to have distinct or characteristic log signatures. Well logs may be influenced by a variety of rock or fluid properties, any combination of which could cause the observed variability within or between Rock Types.

Gamma-Ray: Gamma-ray logs detect radiation emitted by the decay of uranium-, thorium-, or potassium-bearing minerals. Uranium and thorium tend to be concentrated in organic-rich shales or thinly laminated siltstones. Potassium-bearing feldspars, and clay minerals (i.e., illite) influence gamma-ray response in the Morrow sandstones. In general, Type A rocks have the lowest gamma-ray values, but 'clean' gamma-ray signatures may also be associated with tightly cemented sandstones as well. This is evidenced in the narrow range of average gamma-ray values among the Rock Types in Table 8-1. Tightly cemented sandstones contain little or no clay and, therefore, have low gamma-ray values. Pore lining, authigenic illite tends to increase gamma-ray response (to varying degrees) within better reservoir quality sandstones.

Although gamma-ray response varies widely among Rock Types, the gamma-ray log is a useful indicator of depositional facies in the Morrow. The fluvial channel sandstones have a blocky, sharp-based log shape, and are relatively clean with typical gamma-ray values less than 30 API units. These channel sandstones are coarse-grained and tend to have good porosity development. In contrast, the finer grained crevasse splay, bayhead delta mouth bar, marine delta front, and shoreface sandstones exhibit serrate, coarsening-upward log shapes. The irregularity in the gamma-ray log is due to thinly interbedded shales and siltstones. The sandstones are finer grained and typically cemented with quartz yielding a low gamma-ray response similar to the fluvial sandstones. The overall elevated gamma-ray response, however, reflects the interbedded finer grained facies. The key to discriminating these reservoirs from the fluvial sandstones is the log shape.

Resistivity: The deep resistivity curve measures formation resistivity beyond the flushed or invaded zone. It is influenced by the nature of the fluids contained in the formation, the presence of thinly interstratified or dispersed conductive clays, and the resistivity of the rock. Conductive matrix effects will vary with the amount and distribution of authigenic clay. Pore lining, authigenic clays, having high surface area-to-pore volume ratios (i.e., illite and/or chlorite), are the most problematic. Authigenic chlorite is sometimes present in the Morrow sandstones, and will locally affect the resistivity log. Bound water associated with these microporous clays will form a continuous, conductive pathway along the pore walls. Consequently, electric currents will take this path of least resistance through the reservoir, bypassing any gas or oil that may be present in open pores possibly resulting in a low-resistivity reservoir. The conductive matrix effect due to clays will become more pronounced as 1) pore lining clays become more abundant, 2) the microporosity in the clays comprises a larger proportion of the total pore volume, or 3) the clays become better developed. This may explain the steady decrease in saturation exponent (n) as the sandstones become more tightly cemented from Rock Type A to Rock Type F.

Thin-bed effects may also contribute to suppressed resistivity response. As mentioned above, delta front, channel margin, and shoreface sandstones may possess thinly interbedded silty claystones and argillaceous siltstones. These clay-rich lithologies may suppress resistivity, and water saturation calculations derived from the deep resistivity curve may condemn the reservoir. Additionally, the interstratification of thin shale beds will decrease the net-to-gross ratio and may create vertical baffles or barriers to flow. The new array-induction logs may resolve these complex reservoirs better than the traditional induction logs.

Porosity: Logging suites in these wells typically include both density porosity (or bulk density) and neutron porosity curves. Where bulk density curves only were available a density porosity curve was generated using a matrix density of 2.68 g/cc. In general, the density porosity curves tracked with core porosity, although departures of 5 or more porosity units are not uncommon. This may be due to differences in the density log "vintage", and/or the use of different matrix densities when the supplied density porosity curves were calculated.

A cross plot of density porosity and core porosity in Figure 8-1 reveals that density porosity tends to run high relative to core porosity by several porosity units even when the density porosity is calculated using a sandstone value for matrix density. Routine core analysis indicates that Morrow sandstones have an average grain density of 2.67 g/cc. Given this, matrix densities greater than 2.67 g/cc to 2.68 g/cc should probably not be used in the Morrow for calculating density porosity.

Neutron logs detect hydrogen ions existing in hydrocarbons, formation water, and/or structural (clay-bound) water. Average neutron porosity is substantially lower than density porosity in Rock Types A and B, and lower, though within a few porosity units, in the other Rock Types. The sampled sandstones tend to lack significant volumes of pore-bridging or grain-coating clays, which would elevate the neutron porosity response. It must be remembered, however, that the rotary sidewall cores in the sample suite were typically cut in zones that on the well logs appeared to be, at least, prospective reservoirs.

In determining porosity log cutoff values for recognition of reservoir quality, a multi-layered approach is necessary in the Morrow sandstones. Figure 8-2 is a cross plot of measured porosity and permeability discriminated by Morrow reservoir rock type. This plot indicates that sandstones with permeabilities greater than 0.1 md possess porosities greater than 5%. However, there are a number of samples with porosities greater than 5% that also have permeabilities less than 0.1 md. As mentioned in the chapter on Petrophysical Properties, sandstones with relatively good porosity but low permeability tend to be argillaceous. It may be possible to discriminate these sandstones based on neutron porosity. It may also be possible to identify these based on gamma-ray response in rocks where the dominant clay is illite.

The best Morrow reservoirs can be identified by cross plotting density porosity and gamma-ray response. Figure 8-3 is a cross plot of density porosity and gamma-ray response from the well logs for each sample point. The data are discriminated by Rock Type. With only two exceptions, Rock Types A and B (i.e., sandstones with permeabilities greater than 10 md) all plot in a region where gamma-ray response is less than 30 API units and density porosity is greater than 10%. There are six lower permeability samples that also plot in this area, but petrographic analysis indicates that the clay mineral suites in these samples contain very little illite. Instead, chlorite and kaolinite are the more common clays, and neither clay is as radioactive as illite.

Discriminating the lower permeability sandstones in this region may be possible using other log curves. Compared to the high-permeability reservoirs they will probably exhibit: 1) little or no separation between shallow and deep resistivity; 2) little or no crossover of the neutron and density porosity curves; and 3) faster relaxation times and higher BVI on downhole NMR logs.

This detailed analysis of the petrophysical database further documents that density porosity curves, which are calculated from good quality density logs using a matrix density of 2.65 g/cc to 2.67 g/cc, should reflect true porosity within a few porosity units. Although the database contains only rare argillaceous sandstones, it can be expected that zones with neutron porosities greater than density porosities by more than a few porosity units (discounting gas effects) probably contain interstitial clays, which will inhibit permeability.

It is evident from this discussion that only subtle differences exist between rock types, rock type distribution, production data and water saturations between producing and non-producing Morrow sandstones. As previously discussed, Rock Type A displays the best overall reservoir characteristics but comprises only a small fraction (4%) of the productive intervals. Production appears to come predominantly from Rock Types B, C, and D (i.e., greater than 0.1 md).

It has also been noted that the core descriptions document the interbedding of the various rock types. Productive fluvial sandstones in the Morrow may contain several rock types, and attempts to characterize the entire zone based on one rock type, or an "average" rock type suite may be difficult. The intricate reservoir architecture of the channel sandstones, especially those that have been modified by tidal currents, also controls not just the vertical distribution and thickness of the various rock types, but also the lateral extent and total volume of the rock type exposed to the well bore. Detailed evaluation of individual zones using array induction tools (AIT), and conventional core and petrographic analyses will provide important data to assess reservoir quality. Also, calibrated NMR logs will provide an assessment of clay and immobile water contents.

Kh and Initial Production

Three of the recently drilled wells have been analyzed to construct a series of case histories to develop the relationship between Kh and production in the Morrow. The wells include the Enron Oil & Gas Sand Tank "36" State Com No. 1, Chesapeake Operating, Inc. Hampton No. 1, and Louis Dreyfus Natural Gas Corp Greenstone "19" Federal Com No. 1 Wells. The results of these analyses are illustrated in Figures 8-5 through 8-7. In each well the gamma-ray curves were normalized, porosity curves were calibrated to the core data, and a permeability model was created. A payflag was developed to capture the reservoir interval, and the proportions of the various rock types were determined.

SUMMARY

- This study of the Lower and Middle Morrow sandstones in the northern Delaware Basin in Eddy and Lea Counties, New Mexico, is an evaluation of the sequence stratigraphy and petrophysical characteristics of the Morrow sandstones. It is based on stratigraphic, petrographic, and petrophysical data derived from 2762.7 feet of conventional core, and 100 rotary sidewall cores and conventional core plugs.

- Detailed core descriptions of the conventional core from thirty wells document a complexly interstratified succession of alluvial, deltaic, and shoreface/shelf deposits, together with other transitional and bay-fill sediments. Fluvial channel sandstones are the most abundant sandstone-dominated facies in terms of total thickness recovered in the cores, followed in order of decreasing abundance by distributary channels, tidal channels, distributary mouth bar, middle shoreface, and tidal flat. Together these facies constitute 37.4% of the cored intervals.

- The data from the conventional cores enhanced the sequence stratigraphic interpretation of six cross sections constructed across the northern Delaware Basin. This work reveals that the Lower and Middle Morrow clastic section consists of two, stacked, broadly fining upward, third-order sequences defined by basin-wide unconformities and flooding surfaces. These sequences were deposited during a second-order sea level lowstand in the Early Pennsylvanian.

- Deeply incised valleys containing compound fills of fourth- and possibly fifth-order incised-valley fill sequences characterize the Lower Morrow in the northern areas of the basin. These sequences are amalgamated or "nested" as the result of high-frequency sea level oscillations, and typically contain thick, dip-oriented, coarse-grained fluvial channel sandstones

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 has been documented in Morrowan-aged rocks around the world. The shale thins northward, and in several wells 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 fifth-order sea level lowstands. The deposition and architecture 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.

- Petrographic analysis indicates that the Morrow sandstones range widely from very well sorted and very fine-grained to very poorly sorted and very coarse-grained. The Lower Morrow tends to be coarser grained than the Middle Morrow. The sandstones classify predominantly as quartzarenites, with lesser subarkoses and sublitharenites.

- Authigenic quartz is the most abundant cement in the Morrow sandstones, and locally occludes the intergranular pore volume in the finer grained sandstones. Quartz is followed distantly by dolomite, calcite, and siderite. The authigenic clay suite is predominantly kaolinite, which occurs in pore-filling aggregates. Kaolinite is followed in abundance by undifferentiated clay and chlorite.

- Intergranular pores and leached-grain secondary pores occur in roughly subequal volumes, and pore throats are attenuated by quartz overgrowths commonly resulting in isolation of the pore system. Some of the intergranular porosity in deeper sandstones appears to be secondary after the dissolution of an early burial cement. Also, leached-grain secondary pores comprise a greater proportion of the total visible pore volume with depth. Microporosity associated with authigenic clays contributes to the overall pore volume.

- Porosity development and reservoir quality are controlled in part by texture resulting from depositional environment. In contrast to very fine- to medium-grained deltaic, shoreface, and bay-fill sandstones, the coarse- to very coarse-grained fluvial sandstones have retained a greater proportion of their original porosity and permeability in spite of compaction and cementation by quartz. In a few instances, abundant grain-coating chlorite has preserved intergranular porosity by inhibiting quartz cementation. Deep-burial diagenesis appears to have enhanced pore volume by leaching framework grains creating large secondary pores, and locally removing early cements.

- Measured porosity ranges from 1.8% to 17.1% and averages 8.0% in the Lower Morrow, 7.8% in the Middle Morrow, and 6.5% in the Upper Morrow. Permeability ranges from < 0.001 to 319 md, and averages 1.41 md in the Lower Morrow, 0.444 md in the Middle Morrow, and 0.187 in the Upper Morrow. The increase in reservoir quality reflects the larger proportion of coarser grained fluvial sandstones in the Lower Morrow.

- Petrophysical measurements provided the following electrical, capillary pressure, and NMR data for the reservoir sandstones. 1) cementation exponent (m) ranges from 1.75 to 2.33, and averages 2.00 in Lower Morrow sandstones, 2.04 in Middle Morrow sandstones, and 2.07 in Upper Morrow sandstones, 2) saturation exponent (n) ranges from 1.28 to 2.36, and averages 2.15 in Upper Morrow sandstones, 1.75 in Middle Morrow sandstones, and 1.71 in Lower Morrow sandstones, 3) air-mercury displacement pressure ranges from 1 to 450 psia, and 4) height above free water for gas-water displacement ranges from 0.5 to 226 feet.

- Permeability to air (Ka), permeability to air at stress conditions (Ka_{stress}), and effective permeability to gas (Keg) exhibit excellent correlation with values for Keg and Ka_{stress} running less than Ka. In addition, Keg tends to be lower than Ka_{stress}. Keg ranges from 0.516 to 30.8 md and averages 3.31 md in Middle Morrow sandstones, and from 0.113 to 68.0 md and averages 3.97 md in Lower Morrow sandstones. Ka_{stress} ranges from 3.32 to 42.6 md and averages 14.3 md in Middle Morrow sandstones, and from 0.070 to 55.5 md and averages 1.76 md in Lower Morrow sandstones.

- Ka, Ka_{stress}, and Keg all exhibit trends of decreasing water saturation with increasing permeability. The best correlation is between Ka_{stress} and Sw, and indicates that a calculated water saturation on the well logs from a zone in the gas column of 15% corresponds with a stress permeability of 10 md.

- NMR porosity agrees favorably with helium porosity, with bulk volume irreducible (BVI) ranging from 1.0% to 3.1%, and Free Fluid Indices (FFI) ranging from 2.8% to 9.8%. T_2 cutoff times average 24 ms in the Lower Morrow and 20 ms in the Middle Morrow. The mean logarithmic T_2 model appears to be preferable to the Coates permeability model.

- Rock Mechanics testing of the sandstones provided the following acoustical data: 1) Compressional velocity ranges from 14,670 to 17,951 ft/sec and averages 17,089 ft/sec in the Lower Morrow and 15,786 ft/sec in the Middle Morrow, 2) Shear velocity ranges from 9520 to 12,021 ft/sec and averages 11,429 ft/sec in the Lower Morrow and 10,320 ft/sec in the Middle Morrow, 3) Poisson's ratio ranges from 0.08 to 0.16 and averages 0.09 in the Lower Morrow and 0.13 in the Middle Morrow, 4) the Bulk Modulus ranges from 3.12 to 4.82 and averages 3.94 in the Lower Morrow and 3.63 in the Middle Morrow, 5) Young's Modulus ranges from 6.83 to 10.9 and averages 9.69 in the Lower Morrow and 8.14 in the Middle Morrow, and 6) the Shear Modulus ranges from 3.00 to 5.01 and averages 4.43 in the Lower Morrow and 3.62 in the Middle Morrow. Compressional velocity and shear velocity exhibit excellent correlation, and compressional velocity and shear velocity individually correlate very well with stress porosity. A compressional matrix velocity for the Morrow sandstones is 54 μs/ft.

- Six Morrow reservoir Rock Types were defined based solely on permeability. Characteristic petrographic and petrophysical parameters were compiled for each Rock Type, and reveal that with decreasing pore volume and increasing pore system tortuosity, the Archie exponents, irreducible water saturations, and displacement pressures increase, and the free fluid index decreases.

  Rock Type A ($k \geq 100$ md): 1) Average grain size is 641 microns (Lower Coarse Sand), 2) average m = 1.92, 3) average n = 2.07, 4) Swi averages

4.4%, 5) Keg averages 263 md, 6) the free fluid index averages 13.2%, and 7) a gas column 1 foot high will begin to displace gas at the base of the transition zone.

Rock Type B (100 > k ≥ 10 md): 1) Average grain size is 789 microns (Upper Coarse Sand), 2) average m = 1.93, 3) average n = 1.64, 4) Swi averages 13.2%, 5) Keg averages 22.6 md, 6) the free fluid index averages 9.7%, and 7) a gas column almost 2 feet high will begin to displace gas at the base of the transition zone.

Rock Type C (10 > k ≥ 1.0 md): 1) Average grain size is 850 microns (Upper Coarse Sand), 2) average m = 2.02, 3) average n = 1.72, 4) Swi averages 26.1%, 5) Keg averages 2.48 md, 6) the free fluid index averages 6.7%, and 7) a gas column 7.5 feet high will begin to displace gas at the base of the transition zone.

Rock Type D (1.0 > k ≥ 0.1 md): 1) Average grain size is 821 microns (Upper Coarse Sand), 2) average m = 2.06, 3) average n = 1.74, 4) Swi averages 34.5%, 5) Keg averages 0.391 md, 6) the free fluid index averages 5.0%, and 7) a gas column 19.1 feet high will begin to displace gas at the base of the transition zone.

Rock Type E (0.1 > k ≥ 0.01 md): 1) Average grain size is 375 microns (Upper Medium Sand), 2) average m = 2.08, 3) average n = 1.97, 4) Swi averages 44.5%, 5) Keg averages < 0.001 md, 6) the free fluid index averages 2.8%, and 7) a gas column 107 feet high will begin to displace gas at the base of the transition zone.

Rock Type F (0.01 > k): 1) Average grain size is 534 microns (Lower Coarse Sand), 2) average m = 2.32, 3) average n = 2.12, 4) Swi averages 56.7%, 5) Keg was not determined, 6) the free fluid index averages 3.4%, and 7) a gas column 150 feet high will begin to displace gas at the base of the transition zone.

- Log evaluation indicates that the Morrow reservoir Rock Types do not have distinct log signatures. General trends from Rock Types A to F in log response include a subtle increase in gamma-ray response, and a decrease in density porosity and neutron-density cross plot porosity. A crude correlation between density and core porosity suggests that the density curve may provide a close approximation of formation porosity. A cross plot of density porosity and gamma-ray reveals that the best reservoirs (10 md > k) yield a density porosity greater than 10%, and a gamma-ray response of less than 30 api units.

- Given the textural (depositional) control on reservoir quality log shape may play an important role in discriminating rock types in the sub-surface. Porous, coarse-grained, fluvial sandstones often exhibit sharp-based, blocky gamma-ray log patterns, with less than 30 api units. Finer grained deltaic, shoreface, and bay-fill sandstones exhibit coarsening upward or serrate log shapes, and lower permeability. Fluvial channels, which have been partially modified by tidal currents, may exhibit interstratification of productive and non-productive rock types at a scale that may or may not be resolvable with conventional downhole logs.

- Comparison of production data and reservoir Rock Types reveals that producing sandstones tend to have 1 to 2 pu more porosity, slightly higher resistivity, and almost 14 pu less water saturation than non-producing zones. The bulk of production appears to be coming from Rock Types A through D.

- Discriminating pay versus non-pay in the Morrow sandstones is complicated predominantly by the interstratification of rock types within perforated zones, which tends to average production from the constituent rock types. Based on this study, a refined pay-flag would include density-neutron cross plot porosity greater than 4.5%, Sw less than 60%, and Vclay less than 30%.

- Productivity of the Morrow reservoirs is directly related to Kh, and Kh can be used to closely estimate initial production volumes. A Kh between 20 and 30 md-ft corresponds to an initial production between 1000 and 2000 MCFGPD, while a Kh near 2000 md-ft corresponds to an IP of almost 6200 MCFGPD.

- Log analysis could be improved by: 1) using array induction tools (AIT) to provide more accurate resistivity values and resolution of interbedded low-quality rock types, and 2) the use of calibrated NMR logs to identify immobile water and permeability.

- Rock-fluid compatibility tests indicate that the Morrow sandstones are most susceptible to damage caused by migrating fines and fresh water, with lower quality rocks being more sensitive. Generally speaking, fluids used on the Morrow sandstones should contain no less than 2% KCl. The use of hydrochloric acid to stimulate the formation should probably be avoided due to the possible presence of chlorite. If HCl is used we recommend that it be recovered from the formation, and that very aggressive iron-control measures be included in the treatment.