DEPOSITIONAL HISTORY OF THE ATOKAN SUCCESSION (LOWER PENNSYLVANIAN) IN THE PERMIAN BASIN

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ABSTRACT

Atokan-age units in the Permian Basin record a 2nd-order transgression, with aerially restricted, lower Atokan fluvial to shallow-marine siliciclastics followed by pervasive carbonate deposition. In general, Atokan-age siliciclastics dominated deposition in the west of the Permian Basin while carbonate deposition dominated throughout the rest of the basin. Predominance of carbonate facies across most of the Permian Basin is due to (1) lack of siliciclastic supply, (2) overall 2nd-order rising sea level, and (3) progradation of the Upper Marble Falls Formation onto the Eastern Shelf. Progradation was due partly to lower accommodation to the west and backstepping/retreat from encroaching Atokan deltaics to the east.

The beginning of the Atokan is marked by a sea-level drop and subsequent lowstand conditions. A sequence boundary separates the Atokan from the underlying Morrowan carbonate section throughout the Permian Basin. Siliciclastic deposition in and around the Permian Basin is more aerially restricted than in the Morrowan. The earliest Atokan lowstand event is manifested in alluvial and fluvial incised-valley sediments in Lea County, New Mexico, and the Broken Bone Graben (Cottle County, Texas); fan-delta deposits in the Palo Duro Basin and Taylor Draw field (Upton County, Texas); and

post-Lower Marble Falls–pre-Upper Marble falls conglomerates (Gibbons Formation?) on the Llano Uplift. Following the lowstand event, a 2nd-order transgression appears to have dominated throughout the rest of the Atokan; however 3rd- and 4th-order, high-amplitude, sea-level fluctuations also occurred.

During the mid- to late Atokan, deltaic sediments and their deeper water prodelta shales prograded westward out of the Fort Worth Basin onto the Eastern Shelf. This progradation caused an abrupt west and southwestward backstepping of Atokan carbonate platforms and replacement of carbonate facies by deeper water (~100 m) shales (Smithwick Formation). Elongate shore-parallel transgressive sands on the northern Delaware Basin and Northwest Shelf of New Mexico represent either shelf ridges or transgressive barrier-bar systems. These transgressive, siliciclastic, marine-shelf ridge and/or barrier-bar systems are the dominant middle Atokan play type on the Northwest Shelf of New Mexico. Localized tectonic uplift and increased sediment load may have forced progradation in isolated areas of the northwest shelf.

Atokan carbonates were deposited over a larger area in the Permian Basin. A continuous carbonate platform to ramp existed between the Devils River Uplift (Val Verde and Edwards Counties) and the Eastern Shelf. Algally dominated bioherms and higher energy facies (ooid grainstones), affected by burial diagenesis and subsequently fractured, compose the best carbonate reservoirs. Subsidiary proximal-slope debris-flow plays are also likely present. Because producing carbonate reservoirs within the Delaware Basin are products of deep burial diagenesis, they are not readily linked to facies type. However, secondary porosity formed by calcite dissolution during exposure of carbonates should not be discounted as a primary reservoir-creation mechanism in other parts of the

Permian Basin. Atokan basinal and slope carbonates, interfingered with shale (for example, the Smithwick Formation), also hold potential as fractured reservoirs for expulsed shale gas in the Delaware Basin (Reeves, Pecos, and Terrell Counties) and the northern proto-Midland Basin (Martin, Dawson, and Lynn Counties).

New paleographic reconstruction for the Atokan of the Permian Basin illustrates key depositional elements (fig. 1). From east to west, Atokan-age carbonates accumulated over the Llano Uplift, Eastern Shelf, parts of the Val Verde Basin, the Central Basin Platform (CBP), the northern Delaware Basin, and the Diablo Platform. The carbonate platform backstepped (east-facing margin) and prograded (west-facing margin) westward across the Eastern Shelf in response to lower accommodation rates and increased siliciclastic input from the east. Remaining carbonate-dominated areas (that is, Val Verde Basin, the CBP, the northern Delaware Basin, and the Diablo Platform) appear largely aggradational. That these platform carbonates grade to more basinal carbonates and, ultimately, shales in the northern Midland Basin and along the southwestern CBP is proposed. Extensive shales (Smithwick Formation) were also deposited to the east of the Llano Uplift. A small number of Precambrian inliers appear to have been exposed and shed material into the basin (for example, parts of the Ozona Arch and Fort Stockton High, Crockett and Pecos Counties). These and other minor topographically elevated regions were most likely rimmed by carbonates. The Pedernal Uplift provided limited sediment input for the northwest shelf but was disconnected from the other, more northerly channel systems feeding the Mid-continent. a later section of this paper gives a more detailed discussion of Atokan paleogeography.

INTRODUCTION

This paper discusses styles of deposition and facies development of Atokan-age sediments, concluding with a discussion of a revised paleogeography for the Atokan Permian Basin (fig. 1; p. 39). During the course of the paper, siliciclastic Atokan deposition and carbonate affinity are discussed as well. In each section, a regional model for facies patterns and deposition is proposed. Data from areas adjacent to the Permian Basin are used as analogs for facies that are predicted to be present within the study area. Localized studies are used to illustrate certain key aspects (for example, facies type and reservoir quality). However, an initial introduction to the area, placing it in a global perspective, is first presented.

GLOBAL TECTONIC SETTING

Atokan-age sediments (circa 310 Ma) in the Permian Basin were deposited at a near (8–12^{o} south) equatorial position during icehouse conditions (high-amplitude, high-frequency, eustatic sea-level fluctuations). The greater Permian Basin area was undergoing initial tectonic activity of both uplift and subsidence related to the Ouachita-Marathon orogeny and birth of the greater ancestral Rocky Mountains. Figure 2 illustrates the position of Texas (in orange) relative to major tectonic plates and the equator at the beginning of the Pennsylvanian (circa Atokan-Desmoinesian age). During the Atokan, Texas occupied a more equatorial position than during the Morrowan. A less-restricted marine environment during the Atokan (compared with that of the Morrowan) is proposed, given the geometry of the microplates in the reconstruction (figs. 2, 3, "Depositional History of the Morrowan Succession (Lower Pennsylvanian) in the Permian Basin").

REGIONAL TECTONIC SETTING AND FACIES DISTRIBUTION

The outline of the Permian Basin and major geologic features commonly associated with the basin are illustrated in figure 3. All features did not develop simultaneously, and most were only in the early stage of development during the Atokan. Figures 4 through 6 illustrate previous interpretations of facies distribution, uplift, and subsidence patterns for Atokan-age sediments in the Permian Basin and surrounding areas. The interpretations suggest that most of the Permian Basin was dominated by shallow to moderately deep water carbonate deposition. A revised Atokan Permian Basin paleogeography is presented here and discussed later.

Most of the Permian Basin was inferred to comprise carbonate-platform to carbonate-shelf environments by Ye and others (1996), with substantial uplifted area in the Diablo Platform, Ozona Arch, and Eastern Shelf areas (figs. 3, 4).

Areas of uplift, subsidence, and facies distribution in figures 4 through 6 do not all match. In many instances areas of net subsidence in figure 4 appear to correlate with areas of uplift in figure 6. On the basis of Kluth (1986), most of the Permian Basin area is illustrated as an area of net deposition, with subsidence rates ranging from less than or equal to 50 m/MA to approximately 200 to 300 m/Ma (fig. 5). One of the most important differences apparent between figures 4 through 6 is the extent of uplift on the CBP. Uplifted parts range from the south half in the interpretations by Ye and others (1996) and Kluth (1986), to a northeast part (Blakey, 2005), which is not coincident with the outline of the CBP (figs. 3–6). Correcting inconsistencies in the regional paleogeography of the Permian Basin and outlining more detailed depositional patterns are major goals of this paper (fig. 1).

GENERAL STRATIGRAPHY AND NOMENCLATURE

Atokan-age sediments within the Permian Basin include those termed Atokan (generally siliciclastic with rare carbonates), the Bend Group (generally siliciclastics), Bendian (mixed lithologies), the Upper Marble Falls Formation (carbonates), and the Smithwick Formation (shale with subsidiary sandstones). Significant correlation problems have been encountered in establishing the true depositional nature of Atokan-age units. Many studies are of local scale, lacking robust age control, and regional perspective. Different interpretations and inconsistencies exist in defining what units and formation are actually Atokan in age.

Nomenclature

As with the Morrowan interval, Atokan stratigraphic nomenclature is complex and confusing. A detailed correlation of named Atokan-age units is given in table 2 in Appendix 1 of "Depositional History of the Morrowan Succession (Lower Pennsylvanian) in the Permian Basin." The Atokan, as defined in this study, contains all formations, groups, and members that are grouped within the Bend and Lampasas Series between the Morrow and Strawn (table 2, app. 1). In this study, Upper Marble Falls and Smithwick Formation names are applied to Atokan carbonate and shale lithologies, whereas the Bend is used for coarser siliciclastic facies (for example, conglomerates). Historically in the Midland Basin, CBP, and Delaware Basin regions, Atokan-age rocks have been referred to as either Atokan or Bend, regardless of lithology.

Siliciclastic Atokan Deposition

General Depositional Setting

Fan-delta, alluvial-channel, and basin-floor-fan depositional environments dominate in the earliest Atokan, with generally coarse grained, lowstand systems tract sediments. Incised-valley systems, much less widespread than in Morrowan time, are largely restricted to localized, small uplift areas. Uplift of the Ozona Arch area provided a local source for fan-delta and basin-floor-fan sediments in the Midland Basin. Fluvial and alluvial incised-channel systems also funneled sediments into the north margin of the Eastern Shelf, where it meets the Matador Arch. As mid-Atokan sea-level rose, tectonic uplift of the Pedernal area entered a stage of quiescence, and marginal-marine to open-marine deltaic to shelfal siliciclastic sedimentation began to dominate. Shoreline-parallel, barrier-bar to shelf-ridge sedimentation dominated in the Northwest Shelf area of New Mexico, with a sediment source still largely from the northwest. Extensive deposition of shale units (for example, Smithwick Formation) occurred during middle to upper Atokan time as the progradational front to Atokan siliciclastics migrating westward from the Fort Worth Basin. Shales of similar affinity to the Smithwick were deposited in the northern Midland and southern Delaware Basins (fig. 1).

Reservoir Potential

Updip fluvial, amalgamated, stacked channels and thick fan-delta units have the best reservoir potential and quality. Shoreline-parallel sand bodies in the northern Delaware Basin and Northwest Shelf have good reservoir potential owing to extensive lateral connectivity and a more predictable distribution pattern. Smithwick-type shales have reservoir and source potential similar to that of the Barnett Formation shale-gas system.

Diagenesis

Dissolution of feldspar grains within fan-delta units enhanced porosity, whereas reprecipitation of dissolved bioclasts and calcite grains, as calcite cement within more distal fan-delta sediments, resulted in porosity occlusion. Quartz-overgrowth cementation is detrimental to reservoir quality in all coarse-grained facies.

Climate

As in Morrowan time, the Atokan was a time of expansive ice-sheet development, typified by highly fluctuating sea level. The fluctuation consequently plays a role in controlling cyclicity and facies stacking patterns. Such highly fluctuating sea levels generally result in thinner, higher frequency cycles.

PERMIAN BASIN

Eastern Shelf

Atokan siliciclastic units range from sandstones (Bend equivalent?) to shales (Smithwick equivalent?). In general, as elsewhere in the Permian Basin, Atokan units become more carbonate dominated upsection. Siliciclastics of the Bend series in Sutton and Schleicher Counties are Atokan, given the presence of *Fusulinella* fusulinids. However, in Sutton County, the Bend actually comprises a basal, dark shale interbedded with argillaceous limestone, some sandstone, and rare coals and ranges from 0 to 305 m (0–1,000 ft) in thickness. It is overlain by carbonate units. Bend deposits appear to be restricted to structural and topographic depressions, with limestone intervals in the middle massive unit thinning over positive structures and thickening into negative ones.

Presence of sand and glauconite in the Bend section in several of the wells in Sutton and Schleicher Counties led Rall and Rall (1958) to postulate that the Miers Horst (southern Sutton County) had been uplifted before Bend deposition and was supplying Cambrian-age siliciclastics into the area. Deposition of Atokan sediments was probably regionally continuous in the area but was subsequently removed by differential erosion (Conselman, 1954).

Midland Basin

In southern Upton County, Texas (Taylor Draw field), the Atokan comprises fan-delta systems (Troschinetz and Loucks, 1991), which contain low-permeability mud matrix conglomerates, or they are bioclastic. The low-permeability facies were deposited in the distal part of the complex, whereas high-permeability units are more proximal and were deposited as thick alluvial-channel sands (Troschinetz and Loucks, 1991). The most likely source area of these fan-delta sediments is the Ozona Arch (fig. 1). Yang and Dorobek's (1995) structural reconstructions suggest that pre-Desmoinesian tectonic movement was minor across the CBP. However, the semiregional pre-Desmoinesian unconformity indicates that the greatest amount of erosion and uplift occurred on the Ozona Arch. Localized uplift of the Fort Stockton Block southwest of Taylor Draw field may have also contributed sediment to the fan delta (Robert Loucks, Bureau of Economic Geology, personal communication); seismic and structural data do not, however, indicate major uplift of that area until after Atokan deposition.

The coarse-grained siliciclastics of Taylor Draw field appear quite different from typical "Atoka" detrital reservoirs in Andrews County to southeastern Midland County (Candelaria, 1990). The Atokan detrital plays and reservoirs in Andrews and Midland

Counties comprise a series of 15- to 20-ft, thick silty to bioclastic units encased in the Atoka shale. Exact ages of these reservoir intervals are uncertain, but they appear to range from Chesterian, to Morrowan, to Atokan. Producing Midland County fields such as Azalea, Bauman, Bradford Ranch, and Desperado, are considered Atokan in age. Candelaria (1990) proposed that the “Atoka Detrital” units were deposited as basin-margin siliciclastic wedges or submarine fans forming sheetlike units, generally up to 20 ft thick, during lowstand conditions. Midland County Atoka Detrital fields are likely the distal basin-floor-fan extension of the more proximal fan-delta and alluvial deposits of Upton County described by Troschinetz and Loucks (1991). The fauna present in the bioclastic members of the Atoka Detrital is diverse and composed largely of abraded, poorly sorted, shallow-water biota (crinoids and sponge spicules also present), which are sometimes associated with ooids. Detailed studies are unavailable to assess regional depositional environments for the carbonates. Poor sorting and lack of sorting indicate deposition as a debris flow.

Reservoir Quality

In Taylor Draw field, dissolution of bioclasts and calcite grains and reprecipitation of calcite resulted in occlusion of the pore space. The high-permeability facies are chert and quartz rich, with no mud matrix or calcite grains. Minor chalcedony cement is present in these facies (Troschinetz and Loucks, 1991).

Reservoir quality in the basin-floor-fan (Atoka Detrital) reservoirs is moderate, with 6 to 8 percent porosity and permeability at less than 0.1 md, over an average net thickness of 15 ft. Fracturing may, however, substantially elevate reservoir quality by linking reservoir intervals and fracturing encasing shales. Most traps appear stratigraphic and are linked to facies pinch-out. Fractured encasing shales provide a secondary reservoir, as well as the source rock, which is siliceous and calcareous, with 1.1 to 4.7 percent total organic carbon (TOC) as Type II kerogen (Candelaria, 1990).

Delaware Basin

In Vacuum field, Lea County, New Mexico (fig. 7), Atokan-age siliciclastic rocks are divided into a lower fluvial succession and an upper deltaic to marine facies package. Within the lower Atokan, fluvial packages are stacked vertically, aggrading and fining upward, and are informally divided into lower and upper sand. The upper Atokan comprises upward-coarsening, deltaic, progradational sequences capped by flooding events that deposited black organic shale and limestones (Ota, 2001). Only the lower Atokan “lower sand” appears to have good reservoir characteristics. The depositional environment of this sandstone is similar to that of the underlying lower Morrowan, in that it comprises fluvial-channel sands in an incised channel/valley-fill environment. Small channel sand bodies are also present in McDonald field to the north of the Vacuum area (fig. 7). Upper Atokan sandstones are present in unconfined, meandering channels and delta-front to beach/bar-shoreface parallel (NE-SW) systems (James, 1985; Ota, 2001). Figure 7 illustrates the overall depositional environment for Atokan siliciclastics proposed by James (1985) for southwestern New Mexico. Sediment source of minor alluvial sandstones, such as at Buffalo Valley, and marine sandstones is from the northwest (James, 1985). Given the proximity to Morrowan-age uplifted areas on the ancestral CBP, a more eastern to northern source area is likely for Vacuum field. According to James (1985), the prograding shoreface-parallel beach sandstones depicted in figure 7 are progressively younger toward the basin. The path of shoreline movement is numbered 1 through 5, oldest to youngest.

James (1985) proposed that increased sediment load provided by renewed uplift of the Pedernal area (fig. 7) provided the driving force for progradation (that is, forced regression) of siliciclastics into the Delaware Basin during an overall 2nd-order transgression. It seems equally likely that the elongate sand bodies are not beach deposits but sand shelf ridges or transgressive barrier-island bars (Reading and Collinson, 1996; Posamentier, 2002). Shelf ridges are formed by erosion of underlying shelfal sediments and redeposition during transgression. These shelf sand ridges are usually on the order of meters to kilometers wide, up to 20 km long, usually less than tens of meters thick, and encased in muddier to shaly sediments. These parameters match those described by James (1985) for siliciclastics on the north margin of the Delaware Basin. The shelf ridges described by Posamentier (2002) are not that dissimilar to the transgressive barrier-island-arc systems of Reading and Collinson (1996). In transgressive barrier-island sequences, landward migration of the barrier occurs either by shoreface retreat or in-place drowning. In transgressive deposits, shoreline sandstone ridges or barriers backstep rather than prograde (fig. 7). Large, 3rd-order sea-level drops have been documented for the Atokan (Ross and Ross, 1987). But except during the earliest Atokan lowstand, 2nd-order sea level was higher than at any time during the Morrowan. The shoreline therefore had to transgress and backstep relative to its position in the Morrowan and not prograde into the basin.

Reservoir Quality

Atokan production in Empire-Parkway fields (fig. 7) comes from two northeast-southwest-trending marine sand plays. Figure 8 illustrates the typical density neutron log for the Atokan sand interval, which is about 28 ft thick and ranges in porosity from 9 to 12 percent. Overall thin sands down to 5-ft thickness can be good producers because of their flow and drainage characteristics in these elongate, lenticular reservoirs.

REGIONAL STUDIES

Many data regarding depositional environments, facies types, and reservoir quality of Atokan succession have been collected in areas outside the Permian Basin (fig. 3). The greater Matador Arch area, specifically Cottle, King, Knox, and Stonewall Counties, is just at the margin of the Permian Basin, and facies described there are interpreted to continue into the Permian Basin (fig. 1). Units described for the greater Fort Worth, Palo Duro, and Dalhart Basins similarly provide analogs for depositional environments and reservoir attributes for the Upton County Midland Basin and Eddy and Lea Counties Delaware Basin Atokan reservoirs in New Mexico.

Greater Matador Arch Area

Within the Palo Duro and Dalhart Basins, Bend siliciclastics comprise alluvial-fan and proximal and distal fan-delta systems (Dutton, 1980). These units are localized in distribution to the two basins and reflect heightened tectonic activity associated with uplift of Amarillo-Wichita and Sierra Grande Uplifts and Bravo Dome. Isolated uplifted fault blocks along Matador Arch also provided material into the basins. Similar fan-delta systems have been identified in the southern Midland Basin (Upton County) and present a substantial play type if the structural history of the area can be clarified.

Figure 9 illustrates the typical wireline-log signature of Atokan fan-delta systems in the Palo Duro Basin. Figure 10 illustrates the rock character in core, and figure 11 is an overall correlation of the Pennsylvanian and Permian units within the basin. Overall porosity in the fan-delta units (often referred to as Granite Wash) averages 14 percent. Porosity is lessened by the extent of quartz overgrowth and carbonate cementation but enhanced by secondary leaching of feldspar grains. Less aerially significant deltaic sandstone units average about 12 percent porosity.

In King and Cottle Counties medium- to coarse-grained sandstones and conglomerates are present as offshore sand bars encased within calcareous shales (Edwards 1979). These units are analogous to mid- to upper Atokan Delaware Basin shore-parallel sandstone bodies (for example, Empire-Parkway fields, Eddy and Lea Counties, New Mexico). Within Baylor County, to the east of King County, Staples (1986) identified the presence of Atokan-age (Bend Group) fluvial-channel sandstones, which incise into the underlying Morrowan limestone. Ida and Stouffer fields (Baylor County) (1 km apart) produce from fluvial-channel sandstones and are interpreted to be a single reservoir. Overall reservoir quality is 15 to 19 percent porosity over a 28-ft-thick interval.

Broken Bone Graben

In southern Cottle County, the Broken Bone Graben appears to have been a large, fault-controlled depocenter that accumulated a thick succession of Atokan-age sediments (Bend) (see fig. 15 for graben location). The Bend Group reaches a maximum thickness of 5,000 ft, the lower two-thirds of the lower Bend Group being primarily nonmarine. The beginning of regional transgression is recorded in the upper one-third of the lower

Bend Group, which contains thin limestone units interbedded with nonmarine siliciclastic deposits (fig. 12). The Bend succession in Cottle County is analogous to Taylor Draw field in Upton County. Small (2 km long × 7.5 km wide) isolated fault grabens similar to Broken Bone might also exist in Hale and Floyd Counties within the Permian Basin.

All units within the Broken Bone Graben appear to expand in thickness toward the structurally deep parts of the basin. The lower Bend interval in the Broken Bone Graben is probably equivalent to incised channel sands noted by Staples (1986) in Baylor County (fig. 13). Because the graben/basin was thought to have been constantly filled by sediment during its subsidence, only minor topographic relief was present on basin margins. Figure 12 illustrates the gamma-ray log signature and correlation of the entire Atokan interval (Bend and Smithwick Formations). Small red bars to the right of each well log indicate producing reservoir-quality sands, which appear largely unpredictable in distribution. High-resolution seismic over the graben illustrates thickening of units toward the basin center, as well as onlapping and infilling geometries of sediments upward (fig. 14). Attribute analysis of the seismic should provide better constraints on size, architecture, and distribution of incisive and unconfined alluvial channels in this depositional setting.

In a regional sense, continued marine transgression and eventual subsidence of the Palo Duro Basin north of the graben caused the regional depocenter to shift to a position nearer the Wichita-Amarillo mountain front, shutting off the coarse siliciclastic supply to the graben area (Brister and others, 2002). Figure 15 illustrates proposed regional distribution of lower Bend sandstones (Atokan), which are not restricted to the graben area, and data suggest sandstone deposition in Kent and King Counties (Brister and others, 2002) (figs. 1, 15)

The upper Bend Group, which is entirely marine, is composed of calcareous shale and argillaceous basinal carbonate units that correlate to basin-rimming carbonate buildups. Discrete sandstone beds in the upper Bend in a few wells are interpreted to be offshore sandbars deposited locally along the basin rim and similar to those described by Edwards (1979) for the Fort Worth Basin area and James (1985) for the Northwest Shelf of the Permian Basin. The style of siliciclastic deposition in the Broken Bone Graben area is mimicked in the Northern Delaware/Northwest Shelf area, with a basal nonmarine alluvial system giving way to a more marine system. Transgression culminated in a maximum flooding event marked by the Smithwick Shale in the eastern Matador Arch area (fig. 12).

Cycles in the Broken Bone Graben basin fill are attributed to sedimentary response to local basin subsidence, not eustasy. Cyclically stacked sheets of poorly sorted muddy sandstone and mudstone units, alternating with winnowed sand-rich units, were deposited in alternating deltaic and braided-plain environments, depending on base level. Characteristic associated depositional environments are debris fans (pebbly mudstone), overbank sediments (coaly mudstone), and discrete, laterally limited distributary channels (sandstone). During tectonically quiescent periods and after reestablishment of a higher base level, throughgoing stream systems were reestablished, and fine materials were winnowed and carried southward toward the Knox-Baylor Trough, whereas coarser material dropped out of the system over the graben area. The final result was stratigraphically compartmentalized, braided channels that amalgamated laterally into sheetlike deposits. Cross-axial, throughgoing streams are suggested by stratigraphically complex, vertically stacked, and laterally terraced sandbar development within channel systems incised into the pre-Bend strata in the region south of the graben (fig. 13).

Reservoir Quality

Within Rhombochasm field, reservoir quality in the lower Bend Atokan units is moderate, with an average of 12.6 percent porosity and 0.02 md permeability over a net interval of 75 ft encompassing approximately seven sandstone horizons. Figure 16 illustrates the detailed gamma-ray-log, porosity, and resistivity characteristics of the lower Bend stacked sandstone reservoirs over part of the productive interval. The wireline-log signature is similar to those interpreted to indicate fan-delta systems, as in figure 9. However, the Broken Bone succession provides an alternative analog to traditional models (for example, Palo Duro) because it is not governed by eustasy. Similar tectonically driven successions may exist in the northern Permian Basin, and the model may be directly applicable to Taylor Draw field in Upton County.

Greater Fort Worth Basin

Data from the Fort Worth Basin help to establish the amount of siliciclastic progradation into the Permian Basin and also provide depositional analogs. Within the Fort Worth Basin, Atokan siliciclastics are generally thought to have been deposited in a deltaic environment (Ng, 1979; Crowder, 2001). Atokan siliciclastic deposition in Jack, Palo Pinto, Parker, and Wise Counties is considered a product of the rising Ouachita Uplift area on the east and south of the Fort Worth Basin (Ng, 1979). In general, Atokan siliciclastics are considered part of a westward-prograding deltaic succession. The western limit of Atokan progradation was previously considered the Bend Arch, which runs roughly northward through Mills and Comanche Counties. Timing and origin of the Bend Uplift are equivocal. But flexure (not uplift) may have initiated in late Morrowan time, although it was not a major feature until Atokan times. This supposition is supported by uniform thickness of the Lower Marble Falls Limestone across the entire area. Erosion of both Morrowan and Atokan sediments across the Bend and Concho Arch areas makes it difficult to define whether some Atokan sediments were deposited or eroded. However, identification of the Smithwick Shale overlying Bend siliciclastics in Cottle County and identification in core of Marble Falls and Smithwick Formations in McCulloch County indicate that progradation migrated much farther west than previously documented.

The Atokan siliciclastic succession in the Ng (1979) study area is actually dominated by shales with small discontinuous (vertically and laterally) sandstone bodies. Figure 17, a west-east cross section of Palo Pinto and Parker Counties, illustrates a westward-onlapping succession of shales and sands in lower and upper Atokan siliciclastics. The succession of transgressive sands and shales is similar to that described for the Northwest Shelf in New Mexico and Matador Arch areas for the middle to upper Atokan interval. Correlations within the units are subjective at best, given the quality and type of logs used for analysis (SP and resistivity). The upper shale-dominated Atokan of Ng (1979) is the Smithwick Formation and its lateral equivalents.

Smithwick Formation and Coeval Shales

The Smithwick Formation (informally called the Smithwick Shale), as formally defined, includes all shale between the underlying Marble Falls Limestone and the overlying Strawn Limestone. However, it has been recognized that the Smithwick contained several facies and had abrupt and large thickness variation. Additionally, it has been noted that the formation was not only restricted in age to younger than the Upper Marble Falls; it was also its basinal equivalent (Plummer, 1950; Grayson and others, 1989; Groves, 1991; Erlich and Coleman, 2005). The Smithwick Shale, as defined, is not acknowledged in the Midland, Val Verde, or Kerr Basins to the west and south (Erlich and Coleman, 2005). However, the Bend succession in Schleicher and Sutton Counties is characterized by its abundance of shale through the defining interval (for example, Marble Falls to Strawn). Given the regional analysis, coeval shales are also probably present in the western Delaware Basin and within Gaines, Andrews, Dawson, and Lubbock Counties in the northern Midland Basin (fig. 1). In this study the Smithwick Formation is considered a deeper water, lateral equivalent to Atokan siliciclastics in the Fort Worth Basin, the Upper Marble Falls Formation on the Llano Uplift/Eastern Shelf, and the basal Atokan "Caddo" Formation on the Eastern Shelf. Understanding the depositional environment and establishing a regional correlation of the Smithwick Formation and its lateral equivalents are vital to the understanding of development of the Permian Basin. These shales potentially provide the only throughgoing (across platform and shelf and into the basin) lithologies and timelines that can be used to construct a sequence stratigraphic framework for the Atokan.

The Smithwick is a black, fissile, siliceous, phosphatic shale containing calcareous planktonic foraminifera and rare ammonoid and gastropod fauna. The upper section of the Smithwick, however, is coarser grained silt to sand, containing abundant bed forms in the Llano area. At the type locality, the Smithwick is 301 ft thick (Plummer, 1950). McBride and Kimberly (1963) performed a regional study of the Smithwick in the

Llano area and noted thicknesses of 400 ft in boreholes near the study area and over 5,600 ft of shale in the S. E. Purcell well No.1 in Williamson County. Figure 18 illustrates facies relationships between the Upper Marble Falls and the Smithwick north of the Llano area and the increased thickness of the Smithwick to the west. Proportions of sandstone increase upward in the Smithwick Formation and are generally thin (<2 ft), although containing abundant ripple cross-lamination, sole marks, flute casts, and other bedding-plane structures. Paleocurrent data indicate an average flow direction of S19^{o}W; therefore, a northeastern source area is presumed. In general, McBride and Kimberly (1963) considered the entire Smithwick marine in origin and upper sandstone units as deep-water turbidites. Erlich and Coleman (2005) interpreted Smithwick shales in the Llano as being deposited in the outer-shelf to upper-slope environments. The shale also interbeds with platform-margin limestones, probably as a result of 3rd- and 4th-order flooding events.

Reservoir Quality

The importance of the Smithwick Formation lies not only in its helping us to understand overall sedimentology of the Permian Basin, but also its being an exploration target. On the Llano Uplift, high organic carbon contents (7.5 percent TOC) and a potential similarity in grain character to the Barnett Formation make the Smithwick Shale a potential self-sourcing shale-gas system similar to that of the Barnett Formation in the Fort Worth Basin. In the Broken Bone Graben, Atokan shales within siliciclastics of the Bend Group and the Smithwick Formation have source potential in this deep-basin setting (Brister and others, 2002). Mean TOC is 4.98 percent but ranges up to 20.01 percent and falls as low as 1.05 percent. The upper Bend group yields primarily unstructured, lipid organic matter, with lower percentages of terrigenous vitrinite and inertinite, whereas the Lower Bend Group includes a high percentage of vitrinite (type III).

DISTRIBUTION OF ATOKAN SEDIMENTS

Interpretations of Atokan sedimentation patterns in the Midland Basin historically relied heavily on structural interpretation of the CBP. According to seismic and wireline-log correlations, it appears that only small, localized areas of the CBP were uplifted before the end of the Atokan. Regional reconstructions by Tai and Dorobek (1999; 2000) show no influence of the CBP on Atokan sedimentation patterns in the Midland Basin (figs. 19, 20). Distribution of Atokan-age sediments is relatively uniform in thickness and aerial distribution across Delaware and Midland Basins (Van der Loop, 1991; Yang and Dorobek, 1995). Yang and Dorobek (1995) illustrated numerous cross sections of Delaware and Midland Basins, illustrating only a slight thickening of Atokan-age units toward the proposed western boundary of the CBP. Most sedimentation appeared largely unaffected by uplift. A pre-Desmoinesian unconformity does exist, which results in the cutting out of variable amounts of the stratigraphic section. Post-Atokan differential uplift of blocks within the CBP resulted in erosion from Upper Pennsylvania units down to the Precambrian basement. Erosion and faulting make it difficult to decide confidently whether deposition of Atokan sediments occurred across the entire Permian Basin. However, it appears that Atokan sediments were pervasive across much of what would become the CBP during the Desmoinesian to Virgilian. Subtle thickness variations suggest that localized uplift of small blocks in the CBP area affected local deposition patterns and thickening of units. However, overall uplift appears to have been minor, and areas without Atokan sediments are largely a product of later uplift and erosion. Estimated time of major uplift of the CBP is Desmoinesian (Strawn) (Van der Loop, 1991; Yang and Dorobek, 1995; Ye and others, 1996). Earliest structural estimates for uplift of the CBP are Desmoinesian as well. However, given the regional distribution of the Desmoinesian Strawn Formation, it is more likely that uplift occurred during the Missourian to Virgilian.

Summary of Atokan Siliciclastic Deposition

Overall, siliciclastic deposition in and around the Permian Basin is more aerially restricted than in the Morrowan. Atokan siliciclastic deposition starts in the earliest Atokan with a lowstand event. This event is manifested in alluvial and fluvial incised-valley sediments in Lea County, New Mexico, and the Broken Bone Graben (Cottle County, Texas); fan-delta deposits in the Palo Duro Basin and Taylor Draw field (Upton County, Texas); and post-Lower Marble Falls–pre-Upper Marble Falls conglomerates (Gibbons Formation?) on the Llano Uplift. Following the lowstand event, a 2^{nd}-order transgression appears to have dominated the rest of the Atokan, although 3^{rd}- and 4^{th}-order, high-amplitude, sea-level fluctuations also occurred.

Regional progradation of deltaic sediments and their deeper water counterpart shales migrated westward from the Fort Worth Basin onto the Eastern Shelf. This progradation caused an abrupt west-southwest backstepping of the lower Atokan carbonate platforms previously in that area and replacement of the carbonate facies by deeper water (~100-m) shales (Smithwick Formation). Elongate, shore-parallel, transgression sands on the northern Delaware Basin and Northwest Shelf of New Mexico are either shelf ridges or transgressive barrier-bar systems. Localized tectonic uplift and increased sediment load forced progradation in isolated areas of the northwest shelf. High rates of subsidence within the Palo Duro Basin and the Broken Bone Graben funneled extensive amounts of localized siliciclastic sediments into each area. Subsidence in the Palo Duro Basin eventually outpaced that of the Broken Bone Graben/Matador Arch area, coinciding with uplifted areas migrating westward and toward the Permian Basin. A 2^{nd}-order transgression became the driving force, and sedimentation rates decreased in the Broken Bone Graben, resulting in deposition of shales and argillaceous carbonates, which were eventually displaced by the Smithwick Shale from the east.

Fan-delta and basin-floor-fan assemblages in Upton, Midland, and Andrews Counties appear to have been sourced by the Ozona Arch area. Aerial distribution of the fan deltas and basin-floor fans is still poorly defined. Two areas of shale deposition occurring in Culberson, Gaines, and Andrews Counties are separate from the Smithwick Formation on the Eastern Shelf and eastern Midland Basin. The Smithwick Formation and its equivalent shales (average TOC 6.24 percent) throughout the Permian Basin have potential as an underexplored, untapped shale-gas system similar to that of the Barnett Formation.

Atokan Carbonate Deposition

Broad Approach

Carbonate rocks of Atokan age in the Permian Basin have been studied primarily in the Chapman Deep field area, Delaware Basin. In this study it is thought that Atokan-age carbonates present in the Permian Basin are laterally equivalent to extensive carbonates developed on the Eastern Shelf (that is, the Upper Marble Falls Formation). It is postulated that these adjacent areas act as excellent analogs for equivalent underexploited sections within the Permian Basin. Consequently, the approach taken in this paper is to discuss development of the Upper Marble Falls Formation, along with Delaware Basin units. Although Upper Marble Falls field localities are not geographically part of the study area, extensions of that carbonate platform are present in the subsurface of the Permian Basin.

General Depositional Setting

Atokan-age carbonates were deposited widely across the Permian Basin on low-angle ramps that developed to more platformlike geometries through time.

Reservoir Potential

Shallow-water *Donezella* algal bioherms and oolitic-bioclastic grainstones are the most favorable reservoir facies because they may preserve excellent intergranular and intragranular porosity. Reservoir intervals are not confined to a particular facies or exposure surface, at least within the Delaware Basin. Off-platform, proximal, coarse-grained slope facies are a potentially overlooked reservoir target.

Diagenesis

Primary porosity appears largely occluded during early diagenesis. Extensive development of secondary dissolution porosity during burial, coupled with a microfracture network, results in good reservoir quality. In the Delaware Basin, dolomitization occurs during both early and late diagenesis, with positive and negative results in reservoir quality, respectively.

Detailed data on Atokan-age carbonate units in the greater Permian Basin are provided primarily by studies of the Atokan-age Chapman Deep field area of northern Reeves (Texas) and southern Eddy (New Mexico) Counties and the Upper Marble Falls

Formation of the Eastern Shelf/Llano Uplift area. Upper Marble Falls data and discussion are included in this paper because the Upper Marble Falls succession prograded from the Llano Uplift area onto the Eastern Shelf during the Atokan. These Eastern Shelf carbonates appear to be attached to the carbonate-platform to -ramp succession present in the Val Verde Basin. Upper Marble Falls studies provide detailed sedimentological and facies analogs for describing shallow- to deeper water carbonates present throughout the Permian Basin in middle to late Atokan times.

Delaware Basin

In the Delaware Basin, Reeves County carbonate facies age equivalent to the Upper Marble Falls Formation are present at Chapman Deep field, Reeves County (fig. 21). These consist of (1) shallow-water bank facies of *Donezella* algal bioherms, oolitic-bioclastic grainstones, and interbank to lagoonal lower energy facies; (2) slope facies that are spiculitic and crinoidal argillaceous limestones and interbedded shales; (3) basinal carbonate and siliciclastic turbidite facies (Mazzullo, 1981; Von Bergen, 1985). In the Chapman Deep field area, total thickness of the Atokan series ranges from 205 to 370 m (670–1,200 ft) and is divided into three major environments—basinal (<213-m [700-ft] water depth) (member A), proximal to distal slope (member B), and shallow-water ramp to platform (member C), with reservoirs being restricted to the latter. However, in Desmoinesian- to Virgilian-age carbonate units, proximal slope facies (member B), which are characterized by coarse debris, are also reservoir intervals and should not be overlooked from an exploration standpoint. A generalized sequence stratigraphic framework has been added to figure 21 to illustrate lateral facies packaging and the association of reservoir facies with highstand carbonate deposition.

Reservoir Quality

Within shallow-water carbonates (member C), the reservoir interval is not confined to a particular facies, and porosity and permeability are dominantly secondary in origin, occurring during deep-burial diagenesis. Figure 22 illustrates the abrupt vertical facies changes and lack of correspondence between facies type and/or subaerial exposure surfaces. Lateral facies changes are also pronounced. The lack of correspondence between facies and reservoir interval extends to the wireline-log signature, where gamma-ray and sonic logs do not show indicative profiles for any individual facies type (fig. 22). The pay zone in the Texaco Reeves “AZ” Fee #1 well is approximately 50 m (164 ft) thick (fig. 22).

Diagenesis of the carbonates is complicated but can be distilled into two categories (Mazzullo, 1981; Von Bergen, 1985; Eren, 2005). (1) Early diagenesis involved both vadose and phreatic dissolution and cementation but resulted in overall occlusion of primary and secondary pores, except for thin, volumetrically minor intervals below exposure surfaces. (2) Late diagenesis in the deep burial environment (3,962 m [13,000 ft]) resulted in establishment of a secondary pore and fracture network. This network is thought to be a result of moldic porosity forming from dissolution of ooids, inter- and intraparticle calcite cements, by undersaturated fluids expulsed from organic compounds along stylolites. Later tectonic movement and erosional unloading produced a microfracture system that crosscuts grains and earlier cements. Eren (2005), however, contended that microfracture and stylolite development are synchronous in Atokan carbonates in southern Eddy County, New Mexico, and cannot be linked to regional stress fields. Regardless of the cause of fracturing, this system, coupled with the pore dissolution system, resulted in the producing-reservoir interval. Stylolites contributing to enhanced reservoir quality are best developed within relatively clean, impurity-free limestones and are thereby related to lithology and facies type (Von Bergen, 1985).

Dolomitization also plays a key role in reservoir development. Dolomite is found as both an early diagenetic phase (dolo-silt) and a late replacive and cementing fracture-fill phase in Atokan carbonates of the Delaware Basin (Von Bergen and Mazzullo, 1981; Eren, 2005). Late fracture fill and replacive dolomite generally have negative effects on porosity via occlusion but may be indicators of high-temperature fluid flow related to petroleum migration. In Chapman Deep field, saddle dolomite (in a strict sense, nonplanar C [Sibley and Gregg, 1987]) partly to completely occludes fracture porosity. Within Eddy County, Eren (2005) used stable isotope data to argue that ferroan saddle dolomite precipitated from 52 to 55^{o}C fluids. However, this temperature regime appears too low for saddle dolomite (nonplanar-C) formation (Wright, 2001). Understanding dolomitization temperature and fluid-flow regime is important for predicting enhanced or diminished reservoir quality because dolomite appears restricted to the Delaware Basin during the Pennsylvanian.

In the southern Delaware Basin, the Atokan section at Rojo Caballos field (northwest Pecos County) consists of shale interbedded with limestone, capped and based by dark-gray shale (Hanson and Guinan, 1992). Limestone is a siliceous biomicrite with foraminifera and crinoids. A deep-marine embayment is the proposed depositional environment for Atokan carbonates and shales (Hanson and Guinan, 1992). Presence of siliceous biomicrites and shales indicates that the Rojo Caballos section is analogous to off-platform facies in the Upper Marble Falls in the Eastern Shelf and Llano regions. The

Upper Marble Falls succession thus provides an excellent outcrop analog area in which to understand facies distribution patterns in Rojo Caballos. Gross average thickness of the Atokan-Morrowan interval at Rojo Caballos is 210 m (700 ft). Net thickness of the producing zone is 4 5 m (150 ft), with a maximum of 75 m (250 ft). Porosity is a mixture of vug and dissolution that averages 12 percent. Permeability averages 0.1 md. Cumulative gas production at Rojo Caballos is 38,789 Bcf.

Data on the Atokan from the Northwest Shelf within New Mexico are sparse. Overall, total Atokan thickness decreases to approximately 150 m northward, given the estimates of 200 to 370 m in the center of the Delaware Basin. On the Northwest Shelf the Atokan comprises basal quartz sandstone interbedded with gray shales grading upward into tan, cherty limestones (Kues and Giles, 2004). Atokan sediments are continuous over Matador Arch but are thought to thin (Kues and Giles, 2004).

Eastern Shelf and Llano Uplift

Comparison of Upper Marble Falls and Lower Marble Falls Formations indicates that Atokan carbonates tend to be finer grained overall, with more widespread interbedded spiculitic shales and limestones. Southeast of the Llano Uplift, the Upper Marble Falls reaches a thickness of 150 m (495 ft). To the west-southwest in Sutton and Schleicher Counties, Atokan-age limestones are interpreted to be Upper Marble Falls that prograded westward from the Llano area. These units, which overlie the siliciclastics previously described, compose a middle unit of light-colored massive limestone on the order of 46 to 76 m (150–250 ft) thick, overlain by an uppermost unit that is a variable mix of thin-bedded, light-colored limestone and shale (Smithwick Formation?) of varying description (Rall and Rall, 1958). To the northeast, within Wise County, in the Fort

Worth Basin, the Upper Marble Falls averages approximately 61 m (200 ft) in thickness (fig. 40, “Depositional History of the Morrowan Succession (Lower Pennsylvanian) in the Permian Basin”).

Erlich and Coleman (2005) defined seven lithofacies for the Upper Marble Falls Formation that range from low-energy fusulinid and spiculitic limestones to shallower water, subtidal algal and conglomeratic limestones and intertidal beach rock. Overall the depositional environment of the Upper Marble Falls Limestone is not dissimilar to that of the Lower Marble Falls and does not warrant a repetition of earlier discussion of the Lower Marble Falls.

However, the subtidal algal limestone identified in the Upper Marble Falls is distinctive enough from the underlying Lower Marble Falls facies that it requires discussion. This facies comprises skeletal sand shoals and mounds dominated and constructed by the green algae *Komia* spp., found in association with high-energy beach rock (fig. 23). Shape and size of the mound and shoal facies in the Upper Marble Falls are similar to those of the mound facies illustrated in the Lower Marble Falls (fig. 37, “Depositional History of the Morrowan Succession (Lower Pennsylvanian) in the Permian Basin”). Constituent grains and lithifying agents of the two mound types may be very different. This facies has reservoir potential because diagenetic modification (leaching) and primary porosity are greater than in the lower energy facies. This higher energy facies is also similar to mound and bioherm facies in the overlying Strawn succession, which are good reservoirs. Overall distribution and occurrence of these algal facies are important to regional exploration for Pennsylvanian carbonate plays, as illustrated by Mazzullo (1981) for Chapman Deep field in the Delaware Basin. Both environment and, possibly, age are related to the type of organism creating bioherms/shoals. In the Lower Marble Falls, mounds are dominated by *Cuneiphycus* and *Donezella*, whereas in the Upper Marble Falls they are dominated by *Komia* and *Chaetetes*. The energy of the environment may be responsible for change in the algal community because *Komia* and *Chaetetes* are much more robust, high-energy, tolerant forms than *Cuneiphycus* and *Donezella*. In general, the aforementioned algae appear to give way in dominance to phylloid algae in younger units (Desmoinesian-Virgilian).

Reservoir Quality

The Upper Marble Falls higher energy mound/shoal facies have the best reservoir quality, with average porosity of 10 percent and 2 to 6 md permeability (Brown and Garrett, 1989) Llano Uplift/Eastern Shelf fields in Coleman, Brown, and Eastland Counties have produced approximately 127.1 Bcf of gas (circa 1989). Trapping style is generally stratigraphic (for example, facies pinch-out) with or without a structural overprint.

Facies Patterns and Sequence Stratigraphy

The relationship between the Smithwick Formation and carbonate units reflects a backstepping and drowning of the Upper Marble Falls platform/ramp. However, Upper Marble Falls sediments are characterized by an upward-shallowing sequence capped by a Type 1 unconformity and sequence boundary. It therefore appears that 3^{rd}-order sea-level change dominated in controlling unconformities and sequences represented in the Upper Marble Falls, and overall lack of accommodation caused the final demise of the platform (Erlich and Coleman, 2005). The backstepping of the Upper Marble Falls relative to the Lower Marble Falls is illustrated in figures 41 and 42 of “Depositional History of the

Morrowan Succession (Lower Pennsylvanian) in the Permian Basin." Note that in figure 41, the terminal position of the Upper Marble Falls platform is more than 100 km farther to the southwest and west than illustrated (Erlich and Coleman, 2005) (compare with fig. 1, "Depositional History of the Morrowan Succession (Lower Pennsylvanian) in the Permian Basin"). Final death of the carbonate factory occurred as Smithwick shales and Atokan siliciclastics prograded from the east over the greater Llano area.

It is apparent from current research that the distally steepened Lower Marble Falls ramp evolved into a steeper sided platform or rimmed shelf during transgression. The platform to rimmed-shelf area caught up and kept up with sea-level rise during transgression, resulting in units that display upward-shallowing trends. Mazzullo (1981) proposed a similar change from ramp to platform architecture for Atokan carbonates within Chapman Deep field, which was discussed in the previous section.

Understanding growth of the carbonate system (for example, platforms, ramps) and its response to high-frequency, high-amplitude, icehouse-condition, sea-level fluctuation and overall 2^{nd}-order global sea-level rise of the Morrowan to mid-Virgilian is vitally important in creating a proper exploration model for the Permian Basin. In a standard abruptly backstepping and/or prograding carbonate platform, the overlying carbonate platform and potential reservoir are displaced relative to the underlying carbonate platform and reservoir (for example, Erlich and Coleman [2005] model). A change in architecture from ramp to platform and/or shelf in response to sea level will result in a greater likelihood of stacked carbonates and reservoir successions (for example, Read, 1985, type model). This observation becomes even more critical when trying to understand the nature of carbonates overlying Atokan-age units in the Permian

Basin. The Upper Marble Falls succession present in Eastern Shelf and Llano Uplift areas provides detailed data that are needed in understanding and mapping regional distribution of the subsurface Atokan carbonate facies in the Midland Basin, CBP, and the Delaware Basin.

DISTRIBUTION OF ATOKAN CARBONATES

Distribution of Atokan-age carbonates illustrated in figure 1 is the result of analysis of well logs, wireline logs, and detailed sedimentological data (for example, Llano Uplift and Delaware Basin areas). Overall, carbonate deposition is much more widespread in the Atokan than in the Morrowan. Westward progradation of the Upper Marble Falls Platform resulted in carbonate deposition across the Eastern Shelf. This carbonate platform appears to connect with a thick succession of carbonates nucleating on the Devils River Uplift in Val Verde and Edwards Counties. According to seismic and well log correlations, most of what later became the CBP was covered by a relatively uniformly thick succession of carbonates. This carbonate platform was linked eastward with the Eastern Shelf, southeastward with the Devils River Uplift, and westward with the northern Delaware Basin ramp to platform area. Given previous interpretations of the Diablo Platform and northern Northwest Shelf area, the Atokan was a time of more widespread carbonate deposition relative to the underlying Morrowan

SUMMARY OF ATOKAN CARBONATE SUCCESSION

Because relatively little is known about Permian Basin Atokan-age carbonates, understanding and documenting the Upper Marble Falls Formation from both outcrop and subsurface datasets are key to proper interpretation of the Permian Basin succession. Chapman Deep and Marble Falls type carbonates have potential as both a primary (for example, leaching of bioclasts and primary porosity) and a secondary (fracture) reservoir. Atokan carbonates in the Permian Basin may be overlooked hydrocarbon targets, especially with respect to proximal slope facies targets. Interfingering of Smithwick Formation shales and equivalents with Atokan carbonates results in an interesting source/trap situation, where Upper Marble Falls Formation carbonates may also hold potential as fractured reservoirs for shale gas.

When comparing the carbonate succession regionally, one obvious factor that must be understood is apparent response to eustasy and tectonics between the greater Eastern Shelf/Llano uplift area, Northwest Shelf/Delaware Basin margin, and the CBP. At a 2nd-order eustasy level, all parts of the greater Permian Basin area appear to be reacting similarly (for example, lowstand followed by transgression). The 3rd- and 4th-order eustatic fluctuations are more important for overall reservoir organization and quality but are not defined well enough currently to help with exploration or production. Localized differences in rate of sediment supply also affected carbonate deposition by siliciclastic poisoning, such as in the areas of the Ozona Uplift and Gaines County Uplift.

In summary several key issues are crucial to an understanding of Atokan-age carbonates. Many of these issues have a direct bearing on exploitation of, and exploration for, new reservoirs in the Permian Basin.

1. Scale: Studies within and external to the Permian Basin must be put into regional sequence stratigraphic context.
2. Structure: Many stratigraphic relationships proposed for the Pennsylvanian rely heavily on interpretation and identification of structure (for example, the CBP). However, many of the studies present conflicting or, at best, ambiguous

structural/stratigraphic interpretations. Unraveling of the structural evolution of the Permian Basin requires intense, dedicated study and is discussed in its own paper.

3. Nomenclature: A concerted effort must be made to unify the stratigraphic nomenclature applied to Atokan carbonates. It is proposed that the term Upper Marble Falls Formation be used for all platform to ramp carbonates in the greater Permian Basin area in outcrop and subsurface.

DISCUSSION AND SUMMARY OF THE ATOKAN IN THE PERMIAN BASIN

Atokan coarse-grained, siliciclastic deposits are confined largely to the north and south margins of the Permian Basin (that is, the Northwest Shelf, Kent and Kinney Counties) and small areas in the center of the basin (that is, Upton and Midland Counties). These siliciclastics are coarse-grained, alluvial deposits at the base but are more marine upsection, in contrast to those of the Morrowan. Marine, shore-parallel sandstone bodies found in the Northwest Shelf and Matador Uplift areas provide a more geometrically and geographically definable play than do the underlying lower Atokan and Morrowan incised-valley-fill sediments. The presence of an extensive fan-delta to basin-floor-fan complex across Upton to Midland County, indicates that basin-floor-fan type plays might be present in other parts of the Permian Basin near uplifted areas (for example, Gaines, Dawson, Pecos, and Terrell Counties). Siliciclastics illustrated in figure 1 in Kinney and Uvalde Counties (that is, Kerr Basin) appear to have had an easterly source but did not migrate into the Val Verde owing to the carbonate platform associated with the paleohigh of the Devils River Uplift.

Carbonate deposition was widespread across much of the basin during most of the Atokan, varying from shallow-water, high-energy to basinal low-energy facies. The effects of 3rd- and 4th-order sea-level falls are manifested in carbonates as subaerial exposure surfaces. Although these surfaces/events do not appear to control reservoir development within the Chapman Deep area, other reservoirs within the Permian Basin may nevertheless be largely controlled by diagenesis caused during exposure. The link of subaerial exposure to enhanced reservoir quality is extremely important in younger Desmoinesian- to Virgilian-age carbonate reservoirs in the Permian Basin.

Given the organic-carbon-content values of the Smithwick Shale and equivalents, more study is needed to further delineate distribution of these units because they have good potential as shale-gas reservoirs in the northern Midland Basin and southern Delaware Basin.

PALEOGEOGRAPHIC SUMMARY

Proposed distribution of Atokan-age sediments across the Permian Basin and surrounding areas, which is based on interpretations in this paper, is illustrated in figure 1. Exact age of the reconstruction is lower to middle Atokan. Areas of siliciclastic deposition illustrated in Upton, Midland, Kent, Stonewall, King, Knox, Cottle, Foard, and Hardeman Counties were transgressed by middle to late Atokan time and comprise carbonate and shale facies. In the late Atokan, carbonate lithologies dominated over the Ozona Arch area, whereas in the Matador Uplift area, the Smithwick Formation was present. In Eddy and Lea Counties, New Mexico, carbonate rocks with interbedded shales dominated by the late Atokan. The boundary between basinal carbonates and shales (Smithwick Formation) across the Llano Uplift and northward corresponds to latest Atokan time.

Early Atokan-age siliciclastics dominated deposition in the far west of the Permian Basin, northwest of the Ozona Arch, and east of the Matador Uplift, while carbonate deposition dominated elsewhere (fig. 1). The predominance of carbonate facies across most of the Permian Basin is a result of (1) lack of siliciclastic supply, (2) overall 2nd-order rising sea level, and (3) progradation of the west-facing margin of the Upper Marble Falls Formation westward owing to lower accommodation and backstepping of the east margin retreating from the encroaching Atokan deltaics from the east. A transition from platform and/or ramp carbonates to more basinal carbonates and, ultimately, shales in the center of the Midland Basin, CBP, and Delaware Basin is implied. This is supported by well data in the Midland Basin, indicating a westward shift from carbonates to shalier lithologies. A large area of platform to ramp carbonates is thought to have existed along the trend of the antecedent CBP and links with the northern Delaware Basin and Eastern Shelf.

A small number of Precambrian inliers on the CBP trend appear to have been exposed and to have been shedding material into the basin (for example, Lea County, New Mexico, and Pecos and Crockett Counties, Texas). One of these uplifted blocks is the Ozona Arch, which provided the source for alluvial channels of Upton County and basin-floor fans of Midland County, during the lowstand event at the beginning of the Atokan. At roughly the same time, a small uplifted area on or near the Fort Stockton High in Pecos County also emerged. According to seismic and facies data, a similar small, uplifted area also existed in Eddy and Gaines Counties. Another such positive feature is also apparent in Roosevelt County, New Mexico. This area corresponds roughly to the Bravo Dome area. The uplift of this area probably helped diminish the southward influx of sediments from the Pedernal Uplift and also funneled them into the Palo Duro Basin. A shallow seaway probably still extended between the uplift (Bravo Dome) and the Pedernal highlands.

Siliciclastics in the Kerr Basin (for example, Kinney, Uvalde, and Zavala Counties) were sourced from the east by a sutured zone along the Ouachita Foldbelt. Although illustrated as marine to alluvial siliciclastics in figure 1, data are sparse, and sediments may instead reflect deposition from gravity-flow processes. In the Delaware Basin the siliciclastic lowstand succession was dominated by localized incised valleys. Valley systems were infilled by multiple transgressive facies types. Areas of shale deposition in the northern Midland and southern Delaware Basins reflect ensuing subsidence of these two basins, which becomes more prominent in younger successions.

KEY CONCLUSIONS

- Atokan-age units in the Permian Basin reflect an abrupt 2nd-order transgression from alluvial and shallow-marine siliciclastic deposition to carbonate deposition.

- Atokan-age siliciclastics dominated deposition in the northwest of the Permian Basin, while carbonate deposition dominated throughout the remainder of the basin.

- Early Atokan siliciclastic deposition took place in isolated incised-valley-fill systems. However, these systems were quickly replaced by shore-parallel, open-marine facies. The shore-parallel sands provide attractive exploration targets because they are geometrically and geographically constrained. Shore-parallel sandstone bodies are probably transgressive barrier bars or shelf ridges, not regressive deltaic and/or shoreline sands.

- In the southern Midland Basin, an incised valley sourced from the Ozona Arch and the CBP served as a conduit for fan-delta deposition and shelf-margin bypass, resulting in deposition of basin-floor-fan deposits in Midland County.

- The Smithwick Formation and shales of equivalent age within the Permian Basin have sedimentological characteristics and TOC similar to those of the Barnett Formation and ultimately may be good shale-gas targets.

- Atokan carbonates were deposited over a much larger area in the Permian Basin than previously documented. Especially important is the proposed link between carbonates on the Devils River Uplift (Val Verde and Edwards Counties.) and the Eastern Shelf. Algally dominated bioherms and higher energy facies (ooid grainstones), which were affected by burial diagenesis and subsequently fractured, comprise the best carbonate reservoirs. However, secondary porosity formed during exposure should not be discounted as a primary reservoir-creation mechanism. Proximal coarse-grain slope-carbonate facies are potentially another exploration target. Atokan basinal and slope carbonates interfingered with shale (for example, the Smithwick Formation) also hold potential as fractured reservoirs for expulsed shale gas.

- The Smithwick Formation and its lateral shale equivalents have high enough TOC values to warrant studies to define their distribution and origin as potential shale-gas sources and reservoirs similar to those of the Barnett Formation.

Conclusions drawn herein should provide guidelines and ideas for interpretation of the Atokan section within the Permian Basin.

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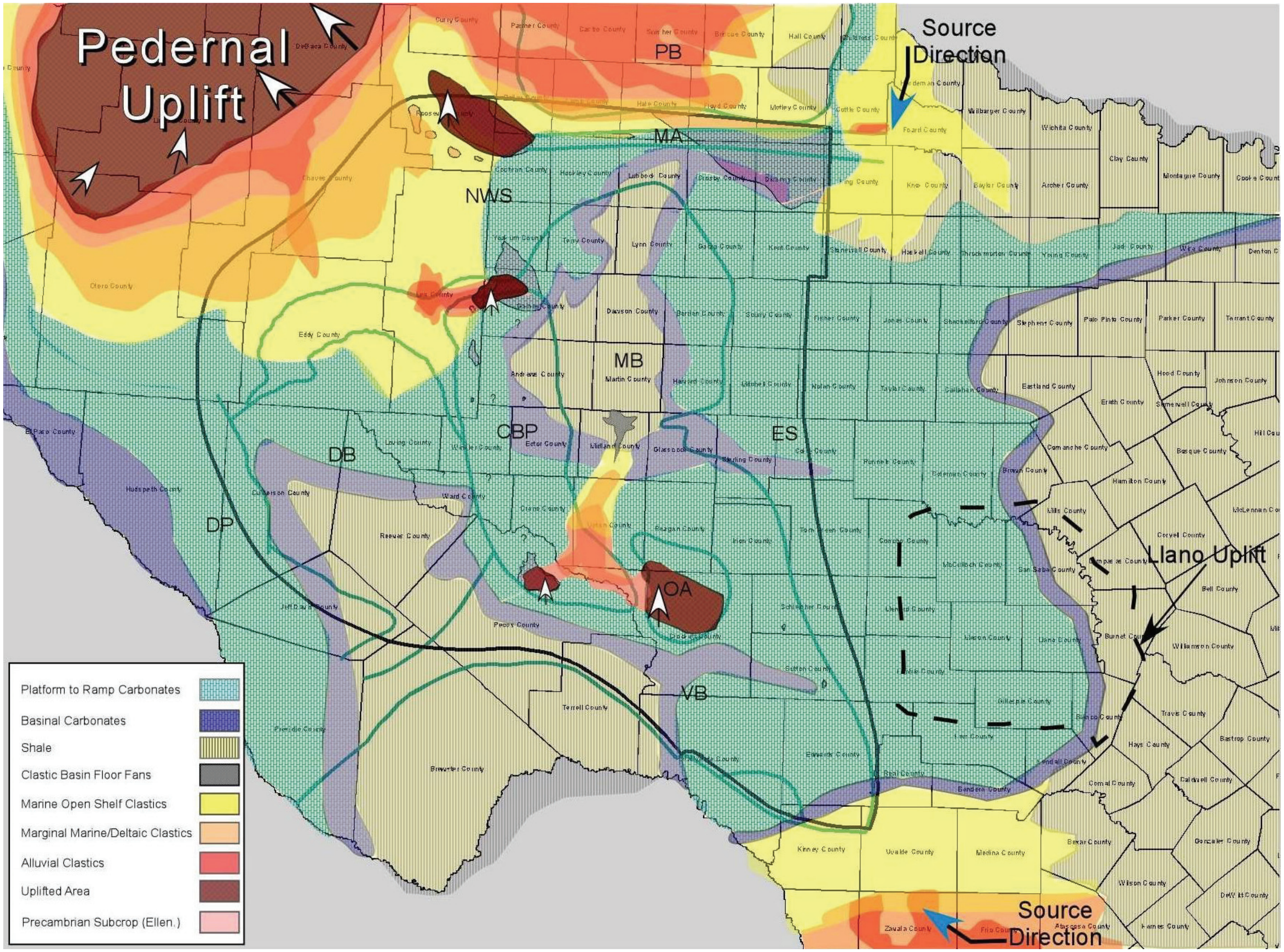


Figure 1. Atokan paleogeography and facies distribution map for the greater Permian Basin region during the early to middle Atokan. Siliciclastics illustrated in Upton, Midland, King, Cottle, Eddy and Lea Counties are largely transgressed by shales and carbonates by mid- to late Atokan times. Major subregions outlined by dark-green lines: 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), Val Verde Basin (VB). Orange alluvial siliciclastic zone centered in Cottle County corresponds to Broken Bone Graben. Fort Worth Basin centered in Wise County. Llano Uplift area outlined by black dashed line. Sizes of arrows surrounding Pedernal and other uplifted areas correspond to relative amount of uplift (the larger the arrow, the greater the relative uplift).

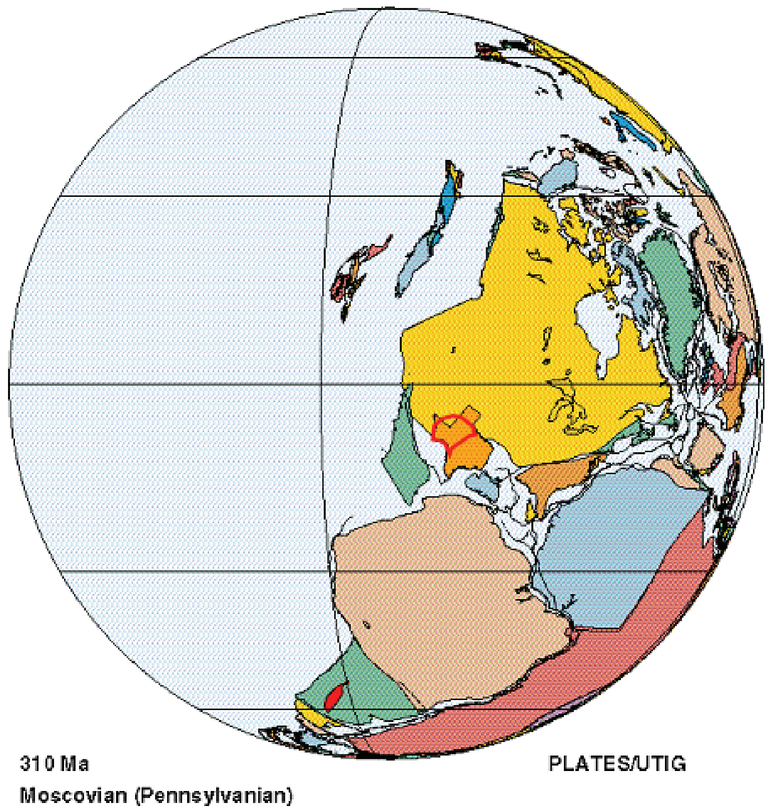


Figure 2. Atokan-age (circa 310 Ma) Texas plate tectonic reconstruction. Note marine (light-blue) to continental (light-orange) transition that occurs across Texas (dark-orange) in the area of the Permian Basin (red polygon). Suturing of continents has resulted in partly restricted marine subbasin between the plates. Diagram modified from Dalziel and others (2002). Permian Basin migrated north (that is, more equatorial) relative to its Morrowan position.

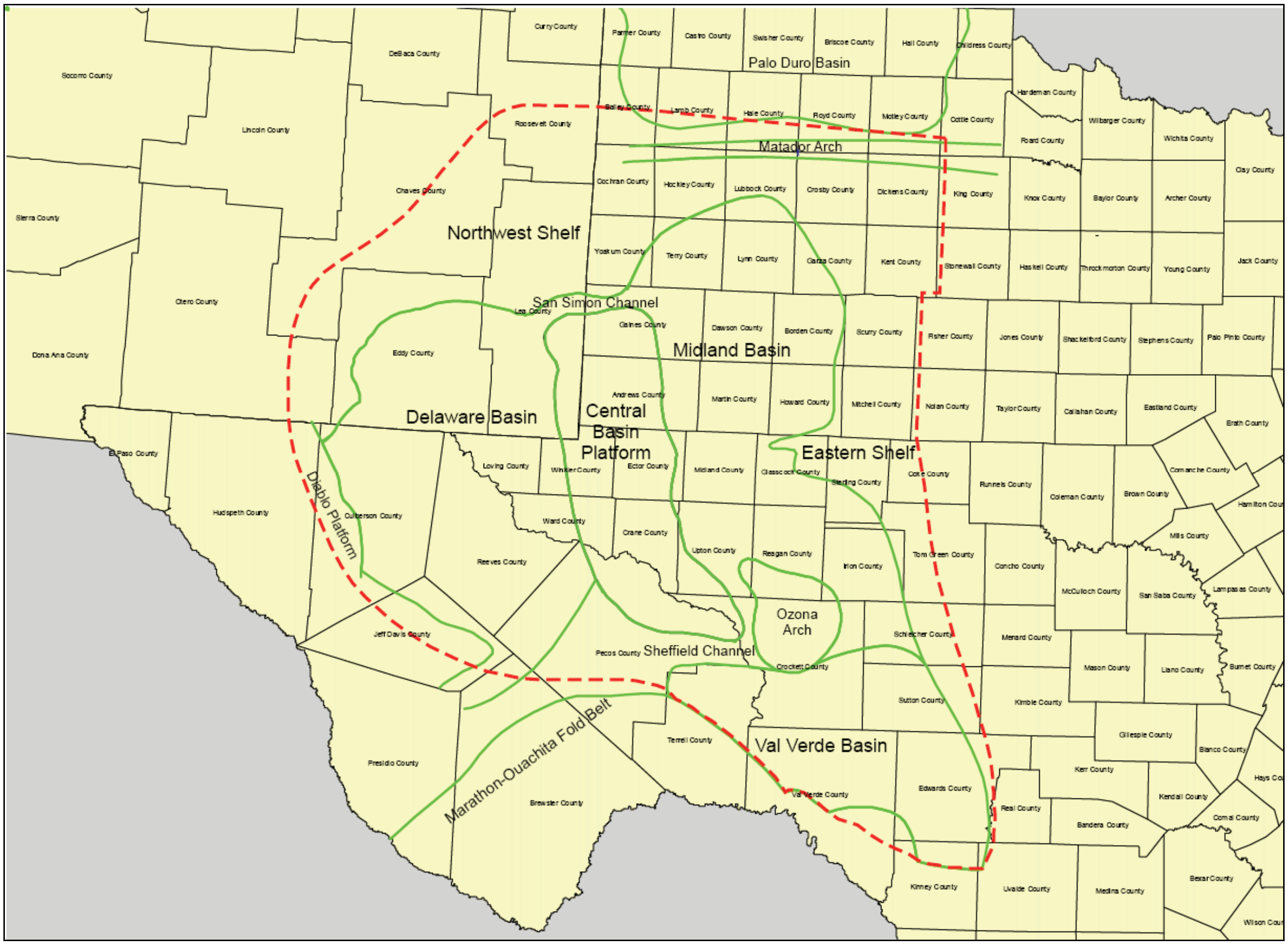


Figure 3. Permian Basin (dashed red line) and major geologic features. Many of the features were in the early stages of development during the Atokan. Compare figure 3 and figures 4 through 6 for previous models of facies distribution relative to the basin outline. Figure 1 illustrates the facies distribution for the greater Permian Basin area derived from this study. The west margin of the Fort Worth Basin runs north-south through Palo Pinto County.

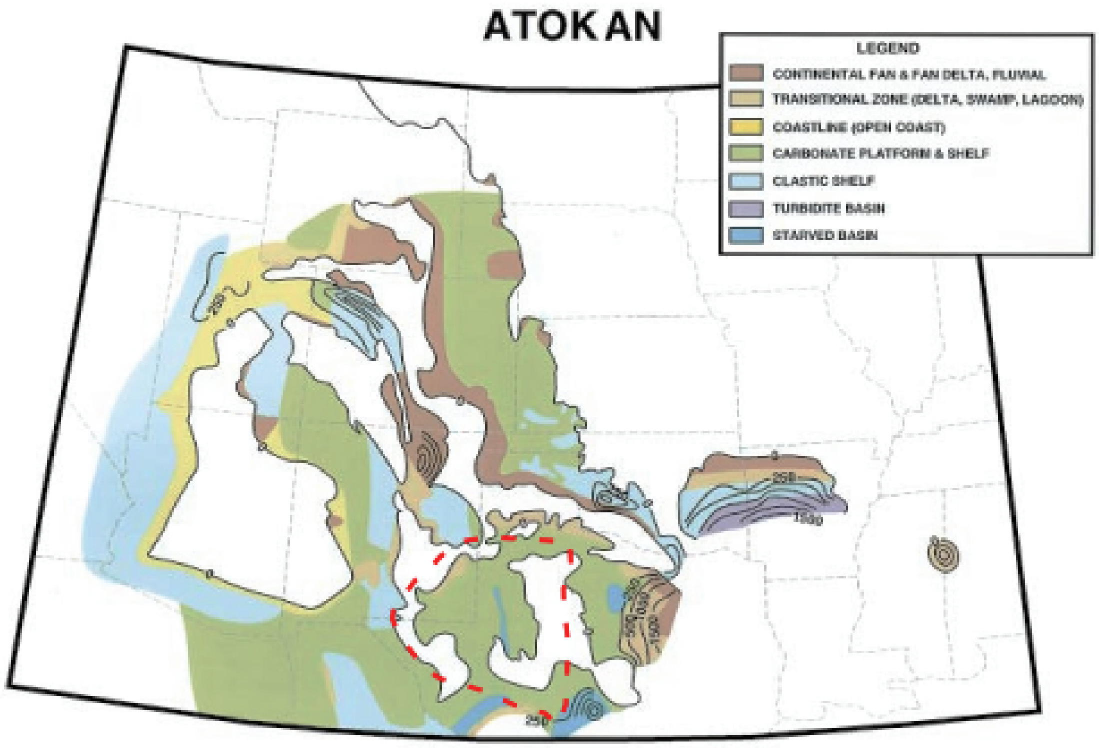


Figure 4. Generalized Rocky Mountain region and southern Midcontinent Atokan paleogeography (from Ye and others, 1996). White areas indicate either nondeposition or erosion (not clarified in the original text). Note that most of the Permian Basin (outlined by red dashed polygon) was considered a carbonate platform and/or shelf by Ye and others (1996). The Diablo Platform, Ozona Arch, and Eastern Shelf areas appear substantially uplifted in this model (fig. 3).

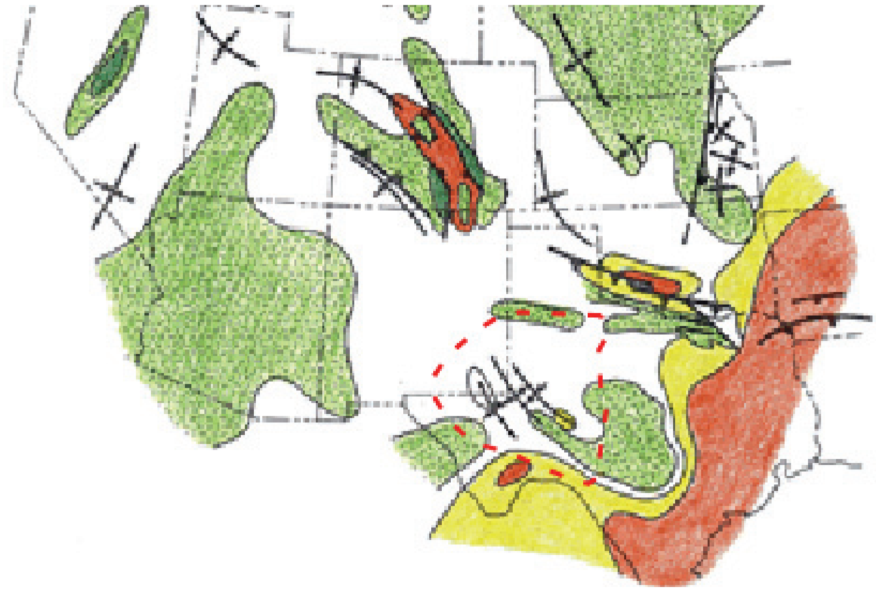


Figure 5. Areas of net subsidence (white <50 m/Ma to red >300 m/Ma) and net uplift (green <50 m/Ma) for the Atokan series (after Kluth, 1986). This interpretation shows that Llano and Ozona Arch areas were both uplifted and connected.

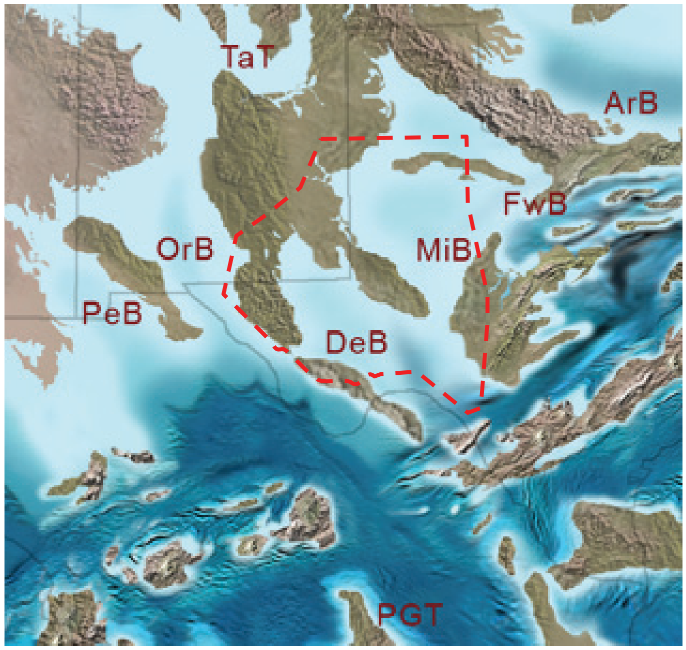


Figure 6. Regional paleogeography for the Atokan (circa 315 Ma). DeB and MiB refer to Delaware and Midland Basins, respectively. Permian Basin outlined by red dashed polygon. ArB—Anadarko Basin, FwB—Fort Worth Basin, OrB—Orogrande Basin, PeB—Pedregosa Basin, TaT—Taos Trough. Uplifted areas represented by browns, shallow marine by light- to medium-blues, and deep marine by dark-blue (from Blakey, 2005). Note prominent differences in uplifting and subsiding areas from those of figure 4, especially with respect to eastern and southeastern New Mexico and location of Pedernal Uplift, Central Basin Platform, and Eastern Shelf regions (figs. 1, 3).

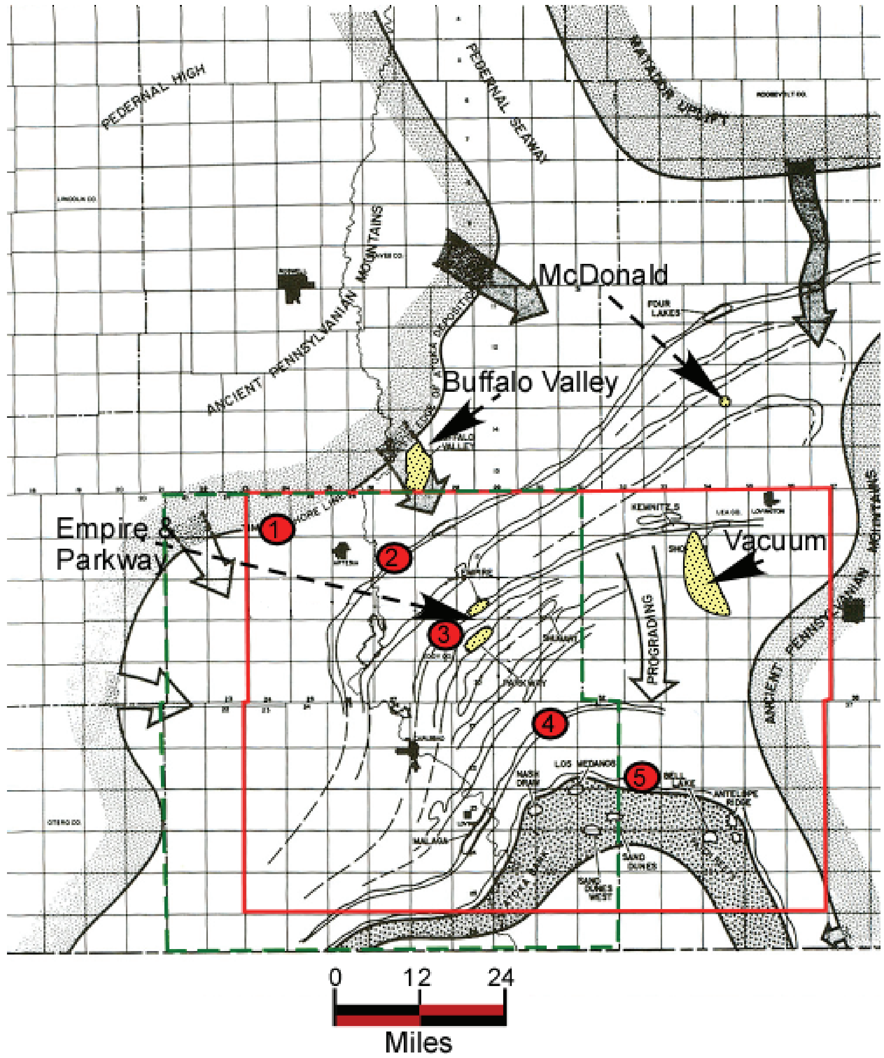


Figure 7. Atokan-age depositional paleogeography for the north Delaware Basin and Northwest Shelf (from James, 1985). James (1985) interpreted the shoreline position to step basinward through time (1 to 5 [oldest to youngest]). It is alternatively possible that shelf ridges or barrier bars formed during transgression and are younger updip (oldest at shoreline, 5 and youngest at 1). Note the need for an eastern source area for Vacuum field coarse valley-fill sediments because it is isolated from the Pedernal High to the northwest.

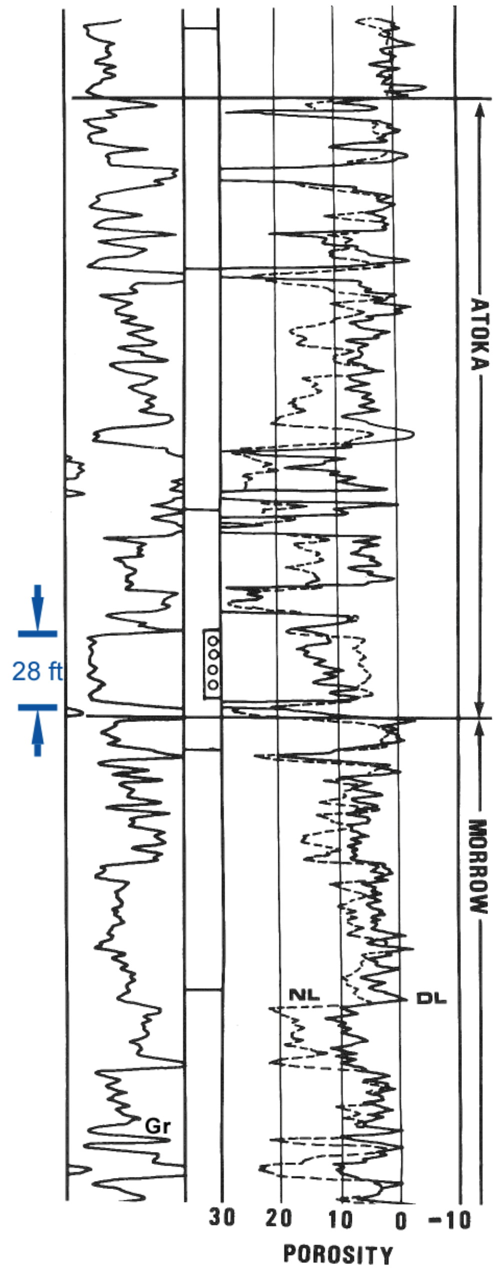


Figure 8. Typical log character of the Atokan section in the Southland Royalty "A" No.1 well in Empire field, Eddy County, New Mexico. Neutron-density crossover indicates gas effect on well log response.

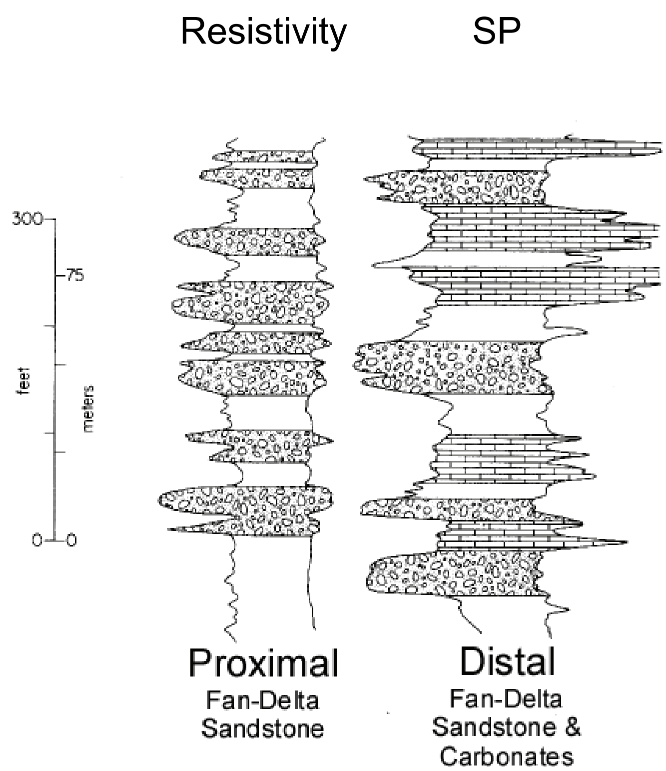
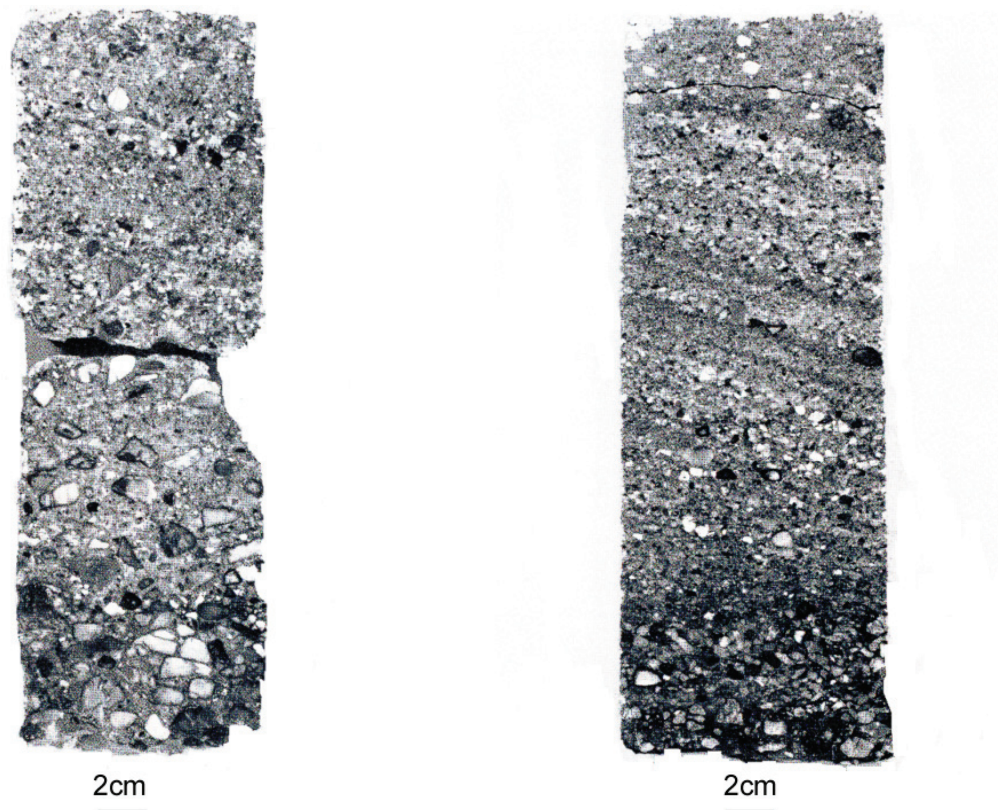


Figure 9. Schematic wireline-log signature for fan-delta facies (after Dutton, 1980).



Upward-fining sequence in Atokan fan-delta from Standard and Robinson #2 Tippen well, Cottle Co.

Crossbedding in Atokan fan-delta, from Standard Oil #1 Barron well, Cottle Co.

Figure 10. Core-slab photographs of typical coarse-grained fan-delta facies (after Dutton, 1980).

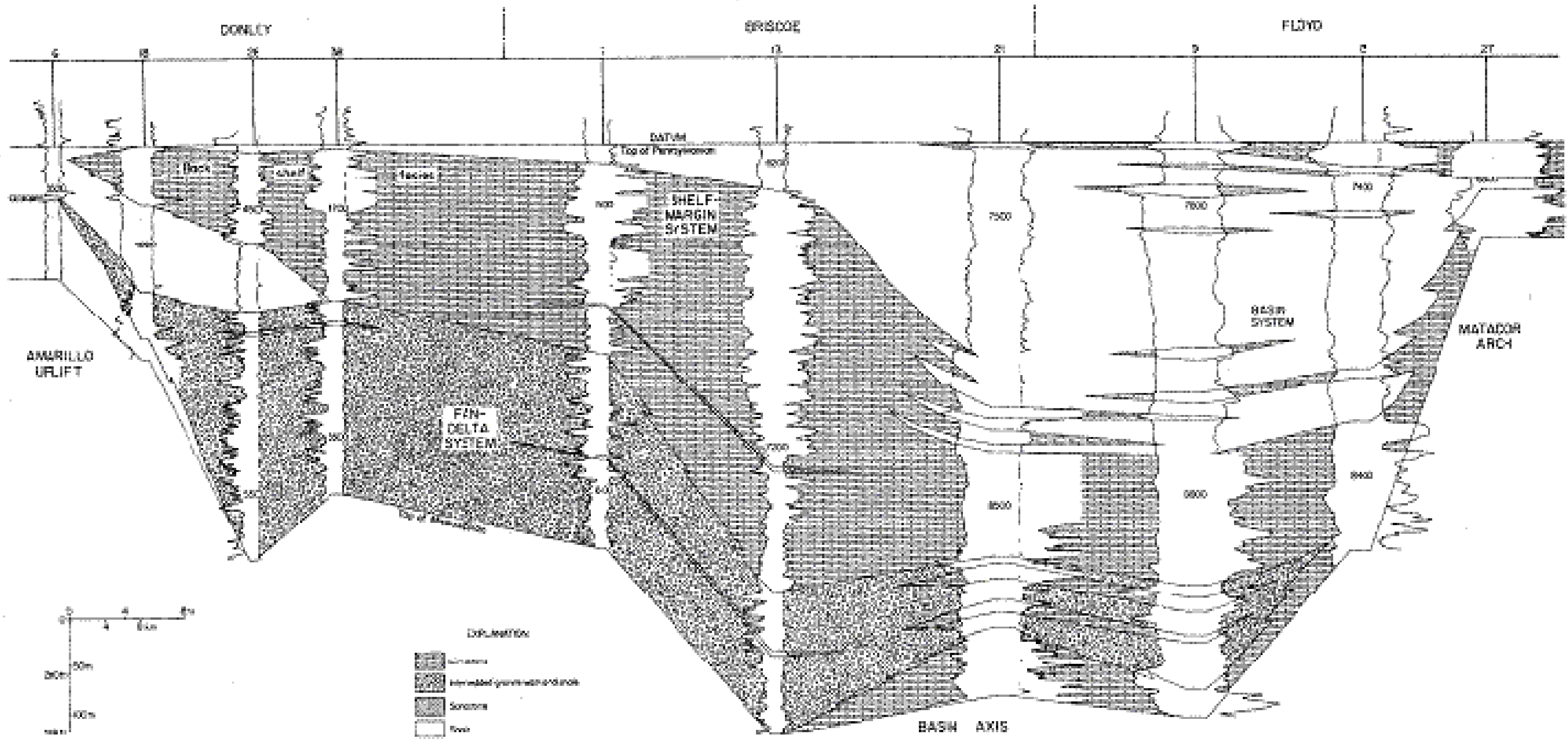


Figure 11. Regional correlation of Pennsylvanian units within the Palo Duro Basin (after Dutton, 1980). The fan-delta system is Atokan in age and is similar to fan deltas described for the Midland Basin (for example, Upton County).

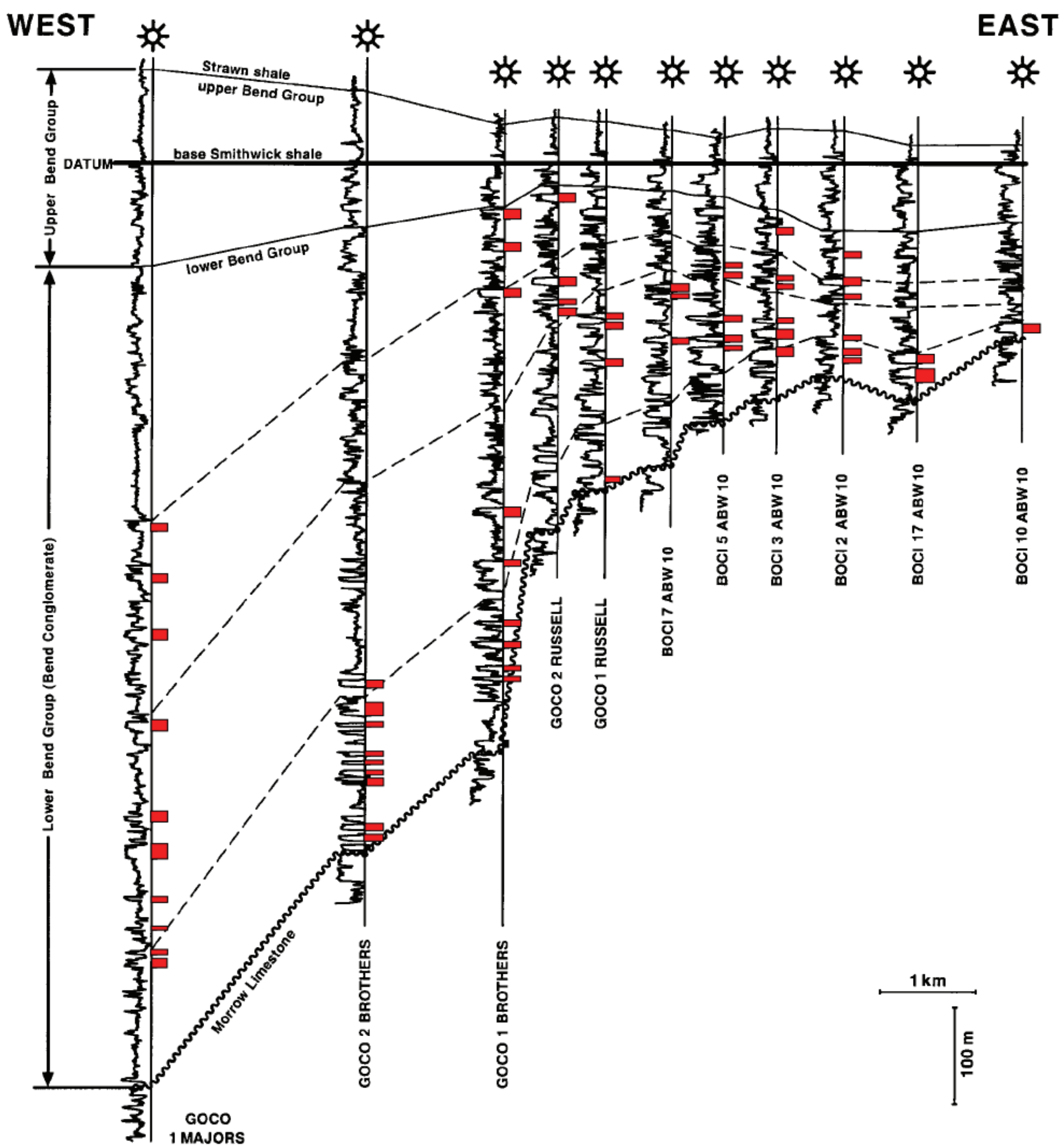


Figure 12. Gamma-ray log west-east correlation of entire Atokan interval (Bend and Smithwick Formations) within Broken Bone Graben. Small red bars on right-hand side of each well log indicate producing reservoir-quality sandstones. Note large number of reservoir-quality sandstones within lower unit that are disconnected from reservoir-grade intervals on upper flank of the structure (after Brister and others, 2002).

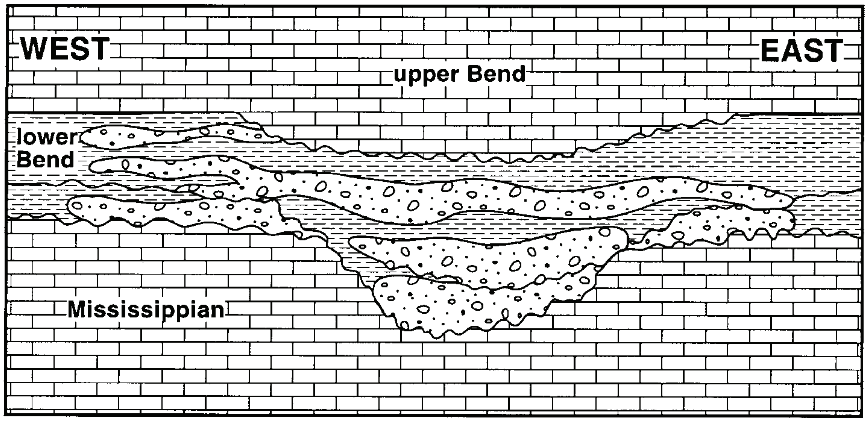


Figure 13. Illustration of incisive and unconfined alluvial channels encased in shale in lower Bend (Atokan age), overlain by dominantly carbonate upper Bend (modified from Brister and others, 2002). Architecture analogous to proximal alluvial facies in Taylor Draw field (Upton County), as well as “lower sand” interval in Vacuum field (Lea County, New Mexico).

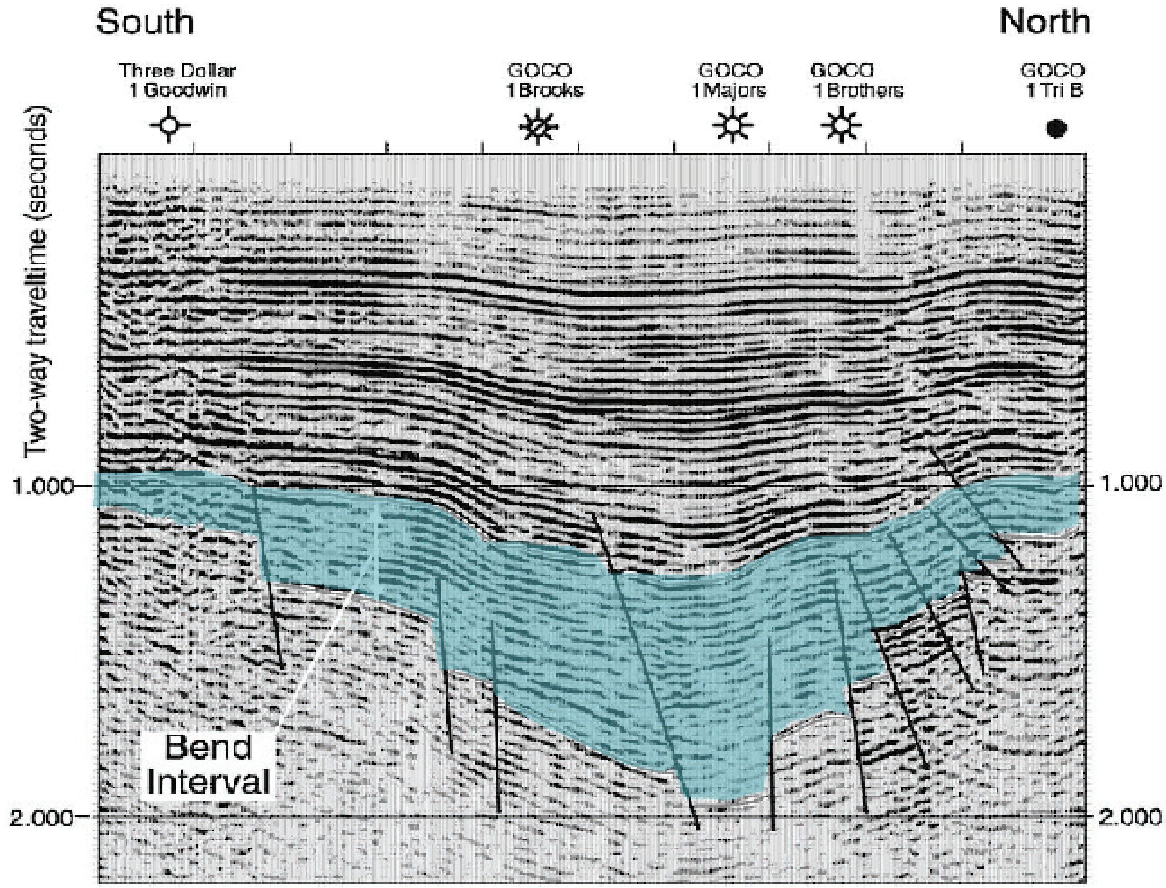


Figure 14. High-resolution seismic over Broken Bone Graben. Atokan-age Bend interval (upper and lower Bend and Smithwick) imaged and highlighted in blue. Note that orientation of seismic line is perpendicular to wireline cross section in figure 12. Onlapping geometries and changes in seismic character at approximately 1.7 and 1.5 s two-way traveltime potentially correspond to switch from nonmarine to marine sedimentation. Onlapping geometries also suggest pinch-out of facies and stratification of reservoir intervals in this type of setting, which might not be indicated by wireline-log correlation.

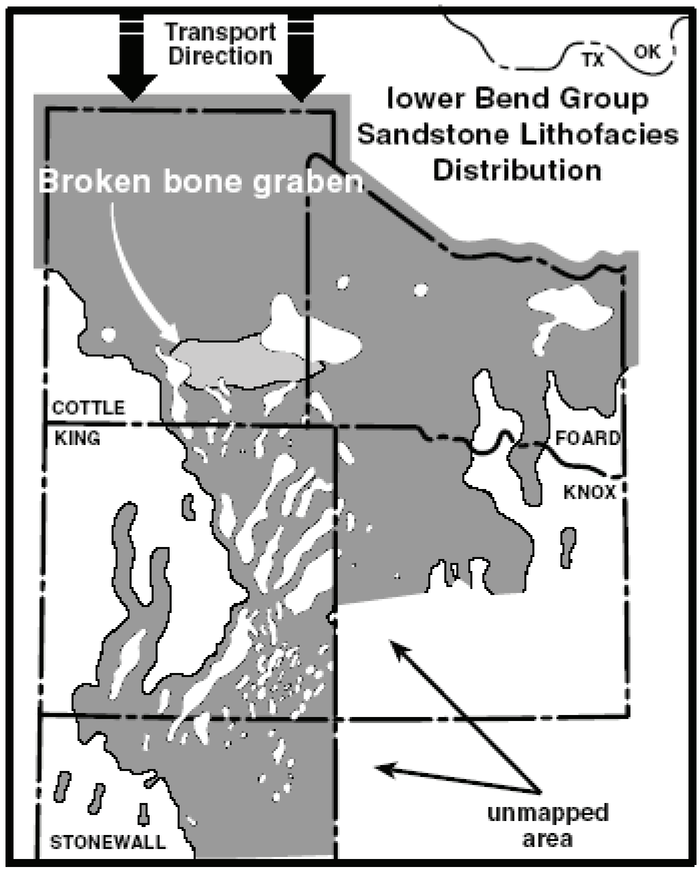


Figure 15. Distribution of lower Bend Group sandstones in gray. Light-gray area denotes Broken Bone Graben. White areas are either unmapped or they did not receive siliciclastic sediments. Note overall transport direction from the north toward the Permian Basin (after Brister and others, 2002). Note potential for encountering sandstones in southern Stonewall County and westward into Kent County. Alluvial-channel sands have already been identified in Baylor County, to the east of Knox County.

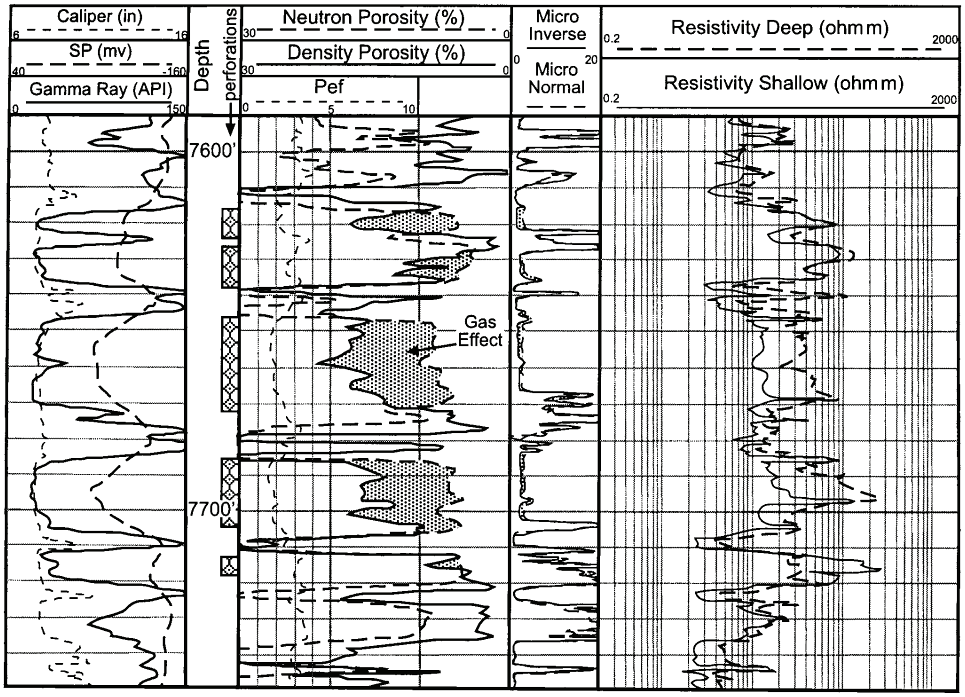


Figure 16. Detailed wireline-log-suite signature of lower Bend stacked sand pay horizons from Rhombochasm field. Productive sands are present in the interval, and low-resistivity high-gamma-ray mudstones/shales separate the sands. Figure modified from Brister and others (2002).

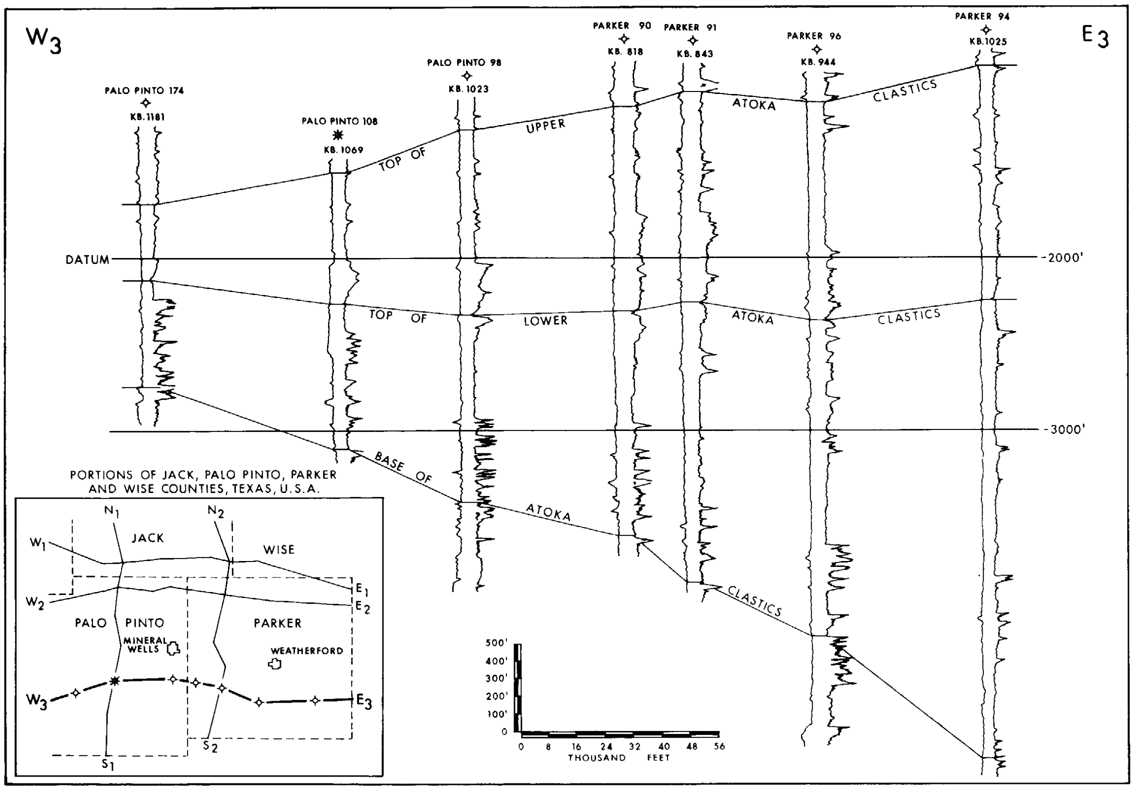


Figure 17. West-east SP- and resistivity-log correlation of Atokan-age units in Palo Pinto and Parker Counties (after Ng, 1979). According to upper and lower log picks of Ng (1979), lower Atokan siliciclastics appear to thin and onlap westward; however, the high-resistivity log interval is relatively uniform in thickness and does not indicate substantial thinning or onlap. The upper Atokan shale-dominated interval is equivalent to the Smithwick Formation.

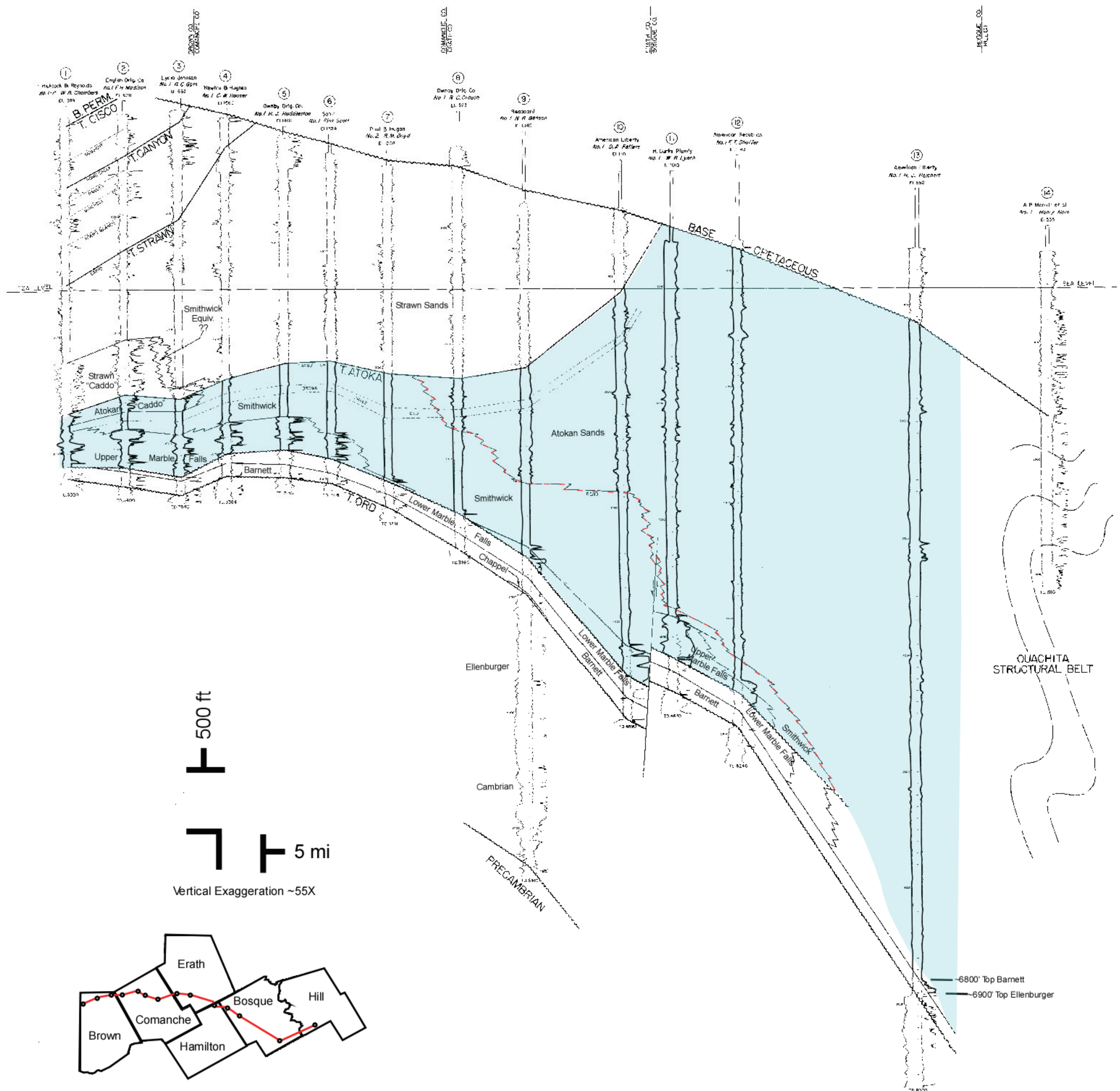


Figure 18. Regional west-east SP-resistivity well log correlation of Upper Mississippian and Pennsylvanian of Brown to Hill Counties north and northeast of the Llano Uplift. Atokan-age sediments highlighted in light-blue. Note east-west thickening of Upper Marble Falls limestone and thinning of coeval and younger Smithwick Formation in the same direction. All correlations are from original figure modified from Fort Worth Geological Society (1957). Presence of Smithwick between Upper Marble Falls and Strawn Formation may allow for regional correlation of this unit into the Permian Basin.

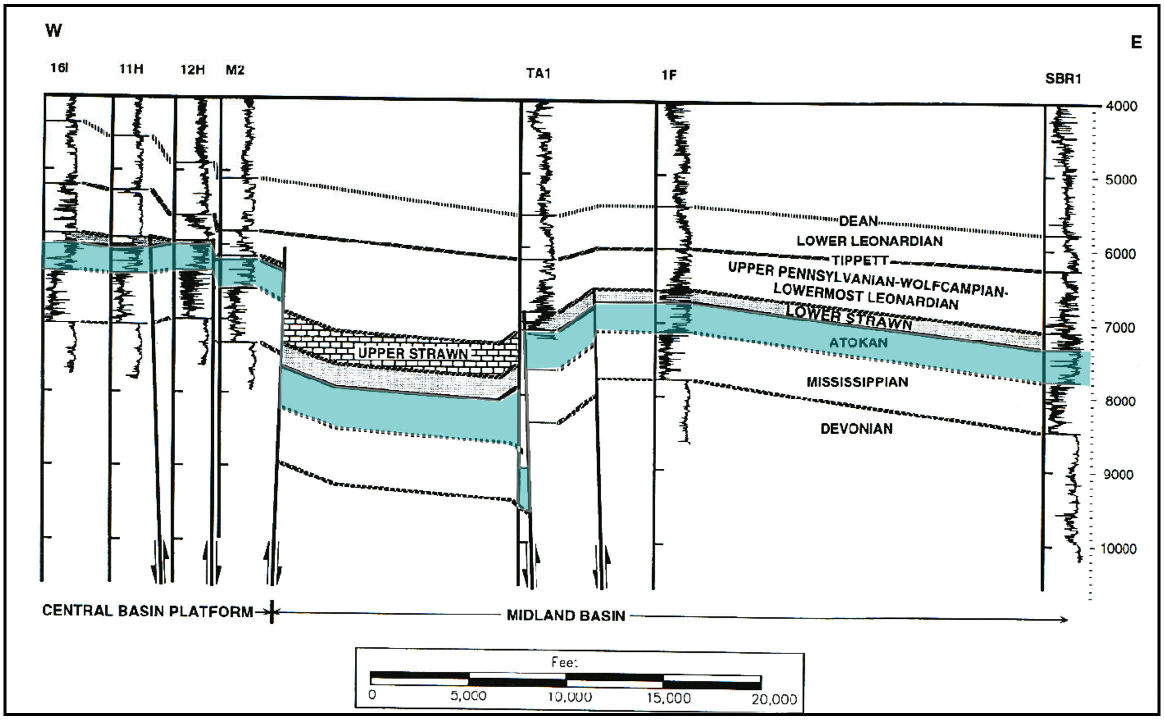


Figure 19. West-east structural cross section of 3D seismic grid over Wilshire field, central Upton County (cross section modified from Tai and Dorobek, 1999). Note Atokan, highlighted in blue, showing no thickness or wireline-log character changes from the Central Basin Platform into the Midland Basin.

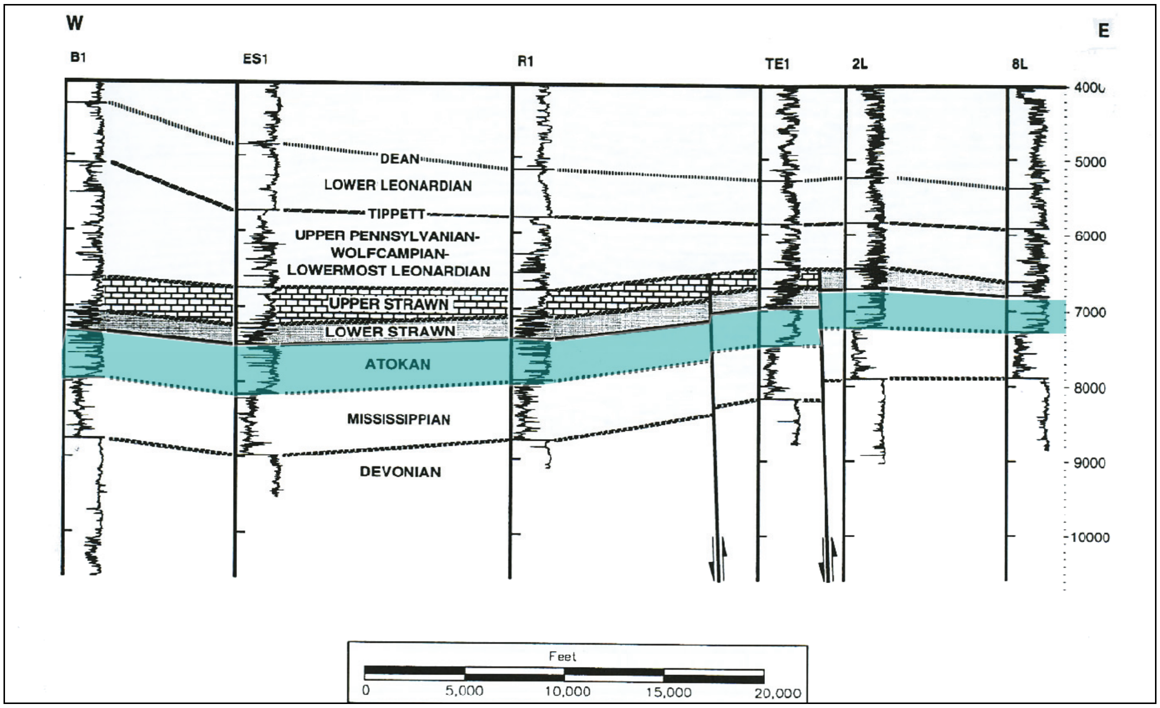


Figure 20. West-east structural cross section of 3D seismic grid over Wilshire field, central Upton County (cross section after Tai and Dorobek, 1999). Note Atokan, highlighted in blue, showing minor consistent thickness decrease to the east over the Wilshire structure. Wireline-log character does not change from west to east.

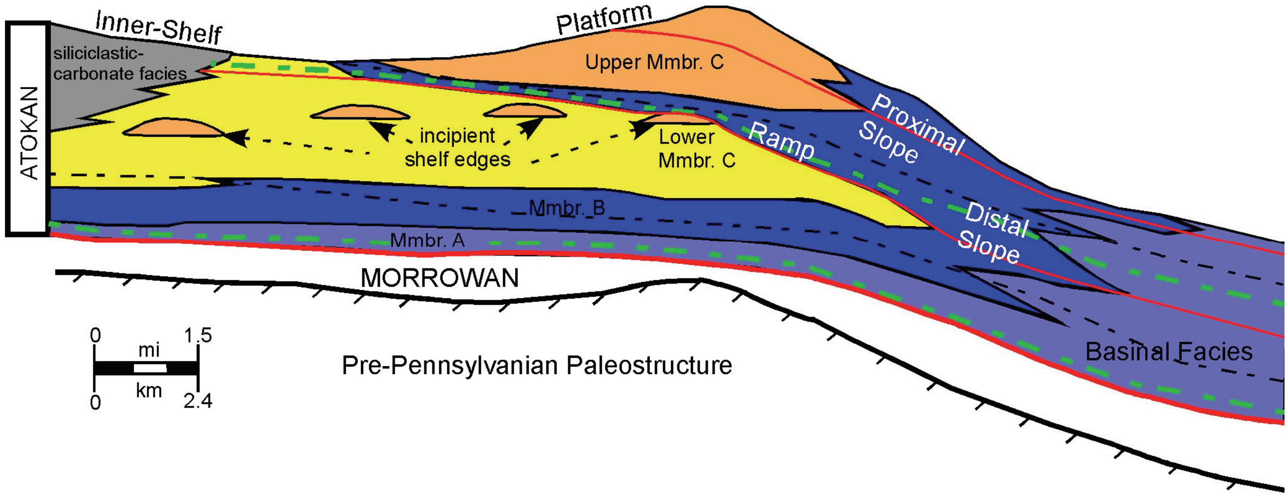


Figure 21. Schematic representation of facies architecture and sequence stratigraphic surfaces in the Chapman Deep Field area, Reeves County (modified from Mazzullo, 1981). Member A represents the basinal (<213-m [700-ft] water depth) environment, Member B represents the proximal to distal slope facies, and Member C comprises shallow-water ramp to platform facies. Sequence stratigraphic surfaces have been added to illustrate the lateral facies variations within each sequence tract. Transgressive surfaces are indicated by dashed green lines, flooding surfaces by black dotted and dashed lines, and sequence boundaries by solid red lines. Most of the reservoirs occur within highstand sequence tracts.

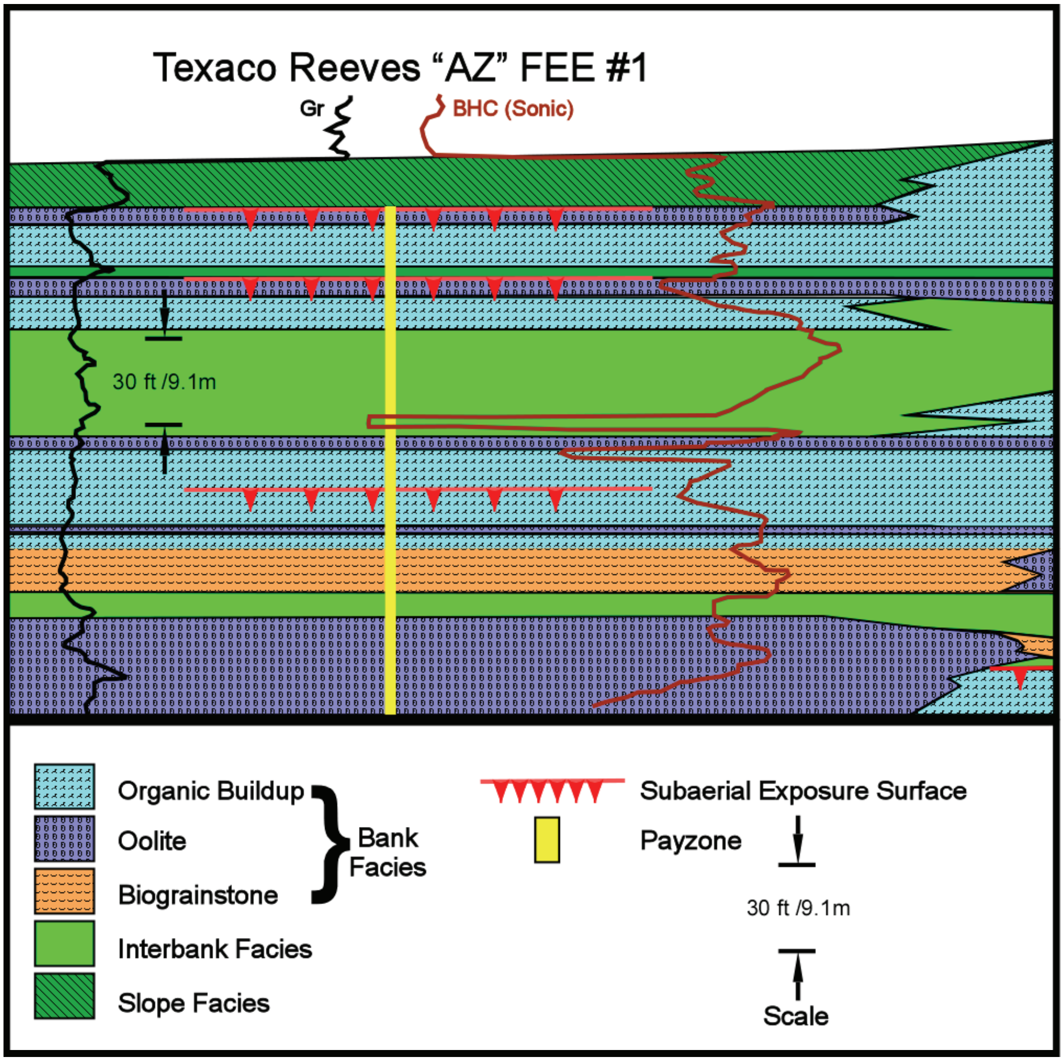


Figure 22. Type example of vertical and lateral facies variation in Atokan carbonate units of Delaware Basin (Chapman Deep field area) (modified from Mazzullo, 1981). Solid yellow vertical line indicates pay zone. Note lack of correlation between facies, pay zone, exposure surface, or wireline-log signature.

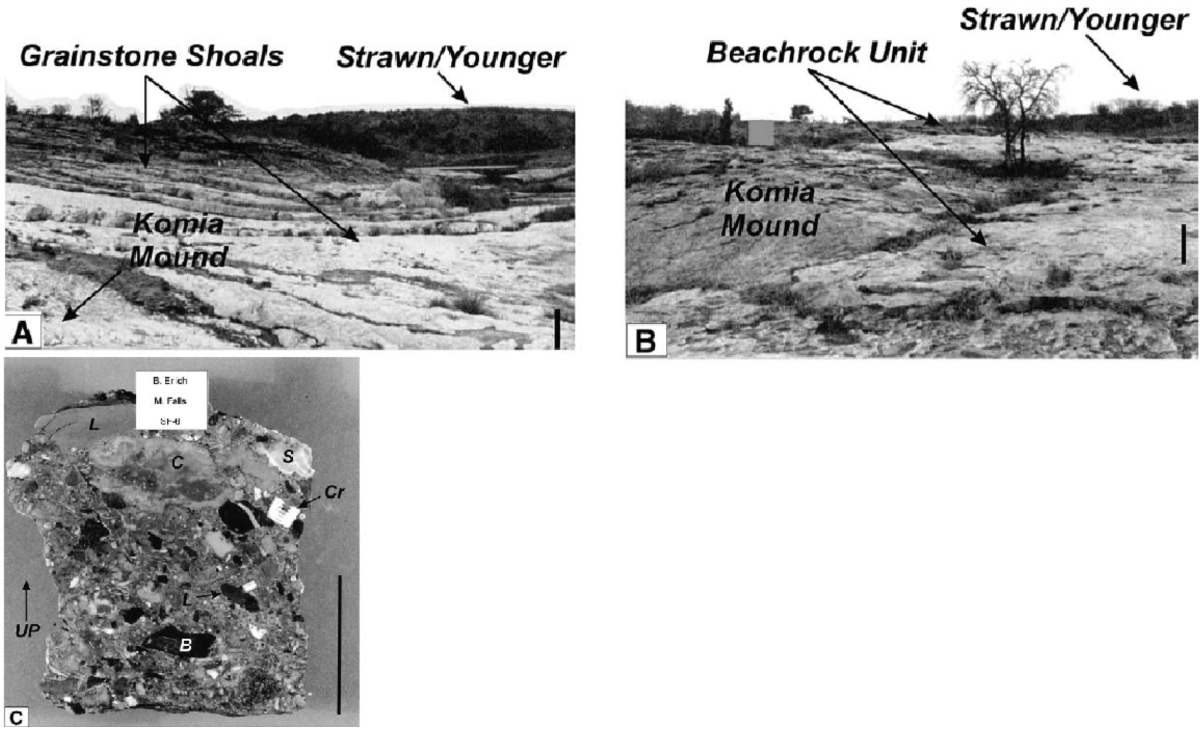


Figure 23. Upper Marble Falls Formation mound facies outcrop photographs and hand-specimen example of high-energy beach rock. (A) Crossbedded skeletal grainstone shoals. Paleobathymetric relief between *Komia* spp. algal mounds filled with migrating grainstone shoals. (B) *Komia* spp. algal mound onlapped by Upper Marble Falls beach-rock unit. Scale bar at right = 1 m. (C) Beach-rock unit from B; B = bryozoan, Cr = crinoid, S = stromatoporoid, C = coral, L = lithoclast. Scale bar at right = 5 cm. Size, geometry, and facies association of algal mounds and grainstones are similar to those encountered in Atokan Chapman Deep reservoirs and Morrowan Lower Marble Falls Formation (after Erlich and Coleman, 2005).