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

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ABSTRACT

Morrowan-age units in the Permian Basin appear to show a "second-order" transgression from siliciclastic fluvial-deltaic to shallow-marine and subsequently to carbonate deposition. In general, Morrowan-age siliciclastics dominate deposition in the west of the Permian Basin, while carbonate deposition dominates in the east. The predominance of carbonate facies in the east is due to a lack of siliciclastic supply to that part of the basin.

Morrowan siliciclastic deposition is interpreted to have developed in a large incised-valley-fill system. An updip-to-downdip transition from fluvial and deltaic to estuarine and open-marine facies is interpreted. Excellent reservoir potential is noted in amalgamated, stacked channel systems and bayhead deltas. Significantly, these incising valleys may have served as conduits for shelf-margin bypass during periods of lowstand. It is proposed that such bypass channels may have fed sediment into the deeper basin, developing lowstand basin-floor-fan deposits. The Morrowan of the Permian Basin needs to be reassessed in terms of such a new play type, as basin-floor fans are known for their excellent reservoir potential.

This succession is overlain by Upper Morrowan carbonates. The deposition of the Upper Morrowan carbonate unit in the Permian Basin area probably indicates a switch from local tectonic to regional eustatic control as tectonism diminished in the hinterland and sediment supply from the north/northwest shut off. Overall, it appears that carbonate deposition occurred over a much larger area in the Permian Basin (Eastern Shelf and Delaware Basin) than previously documented. The presence of algally dominated bioherms and higher energy facies (ooid grainstones), augmented by fracture porosity, indicate potentially overlooked reservoir intervals. With the current explosion of interest in the shale gas systems (primarily the Barnett

but also the Smithwick), an overlying Marble Falls–type carbonate system may also hold potential as a fractured reservoir for expulsed "Barnett" gas.

A new paleographic reconstruction for the Morrow of the Permian Basin is presented (fig. 1). In brief, from east to west, Morrowan-age carbonates are distributed over the Eastern Shelf and Llano Uplift. The depositional environment is interpreted to be a distally steepening east- and possibly southeast-facing ramp. A transition from the platform and/or ramp carbonates to more basinal carbonates and ultimately shales along the Eastern Shelf (ES), Midland Basin (MB), and Central Basin Platform (CBP) is speculated. A small number of Precambrian inliers appear to have been exposed and shed material into the basin. These and other minor topographically elevated regions are most likely rimmed by carbonates. Farther west, multiple amalgamated incised-valley systems are interpreted in the Delaware Basin, some of which may feed deeper water basin-floor fans. The Pedernal Uplift provides much of the sediment input and appears linked to the north with other channel systems feeding the Midcontinent. See the Paleogeographic Summary for a more detailed discussion of this paleogeography.

INTRODUCTION

This report discusses the styles of deposition and facies development of Morrowan-age sediments, concluding with a new paleogeography for the Morrowan Permian Basin (see Paleogeographic Summary). Morrowan deposition is discussed in two sections, one dealing with siliciclastic deposits and the other with deposits having a carbonate affinity. 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. More localized studies will be used to illustrate certain key aspects (for example, facies type, reservoir quality). However, an initial introduction to the area, placing it in a global perspective, will first be presented.

GLOBAL TECTONIC SETTING

Morrowan-age sediments in the Permian Basin are characterized as being deposited at a near-equatorial (10–15^{o} south) position during the early stages of icehouse high-amplitude, high-frequency eustatic sea-level fluctuations, in an area undergoing initial tectonic activity of both uplift and subsidence related to the Ouachita-Marathon Orogeny and the birth of the greater ancestral Rocky Mountains. Figures 2 and 3 illustrate two of many interpretations as to the position of Texas (in orange in fig. 2) relative to the major tectonic plates and the equator at the beginning of the Pennsylvanian (circa Morrowan age). The Pennsylvanian Epoch is characterized by increasing restriction caused by plate drift resulting in diminishing sea masses between Laurussia/Eurasia and Gondwana as the Pangean supercontinent was forming. This closure of a possible subequatorial seaway at the site of present-day Texas and the Permian Basin has profound implications on establishing and understanding the paleogeography and facies distribution of the region. However, currently too much controversy exists between Pennsylvanian paleogeographic plate reconstructions to be useful on the basin scale (Van der Voo and Torsvik, 2001; Saltzman, 2003; Torsvik and Cocks, 2004).

Figure 3 illustrates the potential dramatic changes in facies relationships and amount of marine influence in the area of the Permian Basin after closing of a proposed seaway by Morrowan time. Although detail is lacking from the Permian Basin area (red star in fig. 3), it is important to note that a global understanding of the region is required to make reasonable detailed geologic models of the area. However, the detailed data (core descriptions, facies interpretations, and log data) presented in this study must be incorporated into any paleogeographic and plate tectonic model for the Permian Basin and will probably result in substantial changes to current reconstructions.

REGIONAL TECTONIC SETTING AND FACIES DISTRIBUTION

Figure 4 illustrates the outline of the Permian Basin used in this study and the major geologic features commonly associated with the basin. Note, however, that not all the features developed simultaneously, and most were only incipient at Morrowan time. Figure 4 allows one to compare the Permian Basin with the regional paleogeography. Figures 5 and 6 depict previous facies distribution and uplift and subsidence patterns for Morrowan-age sediments in the Permian Basin and surrounding areas. The revised Permian Basin paleogeography presented in figure 1 is an attempt to incorporate previous interpretations where valid, in light of new and regionally synthesized data presented in this chapter.

Within the Permian Basin study area, facies appear largely restricted to depositional environments such as transitional zones (for example, lagoonal, deltaic), open-marine coastlines, clastic shelves, and minor carbonate platform to shelfal areas. An area denoted as a starved basin is also prominent and is centered on the New Mexico–Texas border in Lea and Winkler Counties, respectively (fig. 5). However, seismic, well, and cross-sectional information indicates “thick” intervals of Morrowan-age sediments across the entire Delaware and Midland Basins (for example, Yang and Dorobek, 1995), although many authors would consider the basin centers to be largely starved of sediment. The most notable feature of the map by Ye and others (1996) is the lack of Morrowan-age sediments in most of the Permian Basin. In general, the Morrowan paleogeography is indicative of siliciclastic deposition in the northwest and north and carbonate deposition in the southeast.

The regional tectonic framework of Kluth (1986) for Mississippian to Morrowan time is generalized but indicates uplift (≤50 m/Ma) near or on the Central Basin Platform and the margins of the larger Permian Basin. Most data indicate no Morrowan-age units on the Central Basin Platform (fig. 6). The absence of sediments is commonly interpreted as a product of deep weathering over uplifted blocks; however, the data do not preclude the possibility of nondeposition in those regions.

It is quite obvious that the uplift and subsidence areas in figure 6 do not match the facies distribution outlined in figure 5 in the greater Permian Basin area. In many instances areas of net subsidence in figure 6 appear to correlate with areas of nondeposition (white) in figure 5. Correcting inconsistencies in the regional paleogeography of the Permian Basin and outlining more detailed depositional patterns were among the major goals of this chapter. The updated Permian Basin paleography previously presented is discussed within the Paleographic summary.

AGE RELATIONSHIPS

Correlation problems exist with establishing the true depositional nature of Morrowan-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 formations are actually Morrowan in age (fig. 7). In this study the upper Barnett Formation is considered laterally equivalent to lower Morrow sediments (fig. 7). This interpretation is based on paleontological data, regional correlations, and the transgressive nature of the Barnett Formation. Figure 7 illustrates the two contrasting interpretations of where the Mississippian/Pennsylvanian boundary can be placed noted by the large and small arrows. The interpretation in this study (large arrow) contrasts with many interpretations placing the base Morrowan-age units on top of the Barnett Formation in an angularly unconformable relationship (figs. 8 and 9). Many authors contend that all Pennsylvanian sediments are in an unconformable relationship with Mississippian and/or older units (for example, Mazzullo, 1999; Roberts and Kohl, 1999), but conformable relationships have also been described (Harrell and Anonymous, 2003; Harrell and others, 2004).

SILICICLASTIC MORROWAN DEPOSITION

- **Broad Approach:** Observations from more regional studies are used as a reference framework for interpreting and integrating studies in the Permian Basin. Permian Basin data are presented and integrated into this overall depositional model.
- **General Depositional Setting:** Incised fluvial valley-fill system, grading from an updip fluvial system to downdip deltaic and estuarine conditions. The drainage system is largely sourced from the northwest. The adoption of a fluvial to estuarine facies distribution model over a standard open-marine layer-cake model will allow much more accurate prediction of compartmentalized reservoirs.
- **Reservoir Potential:** Updip fluvial amalgamated, stacked channels provide the best reservoir potential. In the transitional facies toward the downdip estuarine section, the fluvial channels are separated by lower quality reservoir estuarine sands, and reservoir quality, noticeably permeability, is decreased in these thinner, more marine facies. In the downdip facies tract (estuarine), reservoir facies are sparsely developed; the fluvial channels are narrow, disconnected, and thin, and they are separated by thick estuarine basin shales. However, bayfill deltas provide excellent local potential.
- **Diagenesis:** Dissolution of detrital grains and authigenic clays generating secondary porosity and permeability is very important to development of good reservoir quality, especially in the more estuarine to marine sands. The Middle Morrow sandstones are more compositionally variable and appear to have the best production.
- **Climate:** The Morrowan was a time of expansive ice-sheet development, and such times are typified by highly fluctuating sea level, which plays a role in controlling cyclicity and facies stacking patterns. Such highly fluctuating sea levels generally result in thinner, higher frequency cycles.

Before a discussion of the sediments and facies can be undertaken, the organization used for dividing the Morrowan-age siliciclastic units must be discussed. The convention within the petroleum industry is to deem Morrowan-age units as Morrow Formation siliciclastics with subsidiary carbonates. Within the Permian Basin (Delaware Basin, in particular) the Morrow Formation is generally separated into three units (figs. 8, 9). These units are termed the Lower, Middle, and Upper. Only the Lower and Middle Morrow "unit" facies are siliciclastic. Note that on the stratigraphic column in figures 8 and 9 the authors consider the Mississippian and Pennsylvanian contact as unconformable. The unconformable nature of the contact is not tenable throughout the entire Permian Basin and is largely a localized occurrence. The tripartite division of the Morrow in figure 8 is not universally accepted, and genetic divisions based on sequence stratigraphy have recently been proposed. The nomenclature used for dividing the Morrowan-age sediments and the Morrow Formation in the Delaware Basin and Northwest Shelf was proposed in isolation from other parts of the Permian Basin and the region.

Broadly, the Morrowan-age units in the Delaware Basin and Northwest Shelf of the Permian Basin appear to show a "second-order" transgression from siliciclastic fluvial-deltaic to shallow-marine and subsequently to carbonate deposition. Higher order cyclicity is evident, but regional correlation is not possible on the basis of the present dataset. The following section summarizes the depositional model for the Morrowan-age section in the Permian Basin area.

Regional Studies—Depositional Model

The proposed depositional model for the Morrowan-age section of the western Permian Basin is largely based on two regional studies outside the Permian Basin. In summary, siliciclastic deposition of the Morrowan-age units (Lower and Middle Morrow, figs. 8, 9) occurred in a large incised valley-fill system under icehouse conditions. Fluvial, deltaic, estuarine, and open-marine facies compose the valley-fill and intervalley sediments in updip, transitional, and downdip facies tracts.

Published literature on recent regional- and local-scale analysis of the depositional environments in a sequence-stratigraphic context for Morrowan-age sediments (generally Morrow Formation siliciclastics) has largely been restricted to occurrences outside of Texas. Bowen and Weimer (2003, 2004) established the regional sequence-stratigraphic framework and reservoir geology in western Kansas and eastern Colorado. As with studies in the Permian Basin, the Morrow Formation is considered Early Pennsylvanian in age with an angular unconformity, the result of a Late Mississippian tectonic event, separating it from the underlying Mississippian carbonate strata. In contrast to New Mexico and Texas, the Morrowan strata in eastern Colorado and western Kansas are informally divided into a lower Morrow limestone interval and an upper Morrow siliciclastic-dominated interval (fig. 10).

The Morrow Formation in western Kansas and eastern Colorado is bounded at its base by a second-order sequence boundary (Sloss, 1963; Ross and Ross, 1988) and at its top by a third-order sequence boundary that separates Morrow siliciclastic strata from Atokan carbonate strata. The upper Morrow siliciclastic interval comprises at least five fourth-order depositional sequences. The thickness of the lower Morrow carbonate interval of Bowen and Weimer (2003, 2004) is decidedly thinner than the lower Morrow siliciclastic section in New Mexico (for example, 50 ft versus 200+ ft) (fig. 10).

In general, the upper Morrow interval is dominated by shallow-marine shales that were deposited on a low-gradient shelf northwest of the Anadarko Basin during relative highstands in sea level (Bowen and Weimer, 2003). Enclosed in the shale are valley-fill strata consisting of interbedded sandstones, siltstones, and shale. These valley fills (updip widths of 0.5–2.0 mi [0.8–3.2 km] and downdip of 1.0–4.0 mi [1.6–6.4 km]) developed when extensive river systems incised the subaerially exposed marine shelf during periods of relative lowstand. The simple and compound valleys incised to depths of as much as 100 ft (30.5m). The size of incisement is similar to that seen in the Buffalo Valley field in New Mexico within the Permian Basin.

Overall depositional environments *within* the valley fill vary from fluvial (braided to low-sinuosity to high-sinuosity river systems), estuarine, to marine. The medium- to coarse-grained fluvial sandstone valley-fill facies are the best reservoirs, with porosity values ranging from 18 to 28 percent and permeability ranging from 0.5 to 2.0 md. The overlying estuarine reservoirs commonly have lower porosity (8–18 percent) and lower permeability (10.0–500 md) than the fluvial reservoirs. A major flooding surface marks the top of the valley fill. Of key importance is that Bowen and Weimer (2003) note that within their study area individual valley-fill systems can be correlated, mapped, and put in a sequence-stratigraphic context over a large area (for example, single channel system mapped for 283 km). The other key observation in Bowen and Weimer (2003) is the overall extent of facies tract dislocation (~281 km/175 mi) between lowstand and highstand shoreline deposits. This extensive tract dislocation results in large regions where identification of the overlying systems (for example, highstand) tract may not be possible and results in stacked lowstand or transgressive tracts within a valley-fill succession. The facies tract dislocation also requires a much greater areal distribution to be considered when exploring for new targets because the lowstand alluvial and fluvial sands of a sequence could be as much as 175 mi more basinward in relation to its underlying highstand shoreline deposits.

Observations from more regional studies provide a reference framework for interpreting and integrating studies in the Permian Basin. Figure 11 illustrates the key core descriptions and wireline log signatures for updip, transitional, and downdip facies tracts of valley-fill systems. These core and wireline signatures are similar to those from the Permian Basin, although historically interpreted differently. Figure 12 illustrates the overall upward change of succession from the lowstand systems tract incised valley upward into the overlying transgressive systems tract within a single well (Bowen and Weimer, 2003). The single-well succession illustrates a level of facies discrimination that is only possible using core data, as the wireline log signature for the lowstand and transgressive systems tract will be similar. The juxtaposition of the transgressive systems tract (shales at the base of the Bayhead Delta) on top of the lowstand coarse sands will result in localized and possibly regional compartmentalization of reservoir units when they are stacked in this manner. The well illustrated in figure 12 typifies the downdip facies tract of Bowen and Weimer (2003).

Bowen and Weimer (2003) illustrated the cross-sectional architecture of their informal facies tracts within a sequence-stratigraphic and reservoir-quality framework (figs. 13, 14). From an exploration and development perspective, recognizing which facies tract you are in is very important because the size, connectivity, and quality of the potential reservoirs all diminish downdip (fig. 13). In the updip position a well would penetrate amalgamated fluvial channels and have excellent reservoir potential through the entire interval, whereas in the transitional facies tract the fluvial channels are separated by lower quality reservoir estuarine sands (fig. 11B). In the downdip facies tract, a well may be likely to intersect no reservoir facies, as the fluvial channels are narrow, disconnected, thin, and separated by thick estuarine basin shales (fig. 13). From figure 14 and table 1 one can see that the updip amalgamated fluvial facies have the best reservoir quality.

Table 1. Morrowan and Atokan stratigraphic correlation chart (modified from Kier, 1980). The Morrow Formation is highlighted in blue, and the Atokan-age units are encompassed by the green highlighted area above the Morrowan to Atokan sequence boundary. Formations and members listed are of both carbonate and siliciclastic character.

<table>
<tr><th colspan="3">Series</th><th colspan="4">Group</th><th colspan="7">Formation</th><th colspan="3">Member</th></tr>
<tr><td rowspan="2">Lampasas</td><td rowspan="2">Bend</td><td rowspan="2">Bend (Atokan Series)</td><td></td><td>Smithwick</td><td rowspan="3">Bend</td><td rowspan="2">Bend outcrop</td><td>Smithwick</td><td>Parks
Caddo Pool
Eastland Lake</td><td colspan="4">Smithwick</td><td rowspan="3">Bend Subsurface</td><td>Smithwick</td><td>Siltstone facies
Shale facies</td><td>Lower Caddo Ls.
Lake Sandstone</td></tr>
<tr><td rowspan="2">Marble Falls</td><td>Big Saline</td><td>Upper Marble Falls</td><td>Sipe Springs
De Leon</td><td>Big Saline</td><td>Big Saline Upper Marble Falls</td><td>Big Saline</td><td rowspan="2">Marble Falls</td><td>Lemons Bluff
Big Saline</td><td>Brister Bluff/Soldiers Hole
Lemons Bluff
Aylor bluff/Brook
Gibbons Cong.</td><td>Brister
Lemons Bluff
Gibbons Cong.</td></tr>
<tr><td colspan="2">Morrow</td><td>(Upper Morrow)</td><td>Marble Falls</td><td></td><td>Lower Marble Falls</td><td>Comyn</td><td>Sloan</td><td>Comyn (subsurf.) Lower Marble Falls</td><td>Sloan</td><td>Sloan Gibbons Cong.</td><td>Undivided</td><td>Aylor
Sloan</td></tr>
</table>

The transitional or downdip facies tracts, although poorer in overall reservoir quality than the updip facies tract, have intervals of excellent reservoir quality where reservoirs can be productive if they are understood. Bowen and Weimer (2004) expanded their discussion of the downdip “valley fill” to encompass estuarine systems in the upper Morrow Formation. Figure 15 is a comparison of the “updip incised valley system” (actually the transitional facies tract of Bowen and Weimer, 2003, fig. 13) with the downdip valley system. The change in scale of the environments is quite apparent with the distal estuarine system being much broader and having multiple input points. Multiple inputs into the less confined estuary allow for differentiation of the sediments into proximal and distal packages and are the key to having reservoir intervals.

After deposition of the minor fluvial fill, transgression flooded the area, and subsequently the estuary was partly filled by prograding bayfill deltas. In terms of reservoir quality in these distal, less confined estuaries, coarse-grained fluvial fill is still locally present at the base of the facies tract but is relegated to the minor role of linkage control in reservoir development and production. Distal areas of the deltas are nonreservoir owing to intense bioturbation resulting in mixing of the more abundant clays into the sands. However, the proximal areas of the deltas have excellent porosity and permeability resulting in good production. Overall, these bayfill deltas result in isolated reservoir compartments, unless linked at the base by fluvial “channel-fill” sands. Figures 16 and 17 illustrate some of the typical features found in core from these environments, as well as the overall well log correlation illustrating facies variability. The surfaces and features noted in figure 16 are put in their vertical, lateral, and sedimentological context on the core logs in figure 17. Note the estuary central basin shale facies directly overlies the marine shale facies. Without detailed core data the ability to define these two facies and their associated boundaries would be nearly impossible using solely wireline logs (figs. 16, 17, J and L). The encasement of reservoir sands within estuary shale facies is potentially one of several analogs for the Permian Basin succession.

Climatic Conditions

A generalized conceptual sequence-stratigraphic model was put forward by Bowen and Weimer (2003) exhibiting decided differences in facies architecture between the idealized greenhouse model for incised-valley-fill systems (per Zaitlin and others, 1994) and their model in icehouse conditions of rapid and large sea-level fluctuation across a very wide low-angle muddy shelf (fig. 18). The applicability of the Bowen and Weimer (2003) model to the Permian Basin should be noted because most sequence-stratigraphic models are developed from units deposited under greenhouse conditions, whereas the Morrowan was a time of expansive ice-sheet development (see fig. 3), and such times are typified by highly fluctuating sea level. The sea-floor gradient in the Permian Basin (especially the Delaware Basin) is not well constrained and may be steeper than that used by Bowen and Weimer (2003). However, an icehouse sequence-stratigraphic model that reflects the thinner higher frequency cycles and greater dip length of facies groups must still be applied to the Permian Basin.

Ichnofacies

Another study performed outside the Permian Basin on the Morrow Formation provides insight into the significance of using ichnofacies to aid in correlating units and generating depositional models. In southwest Kansas, Buatois and others (2002) studied the lower Morrow sandstone. In contrast, Bowen and Weimer (2003, 2004) concentrated on the “upper” Morrow because the “lower” Morrow in their area was limestone. Before Buatois and others (2002) completed their study, the lower Morrow in Kansas was interpreted as regionally extensive offshore shales, and shoreface and offshore-bar sandstones. Buatois and others (2002) recognized and detailed extensive estuarine systems similar to those of Bowen and Weimer

(2004). The depositional models drew heavily on the use of ichnofacies as indicators of environment, as well as establishing facies architecture in a sequence-stratigraphic framework (for example, identification of a tidal-ravinement surface). Overall the Buatois and others (2002) model differs from that of Bowen and Weimer (2004) by having the discharge empty into an unconfined sea (fig. 19). A similar conceptual model was proposed by James (1984) for the Delaware Basin. The adoption of a fluvial to estuarine facies distribution model over a standard open-marine layer-cake model results in a much more accurate prediction of the compartmentalized reservoirs. Reservoir quality within the Buatois and others (2002) model is best within facies A, C, and I (up to 20 percent porosity), marginal in facies H, E, and J, and poor to nonexistent in facies B, D, F, G, K, L, M, N, and O (fig. 19). Figures 21 and 22 illustrate a lower Morrow correlation and core description showing indicator facies for the estuarine and shoreface environments. Figure 20 further illustrates the vertical stacking patterns of the facies highlighted in figure 19. As with the Bowen and Weimer (2004) study, the model by Buatois and others (2002) highlights the importance and difficulty of separating and defining the estuarine shale from those of more open marine affinity. This observation may not appear crucial to many because neither facies has any reservoir quality, but miscorrelation and identification of these units, in a sequence-stratigraphic context, will result in decreased exploration potential and misunderstandings in terms of reservoir lateral connectivity (fig. 20). Figure 20 also illustrates the composite nature of many of the sequence-stratigraphic boundaries (for example flooding surface [FS] and basal sequence boundary [SB] are picked at the same spot on well Fretz 16-1). Figure 23 illustrates the sequence-stratigraphic significance of the ichnofacies and guilds proposed by Buatois and others (2002). This type of data and classification system is very applicable to the Morrowan-age units in the Permian Basin and may aid in the identification of depositional environments and correlation. The depositional model for the lower Morrow by Buatois and others (2002) is subtly different from that proposed by Bowen and Weimer (2003, 2004), but all the models have similarities to facies patterns recognized in the Morrowan siliciclastic in the Permian Basin (for example, Rutan and others, 2002).

Permian Basin Data

The following section details a number of studies of the Morrowan-age section in the Permian Basin area. Most of these studies are at the field scale only and therefore reflect different interpretations of the depositional environment. Broadly, the Morrowan-age units in the Permian Basin appear to show a second-order transgression from fluvial-deltaic to shallow-marine and subsequently to carbonate deposition. Higher order cyclicity is evident and is a key to understanding facies relationships; regional correlation, however, is difficult. The fields discussed below are illustrated in figure 24 and are centered on Eddy County, New Mexico, relative to the Permian Basin in figure 4. Regional thickness estimates for the Morrow Formation (including carbonates) range from essentially zero in the north and northwest parts of the Northwestern Shelf and Tatum Basin to 518 m in the southeast (northeast corner of the Delaware Basin) (fig. 4).

In the northern Delaware Basin (Logan Draw–Crow Flats field area), the historic Lower and Middle Morrowan interpretation for the area was deposition in low-accommodation fluvial, deltaic, and nearshore environments (fig. 24). Contrary to historical interpretations, Rutan and others (2002) suggested widespread transgressive valley-fill deposition after extensive incision into the underlying units, similar to the interpretation of Bowen and Weimer (2003). They further divided the lower part of the Morrow Formation into three genetic packages, the two lowermost packages representing valley fill and the uppermost youngest package representing transgressive deposition of thin marine shore-parallel sands. Retrogradational to progradational estuary fill overlain by marine shales represents the lowermost package, wherein estuary-mouth sands have the best reservoir quality, similar to the Bowen and Weimer (2004) and Buatois and others (2002) models. This package is overlain by marine sands and shales, which are in turn overlain by stacked sands thought to be of point-bar affinity (for example, Buatois and others, 2002). The stacked sands are excellent reservoirs in a multiply scoured succession of angular to coarse-grained upward-fining units. Downdip to the south of Logan Draw and Crow Flats, the stacked sands coalesce into a strike-oriented sand body about 75 m thick in a wave-dominated delta (for example, figs. 17, 18, Facies J). Overall, the thin strike-parallel marine sands of the uppermost unit are poor reservoirs unless transected by dip-oriented tidal channels (Rutan and others, 2002).

From the Cedar Lake area of the Delaware Basin, Carlile and Anonymous (1997) painted a slightly different picture for Morrow Formation deposition (fig. 24). He divided the Morrow sandstones into two facies tracts (the Lower and Middle Morrow), which are separated by marine Middle Morrow Shale. The Lower Morrow (sensu Carlile and Anonymous, 1997) is interpreted as a coarse-grained fluvial system. The paralic section of the Lower Morrow (sensu Carlile and

Anonymous, 1997) is characterized by backstepping, retrogradational parasequences bound by transgressive lags. This interval may be equivalent to the uppermost lower Morrow of Rutan and others (2002). Overlying these two facies tracts is the Middle Morrow, which is defined as a progradational (typical fine-grained sandstones in upward-coarsening cycles) delta system building toward the basin.

Differences between the Rutan and others (2002) and Carlile and Anonymous (1997) studies are related to different order cycle comparison (for example, fourth and fifth versus third and fourth order) and geography, both in potential source areas and in proximal and distal relationships to each other.

Farther to the southwest from the two previous studies Malon and others (2000) interpreted the Morrow in the White City field as possessing a lower half that consists of two southeast progradational fluvial-deltaic systems (fig. 24). This interpretation contrasts with previous findings of studies where a transgressive event is followed by a regressive event. In closer detail the packages are interleaved with short-duration higher order aggradational and retrogradational cycles. The overall progradational signal noted by Malon and others (2000) could be due to increased sediment load in their area. It was proposed that delta-lobe abandonment, possibly coupled with compaction or syndepositional faulting, or both, lead to marine incursion with abundant shale deposition (Malon and others, 2000). At the parasequence scale the upper portions of many of the sandstone packages contain thin reworked channel-mouth bars and beach barrier bar deposits. These "lowstand?" facies are commonly capped by transgressive marine shales and thin oolitic carbonates. Overall their interpretation could be put into the framework of the downdip facies tract of the estuarine model proposed by Bowen and Weimer (2004).

In the Osudo field area, the primary sediment source is the Pedernal Uplift, and a secondary source is a portion of the uplifting Central Basin Platform (James, 1984; Roberts and Kohles, 1999) (fig. 24). The Coker (2003) study of Osudo followed the tripartite division of the Morrow Formation from Mazzullo (1983) and Speer (1993) (figs. 8 and 9). Overall the lower Morrow Formation (sensu Coker, 2003) contains sediments reflecting four depositional environments ranging from (1) alluvial plain facies, (2) transitional marine, (3) shoreline to inner shelf, and (4) midshelf to basinal. The middle Morrow is separated from the lower Morrow by a transgressive radioactive marine shale, as noted by Malon and others (2000) and Carlile and

Anonymous (1997). The middle Morrow is part of a delta-front package and presents the same depositional environments as the lower Morrow with the addition of a proximal fluvial facies. Facies maps from Coker (2003) indicate a slight progradation (overall regression) of the middle Morrow environments relative to the lower Morrow, similar to that of James (1984) and Mallon and others (2000) (fig. 25). However, the regional layer-cake-style parallel facies bands illustrated by Coker (2003) do not appear realistic, given the scale, and don't reflect the perceived complicated juxtaposition of facies (for example, valley-fill channels vs. deltaic muds) that are present (fig. 25). Changes in the sediment-load conditions from the Lower to Middle Morrow were potentially influenced by Central Basin Platform uplift or quiescence. The Lower and Middle Morrowan facies patterns in eastern Lea County and western Winkler County may be quite different from those farther west and southwest, where other sediment sources or eustatic conditions dominated.

Within the lower and middle Morrow divisions multiple transgressive and regressive events can be documented, thereby making correlation of these cycles quite difficult (Coker, 2003). A shale is defined as the upper boundary of the Middle Morrow with carbonate deposition (Upper Morrow) above. This limestone is poorly defined and is discussed in the carbonate section of this chapter.

In terms of reservoir quality, the middle Morrow has the best production, yielding a cumulative production of 208 Bcf, largely from coarse-grained distributary channel sandstones. Coker (2003) suggested the possibility of syndepositional faulting controlling sedimentation patterns and resultant reservoir quality.

Mazzullo (1999) and Roberts and Kohles (1999) discussed the Morrow in a regional sense without major emphasis on field-scale heterogeneity. A subregional paleogeographic reconstruction for the entire Morrow Formation for southeastern New Mexico illustrates the complex facies interrelations possibly present over field-scale areas (fig. 24). On the basin-wide scale, Roberts and Kohles (1999) noted that the overall transgression in the Morrow is apparent; with the lower Morrow (A zone) being delta plain, the overlying younger middle Morrow (B zone) representing delta front, and the youngest upper Morrow (C zone) being carbonate shelf (fig. 9). Note, however, that in figure 24 the more basinal and marine sediments of the lower Morrow (A zone) are not illustrated and those displayed are actually younger zone B and zone C sediments. The correlation of Morrowan-age units in southeast New Mexico was expanded and completed by Geological Data Services (GDS) (Roberts, personal communication, 2005) and further illustrates the difficulty and complexity of correlation within the aforementioned environments. Issues exist with picking the top of the Morrow (Upper Morrow Zone C) from the overlying Atoka “shaly” carbonates. The basal lower Morrow transgressive shale appears to be the most readily correlative over large areas, whereas the shale at the top of the middle Morrow is not as thick, distinct, or widespread and is more difficult to correlate, contrary to several other interpretations (fig. 26). Accurate identification of the base of the Morrow Formation relies heavily on the identification of Mississippian-age sandstones (informally Carlsbad Sand) within and equivalent to the Barnett Shale (fig. 26). The wireline log signature of the GDS type well is similar to the type log used by Bowen and Weimer (2003) (figs. 10 and 26).

Figure 27 illustrates a schematic regional cross section across Eddy County, New Mexico, employing about 1,000 wells. The model interpreted by Roberts and Kohles (1999) and Roberts (personal communication) relied heavily on the paleogeographic reconstruction put forth by James (1984) with prograding fluvial-deltaic channels and point bars sourced dominantly from the northwest during lower Morrow deposition. The Roberts and Kohles (1999) correlation in figure 27 appears the most realistic for publicly available Morrow Formation interpretations in New Mexico. However, an addition of deeply incised valleys is certainly required for the Lower Morrow section. Evidence of this incision is provided by the seismic data in the Van Dock and Gaiser (2001) study and the well log correlations by Lambert (1989).

James (1984) interpreted the shale (MMSH) dividing the lower Morrow from the middle as lagoonal in origin and not a transgressive open-marine shale (fig. 28). That interpretation may be supported by the inability of Roberts and Kohles (1999) to regionally correlate it. The middle Morrow succession in the Parkway area, is proposed to be transgressive beach and submarine bars that trend parallel to depositional strike, an interpretation supported by Lambert (1989) in the Empire field and Rutan and others (2002) in the Crow Flats field. Figures 28 and 29 illustrate the type log and characteristic facies relationships to petrophysical character used by James (1984). Note that in figure 28 there is no identification of a Mississippian sand by James (1984). However, a comparison of the log signatures from the two studies indicates a possible equivalent pick in the Parkway well to that in the Big Eddy well (figs. 26, 28). If either pick is correct, it changes the potential top Mississippian pick by more than 100 ft. The well log character in figure 29 is very similar to those illustrated by Bowen and Weimer (2003) and Buatois and others

(2002) and could reflect an incised valley fill overlain by an estuarine sequence, as opposed to the mouth-bar system proposed by James (1984). Only detailed core data could resolve this discrepancy.

Mazzullo (1999) illustrated the potential problems of regional wireline log correlation in these environments and proposed that tectonic effects may also control deposition of the units. Mazzullo (1999) noted that following a Late Mississippian tectonic event, the Central Basin Platform area probably had low relief and that regional large-scale tilting and erosion occurred after this event, thereby resulting in an irregular topography on which the Morrowan-age sediments were deposited. Uplifts during Morrowan-age sedimentation also resulted in possible areas of nondeposition and erosion (fig. 30). Further tectonic episodes with uplift and erosion during the Atokan through Wolfcampian stages further modified the continuity of Morrowan sediment patterns, resulting in the present-day mapped distribution.

From work on Empire field, Lambert (1989) suggested that the lower Morrow interval sandstones were deposited in a broad coastal plain environment dissected by channels (fig. 24). The upper delta-plain environment with its thick stacked sand bodies was gradually replaced by thinner sandstones and siltstones of the lower delta plain, eventually culminating in the probable maximum flooding surface noted as the highly radioactive Morrow shale. After a minor regressive event in the lower middle Morrow, a continued transgression influenced deposition of lower delta plain through to open-shelf marine sands in the middle Morrow. Lambert (1989) cited the presence of glauconite pellets as further evidence of the more open marine nature of the middle Morrow siliciclastics. Figure 31 is a strike-oriented well log cross section through the lower and middle Morrow Formation intervals in Empire field. The geometry of the facies illustrated in figure 31 is also consistent with a large-scale incised-valley system composed of both simple and compound valleys. Incision appears to go into the underlying Chester Formation, and channel thicknesses are on the order of 100 ft. In Empire field, the lower Morrow Formation sandstones display reservoir-quality linkage to depositional environment (multiple stacked fluvial channels). Middle Morrow sandstones, which appear more compositionally variable, possess the best reservoir quality after development of secondary porosity via dissolution of detrital grains and clays (Mazzullo and Mazzullo, 1984; Lambert, 1989). As in several other studies of the lower Morrow Formation, the best reservoir quality is present in multiple stacked fluvial channels (porosity of as much as 8 to 17 percent and permeabilities of as much as 250 md). Reservoir quality, noticeably permeability, is decreased in the thinner, more marine facies. Dissolution of detrital grains and authigenic clays generating secondary porosity and permeability is very important to reservoir quality development, especially in the more estuarine to marine sands.

Seismic Data

Most of the publicly available data and interpretations on Morrowan-age sediments do not present or highlight the use of geophysical data. However, Van Dok and Gaiser (2001) noted that historically the Morrow Formation is an extremely difficult formation to resolve accurately using conventional compressional wave seismic data. In their study of Buffalo Valley, New Mexico, converted shear wave data was used for interpretation of the Morrow Formation (fig. 24). Improved shallow resolution appears to be provided by the shear wave data. Figure 32 illustrates a vertical shear wave data traverse through the field, highlighting the base of the incised valley in yellow overlain by lower and upper Morrow (green horizon) sediment. Interpretation of the image would indicate incision of the upper Morrow into the lower Morrow, as well as possible lower Morrow incision into the Barnett/Chester. The upper Morrow sand top pick in green would therefore be a composite sequence boundary for the Chester/Barnett to lower and upper Morrow, as well as the Atoka. The incisive nature of the facies and possible composite boundaries highlights the inadequacies of correlation in the Morrowan-age siliciclastics using only standard wireline logs. An isochron map compiled between the Atoka and Chester picks clearly outlines a large incised valley (fig. 33). The scale of the incised valley illustrated in figure 32 is similar to those illustrated by Bowen and Weimer (2003).

Good-quality seismic data and interpretations, coupled with extensive core logging and regional sequence-stratigraphic correlations, appear to be the only way to decipher the complexities of the Morrowan-age siliciclastics in the Permian Basin.

Equivocal Morrowan-Age Sediments

To add further to the complexities of the Morrowan-age siliciclastics in the Permian Basin, within Sutton and Schleicher Counties (technically Eastern Shelf) sediments of possible Morrowan age are informally termed the Penn “Detrital Zone.” These sediments have a variable lithologic character but appear dominated by red, green, or dark-gray shales having abundant poorly sorted, poorly rounded chert pebbles and quartz grains. Thin sandstones and limestones are also present. The entire unit may rarely be composed entirely of chert pebbles. Overall, the unit averages 15 ft in thickness but can increase to a maximum of 150 ft (Rall and Rall, 1958). Recent interpretations of the "Penn Detrital" unit tend more toward an Atokan to Desmoinesian age (for example, Arenoso field, Winker County, and Rojo Caballos, South, Pecos County) rather than Morrowan age; however, without excellent biostratigraphic and seismic control, the age of some of these units remains ambiguous (Van Der Loop, 1991; Hanson and Guinan, 1992). Other channel-fill sandstones of possible Morrowan-Atokan age have been documented in Baylor County on the "Texas Craton" south of the Palo Duro Basin (Staples, 1986). These siliciclastic sediments are included in the "Bend Group, Bend Clastic," which is also present in the Palo Duro Basin (Dutton, 1980; Dutton and others, 1982). Bend clastics are also a substantial natural gas reservoir in Cottle and King Counties along the Matador Arch (Brister and others, 2002). In the Broken Bone graben the Bend Group (informally "Bend Conglomerate") is considered to be of Atokan age, as it overlies a limestone thought to be of Morrowan age.

Summary of Morrowan Siliciclastic Deposition

Overall the Morrowan-age siliciclastics are best described as being deposited in a large-scale incised valley system. These valleys were back-filled by several different facies during transgression. Progradational and retrogradational geometries are linked to uplift and sediment input rates, as well as eustatic sea-level fluctuation. There are several key issues that can help to better understand the depositional geometries of the Morrowan-age siliciclastics. Many of these issues have a direct bearing on exploitation of, and exploration for, new reservoirs in the Permian Basin.

1. Scale and Stacking Patterns: Understanding and identifying higher order cyclicity in sediment packages is extremely important for establishing reservoir continuity for production and exploration. In icehouse time spans such as the Pennsylvanian, the higher order eustatic fluctuations can dominate over the lower order oscillations (for example, extensive progradation during transgression). Stacking patterns and facies tracts in icehouse systems may have substantially different geometries from those conventionally proposed for greenhouse situations. An example would be that the dip length of a fourth-

order fluvial system deposited during icehouse conditions is about three times longer than the equivalent third-order cycle in a greenhouse setting (per Bowen and Weimer, 2003).

2. Unconformities: Many of the stratigraphic relationships proposed for the Pennsylvanian rely heavily on the interpretation and identification of unconformities. Of particular importance is to understand the proposed end Mississippian unconformity and confirming whether it is truly a global event (type 1? sequence boundary) or is a type 2 sequence boundary. Understanding the nature, extensiveness, and duration of the unconformities and their correlative conformities in the Pennsylvanian section will have profound effects on how sequence-stratigraphic architectural models are applied. An example would be to conclude that the Barnett Formation is a transgressive systems tract and the overlying lower Morrow is part of the highstand systems tract. Alternatively, as illustrated in figure 27, the Barnett Formation could represent a lowstand prograding wedge with the Mississippian/Pennsylvanian boundary only equating to a transgressive surface and the overlying lower Morrow being the transgressive systems tract. These types of issues cannot be resolved in a review such as this; however, they are key to proper prediction of facies geometries and associations.
3. Sediment Supply: Sediment supply may be the largest controlling factor in Morrow siliciclastic sedimentation patterns. Extremely high or low sedimentation rates can produce sequence and facies stacking patterns that contradict those modeled for constant rates of sedimentation.

CARBONATE MORROWAN DEPOSITION

- **Broad Approach:** Carbonate rocks of Morrowan age in the Permian Basin have had little study historically. In this study it is thought that Morrowan-age carbonates present in the Permian Basin are laterally equivalent to extensive carbonates developed in adjacent areas such as the 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 that will be taken in this chapter is to discuss development of the Marble Falls Group, even though it is not geographically part of the study area, so as to provide an analog to what is thought to be present in the Permian Basin.

- **General Depositional Setting:** Morrowan-age carbonates were deposited quite widely across the Permian Basin on a low-angle distally steepening east- and west-facing ramp. Isolated platforms or buildups are interpreted on or near the area of the Central Basin Platform.
- **Reservoir Potential:** Algal bioherms appear to be the most favorable reservoir facies. They may preserve excellent shelter porosity, and intergranular and vuggy porosity have also been locally retained in algal bioherms. Siliciclastic channels crosscutting these bioherms also provide excellent reservoir potential.
- **Diagenesis:** From analog study of the Marble Falls Formation very little primary porosity is retained in Morrowan carbonates. Fracture porosity appears critically important for production from Morrowan carbonate intervals. In units that possessed primary porosity, extensive calcite cementation and silicification have occurred, occluding the pore space. Although algal bioherms appear to provide the best primary (unfractured) reservoir potential, blocky calcite spar may occlude the pore space, resulting in a tight unit.

The only Morrowan carbonate unit near the Permian Basin is the Marble Falls Formation. The lower Marble Falls Morrowan carbonate unit has not been mapped in the Permian Basin but is located in the Llano Uplift area to the east (fig. 34). Although the Marble Falls limestone has been studied using outcrop and borehole data from areas outside the Permian Basin, little hard data are available for this section of Morrowan strata in the Permian Basin. In this study, it is thought that Morrowan-age carbonates are indeed present in the Permian Basin but have simply not been referred to as the Lower Marble Falls Formation, even though they are the most likely lateral equivalents. The extent of the Marble Falls is probably much greater than previously proposed, and the formation may extend into Runnels, Nolan, Coke, and Tom Green Counties within the Permian Basin. Kier (1980) further noted that the distribution of the Marble Falls included areas of the Concho Platform/Eastern Shelf, as well as near the Matador Arch, on the Northern Shelf of the Permian Basin. Figure 1 illustrates the proposed extent of the Lower Marble Falls limestone and its equivalents.

Marble Falls Group—Analog to Underexplored Permian Basin Equivalent Section

The focus of this section will be the Lower Marble Falls Formation of the Marble Falls Group as defined by Manger and Sutherland (1984), Groves (1991), and Erlich and Coleman (2005), which is wholly Morrowan in age. Figure 35 illustrates the lithostratigraphic relationships of the Morrowan-age units discussed in the Erlich and Coleman (2005) study. Some further detail regarding the age and stratigraphic relationship of the Marble Falls Formation can be found in the appendix.

Facies Associations and Depositional Environment

Overall the Morrowan-age carbonates were deposited quite widely across the Permian Basin on a low-angle distally steepening east- and west-facing ramp. Carbonates deposited on or near the area of the Central Basin Platform were isolated platforms or buildups. A wide variety of facies are present, with a shallow-water facies transition to deeper water carbonates and eventually shales that are Barnett Formation equivalents in the south part of the Permian Basin and the Fort Worth Basin.

The lower Marble Falls carbonate unit is characterized by several different facies types and associated depositional environments. In general, the formation comprises light to dark cherty limestones and thin shale beds (Kier, 1980). Algal biomicrites, biosparites, oosparite, spiculitic biomicrite, pelmicrite, micrite, mixed skeletal biosparite and micrite, coral and algal biolithite compose the limestone facies. The spiculitic biomicrite, micrite, and shale are considered off-platform, whereas the other facies are considered platform (fig. 36). Two depositional models have been proposed, first by Kier (1980) and secondly by Namy (1980) and Erlich and Coleman (2005), and will be discussed in that order.

As illustrated by fig. 36, Kier (1980) proposed that the platform margin was defined by an oolitic sand belt (oosparite facies) having minor seaward and landward spillover lobes. The platform interior comprises pelletal sand (peletal biomicrite and biosparite), tubular, coralline and phylloid algae (for example, coral/algal biolithites) bands. Kier (1980) suggested that owing to better winnowing conditions near the margin of the platform the algal facies dominated with phylloidal and tubular algae occupying a slightly more landward position than the coralline algae. The platform and platform margin are dissected by channels filled with dominantly coarse crinoidal fill (for example, mixed skeletal biosparites and biomicrites). Although not illustrated in figure 36, the algal biomicrite-biosparite and biolithites occur as platform interior buildups and overall are the most widely occurring rock types. These bioherms are thought to be *Cuneiphycus* (red algae) constructions and rarer *Donezella* boundstones and range in thickness from 1 to 10 m (Choh, 2004). In the off-platform and intermound (biohermal) areas spiculite-bearing facies dominate and are thought to be forming in quiet waters below wave base. This facies is associated with pure micrite and rarer shale.

In general Kier (1980) proposed that the lower Marble Falls member was deposited on a Bahamian-type platform on antecedent topography associated with the Llano Uplift. Namy (1980) and Erlich and Coleman (2005) contended that the Lower Marble Falls member (in the same area as Kier [1980]) was deposited on a southeast-facing distally steepening ramp. In this competing model, a thick (coalesced and stacked to ~120 ft [37 m]) algal bank complex forms at the shelf margin and rapidly grades to heavily bioturbated and eventually laminated spiculitic biomicrites seaward (Namy, 1980). Seaward of the algal banks minor channels (storm debris) filled with intraclasts of the algal banks, as well as crinoidal debris, occur punctuated by small coral reefs and algal mounds. Namy (1980) and Kier (1980) disagreed on the overall depositional environment for the lower Marble Falls Morrowan-age carbonates, but they did not place their studies in a sequence-stratigraphic context to aid comparison and interpretation. Lower Marble Falls facies stacking patterns documented by them indicate an overall regression during deposition, culminating in exposure and the formation of the sequence boundary separating the lower Marble Falls from the upper Marble Falls member. This overall regression is consistent with the sea-level curves of Ross and Ross (1987), at least at the second- and third-order scale (fig. 35). However, the third-order eustatic fluctuations are much higher amplitude than those of the second order and indicate a potentially sizable transgressive event prior to the final regression. Groves (1991) and Manger and Sutherland (1984) studied the Marble Falls Formation from a biostratigraphic point of view. They found algal-bearing and higher energy facies present in more proximal areas adjacent to the Llano Uplift, as well as punctuating the spiculitic dominated successions (fig. 39).

McCrary (2003) undertook a sequence-stratigraphic study of the Marble Falls limestone in the Pedernales Falls State Park area of Blanco County (fig. 34). Three outcrop sections (Archer Ranch, Maund Ranch, Maples Ranch/Pedernales Falls) over an area of approximately 5 mi were studied, and the Lower Marble Falls Member was found to be present at all localities.

Examples of facies and geometries observed in the Pedernales Falls area during recent field work are shown in figures 37 and 38.

McCrary (2003) divided the Lower Marble Falls into two parasequences. Parasequence 1 is characterized by a basal spiculitic packstone member approximately 70 ft (21 m) thick, which is overlain by medium- to thick-bedded mudstones and crinoidal packstones. In the Pedernales Falls section, several intercalations of crinoidal wackestone and spiculitic packstone are present above the thick-bedded mudstones. The uppermost facies present in the study area was an ooid grainstone. Overlying the ooid grainstone is either a fossiliferous and/or crinoidal packstone. Parasequence 2 was dominated by crinoidal packstones. The facies pattern of parasequence 1 is interpreted as a highstand systems tract capped by a sequence boundary. The sequence boundary is then overlain by a transgressive unit of fossiliferous packstone. The overall facies patterns above the sequence boundary suggest rising sea level (TST).

Reservoir Quality and Log Characteristics

On the basis of interpretation of the McCrary (2003) photomicrographs, very little primary porosity is retained in any of the facies of the lower and/or upper Marble Falls. In units that possessed primary porosity, extensive calcite cementation and silicification have occurred, thus occluding the pore space. Within the *Cuneiphycus* algal bioherms, excellent shelter porosity was preserved underneath algal thalli (Choh, 2004). However, early blocky calcite spar largely occluded the pore space, resulting in a tight unit.

In terms of production, Jackson (1980) noted that within Brown County and eastern Coleman County at least six mappable units produce gas from the Marble Falls. Three main fields from shelf-edge buildups (Palo Davis and Lewis–Brown County and Santa Anna–Coleman County) dominated production but underwent rapid declines in production to 10 to 20 percent of their original potential. Oil was produced in the initial phases (API of 40–42) but largely gave way to high (~1,200) BTU gas. Overall, the reservoirs appear to be relatively tight but benefit from fracture porosity for production. Rothrock (1957), however, noted that intergranular (primary and secondary) and vuggy porosity are present in coarse-grained crinoidal/bioclastic calcarenites and limestones and that the reservoir is thought to be an algal bioherm. Within the Walton field, north of the Santa Anna and Pottsfield, production occurred from siliciclastic channels crosscutting a bioherm, as well as within the bioherm itself (Harmon, 1957). The bioherm is largely ovoid and approximately 200 ft (61 m) in thickness with a width of approximately 2000 ft (610 m). Figure 40 illustrates the typical wireline log character for the lower and upper Marble Falls within the Fort Worth Basin. The log character and thickness of the lower Marble Falls member changes quite rapidly between relatively closely spaced wells.

In summary, fracture porosity, vuggy porosity, and local intergranular porosity are necessary to produce from Morrowan-age carbonates. Calcite cementation and silicification can occlude pore space and result in tight units. Fracture porosity is considered of prime importance. The Morrowan carbonates from the Llano Uplift area just east of the Permian Basin should be considered an excellent analog for reservoir quality of Morrowan carbonates present within the Permian Basin.

Distribution

Distribution of the Morrowan-age carbonates is difficult to ascertain, as much of the analysis has been restricted to the Llano Uplift area. As mentioned previously, the extent of the Marble Falls is probably much greater than previously proposed and may extend into Runnels, Nolan, Coke, and Tom Green Counties within the Permian Basin. Kier (1980) also noted that the distribution of the Marble Falls included areas of the Concho Platform/Eastern Shelf, as well as areas near the Matador Arch on the Northern Shelf of the Permian Basin. Figure 1 illustrates the proposed extent of the Lower Marble Falls limestone and its equivalents.

The trend of the Lower Marble Falls bears little or no relation to the structural outline of the Llano Uplift (fig. 41). The extent of the Marble Falls is much greater than illustrated in that figure, as evidenced by fields producing from the Marble Falls in Brown and Coleman Counties (Jackson, 1980), neither of which is included in the outline of the Marble Falls Formation in figure 41. This and other evidence such as thinning of the Lower Marble Falls Formation by erosion over post-Morrowan-age uplifted localized areas points to the conclusion that the Marble Falls was of regional extent far beyond what has been previously considered and is interpreted to be present on the Eastern Shelf of the Permian Basin.

Erlich and Coleman (2005) illustrated in cross section, on the basis of well and outcrop data, the geometry of the lower Marble Falls member across the Llano Uplift from east to west (fig. 42). They indicated a major “thinning” south and west of the lower Marble Falls member from its maximum thickness of 230 ft (70 m) along the west margin of the Fort Worth Basin. An estimated 33 to 66 ft (10 to 20 m) of the lower Marble Falls is thought to have been removed by erosion prior to deposition of the Upper Marble Falls (Erlich and Coleman, 2005). The extent of erosion of the Lower Marble Falls is poorly constrained and may have been much greater across the Bend Arch and Concho Platform and onto the Eastern Shelf. Consequently, thick sections of Lower Marble Falls-equivalent units may be preserved in the Permian Basin**.**

Permian Basin Data

Within the Permian Basin, Morrowan-age carbonates are present as a unit overlying two basal siliciclastic units on the Northern Shelf and the northern Delaware Basin within New Mexico and Texas (Malon and others, 2000). The carbonate unit is poorly described as a transgressive shallow-water, shelfal, gray limestone, dominantly oolitic with interbedded marine shales (James, 1984; Casavant, 1986; Malon and others, 2000). This unit is termed the "Upper Morrow" and is thought to be separated from the underlying Lower and Middle Morrow by a transgressive shale. Shallow shelfal carbonates were thought to be present in areas more basinward (that is, south into the Delaware Basin) from the Lower and Middle Morrowan alluvial, valley-fill, and deltaic successions (James, 1984). Morrowan-age oolitic limestones are also present in the McDonald field in Lea County, New Mexico, and Homman field, Gaines County, Texas.

Equivocal Carbonate Morrowan Deposition

Outside of the Permian Basin, to the north, a limestone of possible Morrowan age also exists below the "Bend"-age fan-delta siliciclastic succession in the Palo Duro and Dalhart Basins, whereas the Lower Morrow limestone in Kansas and Colorado is grainstone facies that occurs stratigraphically beneath the valley-fill succession described by Bowen and Weimer (2003).

Summary of Upper Morrow Carbonate Deposition

Because so little is known about the Permian Basin Morrowan-age carbonates, understanding and documenting the lower Marble Falls Formation helps to create possible outcrop and subsurface analogs. The Marble Falls–type carbonates have potential as both a primary (for example, leaching of bioclasts and primary porosity) and a secondary (fracture) reservoir. Their possible equivalent units within the Permian Basin may be overlooked targets. With the current explosion of interest in the shale gas systems (primarily the Barnett but also the Smithwick) an overlying Marble Falls–type carbonate system may also hold potential as a fractured reservoir for expulsed Barnett gas.

When comparing the carbonate succession regionally, one obvious factor that must be understood is the apparent differing response to eustasy and tectonics between the greater Llano Uplift area and the Northwest Shelf/Delaware Basin margin. Biostratigraphically the lower Marble Falls Formation (minus tens of meters removed by erosion) is time equivalent to the entire Morrowan siliciclastic and carbonate succession in New Mexico.

Broadly similar transgression and regression cycles are noted in the Permian Basin New Mexico study area and the Llano area, in that there is generally a regional transgression punctuated by a major regression. Local differences between the areas probably relate to the rate of sediment supply. Sediment input into the northwest Permian Basin is linked to rates of Pedernal area uplift. An increased sediment supply during uplift could outpace accommodation and result in progradation (apparent regression), whereas during times of quiescence or diminished uplift sediment supply diminishes or stops and results in apparent transgression (retrogradation). The deposition of the Upper Morrow carbonate unit in the Delaware Basin area probably indicates a switch from local tectonic to regional eustatic control as sediment supply shuts off and tectonism diminishes in the hinterland.

In summary, there are several key issues regarding the understanding of the Morrowan-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 need to be put into regional sequence-stratigraphic context.
2. Unconformities: Many of the stratigraphic relationships proposed for the Pennsylvanian rely heavily on the interpretation and identification of unconformities. However, many of the studies present conflicting or at best ambiguous stratigraphic interpretations. Understanding the nature, extensiveness, and duration of the unconformities and their correlative conformities in the Pennsylvanian section will strongly influence how sequence-stratigraphic architectural models are put forth. As illustrated in figure 35 the Barnett Formation probably represents a time-equivalent basinal facies to Mississippian

shallow-water carbonates, as well as Morrowan-age siliciclastics and ramp carbonates. Secondly, the presence of the unconformity between the Lower Marble Falls and Upper Marble Falls Formations should be confirmed and extended in the Permian Basin, if possible, for correlation purposes, and such an exposure surface could have strong bearing on the development of secondary porosity.

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

OVERALL DISCUSSION AND SUMMARY

Within the Permian Basin, confirming the presence of Morrowan valley-fill systems and understanding their processes is important. An incised valley-fill depositional model appears most compatible with the Morrowan-age siliciclastics in the Permian Basin. The exploration strategy and approach for un-incised lowstand bypass systems versus those that are incised is different (Posamentier, 2001). In bypass systems excellent reservoir potential may be developed in the deeper basin, whereas in incised systems amalgamated stacked on-shelf channels provide excellent reservoirs. If shelf-edge bypass occurred, then previously unidentified plays may exist.

Incised valley-fill systems contain a much broader spectrum of facies and environments than standard un-incised lowstand alluvial systems (that is, range from alluvial to open marine). Overall, the areal extent of an un-incised alluvial system is greater than that of an incised valley fill. The more limited extent of valley-fill systems is a product of the duration of the period of sea-level fluctuation, erodibility of the substrate, and fluvial discharge (fig. 1).

The incision critical to valley-fill systems can be generated by sea-level fall, tectonic tilting/uplift, or discharge reduction. Given the amount and length of incision (that is, simultaneous incision over the entire length) in the Morrowan siliciclastics in New Mexico, Kansas, and Oklahoma, the ancestral Rocky Mountain tectonic uplift resulted in increased stream flow, thereby becoming a major controlling factor in incision. Within the Permian Basin, the uplift of the Pedernal Highland and possibly localized areas of the Central Basin Platform resulted in incision. Given the paleogeography of the Permian Basin, this system may have been linked to those drainage systems farther north and east in Colorado and Kansas (fig. 1).

Rapid and high-amplitude sea-level falls probably also contributed to incision of the Morrow Formation valley fills. Galloway (2001) illustrated a much larger but more confined (that is, single) depocenter that results in sediments bypassing the shelf edge during icehouse conditions, as compared with a greenhouse situation (fig. 43). The Delaware Basin was most likely a depocenter and had been for some time (for example, supporting data include thickness patterns of the Woodford Shale and gravity/magnetic data); therefore, the sea-floor gradient was potentially quite high, resulting in major incision during sea-level falls. Rapid and high-amplitude sea-level rises could allow rapid infilling and capping of the alluvial sediments within the valleys and result in facies-controlled traps and seals.

The potential for deepwater deposits in the Delaware was high, owing to shelf bypass. If the 125-mi-plus (200-km) estimates by Bowen and Weimer (2003) and Posamentier (2001) for valley incision and facies dislocation are applied to the Permian Basin, lowstand facies could be present much farther to the south within the Delaware and Midland Basins. In the deepest parts of the Delaware Basin, basin-floor fans might be present. Facies dislocations caused by eustasy and tectonic uplift require a reappraisal of the deeper Delaware Basin for lowstand deposits of Lower Morrow affinity as far south as Loving and possibly Reeves County.

Understanding Morrowan-age carbonate deposition in the Permian Basin is hampered by a lack of detailed data and regional interpretations. Overall, it appears that carbonate deposition occurred over a much larger area in the Permian Basin (Eastern Shelf and Delaware Basin) than previously documented. The presence of algally dominated bioherms and higher energy facies (ooid grainstones), augmented by fracture porosity, indicates potentially overlooked reservoir intervals. The Morrowan-age carbonate outcrop succession in the Llano Uplift area provides an analog for size, distribution, and reservoir character for “undiscovered” Permian Basin Morrowan carbonates.

PALEOGEOGRAPHIC SUMMARY

The proposed distribution of Morrowan-age (Middle Morrowan as per Delaware Basin siliciclastic succession) sediments across the Permian Basin and surrounding areas based on the above interpretations is illustrated in figure 1. The following discussion refers to interpretations represented in figure 1. Because much of the data is restricted to the Delaware Basin and the

Llano Uplift, facies interpretations across the Midland Basin (MB), Ozona Arch (OA), Val Verde Basin (VB), and the southern portion of the Delaware Basin (DB) are tentative.

Broadly, Morrowan-age siliciclastics dominate deposition in the west of the Permian Basin, whereas carbonate deposition dominates in the east. The predominance of carbonate facies in the east is due to the lack of siliciclastic supply to that part of the basin. The transition from the platform and/or ramp carbonates to more basinal carbonates and ultimately shales along the Eastern Shelf (ES), Midland Basin (MB), and Central Basin Platform (CBP) is suggested. This transition is supported by well log data in the Midland Basin, which indicate a westward change from carbonates to shalier lithologies. A small peninsula of platform to ramp carbonates is thought to have existed along the trend of the antecedent Central Basin Platform (CBP). Some Precambrian inliers on this trend appear to have been exposed and shedded material into the basin (for example, Eddy County, New Mexico), and it is assumed that along the margin of these inliers and other uplifting basement-cored highs carbonate deposition could also have occurred.

In the Delaware Basin (DB) the siliciclastic lowstand succession was dominated by extensive incised valleys. The valley systems were infilled by multiple facies types. The interpreted deepwater fan systems would be sourced through the incised valleys that bypass sediment to the deeper water. The size, geometry, and position of the deepwater siliciclastics depend largely on the gradient of the shelf-to-slope transition. The fan systems could be encased in deepwater carbonates or shales. If parts of the DB reflect a pre-Pennsylvanian depocenter, the transition zone from basinal carbonate to shale may not have existed and the region in Jeff Davis and Pecos Counties may have been an area of platform to ramp shallow-water carbonate deposition. The siliciclastic succession is shown to be dominantly receiving its sediment load from the east-southeast margin of the Pedernal Uplift. However, regionally the DB valley-fill system is linked to the north with other channel systems feeding the Midcontinent. To the west in Hudspeth and El Paso Counties siliciclastic influx appears to have been less, and a possible uplift of the Diablo Platform (DP) area resulted in carbonate deposition in a possibly double-sided ramp configuration.

KEY CONCLUSIONS

- Broadly, the Morrowan-age units in the Permian Basin appear to show a "second-order" transgression from siliciclastic fluvial deltaic to shallow marine and subsequently to carbonate deposition.
- Morrowan-age siliciclastics dominate deposition in the west of the Permian Basin, whereas carbonate deposition dominates in the east. The predominance of carbonate facies in the east is probably due to a lack of siliciclastic supply to that part of the basin. The deposition of the Upper Morrow carbonate unit probably indicates a switch from local tectonic to regional eustatic control as tectonism diminished in the hinterland and sediment supply from the north/northwest shut off
- Siliciclastic deposition of the Morrowan-age units occurred in a large incised valley-fill system. Fluvial, deltaic, estuarine, and open-marine facies are interpreted. Excellent reservoir potential is noted in amalgamated, stacked channel systems and bayhead deltas.
- These incising valleys may have served as conduits for shelf-margin bypass during periods of lowstand. It is proposed that such bypass channels may have fed sediment into the deeper basin, developing lowstand basin-floor-fan deposits. This represents an exciting new play type for the region.
- The Upper Morrowan carbonates were deposited over a much larger area in the Permian Basin (Eastern Shelf and Delaware Basin) than previously documented. The presence of algally dominated bioherms and higher energy facies (ooid grainstones), augmented by fracture porosity, indicates potentially overlooked reservoir intervals. These Morrowan carbonates hold potential as a fractured reservoir for expulsed "Barnett" gas.
- The conclusions drawn herein should provide guidelines and ideas for interpretation of the Morrowan section within the Permian Basin.

APPENDIX. MARBLE FALLS

The term "Marble Falls" has been used as both a group and formation name (Cheney, 1940; Plummer, 1944; Cheney, 1947; Plummer, 1947, 1950; Cheney, 1951; Cheney and Goss, 1952). Table 2 illustrates the different classification systems and time equivalencies devised for this time unit. Formations within the Marble Falls Group are historically the Sloan, Comyn, Lower Marble Falls, Upper Marble Falls, and Big Saline. If the Marble Falls is taken as a formation, it is commonly designated “lower” (including the Sloan and occasionally the Gibbons conglomerate members) and “upper” (with Gibbons Conglomerate, Big Saline, and Lemons Bluff Members). The term “Comyn Formation” is commonly used for the lower Marble Falls in the subsurface.

The Barnett and the Marble Falls Formations are thought to straddle the Mississippian/ Pennsylvanian boundary, and within the northern Midcontinent this boundary is marked by a distinct paleosol (for example, Keir, 1980; Groves, 1991). A debate exists as to the placement and the conformability of the Mississippian/Pennsylvanian (basal Morrowan) boundary and the formation(s) within which it lies.

Biostratigraphic studies of the Barnett–Marble Falls succession in the Llano Uplift (Hoare and Merrill, 2004) indicate a conformable contact between the Barnett Formation and Marble Falls Group (fig. 7). Erlich and Coleman (2005) argued that the Barnett Formation–Marble Falls Formation contact is conformable in the westernmost Fort Worth Basin but unconformable, at least locally, on the Llano Uplift, where the upper Marble Falls overlies Mississippian Barnett Formation, Devonian, or Ordovician units.

Groves (1991) used fusulinid biostratigraphy to date the Lower Marble Falls “member” as Morrowan in age and the upper Marble Falls “member” as Atokan in age. Manger and Sutherland (1984) also proposed the same division on the basis of conodont biostratigraphy. They did note, however, that the entire lower Marble Falls member at the type section locality is biostratigraphically younger than the lithostratigraphically equivalent interval to the northeast.

An unconformity between the lower and upper Marble Falls members was noted by Groves (1991), Kier (1980), Watson (1980), Namy (1982), Manger and Sutherland (1984), and Erlich and Coleman (2005). Groves (1991), however, also noted that the Gibbons conglomerate overlies the lower/upper Marble Falls unconformity. Manger and Sutherland (1984) noted the presence of a limestone pebble conglomerate (termed “Sloan Conglomerate”) at the same unconformity.

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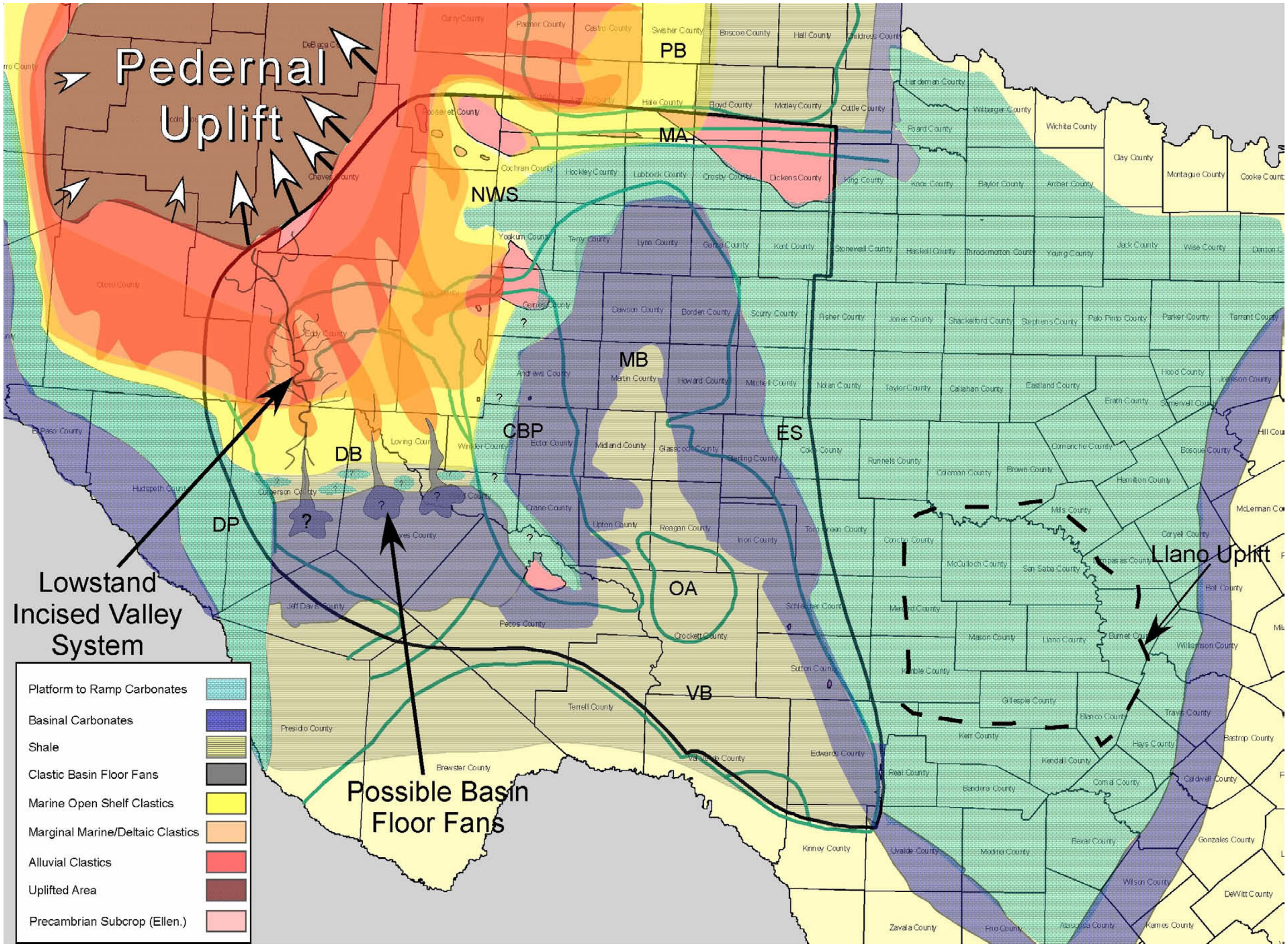

Figure 1. Regional paleographic reconstruction of Morrowan-age sediments. The illustration is based on a time slice possibly equivalent to the Middle Morrow Formation in the Delaware Basin during a lowstand event. Major subregions are labeled as follows and are outlined by dark-green lines: Central Basin 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), and Val Verde Basin (VB). Question marks indicate areas of inferred depositional environment and facies with limited data control. All geometries are schematic only and may not correspond to actual size and distribution. Llano Uplift area outlined by black dashed line. Sizes of arrows surrounding the Pedernal Uplift correspond to relative amount of uplift (that is, larger arrow equals greater relative uplift). Note that Pedernal Uplift is possibly linked to Sierra Grande Uplift to the north.

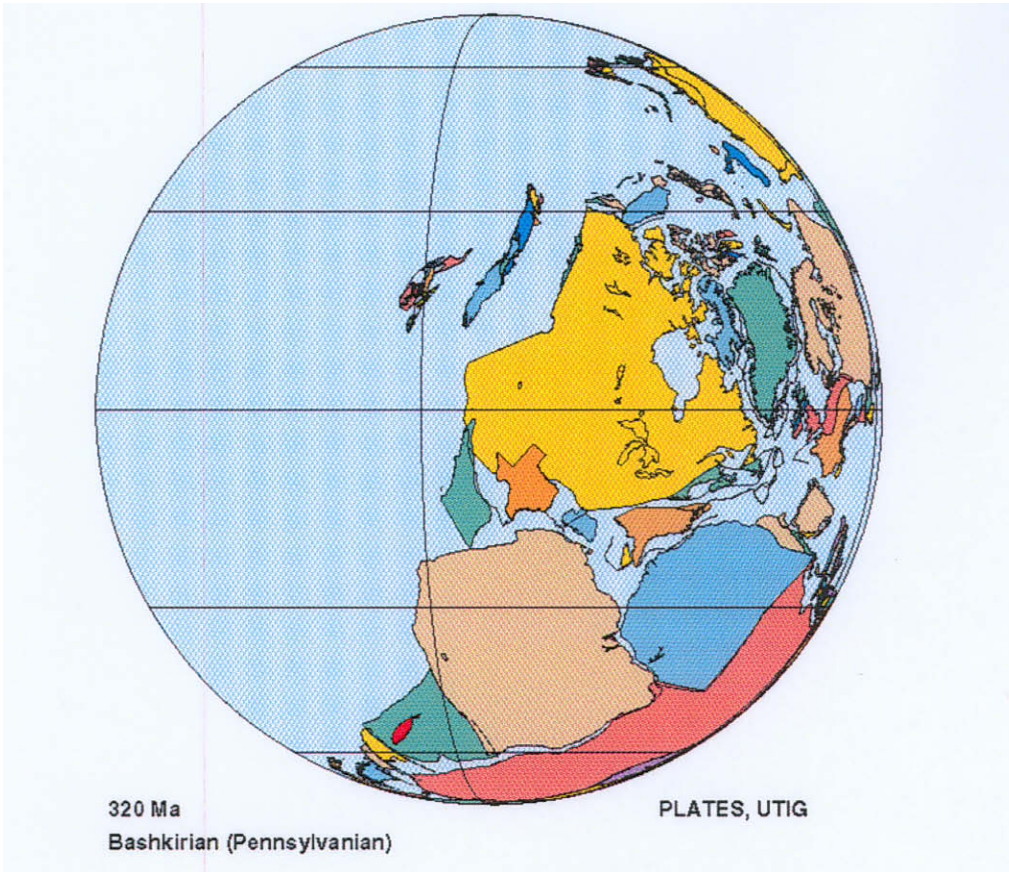

Figure 2. Morrowan-age Texas plate tectonic reconstruction. Note the marine (light-blue) to continental (light-orange) transition that occurs across Texas (dark-orange) in the area of the Permian Basin. Also note that suturing of the continents has resulted in a marine inland sea between the green, brown, dark-blue, and light-orange plates. Diagram modified from Dalziel and others (2002). Compare proposed extent of continental suturing in the Permian Basin area in figures 2 and 3.

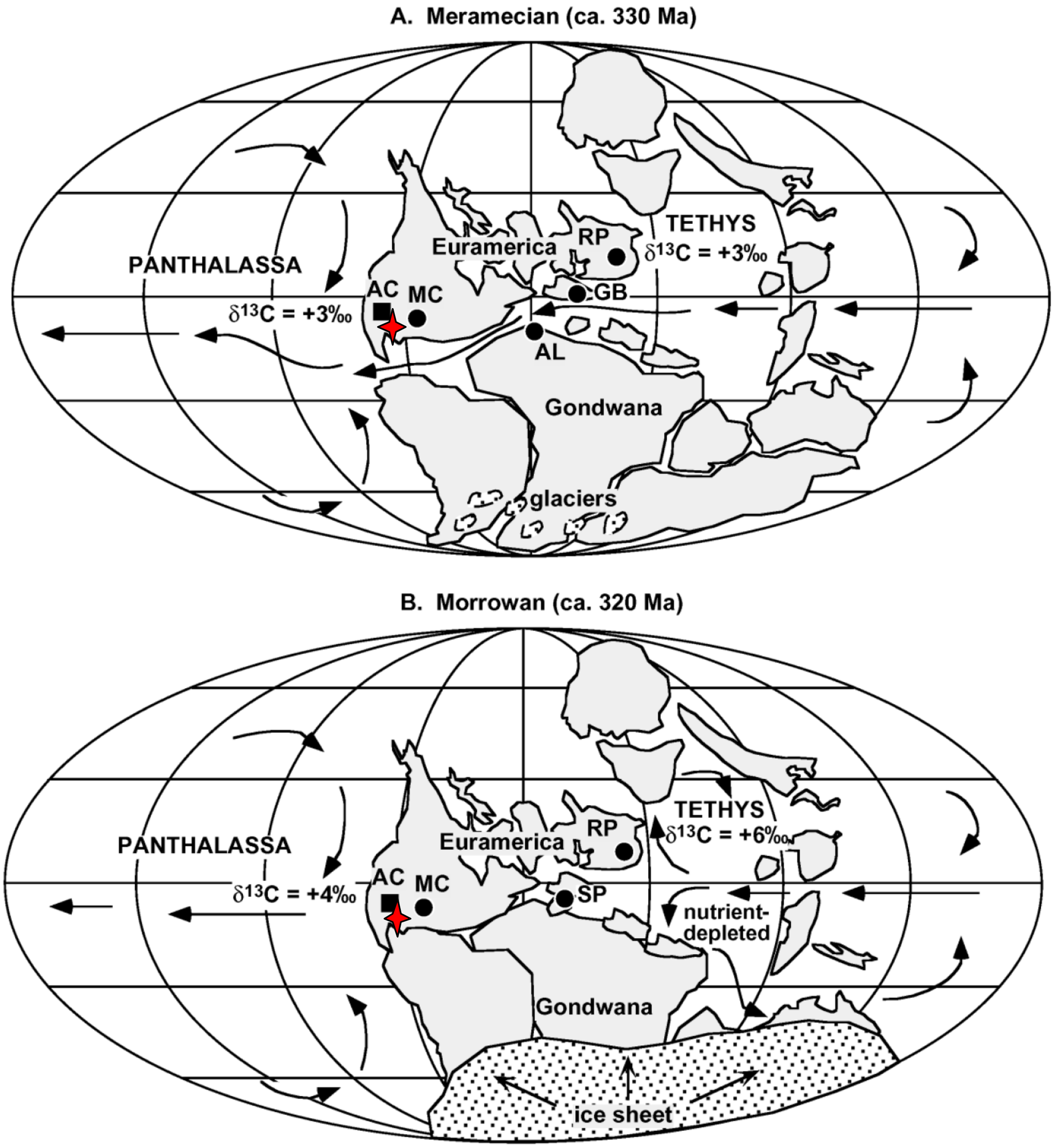

Figure 3. Paleogeographic global reconstructions illustrating simplified extent of glaciation, ocean-water circulation, and carbon isotope water mass values. Red star indicates approximate region of the Permian Basin. AC = Arrow Canyon, Nevada; MC = Midcontinent, USA. Note restructuring of oceanic currents from Merrimecian to Morrowan times coincident with the closing of the seaway between Euramerica and Gondwana. Diagram modified from Saltzman (2003). Note that Morrowan plate geometries in figure 3 are similar to those presented by Scotese (2004).

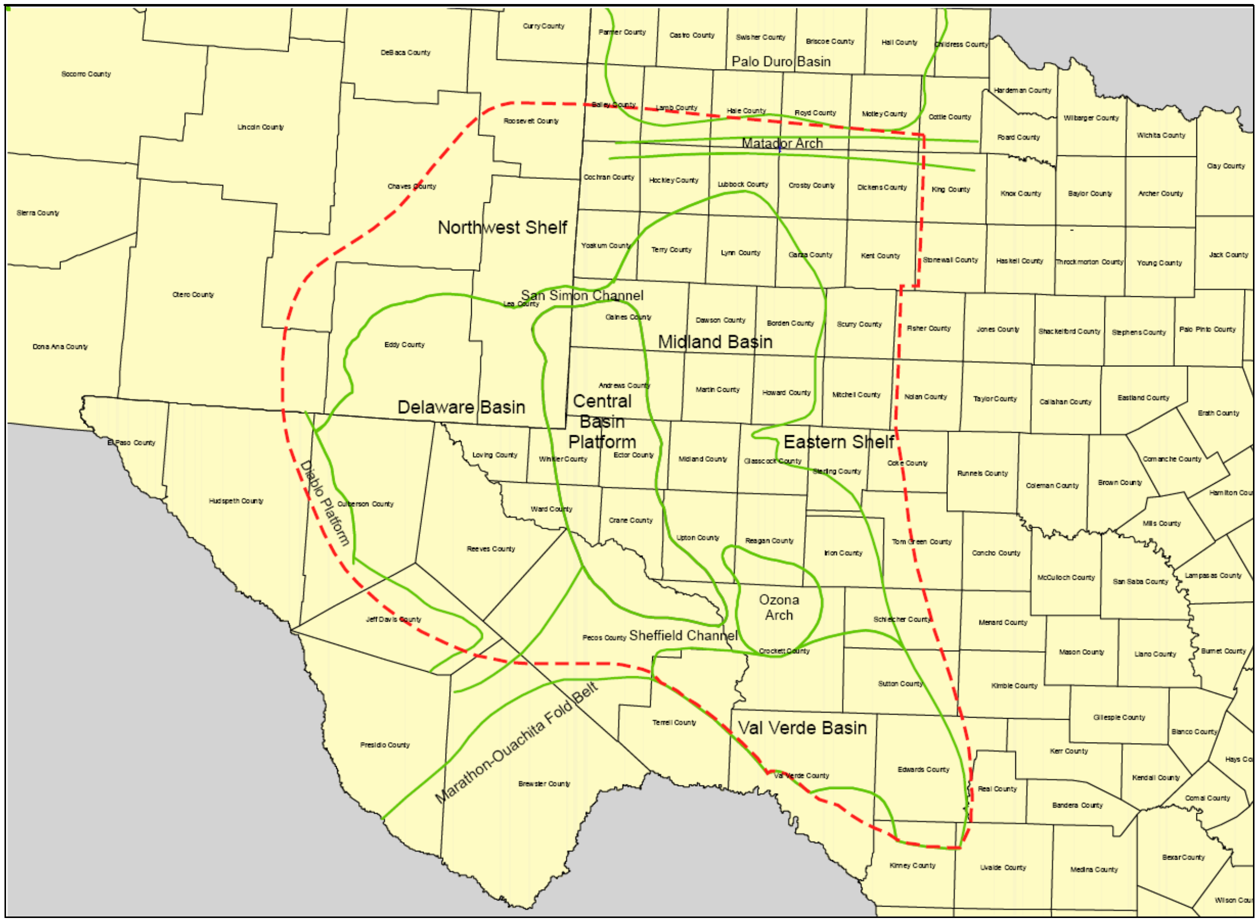

Figure 4. Permian Basin outline (dashed red) and major geologic features. Note that many features were not developed at Morrowan time. Also compare figure 4 with figures 5 and 6 for an idea of the distribution of facies relative to the basin outline.

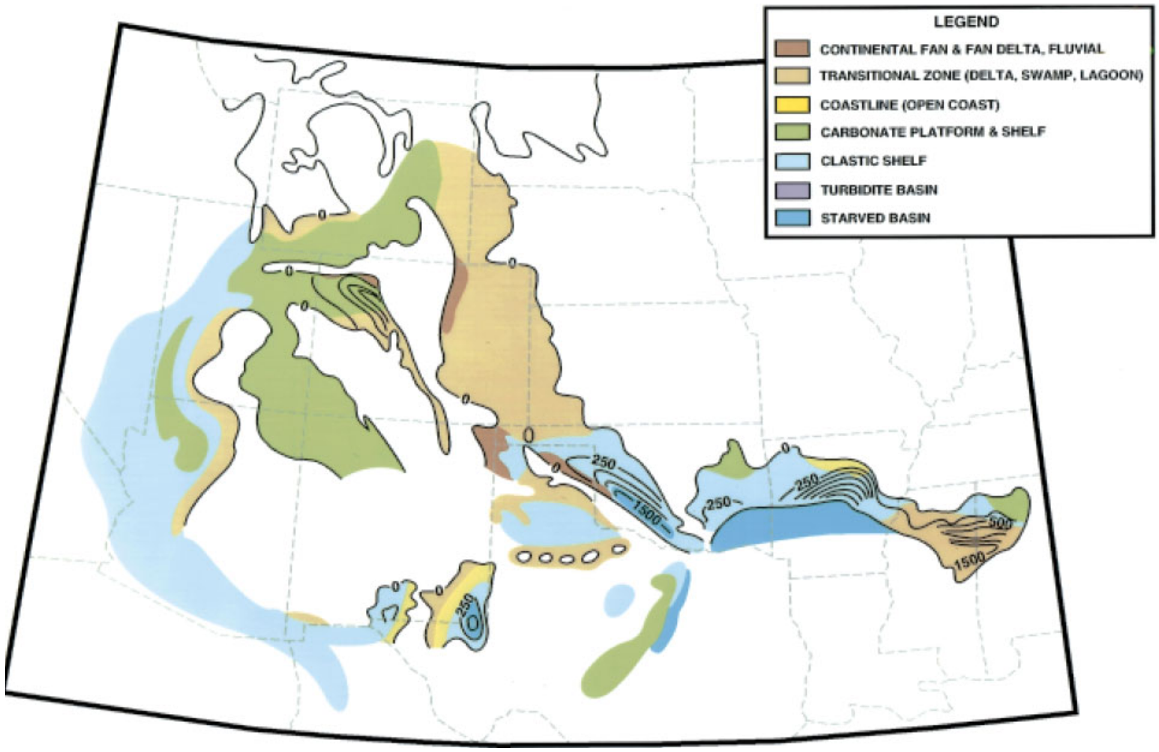

Figure 5. Generalized Rocky Mountain region and southern Midcontinent Morrowan paleogeography (modified from Ye and others, 1996). White areas indicate either nondeposition or erosion (not clarified in original text). Note that most of the Permian Basin was considered devoid of Morrowan sediments by Ye and others (1996).

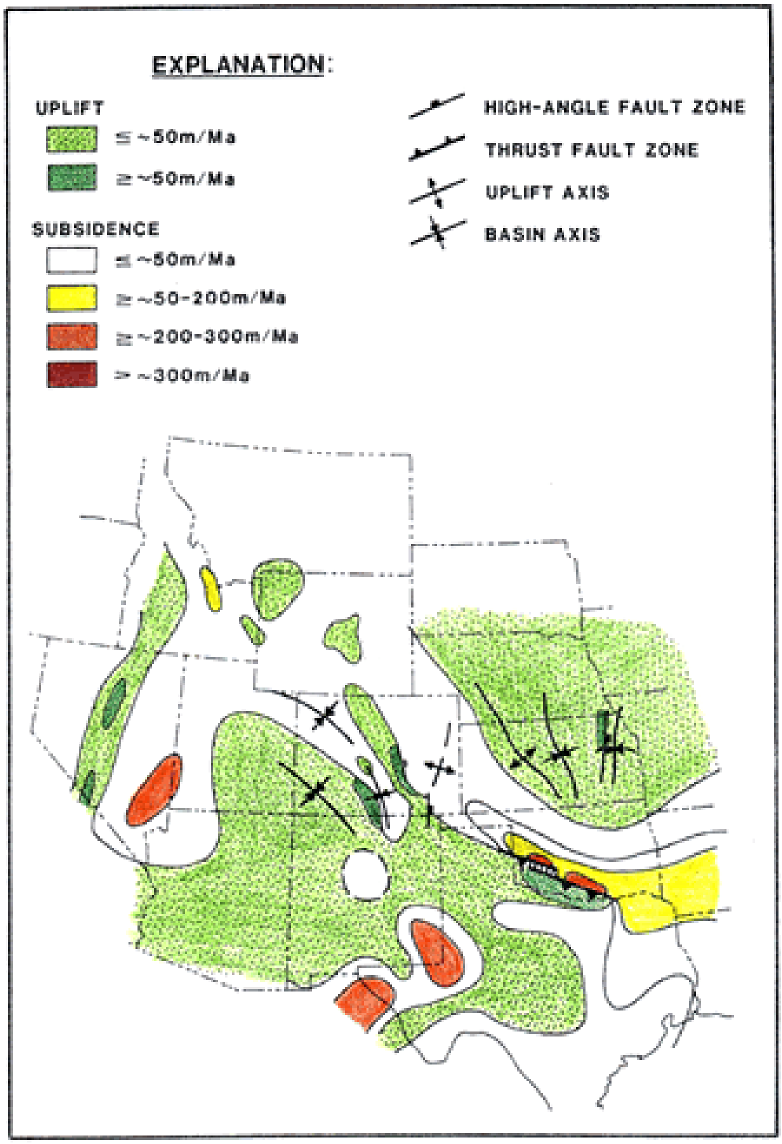

Figure 6. Morrowan net subsidence and uplift patterns for the Southern Rocky Mountain and Midcontinent regions (modified from Kluth, 1986). Green areas indicate net uplift, whereas white to red areas indicate net subsidence.

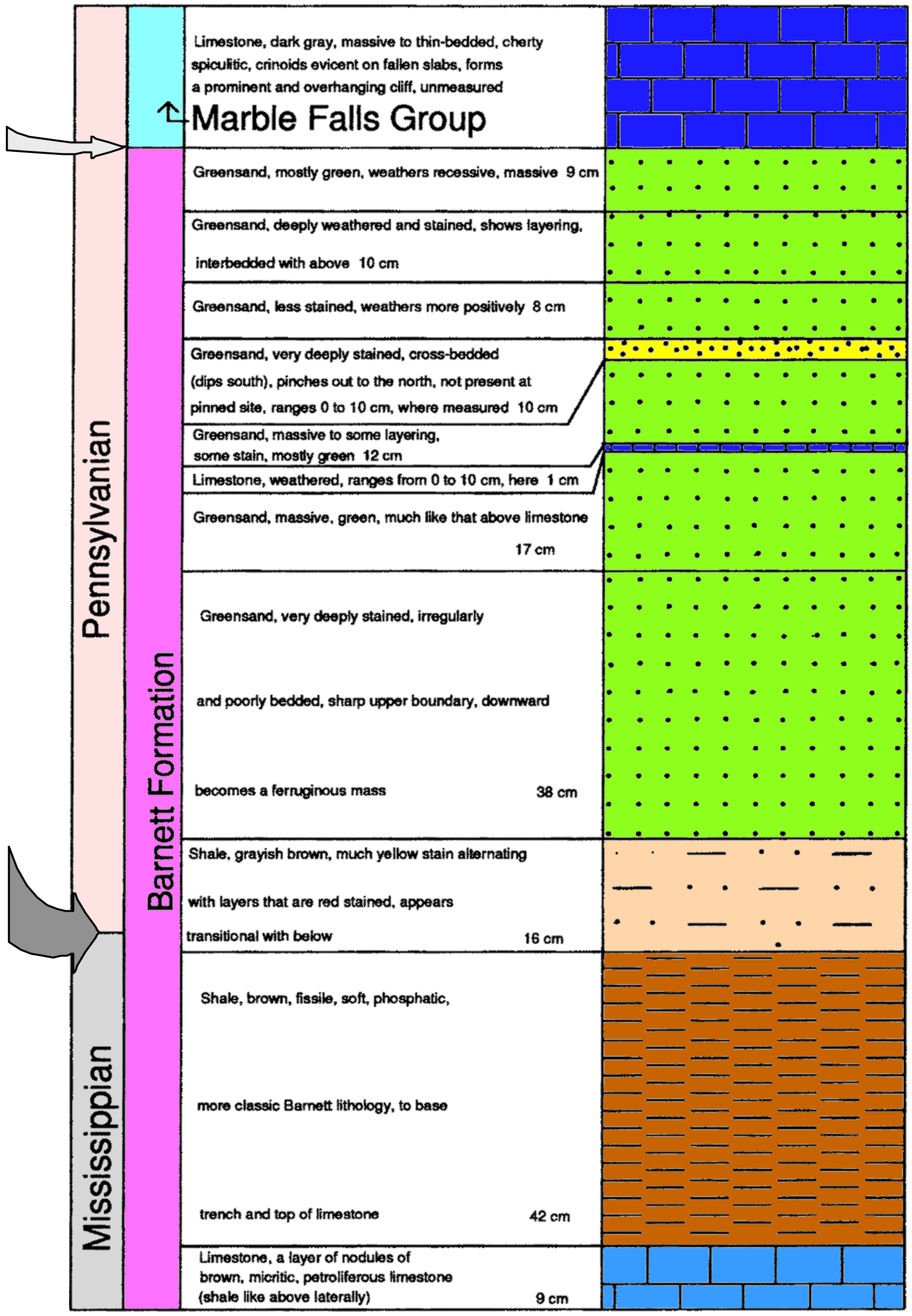

Figure 7. Llano Uplift stratigraphic column for a conformable Mississippian to Pennsylvanian transition (modified from Hoare and Merrill, 2004). Note that the Mississippian/Pennsylvanian boundary is placed within the Barnett Formation (large arrow), making the Upper Barnett (1.4 m [4.6 ft]) Pennsylvanian in age. Previous interpretations commonly place the Mississippian/Pennsylvanian boundary at the base of the Marble Falls Formation (small arrow).

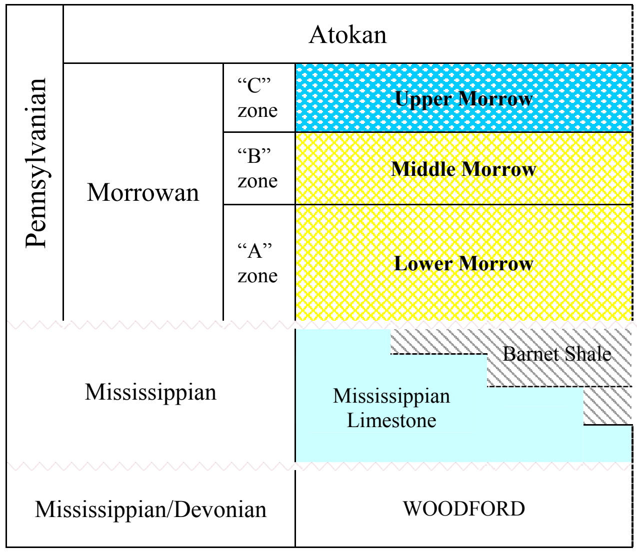

Figure 8. General stratigraphic column for Mississippian- and Pennsylvanian-age units in Northwest Delaware region of the Permian Basin (modified from Coker, 2003). Within Morrowan-age units the yellow fill in the Lower and Middle Morrow indicates a dominance of siliciclastic deposition in that area, whereas the blue fill of the Upper Morrow indicates carbonate deposition.

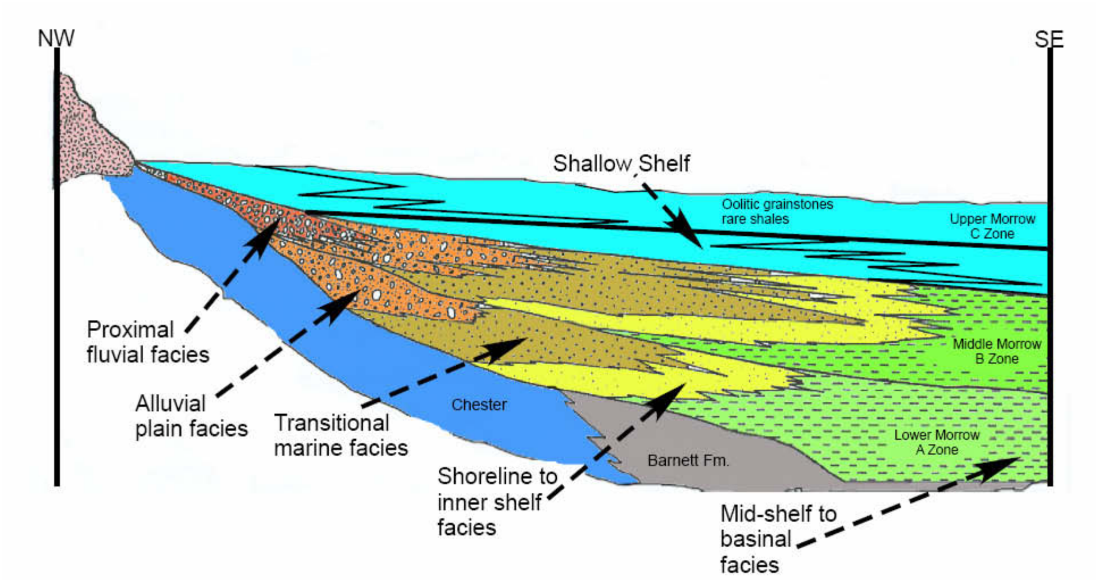

Figure 9. Schematic representation of Morrowan-age depositional environments, geometries, and the relationship to underlying units in New Mexico (modified from Mazzullo, 1984). However, in this study the uppermost Barnett Formation is included in the Lower Morrow.

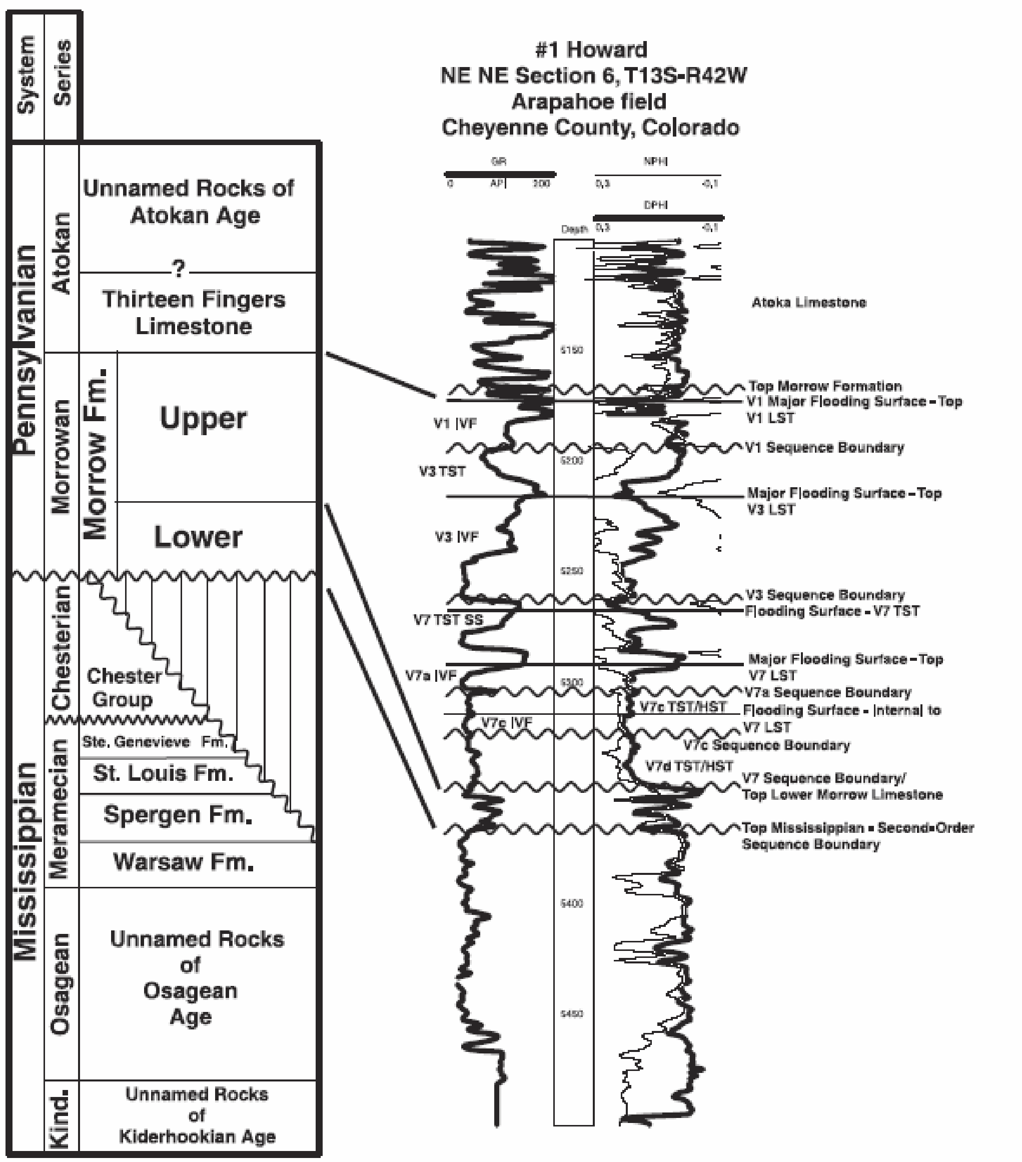

Figure 10. Type wireline-log section for Morrow Formation in western Kansas and eastern Colorado (modified from Bowen and Weimer, 2003). Note that Lower Morrow is carbonate, whereas Upper Morrow is siliciclastic. Also note V7 major flooding surface above the lowstand systems tract (LST). See figures 12 and 13 for relationship of flooding surface to facies descriptions and geometries.

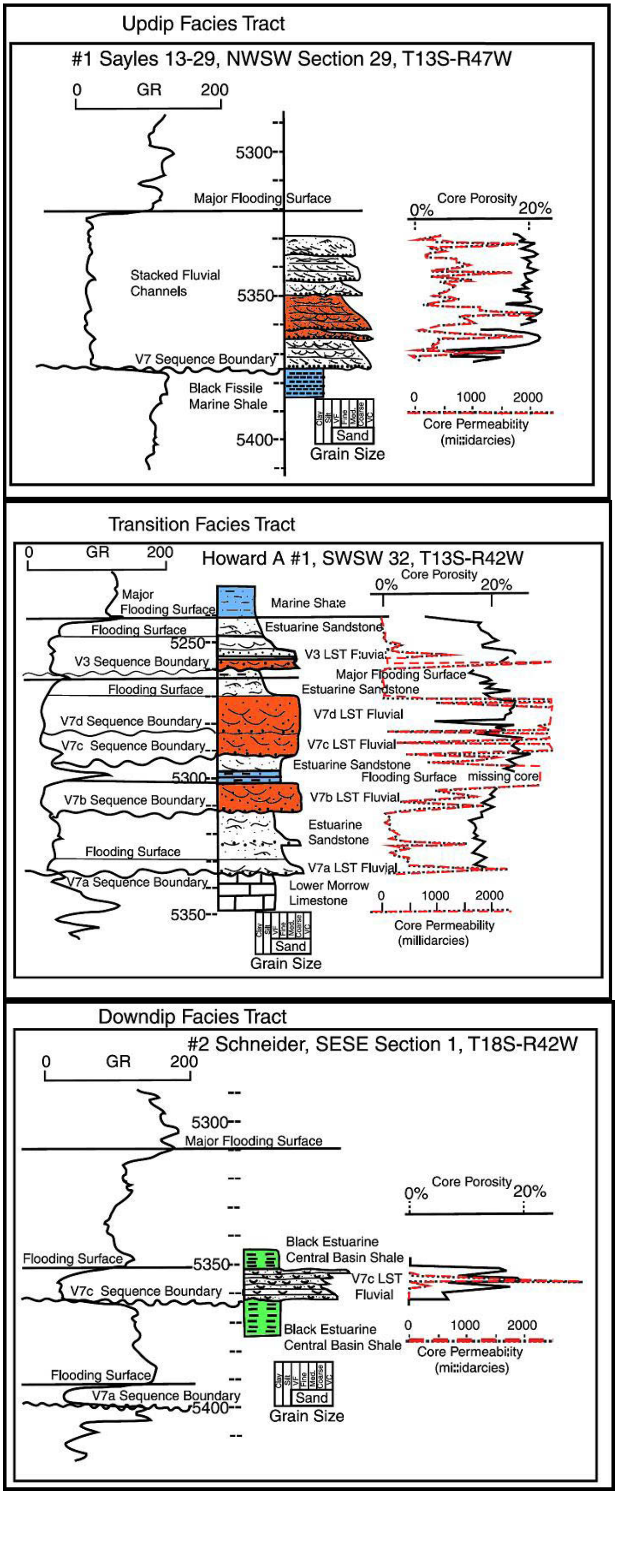

Figure 11. Core descriptions and wireline-log signatures for facies tracts defined by Bowen and Weimer (2003). Red dashed line indicates core permeability in millidarcys. Note different facies interpretation when compared with figure 29 by James (1984) for similar gamma patterns. Also note that within a given facies environment having consistent porosity, high permeability values are much more restricted (for example, updip facies tract of stacked fluvial channels highlighted in red). Modified from Bowen and Weimer (2003).

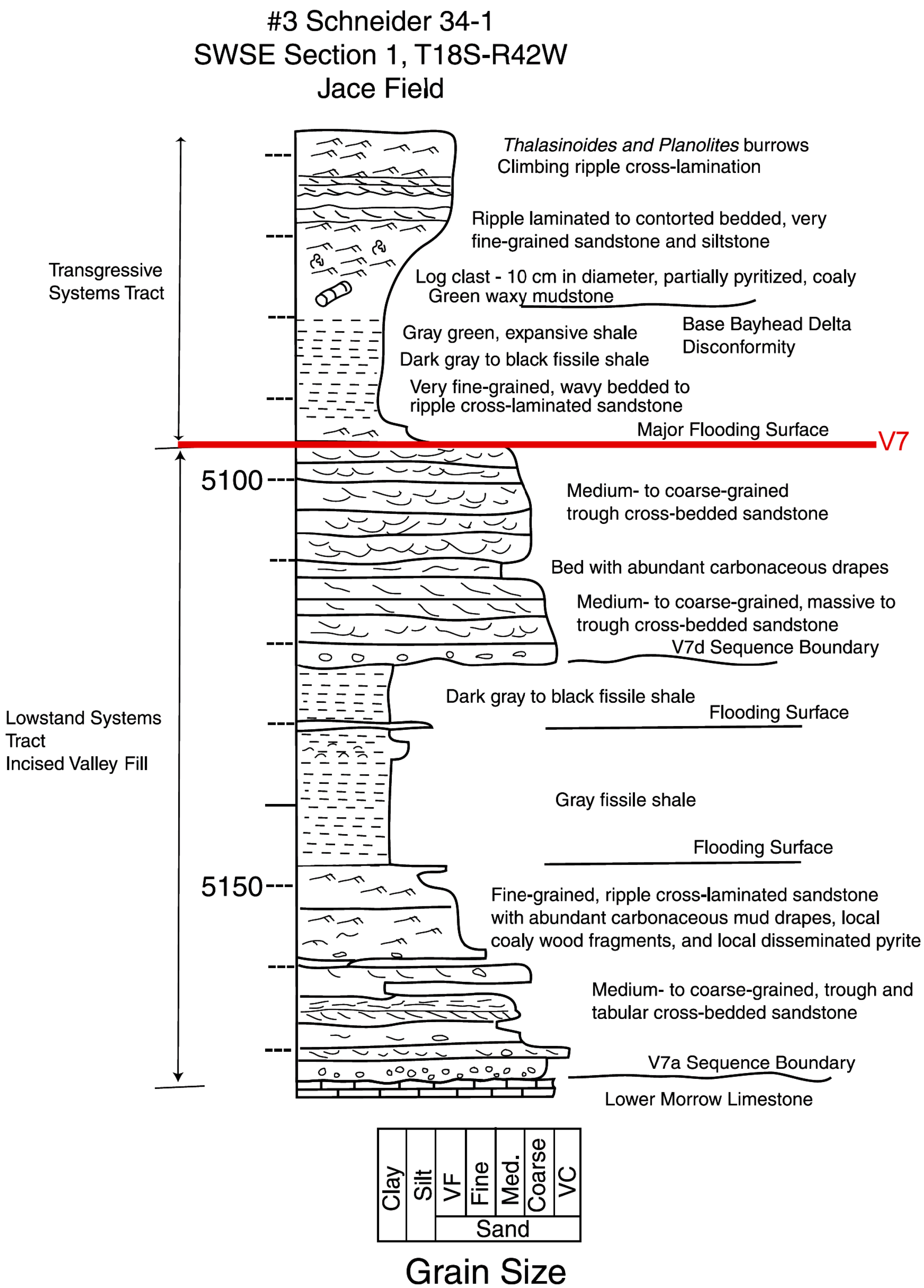

Figure 12. Sedimentological descriptive log for No. 3 Schneider 34-1 well illustrating facies stacking patterns for a "downdip facies tract." See Bowen and Weimer's (2003) figure 7a for accompanying core photos. Note V7 "regional" flooding surface highlighted in red. Note change from lowstand to transgressive systems tract that will not be overly apparent on wireline logs.

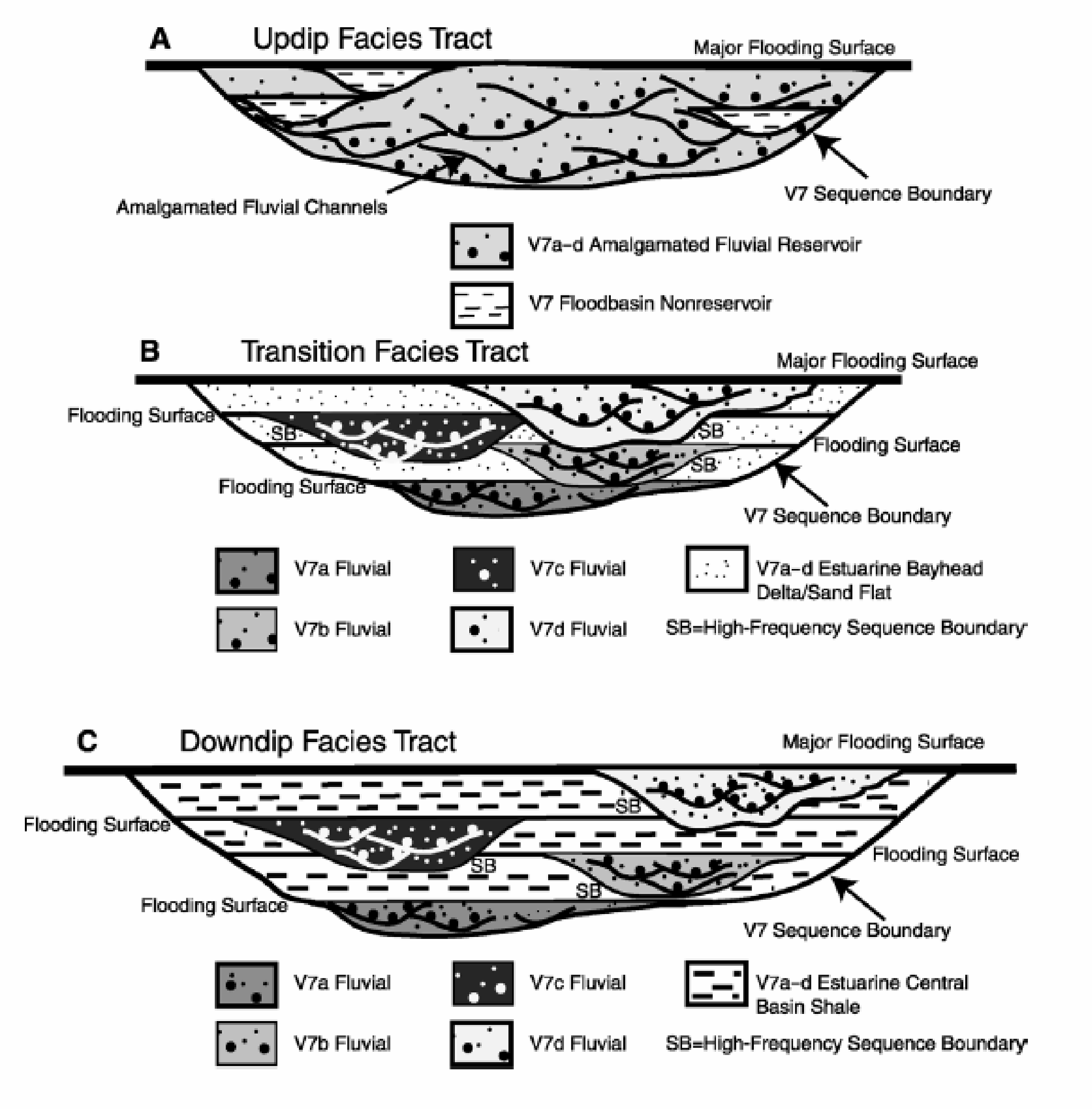

Figure 13. Illustration of the cross-sectional profiles and facies stacking patterns for updip, transitional, and downdip tracts (modified from Bowen and Weimer, 2003). Note that extent, quality, and connectivity of the reservoirs change between facies tracts. Note that major flooding surface (V7) at the top of each facies tract is equivalent.

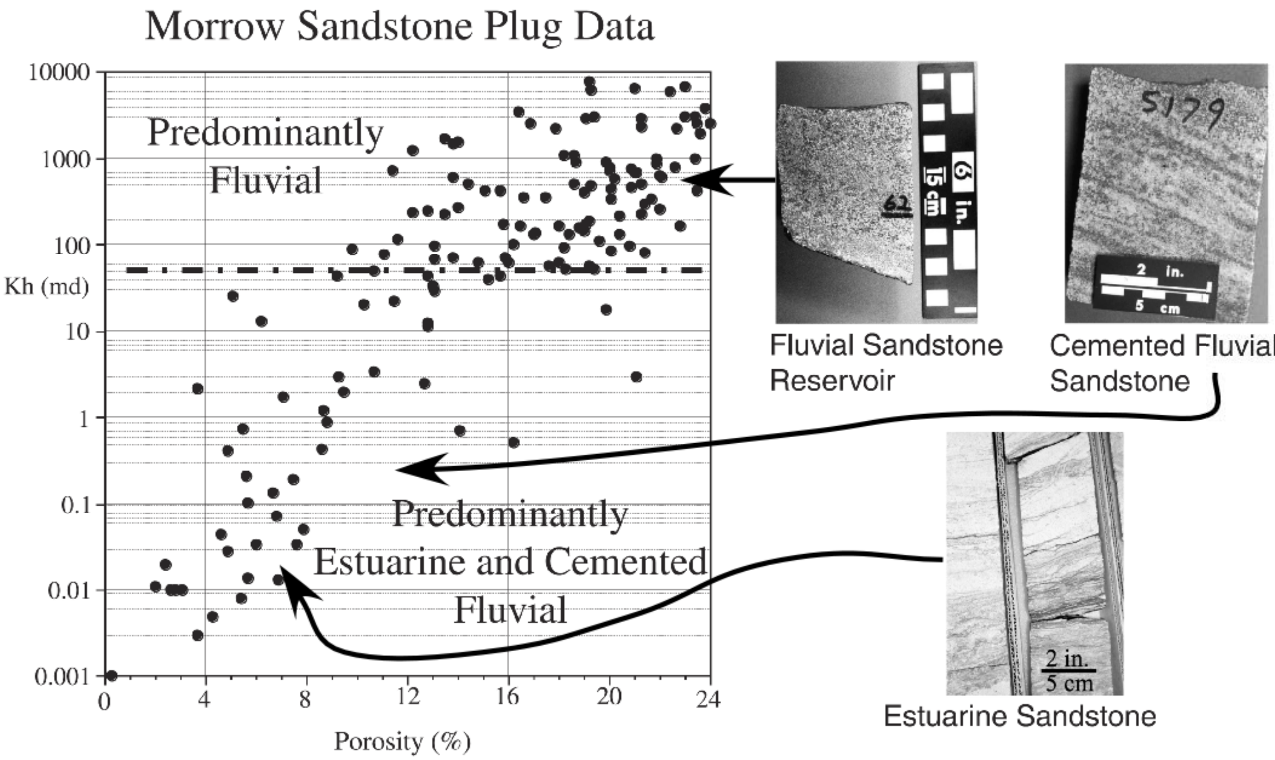

Figure 14. Porosity versus permeability cross plot with respective core photographs of associated facies. Note better reservoir quality in the fluvial sediments. Also note that the cemented fluvial facies with its decreased reservoir quality may be associated with the permeability trend noted in figure 11A (modified from Bowen and Weimer, 2003). In figures 11B and 10 the decreased reservoir quality of the estuarine sandstones is not apparent on wireline logs because porosity is relatively similar for fluvial and estuarine facies.

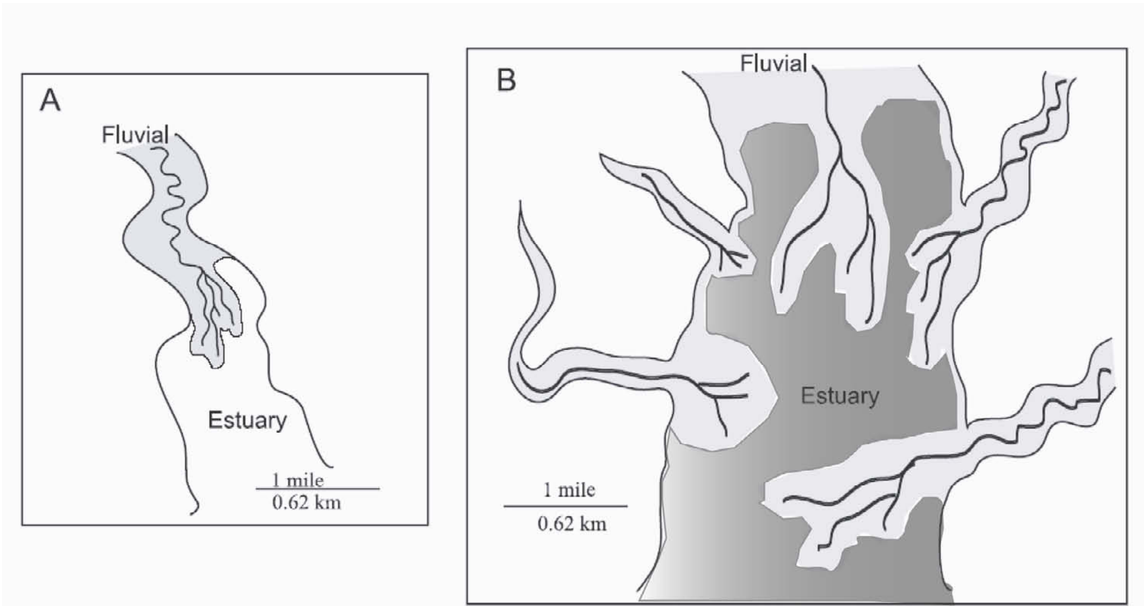

Figure 15. Aerial comparison of bayfill delta depositional area in (A) “updip” (transitional facies tract of Bowen and Weimer, 2003) confined valley-fill system versus (B) broader “down-dip” tributary estuary (modified from Bowen and Weimer, 2004). Note that a high proportion of shale is deposited in interdelta lobe areas (dark-gray) in the estuary. Bayhead delta (both proximal and distal) facies are in light-gray.

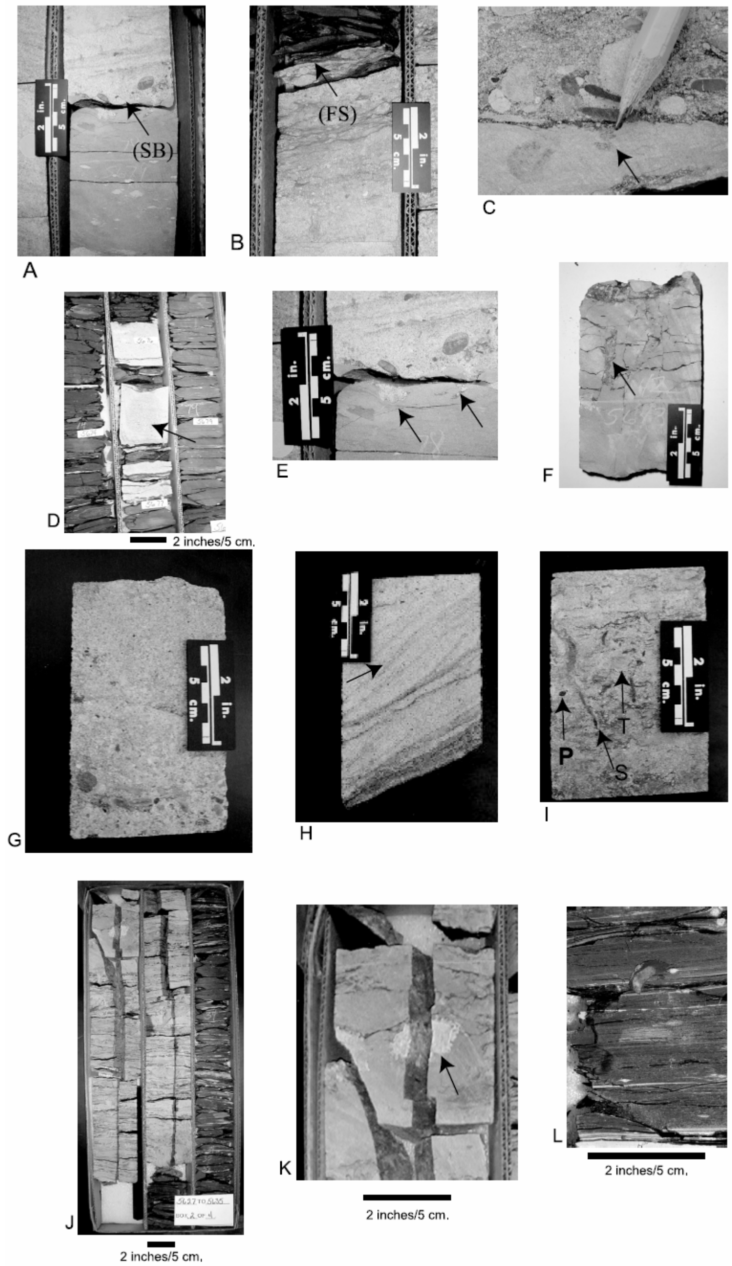

Figure 16. Key features identifiable in core (A) basal Morrow sequence boundary, (B) flooding surface at top of fluvial succession, (C) basal bayfill delta disconformity (*Glossifungites* surface), (D) transgressive lag at major flooding surface, (E) sand-filled burrows at base fluvial unconformity (*Glossifungites* surface), (F) pedogenic fractures in the Mississippian Chester Formation, (G) medium to coarse pebbly arkosic sand, (H) potential tidal influence (reactivation surface and double mud drapes), (I) bioturbated zone (includes *Skolithus*, *Planolites*, and *Teichicnus*), (J) laminated central "basin" estuary shale overlain by distal bayhead delta facies, (K) solitary coral from upper bayhead delta facies, and (L) marine shale above major flooding surface (modified from Bowen and Weimer, 2004). Note that all photos are related to core description and facies shown in figure 17.

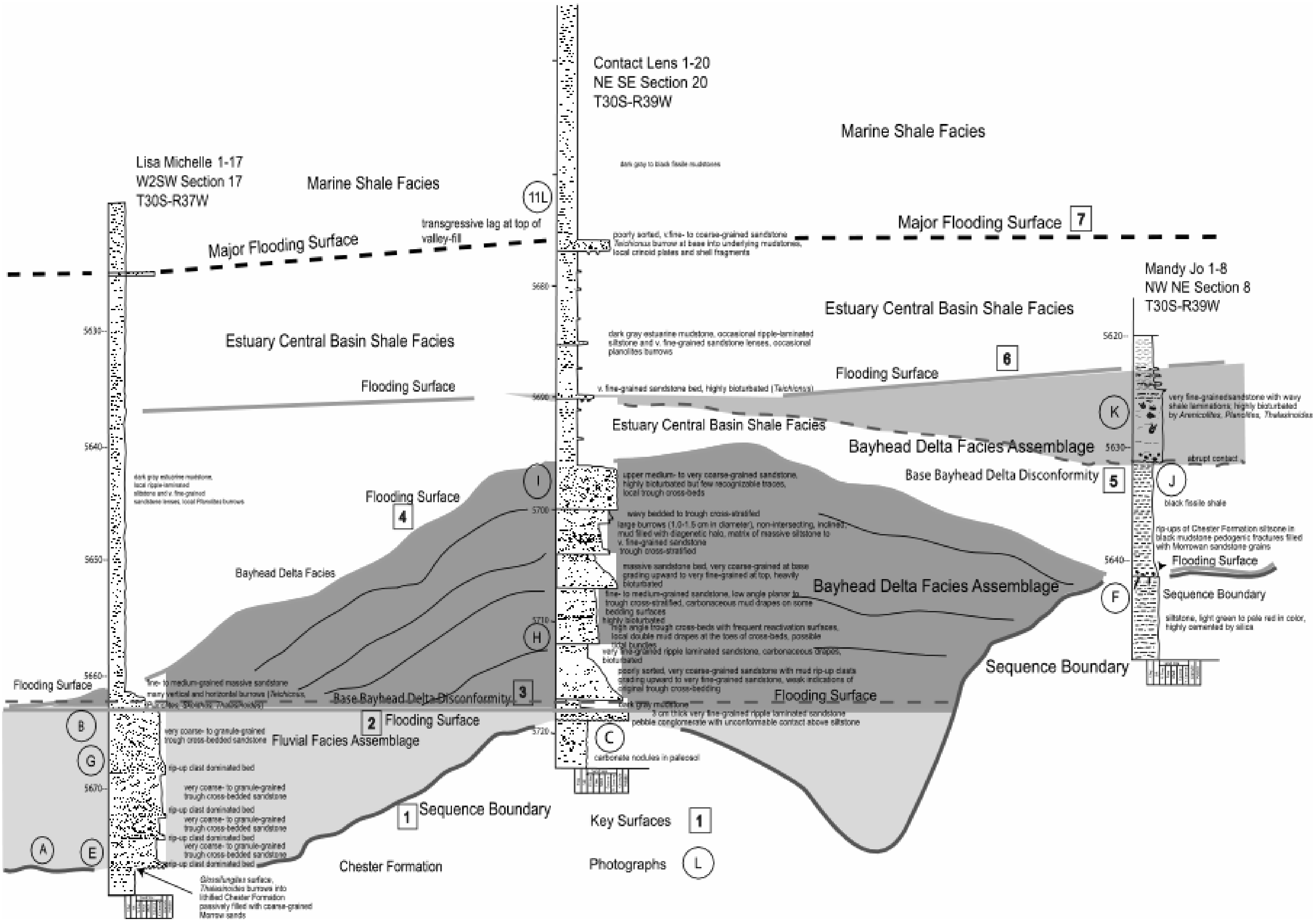

Figure 17. Descriptive log correlation illustrating facies interrelations between basal fluvial, bayhead delta, and estuarine shales within a large estuary complex (modified from Bowen and Weimer, 2004). Note stacked shale succession in Contact Lens 1-20 well.

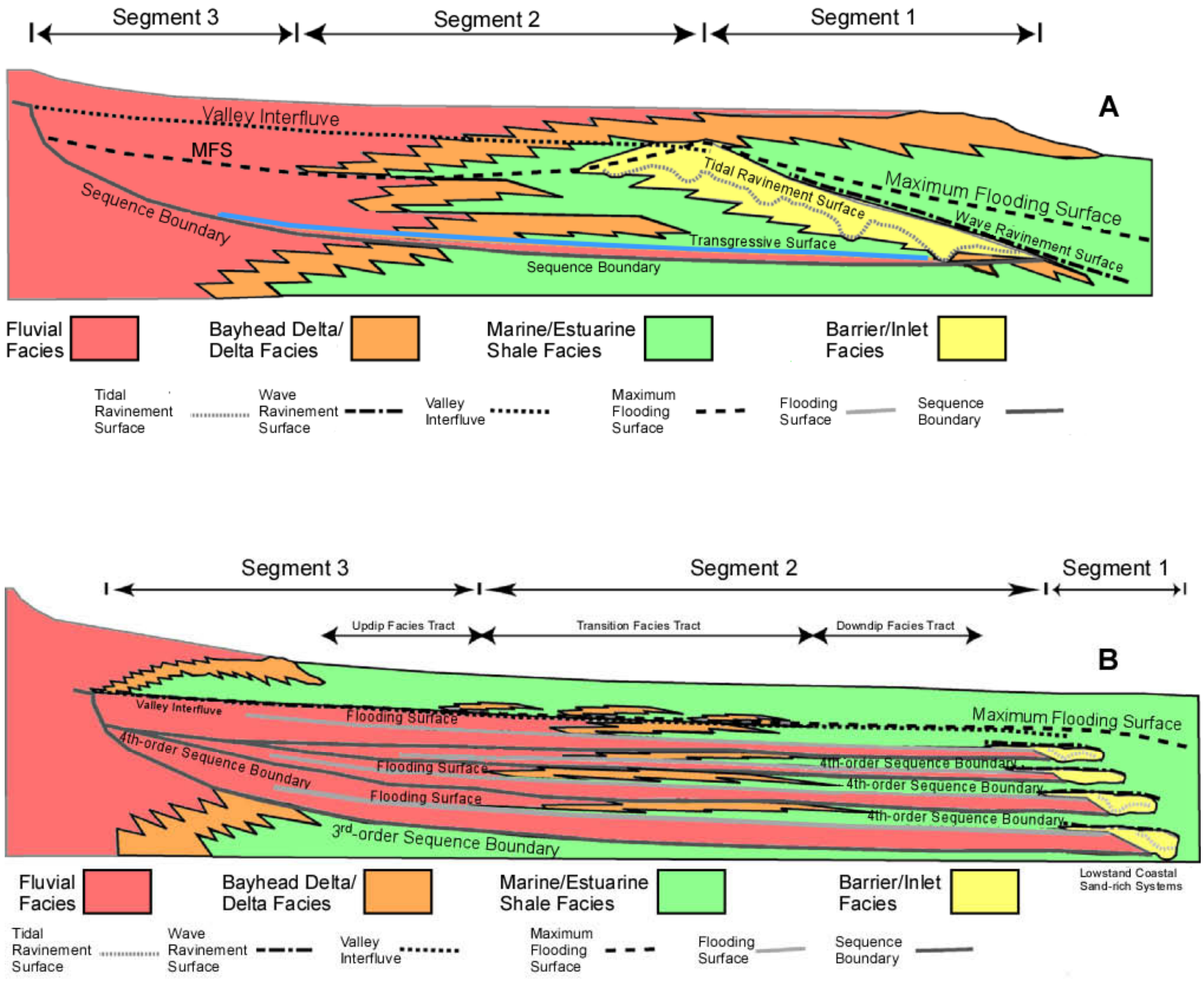

Figure 18. Sequence-stratigraphic architectural models for valley-fill-type sedimentation. (A) Greenhouse model devised by Zaitlin and others (1994), and (B) icehouse model designed by Bowen and Weimer (2003). Note differences in unit thicknesses, lengths, and segment area, as well as extent and position of wave and tidal ravinement surfaces.

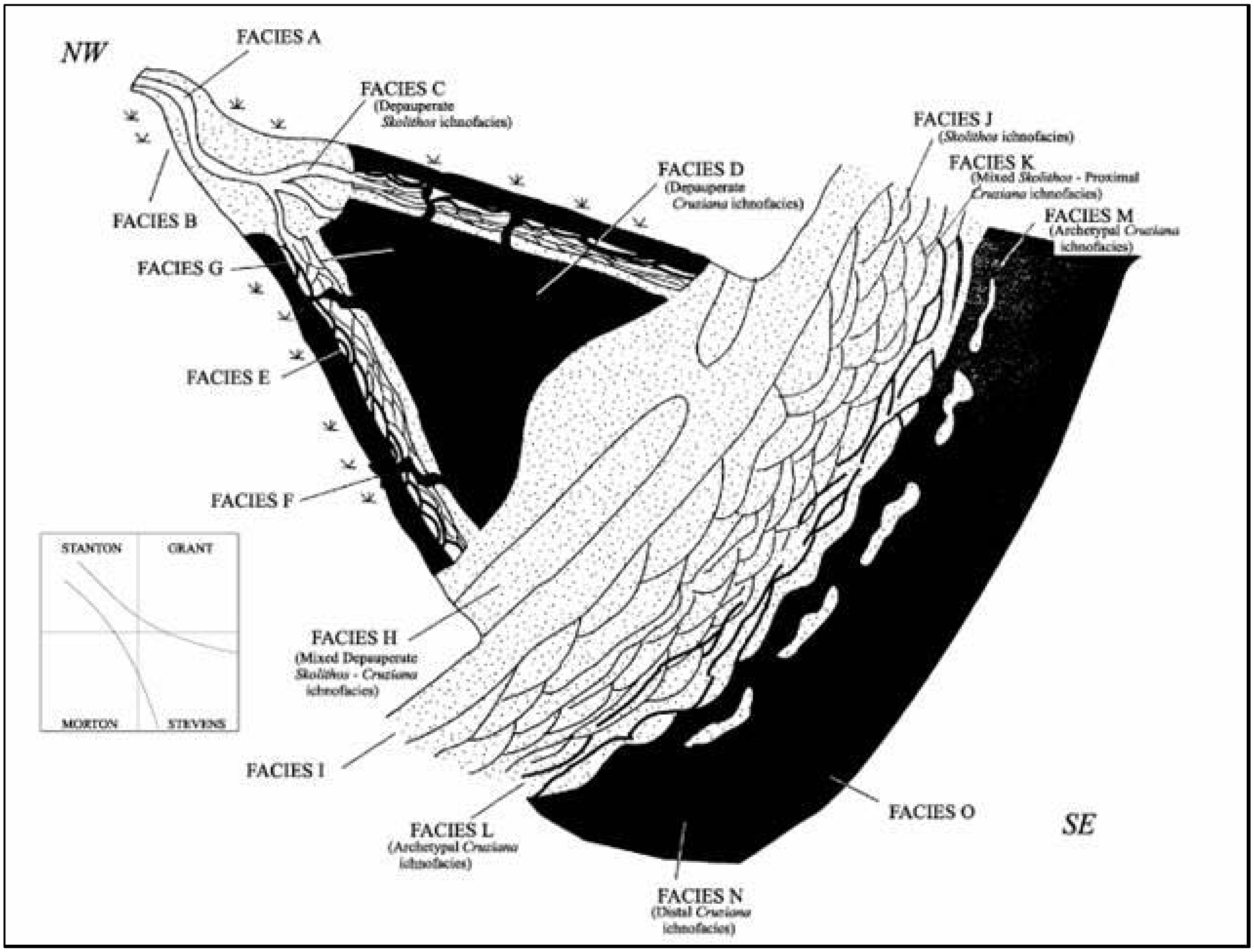

Figure 19. Depositional model for the Lower Morrow. Note similarity to regional model proposed by James 1985 (fig. 24). On the depositional model ichnofacies guilds and associations are also highlighted, resulting in better constraints for correlation (modified from Buatois and others, 2002). Best reservoir quality is in facies A.

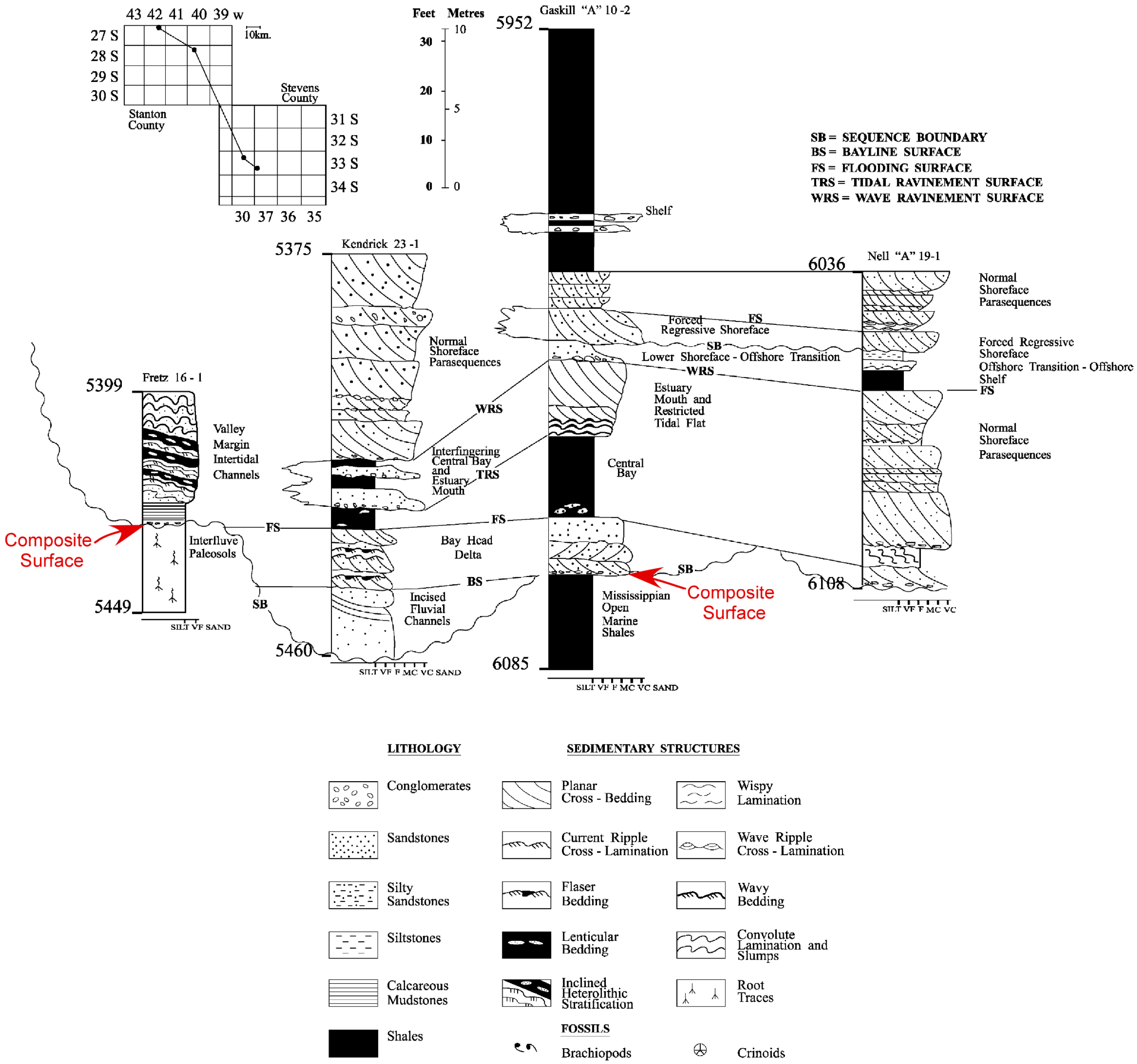

Figure 20. Log and core correlation of Lower Morrow in southwest Kansas. Note abrupt facies transitions between wells and upward replacement of estuarine shales by more marine shales Modified from Buatois and others (2002).

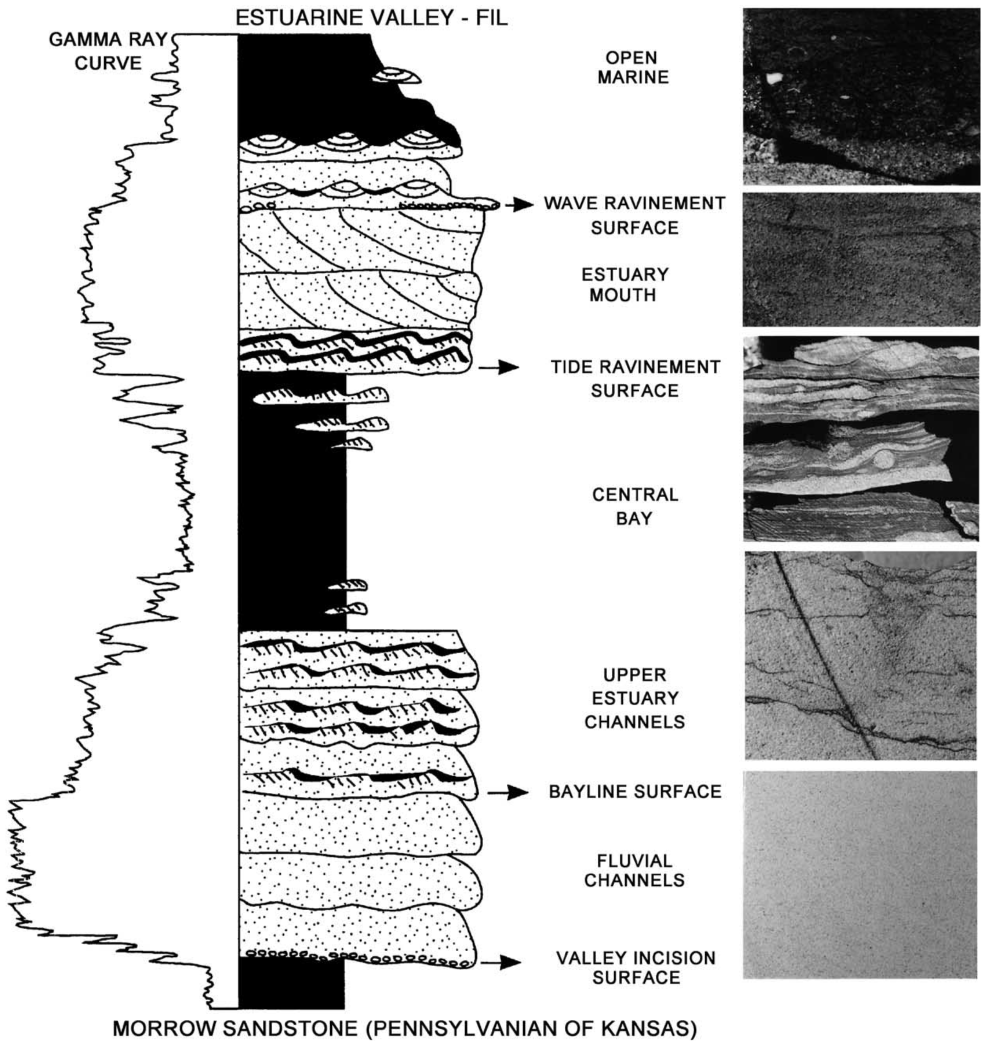

Figure 21. Core photographs, descriptive log, and gamma-ray correlation of estuarine valley-fill sediments. Note the gamma-ray values in upper estuary channel sands and equivalent gamma-ray values for open-marine and estuarine shales. Modified from Buatois and others (2002).

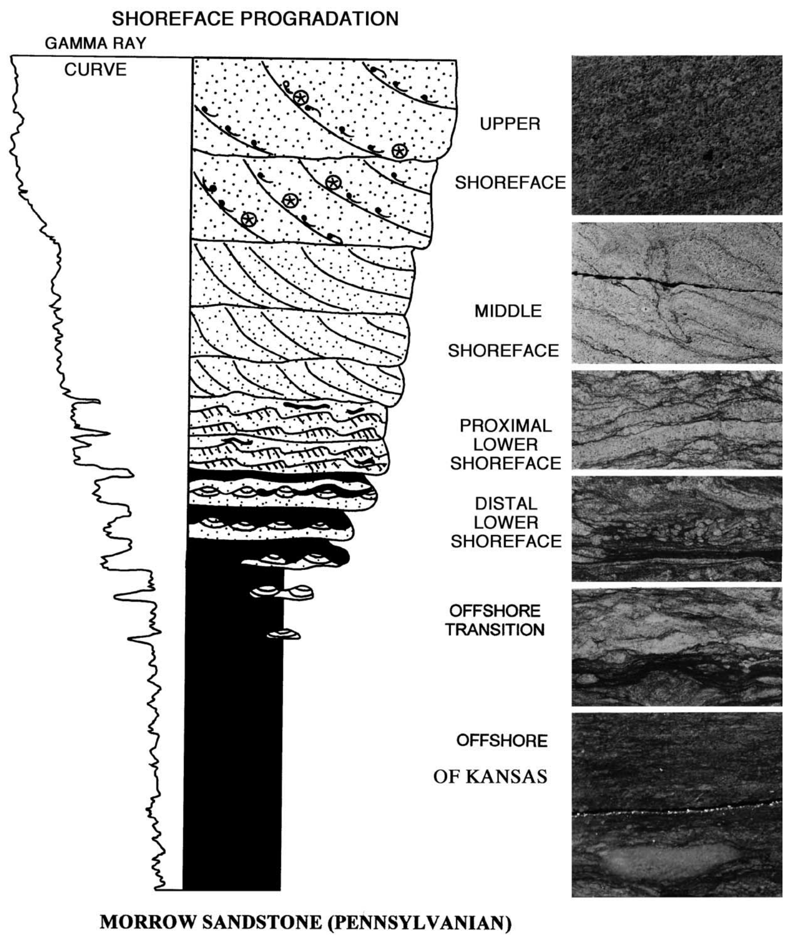

Figure 22. Core photographs, descriptive log, and gamma-ray correlation of the open-marine to shoreface cycles. Note similarity in gamma-ray values between estuary (fig. 21) and open-marine shales Modified from Buatois and others (2002).

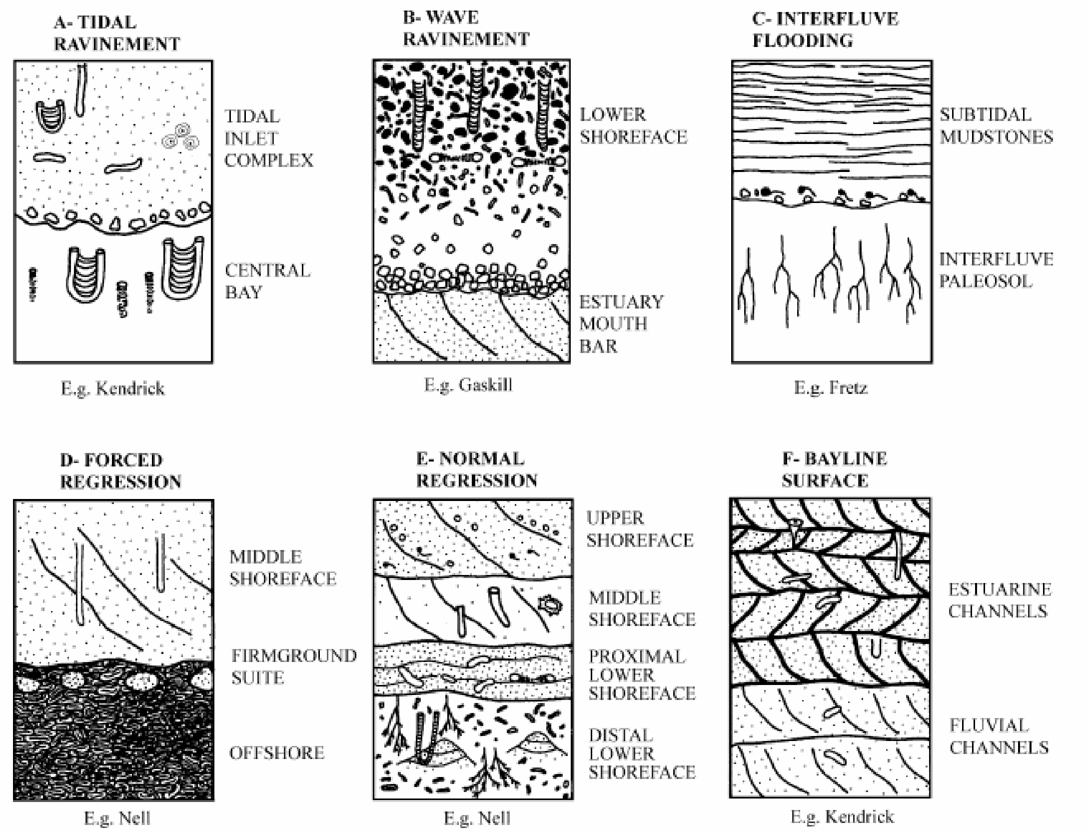

Figure 23. Schematic diagrams illustrating sequence-stratigraphic and sedimentologic significance of ichnofossils from the Lower Morrow in Kansas. (A) Tidal-ravinement surface with low-diversity suites of *Diplocraterion* and *Teichichnus* below surface being replaced by *Palaeophycus*, *Asterosoma, Diplocraterion, and Skolithos*; (B) wave-ravinement surface with passage from estuarine environment to intensely bioturbated shoreface deposits with tiered suites of open-marine *Cruziana* ichnofacies, including long *Diplocraterion*, *Rhizocorallium*, *Palaeophycus,* and *Planolites*; (C) paleosol interfluve flooding with vertical replacement of paleosols (root traces) by subtidal mudstones; a transgressive lag occurs on top of paleosols; (D) forced regression illustrated by intense bioturbated offshore deposits having a distal *Cruziana* assemblage, including *Thalassinoides*, *Chondrites,* and *Phycosiphon* being abruptly replaced by erosive-based, middle-shoreface deposits with elements of the *Skolithos* ichnofacies; erosive contact further demarcated by a *Thalassinoides* firmground; (E) normal regression with a gradual change in softground trace fossil assemblages; archetypal *Cruziana* ichnofacies occurs in distal lower shoreface, whereas a combined *Skolithos*-proximal *Cruziana* ichnofacies characterizes the proximal lower shoreface; *Skolithos* ichnofacies present in the middle shoreface, whereas the upper shoreface is mostly unbioturbated; (F) bayline flooding surface with bayhead delta deposits of overlying lowstand fluvial deposits, as indicated by appearance of clay drapes of tidal origin and *Skolithos* and *Monocraterion.* Modified from Buatois and others (2002).

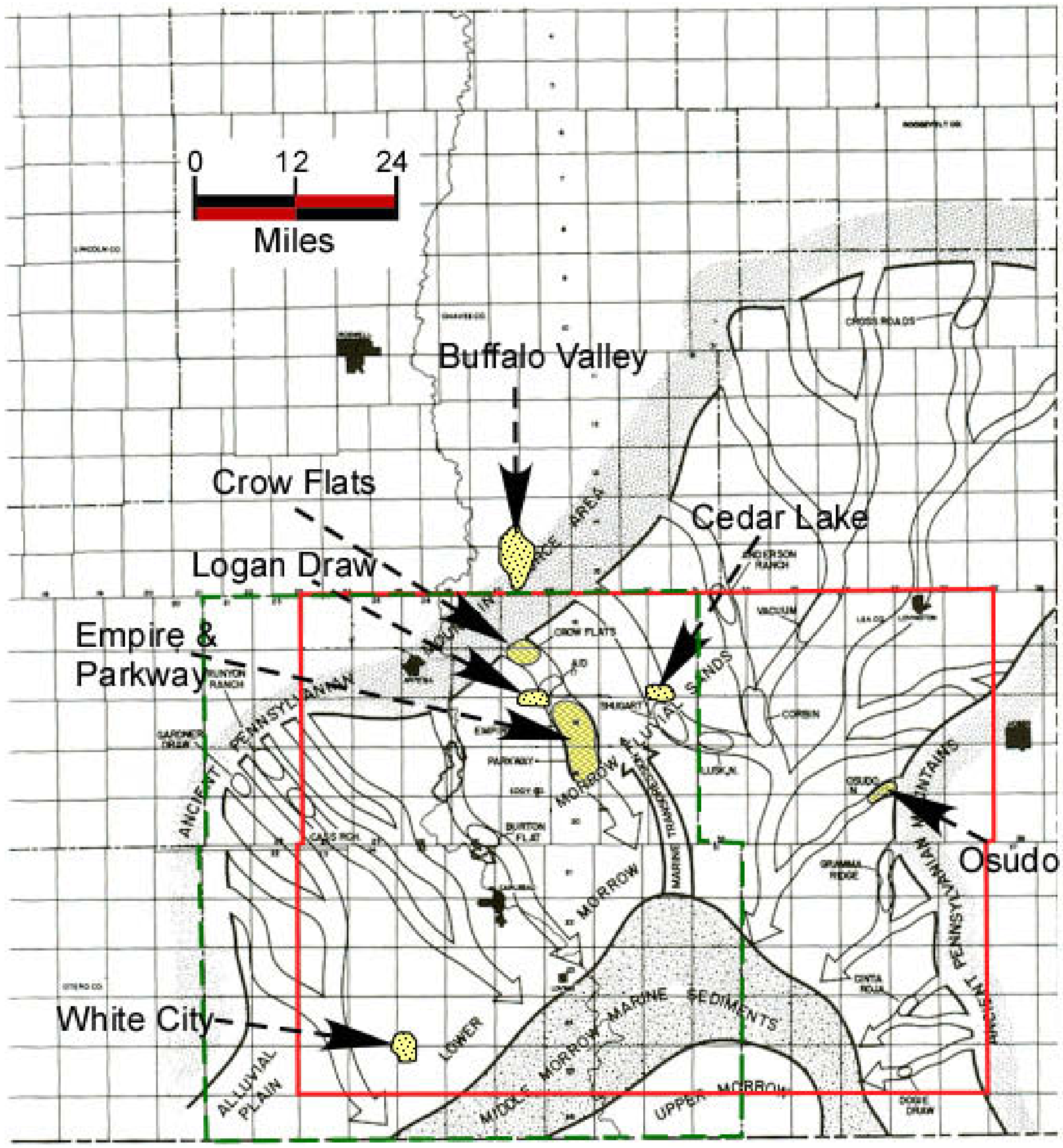

Figure 24. Regional distribution of Morrowan fields in New Mexico and generalized Morrowan paleogeography. Diagram modified from James (1984), with fields highlighted in yellow, Eddy County outlined in green. Facies tract area of Coker (2003) outlined in red corresponds to facies maps in figure 25.

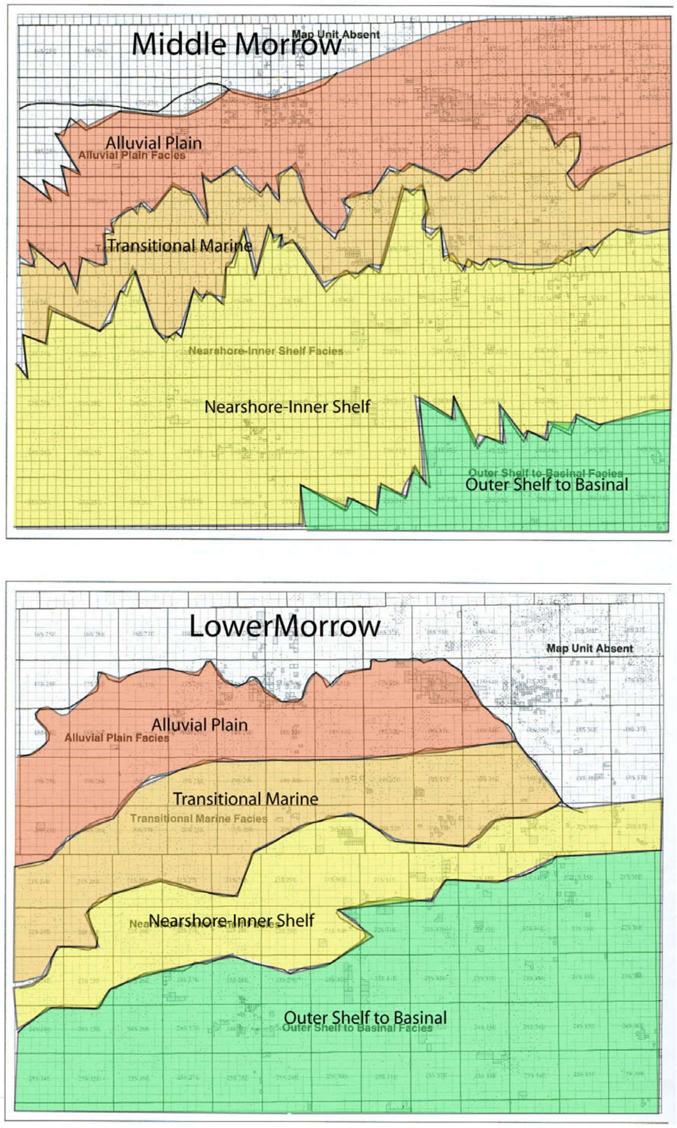

Figure 25. Facies progradation between Lower and Middle Morrow (modified from Coker, 2003). Note expansion and shift southeastward of the nearshore inner shelf facies belt. Overall, the siliciclastic succession is thought to thicken to the south. Note oversimplified layer-cake parallel facies distribution patterns and compare with figure 24. Note that area of the diagram corresponds to red outline in figure 24.

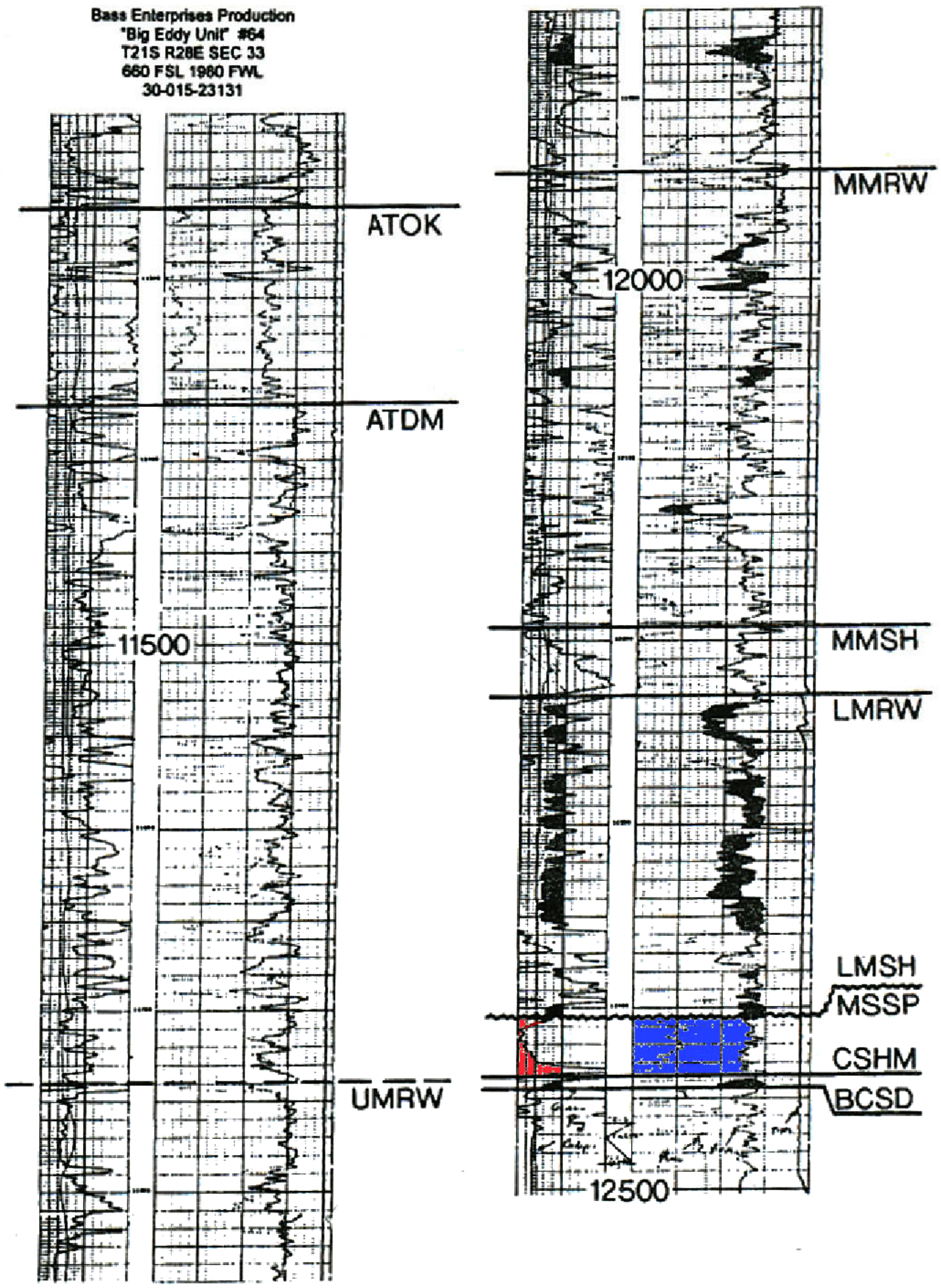

Figure 26. Type log for Morrowan-age sediments in New Mexico (modified from Roberts and Kohles, 1999). BCSD = base of Carlsbad sand, CSHM = Carlsbad shale marker, MSSP = top Mississippian (unconformity), LMSH = top of Lower Morrow marine shale, MMSH = top of Middle Morrow marine shale, ATOK = Atoka. Note that Middle Morrow shale is not considered correlative basinwide. Blue and red highlighted section of well log is proposed Mississippian-age Carlsbad sand.

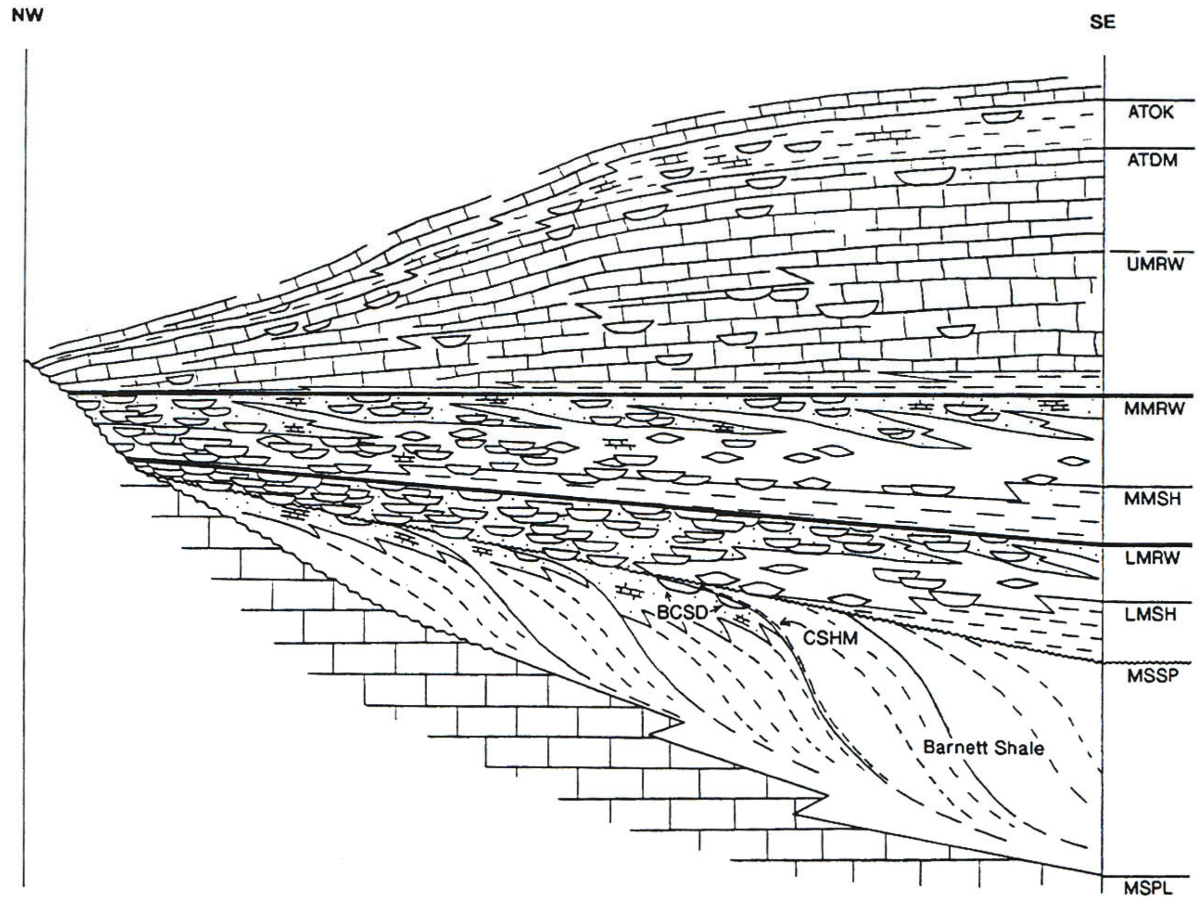

Figure 27. Schematic cross section of Morrowan and Atokan sediments in New Mexico (modified from Roberts and Kohles, 1999). Note apparent transgression in Lower Morrow (LMRW) and regression in Middle Morrow (MMRW).

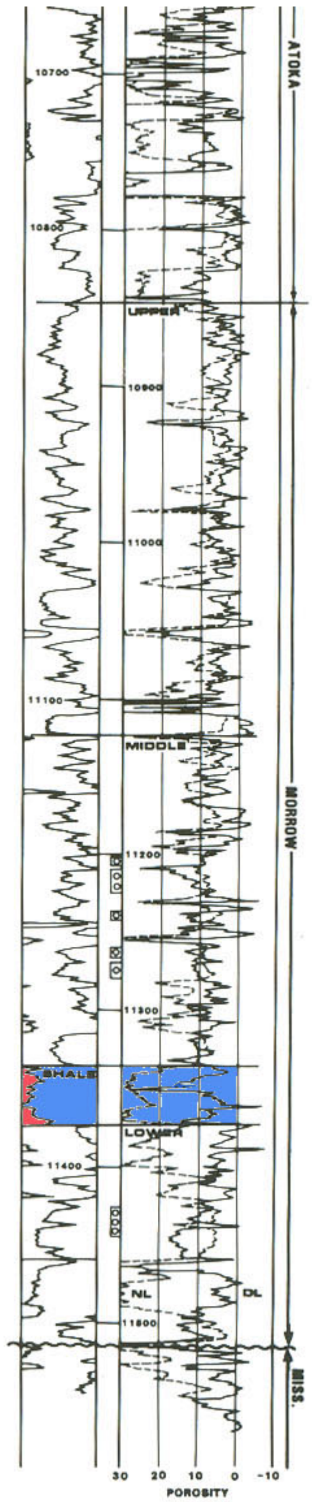

Figure 28. Southland Roy Parkway St. No.1 gamma-ray and compensated neutron-density log for Morrowan and Atokan sediments in New Mexico. Note lack of Mississippian-age siliciclastic unit (modified from James, 1984). Blue and red highlighted area is potential Carlsbad Sand used by Roberts and Kohles (1999).

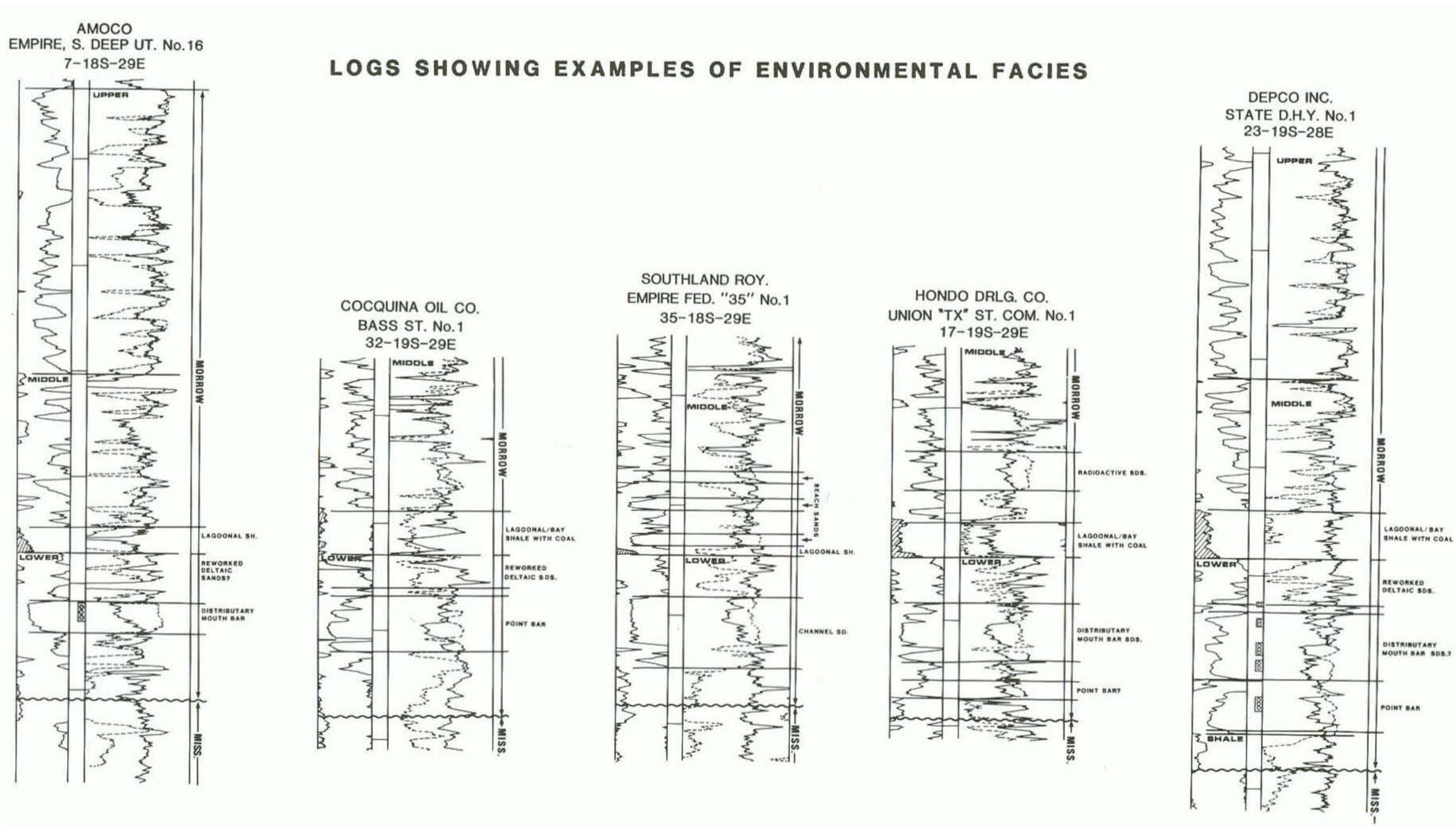

Figure 29. Petrophysical characteristics of Morrow Formation siliciclastic facies. Note environments ranging from mouth bar, lagoon, channel, to point bar, etc. (modified from James, 1984). An alternative depositional environment would be incised-valley fill overlain by estuarine to marine sediments. Note similarity in wireline-log character to that of figures 11, 12, 20, and 21.

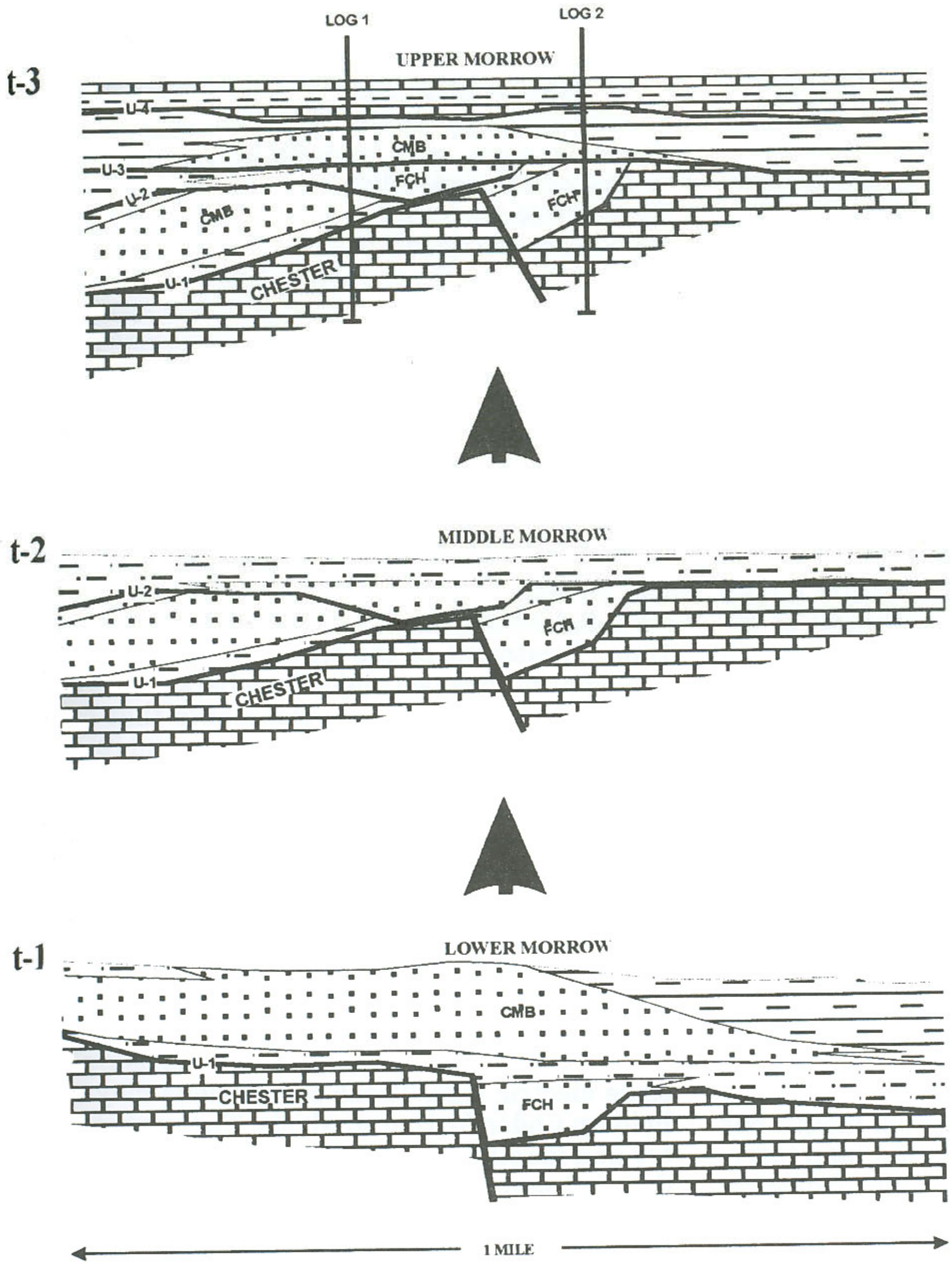

Figure 30. Predepositional and syndepositional controls on facies architecture in Morrow siliciclastics (modified from Mazzullo, 1999). Time = t, with t-1 being the oldest. U1-U4 = unconformity. FCH = fluvial channel, and CMB = channel-mouth bar.

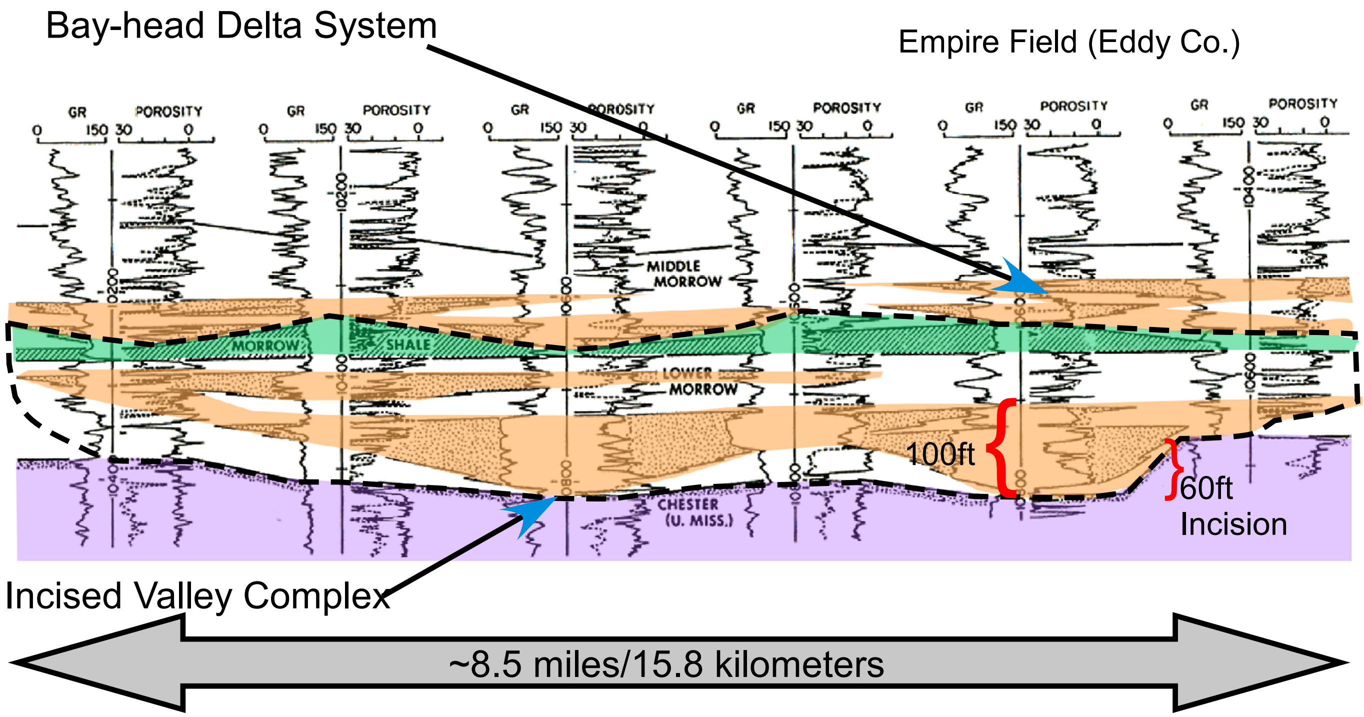

Figure 31. Strike-oriented stratigraphic cross section of Morrow Formation in Empire field, New Mexico (modified from Lambert, 1989). Note large incised valley-fill complex in Lower Morrow and smaller, more discontinuous bayhead delta sands in Middle Morrow.

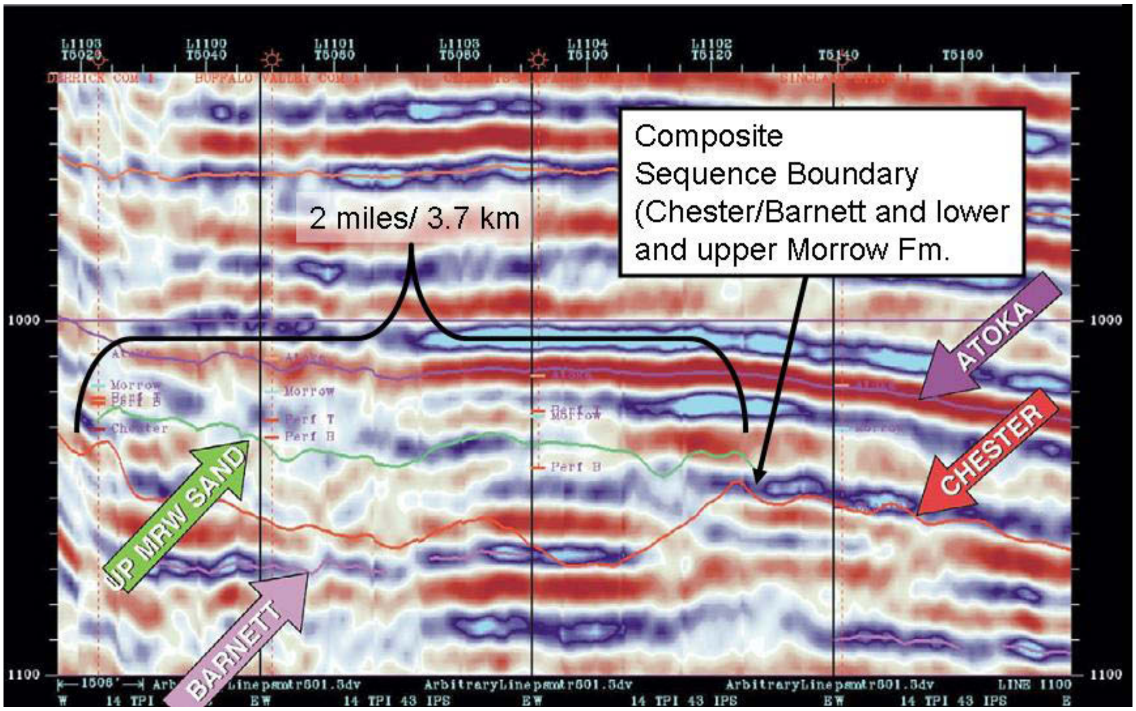

Figure 32. Vertical shear wave traversing through Buffalo Valley field, New Mexico. Note channel shape of Upper Morrow sand pick (top = green); Barnett top pick = lilac. Base of overlying Atoka Formation highlighted in purple. Modified from Van Dok and Gaiser (2001).

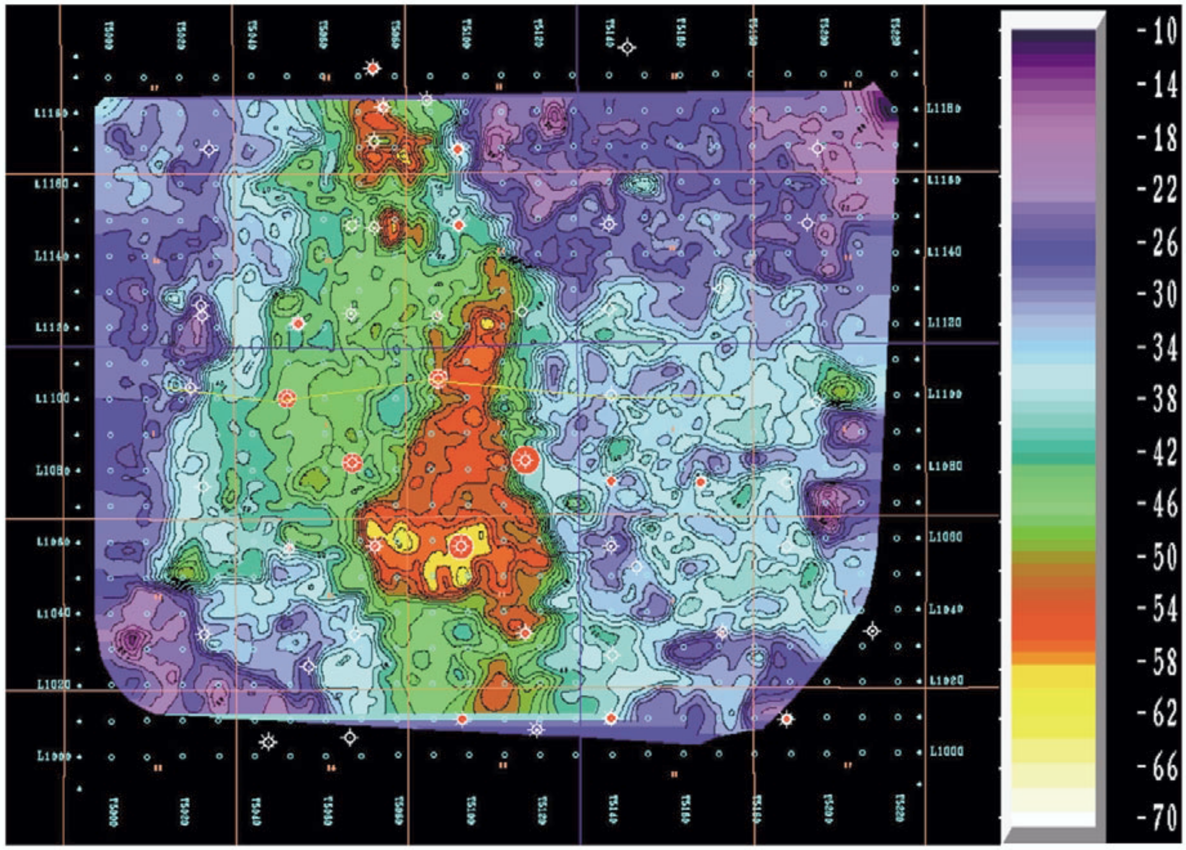

Figure 33. Atoka Formation (top) to Chester (base) isochron map illustrating valley-fill-type geometry (red) of sands in Buffalo Valley field. Modified from Van Dok and Gaiser (2001).

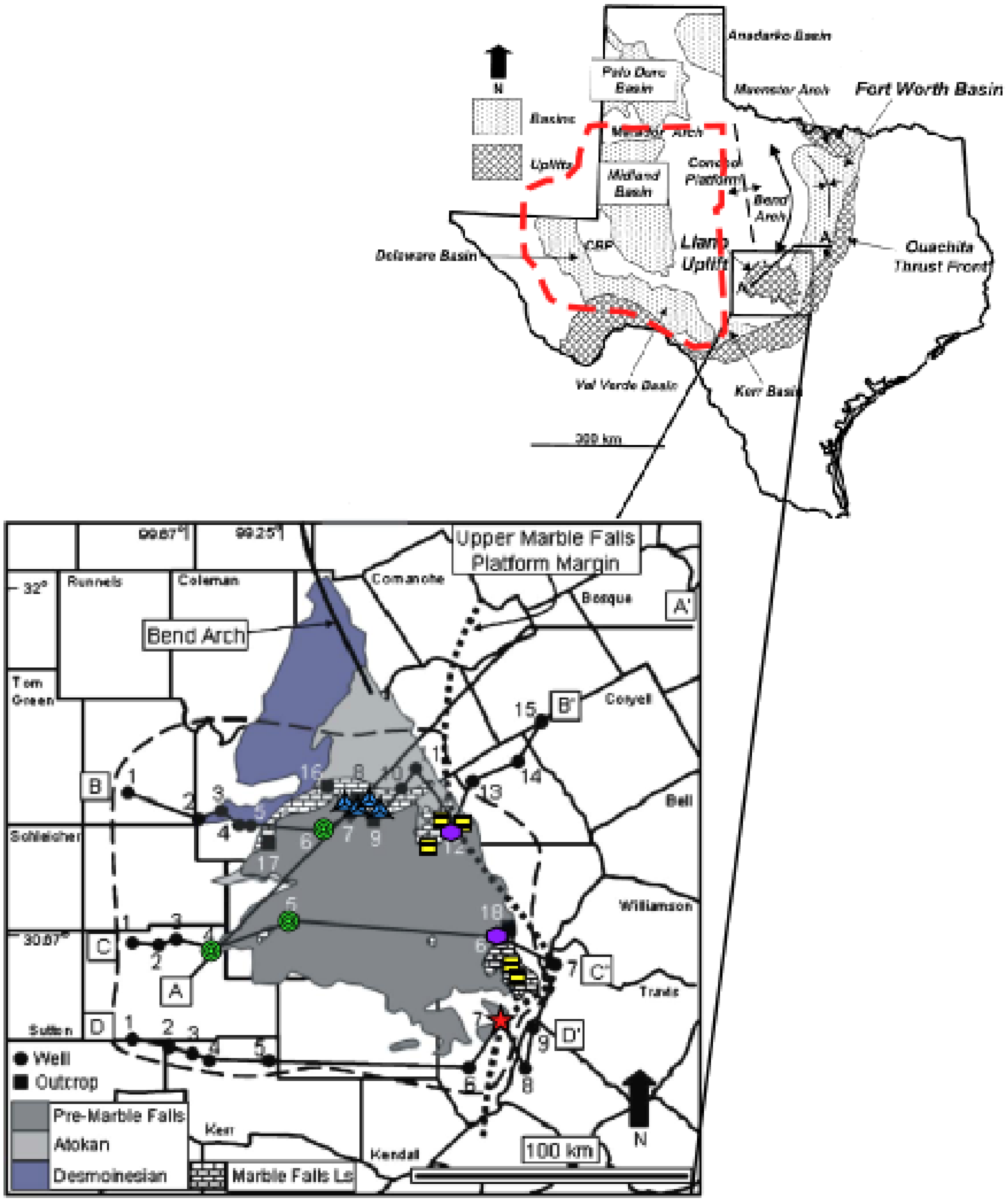

Figure 34. Field and regional area map of Marble Falls Formation. Note that the boundary of the Permian Basin as defined in this study is shown by the dashed red polygon on the regional-scale map (modified from Erlich and Coleman, 2005). Black dashed line is outline of Llano Uplift as proposed by Caran and others (1981). Study localities indicated by green bull's-eye Groves (1991), blue diamond (Bell, 1957), yellow dashed box (Manger and Sutherland, 1984), light-blue hexagon (Plummer, 1950), and red star (McCrary, 2003). Note that red star = Pedernales Falls State Park outcrop area. Kier (1980), Namy (1980), and Erlich and Coleman (2005) used most of the available outcrop data in their studies.

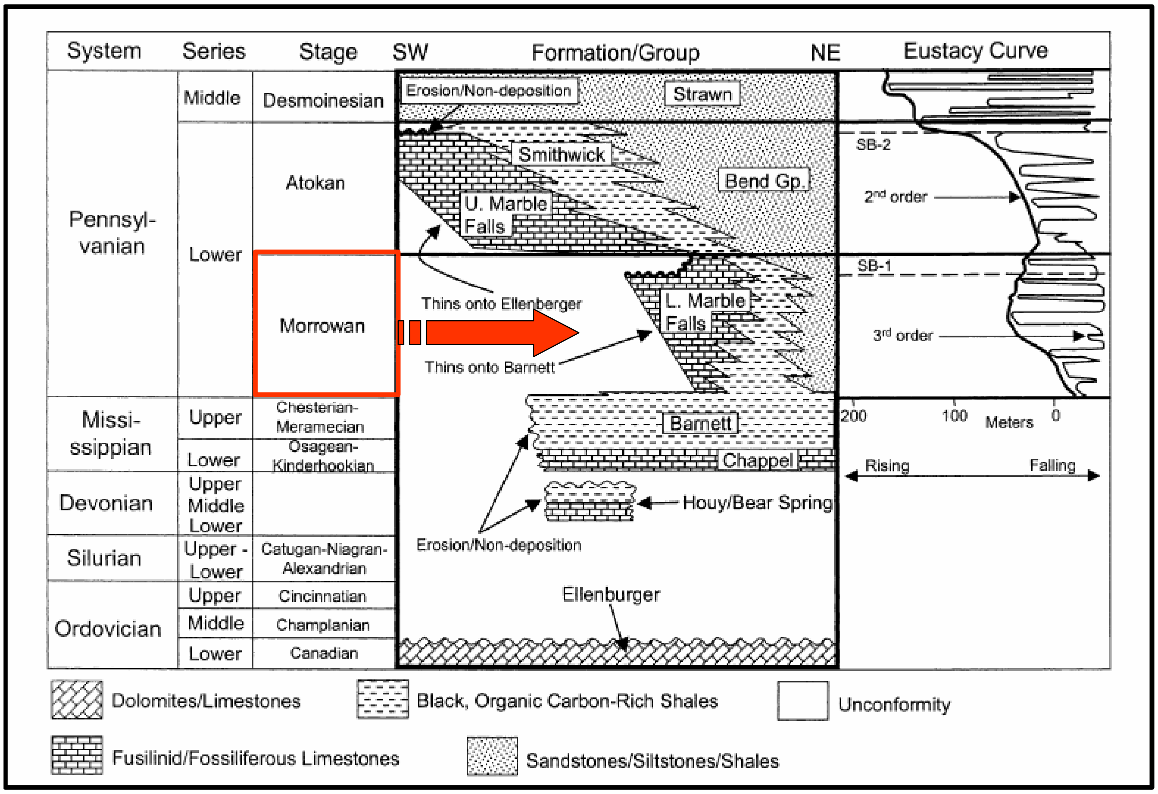

Figure 35. Lithostratigraphy and eustasy data for Llano Uplift region (from Erlich and Coleman, 2005). Eustasy data are from Ross and Ross (1987). Note lateral equivalence of Lower Marble Falls to Barnett and siliciclastics of the Bend Group.

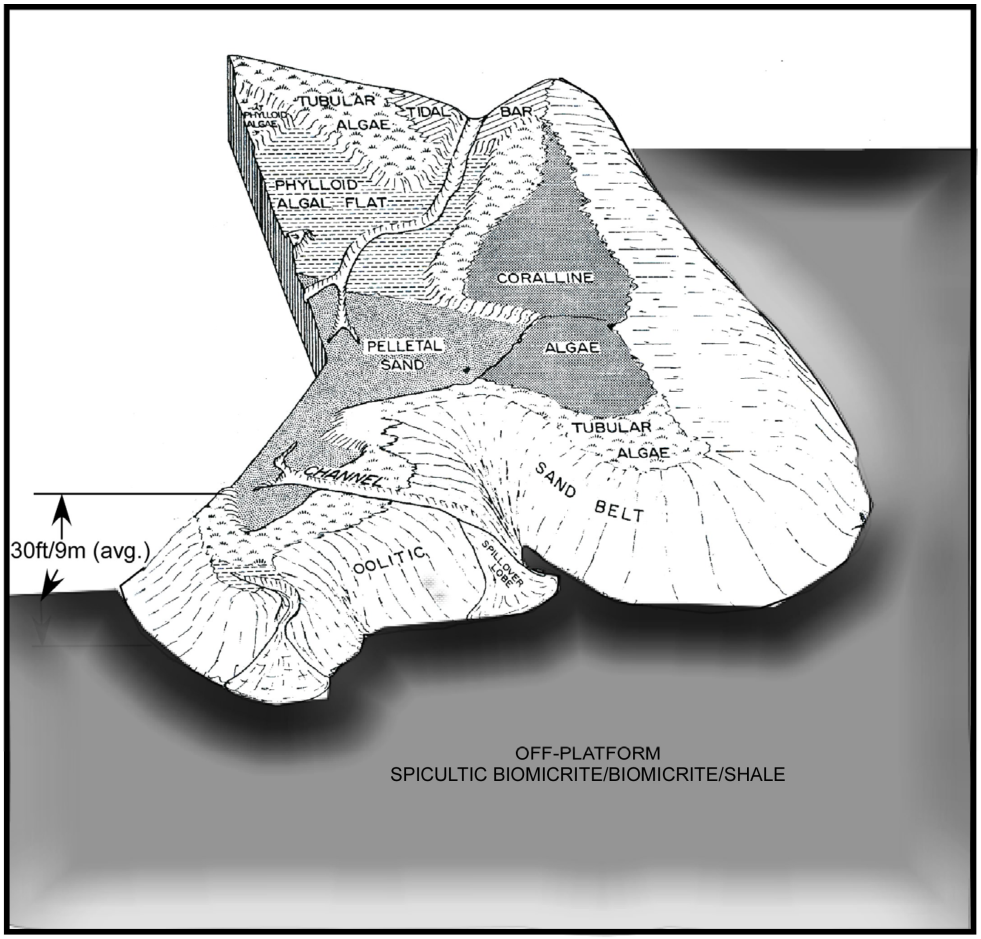

Figure 36. Generalized depositional model for Morrowan lower Marble Falls Formation (from Kier, 1980). General relief at platform margin thought to be 30 ft (9 m) on average. Average relief on platform interior thought to be as much as 16 ft (4.9 m).

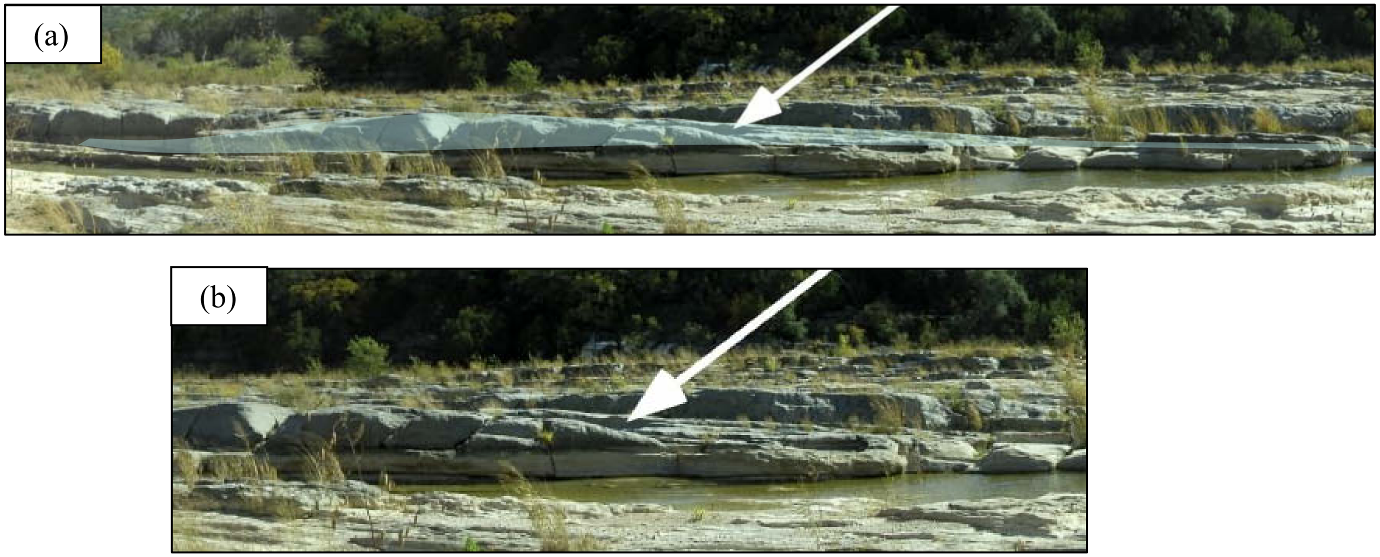

Figure 37. Mound facies (a) and flanking interbeds (b) in proposed Lower Marble Falls (Pedernales Falls State Park). Arrow denotes edge of small mound/bioherm and transition to flanking bed. Average thickness of mound is ~1.25 m.

Figure 38. Lower Marble Falls facies with high-energy bedforms in section. Previously thought to be dominated by spiculitic facies. Hammer is 12.5 inches (0.31 m) high.

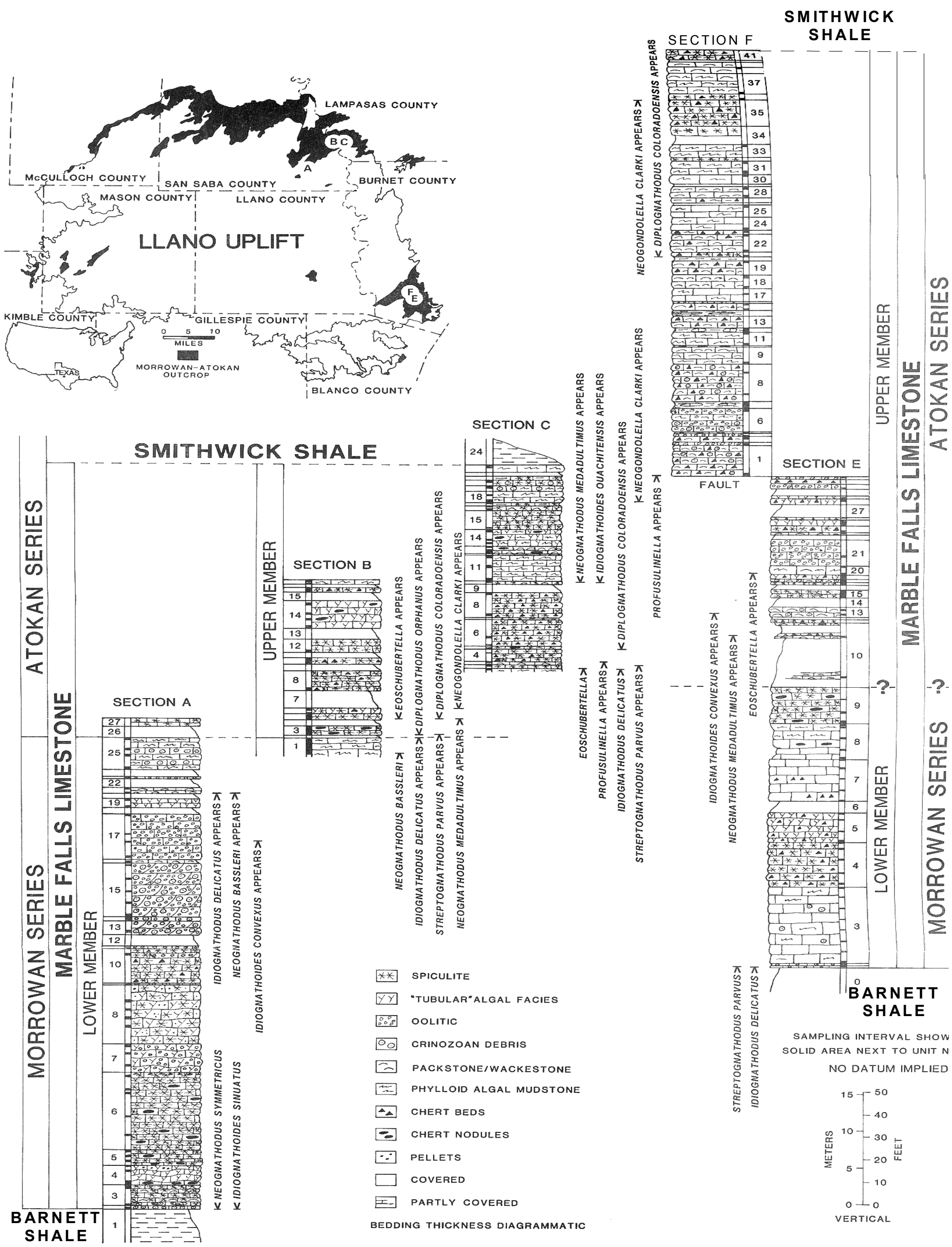

Figure 39. Regional outcrop correlation of Lower and Upper Marble Falls Formation along the east-northeast margin of Llano Uplift (modified from Manger and Sutherland, 1984). Note higher energy facies (oolites dominate) in section A compared with that of section E.

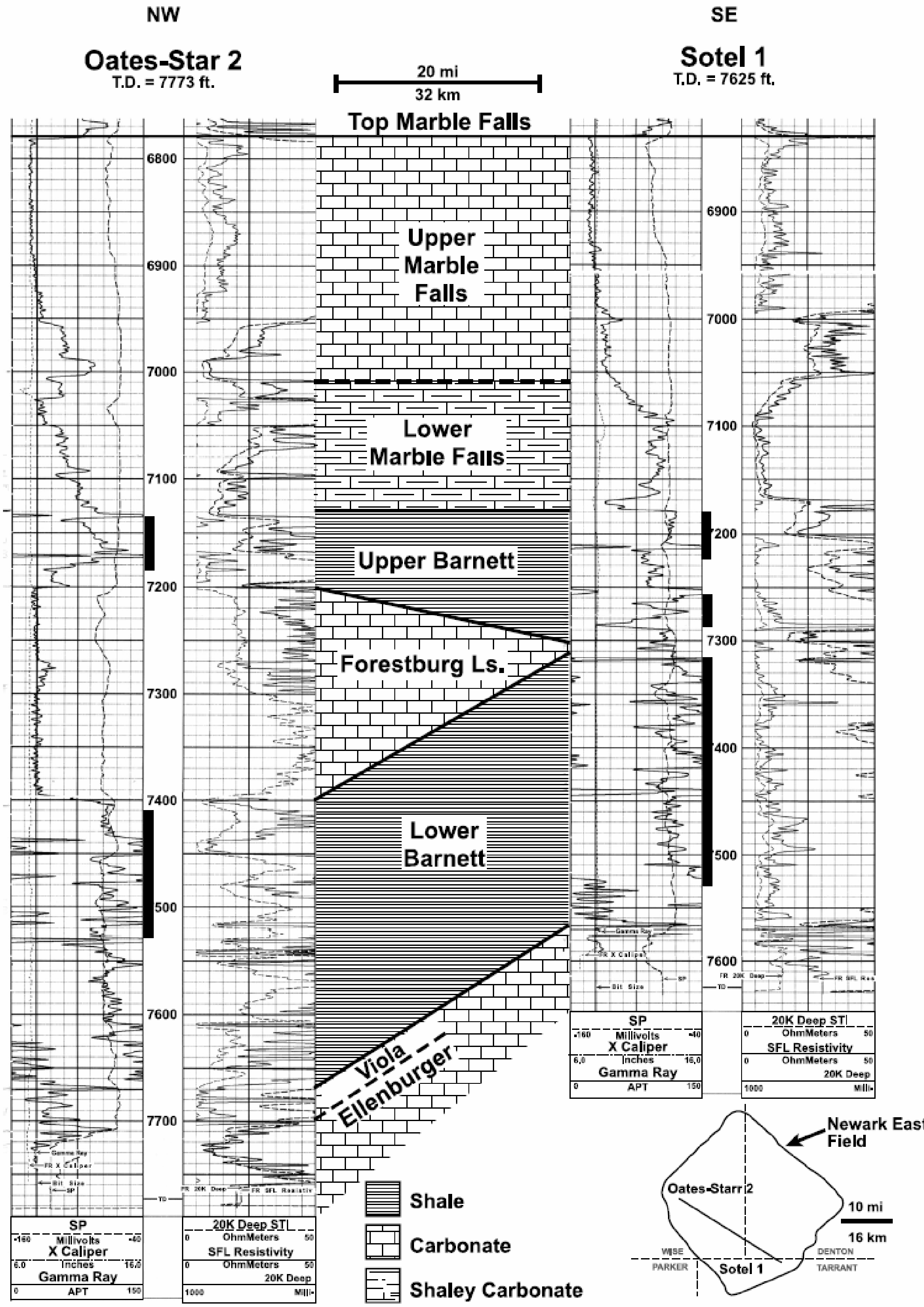

Figure 40. Sample logs to show typical wireline-log character of Barnett Formation through Upper Marble Falls Formation. Note log character differences between two wells at Lower Marble Falls interval.

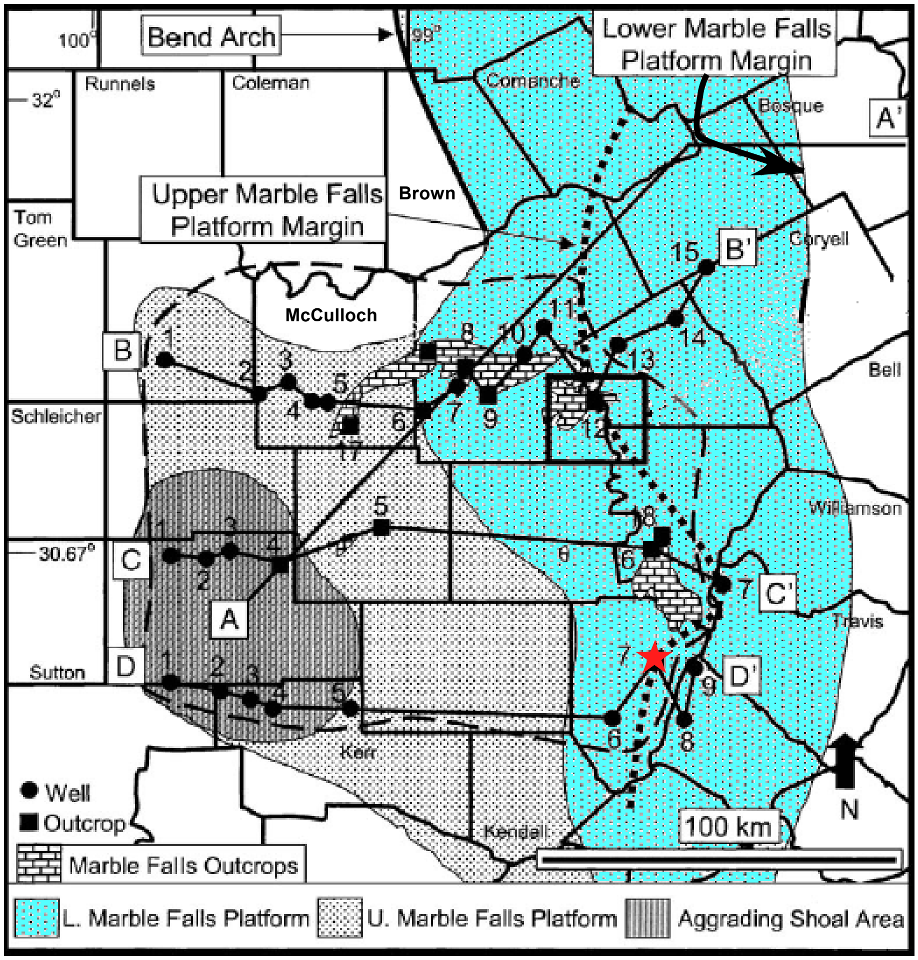

Figure 41. Regional distribution of Lower and Upper Marble Falls Platform (from Erlich and Coleman 2005). Note north-south orientation of Lower Marble Falls succession and lack of coincidence between platform and Llano Uplift boundary (long dashed line). Note position of platforms relative to Coleman and Brown Counties. Red star indicates Pedernales Falls State Park outcrop section studied by McCrary (2003).

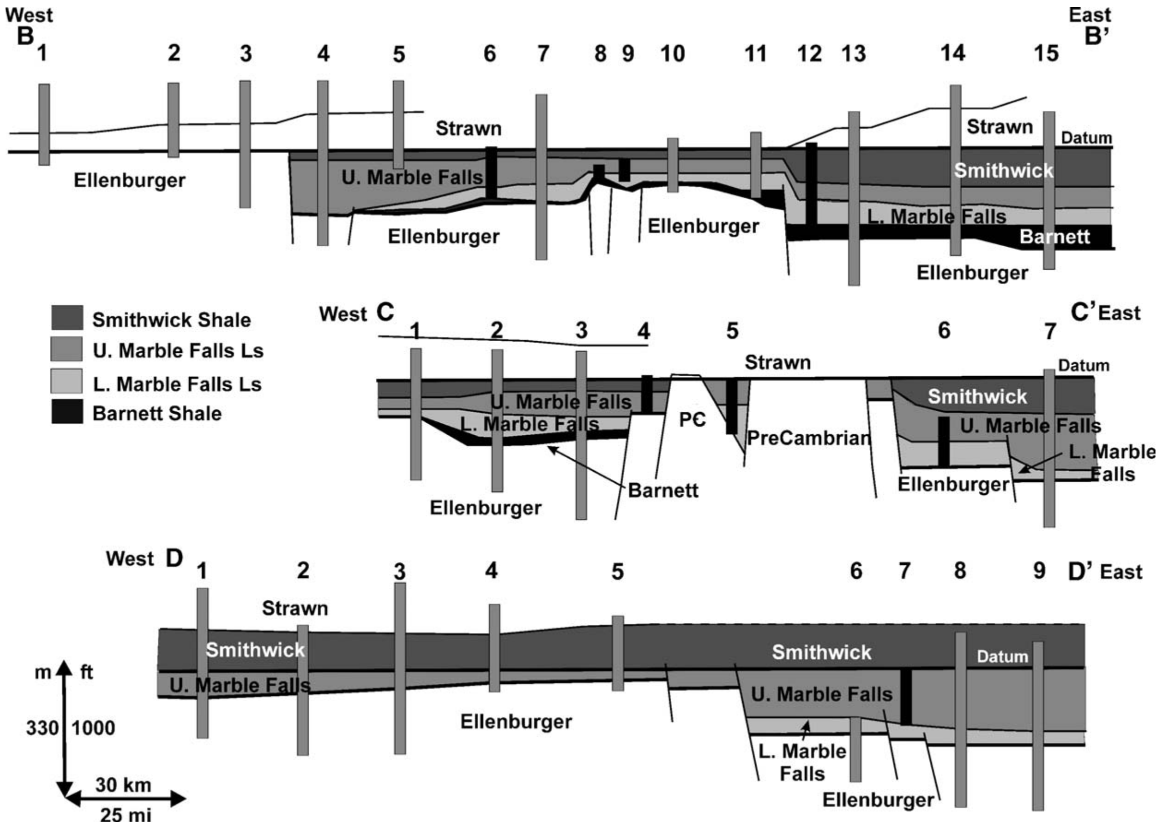

Figure 42. Stratigraphic cross sections of Llano Uplift. Well data are indicated by gray bars, whereas outcrop data are indicated by black bars (modified from Erlich and Coleman, 2005). Note that datum used in cross sections B-B′ and C-C′ is the top of the Smithwick Formation, whereas in section D-D′ it is the top of the Marble Falls Formation. Location of section lines shown in figure 41. Note that location 7 on section D-D′ is Pedernales Falls State Park and was considered wholly Upper Marble Falls by Erlich and Coleman (2005).

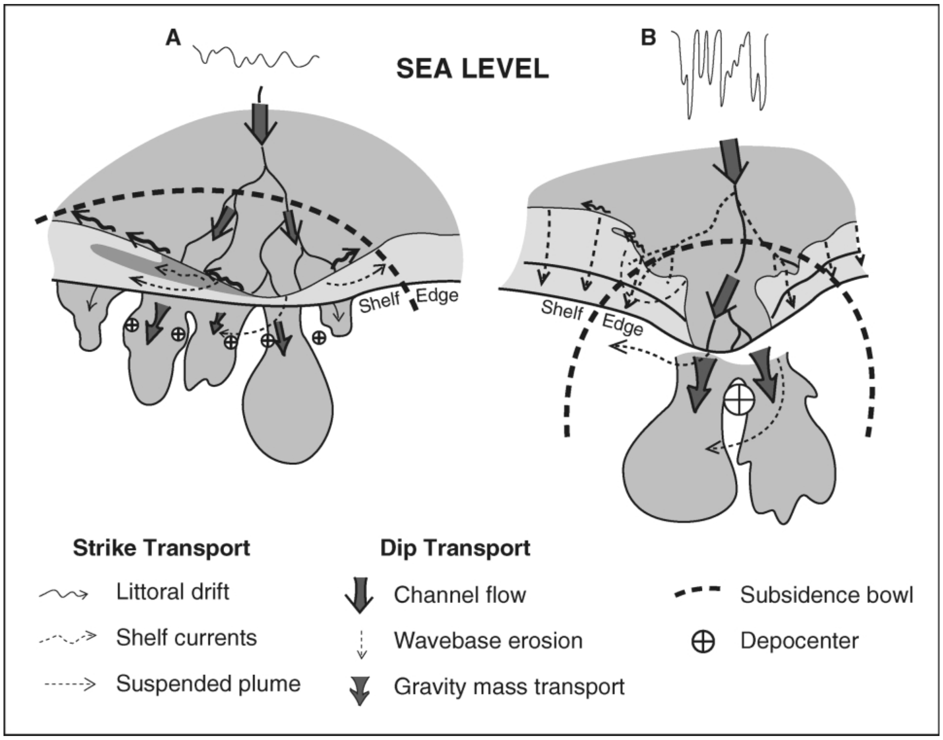

Figure 43. Differences in response of alluvial system transport past shelf edge during (A) greenhouse conditions versus (B) icehouse conditions. Note more confined but larger single depocenter during icehouse conditions (B). Modified from Galloway (2001).