TITLE: INTEGRATED SYNTHESIS OF THE PERMIAN BASIN: DATA AND MODELS FOR RECOVERING EXISTING AND UNDISCOVERED OIL RESOURCES FROM THE LARGEST OIL-BEARING BASIN IN THE U.S.

TOPICAL REPORT

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Abstract

Work being conducted to prepare written, illustrated syntheses of major Permian Basin reservoir plays is resulting in new understandings of the formation, composition, and distribution of reservoir facies in the Permian Basin. These new data and interpretations will constitute a fundamental resource based for geologists and engineers developing and exploring the Permian Basin for decades to come. Examples of the key learnings derived from these studies are given for selected reservoir plays including the Guadalupian Artesia Group, the Pennsylvanian Morrow interval, the Pennsylvanian Atoka interval, the Pennsylvanian Strawn succession, the Mississippian Barnett Shale, the Devonian Thirtyone chert succession, and the Lower Ordovician Ellenburger Group.

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Introduction

We have continued to make excellent progress toward project goals and objectives. Presentation of all the geological data completed so far (11 plays have been completed comprising more than 500 pages of written text and illustrations) is beyond the scope of this report. However, the report does provide an overview of some of the technical results obtained in the first 18 months of the project. A map of the geographic area being covered by the study is displayed in figure 1.

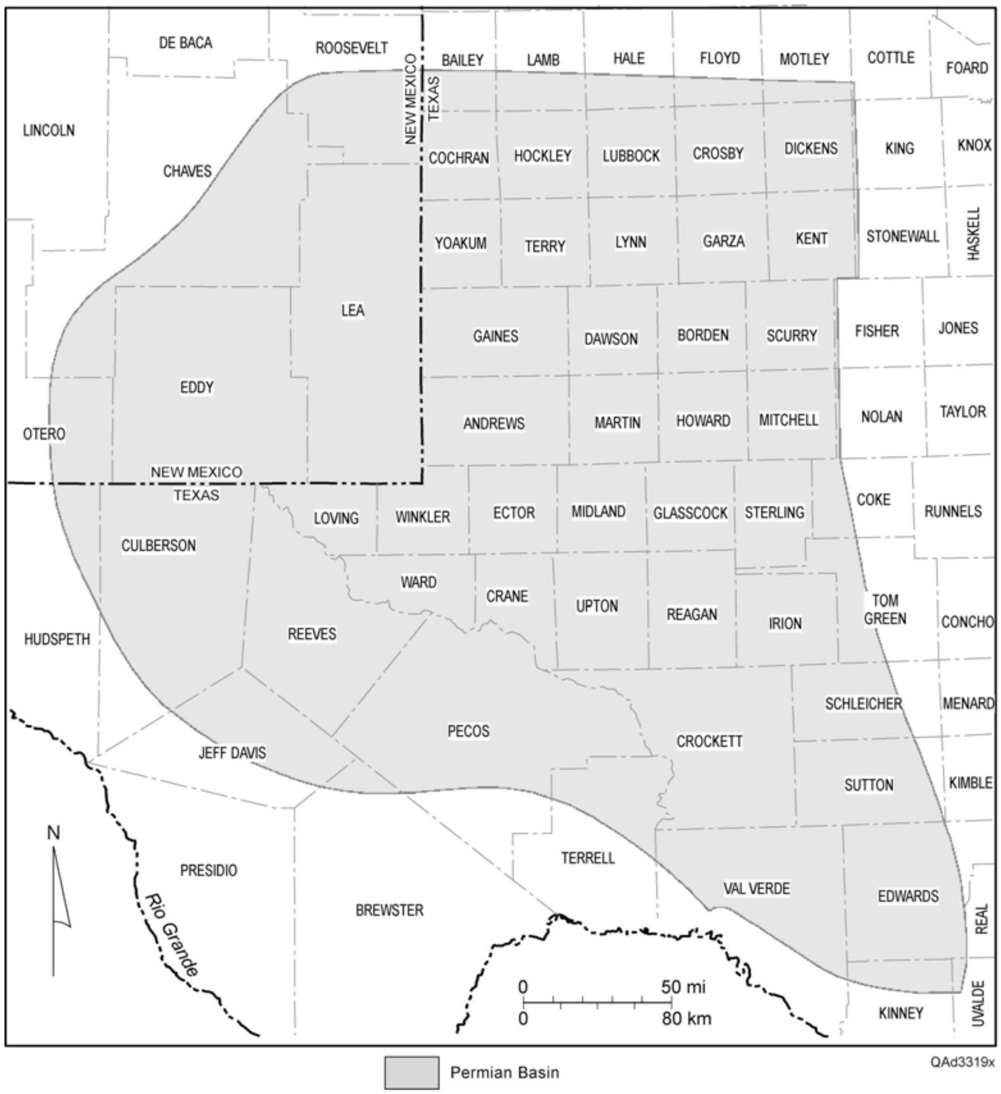

Figure 1. Map of West Texas and New Mexico showing area encompassed by project.

Executive Summary

Preparation of the approximately half of written reports on specific reservoir plays in the Permian basin is complete. These include the Lower Ordovician Ellenburger Group, the Lower Silurian Fusselman Formation, the Upper Silurian Wristen Group, the Lower Devonian Thirtyone Formation, the Upper Devonian Woodford Formation, the Mississippian Barnett Formation, the Lower Pennsylvanian Morrow, the Lower Pennsylvanian Atoka, the Middle Pennsylvanian Strawn, the Lower Leonardian slope carbonate succession, and the upper Guadalupian Artesia Group. Significant new understandings of the geology and controls on reservoir development have been made in the process of conducting these play syntheses. Examples of these findings, which include new maps of reservoir play types, new depositional models, new concepts of reservoir development and distribution, are given for selected plays. These data and interpretations are providing an important new focus for companies developing the Permian Basin.

Data collection and construction of a GIS database is also proceeding smoothly. Our primary efforts in data collection were initially focused on the Thirtyone Formation, the Woodford Formation, and the Barnett Formation. Data from these plays were collected, checked for accuracy, then loaded into the project ARC/GIS database. Data have also been collected and uploaded as available from other plays including the San Andres, Clear Fork, and Grayburg formations. Data are now being assembled for the Ellenburger and Clear Fork plays.

Methodology

A two-pronged approach is being used to conduct the project. The first involves assembling and writing illustrated summaries of all depositional intervals, or plays, in the

Paleozoic reservoir succession in the Permian Basin. To do this we are gathering all published information and combining this with new direct observations. We are then integrating and synthesizing all data into written summary reports. The second approach is designed to create a comprehensive ARC-GIS database. To accomplish this, we are collecting, organizing, and interrelating all available data. These data are then loaded into a GIS project to create a spatially interrelated geological database. Progress is excellent on both fronts. This report contains some of the conclusions that have come from the first part of the project: the assembling and writing summaries of reservoir plays.

It should be noted that these results have already been shared with industry geologists and engineers and are already being incorporated into concepts for drilling for oil and gas.

Results and Discussion

Written technical syntheses have been completed for 11 major reservoir plays in the Permian Basin. The primary goal of these syntheses is to provide summary details of important geological components of each play based on critical review of published reports and collection and interpretation of new data. Completed reservoir play syntheses include the Lower Ordovician Ellenburger Group, the Lower Silurian Fusselman Formation, the Upper Silurian Wristen Group, the Lower Devonian Thirtyone Formation, the Upper Devonian Woodford Formation, the Mississippian Barnett Formation, the Lower Pennsylvanian Morrow, the Lower Pennsylvanian Atoka, the Middle Pennsylvanian Strawn, the Lower Leonardian slope carbonate succession, and the upper Guadalupian Artesia Group. In addition to providing valuable overviews for industry geoscientists and engineers, these document offer important insights into the geologic controls of reservoir development and key learnings that should be considered in all reservoirs in each play. Examples of the types of key findings from the play analyses completed so far are given below.

<u>Lower Ordovician Ellenburger Group</u>

The Ellenburger is dominated by karst-related features. The coalesced, collapsed paleocave systems that typify the Ellenburger are megascale geologic features that can have dimensions of hundreds to thousands of square miles laterally and several thousand feet vertically. Strata above and below the unconformity are affected by late collapse in the subsurface (Figure 2). A coalesced collapsed paleocave system can be divided into two parts: (1) a lower section of karsted strata that contains collapsed paleocaves and (2) an upper section of strata that is deformed to various degrees (suprastratal deformation) by the collapse and compaction of the lower section of paleocave-bearing strata.

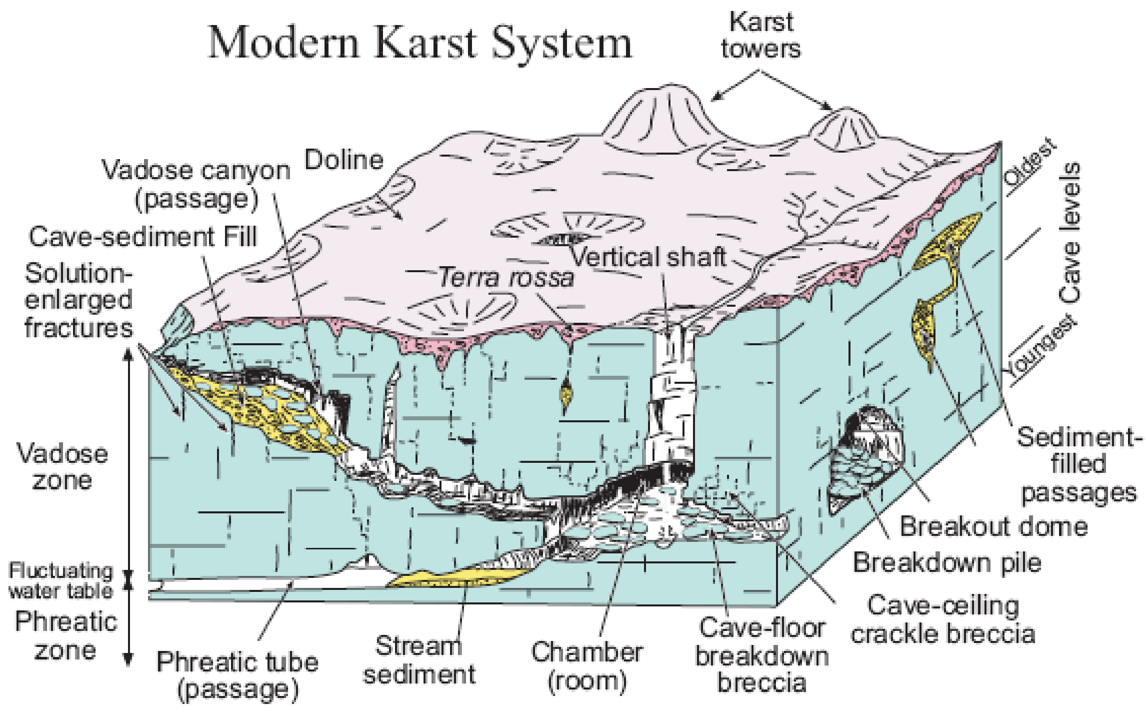

Figure 2. Typical development of modern karst systems. Most of these features are readily identified in Ellenburger reservoirs.

Pore networks in the Ellenburger are especially complex because of the amount of brecciation and fracturing associated with karsting (Figure 2). The pore networks can consist of any combination of the following pore types depending on depth of burial: (1) 32 matrix, (2) cavernous, (3) interclast, (4) crackle/mosaic breccia fractures, or (5) tectonic related fractures. Pore networks evolved during burial and diagenesis.

The regional pattern of karsted Ellenburger reservoirs probably follows a rectilinear pattern as a result of regional fractures controlling original cave-system development. Field development of paleocave reservoirs should be based on integrated studies that include data from 3-D seismic surveys, cores, borehole image logs, conventional wireline logs, and engineering data. In some cases it is possible to identify cavernous or intraclast porosity from 3-D seismic data (Figure 3). Cores and borehole image logs are necessary to recognize and describe paleocave reservoir facies. Whole-core data are recommended over core-plug data because of the scale and complexity of pore systems in paleocave reservoirs. Sags associated with cave collapse should be mapped because they may indicate location of the best coalesced reservoirs (Figure 3). Different cave passage levels of the paleocave system need to be identified and analyzed to determine whether they are separate reservoirs or in vertical communication. Because of the significant spatial complexity within coalesced paleocave systems, horizontal wells may be an option for improving recovery.

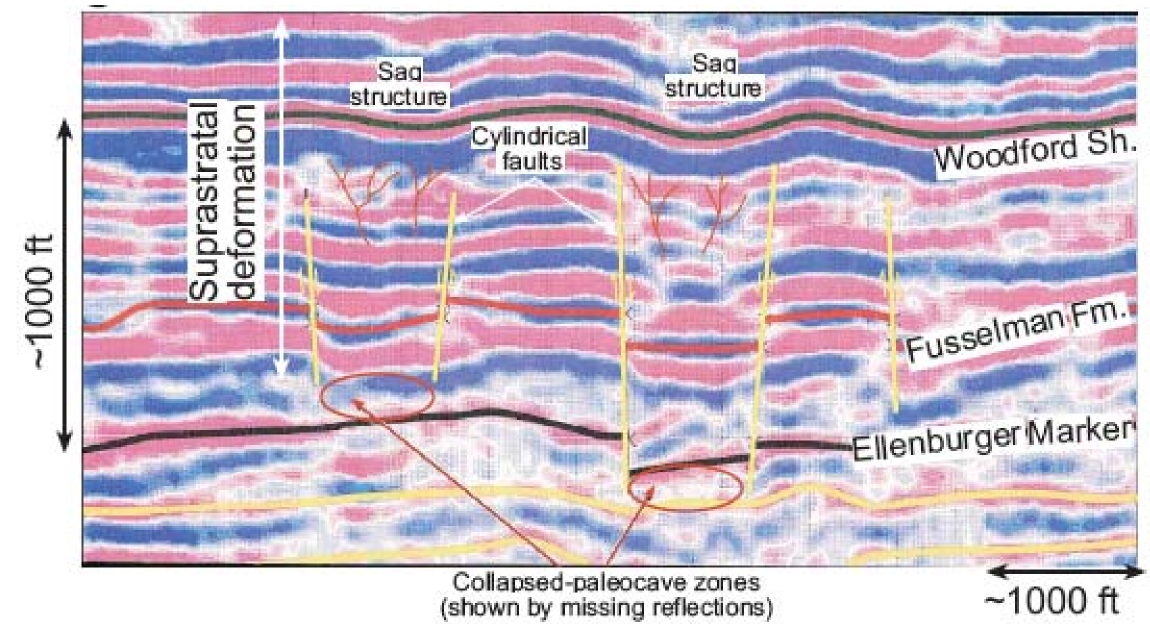

Figure 3. Seismic line showing cylindrical faults and sag features caused by collapse in the Ellenburger. These features along with weak seismic reflectors in the Ellenburger are strong indicators of karsting.

<u>Lower Devonian Thirtyone Formation</u>

The Thirtyone Formation documents early Devonian infilling of a Silurian cratonic basin on the southern margin of the Laurussian paleocontinent. Deposition was dominated by deep water gravity transport and re-distribution of platform derived carbonate debris and siliceous fauna (sponge spicules and radiolarians). Facies vary from hemipelagic mudstones to relatively high energy, grain-rich, silica (chert) packstones reflecting vastly differing energy regimes ranging from high energy gravity flows to low energy, below wave base conditions. Updip areas, in stark contrast, comprise high energy, shallow water carbonate shoal grainstones that reflect basinward progradation and accommodation filling (Figure 4).

Most reservoir development is associated with high porosity/moderate permeability chert facies whose character reflects a combination of depositional regime and early silica diagenesis. Best reservoir quality is associated with grain-rich chert facies that were deposited as debris flows. Lower energy burrowed facies are less porous and usually of poorer reservoir quality, however variations in chert diagenesis locally overprint this trend. Updip carbonate facies are generally of much lower porosity but still locally quite productive. Reservoir quality in these rocks is controlled by diagenesis. Strongly dolomitized intervals provide the best porosity development but partially dolomitized, leached, and/or silicified sections also locally very productive .

Thirtyone chert and carbonate reservoirs contain a large remaining oil resource that is a target for more efficient exploitation techniques based on a better understanding of the geological controls on heterogeneity. Because these controls differ systematically between chert reservoirs developed in updip, proximal settings and downdip, distal settings, and among updip carbonate sections exposed to different styles of diagenesis, it is crucial that both regional and local geologic models of deposition and diagenesis be incorporated into modern reservoir characterization and exploitation efforts.

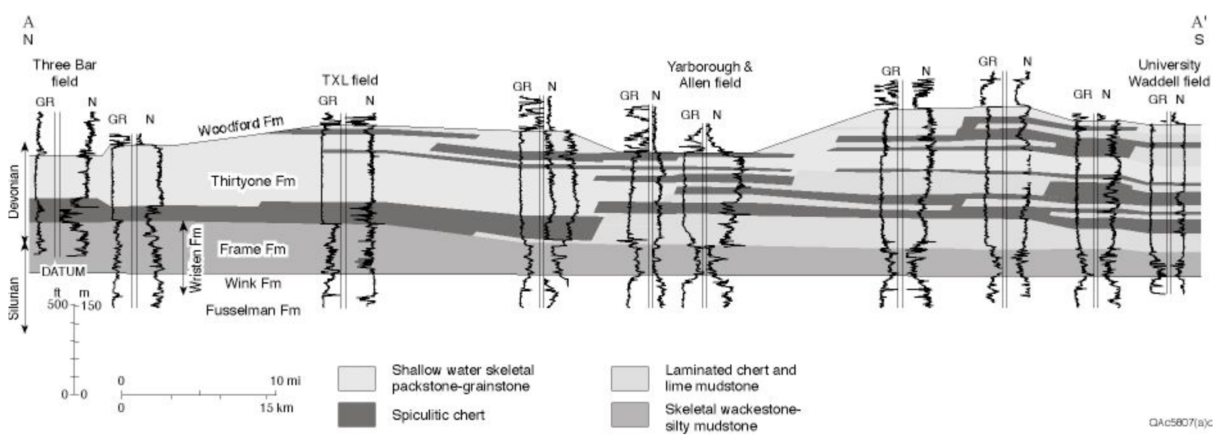

Figure 4. Vertical and lateral development of Thirtyone facies along a dip section through the Permian Basin.

Mississippian Barnett Formation

The Barnett Formation is a succession of dark-colored shales and mudstones that were deposited along the southern margin of the Laurentian paleocontinent during the Mississippian. These rocks accumulated in anoxic, below wave base conditions in a deep-water platform to slope setting. The margin between shallow water carbonate deposition to the north and deeper water, hemipelagic and gravity transport deposition to the south extends east-west across most of the Permian Basin area (Figure 5). Barnett facies reach thicknesses of more than 2000 ft locally in the southern part of the Permian Basin but pinch out a short distance north of the platform margin (in Gaines and Lea counties). Limited cores combined with data and models from outcrops in New Mexico provide constraints for interpretation of the equivalent updip carbonate platform facies. The character of the Barnett is best defined by the more than 25 cores and outcrops studied in the Ft. Worth Basin area. These cores provide an excellent basis for defining the sedimentology, mineralogy, and facture character of the Barnett and serve as a basis for calibration of wireline logs. Critical issues still being investigated include (1) is the Permian Basin Barnett analogous to the Ft. Worth Basin succession?, (2) what role do fractures play is production response?, (3) how do depositional and mineralogical facies vary across the basin?

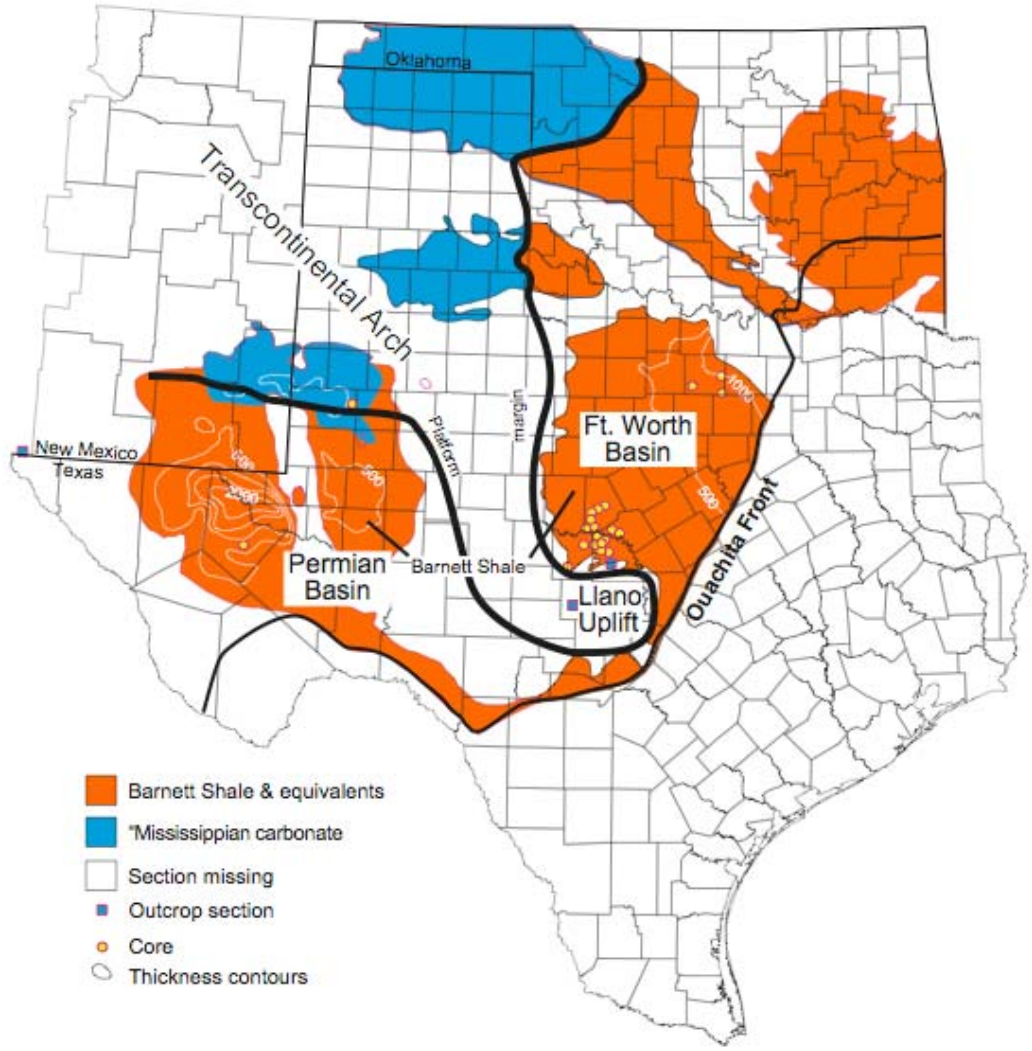

Figure 5. Distribution of Barnett and equivalent rocks in the Permian Basin and adjacent areas.

Pennsylvanian Morrowan Series

Analysis of Morrowan age deposits across the Permian Basin in a regional sequence stratigraphic context has resulted in new insights in basin evolution, reservoir facies distribution, and exploitation potential. The basin as a whole reflects deposition during a 2nd order transgression. During the Morrowan, siliciclastics dominated deposition in the western part of the Permian Basin, whereas carbonate deposition dominated the east (Figure 6).

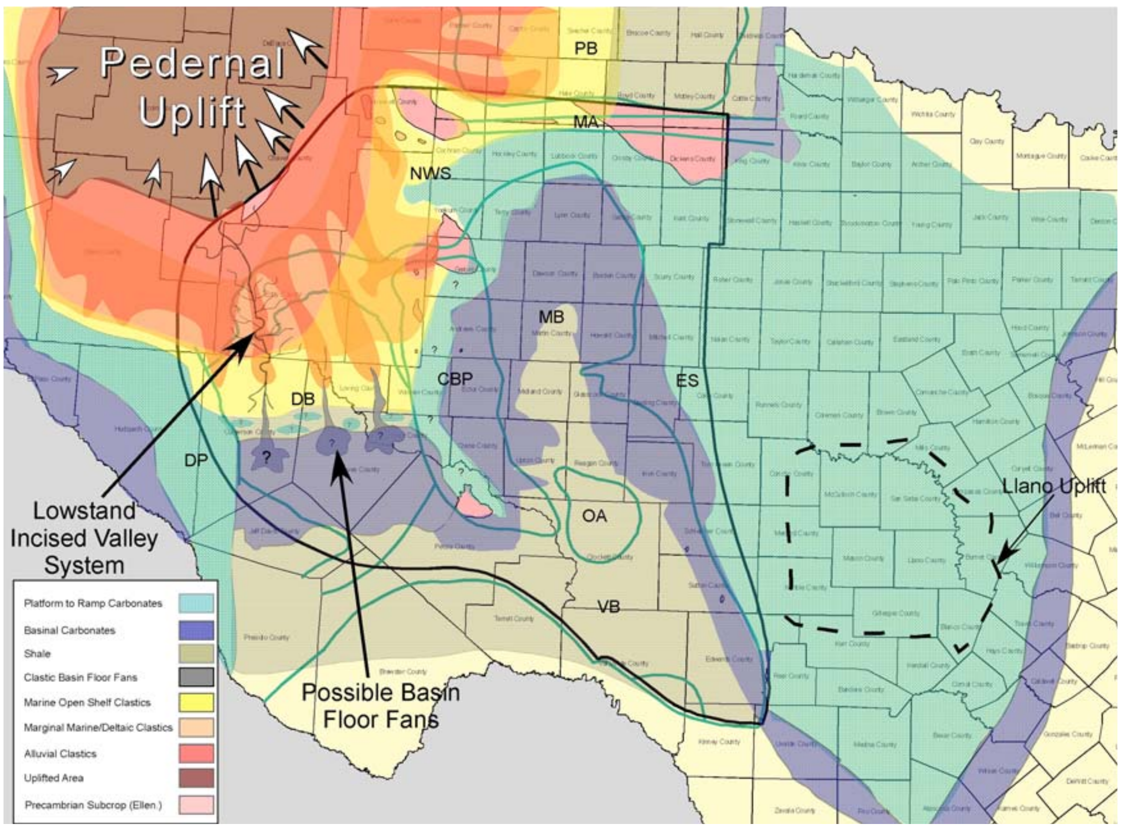

Figure 6. Regional paleographic reconstruction for Morrowan-age sediments. Central Basin Platform (CBP), Delaware Basin (DB), Diablo Platform (DP), Eastern Shelf (ES), Matador Arch (MA), Midland Basin (MB), Northwest Shelf (NWS), Ozona Arch (OA), Palo Duro Basin (PB), and Val Verde Basin (VB).

New interpretations indicate that the northwest shelf was dominated by a large incised valley system sourced from the Pedernal Uplift. These findings also suggest that bypass of the shelf-margin during lowstands may have resulted in the accumulation of basin-floor fan deposits in the southern Delaware Basin. The recognition of these of basin-floor fans represents a new play concept for this part of the Basin (Figure 6). Studies of Morrowan carbonates in the eastern part of the basin suggest a much more extensive shallow-water carbonate succession in this area. These intervals of mixed biohermal and high energy, grain-rich energy facies are augmented by fracture porosity and are overlooked potential reservoir successions.

Pennsylvanian Atokan Series

In contrast to the underlying Morrowan, depositional geometries of Atokan siliciclastic units are largely a function of eustasy, not local tectonics. Lower Atokan rocks are dominated by alluvial and fluvial incised valley deposits. By mid-Atokan time, marginal marine to open marine siliciclastic depositional environments dominate the region. Our recent work indicates that the source for Atoka clastics in the Permian Basin is the Ozona Arch rather than the Central Basin Platform suggested by previous workers. Fan delta deposits in Upton County are proximal facies that link to basin-floor fans in Midland and Andrews Counties. Our work strongly suggests that Middle Atokan siliciclastic deposits on the Northwest shelf represent shelf-ridges (SR) or barrier island arc sediments (BIA) rather than the prograding deltaic system proposed by others. The shelf ridge/barrier island model is consistent with other data from the Permian Basin that support a rise in sea level at this time. This new interpretation implies sediments that young to the north with onlapping geometries toward the shoreline (NW).

Atokan age shales such as the Smithwick Formation of the Eastern Shelf and in the Fort Worth Basin have maturation values similar to that of the Barnett Fm. Similar age shales are interpreted to exist in the Delaware Basin and in the proto Midland Basin in Dawson and Martin Counties. Thus, these shales may also have potential as shale gas plays.

Atokan age carbonates are better understood by comparison to the Eastern Shelf outcrop and subsurface analogues of the Upper Marble Falls Fm. The Marble Falls carbonate plays contain small *Komia* and *Chaetetes* bioherms that display average porosities of 10% and 2 to 6 mD in permeability. Permeability and porosity is enhanced in these deposits by leaching during burial diagenesis and microfracturing. This play type is underexplored and extends over much larger areas than previously thought. The Eastern Shelf Upper Marble Falls Formation is laterally connected to a thick succession of carbonates on the Devils River Uplift in Val Verde and Edwards Counties; this succession merges with carbonates that accumulated across the proto-Central Basin Platform.

Pennsylvanian Desmoinesian Series

During the Desmoinesian carbonate sedimentation dominated almost the entire Permian Basin (Figure 7). Rare delta front siliciclastic facies and plays along the Eastern shelf are linked up-dip onto central Texas and the Llano uplift and associated alluvial channels. Pervasive carbonate deposition in the Permian Basin is most dominant in the Early Desmoinesian and Middle to Late Desmoinesian. Early Desmoinesian carbonates have poorer overall reservoir quality than the Middle and Upper Desmoinesian succession due to less numerous exposure related diagenetic events, which in turn are directly linked to a lower amplitude and frequency of eustatic sea level falls at this time. As second key finding is the identification of a regional exposure event (sequence boundary) between the lower Desmoinesian (lower Strawn Group) and the middle and upper Desmoinesian (upper Strawn Group). Reservoir quality in the lower Strawn is typically highest immediately below this major sequence boundary.

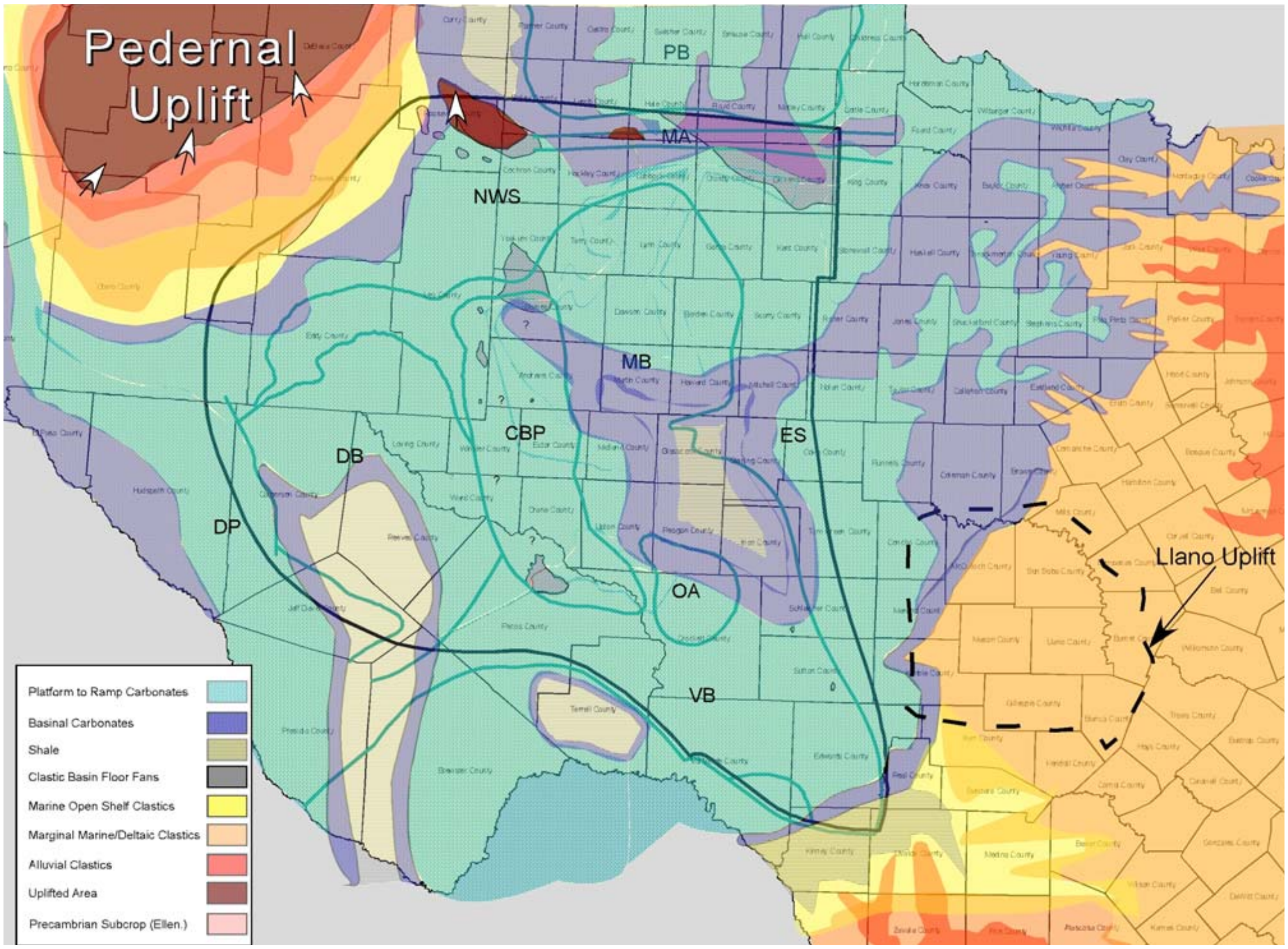

Figure 7. Late Desmoinesian paleogeography and facies distribution map in the greater Permian Basin region. CBP = Central Basin Platform, DB = Delaware Basin, DP = Diablo Platform, ES = Eastern Shelf, MA = Matador Arch, MB = Midland Basin, NS = Northwest Shelf, OA = Ozona Arch, PB = Palo Duro Basin, VB = Val Verde Basin.

A regional sequence boundary also separate the Desmoinesian Strawn Group carbonates from the overlying Missourian Canyon Group carbonates. The uppermost Strawn also displays very good reservoir quality with porous zones ranges from 300 meters to several kilometers across. Desmoinesian carbonates are present in the Val Verde Basin in both a sub-thrusted and thrusted position. The largely undocumented sub-thrusted plays are a potential deep drilling target. The succession appears very similar to Desmoinesian carbonates in other areas of the Permian basin (reservoir quality tied to facies type and extent of subaerial exposure).

Guadalupian Artesia Group

The most productive sandstone reservoirs (Queen, Seven Rivers, and Yates Formations) in the Artesia Group are typified by gas-productive Yates Formation strata that were deposited in a middle shelf setting on the margins of the Central Basin Platform and Northwest Shelf. Sandstones comprise laterally extensive, strike-aligned sheets that were deposited in depositional cycles that vary in vertical facies succession along dip. Cyclic successions comprise basal sandstones that were originally deposited as eolian- and associated desert deposits during sea-level lowstands, then subsequently reworked by marine processes during marine transgression. Carbonates (now dolomite) overlie sandstones and record deposition under shallow water conditions during sea-level highstands. Carbonates grade from shoal grainstone to lagoonal mudstone updip. Evaporites are increasingly abundant (and carbonates increasingly rare) updip. Halite is the dominant evaporate mineral in the most updip areas. Hydrocarbons are most commonly trapped in middle-shelf cycle base sandstones by (1) cycle top, impermeable carbonates and evaporites and (2) porosity occlusion in updip sandstones by evaporite cements.

Conclusions

The work completed to date on collecting and synthesizing the geological elements of the major Paleozoic plays of the Permian Basin has begun to elucidate key aspects that have an important bearing on designing strategies for recovering additional oil and gas from the Permian Basin. The examples presented above demonstrate just some of the important learnings that have already come from the project. These compilations will prove to be a critical guide for future exploration and development activities in the Basin for decades to come.