DEPOSITIONAL HISTORY OF THE MISSOURIAN AND VIRGILIAN SUCCESSION (UPPER PENNSYLVANIAN) IN THE PERMIAN BASIN

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ABSTRACT

Missourian and Virgilian sediment distribution reflects a transgressive phase, followed by a more regressive phase of deposition. Because of increased subsidence in the Midland and Delaware Basins, the Canyon and Cisco depositional environments were generally fixed in geographic position. The 2^{nd}-order transgression culminated in latest Missourian to early Virgilian, and mid- to late Virgilian sediments were deposited early in the succeeding 2^{nd}-order regression.

Earliest Missourian deposition is reflected in continued aggradational carbonate growth on the Northeast Shelf, Central Basin Platform (CBP), Horseshoe Platform, and Eastern Shelf. Pronounced aggradational carbonate growth on the margins of the Midland Basin was a result of continued downwarping and subsidence of the basin, which began in the Desmoinesian. In general, deposition of coarse, siliciclastic sediments during the Missourian was restricted to areas east of the Fort Chadbourne high. Fine-grained siliciclastics were deposited in the Delaware, Val Verde, and Midland Basins. Owing to increased subsidence in all basins and an overall transgressive eustatic environment, most basin centers received only small volumes of sediment during the Missourian (starved

basins). High-amplitude, high-frequency, eustatic 3rd- and higher order fluctuations strongly influenced carbonate and siliciclastic facies distribution, composition, and deposition during the Missourian. Early Virgilian sedimentation mimicked patterns established during the Missourian, whereas the late Virgilian was a time of low sediment accumulation and drowning of previous areas of net sedimentation. Most late Virgilian sediments are shales.

Missourian carbonates, which compose the Canyon Group, were deposited over preexisting highs, shelf margins, and platforms around basin margins (for example, Delaware, Midland, and Val Verde) and on the CBP. Phylloid-algal-dominated bioherms and higher-energy facies (ooid grainstones) affected by exposure-related meteoric diagenesis compose the best carbonate reservoirs.

Early to middle Virgilian carbonates (composing the Cisco Group) were generally deposited in the same areas as those of Missourian age; however, the aerial extent of carbonate deposition was less, indicating an overall flooding of areas suitable for carbonate deposition. The late Virgilian (including the Bursam stage) was a time of sea-level fall at the 2nd- and 3rd- order scale, with progradation of carbonates occurring in isolated areas. Decreased accommodation during the mid- to late Virgilian within the Midland Basin resulted in thinner facies stacking patterns and greater proportions of shales thought to be fluvial or deltaic.

New paleographic reconstructions of the Missourian and Virgilian of the Permian Basin are presented (figs. 1, 2). Figure 1 is a reconstruction of a mid- to late Missourian time (mid- to late Canyon/Palo Pinto to Home Creek), whereas figure 2 is a mid- to late

Virgilian reconstruction during approximately the mid- to late Cisco/Breckenridge depositional episode.

Missourian alluvial and deltaic siliciclastics are restricted to the periphery of the Permian Basin (for example, east of the Eastern Shelf margin and within the eastern periphery of the Val Verde Basin). Marine siliciclastic shales are prevalent in the centers of the Midland and Delaware Basins; however, their ages are poorly defined. Widespread platform-carbonate deposition on the CBP, Midland and Delaware Basin margins, and Eastern Shelf occurred during the Missourian. Rapid downwarping and subsidence led to an increased area of deeper water within Midland and Delaware Basins, and carbonates around the margins responded to the increased accommodation by aggrading and backstepping.

Structural development of the Val Verde Basin in Terrell County intensified during the Missourian and Virgilian, and sediments contained in the basin are dominantly sandstones and shales deposited in channelized submarine-fan complexes within the emerging foreland basin. In the extreme southeast part of the Permian Basin, within the Kerr subbasin, coals of Virgilian age have been documented, indicating a depositional environment much shallower than along strike to the west of the Val Verde Basin. The northern Eastern Shelf, north of the Llano Uplift, comprises a series of cyclic carbonate and siliciclastic units similar to the underlying Desmoinesian succession. During the Missourian, marginal marine and alluvial siliciclastics (Devils Hollow, Turkey Creek, and Fambro sandstones) fed the Bowie, Perrin, Eastland, Oran, and Fambro delta systems in Callahan, Eastland, Shackelford, Stephens, Palo Pinto, Young, Archer, Clay, and Jack Counties) (fig. 1). To the west of the deltas, the Palo Pinto carbonate bank and shelf systems (synonymous with the Canyon Platform) and the younger Home Creek carbonate shelf margin complex developed (fig.1). Because of continued subsidence of the Midland Basin, a shallow trough possibly ran from the Knox and Baylor County area (Knox-Baylor Trough) and connected to the Midlands in Mitchell and Fisher Counties. A deepening of the basin also occurred in the Hockley-Lubbock County area. Subsidence in this area potentially led to development of a carbonate shelf margin in Hockley and Lubbock Counties, which would correspond roughly to the north margin of the Horseshoe Atoll. The paleogeographic summary at the end of this chapter should be referred to for a more detailed discussion of the Missourian and Virgilian paleodepositional geography.

On the northern Eastern Shelf, eastern-sourced siliciclastics dominated the highstand and lowstand systems tracts but did not extend past the Home Creek shelf edge during the Missourian (Brown and others, 1990). This situation resulted in a predominance of hemipelagic sedimentation in a starved-basin scenario for the eastern Midland Basin. During the Virgilian, siliciclastic sedimentation was cyclic, with several episodes of greater retrogradation and progradation toward the Permian Basin. Ultimately, basin-plain and -floor submarine fans and prograding slopes were deposited in the eastern Midland Basin (Mitchell, Nolan, and Fisher Counties) during the mid- to late Virgilian in three episodes—Gunsight to Ivan, Blach Ranch to Breckenridge, and Crystal Falls to Flippen. The youngest episode of Pennsylvanian siliciclastic deposition on the Eastern Shelf resulted in a major lowstand leveed-slope and submarine-fan complex covering western Fisher and Nolan Counties, as well as eastern Scurry and Mitchell Counties. These submarine-fan complexes onlap against the base of the aggradational and transgressive carbonate platform of Scurry, Kent, and Howard Counties (Horseshoe Atoll). On the southern Eastern Shelf, volumetrically minor but depositionally significant coarse siliciclastics were deposited in Schleicher County, within the Permian Basin. These sandstones appear to represent distal sheet sands.

CBP was a site of aggradational (Missourian) and progradational (Virgilian) carbonate growth on its east margin. The west margin probably began uplifting to the point of possible erosion during the Missourian in several disconnected segments. During the Virgilian the west margin continued to uplift and generally coalesced into one feature.

The bulk of the Delaware Basin appears to have been largely an area of shale deposition during both the Missourian and Virgilian but lack of age estimates for the shale succession means that the entire package could be of Permian age, and the basin may have been largely sediment starved during the Late Pennsylvanian. On the Northwest Shelf margin of the basin, carbonates were depositing on ramp setting and now compose aggradational, retrogradational, and progradational asymmetric clinoformal composite sequences. Producing fields on the Northwest Shelf appear dominantly in the mid- to outer-ramp position in moderately deep water. Extensive dolomitization is also prominent in this area. The poorly defined west margin of the Delaware Basin consists largely of outcrop exposure, with limited access. This area of the Diablo Platform/Uplift contains a relatively continuous succession of shallow- and deeper-water carbonate and siliciclastic sediments spanning the Pennsylvanian, including Missourian and Virgilian shelfal carbonates. The southern Diablo Platform/Uplift in Culberson, Jeff Davis, and Hudspeth Counties is poorly defined, with an unconformity present that juxtaposes basement and middle-Wolfcampian units. Therefore, either a model of pre-Missourian-age uplift and nondeposition or early Wolfcampian uplift or erosion can be postulated for this region.

INTRODUCTION

This chapter discusses styles of deposition and facies development of Missourian- and Virgilian-age sediments, concluding with a discussion of revised paleodepositional maps for both stages in the Permian Basin (figs. 1, 2; Summary). Siliciclastic deposition and carbonate deposition are discussed separately, with a regional model for facies patterns and deposition proposed for each section. 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 are used to illustrate certain key aspects (for example, facies type and reservoir quality). First, an initial introduction to the area, placing it in a global perspective, is presented.

GLOBAL TECTONIC SETTING

Recent plate models suggest that the Permian Basin was still in the southern latitudes during the Missourian and Virgilian (4 –8^{o} south) (Dalziel and others, 2002) or in the northern latitudes (0 –4^{o} north) (Walker and others, 1995) (fig. 3). In either case, Missourian- and Virgilian-age sediments in the Permian Basin are characterized as having been deposited at a near-equatorial position during the late stages of icehouse, high-amplitude, high-frequency, relative-sea-level fluctuations. Also during this time, the Permian Basin was undergoing heightened tectonic activity of both uplift and subsidence related to the Ouachita–Marathon Orogeny. Figure 3 illustrates the position of Texas (in orange) relative to major tectonic plates and the equator during Missourian and late Virgilian times.

REGIONAL TECTONIC SETTING AND FACIES DISTRIBUTION

The outline of the Permian Basin and major geologic features commonly associated with the basin are illustrated in figure 4. The main features had developed by the mid-Missourian and stayed largely in a similar configuration through the Middle Permian. Figures 5 through 7 illustrate previous interpretations of facies distribution, uplift, and subsidence patterns for Missourian- to Virgilian-age sediments in the Permian Basin and surrounding areas. Previous interpretations suggest that the Delaware and Midland Basins of the Permian Basin were areas of net subsidence rimmed by carbonate-platform to shelfal environments, with substantial uplift in areas of the Diablo Platform, Central Basin Platform (CBP), and the Marathon–Ouachita foldbelt margin (Kluth, 1986; Ye and others, 1996; Blakey, 2005) (figs. 4–7).

Areas of uplift, subsidence, and facies distribution in figures 5 through 7 are roughly consistent between one another. According to Kluth (1986), most of the Permian Basin area is an area of net subsidence, with rate ranging from less than or equal to 50 m/Ma to approximately 200 m/Ma (fig. 6). Development of the foreland-thrust-bound Val Verde Basin is prominent on all Virgilian-age paleogeographic reconstructions. Continued uplift of the CBP and deepening of the foreland trough in the Val Verde Basin appear to be dominant areas of active tectonism in the Permian Basin during the Virgilian (Kluth, 1986; Ye and others, 1996; Blakey, 2005) (figs. 5–7). With the exception of the Blakey (2005) reconstructions, previous regional models neglect the west part of the

Delaware Basin and issues regarding development of the Diablo Platform/Uplift. Current facies distribution models of the Missourian and Virgilian series in the greater Permian Basin are discussed in the paleogeographic summary and differ substantially from those previously generated (figs. 1, 2). Details regarding structural configuration and development of the Permian Basin are reserved for a separate chapter.

GENERAL STRATIGRAPHY AND NOMENCLATURE

Missourian-age sediments within the Permian Basin include those termed *Canyon Formation* (predominantly carbonates) and those of the Canyon Group. Within the Permian Basin, most Missourian-age sediments are referred to as the Canyon Formation, and they are overwhelmingly carbonates. Virgilian-age sediments within the Permian Basin include those termed *Cisco Formation* (predominantly carbonates and shales) and those of the Cisco Group. However, on the Eastern Shelf, Missourian and Virgilian stratigraphy is divided into multiple carbonate and siliciclastic units.

Nomenclature

As is true of the underlying intervals, stratigraphic nomenclature for the Missourian and Virgilian interval on the Eastern Shelf is highly subdivided, stemming largely from extensive outcrop study in central Texas (figs. 8, 9). One point crucial to those readers unfamiliar with the Permian Basin succession is that the Cisco Group (*sensu stricto*) is not wholly Pennsylvanian and contains almost the entire Permian Wolfcampian succession at formal type localities.

SILICICLASTIC MISSOURIAN DEPOSITION

General Depositional Setting

Deltaic, fan-delta, and incised-valley systems occur throughout the Missourian, the latter of which are restricted largely to North-Central Texas, west of the Fort Worth Basin. Multiple deltaic depocenters were active during the Missourian, funneling sediment onto the northeast and east margin of the Eastern Shelf. Slope-fan and slope-wedge sediments appear to be locally present in Kent, Mitchell, Nolan, Sterling, Tom Green, Schleicher, and Sutton Counties along the Eastern Shelf (fig. 4). Coarse-grained siliciclastic sediments were restricted to the extreme east margin of the Permian Basin (as defined in this study). Locally the Llano Uplift appears to be the likely source area of a minor siliciclastic depositional episode on the southern Eastern Shelf. Historically, many of the siliciclastic reservoir intervals along the Eastern Shelf are termed Canyon sands. However, reinterpretation of these plays via seismic and wireline-log correlations indicates that most are Permian in age (Wolfcampian to Leonardian), and only a few are Pennsylvanian. These reservoirs will therefore not be discussed in this chapter.

Although the Pedernal Uplift appears to have entered a renewed stage of uplift, it contributed little in the way of siliciclastic sediments to the Delaware Basin. The San Simon Channel manifested itself between the northernmost part of the CBP and the Northwest Shelf. In the Permian Basin, 2^{nd}-order transgression during the Missourian resulted largely in deposition of carbonates at the expense of coarse siliciclastic lithologies. During the Missourian, centers of the Midland and Delaware Basins seem to have received minimal sediment input, resulting in a starved-basin succession.

The role of the Diablo Uplift/Platform as a potential sediment source of the Delaware Basin is largely undefined. Fine siliciclastics may have been sourced from the southern Diablo Platform during a possible uplift and erosion event during the Virgilian.

The Val Verde Basin was generally starved of sediment, with rare channelized turbidite systems present, whereas in the Kerr subbasin to the east of the Val Verde Basin, Virgilian-age coals are present, indicating a dramatic decrease in accommodation between the two contiguous areas.

Reservoir Potential

Updip fluvial, amalgamated, stacked channels and thick fan-delta units have the best reservoir potential and quality. However, most, if not all, of the proximal facies occur to the east of the Permian Basin. Few data exist to confirm the presence of Missourian-age, deeper-water siliciclastic facies within the Midland or Delaware Basin. In general, only along the north part of the Eastern Shelf do shelf to basinal gradients appear steep enough to result in deposition of Missourian or Virgilian slope or basin-floor deposits.

Diagenesis

Clay diagenesis is likely the most important factor in determining productive Missourian- or Virgilian-age siliciclastic reservoirs in the Permian Basin. In the slope and basin-floor setting, amount of detrital clay and its subsequent diagenesis (growth and or dissolution) will largely control porosity and permeability.

Climate

The Missourian and Virgilian were times of expansive ice-sheet development typified by a highly fluctuating relative sea level. Amplitude and frequency of sea-level change are greater than at any other time during the Pennsylvanian. Highly fluctuating sea levels generally resulted in thinner, higher-frequency cycles and numerous periods of exposure. Given the relative changes of coastal onlap, the end of the Missourian stage marks the 2nd-order transgressive Pennsylvanian climax.

PERMIAN BASIN DATA

Eastern Shelf

Detailed studies were performed by Cleaves (1975, 1993, 2000) and Cleaves and Erxleben (1982, 1985) on the siliciclastic depositional patterns of the northern Missourian Eastern Shelf. Figure 8 illustrates a schematic representation of Missourian (Canyon Group) sedimentation patterns along the northern Eastern Shelf and farther eastward into the greater Fort Worth Basin. During the Missourian, siliciclastic sediments encroached upon the Eastern Shelf but never breached the carbonate-shelf margin-bank system (Palo Pinto Bank). In the northern Eastern Shelf, influx episodes are associated with Devils Hollow, Turkey Creek, and Fambro Sandstones (fig. 8). During the Virgilian, sedimentation is skewed 2:1 toward siliciclastics over carbonates, with the southern Eastern Shelf generally having more frequent transgressive carbonate deposition (fig. 9). During the Missourian, no highstand deltaics prograded across the entire shelf (Eastern Shelf), and ramp and shelf-margin sediments are either carbonate or condensed marine shales. A proposed slope system exists in Knox and Baylor Counties (fig. 10). This succession, termed the *Knox Slope System* or, alternatively, the *Canyon Slope System* contains thin sandstones encased in shale. The origin of this slope system is equivocal and may be linked updip to the east across the carbonate-bank system (fig. 10) or alternatively linked northward. A northern/northeastern source appears more likely because no stratigraphic data support a siliciclastic depositional episode breaching the carbonate-shelf margin during this time. The Knox Slope System is coincident with a depositional low that trends northeastward from Mitchell to Baylor County that was established during the late Desmoinesian (fig. 2—Depositional architecture of the Desmoinesian in the Permian Basin). This trough became more pronounced during the Missourian as a result of high rates of aggradation in the carbonates and localized increased subsidence. Downslope and along strike, processes may have distributed thin sands toward the Permian Basin into Stonewall, Fisher, and Scurry Counties. Given the shelf-edge positions during the Missourian, the Knox Slope deposits would have been deposited at a time between Palo Pinto and Home Creek Formations (figs. 8, 9).

On the southern Eastern Shelf in Schleicher County, thin, discontinuous sandstones are present between Strawn carbonates and overlying Palo Pinto and Adams Branch limestones. These sandstones have various names in the subsurface, including Camar (possibly upper Missourian), Tillery, Harkey, and Crosscut. Because these sandstone bodies can be constrained to occurring below Missourian limestones (Palo Pinto and Adams Branch) and above true Desmoinesian carbonate (Strawn), they are truly Canyon sands (Missourian), as opposed to the “Canyon” sand of Sutton and Val Verde Counties, which are Permian in age. Examples of this play type are Camar and Tillery fields in eastern Schleicher County (figs. 11, 12). Missourian-age sandstones are historically interpreted to have been deposited in fluvial-deltaic channels (Hoffacker, 1990; McGookey, 1990). Apparent along-strike continuity of the sandstone bodies and their thickness (<100 ft) may indicate a more sheetlike geometry inconsistent with a channel origin (fig. 12). Dove Creek field, which straddles Irion, Schleicher, and Tom Green Counties, was proposed by Becker (1990) to contain numerous Missourian-age sandstones (Canyon D-A). However, well logs from that field do not indicate limestones, which are needed to put the reservoir into its proper stratigraphic position. Because of this lack of correlation, the field at Dove Creek and many others that extend across Irion and Sterling Counties are potentially Virgilian or younger.

To the south, in Sutton and Crockett Counties (technically Val Verde to Kerr subbasins), the entire Missourian and Virgilian succession is represented by a 0- to 200-m-thick condensed zone of hemipelagic drape sediments (Hamlin, 1999). This observation is important because it requires any Missourian-age siliciclastic unit on the southern Eastern Shelf (Coke, Tom Green, Irion, Schleicher, and Menard Counties) to have a source area to the east or east-northeast, in the area of the Llano Uplift. Reservoir quality of the Tillery sandstone (Tillery field, Schleicher County) ranges from 15- to 20-percent porosity (average 16 percent) over 50 gross ft (McGookey, 1990). Camar sandstones average 15-percent porosity and have permeability that ranges from 70 to 100 md.

MIDLAND AND DELAWARE BASINS

Siliciclastic deposition within the Midland and Delaware Basins appears to be largely restricted to basin-center shales. No data are available about the sedimentology of these facies. In general, basin subsidence in both Midland and Delaware Basins seems to have been high during the Missourian (fig. 1) and continued to increase dramatically in the Virgilian (fig. 2). However, regional structural interpretations indicate that subsidence rates between the Delaware, Midland, and Val Verde Basins were not equal (Tai, 2001). Further, subsidence rates within the Midland Basin appear much greater on the east side, along the Eastern Shelf, than along the west margin, which is the edge of the CBP (Tai, 2001).

DISTRIBUTION OF MISSOURIAN SILICICLASTIC SEDIMENTS

Given seismic and wireline-log correlations, it appears that the entire CBP was transgressed and covered by carbonate sediments by the early Desmoinesian. Regional reconstructions by Tai and Dorobek (1999; 2000) and Tai (2001) suggest an onlapping wedge-shaped geometry for the Missourian- to Wolfcampian-age sediments on the southern CBP in the Midland and Delaware Basins. Defining the geometry of Missourian- and Virgilian-age sediments is problematic because well logs and seismic do not indicate a definable break in lithology (that is, all high-gamma-ray shales) or geometry of this interval. The interval, commonly referred to as the *Late Pennsylvanian-Wolfcampian* (Tai, 2001), is characterized by abrupt and dramatic thickness changes across the southern CBP. Numerous cross sections of the Delaware, Midland, and Val Verde Basins illustrate differential thicknesses of Missourian and Virgilian sediments (termed *Canyon* and *Cisco*) (Tai and Dorobek, 1999) (fig. 13). Many sedimentation patterns appear to have been affected by uplift events. However, uplift and subsidence patterns are not uniform within or between the Delaware, Midland, and Val Verde Basins. In general, areas of greatest uplift along the south and west margins of the CBP were sites of carbonate deposition. These areas grade rapidly "basinward" into siliciclastic and carbonate-rich shales, which compose most of the basin center fill across the Permian Basin. One of the more problematic issues regarding siliciclastic shales in the southern Permian Basin is defining a source area. Noncarbonate lithologies are rare on the CBP in the Pennsylvanian succession, and areas to the north of Fort Stockton had extensive carbonate deposition during the Missourian and Virgilian. Therefore, siliciclastics either came from the west (Diablo Uplift area) or from the south. Southern sources are unlikely, given the detailed studies of the Val Verde Basin (Hamlin, 1999), which describe the Missourian and Virgilian succession there as a thin, condensed, hemipelagic interval. In the absence of biostratigraphic and seismic data, it is possible that many of the Missourian and Virgilian shales of the southern Permian Basin are actually Permian in age.

VIRGILIAN SILICICLASTIC SEDIMENTS

Brown and others (1990) defined nine cyclic carbonate-siliciclastic depositional sequences on the northern Eastern Shelf for the Virgilian. Virgilian siliciclastic sediments do not consistently reach the Midland Basin and are largely stranded to the east in Stonewall, Fisher, and Nolan Counties. Siliciclastics that might reach the Midland Basin would largely be basin-plain to rare, prograding-slope, and basin-floor-fan sediments. The level of detail provided by Brown and others (1990) on Virgilian sedimentation on the Eastern Shelf will not be attempted here, but three summary figures based on that work will help explain temporal and along-strike variability of the position of the shelf margin during the Virgilian, as well as the Missourian (figs. 14–16). At the end of the Virgilian, the northern Eastern Shelf margin (Flippen Limestone) was located as close to the Permian Basin boundary (as defined in this study) as it had been during the entire Virgilian (figs. 14–16). Virgilian carbonate margins acted as barriers to siliciclastic input into the Midland Basin (figs. 14–16), although north-south variability in the amount of aggradation and progradation was extensive. As during the Missourian, the Midland Basin appears largely starved of siliciclastic sediment, with the exception of basin-centered shales. True westward progradation and encasement of Virgilian carbonates in the Midland Basin did not occur until the Permian.

SUMMARY OF MISSOURIAN AND VIRGILIAN SILICICLASTIC SEDIMENTS

Missourian and Virgilian siliciclastic deposition in and around the Permian Basin has a distribution pattern similar to that of the Desmoinesian, with siliciclastic and carbonate reciprocal sedimentation. Given the placement of Missourian and Virgilian shelf edges on the Eastern Shelf, the maximum 2nd-order transgression seems to have culminated at the end of the Missourian, and a 2nd-order regression initiated during the Virgilian. However, as in the Desmoinesian, 3rd- and 4th-order, high-amplitude, sea-level fluctuations occurred at a high frequency. The result was an interlayered carbonate and siliciclastic stacking pattern on a 3rd-order scale. In general, siliciclastic highstand progradational platform-fan, fan-delta, and deltaic sediments dominate deposition on the Eastern Shelf but did not contribute volumetrically to Permian Basin succession. Deltaic sediments continued their westward progradation from the Fort Worth Basin farther onto the Eastern Shelf, which initiated in the Atokan and was governed largely by convergence of the Ouachita thrust foldbelt to the east of the Fort Worth Basin. During the Missourian and Virgilian, subsidence in the Midland Basin increased, siliciclastic progradation advanced farther westward (that is, the Flippen Limestone equivalent). Aerially restricted Missourian-age siliciclastics on the southern Eastern Shelf (within the Permian Basin) probably had a source area in the Llano Uplift to the east and may not have been connected to the large deltaic systems to the north.

In the Delaware and Midland Basins, thick shales appear to have been deposited during the Missourian and Virgilian. However, because of sparse biostratigraphic control and a lack of lithologic variation, the shale succession could be predominantly Permian.

MISSOURIAN AND VIRGILIAN CARBONATE DEPOSITION

Approach

Carbonate rocks of Missourian and Virgilian age in the Permian Basin have been studied extensively in the Midland and Delaware Basins and Northwest and Eastern Shelves. Carbonate formations of the Eastern Shelf include the Palo Pinto, Winchell, Ranger, and Home Creek Limestones, which are within the Missourian Canyon Group, and the Virgilian-age Gonzales, North Leon, Bunger, Gunsight, Ivan, Blach Ranch, Breckenridge, Crystal Falls, and Flippen Limestones, which are part of the Cisco Group (Cleaves, 2000; Yang and Kominz, 2003) (figs. 8, 9, 14–16). Within the Permian Basin (Midland and Delaware), the equivalent carbonate succession is referred to only as the *Canyon and Cisco*.

General Depositional Setting

The carbonate depositional environment during the Missourian and Virgilian was dominated by shelf margins and isolated platforms that had developed their geographic distribution during the late Desmoinesian. However, owing to large variations in basin subsidence and a more distinct separation of subbasins, carbonate depositional architectures are quite varied around the Permian Basin. In the Eastern Shelf succession, the northern section was dominated by a stable aggradational platform during the Missourian, with a separate interior back system developing during the late Missourian transgression. During the earliest Virgilian, westward progradation of the shelf margin was substantial and was followed by middle to late Virgilian aggradation. Regionally, Virgilian carbonates generally compose the transgressive leg of the asymmetric systems tract on the Eastern Shelf. Aggradation, progradation, and retrogradation were **not** consistent along any single Eastern Shelf margin throughout the Missourian or Virgilian (figs. 14–16).

Along the west margin of the Midland Basin (east side of the CBP), carbonates are aggradational through the lower Missourian but have a decidedly eastward (basinward) progradation from the middle Missourian through the Virgilian (middle Canyon to Cisco). On the north margin of the Midland Basin, the stable carbonate platform displays an overall retrogradational, backstepping architecture and reduction in the shallow-water carbonate depositional area associated with the overall 2nd-order transgression. Lowstand carbonate complexes are present basinward of the main platform in the lower Missourian. These complexes may also be interpreted as flooded parts of the earlier keep-up carbonate mounds/subplatforms or possibly as large-scale slope-failure products off the oversteepened platform. With the decrease in available shallow-water carbonate depositional area, the platform margin became steeper through the Virgilian, and downslope debris flows became common.

On the Northwest Shelf, the lower Missourian (Canyon 2 sequence [Tinker and others, 2004]) is characterized by aggradation followed by progradation (Canyon 1 sequence [Tinker and others, 2004]). Missourian sequences are separated from the overlying Virgilian progradational sequence by a major flooding surface equivalent to major transgression identified on the Eastern Shelf (similar to that on the CBP). Missourian and Virgilian carbonate architecture on the Northwest Shelf appears atypical of the Permian Basin, being represented by large-scale, asymmetric, sigmoidal clinoforms.

Reservoir Potential and Diagenesis

Throughout the greater Permian Basin, carbonate reservoir potential and associated diagenesis are more varied spatially and temporally in the Missourian–Virgilian succession than in underlying successions. Dolomitization of Missourian–Virgilian carbonates also played a role in both reservoir creation and destruction that were more substantial than in older parts of the Pennsylvanian succession.

Shallow-water, phylloid-algal banks and mounds dominate the biohermal succession recorded in the Missourian–Virgilian. These phylloid-algal accumulations appear to have diversified during the Late Pennsylvanian, commonly possessing both mound and bank geometries. Grain-dominated facies are also common reservoirs in the Missourian–Virgilian. More atypical reservoirs also present in the basin comprise deeper, subtidal facies with biota more similar to those of the Early Pennsylvanian (for example, non-phylloid-algal boundstones, fusulinid packstones, and crinoidal wackestones).

Phylloid mounds tend to be massive to faintly bedded, with a flat base and distinctly convex upper surface, and were sited on shelf margins and on the top of topographically high carbonate shelves (Wahlman, 2002). The mounds, generally 10 to 20 m in thickness and 1 km or less in diameter, are best developed in normal marine settings at or near the shelf margin, as well as on the inner shelf. The mounds represent concentrated rapid vertical growth. In contrast, phylloid-algal banks are much larger (upward of 50 m in thickness and covering an area 50 km^2), having a tabular to lens shape, and are internally well bedded (Wahlman, 2002). These large banks are thought to have grown on large, broad, topographic highs (for example, delta platforms with accentuated relief at the margins) but did not in themselves produce topography. They tend to have low-diversity fauna dominated by phylloid algae, suggesting a somewhat restricted environment, possibly with very shallow water depths. Concomitant elevated sea temperatures and salinities may have excluded many normal marine oceanic fauna.

Two of the hallmarks of phylloid-algal communities seem to be their resilience and recovery rates. The Late Pennsylvanian, from mid-Desmoinesian to the Permian, is typified by high-frequency and -magnitude eustatic sea-level fluctuations, which may have excluded less-resilient, robust, opportunistic biota, resulting in a *monospecific* bioherm community dominated by phylloid algae. Missourian and Virgilian shelf-margin phylloid-algal mounds have been described in several localities within and surrounding the Permian Basin (for example, Diamond M, Kelly-Snyder, Cogdell, Reineke, University Block 9, and Southwest Andrews fields and the Sacramento and Hueco

Mountains) (Schatzinger 1983, 1987, 1988; Saller and others 1992, 1994,1999a, b, 2004; Kerans and Anonymous, 2001; Saller and Henderson, 2001; Wahlman, 2002). Codiaceans (for example, *Ivanovia*, *Eugonphyllum*), dasycladacean alga (*Epimastopora*), and red alga (*Archaeolithoporella*) are often associated with phylloid-algal bioherms (figs. 17, 18). Fusulinid foraminifera, bryozoans, *Tubiphytes*, brachiopods, and rugose corals also occur in minor abundances (fig. 19). Generally calcisponge-bryozoan mound communities, frequently microbially bound (laminar and encrusting forms), formed seaward of phylloid-algal mounds (fig. 20). During the Missourian and Virgilian, because phylloid- and calcisponge-dominated communities were probably still ecologically separate (Schatzinger, 1983; Wahlman, 2002), in the absence of seismic data, their identification can provide useful data regarding proximity to the shelf margin.

As in the Desmoinesian, primary porosity was largely occluded during early diagenesis, and present reservoir quality is related to the extent of alteration during subaerial exposure. Geometry of potential reservoir intervals varies radically between different carbonate depositional settings, and, coupled with a greater biotic diversity, results in a more complex mosaic of facies susceptible to diagenetic alteration. Duration of exposure events increased during the Missourian and peaked in the Virgilian. The increase in duration resulted in a negative feedback loop, in which too much exposure yielded cementation and occlusion of the secondary pore network.

MIDLAND BASIN

In the Midland Basin, data relating to the depositional style of Missourian and Virgilian carbonates (Canyon and Cisco Formations) come from regional cross sections, seismic data, and field descriptions from the Northern Midland Basin—Horseshoe Atoll, CBP, and the Eastern Shelf. Although all areas are margins of the same basin, architectural style and depositional patterns for each area are distinct.

Figure 21a illustrates the general distribution of Missourian–Virgilian carbonates in the northern Midland Basin. Color change corresponding to overall thickness correlates roughly to age, with thickest intervals in geographically smallest areas containing Virgilian carbonates. According to biostratigraphic correlation, on the east side of the Horseshoe Atoll, isolated subplatforms tend to contain more Virgilian-age rock from south to north (Salt Creek>Cogdell>SACROC) (fig. 21b). Figure 21 illustrates that Missourian carbonates in general have a much larger aerial distribution and a greater and more consistent thickness than the overlying Virgilian carbonates. Studies based on individual subplatforms and fields have yielded a variety of depositional models for the Missourian–Virgilian carbonate succession. Studies at Reinecke field propose a generally stratiform distribution of facies throughout the Virgilian (Saller and others, 2004) (fig. 22a). At SACROC, a more variable distribution of facies comprising grain-dominated units admixed with deeper-water crinoidal wackestone is proposed for the Virgilian succession (Schatzinger, 1987; Kerans and Anonymous, 2001; Janson and Kerans, 2005, 2007) (fig. 22b). Figure 23 illustrates a comparison of wireline-log character of the Virgilian between Reinecke field and SACROC, both wells lying on the crestal part of each structure, and thickness of the Virgilian interval is comparable (~ 250 ft). Topography in the Virgilian succession at Reineke field is thought to be a product of differential shallow-water carbonate growth, karstification, and postplatform, deep-marine erosion (fig. 23). On the other hand at SACROC, Kerans (2001) and Janson and

Kerans (2005, 2007) would contend, a large part of the irregular Virgilian topography is a depositional product of mud-mound and debris-apron formation in deeper water that was subsequently modified by erosion (fig. 22b).

In the northern Midland Basin, the Missourian interval (*Canyon* in the generic sense) is divided into four 4^{th}-order sequences (Wilde 1990; Waite, 1993; Kerans, 2001), with a further biostratigraphic (fusulinid biozones) subdivision of seven units by Waite (1993). At Reineke field, Dickson and Saller (2006) contended that the entire Missourian to Wolfcampian succession is divisible into five units separated by exposure surfaces and indicated by carbon isotope excursions. However, other additional exposure surfaces within the succession do not correspond to isotopic excursions. Their geochemical model, when coupled with biostratigraphic data, indicates that the Virgilian succession is divisible into three units but is wholly middle-Virgilian. The underlying Missourian (*Canyon* in the generic sense) is late Missourian in age, and overlying Wolfcampian sediments are early Wolfcampian; therefore, the early and late Virgilian are missing from their studied succession. Generally for the Virgilian interval, three 4^{th}-order sequences are proposed on the basis of biostratigraphic, seismic, and sequence stratigraphic analyses (Wilde, 1990; Saller and others 2004). However, Kerans (2001) expanded the number of sequences to five for the same interval. Thus, depending on the geographic position of the study area and the methodology employed to define cycles and sequences, the number of total sequences can vary widely.

The complexity and apparent differences between areas such as SACROC and Reinecke may not be entirely a product of individual interpretation (for example, placement and identification of sequence boundaries, seismic interpretation, and depositional environment). Recent work by Kerans and Janson (2005) and Janson and Kerans (2007), indicates that the entire greater platform may be reacting predictably to overall accommodation and relative sea-level changes. Complexity of the facies identified in the Virgilian sediments of SACROC and Cogdell is characterized by mounded crinoidal wackestones with stromatactid cavities; steeply dipping, interbedded, crinoidal packstone; grainstone and grain-dominated packstones interpreted as turbidite flows; and more typical, flat-bedded, crinoidal-fusulinid, grain-dominated packstones (Schatzinger, 1987; Kerans and Janson, 2005; Janson and Kerans, 2007) (figs. 24, 25). Previous well log, core, and 3D seismic interpretation at SACROC also reveal large-scale lithoclastic debris beds and grain flow units flanking and almost encasing the entire platform (including Missourian-age sediments).

Within Virgilian-age sediments there is also high facies and architectural variability on the subplatform to field scale (fig. 22a). A structure-contour map of the top of SACROC field illustrates a flatter, wider profile on the south margin and increasing topography and irregularity to the north (fig. 26). This change is thought to indicate a higher proportion of unfilled to underfilled accommodation in the deeper, northern part of the platform (Kerans and Janson, 2005; Janson and Kerans, 2007). A series of seismic cross sections corresponding to C, B, and A on figure 26 further illustrate the architectural differences across the platform (fig. 27). An analogy has been made between Mississippian-age Lake Valley sequence 2 comprising Waulsortian-type mud mounds and flanking deposits and the Missourian-Virgilian succession in the northern Midland Basin (Kerans and Janson, 2005; Janson and Kerans, 2007). This comparison is one of the fundamental advances in understanding the distribution of facies and overall

architecture on the Horseshoe Atoll. Regional analysis illustrates that architectural control is governed by regional trends in accommodation on a northward-dipping ramp between SACROC and Cogdell (fig. 28a). Size, style, and internal architecture of the Missourian and Virgilian succession can be related directly to their relative positions along this ramp, with flatter, more stratiform architectures in the low-accommodation updip part, grading through more complex mounds with shingling and small, isolated mound tops at the flexural midpoints of the ramp and larger, more hemispherical-shaped architecture in the distal part of the ramp
(fig. 28a). Additionally, outcrop studies of equivalent-aged Virgilian phylloid, mound-bearing carbonates of the Orogrande Basin have produced a similar updip-to-downdip architectural evolution model (Janson, 2007). The Virgilian succession studied by Janson (2007) is one of the few areas providing a viable outcrop analog to the Virgilian succession in the Midland Basin. Current knowledge of internal architecture of the Virgilian succession of the northern Midland Basin is limited by resolution of the seismic data, even when coupled with detailed core and wireline-log data; therefore, outcrop analogs are required to further understanding of reservoir heterogeneity in this succession.

Another complexity in the northern Midland Basin Missourian and Virgilian succession is proposed identification of Missourian-age lowstand carbonate subplatforms/buildups basinward of the main platform edge (fig. 29). These carbonate successions make up a basal phylloid-algal buildup capped by ooid grainstones and are subsequently capped by more phylloid-algal boundstones. The conceptual model put forward by Saller and others (1993) links deposition of these shallow-water carbonates (ooid-rich grainstones and phylloid-algal boundstones) to lowstand events when sea level drops below the main platform margin and synchronous exposure and karsting are occurring on the main platform (fig. 29). BC field succession is thought to be a product of several of these lowstand episodes. Alternatively it is proposed that many of these lowstand carbonate buildups were largely keep-up mounds, with continued growth during both transgression and highstand, were large enough to withstand large fluctuations in sea level, and only met their demise and drowned out during the end of Missourian maximum transgression.

Alternatively, many proposed lowstand deposits may also be downslope debris shed from the main platform. These debris units are commonly composed of shallow-water grain types, such as ooids. As was illustrated in figure 28, phylloid-dominated mounds can form in a variety of water depths below storm-weather wave base (SWWB) and do not require extremely shallow water. Evidence of exposure in some cycles at BC does indicate limited shallow-water deposition, but this exposure could be regional, and recovery of the basinward carbonate factory could be synchronous with that of the main platform.

Lastly, when lowstand carbonate production is discussed, architecture of the main platform must be taken into account. In a high-angle (0.25^{o}) ramp-type system, a large sea-level fall of 20 m would displace the lowstand and shoreface 4.6 km seaward, whereas in a nonramp platform system with steeper sides (5 to 10^{o}), the shoreline is displaced only 228 to 112 m basinward of the initial point. Areal differences in amount of carbonate exposed during a lowstand event that are subject to exposure-related diagenesis are profound (5 km vs. 200 m). Regional depositional geometry (high vs. low angle) must be accounted for when the presence of lowstand carbonate deposits is postulated. The main basinward, south-facing side of the northern Midland Basin isolated platform appears to have had a steep, relatively high relief margin, indicating that any lowstand carbonates would be formed near that platform margin. Only during extreme drops in relative sea level would the carbonate factory be displaced substantially basinward. Overall, genesis of Missourian-age carbonates basinward of the main carbonate platform succession needs to be reevaluated in light of newer seismic data and conceptual models.

The Eastern Shelf carbonate succession during the Missourian and Virgilian is sited largely to the east of the Permian and Midland Basins, as defined in this study (figs. 14–16). However, isolated platforms/buildups, such as Millican, Jameson, and IAB in Coke County, are present to the west of the main north-south-trending shelf margin (Zemkoski, 1985). These successions seem to have facies and stacking patterns similar to those in the northern Midland Basin and span a similar biostratigraphic interval (from early Missourian to late middle Virgilian–pre-Palo Pinto Formation to Blach Ranch). Although these isolated platforms appear to occupy a basinward position relative to the shelf margin (similar to that of BC field), their apparently continuous deposition does not make them viable candidates for punctuated deposition confined to lowstand events. They more likely represent areas of carbonate deposition of size sufficient to experience a keep-up scenario during the overall Missourian 2nd-order transgression.

The CBP side of the Midland Basin contrasts highly with the Missourian–Virgilian carbonate succession on the north Midland Basin margin. Many of the data concerning the Missourian–Virgilian carbonate development on the CBP come from studies of Southwest Andrews and University Block 9 fields. The main architectural difference between the CBP and the northern Midland Basin is that the CBP is an attached system with increased accommodation eastward, toward the center of the Midland Basin. Regional seismic across the Block 9 and Southwest Andrews area indicates that the entire Pennsylvanian is largely stratiform, without any of the topography so dominant along the northern Midland Basin Platform. Facies intercalations and architectures on the CBP are largely below seismic resolution (fig. 30a).

Figure 30b illustrates a three-well correlation of Missourian and Virgilian facies within Andrews County, which are similar to those present in the northern Midland Basin. The Missourian (*Canyon* in the generic sense) is subdivided into three gross packages comprising four biostratigraphic zones: (1) a lower package (lower Canyon) that is spiculitic mudstone and ooid-peloidal grainstone dominated, (2) the middle Canyon that is dominated by phylloid-algal wackestones, and (3) the upper Canyon that has the most facies variability, containing shale, fossiliferous wackestone, phylloid wackestone, and bioclastic grainstones (fig. 30b) (Saller and others, 1999b).

The Virgilian (*Cisco* in the generic sense) was not subdivided by Saller and others (1999b). However, a change in sequence thickness and architecture is apparent between biostratigraphic zones VC-1 and VC-2. Below VC-2 the succession is variable but dominated by bioclastic and ooid-peloid grainstones with minor phylloid and fossiliferous wackestones. The transition to biozone VC-2 is marked by a shale, above which sequences are interpreted as thinner and largely dominated by bioclastic grainstones (fig. 30b). Figure 31 illustrates a fieldwide correlation of the Missourian and Virgilian succession in the University Block 9 area directly south of Southwest Andrews field. Very different facies types are present between the two areas. The equivalent middle Canyon succession dominated by phylloid-algal wackestones in Southwest Andrews is dominated by skeletal-peloidal packstones in the University Block 9 area. The Canyon 3 interval is generally more similar between the two areas, both being dominated by lower energy wackestones. The Virgilian succession in both areas reflects a decrease in accommodation, yielding thinner cycles and abundant exposure; however, in the University Block 9 area there is a relative dearth of high-energy grainstones, and instead phylloid-algal mounds are present (figs. 30b, 31).

Subregionally, there are distinct differences in the abundance and distribution of porous zones in the same successions. Comparison of these two relatively closely spaced areas in an apparently flat lying succession indicates that even across small distances (<5 mi), intrasequence facies distribution will be different, and only by looking at more regional-scale data, including seismic, can we truly understand the architecture of this system. Both areas do highlight a major difference between the CBP and the northern Midland Basin— the Virgilian succession on the CBP appears to undergo basinward progradation while the same interval in the northern Midland Basin takes a decided backstep and decreases in carbonate depositional area.

As discussed for the Desmoinesian, identification of sequence boundaries (both higher and lower orders) and exposure events is vital to an understanding of reservoir architecture and prediction of reservoir quality in the Missourian and Virgilian succession of the Midland Basin. Figure 32 illustrates the proposed cycle stacking pattern and associated cycle thickness and accommodation trends of the Missourian and Virgilian succession in the Southwest Andrews field area. This figure illustrates the relatively dramatic change in cycle thickness between the Missourian and Virgilian succession that appears to be represented basinwide. However, identification of exposure events and cycle boundaries in any succession can be, and often is, highly subjective. Also, Fischer-style plots, commonly used to illustrate cycle stacking and thickness trends, work on the premise that sedimentation rates are constant, which is rarely the case. The cycle thickness illustrated in figure 31 for the same succession as in figure 32 indicates a different architecture within the interval equivalent to the upper Canyon and possessing the thickest cycles relative to the rest of the Missourian succession. This difference in apparent accommodation must be related either to different local accommodation or sedimentation rates or to differences in the method of picking and identifying cycle boundaries because relative sea level should not vary dramatically between two geographically adjacent areas.

Figures 33 through 35 illustrate core photographs and their associated wireline-log and porosity/permeability signatures for the lower Missourian interval at Southwest Andrews field.

In figure 33, the dark crinoidal unit corresponds to the basal part of the Missourian succession (Canyon Formation). Note that high thorium values on the spectral gamma ray (fig. 33) correspond only to the basal 2 ft of this unit and not to the underlying exposure surface. Subtidal crinoidal facies dominate the lower Canyon interval at Southwest Andrews field (fig. 34). The grainstone facies present in the lower Canyon interval is thin (~8 ft) and encased by crinoidal grainstones above and below (figs. 34, 35). Although Saller and others (1999a) interpreted the top of the grainstones as an exposure surface, no corresponding excursion appears in the carbon isotope profile. The lower Missourian grainstones illustrated in figure 35 may not indicate the top of the upward-shallowing cycle (as interpreted by Saller and others 1999a, b), but given their isolated nature, lack of an isotopic excursion, and their blocky wireline-log signature, they could be the result of platform-top shedding into the more shelfal subtidal region. Figures 36 and 37 illustrate the character of the upper Missourian (upper Canyon) interval at Southwest Andrews field. Although the cycle-top boundary between fusulinid wackestones in figure 37 is obvious, there is a high degree of alteration far below the thin grainstone interval (fig. 36). This interval appears to contain large subangular and subrounded clasts and appears more indicative of a debris flow or brecciated exposure horizon than the original description by Saller and others (1999a, b), indicating extensive bioturbation.

Figure 38 illustrates textural, well log, and facies characteristics of Virgilian rocks at Southwest Andrews field. The most obvious difference between this part of the succession and the underlying Missourian (figs. 36, 37) is extent of alteration. Numerous cycle-top exposure events were interpreted in this interval by Saller and others (1999a) (fig. 38). Facies appear to be generally higher energy, but they also contain a predominance of fusulinid and echinoid debris and a general lack of ooids (fig. 38). Overall, cycles and any potential reservoir interval are thinner than in the Missourian. Owing to negative feedback, the increased number and duration of exposure-related events in the Virgilian actually produce poorer reservoirs (that is, too much exposure yields a cemented, nonporous rock).

DELAWARE BASIN

The Missourian and Virgilian carbonate succession in the Delaware Basin is less well studied or understood than the corresponding Midland Basin succession. Missourian and Virgilian shallow-water carbonates (that is, potential reservoirs) are restricted largely to the Northwest Shelf in an arc running across Eddy and Lee Counties, New Mexico (fig. 39). Farther west, across the proposed uplifted Diablo Platform/Uplift, an additional site of carbonate deposition rims the Orogrande Basin. The Orogrande succession has had extensive outcrop study but cannot be linked directly to the Permian Basin succession.

The bulk of data and interpretations of the Permian Basin come from studies of Dagger Draw and Indian Basin fields (fig. 39) (Brinton and others, 1998; Mazzullo, 1998; Tinker and others, 2004). Although the Missourian and Virgilian carbonate succession was conceptually drawn as a series of coalesced and stacked algal bioherms by Mazzullo (1998) (fig. 39, top) with substantial aggradation similar to that of the northern Midland Basin, this interpretation may be largely incorrect. In figure 39, lower generic facies and architectural diagrams more adequately describe the succession; however, facies partitioning types appear different at Dagger Draw field than in the conceptual model. Figure 40 is a dip-oriented seismic section of South Dagger Draw field. Seismic correctly illustrates the low-angle, shingled, sigmoidal, basinward-prograding-clinoform nature of the Missourian and Virgilian succession. This architecture is very different from that in the Midland Basin succession, especially compared to its north and east margins. Missourian to Virgilian progradation is more like that of the CBP succession, as opposed to the general retrogradation recorded in the northern Midland Basin (Horseshoe Atoll, Scurry Reef). The sigmoidal-clinoform architecture also implies a decidedly lower rate of accommodation generation than in the Midland Basin.

The depositional model for the high-frequency sequences at Dagger Draw illustrates early flooding of a low-angle ramp, with deposition of largely argillaceous mudstone-wackestone and shale giving way to more crinoid, brachiopod, and bryozoan-rich wackestone and fusulinid-to-crinoid wackestone and grainstone in the late transgressive systems tract (TST) (fig. 41a). The higher energy grainstone facies of the TST are aerially restricted to the middle ramp behind the true ramp crest (fig. 41a). During the associated early highstand (HST) the depositional area of the fusulinid-to-crinoid wackestones and grainstones expanded to occupy both middle ramp and crest (fig. 41b). The late HST is characterized by development of algal boundstones on the ramp-crest margin, with associated lower energy mudstones facies occupying the middle ramp area within the energy shadow of the crest (fig. 41b). Estimated water depths during the HST ranged from 1 to 2 m in the middle ramp to 10 m at the ramp crest, with the thin outer-ramp succession being deposited in at least 40 m of water (Tinker and others, 2004).

Figure 41 illustrates the conceptual architecture of a high-frequency sequence. High-frequency sequences (HFS's) are components of larger composite sequences (CS's) (fig. 42). Given the sigmoidal-clinoform nature of the Missourian and Virgilian succession, it is imperative that purely wireline-log correlations be avoided. In analyzing a dip section through a composite sequence, even sequence stratigraphic correlations are difficult. In the most proximal areas, the entire CS comprises stacked highstand sediments to the exclusion of other systems tracts (fig. 42—transect A). A well placed just behind the ramp crest would yield a facies package dominated by algal boundstones, creating a false sense of a mounded nature and aggradation (fig. 42—transect B). At the ramp crest, facies and systems tracts are more symmetrical, containing LST-TST and HST sediments (fig. 42—transect C). In outer-ramp areas, the CS is dominated by thick LST-TST legs and thin to absent HST portions of the sequences (fig.42—transect-D).

Analysis of Missourian facies at South Dagger Draw illustrates some key differences when compared with the equivalent succession of the Midland Basin. Algal boundstones at South Dagger Draw, and presumably in many other places along the Northwest Shelf, are formed by encrusting and binding algae such as *Archaeolithophyllum* and *Tubiphytes* and not phylloid algae, which dominate in other areas (fig. 42—left photo; figs. 43a, b, 20). Unlike the Midland Basin, Missourian and Virgilian succession, no true high-energy wave-base-indicative grainstones or peritidal facies were identified in South Dagger Draw (Tinker and others, 2004). Algal boundstones are thought to be the shallowest water facies (<10 m water depth) (fig. 43a, b). The fusulinid packstone and packstone/wackestone facies that commonly occurs in the early HST of the high-frequency sequences is largely nonreservoir, having been deposited in moderate water depths (fig. 43c, d). Crinoidal, brachiopod, and bryozoan mudstone and wackestone represent deepest water, pure carbonate facies, generally occurring in the late TST (fig. 43e, f).

MISSOURIAN AND VIRGILIAN CARBONATE RESERVOIR QUALITY

Midland Basin

Reservoir quality in Missourian and Virgilian carbonates of the Midland Basin is controlled by facies and grain type, as well as extent of diagenetic alteration occurring during subaerial exposure. This situation is similar to that of the Desmoinesian succession in many ways, but variability of facies type, thickness, and amount of exposure-related diagenesis are much greater in the Missourian and Virgilian succession. Following the diagenetic model proposed by Saller and others (1999b), the CBP succession underwent more of what is termed Stage 3 and Stage 4 alteration (figs. 36–38). The exposure-related diagenesis associated with Stage 3 is pervasive through each cycle and is evidenced by micritization, brecciation, and rhizolith formation. On average the cycles are 3 to 4 m thick, and the intergranular porosity of grainstone intervals is occluded largely by blocky calcite cements. Moldic porosity dominates the current open pore network, and minor secondary vuggy and fracture-enhanced porosity is present. Fine-grained wackestones and packstones are mostly tight. Average porosity and permeability in units affected by Stage 3 diagenesis are 3.1 percent and 1.89 md, respectively. Stage 3 diagenesis is most common in the middle to late Missourian and early Virgilian (upper middle and upper Canyon and lower Cisco) (Saller and others, 1999b) (figs. 36–37).

Stage 4 alteration, thought to be the most intense level of subaerial exposure-related diagenesis in the Missourian and Virgilian succession, is most abundant in the upper Virgilian (*upper Cisco* in the generic sense) (fig. 38). Features associated with this level of alteration are fractures, fissures, grikes, and brecciation extending as much as 1 m below the associated exposure surface. Average cycle thickness is less than 2 m. Both primary intergranular and secondary moldic pores are occluded by calcite cement. Vug, fracture, and fissure (grike) porosities are also largely occluded by burial cements. Average porosity and permeability in units affected by Stage 4 diagenesis are 2.2 percent and 0.18 md, respectively. In general, there is less of a correspondence between permeability and porosity in the reservoir intervals of the Virgilian succession than in the underlying Missourian (figs. 36–38).

The Missourian succession (*lower Canyon* per Saller and others, 1999b) has much better reservoir quality than the younger units, as discussed earlier. Overall, cycles are thicker, facies more laterally persistent in architecture, phylloid-algal-dominated units more common, and rocks have experienced a lesser but optimal level of exposure-related diagenetic modification. Stage 2 alteration is most common for the interval, and associated reservoir quality is significantly better than in the overlying succession, with a higher average porosity of 4.27 percent and a much higher permeability of 10.77 md (Saller and others, 1999b).

Figure 44 illustrates a generic average-reservoir-quality plot of the Missourian and Virgilian intervals. These three-well-averaged (both per well and generic sequence) data indicate that the lower Missourian interval is generally the best in terms of overall (porosity and permeability) reservoir quality. However, core-porosity-based correlations from the same wells indicate that the middle Missourian (*middle Canyon* per Saller and others, 1999b) has the best and most extensive reservoir interval throughout the field on a dip section (fig. 45). For this apparent conflict to be addressed, porosity distribution is better viewed in a regional time-slice view. In general, the early Missourian succession (*lower Canyon* per Saller and others, 1999a) has the most aerially extensive high porosity, whereas the middle Missourian (*middle Canyon* per Saller and others, 1999b) has several thick, high-porosity intervals but a much smaller aerial distribution (fig. 46). The Virgilian succession (*Cisco* per Saller and others, 1999b) has the lowest overall porosity, and porous zones are largely laterally discontinuous (figs. 46, 47).

To the south, in University Block 9, we can examine porosity/permeability at a higher resolution (fig. 47). Two observations are readily apparent: (1) the best reservoir quality is also in the Missourian section and (2) it is roughly equivalent to the upper Canyon interval as defined by Saller and others (1999a, b). The reservoir interval is approximately 20 ft thick and averages 4.91 percent porosity and 3.91md permeability. Given the core data, the lower Missourian succession, as illustrated by the University 25 well, has good reservoir quality only in crossbedded ooid grainstones, which are approximately 3 ft thick (average 14.63 percent porosity and 2.125 md permeability) (fig. 31). The Penn #11 well was cored through the middle Canyon to near the top of the Cisco (fig. 31). Core analysis and wireline-log data indicate once again that the upper Canyon interval (F) has the best reservoir quality, with average porosity and permeability of 8.39 percent and 2.82 md, respectively. However, when this interval is examined in more detail it becomes apparent that porosity generally increases upward, even though permeability is highly variable and does not possess a linear correlation with porosity (fig. 48).

Figure 49 illustrates textural and component variability in the upper Canyon interval of the Penn # 11 well (fig. 31). Porosity is strongly controlled by biological constituents of the rock (that is, facies), and distribution of these components has a large bearing on resultant permeability (fig. 49). Slightly below the base of the reservoir interval is a thin grainstone unit, but primary porosity is largely occluded by calcite cement. Current porosity is intercrystalline, associated with coarse nonplanar-C/saddle dolomite, and therefore entirely unrelated to facies or subaerial exposure (fig. 49a, b). Samples from the lower part and center of the interval (depths 9,039, 9,041, and 9,050 ft) illustrate one of the more common forms of porosity in Missourian and Virgilian carbonates of the Permian Basin. These samples illustrate that most pore space is related to molds formed after bioclasts, dominantly phylloid algae (fig. 49c–e). The main issue relating to permeability is the degree of contact between moldic grains. Isolated or clumps of bioclasts/phylloids yield an irregular permeability distribution (fig. 49c, d), whereas more parallel orientation of the grains yields higher permeability (fig. 49e).

As discussed earlier, Virgilian-age (Cisco) reservoir intervals are generally thinner than in the underlying Missourian and are predominantly high energy grainstones. In the case of University Block 9 field, in Penn #11 and 14CE #C6 wells, an algal wackestone to packstone is noted. In thin section these facies appear to be encrusting to laminated algae instead of typical phylloid algae (fig. 49e). Although apparently aerially restricted, this facies has good reservoir quality compared with that of the typical Virgilian tight limestone illustrated in figure 50, which possesses extensive cement both unrelated and related to exposure.

Exposure-related diagenetic events can be difficult to identify and range from subtle cracks and reddening of sediments to brecciation, rhizoliths, alveo-septal fabrics, soil crusts, desiccation cracks and glaebules (fig. 50a, b). In the absence of these identifying features, trace elements and isotopic data are required to confirm whether cements were of either meteoric (for example, exposure related) or marine affinity (fig. 50c, d).

Although reservoir quality on the CBP is variable, it is predictable in a gross sense, with Virgilian units generally of lesser quality and aerial extent. Exposure-related diagenesis is important, but in some instances it is overemphasized because original facies and their architecture are equally important. Take, for example, the isolated platforms of the northern Midland Basin. At SACROC, Schatzinger (1987) performed a detailed core- and thin-section-based facies analysis and combined it with wireline-log data (fig. 51a, b). One key difference between the CBP and the northern Midland Basin is the latter's greater facies and architectural variability, even in the Missourian succession (fig. 51a, b). Figure 51 illustrates log-based porosity variability within a single well and between two wells and its link to facies type. In general, higher-energy oolitic to coated-grain grainstones have the highest porosity in the middle Canyon succession (fig. 51b), whereas the sponge-algal-bryozoan boundstone facies generally has lower porosity over a much thinner interval (fig. 51a). At Reineke field, Saller and others (2004) asserted that porosity and permeability are dominantly linked to exposure-related diagenesis and that reservoir-grade porosity (>4%) and permeability (>1 md) are fairly continuous laterally and vertically in the Virgilian succession. However, core analysis data indicate that facies have moderate control over porosity distribution and strong control over permeability, especially vertically (fig. 52a). Dolomitization has occurred within the Virgilian succession at Reinecke field, and dolomitized facies have generally lower average porosity and higher average permeability than their limestone counterparts (fig. 53). In a single type well for Reinecke field, core and wireline-log porosity are relatively uniform and predominantly above 10 percent throughout the Virgilian succession (fig. 54). However, on close analysis, porosity and to some extent permeability are linked more to specific facies than to alteration zones beneath major sequence boundaries 300, 200, and 100, with which paleosol features have been identified (fig. 54). Therefore, true porosity and permeability distribution seems to be controlled more by higher-order cycles and facies geometry than by long-duration exposure events.

As discussed previously, a layer-cake distribution of facies in the Virgilian succession does not reflect the intraplatform facies architecture. A much more complex geometry is envisaged, with progradational geometries, slope debris, and deep-water mounds commonly developed (figs. 25–28). In the northern Midland Basin, generating an accurate model of facies geometries and platform architecture appears to be of greater importance than identifying exposure-related diagenesis.

Figure 55 illustrates vertical facies variation in the SACROC area. Facies in the lower Canyon succession (*Canyon 1* per Charles Kerans, Jackson School, personal communication) and youngest Cisco sequences are dominated by crinoidal wackestones to packstones (fig. 55). The Canyon 2a sequence has a greater dominance of fusulinid-rich facies (for example, fusulinid-crinoidal-skeletal packstones, grain-dominated packstones and grainstones). Ooid grain-dominated packstones cap higher-order cycles (fig. 55). Canyon 2 and 3 sequences are similar to Canyon 2a in their stacking patterns and general facies composition but contain a greater proportion of higher-energy facies (for example, ooid grainstones and grain-dominated packstones, as well as skeletal rudstones) (fig. 55). The transition from Canyon 2a to Cisco 1 sequences indicates regional transgression, with the Cisco 1 being dominated by subtidal, fusulinid-rich facies.

Reservoir quality in the entire Missourian and Virgilian succession is variable, and both intergranular porosity (largely primary) and moldic pores are present in the grain-rich facies (fig. 55). In general, primary facies type (that is, grain rich or not) is associated with highest porosities both in neutron log and petrographically. Presence of primary pores in many cycle-top facies indicates that not all current porosity is related directly to exposure-related diagenesis. The core photo from the uppermost Cisco 2 sequence illustrates texture of an exposure event; however, because the facies affected was a crinoidal wackestone to packstone little porosity was generated.

The Northwest Shelf Missourian to Virgilian succession is different in architecture and dominant facies type from the Midland Basin successions, as discussed earlier. Current models of porosity generation and preservation stem largely from studies at Dagger Draw and Indian Basin.

Dolomitization appears to play a crucial role in reservoir quality in this area. At Dagger Draw the entire succession is largely dolomitized. The dolomitization model for this area does not invoke early diagenetic fluids for dolomitization. Faults served as conduits for acidic brines, which then promoted dissolution and served as pathways for later pore-occluding hydrothermal (90–170^{o}C) dolomitization, possibly during the Eocene–Oligocene (fig. 56) (Hiemstra and Goldstein, 2004; Tinker and others, 2004). A solution-enhanced fracture and vuggy pore system developed at the crestal position of sigmoidal clinoforms, where the faults, dolomitization, and shallowest water facies (still >10 m below wave base) intersected (fig. 56). This zone forms the reservoir interval when it is capped by transgressive shales, which provide a seal.

No evidence of subaerial exposure-related diagenesis was identified or documented in any of the facies or high-frequency cycles at Dagger Draw field. Macropore geometries vary widely, although all pores are technically intercrystalline (that is, between dolomite crystals) (fig. 57). Depending on the dolomitized facies, pores can range from those reflecting an intergranular, primary origin to moldic pores after leached bioclasts, and even to fenestral or shelter pores associated with algae. Porosity/permeability relationships in dolomitized facies are even more difficult to predict than in their limestone counterparts. Reservoir quality, especially permeability, can often be linked to dolomite crystal size, which is a function of both the size of the replaced precursor as well as saturation of the fluid. Pores are irregularly distributed and moldic and vuggy in nature, and their associated permeability ranges from 0.1 to 1,000 md, being generally confined to four flow units (fig. 57) (Brinton and others, 1998; Tinker and others, 2004).

Regionally the Northwest Shelf Missourian and Virgilian succession is much more dolomitized than the equivalent succession in the rest of the Permian Basin. Such extensive dolomitization events typically require large fluid fluxes and are often associated with early diagenesis and modified seawater. The dolomitization model proposed by Hiemstra and Goldstein (2004) and Tinker and others (2004) is generally supported by data at Dagger Draw; however, this model may not be appropriate for the entire Northwest Shelf.

Across the Diablo Platform/Uplift (figs. 1, 4) within the Orogrande Basin, dolomite is relatively common in the Missourian and Virgilian succession. The general carbonate depositional model in this area is shelf-edge phylloid-algal buildups and associated flank deposits deposited as part of the reciprocal siliciclastic-rich sedimentation system, which is more like the Midland Basin (for example, Eastern Shelf) succession than the Delaware Basin/Northwest Shelf. Dolomitization in the eastern Orogrande Basin is thought to have formed via glacioeustatic transgressive reflux

(Soreghan and others, 2000). This model links eustatic sea-level fluctuation to dolomitization by concentrating the seawater's dolomitization potential during lowstands and flooding the platform with this fluid during early transgression. Although it is not proposed that Northwestern Shelf dolomites are a product of this process, this example illustrates that dolomitization can form via a variety of mechanisms. Each area requires a detailed diagenetic study before models of dolomitization can be inferred. It is the author's contention that several types of dolomite are potentially present within the Missourian to Virgilian succession on the Northwest Shelf. Multiple dolomitization events probably occurred, some diagenetically early, others late, and events could have been superimposed. Although the data from Dagger Draw indicate that subaerial, exposure-related diagenesis was minor to nonexistent in generating current reservoir quality, this assumption cannot be extended to the rest the shelf. Areas more proximal than Dagger Draw may have experienced extensive cycle-top diagenesis and have a reservoir quality distribution and evolution more similar to those of the CBP.

SUMMARY OF THE MISSOURIAN AND VIRGILIAN CARBONATE SUCCESSION

In summary, several key issues come to bear on an understanding of Missourian- and Virgilian-age carbonates. And 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 a regional sequence stratigraphic context. In general, the regional transgression that occurs at the transition from the Missourian to the Virgilian is expressed throughout the Permian Basin, except for in the south (that is, Val Verde), where

the entire succession is expressed as a thin, condensed, pelagic, mudstone interval.

2. Diagenesis: Missourian reservoir development is linked to extent of subaerial exposure and to facies type. During the Virgilian increased frequency of exposure and much more diverse facies mosaic and architecture yielded poorer and less laterally and vertically extensive reservoir intervals. Multiple facies types can have good reservoir quality, and exposure-related diagenesis is often overemphasized. Generally, phylloid-algal bioherms are often the best reservoirs, but grain-dominated shoal successions become increasingly important in the Virgilian.
3. Architecture: The Missourian succession and, primarily, the Virgilian succession express themselves in different styles, depending on their location within the basin. The northern Midland Basin is distinct from the CBP and displays its own updip to downdip subregional variability that is crucial to an understanding of the succession. Accommodation was much greater in the Northern Midland Basin, with Virgilian-age facies often represented by deeper-water, crinoidal, mud-mound facies. This increased accommodation contrasts with the CBP, where the platform was narrower, with limited accommodation throughout its life and consequent progradation through the Virgilian. The Delaware Basin carbonate succession was deposited on a ramp and is dominated by subtidal facies. The regional end-Missourian 2nd-order transgression is identifiable on the Northwest Shelf, but it does not herald the distinct change in facies type, thickness, or

architecture within the overlying Virgilian, which is so prominent in the Midland Basin.

DISCUSSION AND SUMMARY OF THE MISSOURIAN AND VIRGILIAN IN THE PERMIAN BASIN

Globally and regionally a 2nd-order transgression peaked at the end of the Missourian. However, continued icehouse conditions with high-amplitude and -frequency asymmetric fluctuations in base level continued into the Virgilian. Virgilian sedimentation has the overprint of some of the highest amplitude (100 m+) and frequency-base-level falls recorded. These fluctuations help define stratal facies architectures, as well as their being a major driver behind both enhanced and diminished reservoir quality.

Although Missourian-age siliciclastics, present on the southern Eastern Shelf within the Permian Basin, have an eastern source, they are volumetrically minor. Localized development of a slope bypass system into the Midland Basin occurred in the north. Virgilian-age, coarse-grained siliciclastics are largely nonexistent within the basin. Significant siliciclastic deposition occurred to the east of the defined Permian Basin margin during the Virgilian, and the entire sequence is skewed 2:1 to highstand progradational platform-fan, fan-delta, and deltaic siliciclastics over carbonates. Apparent thick shale deposition occurred within the center of the Delaware and Midland Basins. In the Val Verde and Kerr Basins, the Missourian–Virgilian interval comprises a condensed hemipelagic mudstone (0.1–200 ft thick).

Carbonate deposition dominated the Missourian and Virgilian and varied from shallow-water, high-energy to basinal, low-energy facies. Myriad carbonate depositional settings were present during the Missourian, but further diversification, including deep-water mounds, occurred during the Virgilian. Effects of 3rd- and 4th-order sea-level falls are often manifested in carbonates as subaerial exposure surfaces. These surfaces/events contributed to development of reservoir intervals within the Missourian carbonates throughout the Midland Basin. Architectural and facies geometries strongly controlled siting of the reservoir intervals, especially in the Virgilian. In platform areas more susceptible to cycle-top diagenesis, increased frequency and duration of exposure during the early Virgilian resulted in negative feedback, with dissolution being followed by extensive cementation and occlusion of secondary pore networks.

Carbonate successions display aggradational, progradational, and backstepping architectures intrabasinally and extrabasinally. In general, carbonate production was relatively “fixed” in its location and inherited gross geometries from underlying Desmoinesian carbonates. The Eastern Shelf succession displays variable magnitudes of progradation and retrogradation along strike within depositional episodes. Regionally, retrogradational and progradational cycles on the Eastern and Northwest Shelves and CBP are sequence stratigraphically out of phase relative to the northern Midland Basin. The major transgression at the end of the Missourian (*Canyon* in the generic sense) is identifiable throughout the Permian Basin.

On the Eastern Shelf, the northern section was dominated by a stable aggradational platform margin during the Missourian. An interior bank system developed in this area during late Missourian transgression. During the early Virgilian, progradation occurred on the outer-shelf margin, with aggradation occurring during the middle to late Virgilian. Virgilian carbonates compose the transgressive leg of the asymmetric systems tract, which is actually dominated by siliciclastic sedimentation to the east of the Midland Basin.

Over the same time frame, the east-facing margin of the CBP had an apparently simpler evolution, with a general basinward (easterly) progradation from the middle Canyon through the Cisco, which was demarcated by high-energy ooid-grainstone facies. Porosity and permeability were diagenetically enhanced during subaerial exposure on the 3^{rd}-and 4^{th}-order scale. During the Virgilian (*Cisco* in the generic sense), more abundant, accommodation-limited, thinner, and grain-rich cycles were exposed more frequently and for longer intervals, resulting in increased cementation and yielding poorer reservoirs than the underlying Missourian (Canyon) carbonates. Throughout the Permian Basin, the best reservoir exists beneath exposure surfaces of moderate duration, usually confined to the lower to middle Missourian succession.

In the Delaware Basin along the Northwest Shelf, Missourian and Virgilian successions appear very different from those in the Midland Basin. Overall depositional geometry appears more ramplike than platform, and main producing fields are situated in the mid- to outer-ramp setting. Sequence tract architecture is asymmetric, with large-scale sigmoidal clinoformal geometries. This stacking pattern results in decreased to absent parts of the sequence tract (for example, no TST in the interior). The Missourian succession contains a lower aggradational composite sequence (CS 1) (Canyon-2—Tinker and others, 2004) and an overlying progradational composite sequence (CS 2) (Canyon 1—Tinker and others, 2004). CS2 is separated from the overlying progradational CS 3 Cisco (Virgilian) by the regional end-Missourian flooding surface. In general, there is a decided lack of diagenesis associated with exposure, and facies contain a deeper subtidal fauna more similar to that of the Early Pennsylvanian (Morrowan and Atokan). High-energy, shallow-water facies are not prevalent, and main facies types are algal boundstones, fusulinid packstone/wackestones, and crinoidal wackestone. Although dolomite is much more pervasive on the Northwest Shelf than anywhere else in the basin and is crucial to reservoir generation, this diagenetic event is thought to have occurred substantially after deposition, making its prediction difficult.

The Missourian and Virgilian carbonate sedimentation pattern is complex, and many perceived fundamental observations are actually only local in occurrence. The retrogradational pattern (backstepping) from the Canyon–Cisco is really manifested only on isolated platforms of the northern Midland Basin. However, regional transgression at the end of the Missourian was basinwide. Diagenesis associated with exposure was often critical to adequate reservoir quality, but facies geometries and architecture are equally important. Phylloid algal buildups were common in the Missourian and diminished slightly in frequency during the Virgilian, but reservoirs are not restricted to this facies.

Within the Midland Basin, a series of associated lowstand complexes basinward of the main platform in the lower Canyon interval are present. It is difficult to assess whether all these basinward miniplatforms are tied to lowstand events or are better represented as keep-up platforms during the Missourian transgression. These basinward platforms are not identified outbound of the CBP or on the Northwest Shelf. In general, the Missourian succession is dominated by more subtidal facies than the Virgilian throughout the Midland Basin. However, this type of observation is highly subjective, depending on where along the platform the observation was made (for example, deeper-water phylloid-algal boundstones in the University Block 9 area laterally equivalent to grainstones at Southwest Andrews). During the Virgilian on more isolated platforms, downslope debris flows became prevalent once platform-margin relief reached adequate heights. Associated with this debris are deeper-water crinoidal mud mounds. This facies association contradicts the generalization that the Virgilian (Cisco) succession is shallower, more grain rich, and higher energy than the underlying Missourian.

Although it is obvious and has been stated extensively that the Missourian and Virgilian succession is strongly controlled by eustatic variations, amount and local variation of subsidence are probably two of the key controls on facies distribution and architecture in the Permian Basin. The rate of subsidence in the northern Midland Basin was probably much higher than in the south and relative to the Delaware Basin. This differential subsidence is probably linked to differences in major structural and basement terrains of which the Permian Basin is composed.

PALEOGEOGRAPHIC SUMMARY

Based on the above interpretations, proposed distribution of Missourian and Virgilian sediments across the Permian Basin and surrounding areas is illustrated in figures 1 and 2. The following discussion refers to interpretations represented in those figures.

Missourian and Virgilian siliciclastic sedimentation dominated deposition to the east, south, and northwest of the Permian Basin (figs. 1, 2). A narrow zone of siliciclastic sediment appears to have entered the eastern Midland Basin to the south of the carbonate shelfal sequences in Sutton, Schleicher, and Edwards Counties (figs. 1, 2), which was probably sourced by the Llano Uplift. A localized siliciclastic slope system also feeds into a troughlike area in Knox, Baylor, Stonewall, and King Counties along the Eastern Shelf east-southeast of the Matador Uplift. This depositional low initiated in the Desmoinesian, and its margins and configuration were modified numerous times during the Missourian and Virgilian by migration of carbonate shelf edges. Figures 1 and 2 illustrate times of carbonate- and shale-dominated deposition in that area. In the southern Permian Basin, including the Val Verde Basin, deposition of coarse siliciclastics was minimal. Occasional distal turbidites probably fed into the basin, but in general, sediment accumulation was low. On the northwest margin of the Permian Basin, the Pedernal Uplift became active again and expanded southward through the Missourian, potentially linking up with the Diablo Uplift (Diablo Platform) during the latest Virgilian to early Wolfcampian. Local areas along the Matador Arch also experienced renewed uplift, which peaked during the early Wolfcampian. Coarse and fine siliciclastics were shed from the Pedernal Uplift toward the Orogrande Basin to the west and east-southeast toward the Delaware Basin. A trough seems to have existed between the siliciclastics at the northwest margin of the Permian Basin and the midramp carbonates, forming an arc across Eddy County. In general, the siliciclastic input derived from the Pedernal Uplift had a much greater influence on sediments of the Orogrande Basin, where deposition was reciprocal with carbonates and volumetrically dominated by siliciclastics.

During the Missourian and Virgilian, carbonate deposition dominated in the Permian Basin, although volumetrically, shales and/or starved-basin conditions were more regionally pervasive. For the Missourian, over the entire greater Permian Basin there was a general decrease in carbonate depositional area as compared with the Desmoinesian (figs. 1, 2—Depositional History of the Desmoinesian Succession [Middle Pennsylvanian] in the Permian Basin). This decrease in area suitable for carbonate factories continued through the Virgilian and was driven by two forces—a 2nd-order global transgression, which culminated in the late Missourian to early Virgilian, and highly variable differential basinal subsidence rates.

Missourian carbonate deposition on the Eastern Shelf occurred in a broad zone characterized by shelf-margin carbonates; inner-bank systems; and rare, more basinward, isolated buildups/platforms (fig.1). The area covered by carbonates diminished in the Virgilian and was generally restricted to shelf-margin systems (fig. 2). During both stages of evolution, shelf margins migrated only to the eastern periphery of the Midland Basin, consistent with the margin that developed during the Desmoinesian along the Fort Chadbourne fault system and the proto-Midland Basin (fig. 2). Note that the Eastern Shelf is depicted as carbonate dominated in both reconstructions, thus allowing the basin margin to be more accurately defined. In actuality, the Eastern Shelf system was one of reciprocal carbonate and siliciclastic sedimentation, with siliciclastics generally dominating except at the margin of the Midland Basin. Rates and extents of westward progradation of siliciclastics out of the Fort Worth Basin onto the Eastern Shelf controlled deposition in that area. This progradation was driven by continued uplift erosion and compression in the Forth Worth Basin area by the Ouachita Orogeny.

During the Missourian, the east margin of the CBP and the northern Midland Basin were sites of extensive carbonate deposition and appear to have been linked into a single, large, isolated platform (fig. 1). On the west margin of the CBP, uplift was occurring on at least two isolated blocks separated by a central area of carbonate deposition. The northern Midland Basin part of the platform was isolated and separated from the Northwest Shelf by the San Simon Channel and an extension of the deeper-water part of the Palo Duro Basin (figs. 1, 4).

During the Virgilian, the CBP became distinct from the northern Midland Basin Platform probably because of increased subsidence in the northern Midland Basin around Gaines County (fig. 2). The northern Midland Basin Platform (Scurry Reef/Horseshoe) atoll exhibited a 2^{nd}-order backstepping and reduction in carbonate depositional area, whereas the CBP prograded. Subregionally, the northern Midland Basin Platform succession had large-scale architectural updip-downdip variation (initiated in the Missourian) in its isolated subplatforms. In general, the platforms trend north-south from stratiform to shingled to mounded, consistent with increased accommodation in the greater Palo Duro Basin (figs. 1, 2).

On the Northwest Shelf, carbonates were being deposited at the shelf margin in a ramp environment as a series of basinward-prograding sigmoidal clinoformal composite sequences. The facies associated with these deposits are subtidal to deep subtidal and are extensively dolomitized. The Northwest Shelf carbonate depositional area appears to have been connected to the west margin of the Palo Duro Basin across the largely inactive Matador Arch (fig.1). Architecturally and facieswise, Virgilian carbonates are much the same as in the Missourian, but the depositional area covered by these units expanded basinward (fig. 2).

Missourian carbonates on the Diablo Platform/Uplift are less extensive in distribution than in the underlying Desmoinesian (fig.1), and shallow- and deeper-water facies are both present. Diablo Platform carbonates also form the south boundary of the incipient Orogrande Basin (fig.1). Phylloid-algal shelf-margin buildups are common along the east fault-bound margin of the Orogrande Basin. During the Virgilian, subsidence increased in the Orogrande Basin, and the Pedernal Uplift experienced heightened activity (fig.2). It is proposed that the southern section of the Diablo Platform was becoming uplifted to the point of erosion of the pre-Pennsylvanian succession and may have contributed siliciclastic sediment into the marginal areas of the Delaware Basin, but that carbonate factories still dominated deposition on the main platform (fig. 2).

KEY CONCLUSIONS

- Missourian and Virgilian sedimentation patterns and distribution reflect dismantling of the Permian Basin into its separate subbasins (Midland, Delaware, Val Verde), each with its own distinct evolutionary history.
- Varied and potentially extreme rates of differential subsidence between and within basins resulted in different architectures and stratigraphic stacking patterns for the same successions.
- Missourian-age units in the Permian Basin reflect a continuation of the 2^{nd}-order transgression established during the Atokan. Virgilian-age sediments reflect deposition in the initial stage of a 2^{nd}-order regression.
- Missourian- and Virgilian-age siliciclastic sedimentation was still relegated to the periphery of the smaller basins. Extensive, basin-centered shale deposition in the

Midland and Delaware Basins is problematic because source areas are limited and no concrete data exist as to the age of the sediments.

- Missourian and Virgilian dominantly shallow water carbonates were deposited around the north, west, and east margins of the Midland Basin, whereas deeper-water carbonates were deposited along the northwest margin of the Delaware Basin. Carbonate depositional environments and systems varied widely within the Midland Basin, as well as between it and the Delaware Basin. Identification of Virgilian deeper-water crinoidal mud mounds on the northern Midland Basin Platform is contrary to historical generalization that the succession is predominantly shallow-water carbonate facies.
- Reservoir quality within the Missourian Midland Basin carbonates is generally linked to extent and duration of exposure events, and 3^{rd}- and 4^{th}-order sea-level falls are crucial to development of reservoir-grade porosity in the carbonate succession. However, this assertion has been historically overemphasized; depositional geometries and facies distribution are equally important, especially in the younger Virgilian succession. In the Midland Basin, long-duration exposure episodes can lead to cementation of the secondary pore network that developed during initial exposure. Long-duration exposure episodes were especially common in the Virgilian succession, where cycle thicknesses are generally less than in the Missourian.
- The northern Midland Basin Missourian and Virgilian carbonate succession highlights the need for continued research into these systems because new models

indicate that this area has a multicomponent architecture of isolated platforms superimposed on a regional ramp system.

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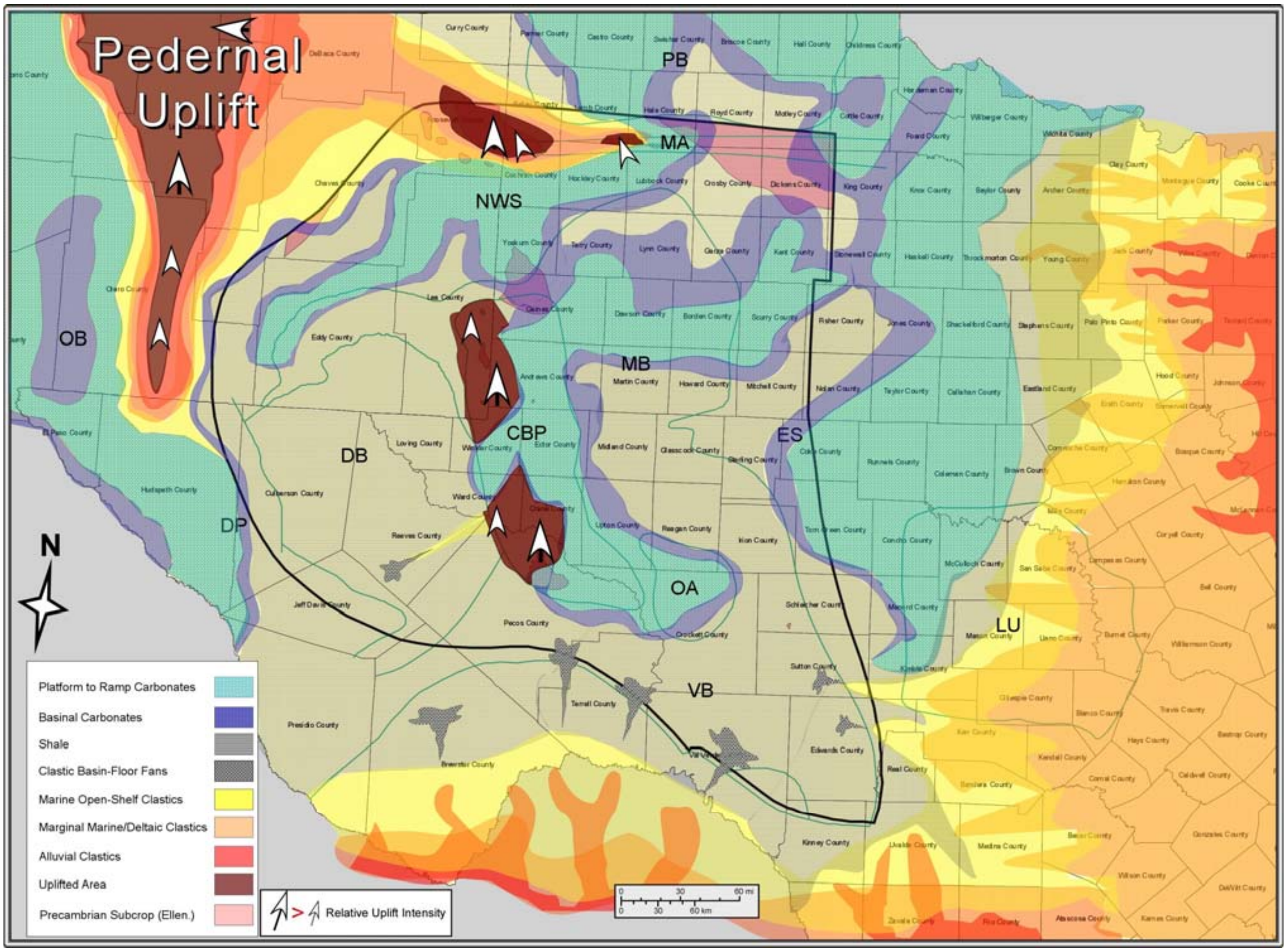


Figure 1. Missourian paleogeography and facies distribution map for the greater Permian Basin region during the early to middle Missourian. Major subregions are outlined by dark-green lines: Central Basin Platform (CBP), Delaware Basin (DB), Diablo Platform (DP), Eastern Shelf (ES), Matador Arch (MA), Midland Basin (MB), Northwest Shelf (NWS), Orogrande Basin (OB), Ozona Arch (OA), Palo Duro Basin (PB), Val Verde Basin (VB), LU (Llano Uplift). The Fort Worth Basin is centered on Wise County. The Llano Uplift area is outlined by the black dashed line. Sizes of arrows surrounding the Pedernal and other uplifted areas correspond to relative amount of uplift (that is, larger arrow, greater relative uplift).

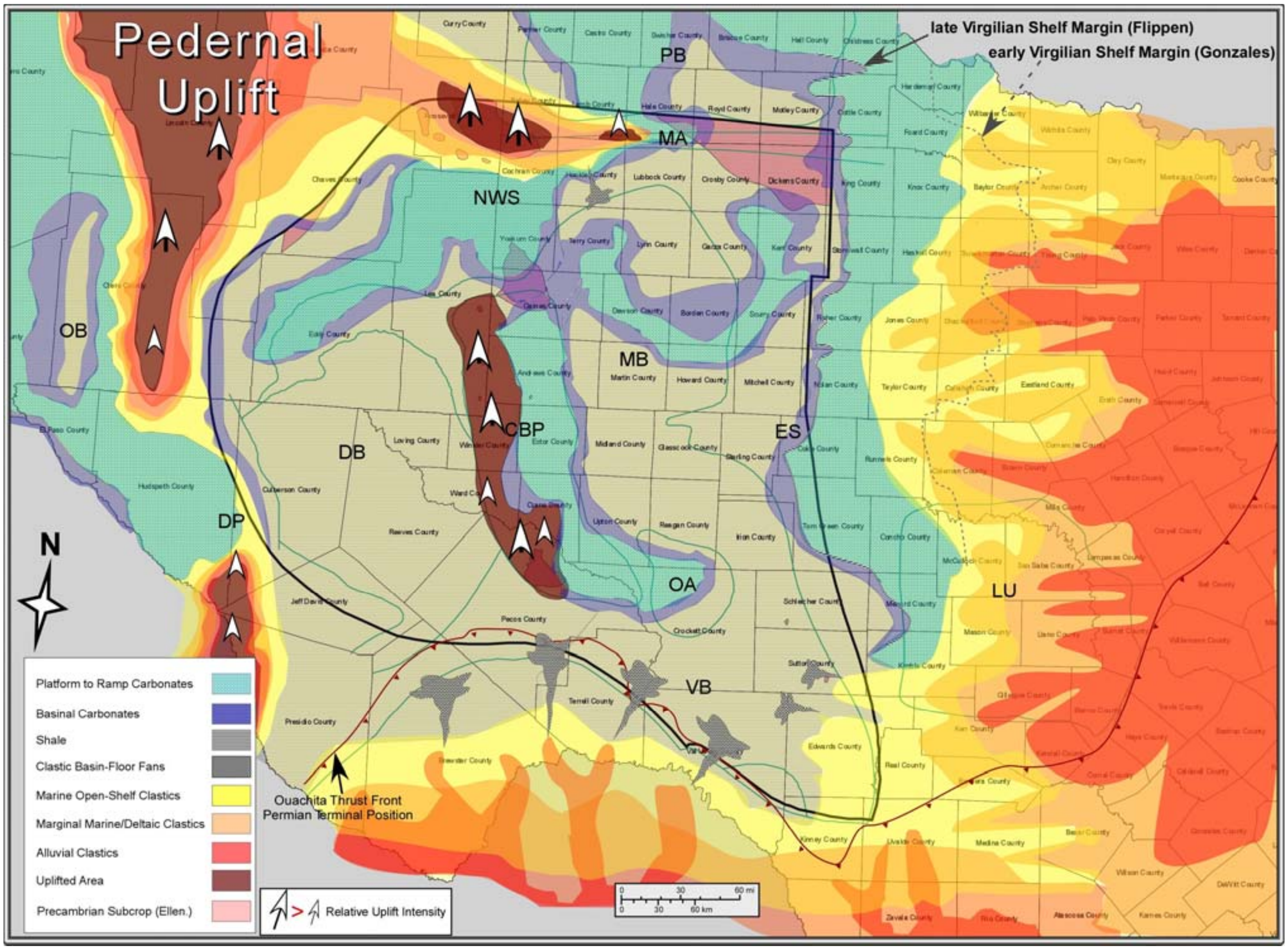
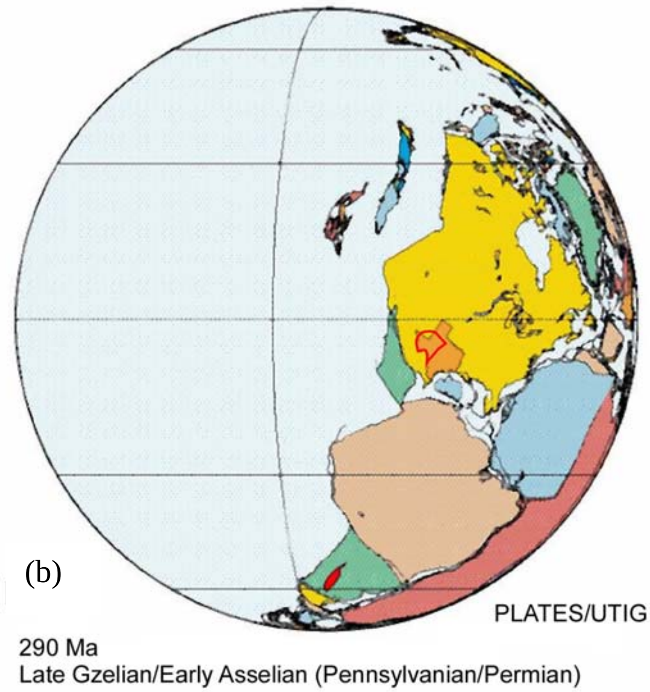


Figure 2. Virgilian paleogeography and facies distribution map for the greater Permian Basin region during the middle to late Virgilian. Major subregions are outlined by dark-green lines; Central Basin Platform (CBP), Delaware Basin (DB), Diablo Platform (DP), Eastern Shelf (ES), Matador Arch (MA), Midland Basin (MB), Northwest Shelf (NWS), Orogrande Basin (OB), Ozona Arch (OA), Palo Duro Basin (PB), Val Verde Basin (VB), and (LU) Llano Uplift. The Fort Worth Basin is centered on Wise County. Sizes of arrows surrounding the Pedernal and other uplifted areas correspond to relative amount of uplift (that is, larger arrow, greater relative uplift).



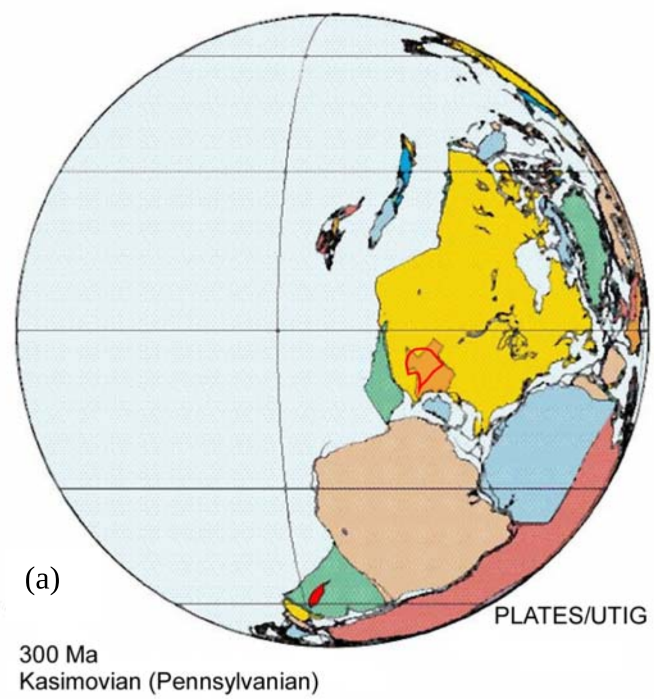


Figure 3. (a) Early Missourian-age (circa 300 Ma) Texas plate tectonic reconstruction. (b) Mid- to late Virgilian age (circa 290 Ma). In these reconstructions, the Permian Basin continues its northward migration (that is, more equatorial) relative to its Desmoinesian position. Diagram modified from Dalziel and others (2002).

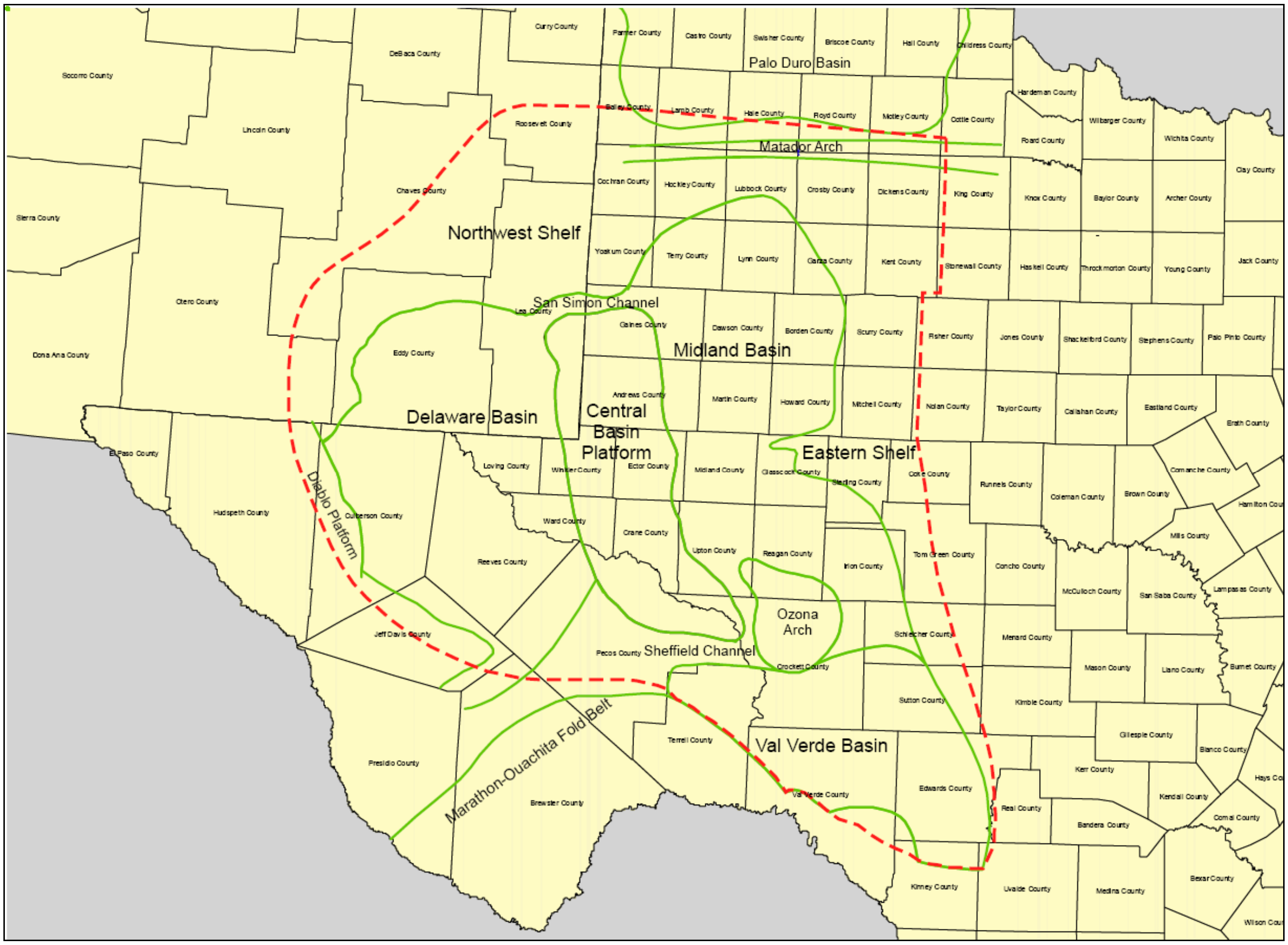
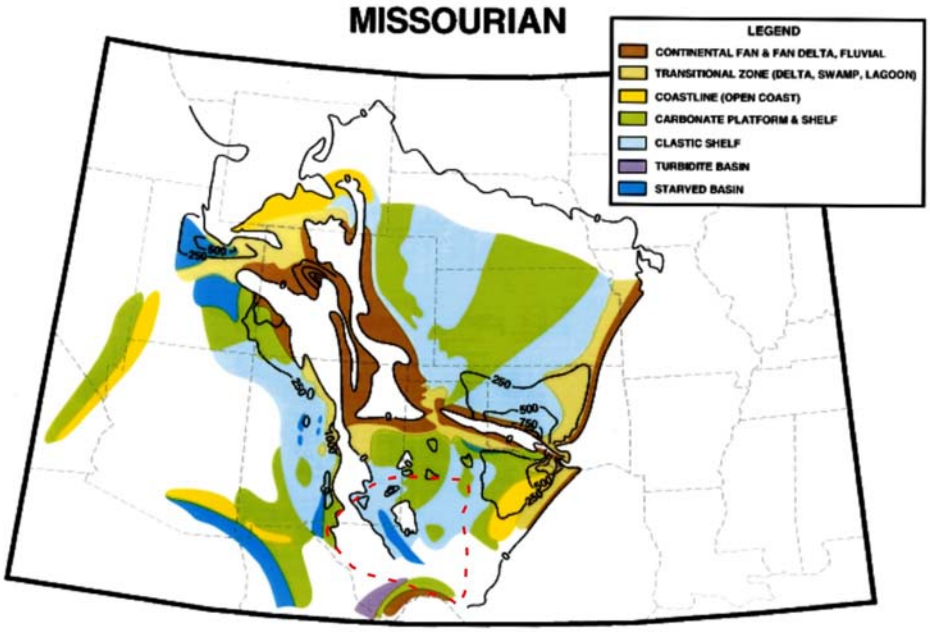


Figure 4. Permian Basin outline (dashed red) and major geologic features. Division of the Permian Basin into its physiomorphic component subbasins and platforms was completed largely by the end of the Missourian. Compare figure 4 with figures 5–7 for previous models of facies distribution relative to the basin outline. Figures 1 and 2 illustrate facies distribution for the greater Permian Basin area derived from this study. The west margin of the Forth Worth Basin runs north-south through Palo Pinto County.

(a)



(b)

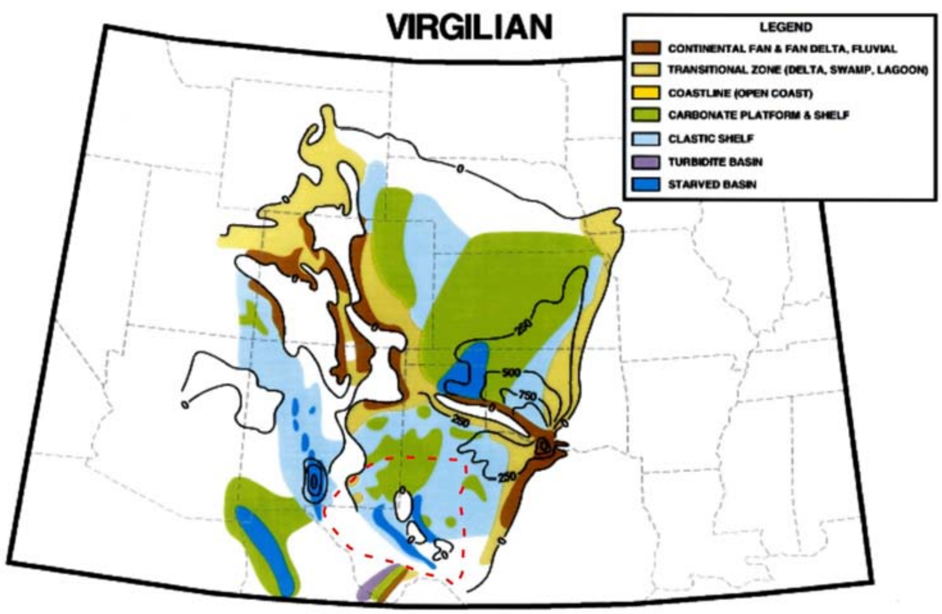
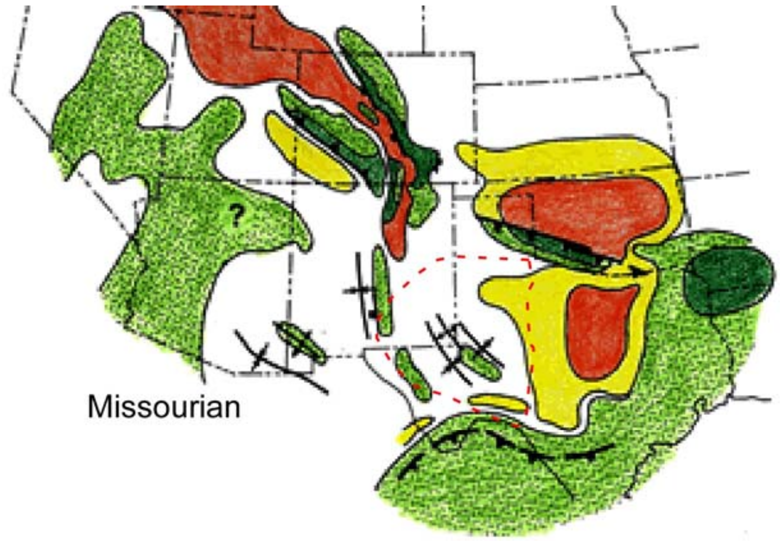


Figure 5. Generalized Rocky Mountain region and southern Midcontinent paleogeography for (a) Missourian and (b) Virgilian stages (from Ye and others, 1996). White areas indicate either nondeposition or erosion (not clarified in the original text). Note that Ye and others (1996) considered the lower half of the Permian Basin (outlined by red dashed polygon) to be either a siliciclastic shelf or an erosionally uplifted area during both the Missourian and Virgilian. Interpretations of the south-east half of the Permian are substantially revised in figures 1 and 2.



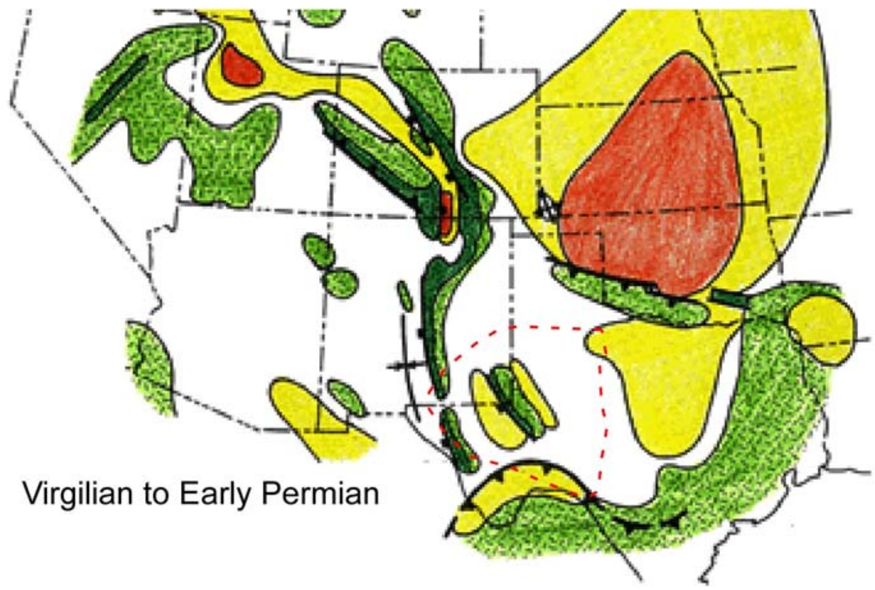


Figure 6. Areas of net subsidence (white <50 m/Ma to red >300 m/Ma) and net uplift (green <50 m/Ma) for the Missourian and Virgilian (after Kluth, 1986). These interpretations show overall net subsidence for the Permian Basin except in the area of the Central Basin Platform, which appears to enlarge from the Missourian to the Early Permian.

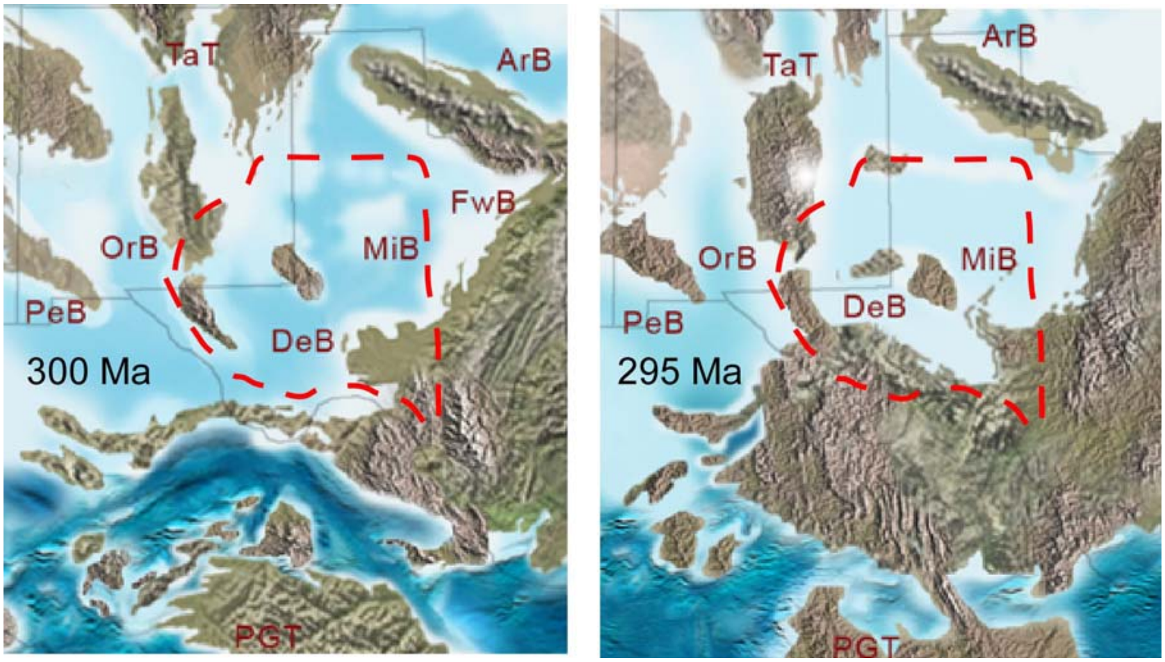


Figure 7. Regional paleogeography for the Missourian (circa 300 Ma) and Virgilian (circa 295 Ma). DeB and MiB refer to Delaware and Midland Basins, respectively. Permian Basin outlined by red dashed polygon. Anadarko Basin (ArB), Fort Worth Basin (FwB), Orogrande Basin (OrB), Pedregosa Basin (PeB), Taos Trough (TaT). Uplifted areas represented by browns, shallow marine by light- to medium-blues and deep marine by dark-blue (from Blakey, 2005). Note extensive increase in exposed landmass in the south part of the Permian Basin from the Missourian to the Virgilian (proposed time span of 5 Ma).

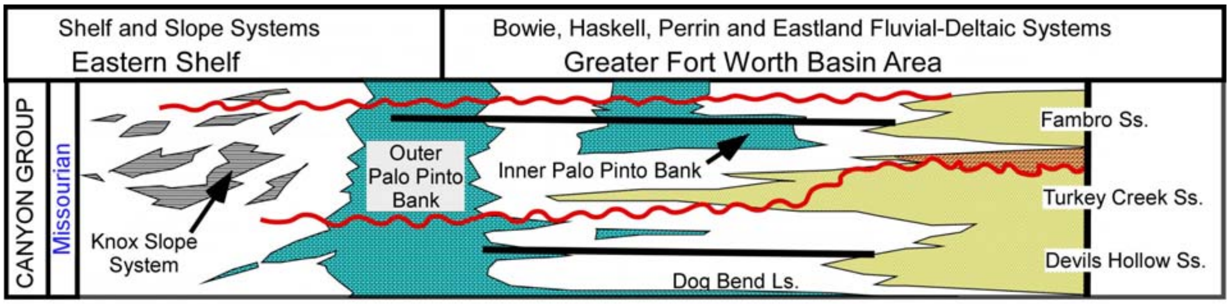


Figure 8. Chrono-, litho-, and sequence stratigraphy of the Canyon Group. In areas of more fixed and continuous carbonate deposition, a Canyon Platform interval is placed between the Palo Pinto bank system and the Home Creek limestone. Figure modified from Cleaves (1993, 2000).

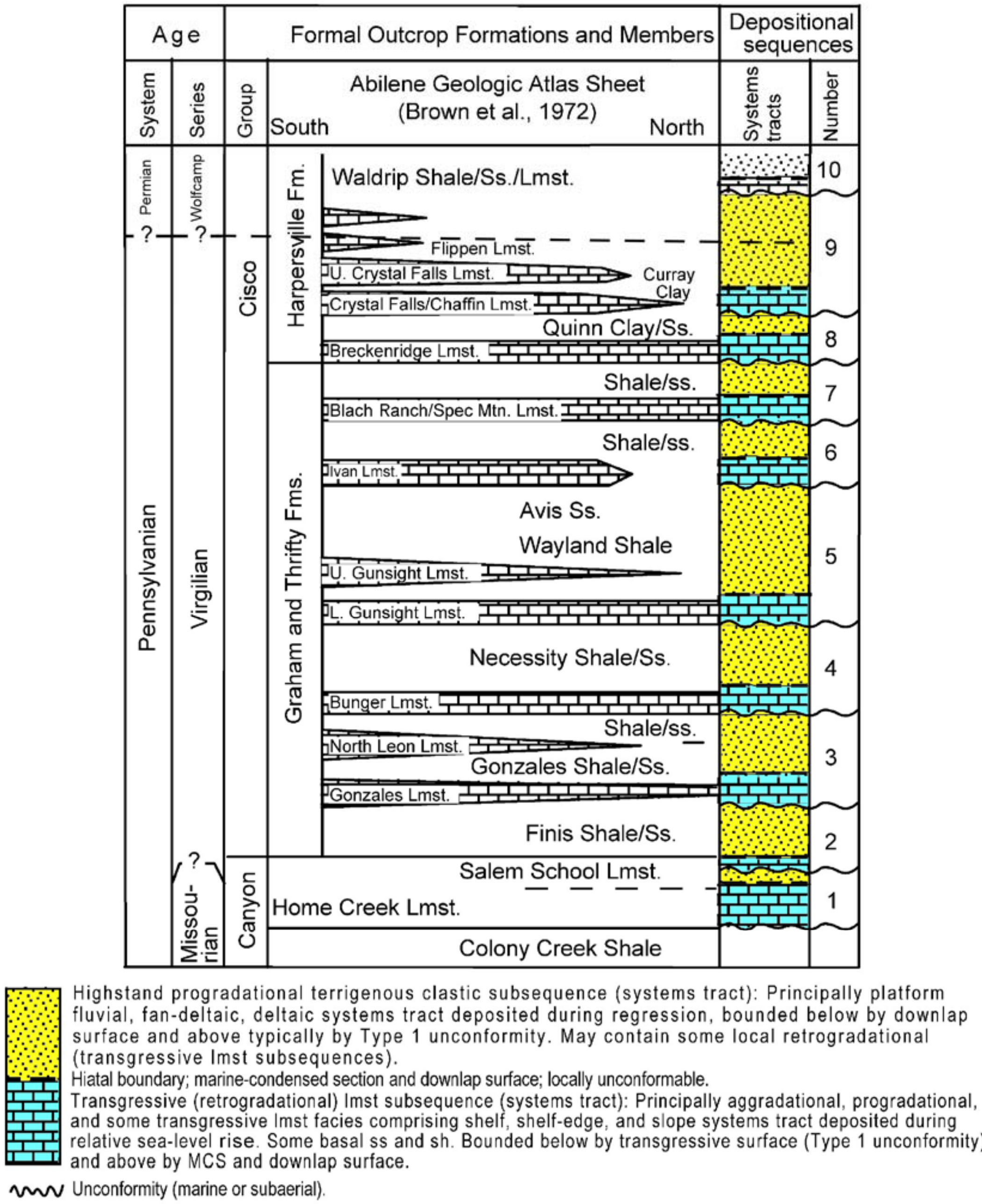


Figure 9. Chrono-, litho-, and sequence stratigraphy of the Cisco Group in a north-south orientation across the Eastern Shelf. Figure modified from Yang and Kominz (2003). Note dominance of highstand progradational siliciclastic systems tracts in the Virgilian when compared with the underlying Missourian succession. These tracts commonly contain facies from fluvial, fan-delta, and deltaic depositional environments.

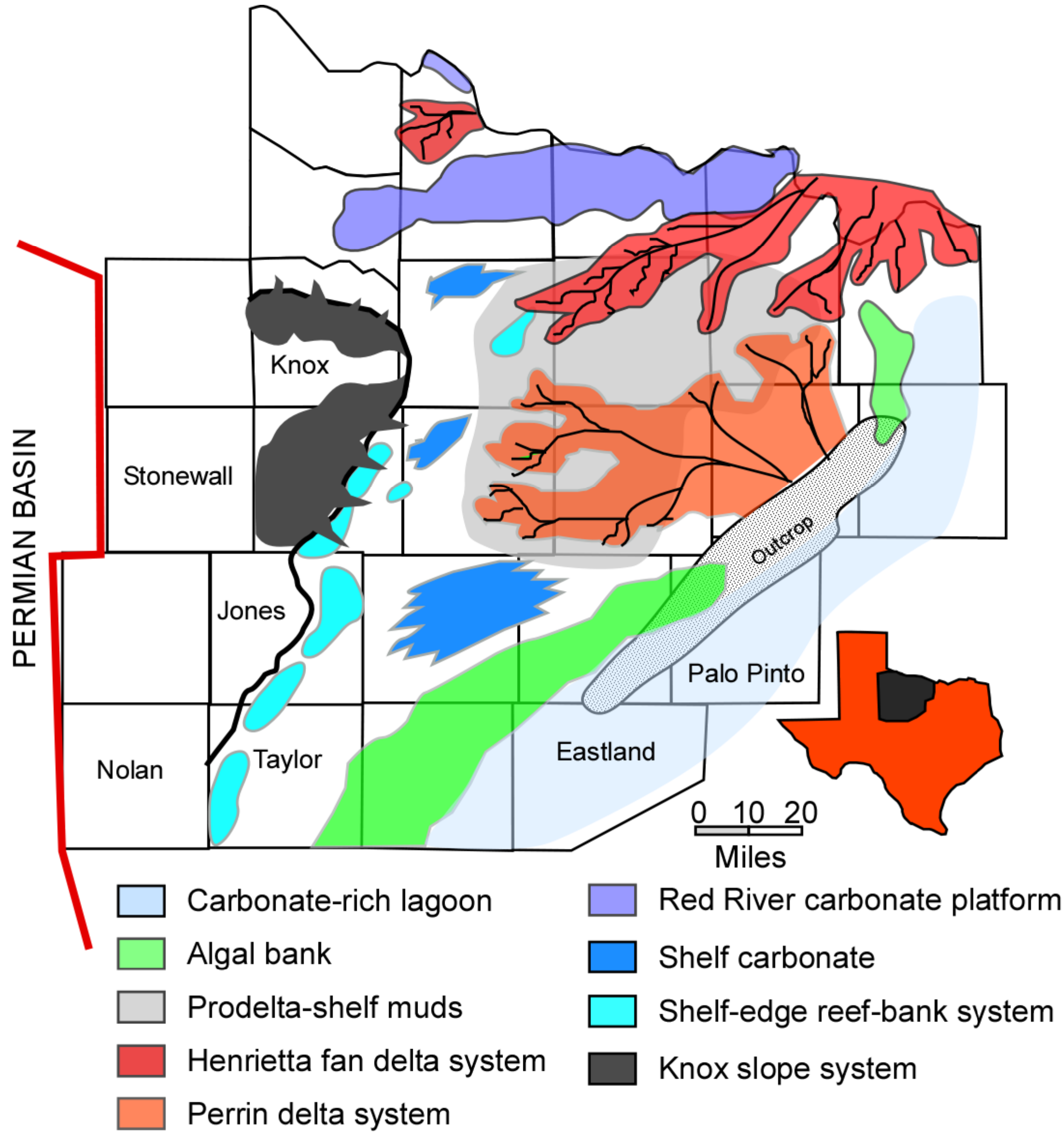


Figure 10. Mid-Canyon-age depiction of depositional environments and paleogeography of North-Central Texas (Eastern Shelf to Fort Worth Basin). Note that coarse or fine siliciclastic sediments are not reaching the Permian Basin (east margin—thick red line). The proposed Missourian-age Knox Slope System is generally confined to Knox and Baylor Counties. After Cleaves (2000).

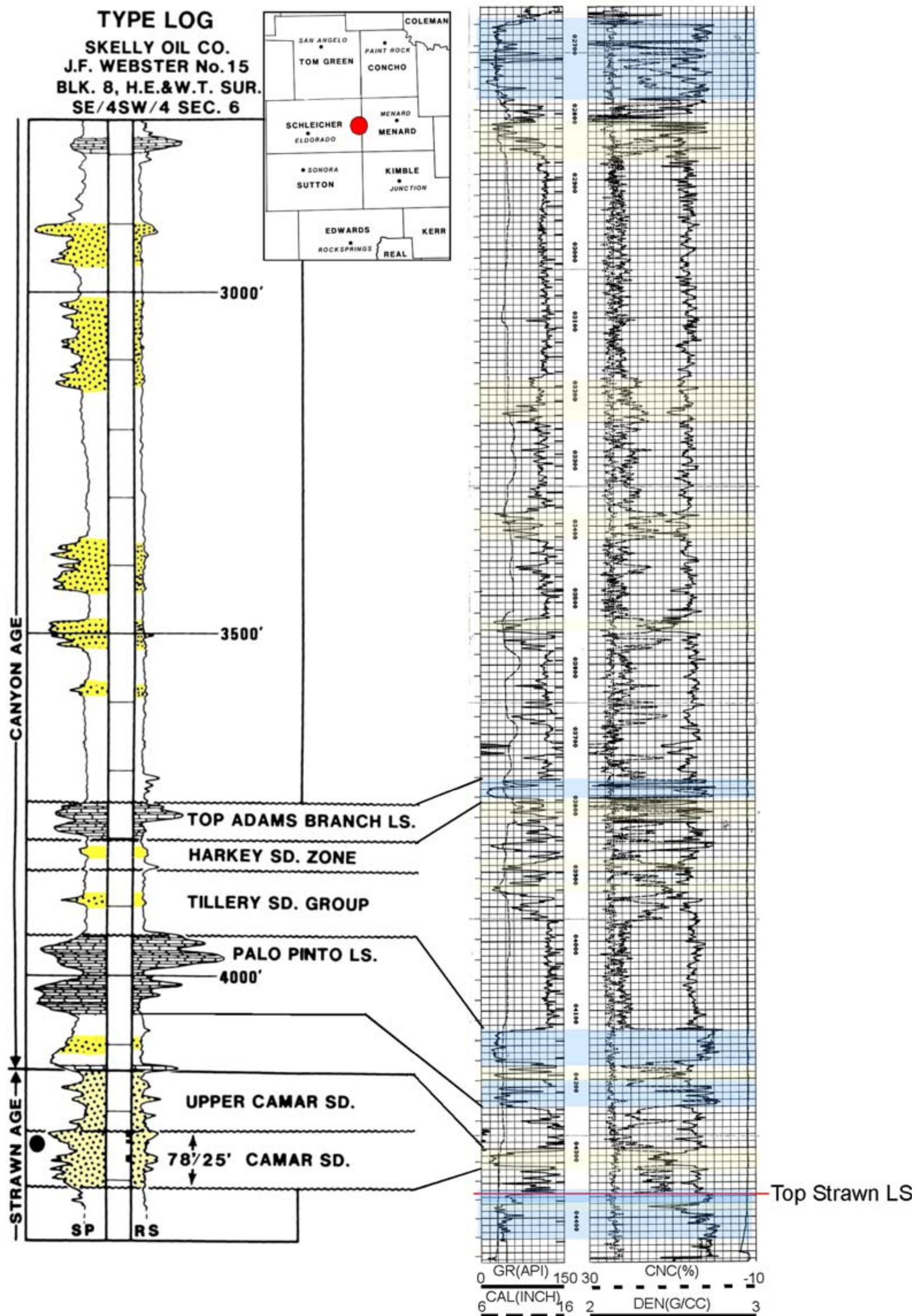


Figure 11. Regional location map of Camar field and type wireline log of Eastern Shelf Missourian sandstone succession on both SP- and GR-based well logs. After Hoffacker (1990). Note that the Adams Branch limestone is a local unit occurring between the Palo Pinto and Home Creek Formations and is not defined in figures 8 or 9.

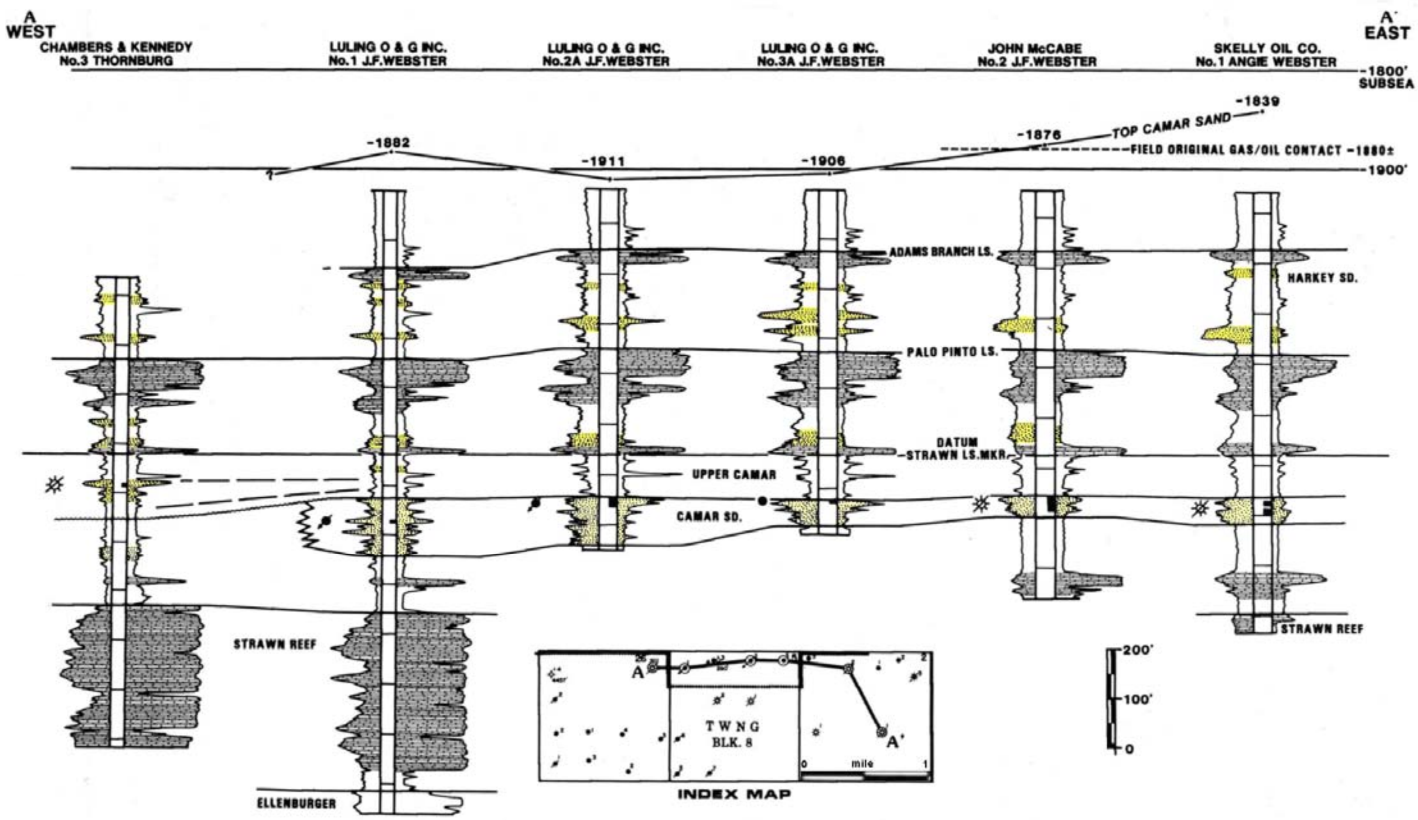


Figure 12. Regional cross section of the Missourian sandstone succession on the Eastern Shelf. Note apparent lateral continuity of sandstone bodies across several miles. Presence of underlying Desmoinesian “Strawn Reef” and overlying Palo Pinto Limestones indicates a true Missourian age for Camar sandstones.

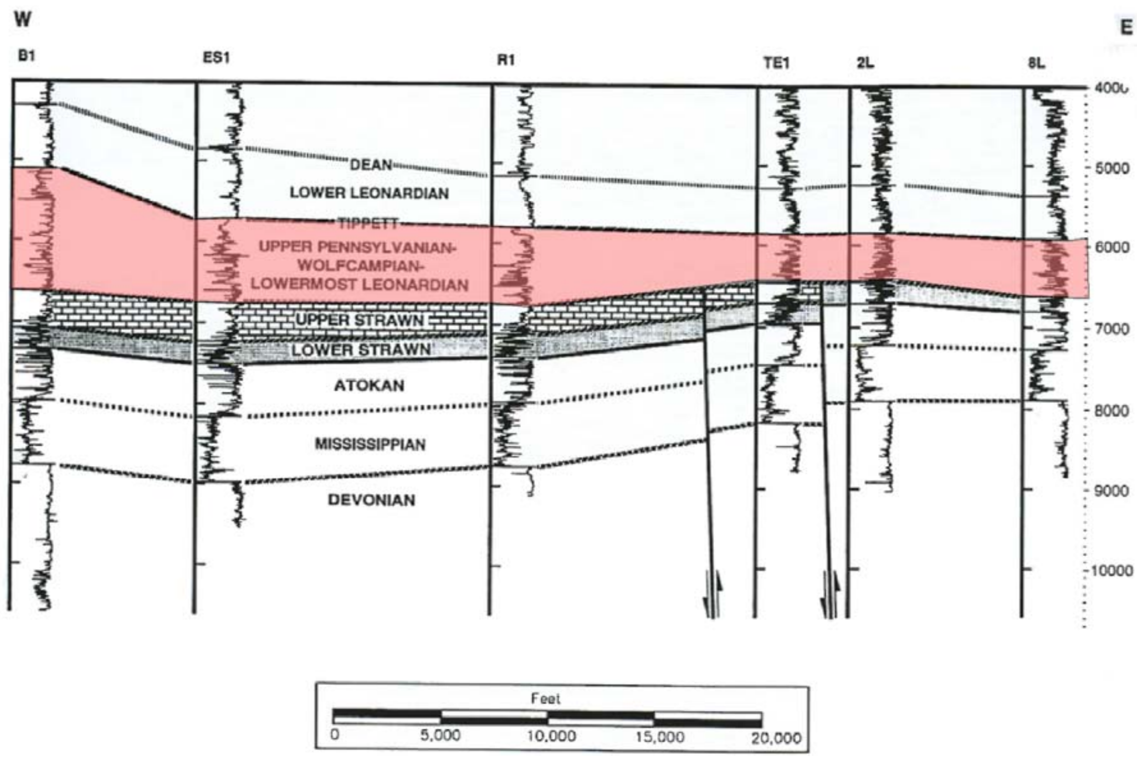


Figure 13. Regional well cross section of Wilshire field, Upton County (after Tai and Dorobek, 1999). Note dominantly shaly wireline-log signature and lack of differentiation in post-Strawn (Desmoinesian) to Leonardian succession.

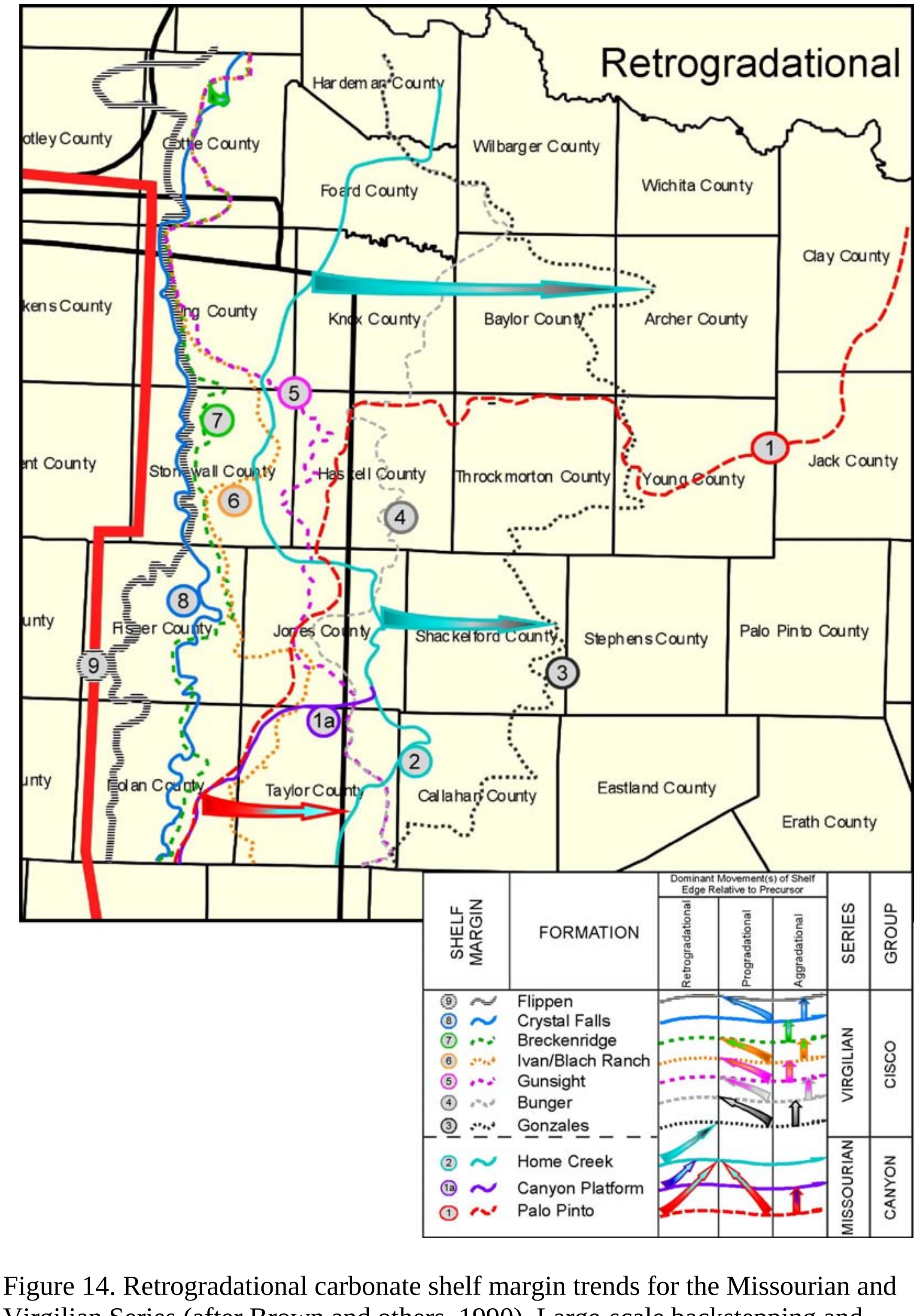


Figure 14. Retrogradational carbonate shelf margin trends for the Missourian and Virgilian Series (after Brown and others, 1990). Large-scale backstepping and retrogradation are largely restricted to the Missourian Series. Color fill of arrows corresponds to color of older margin at the base and new margin location at the arrow tip.

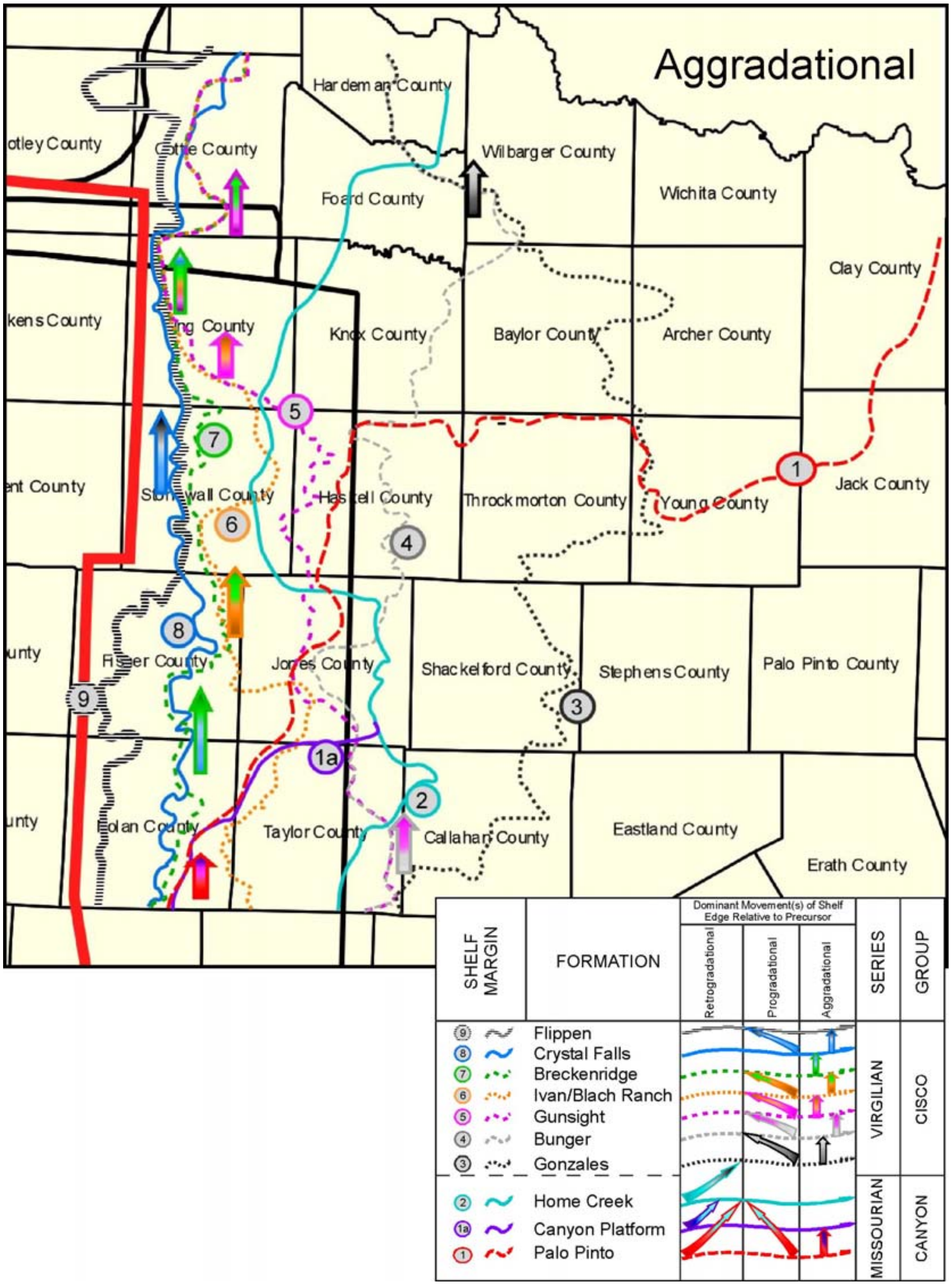


Figure 15. Aggradational carbonate shelf margin trends for the Missourian and Virgilian Series (after Brown and others, 1990). Note that the aggradational component of each trend varies along strike. Color fill of arrows corresponds to color of older margin at the base and new margin location at the arrow tip.

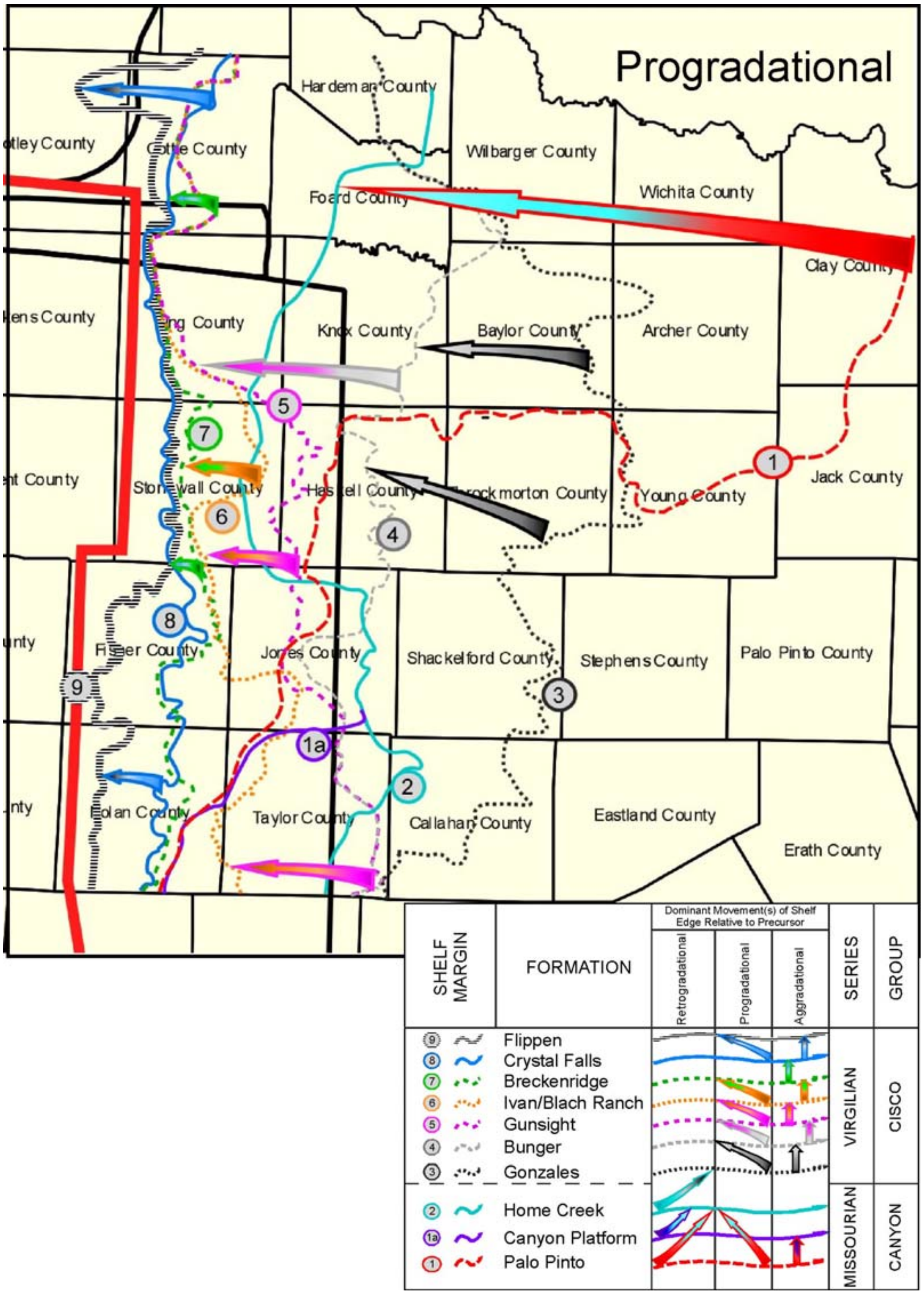


Figure 16. Progradational carbonate shelf margin trends for the Missourian and Virgilian Series (after Brown and others, 1990). Note that shelf margin 9 (Flippen Formation) does not pass into the Permian Basin (as defined by this study). Siliciclastic sediments are trapped largely behind this margin during the Virgilian.

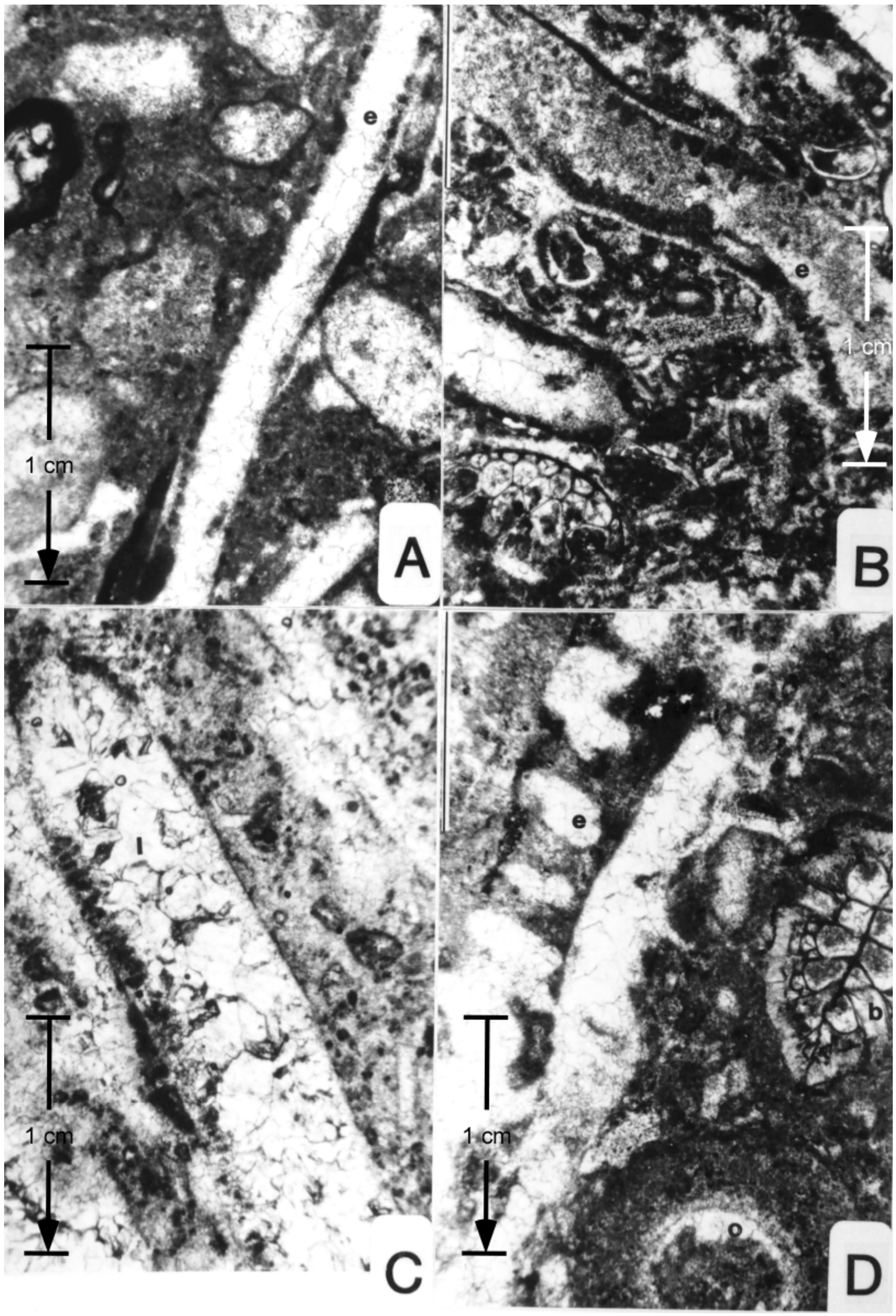


Figure 17. Photomicrographs of calcareous algae within phylloid-foram wackestones. A. and B. Phylloid algae *Eugonophyllum* (e). C. Phylloid; cf. *Ivanovia* (I) in pelletal microspar. D. Dasycladacean algae *Epimastopora* (e) with an oncolite (o) and a bryozoan (b); cf. *Rhombopora*. After Schatzinger (1987).

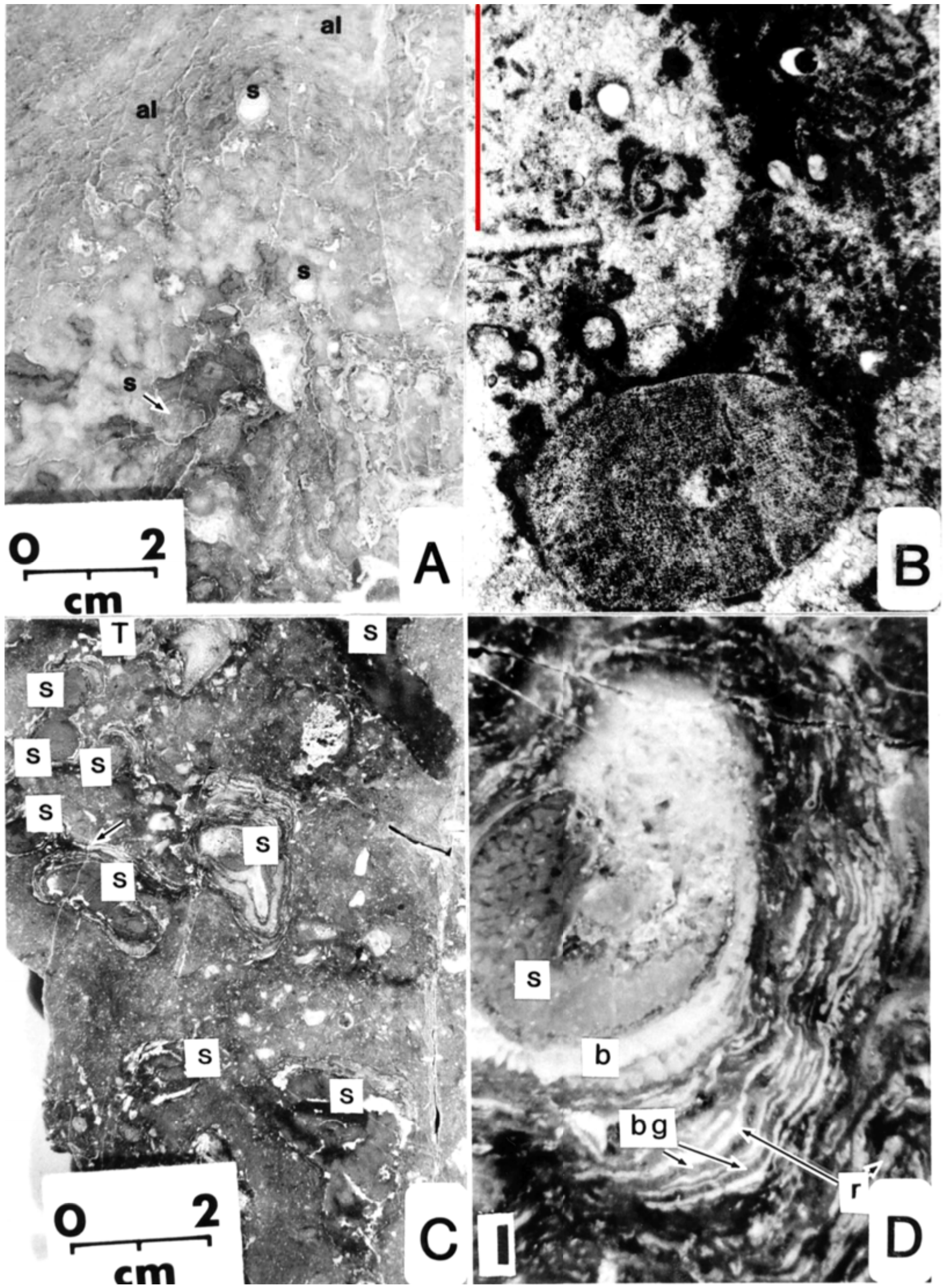


Figure 18. Core slab photos and photomicrographs of sponge-algal-bryozoan boundstone assemblage. A. Calcareous sponges (s) bound together by algal laminae (al). B. Crinoid ossicle and ostracods bound to pelletal micrite lumps. C. Core slab photograph of mound core illustrating numerous encrusted calcareous sponges and *Tubiphytes*. D. Composite rhodolith from C displaying sequential growth by calcareous sponge (s), bryozoa (b), blue-green alga (bg), and red alga (r). After Schatzinger (1987).

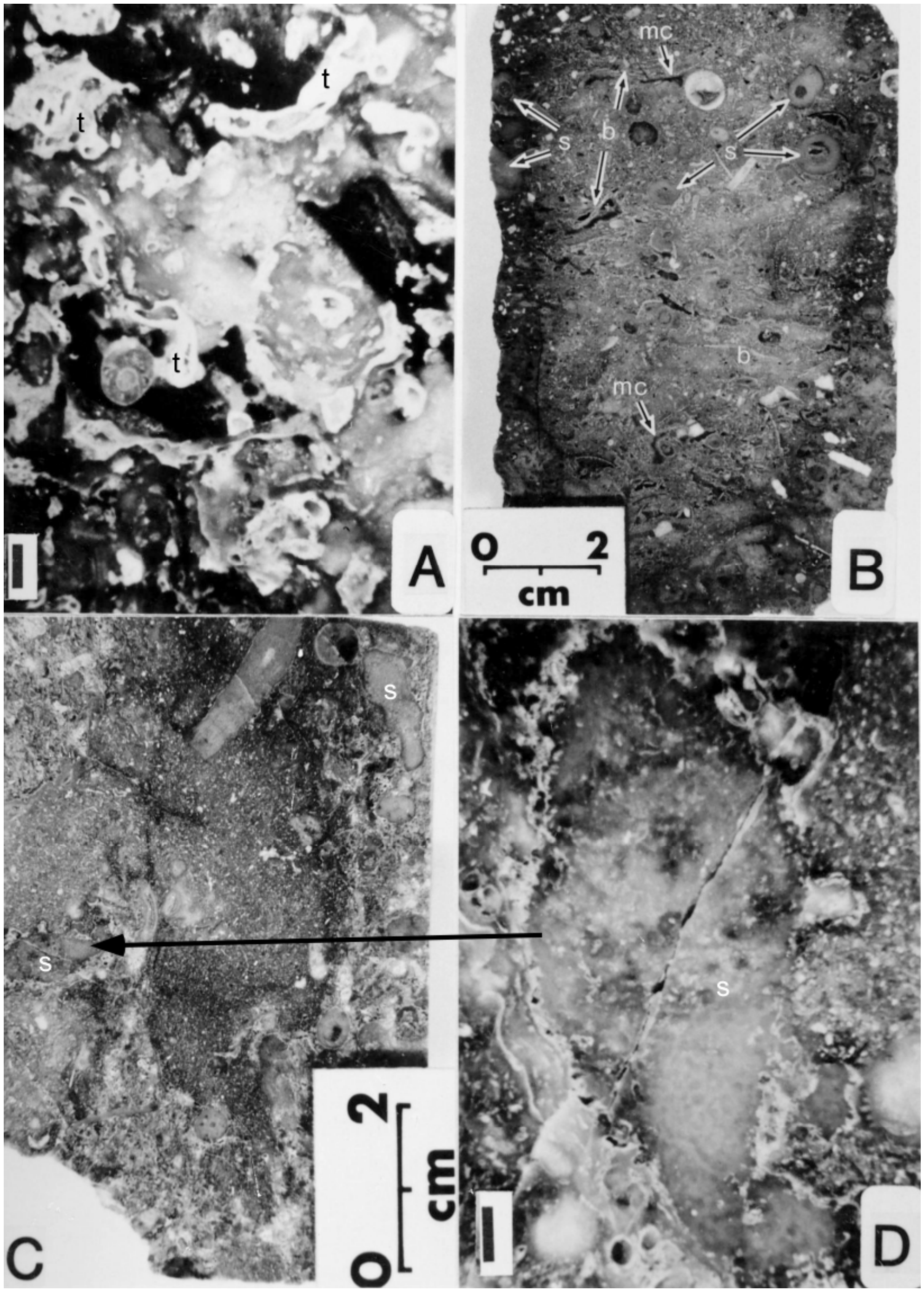


Figure 19. Core slab photos and photomicrographs of sponge-mound facies.
A. *Tubiphytes* (t) boundstone (*Tubiphytes* binding and encrusting micritic lumps and large benthic forams). B. Porous sponge-bryozoan mound flank facies with abundant sponges (s) and bryozoan debris (b), algal coated and stabilized by marine cement (mc). D. Enlarged photo of C highlighting encrustation by algae and forams. After Schatzinger (1987).

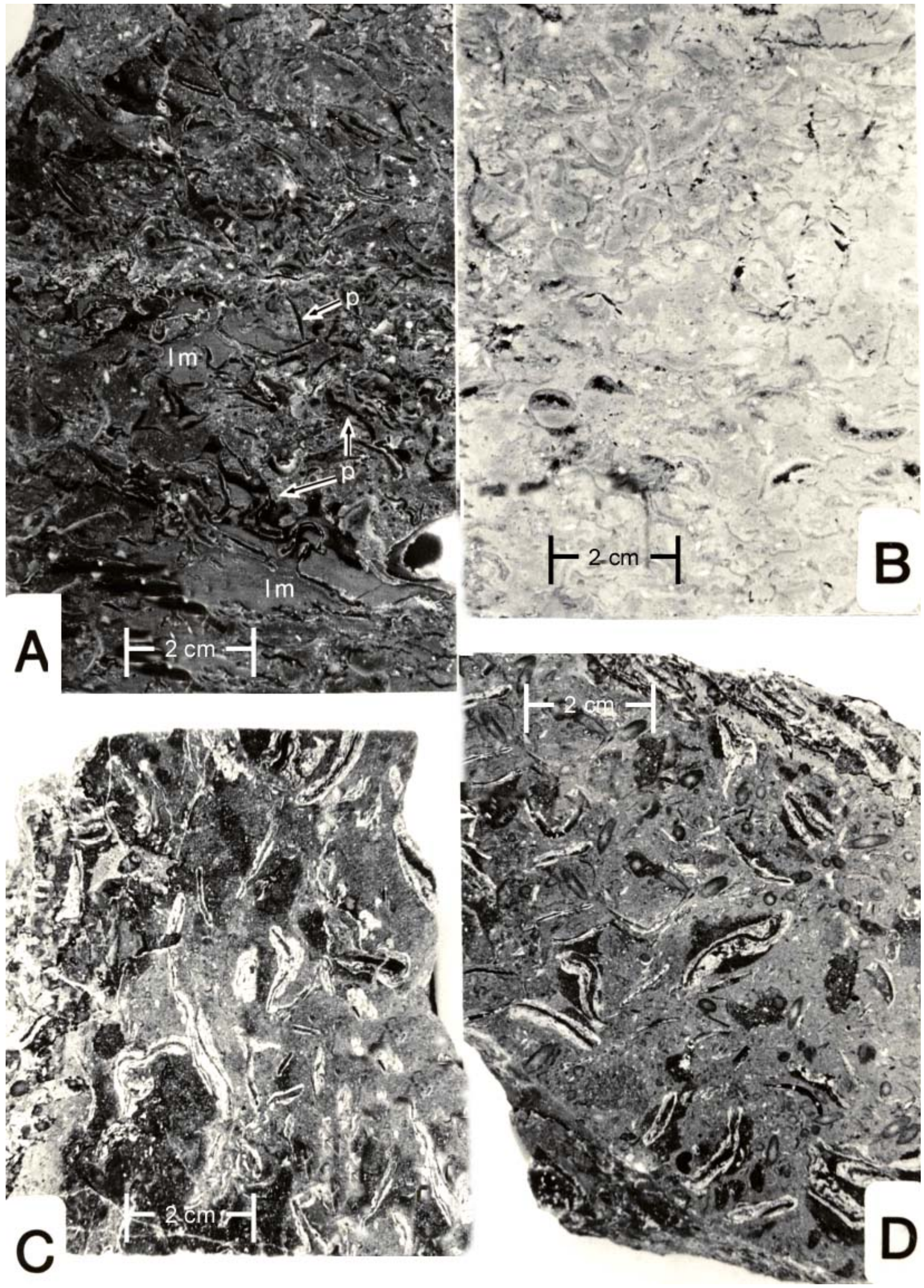


Figure 20. Core slab photographs of algal-mound facies. A. Laminated micrite (lm) deposited with and baffled by phylloid thalli (p), resulting in occlusion of shelter porosity. B. Porous phylloid-foram wackestone with porosity in partly filled brachiopods and leached phylloid thalli. C and D. Nonporous phylloid-foram wackestone with thick foram-algal encrustation (light) on phylloid thalli (dark). After Schatzinger (1987).

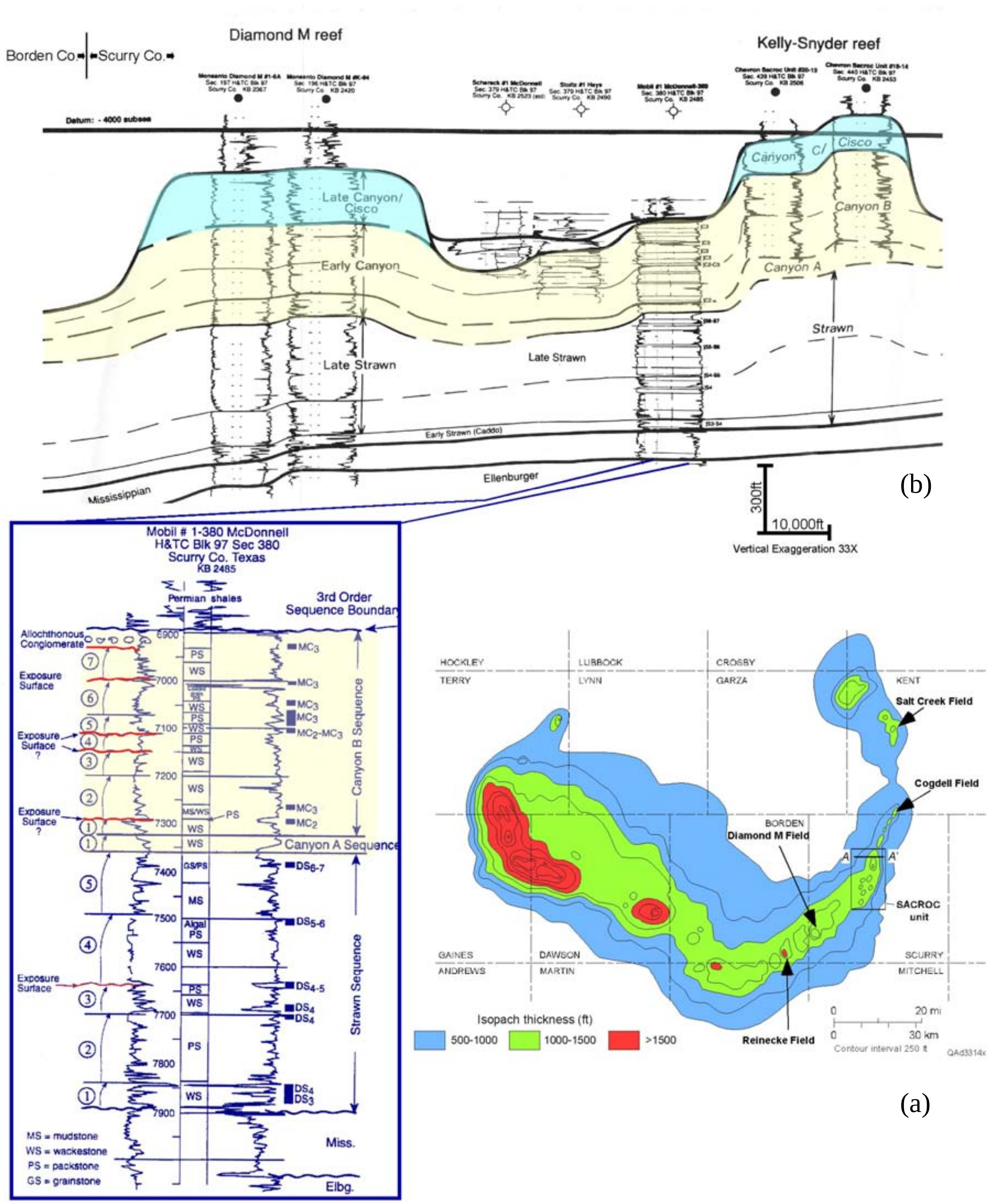
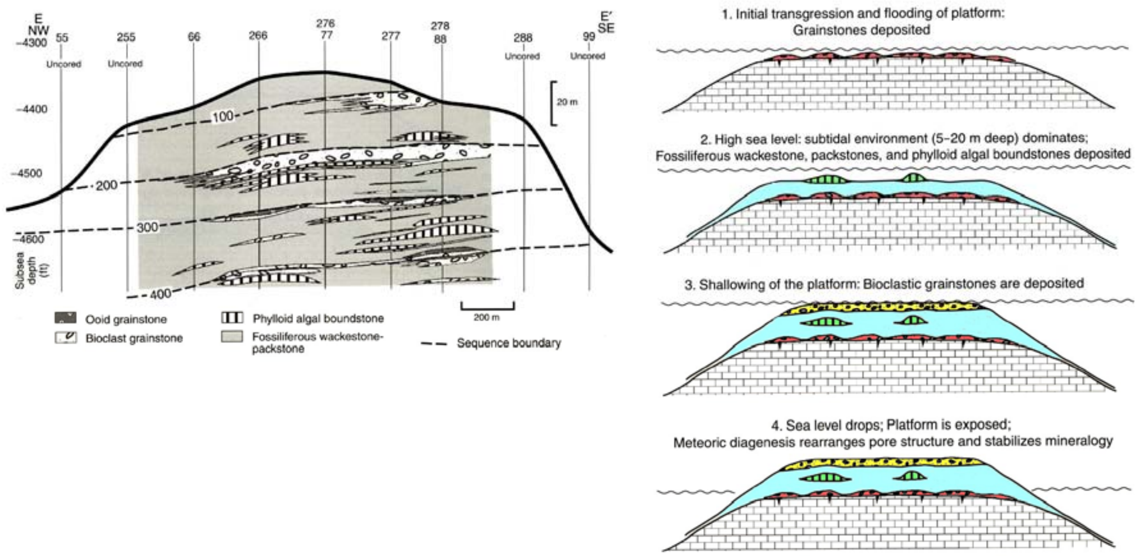
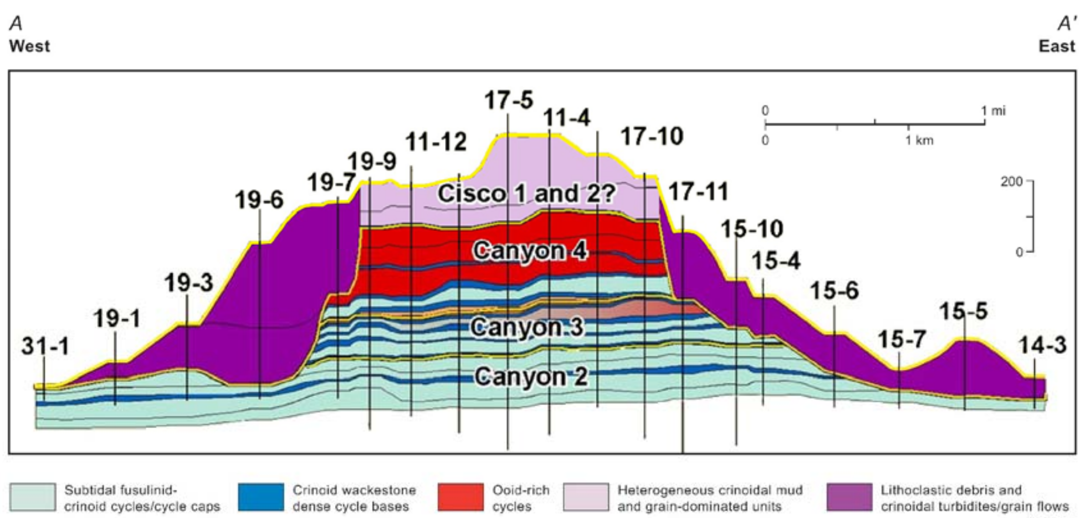


Figure 21. Regional and subregional distribution of Missourian and Virgilian carbonates in the northern Midland Basin. (a) Regional isopach of total carbonate thickness in the Horseshoe Atoll area. Increased thickness generally corresponds to increased proportions of Virgilian-age sediments. (b) Seismic, well log, and biostratigraphic correlation of Missourian (Canyon) and Virgilian. Note increased number of proposed exposure surfaces in the Canyon B sequence compared with those of the underlying Desmoinesian.



(a)



(b)

Figure 22. Facies architecture, distribution and evolution diagrams for Reinecke field (a) and SACROC (b) (after Saller and others, 2004, and Dutton and others, 2004). Upper two illustrations depict proposed stratiform depositional architecture and evolution of Virgilian-age carbonates at Reinecke field (after Saller and others, 2004). Note that although >300 ft of topography is expressed at the margins of the platform, the architecture is still proposed to be stratiform even at the margins. (b) Illustration of facies depositional architecture and evolution of Missourian- and Virgilian-age carbonates at SACROC (after Dutton and others, 2004). Note that at the margins of the platform, lithoclastic debris and crinoidal turbidites drape the structures. Also, Cisco 1 and 2 successions contain crinoidal mud mounds.

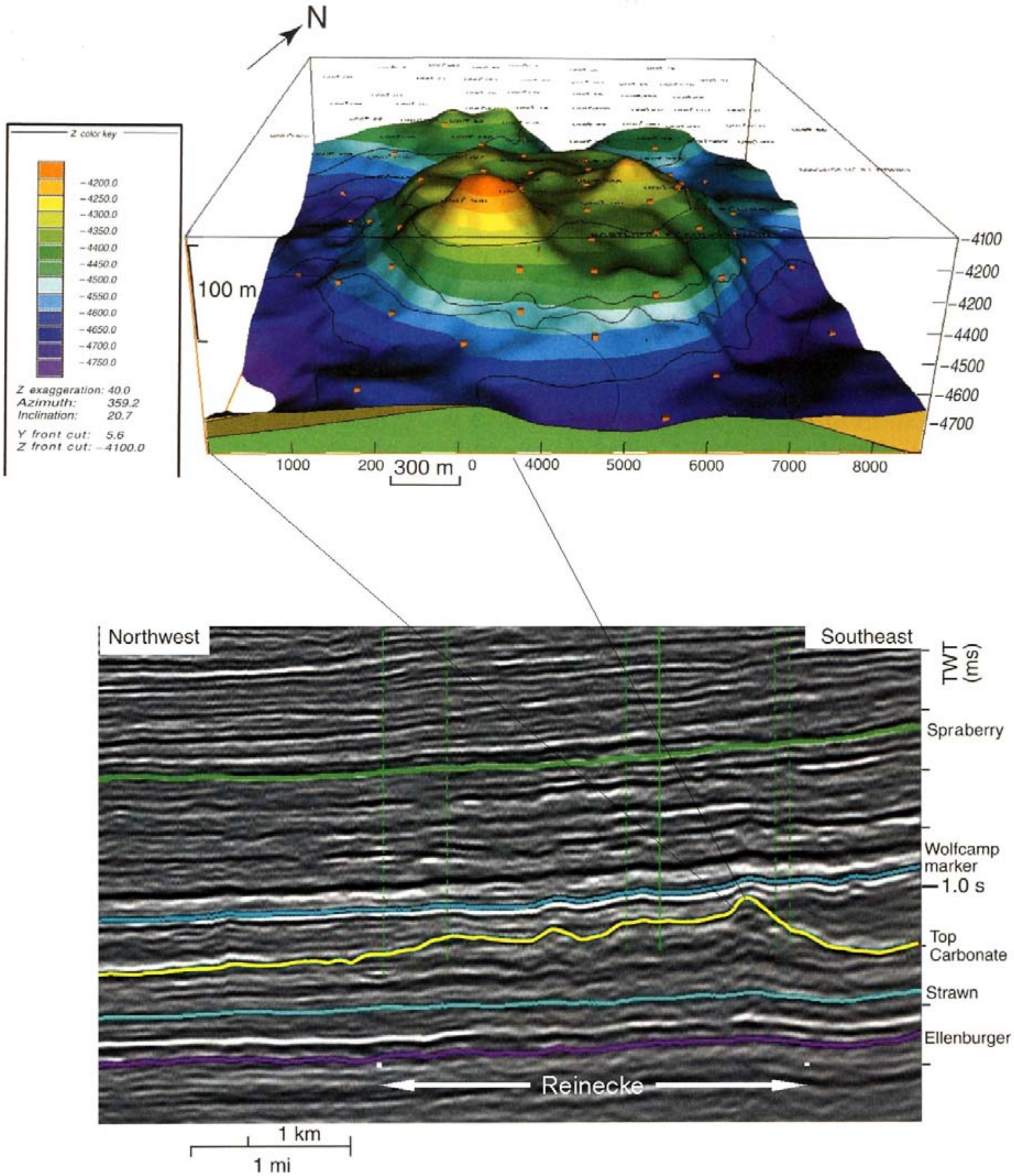


Figure 23. Regional seismic line through Reineke field (bottom) with inset of the South Dome area, top Virgilian carbonate structural map, based on seismic and well logs. Note that the inset is rotated relative to regional seismic (after Saller and others, 2004). This figure illustrates irregularity of the top Virgilian carbonate surface at both local (<300 m) and regional scale (<3 km).

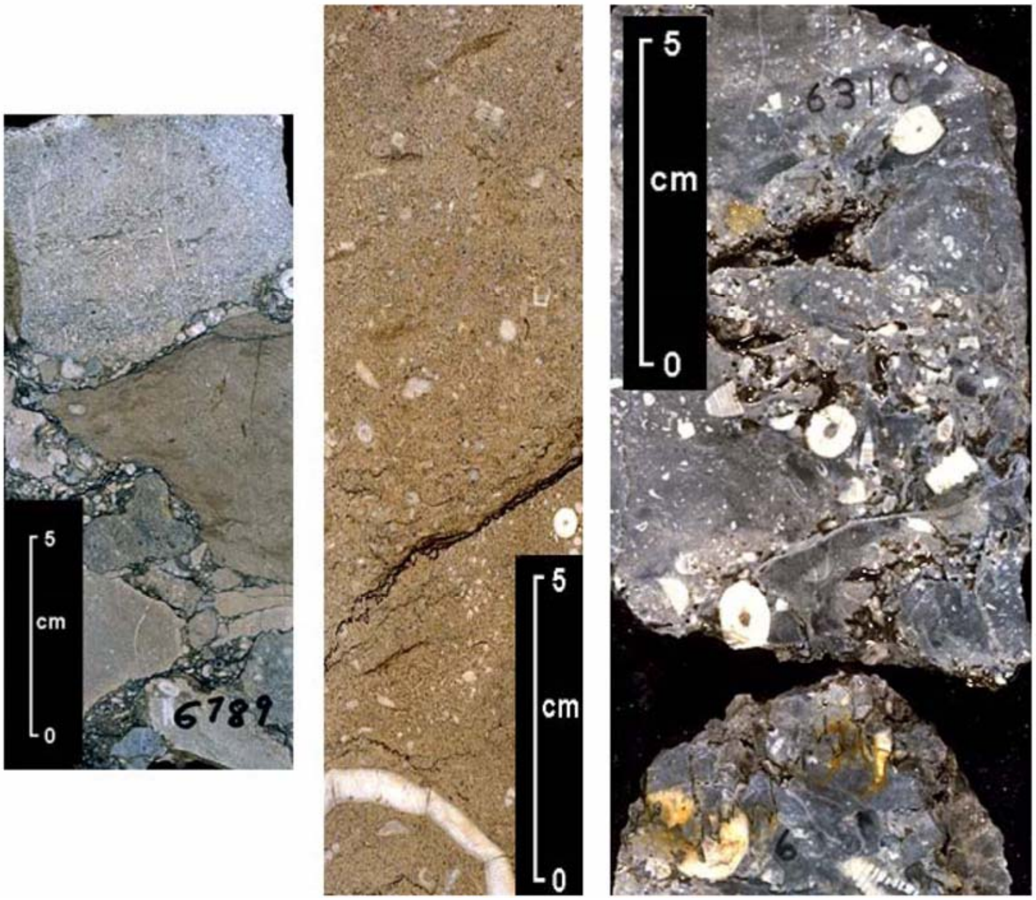


Figure 24. Core slab photos of typical Virgilian (Cisco) facies. Left photograph is a debris flow containing large lithoclasts and crinoidal debris. Middle image is crinoidal turbidite with steeply dipping beds to the left. Right photograph illustrates a stromatactid mud-mound facies with abundant, large, crinoid debris. After Janson and Kerans (2007).

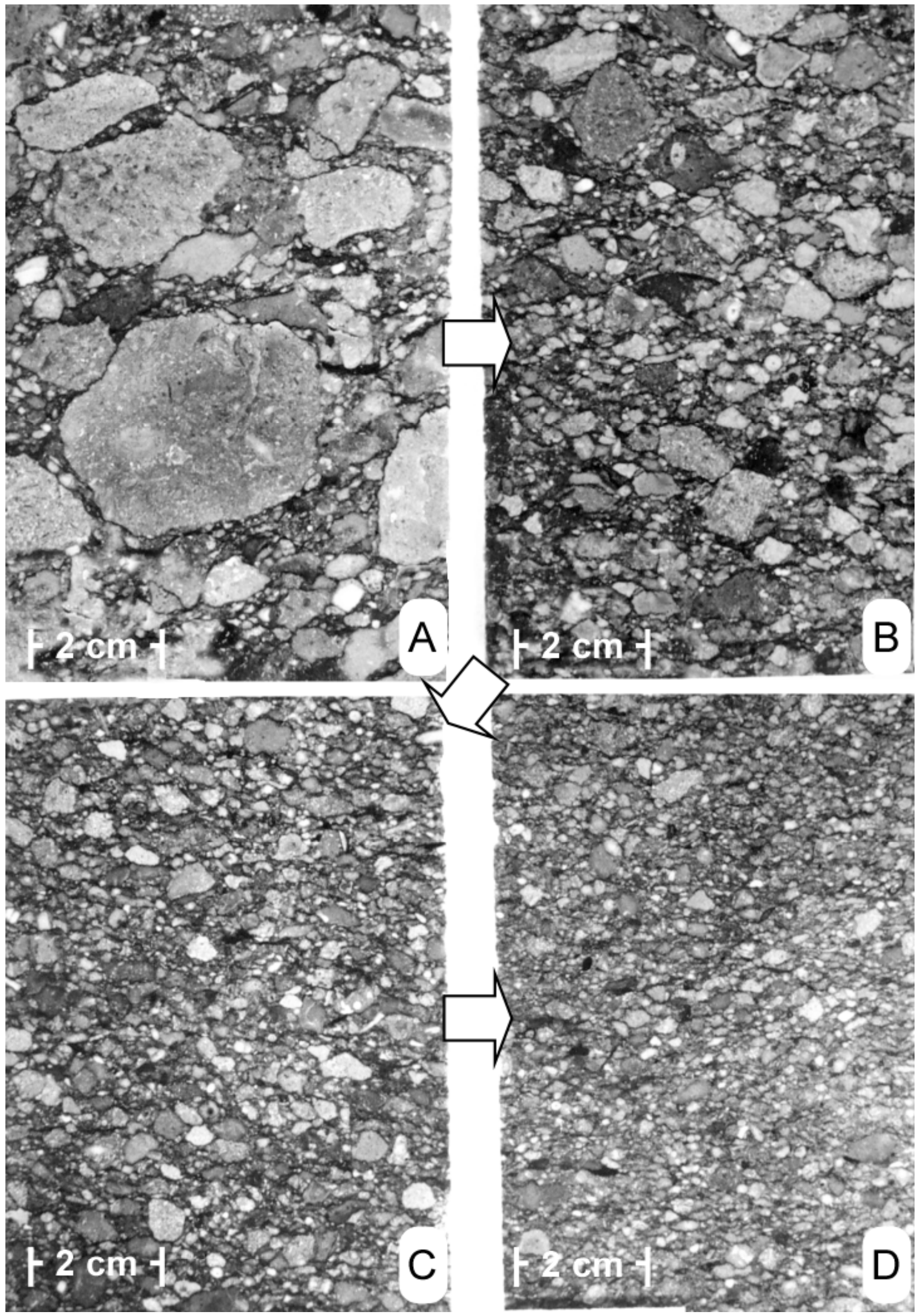


Figure 25. Core slab photographs of lithoclastic debris-flow breccias. A. Coarse base of flow at 2,061 m. B. Moderately coarse middle of flow at 2,059 m. C and D. Upper finer grained parts of the flow at 2,058 and 2,056 m. Note overall upward-fining nature of the sequence. After Schatzinger (1987).

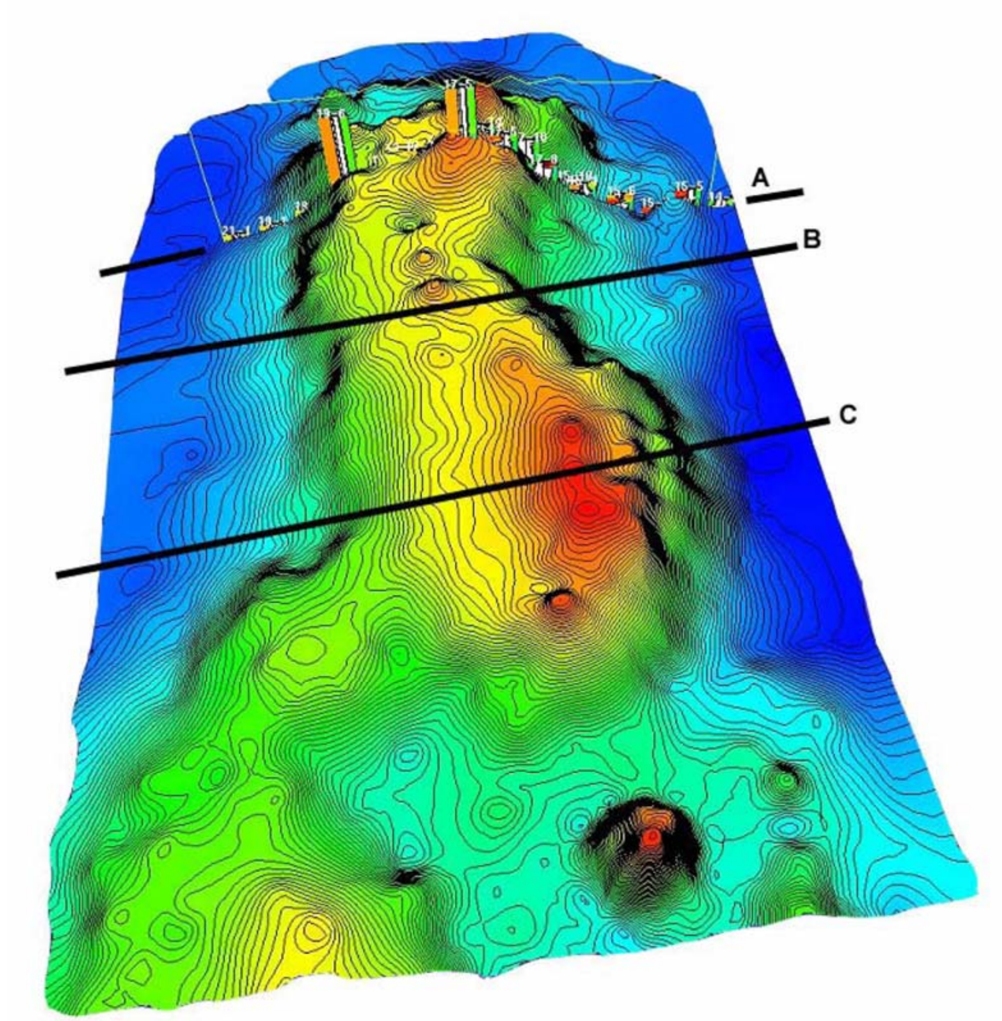
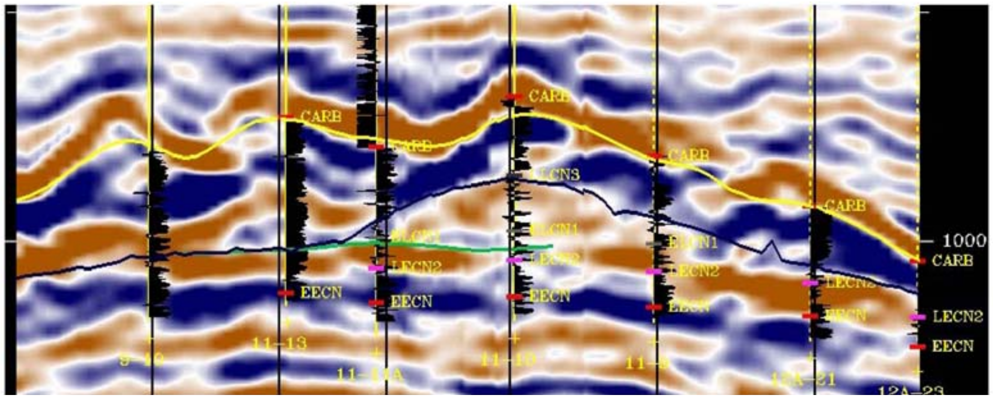
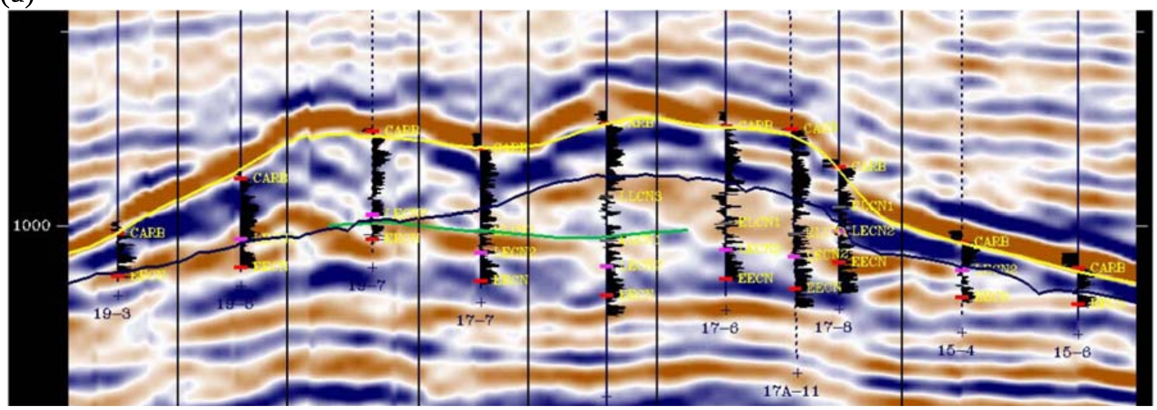


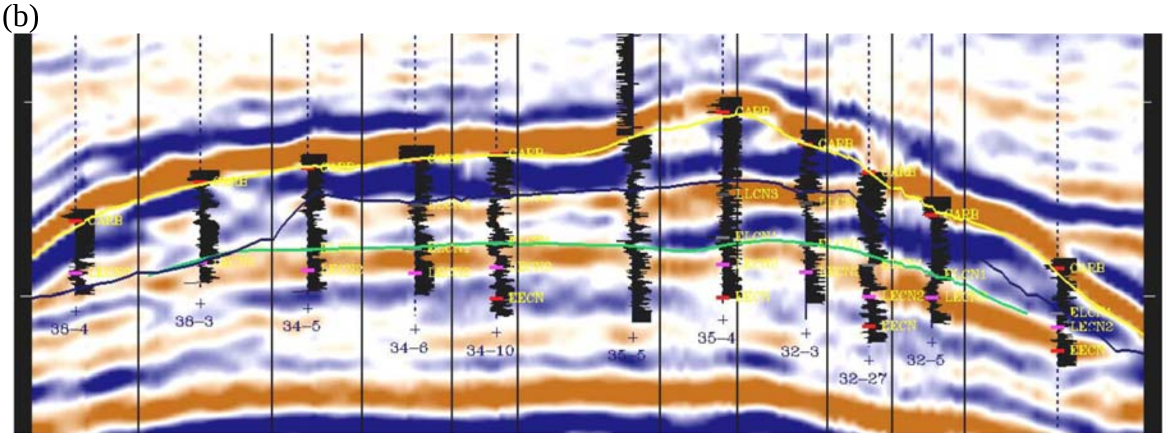
Figure 26. Structure-contour map of the top Virgilian (CISCO) carbonate at SACROC. Note change in architectural style from flat in the south (near C) to more rugose, narrow, and irregular to the north (near A). After Janson and Kerans (2007).



(a)



(b)



(c)

Figure 27. Seismic, cross-sectional profiles of the SACROC platform from south to north (c–a). Line placement indicated on figure 24. Note relatively stratiform architecture in line c, changing to a more mounded and shingled architecture in b, and ultimately to the isolated, high-relief mounds in a. After Janson and Kerans (2007).

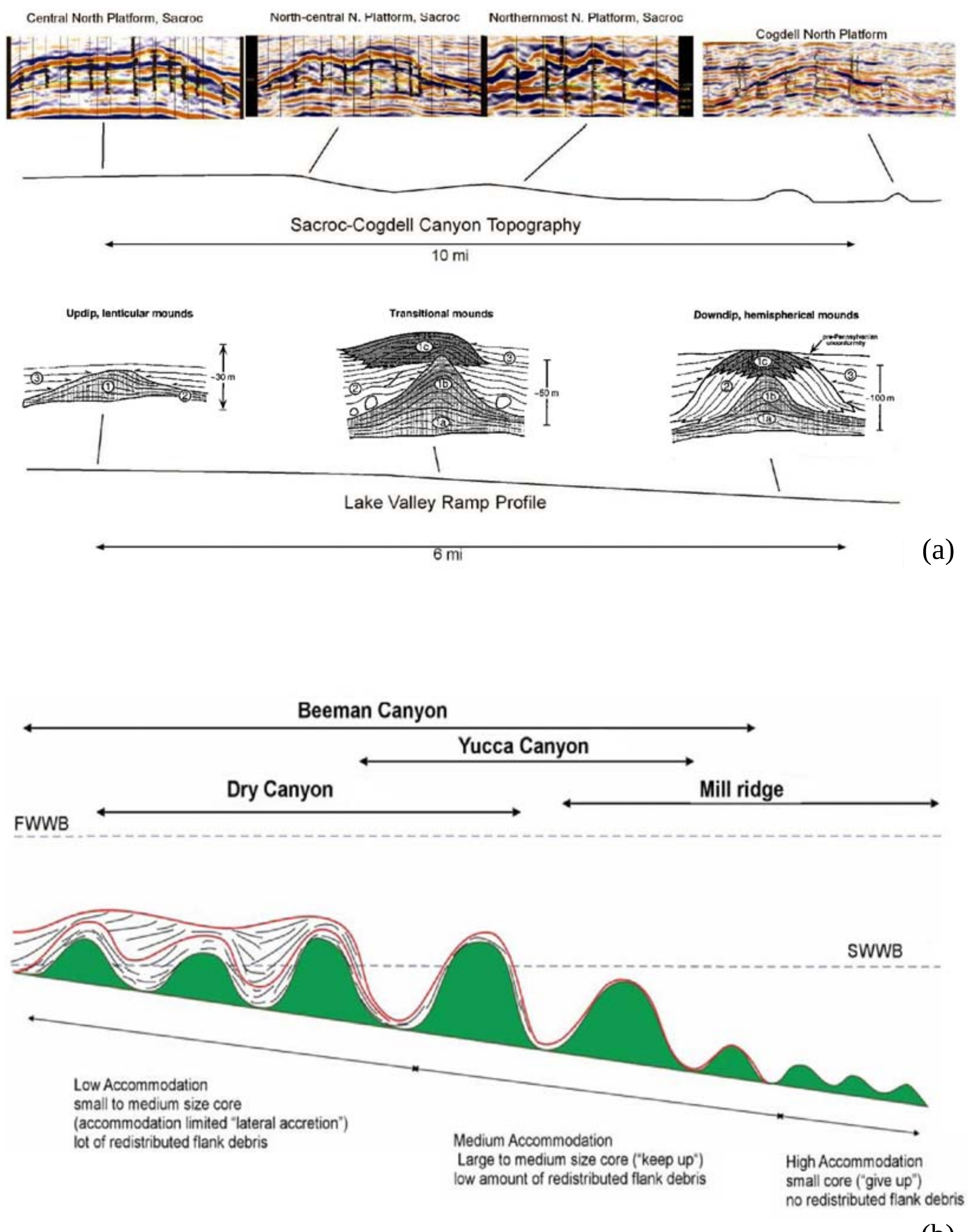


Figure 28. Conceptual models for the development of architectural variations across the northern Midland Basin. (a) Comparison of updip-downdip architectural changes in Missourian and Virgilian carbonate succession of SACROC–Cogdell area with Mississippian-age Lake Valley sequence 2 of Dorobek and Bachtel (2001). (b) Conceptual model of accommodation and hydrodynamic energy control on phylloid mound and flank deposits in the Virgilian succession of the Orogrande Basin. After Janson (2007).

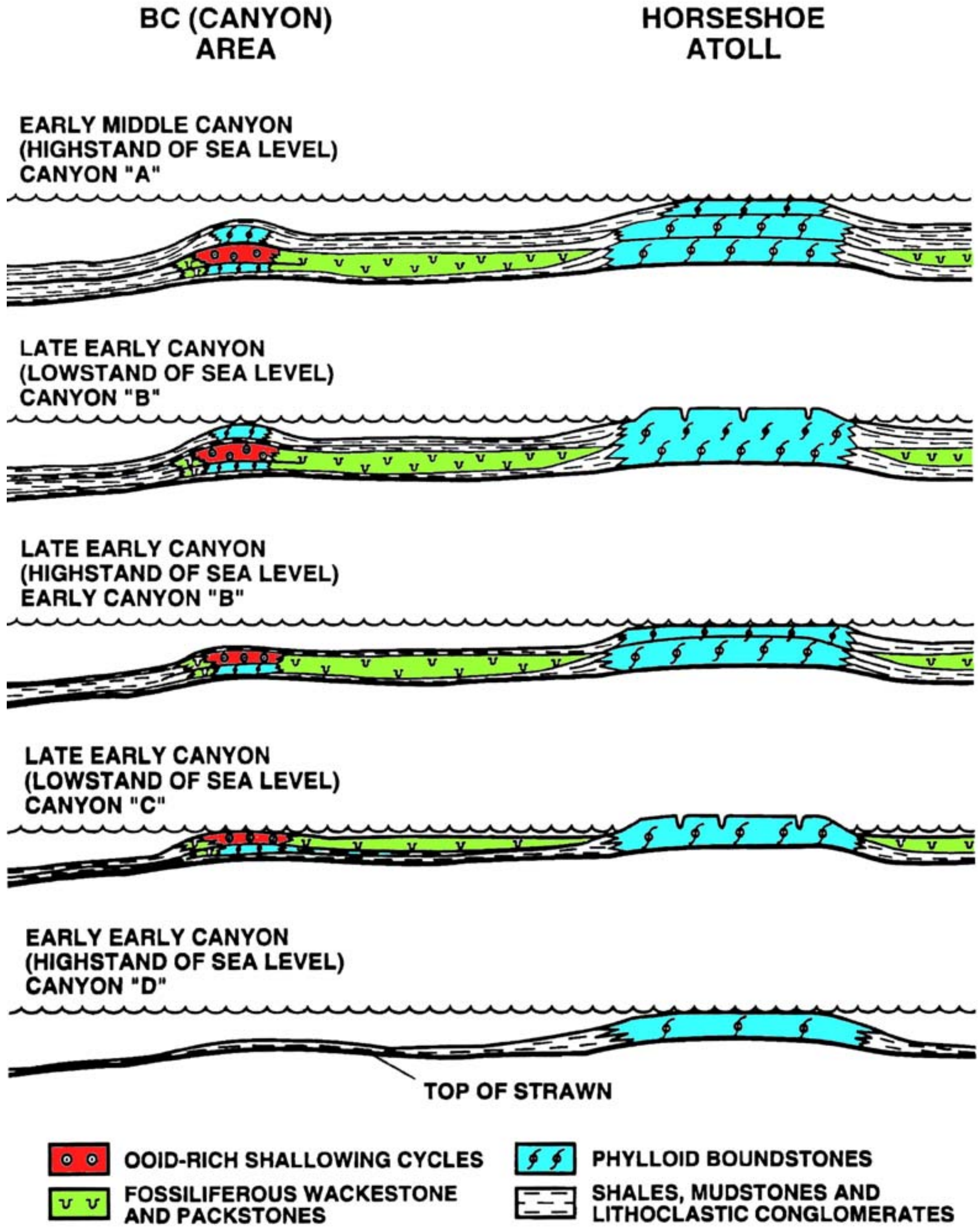


Figure 29. Conceptual model for lowstand carbonate deposition during the Missourian at BC field, Howard County (after Saller and others, 1993). BC is basinward (to the south) of the main carbonate platform. Also, labeling of Canyon sequences D–A is the reverse of the convention used on the main platform by Waite (1993) and others.

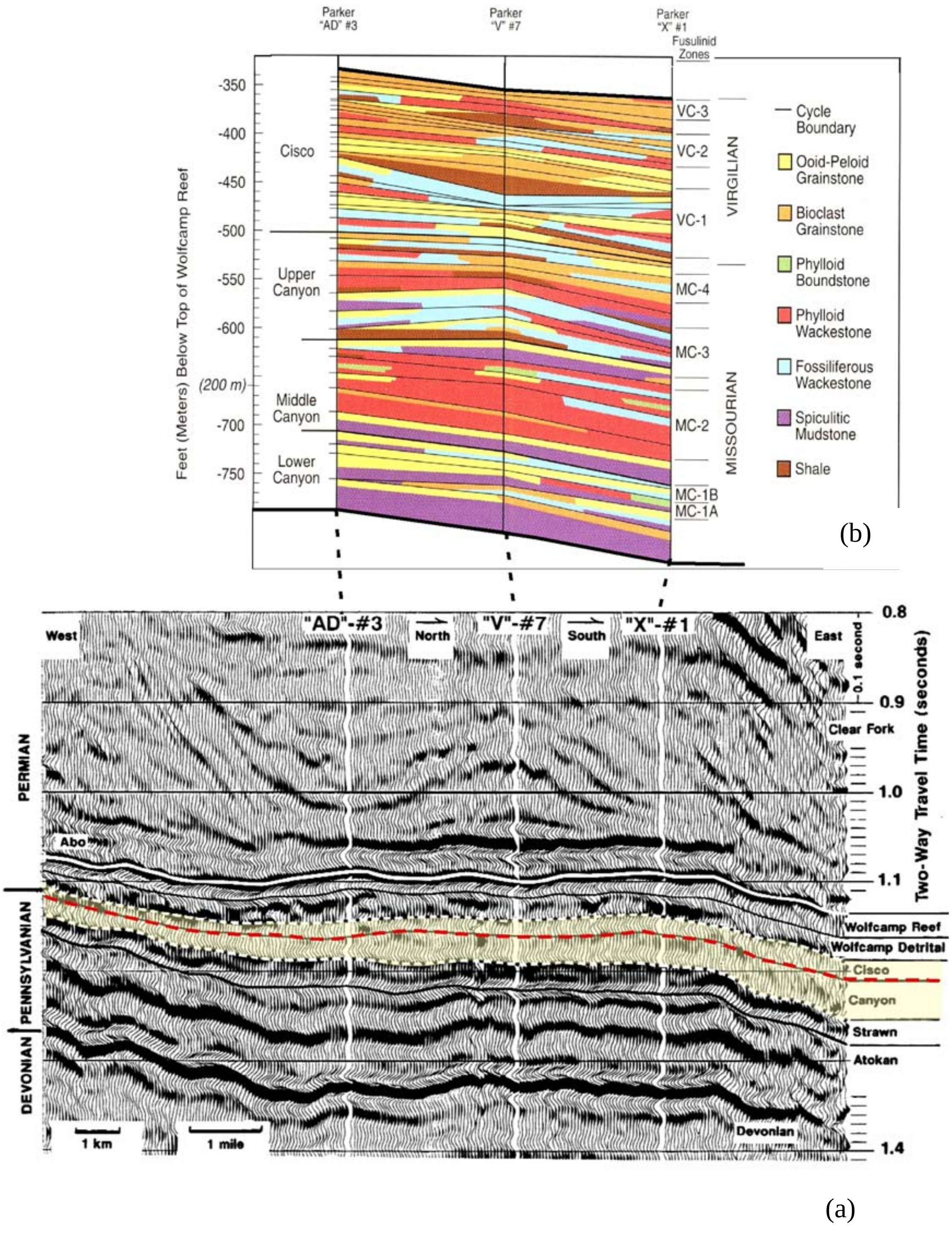


Figure 30. (a) Subregional seismic section of Southwest Andrews area. Yellow fill denotes Missourian and Virgilian succession, with red dashes demarking the transition. Note that the seismic section is chairlike in reality, with wells V#7 and X#1 being equally basinward of AD3 along strike. (b) Facies reconstruction of Missourian and Virgilian in the Southwest Andrews area. Refer also to comment above. After Saller and others (1999a, b).

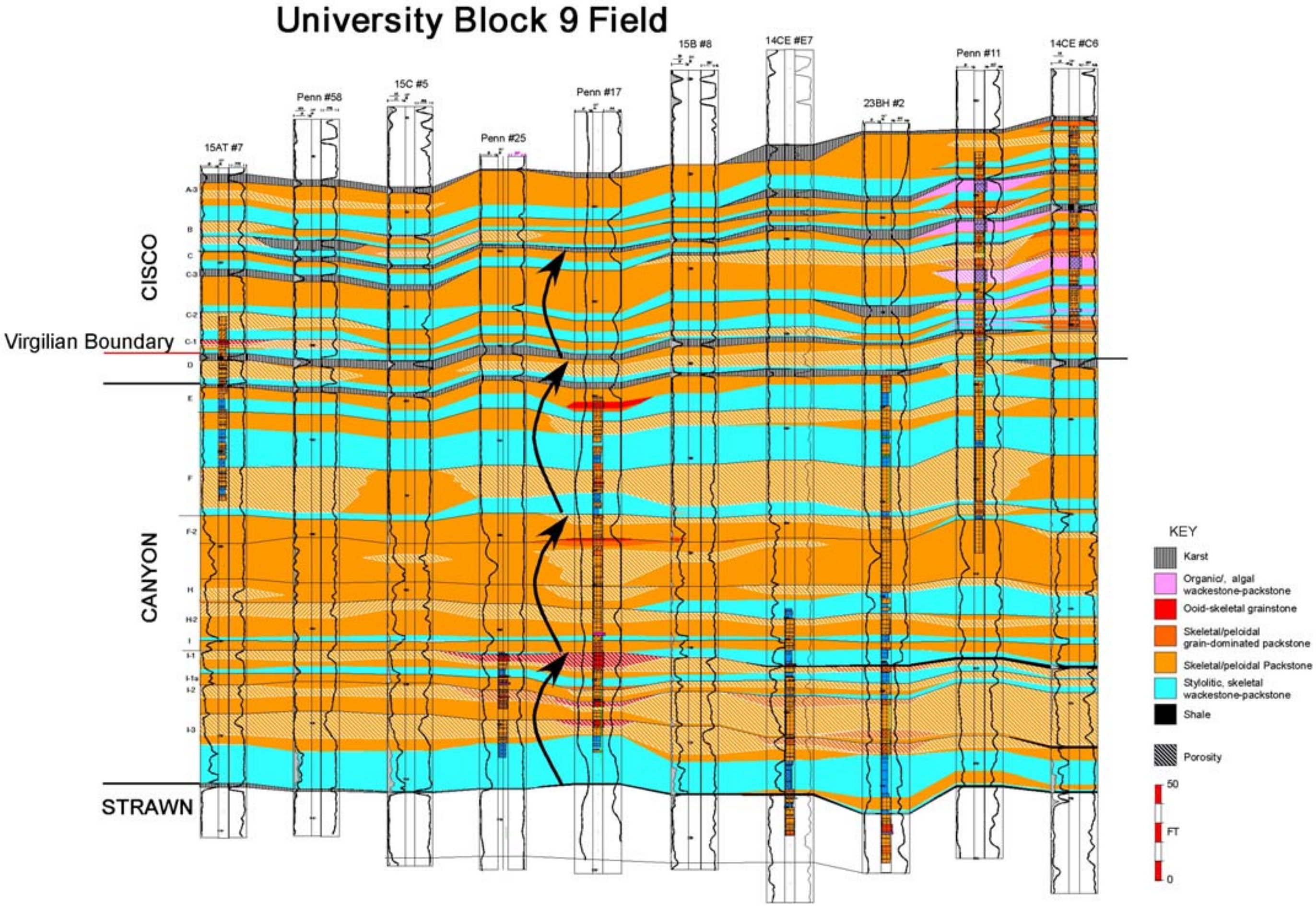


Figure 31. Regional fence diagram across University Block 9 field. Note predominance of skeletal peloidal packstones and wackestones throughout the succession. Three cycles are interpreted for the Missourian (Canyon) and two sequences for the Virgilian (Cisco). Note that porosity development is not always associated with sequence boundaries and exposure. Also note the lack of ooid grainstones, which are prominent in Southwest Andrews field. Modified from Barnaby (unpublished).

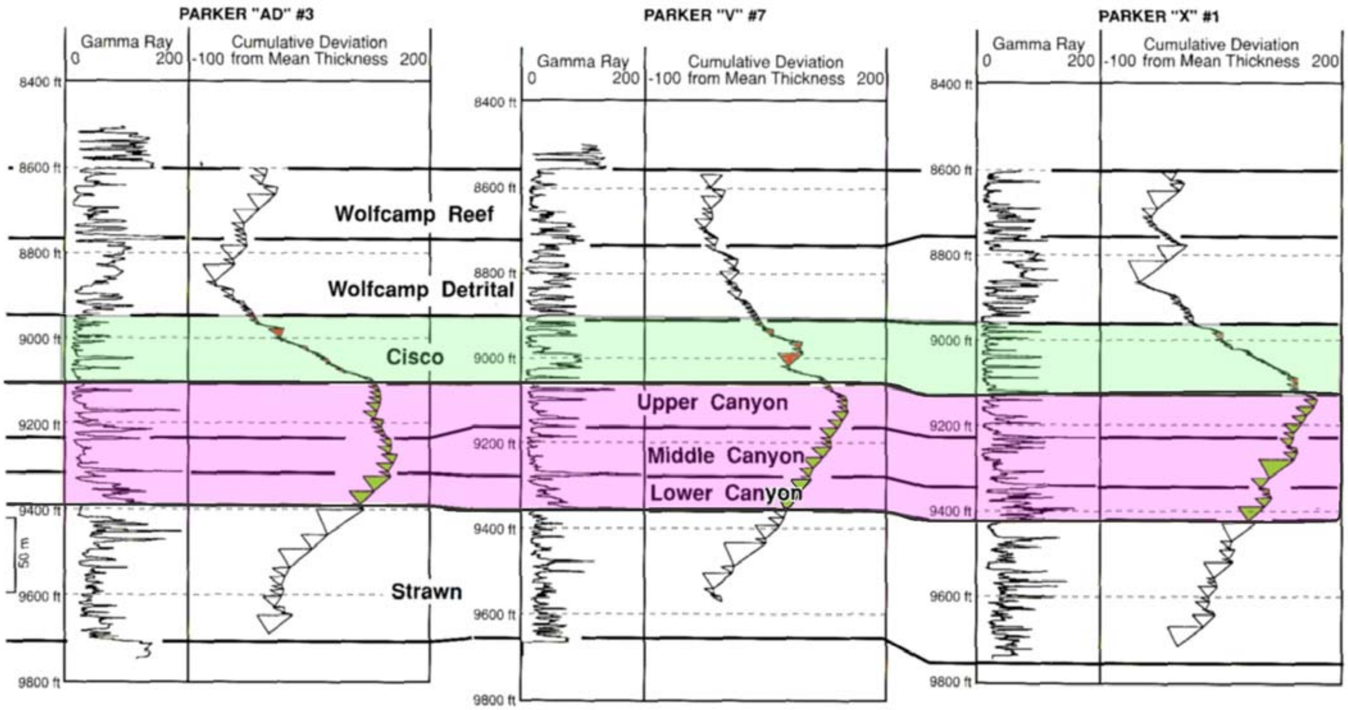


Figure 32. Fischer plot of cycle thickness and accommodation trends for Missourian and Virgilian succession in Southwest Andrews field area (after Saller and others, 1999b). Missourian (Canyon) interval highlighted in pink and Virgilian (Cisco) interval in light-blue. Note that thickness of the Missourian cycles is much greater than that in the Virgilian. Within the Missourian succession a dramatic decrease in cycle thickness from base (lower Canyon) to top (upper Canyon) is also present.

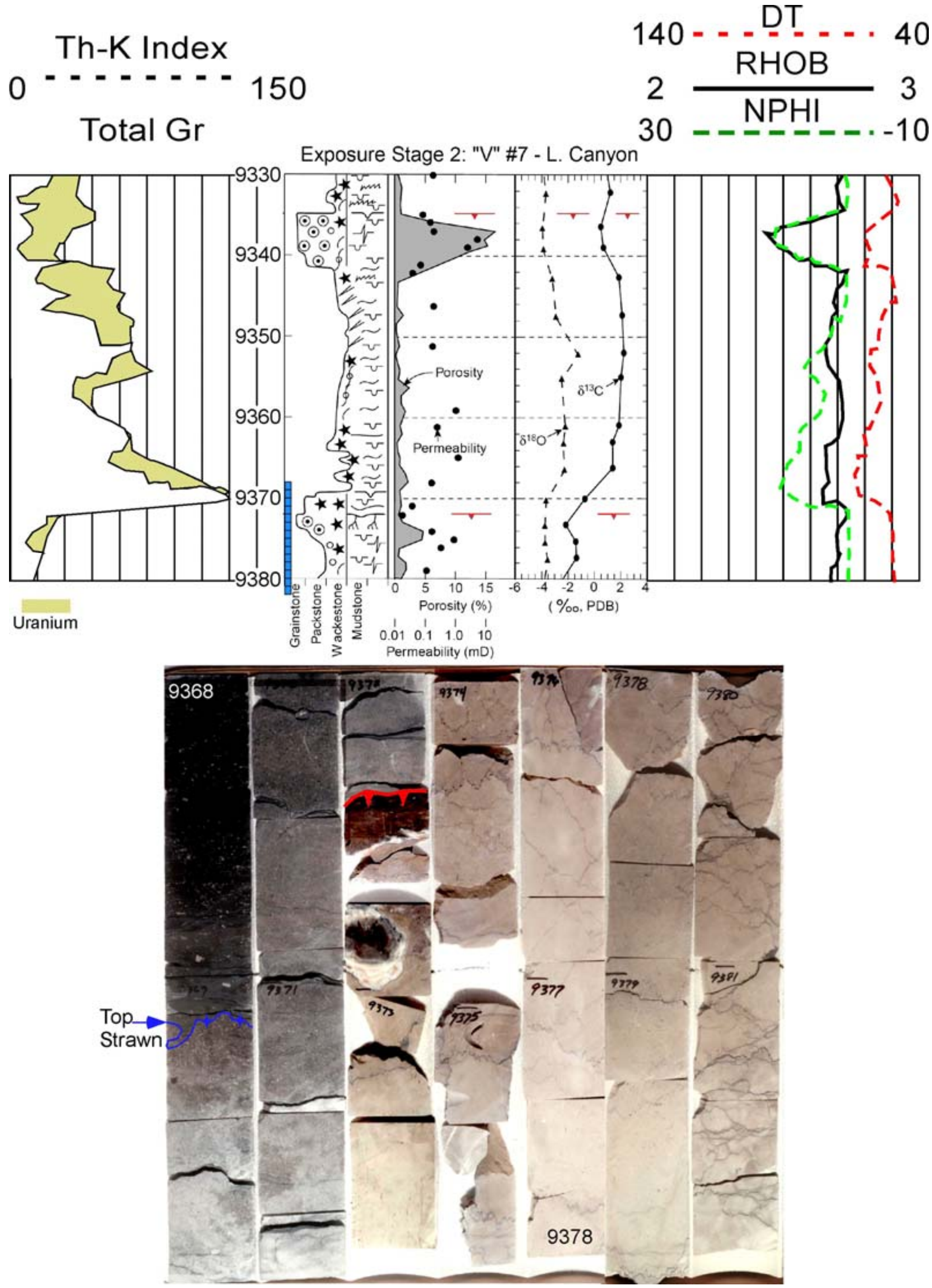


Figure 33. Core photograph, description, wireline-log signature, core analysis data, and stable isotope analysis of the lowermost Missourian (lower Canyon) interval. Proposed exposure surfaces indicated by red horizontal lines with downward-pointing triangles. Note that highest gamma-ray log readings occur above the exposure surface in the overlying crinoidal wackestones of the Missourian succession. Blue vertical bar indicates interval illustrated in core photograph.

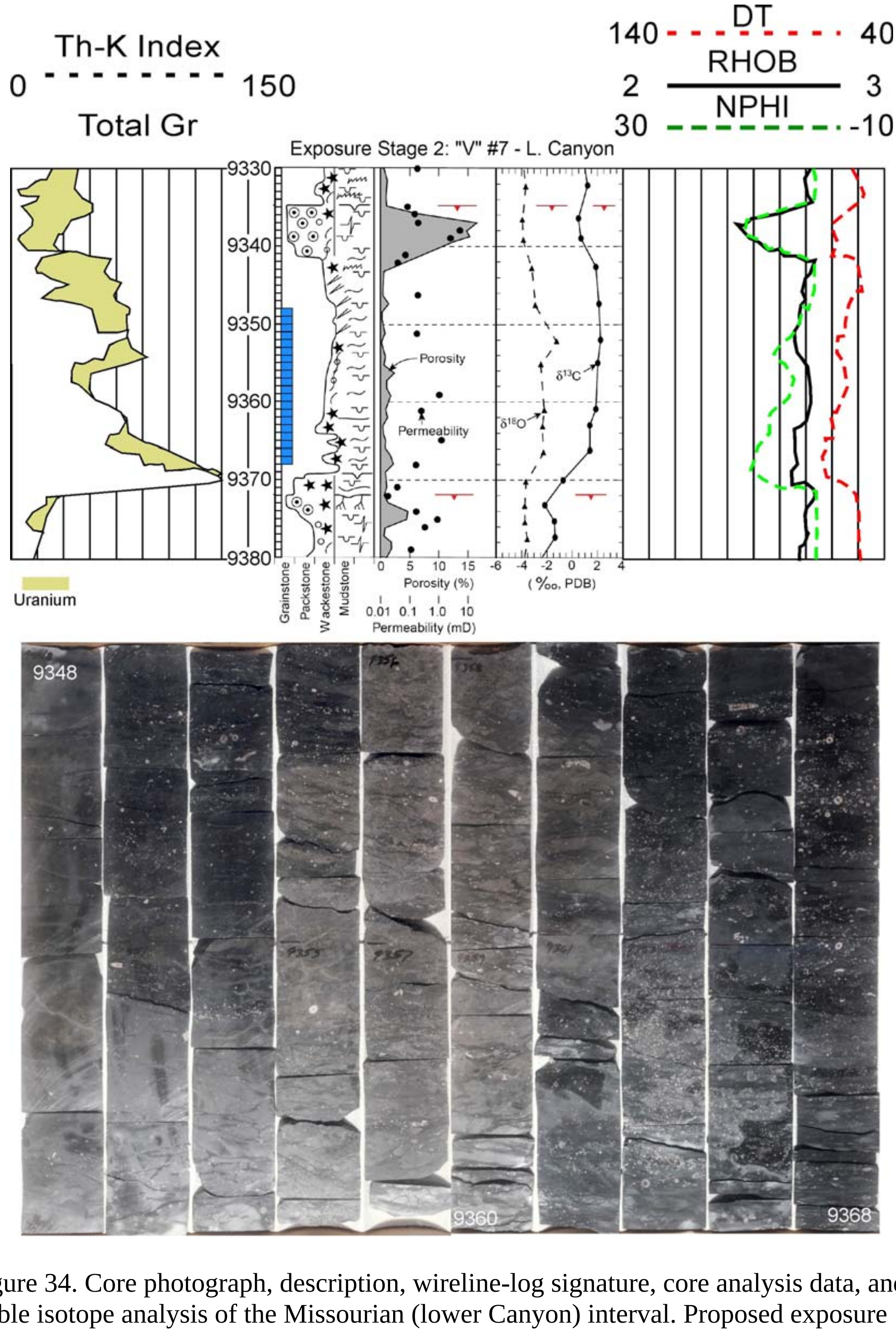


Figure 34. Core photograph, description, wireline-log signature, core analysis data, and stable isotope analysis of the Missourian (lower Canyon) interval. Proposed exposure surfaces indicated by red horizontal lines with downward-pointing triangles. Blue vertical bar indicates interval illustrated in core photograph.

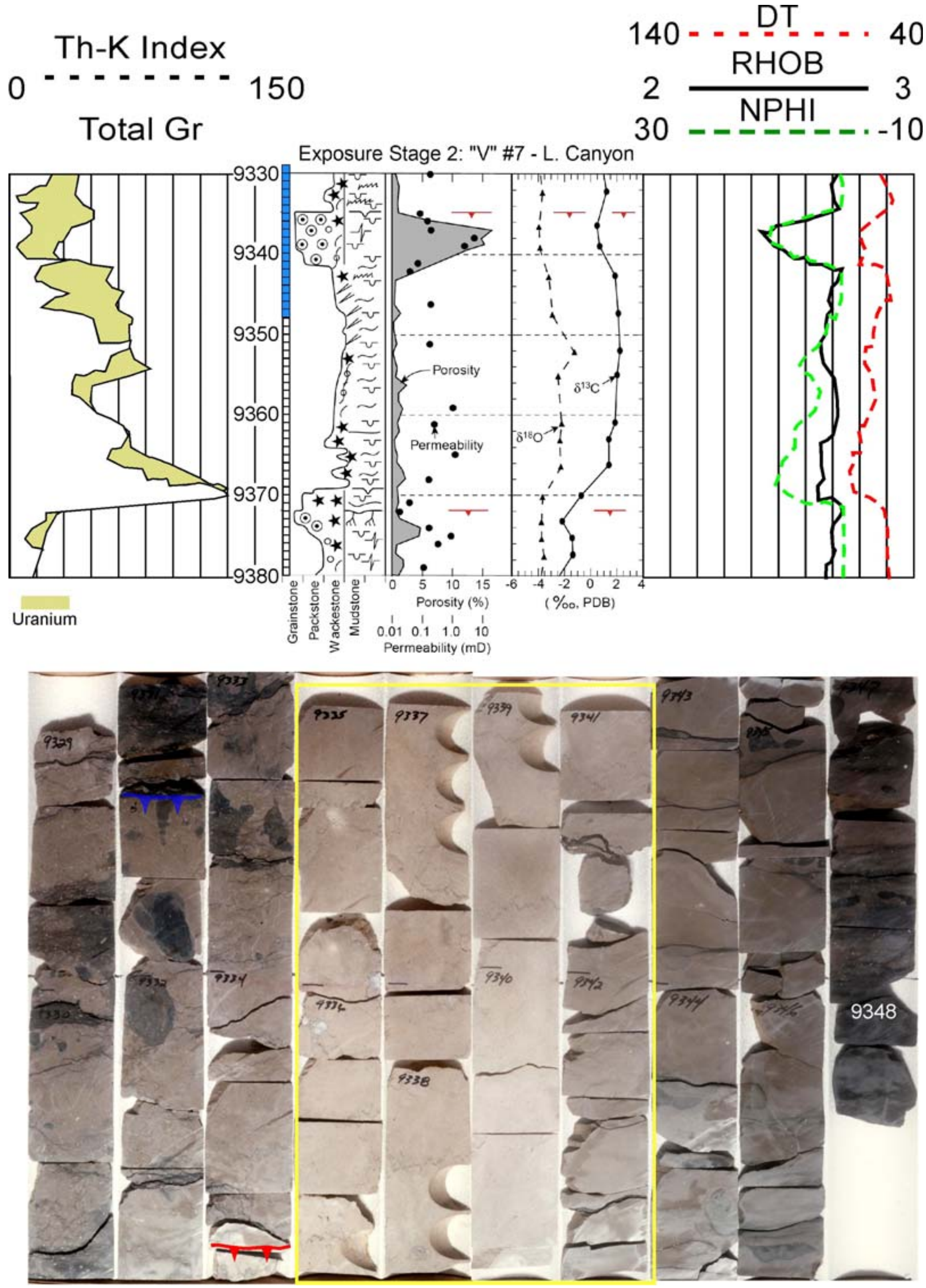


Figure 35. Core photograph, description, wireline-log signature, core analysis data, and stable isotope analysis of the Missourian (lower Canyon) interval. Proposed exposure surfaces indicated by red horizontal lines with downward-pointing triangles. Blue vertical bar indicates interval illustrated in core photograph. High-porosity and -permeability reservoir interval outlined in yellow.

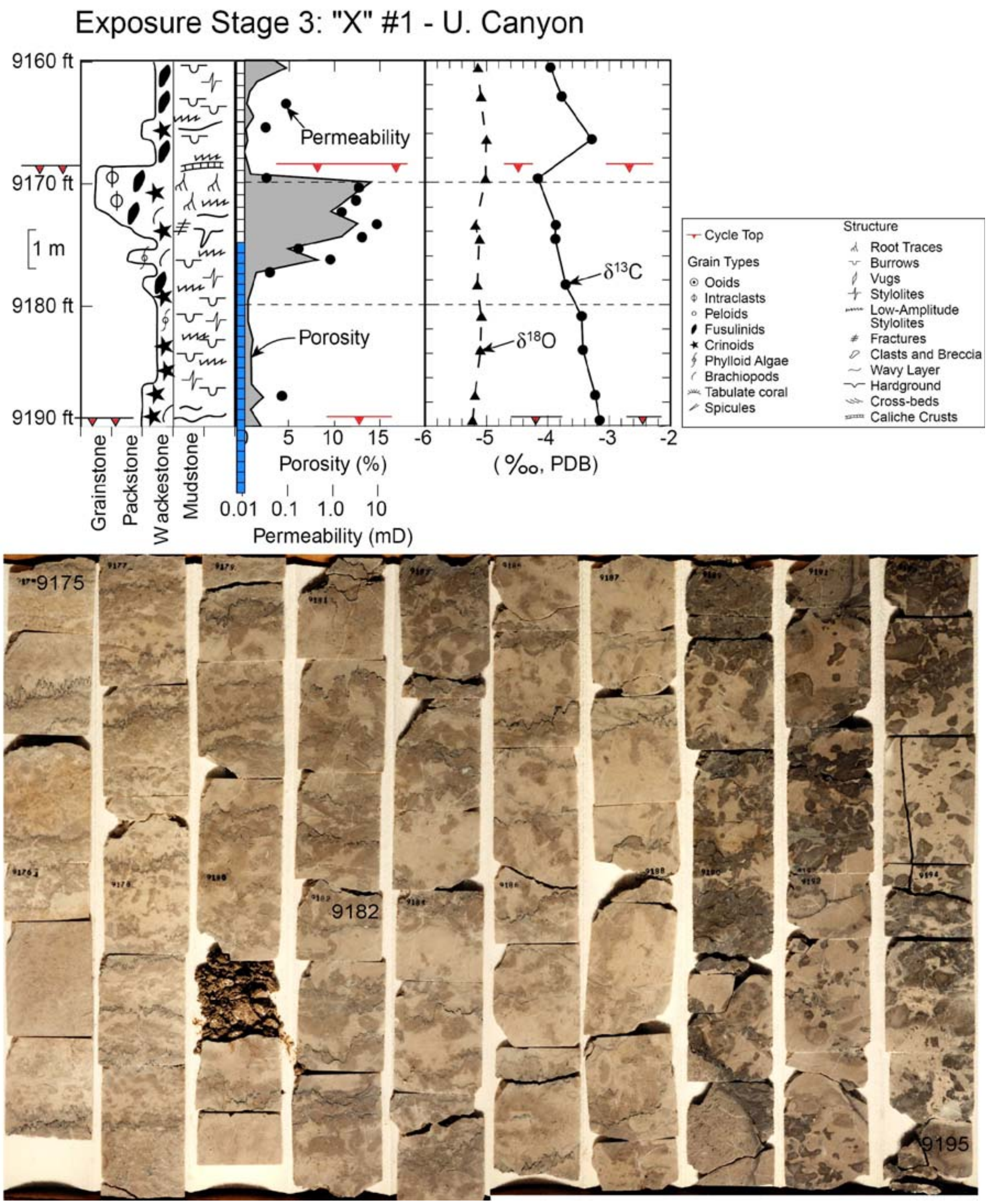


Figure 36. Upper Canyon core photographs, core description, and isotopic profiles (after Saller and others, 1999a, b). Note extensive textural alteration throughout the interval, which makes picking cycle boundaries difficult. Below 9,189 ft the interval seems to be highly brecciated, which may suggest some form of debris flow not indicated on the original interpretation.

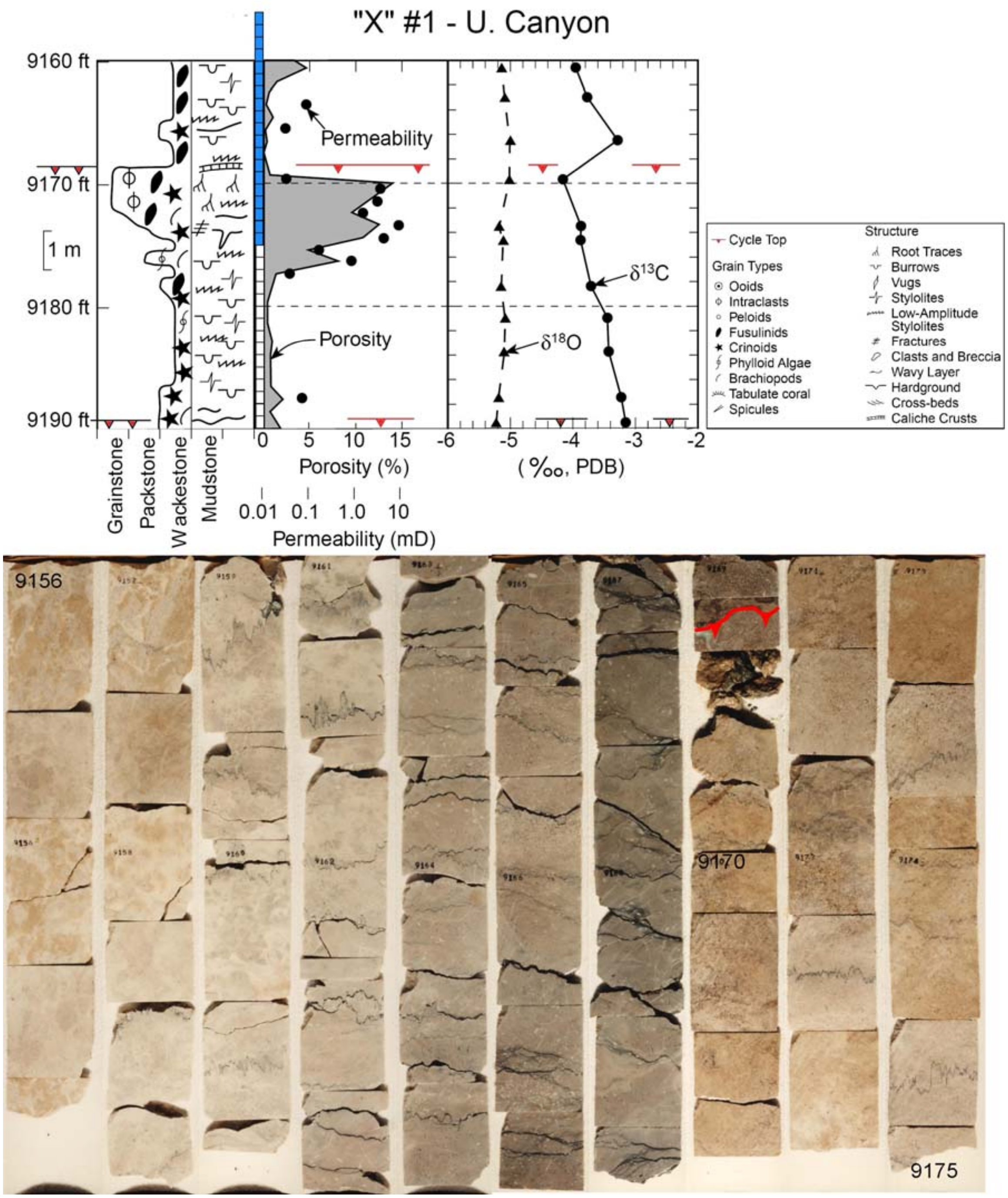


Figure 37. Upper Canyon exposure style 3 core photographs, core description, and isotopic profiles (after Saller and others, 1999a, b). Textural alteration is minimal compared with that of the underlying interval illustrated in figure 36. Cycle tops indicated in red on core photographs. Reservoir interval thickness approximately 8 ft.

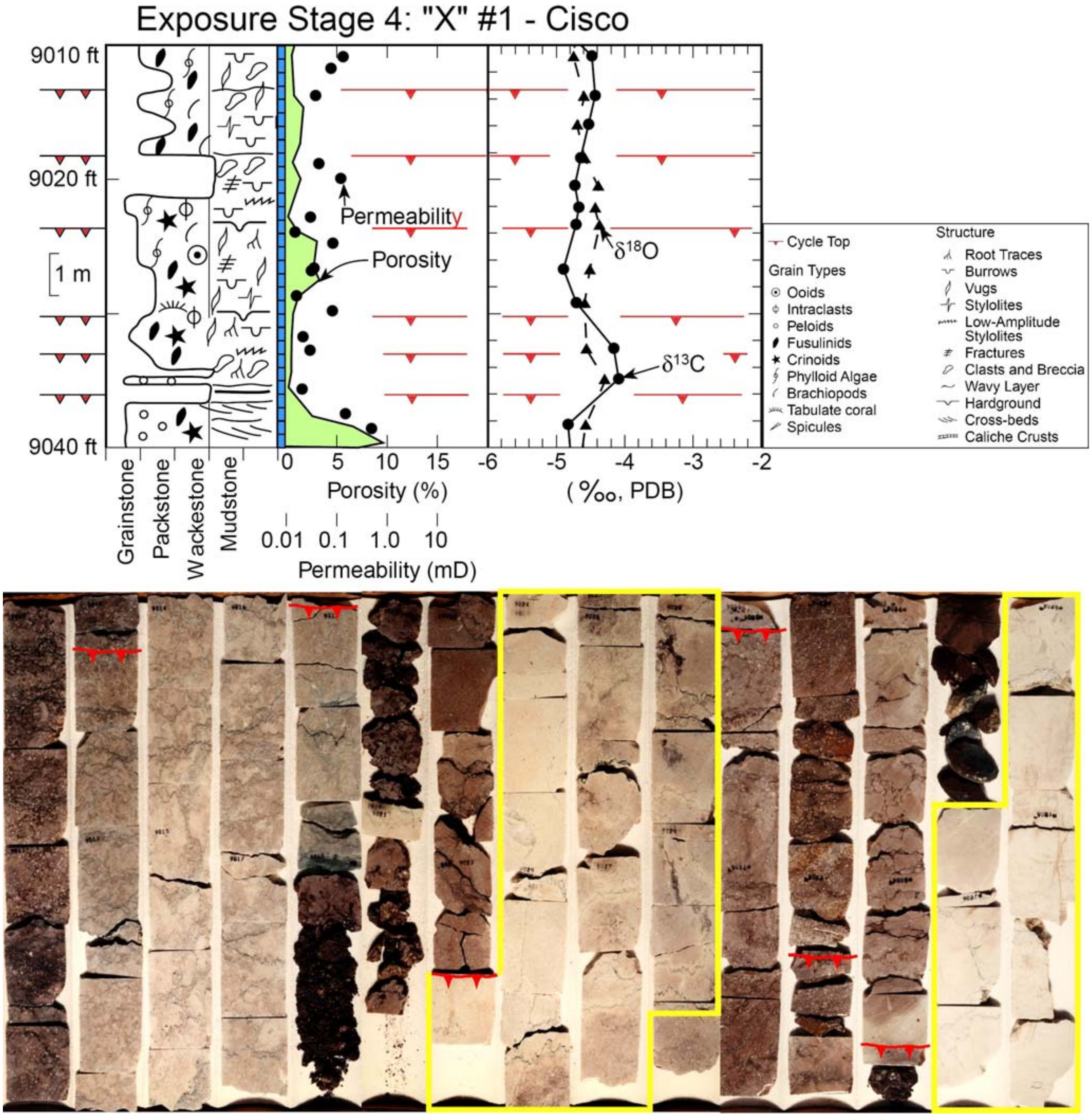
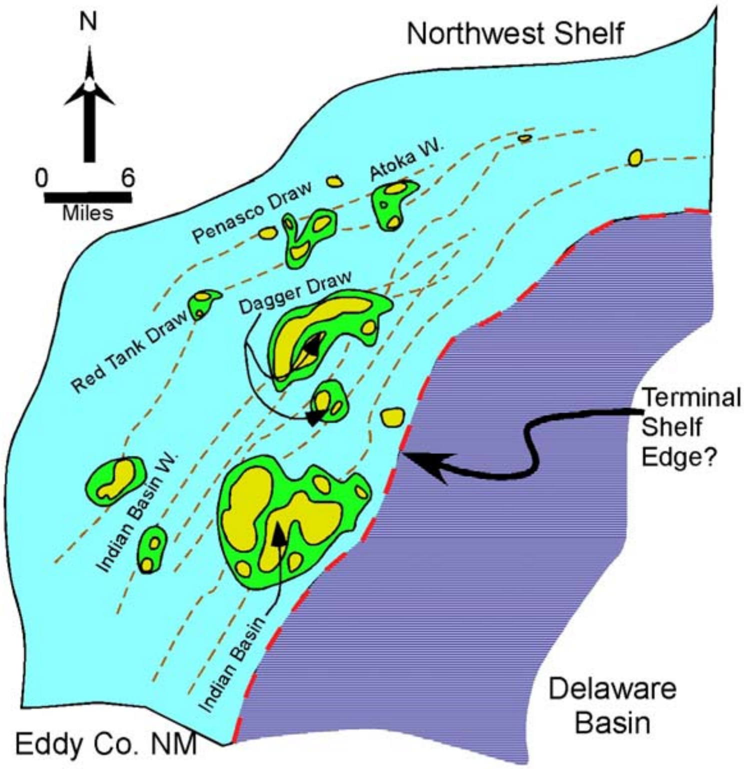


Figure 38. Middle Cisco exposure style 4 core photographs, core description, and isotopic profiles (after Saller and others, 1999a). Textural alteration is extensive compared with that of the underlying interval illustrated in figure 37. Cycle tops indicated in red on core photographs. Upper reservoir interval (yellow outline) thickness is approximately 6 ft, whereas lower is approximately 10 ft (not all depicted).



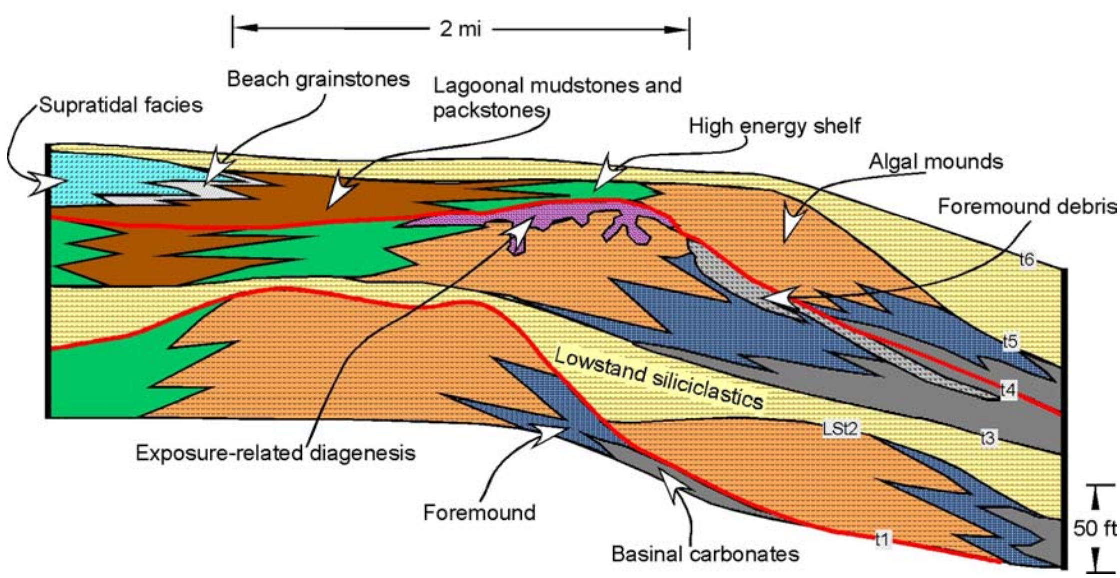


Figure 39. Generalized distribution and architecture of Missourian–Virgilian carbonate succession on the Northwest Shelf (New Mexico) (after Mazzullo, 1998). Red lines on lower schematic indicate sequence boundaries.

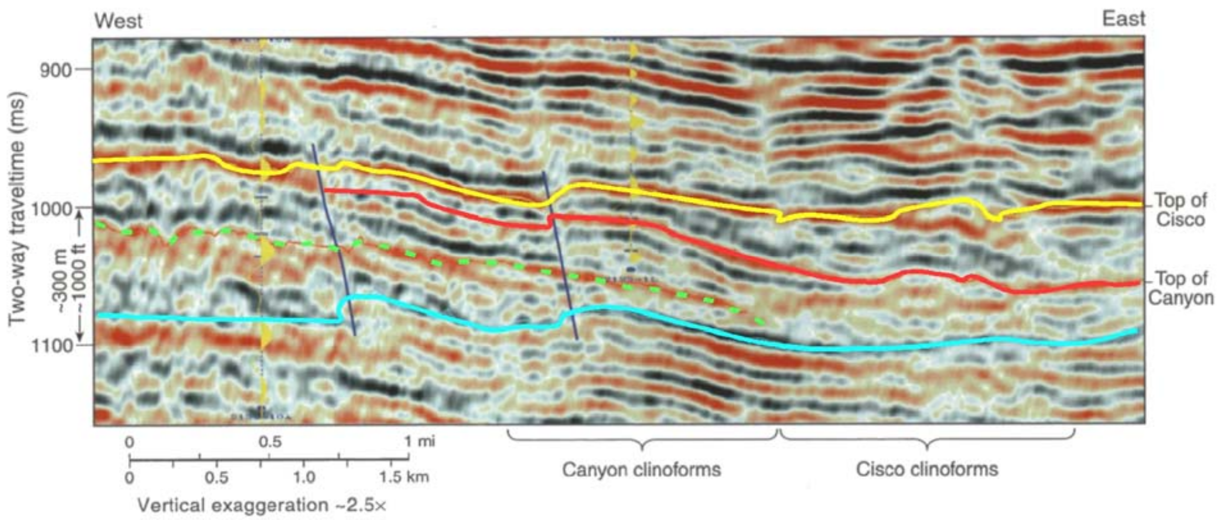


Figure 40. West-to-east (basinward) dip-section seismic line through South Dagger Draw field, Eddy County, New Mexico (after Tinker and others, 2004). Yellow line is interpreted top of Cisco (Virgilian), whereas red line is top of Canyon (Missourian) and blue line is possible base of Canyon. Note low-angle sigmoidal, clinoformal architecture of both successions.

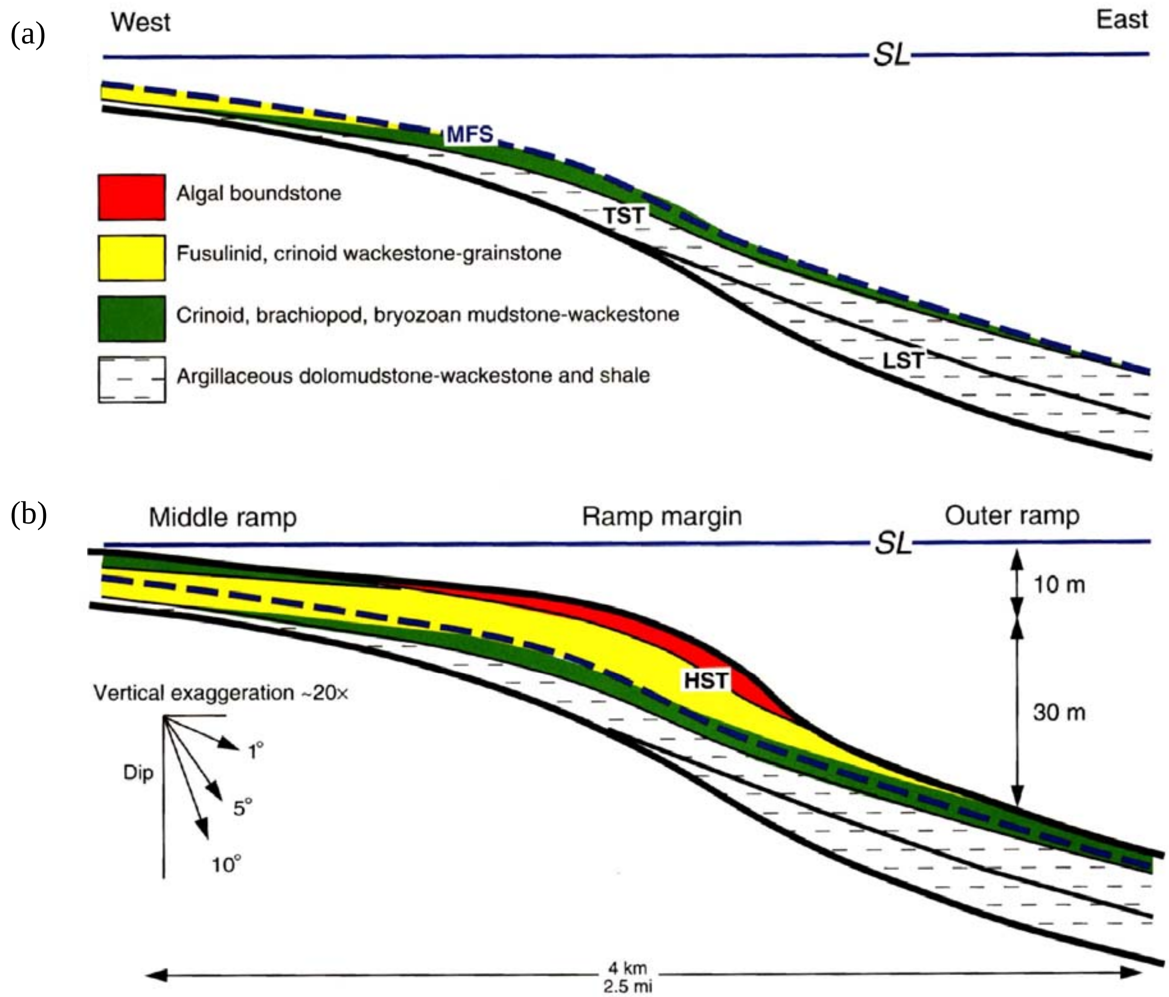


Figure 41. Depositional models for high-frequency stratigraphic architecture of South Dagger Draw field, New Mexico (after Tinker and others, 2004). (a) Facies distribution and depositional environments for lowstand and transgressive systems tracts (LST and TST). Note limited proportion of high-energy facies and their restrictions to the middle ramp area. (b) Facies distribution and depositional environments for highstand systems tract (LST and TST). Note basinward step of HST relative to LST and TST and dominance by higher-energy facies and algal boundstones. Note that water depths even at the ramp crest are thought to be in excess of
10 m.

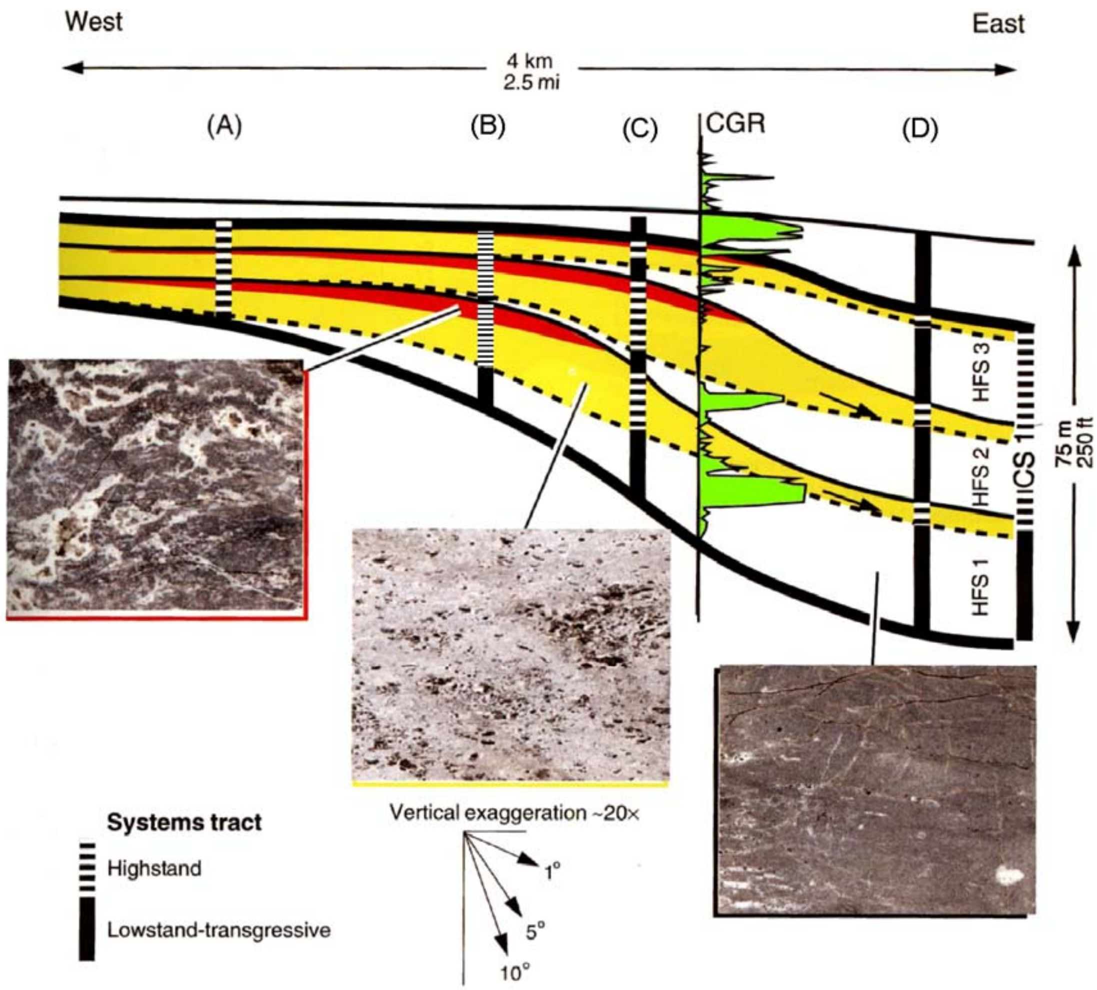


Figure 42. Schematic dip section illustrating stratigraphic hierarchy and lateral tract changes with a composite sequence (CS) (after Tinker and others, 2004). At position A, high-frequency sequences (HFS's) are asymmetrical and dominated by HST deposits. At B, cycles are still largely asymmetrical, with CS LST-TST overly represented. This location would also yield a facies association dominated by algal boundstones and give a false impression of an aggradational buildup. At location C, there is greater symmetry in HFS1, with increasing asymmetry in HFS2 to 3. At location D, HFS's are asymmetrical but dominated by LST-TST facies. Scale of photographs 8 cm horizontal. Left photograph—algal boundstone. Central photograph—fusulinid crinoidal packstone. Right photograph—argillaceous lime mudstone.

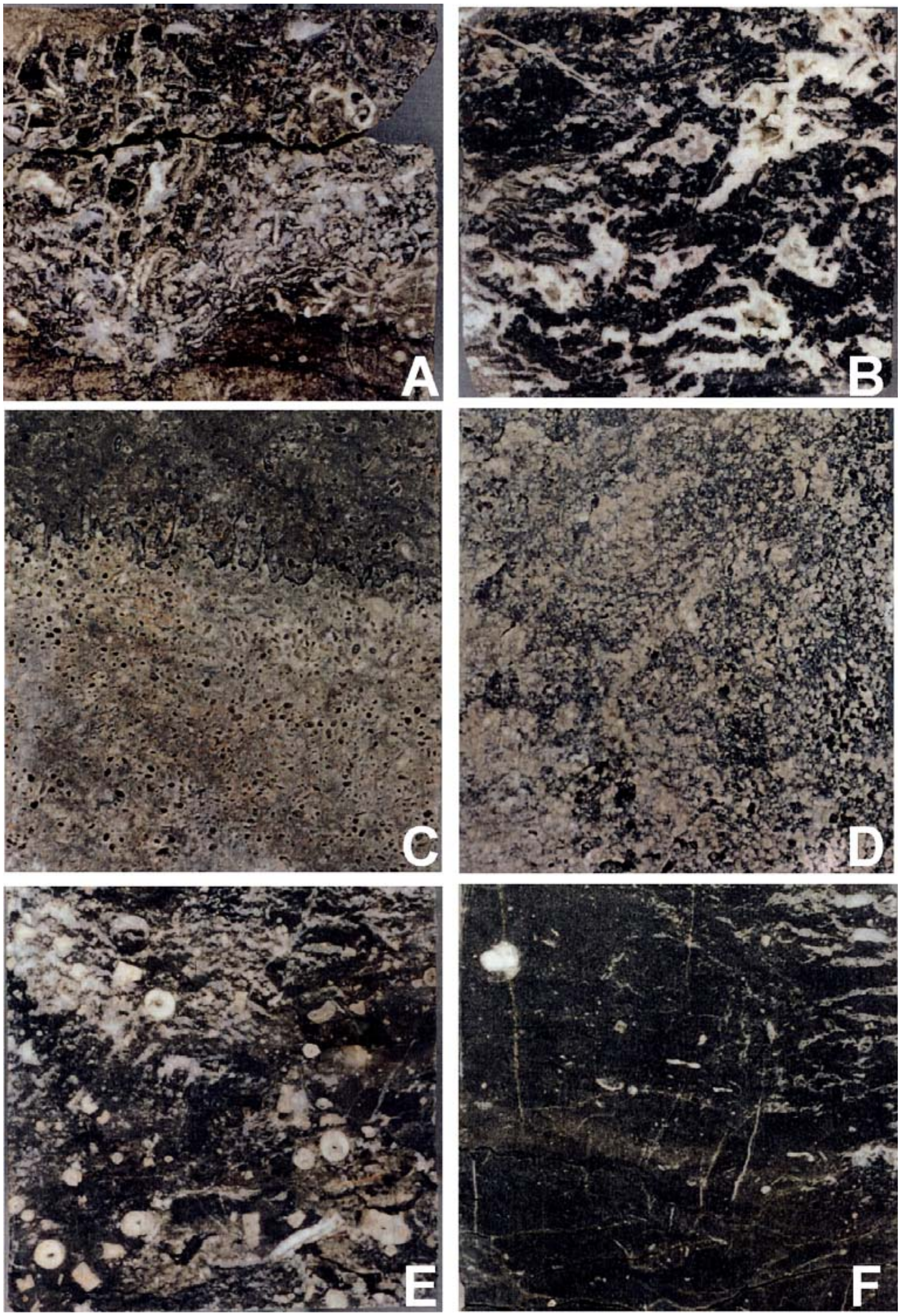


Figure 43. Core slab photographs of dominant Missourian and Virgilian facies at South Dagger Draw (Federal#5 8172C well) (after Brinton and others, 1998). Width of all photos approximately 3.5 inches. A. skeletal algal boundstone—Virgilian. B. Encrinitic algal foram boundstone—Missourian. C. Fusulinid packstone—Missourian. D. Fusulinid, crinoidal, algal, foraminiferal packstone—Virgilian. E and F. Crinoidal wackestone—Missourian.

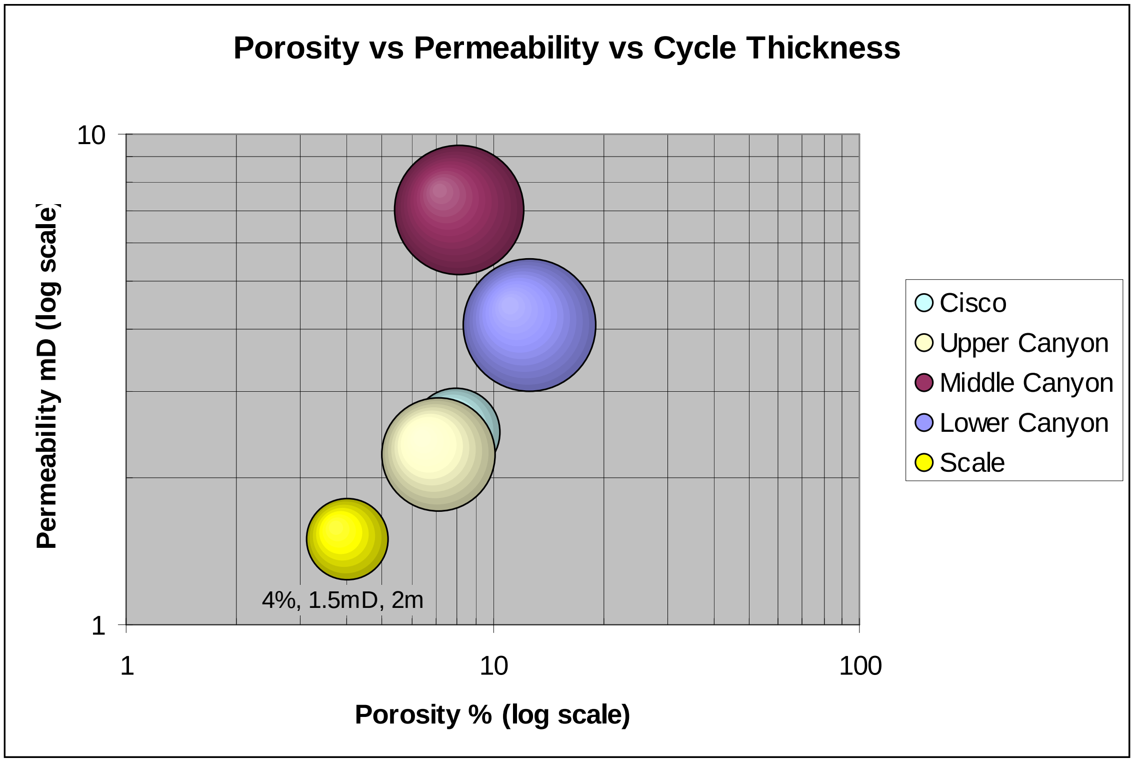


Figure 44. Summary bubble chart of porosity, permeability, and cycle thickness for Missourian and Virgilian carbonate succession in South Andrews field area (data from Saller and others, 1999a). Bubble area corresponds to cycle thickness. Overall, the lower Canyon interval (lower Missourian) has the best reservoir quality. Values used are averages of three wells' data. Note that original values did not include cycles in sequences with porosity less than 4 percent.

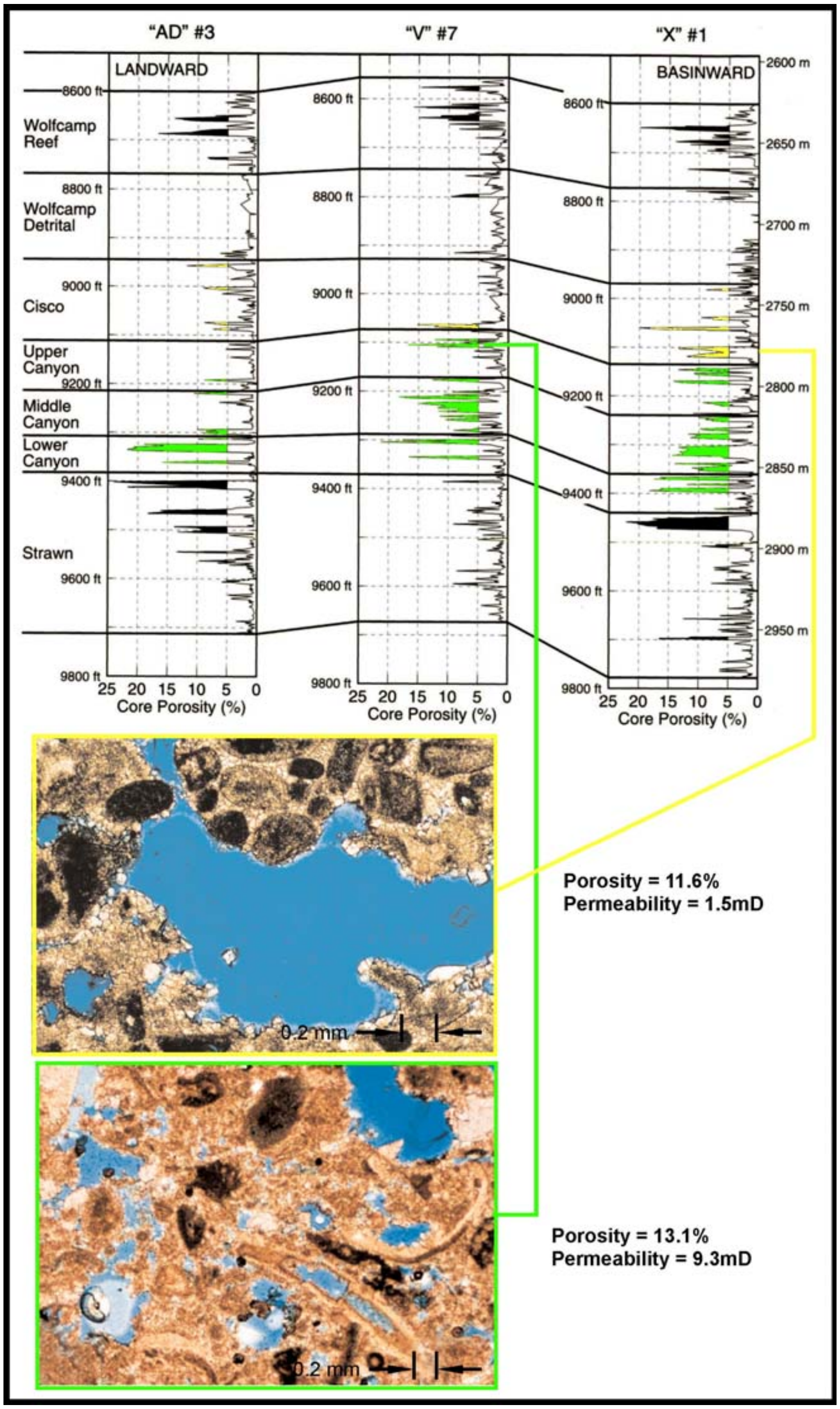


Figure 45. Dip line section through South Andrews field area illustrating distribution of porous intervals relative to sequence (after Saller and others, 1999a). Green infill is used for Missourian succession with greater than 4 percent porosity and yellow for the Virgilian. Photomicrographs correspond to each interval and illustrate moldic to slightly vuggy pore style in the Missourian and greater vug dominance in the Virgilian. Note that all porous zones appear to prograde basinward as they decrease in age.

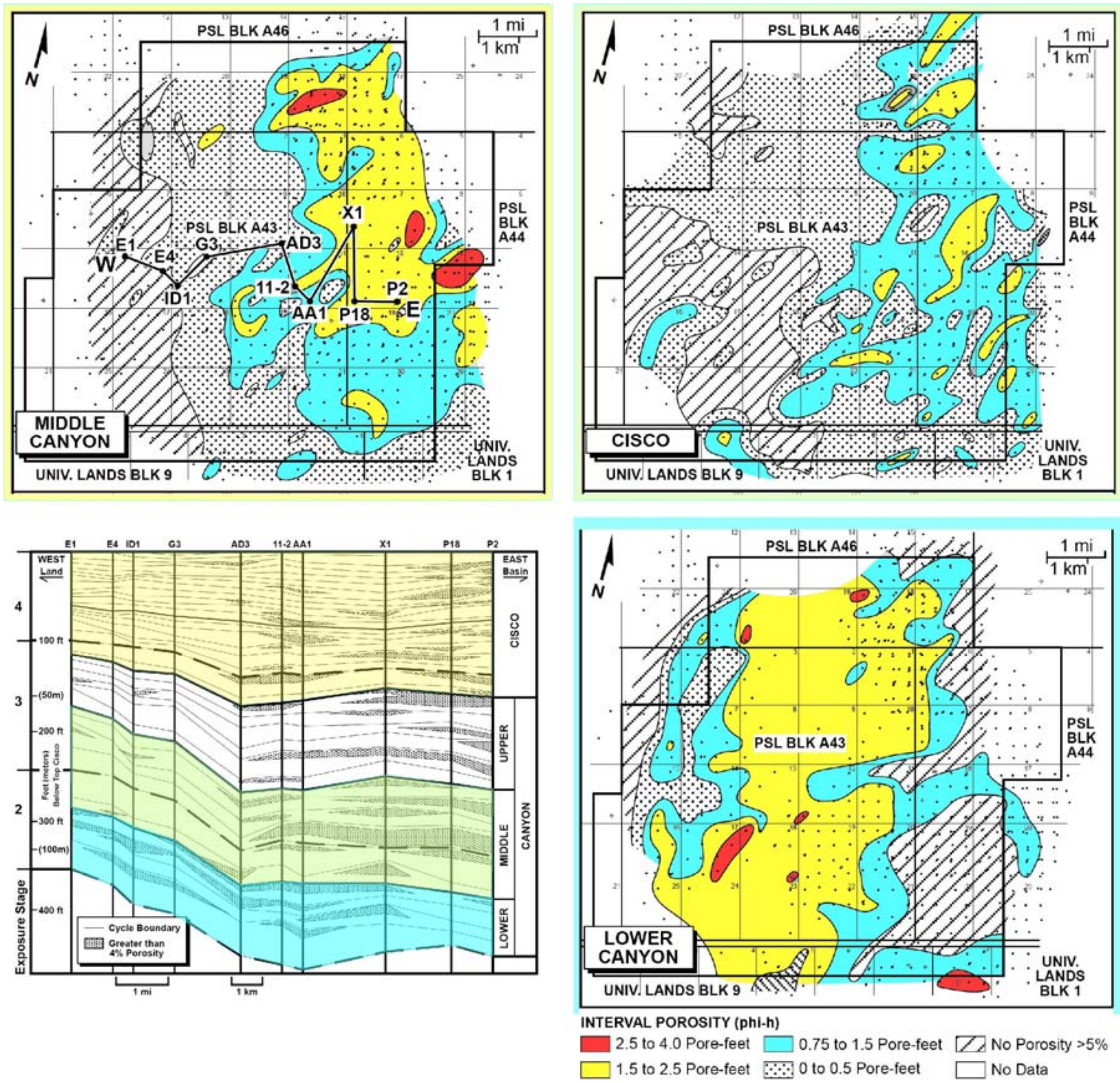


Figure 46. Cross section of porosity related to depositional episodes and exposure stage and corresponding regional maps of porosity versus thickness trends for the same intervals (modified from Saller and others, 1999a). Missourian succession represented by lower and middle Canyon intervals (blue and green, respectively). Virgilian succession represented by Cisco interval outlined in yellow.

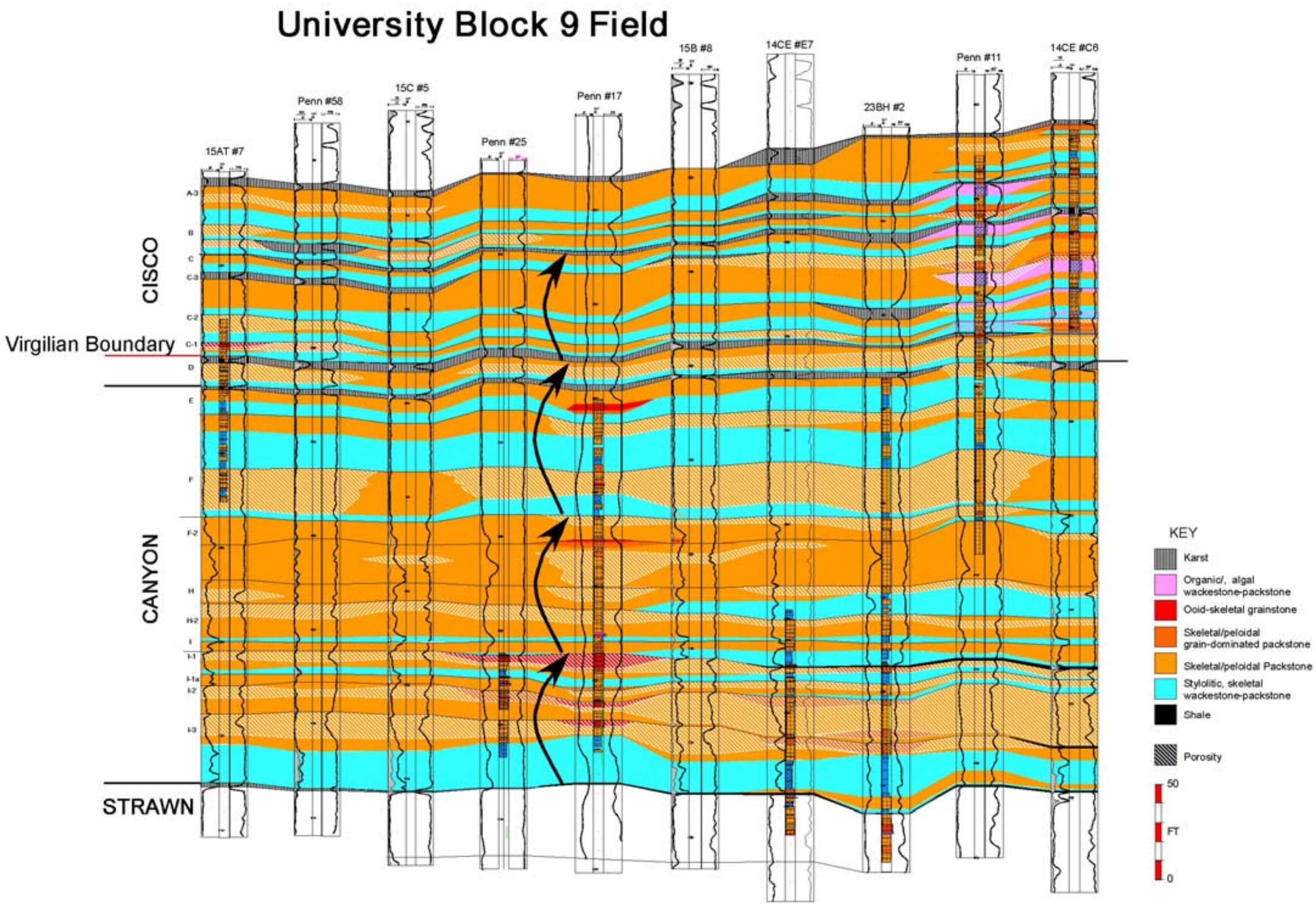
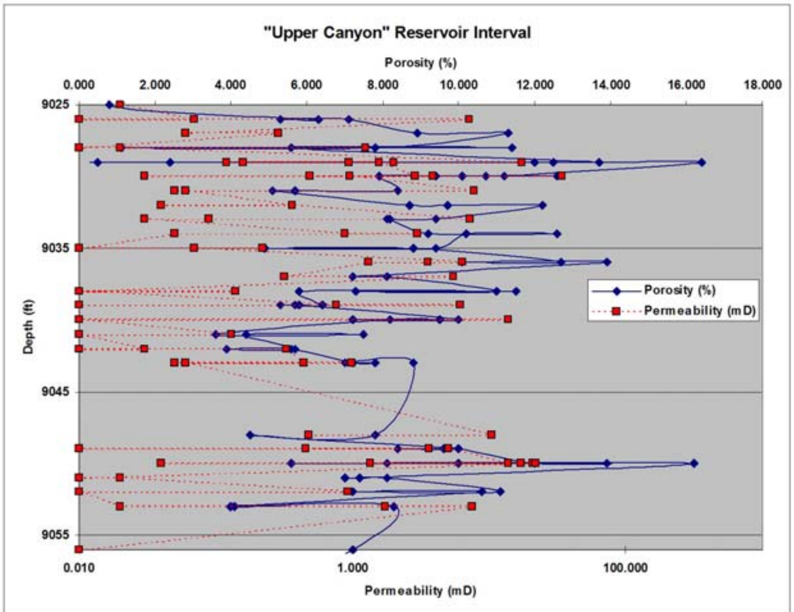


Figure 47. Regional core, FMI, and well-log-based correlation across University Block 9 area (modified from Barnaby, unpublished). Porous zones indicated by inclined hatch marks. The most regionally pervasive high-porosity zone is in cycle F, which is upper Canyon as defined by Saller and others (1999b). Note presence of algal wackestones and packstones in Penn #11 and 14CE #6 wells in the Virgilian succession.



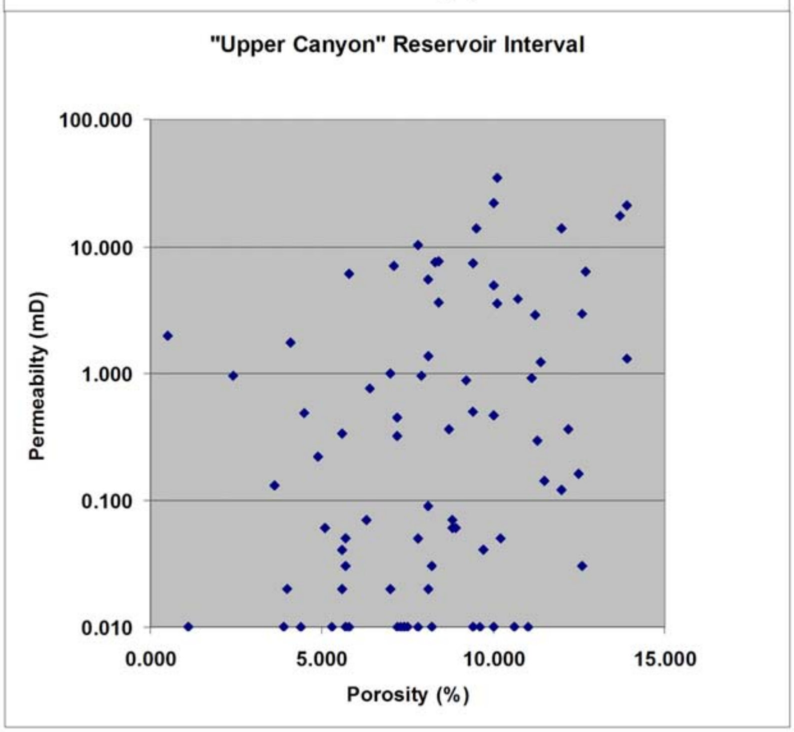


Figure 48. Upper diagram illustrates depth profile of porosity and permeability for the F sequence in University (Penn) #11 well. This interval corresponds roughly to the upper Canyon of Saller and others (1999a). Note that permeability does not increase with porosity throughout the interval, especially from depths 9,030 to 9,040 ft. Lower diagram is a crossplot of porosity and permeability for the same interval as in the upper diagram. Note high degree of scatter and lack of linear correlation between porosity and permeability. Linear correlation R^2 value for this data is 0.12.

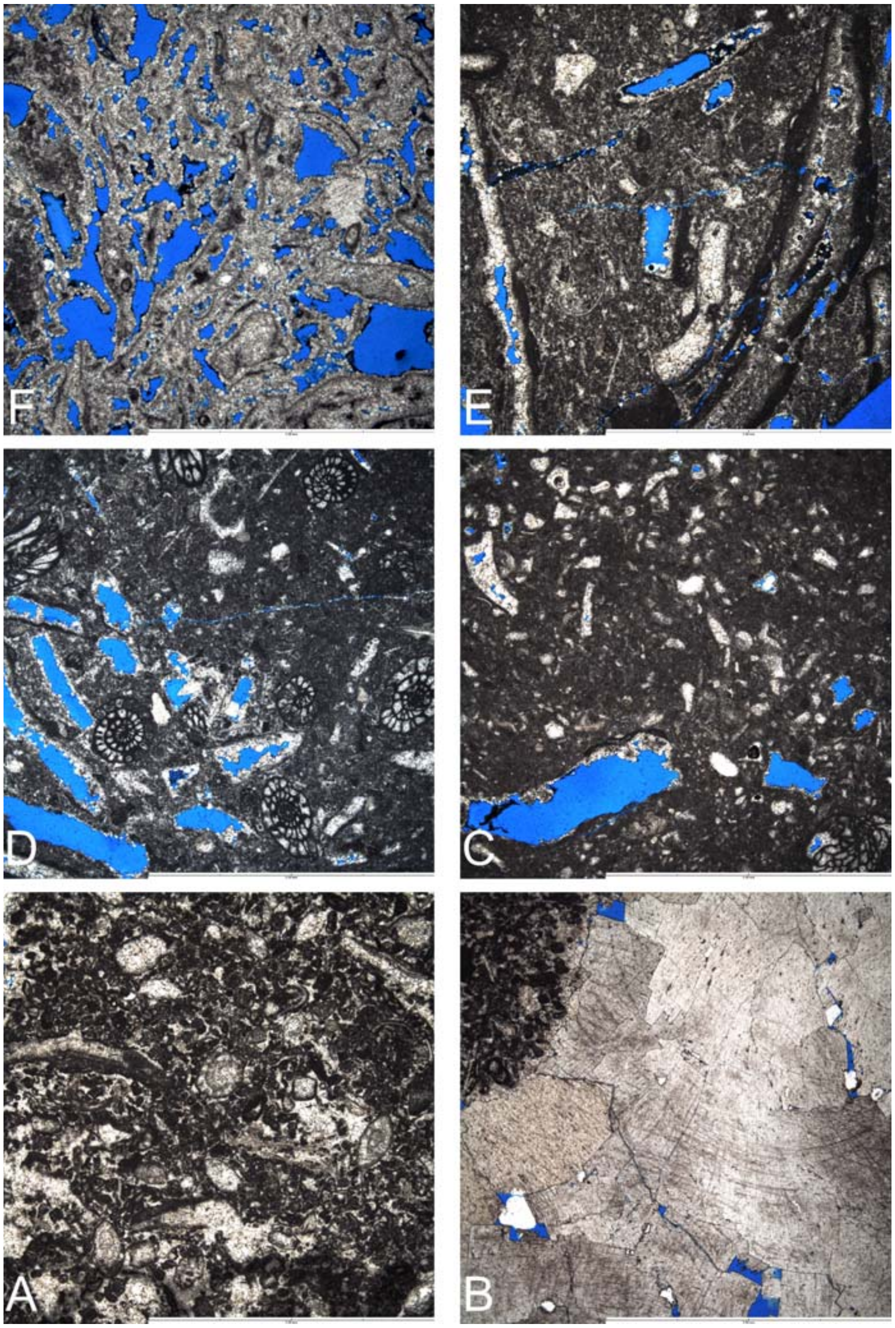


Figure 49. Thin-section photomicrographs of Missourian and Virgilian reservoir intervals (Penn #11 well, University Block 9). Scale bar is 5 mm in all photos. A–E. Upper Canyon reservoir interval. A and B. Calcite-cemented peloidal foraminiferal grainstone with B. Coarse saddle dolomite. Sample depth 9,060 ft core analysis measurements yielded a range of porosity (4.00, 2.90, and 5.70 percent) values and uniform permeability (0.010 md). C. Phylloid algal bioclastic wackestone to packstone with porosity values of 7.4 and 7.00 percent and permeability of 0.01 and 0.02 md. Sample depth 9,051 ft. Note that porosity is in molds after heterogeneously leached bioclasts (phylloid?). D. Phylloid algal foraminiferal packstone to mud-lean packstone with porosity values of 3.6, 7.50 and 4.4 percent and permeability of 0.13 and 0.01 md. Sample depth 9,041 ft. Porosity predominantly moldic within leached phylloid algal plates. E. Peloidal algal packstone with consistent porosity values of 6.4, 5.8, 5.3, and 5.7 percent and variable permeability values of 0.76, 6.190, and 0.01 md. Sample depth 9,039 ft. F. Virgilian reservoir interval depth 8,968 ft. Algal boundstone with porosity values of 4.6 and 12.6 percent and permeability of 0.370 and 1.55 md. Sample depth 8,968 ft.

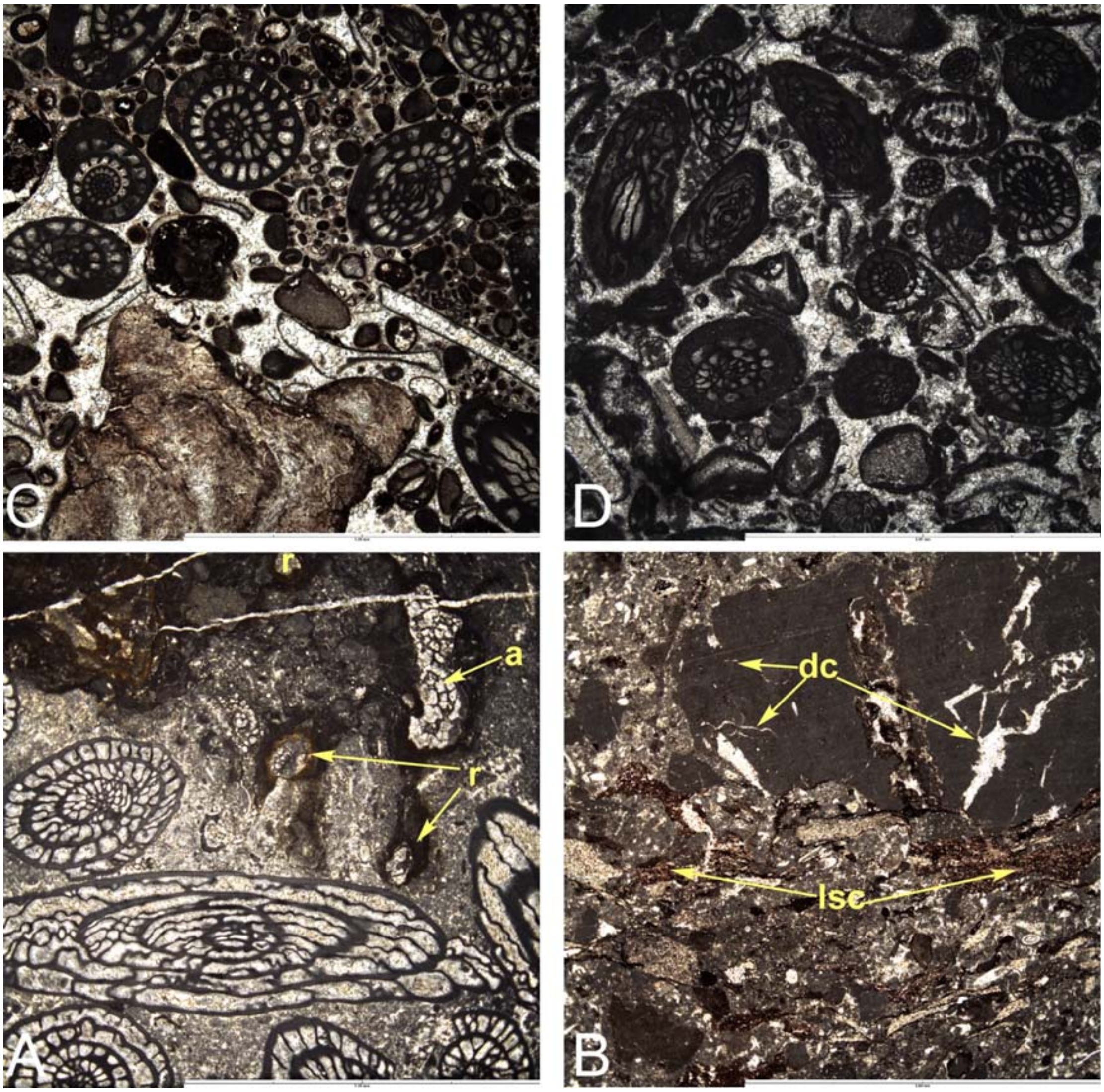


Figure 50. Examples of Virgilian-age (Cisco), exposure-related, diagenetic features and typical facies and corresponding poor reservoir quality. Scale bar is 5 mm in all photos. A. Example of icehouse-style exposure surface with a brecciated, rhizolith- (r) and alveo-septal-bearing (a) soil zone developing directly on a subtidal fusulinid-packstone (sample depth 8,947 ft: 2.9 percent porosity and 0.33 md permeability). B. This sample contains abundant evidence of exposure-related diagenesis, including laminated microcrystalline soil crusts (lsc), rhizoliths (r), and intraclasts with abundant radial desiccation cracks (dc). Many of the intraclasts appear to have incipient circumgranular fractures and may have been weakly developed glaebules prior to erosion. At the thin-section scale, this exposure-related fabric irregularly overlies a spiculitic wackestone (sample depth 8,906 ft; 0.70 percent porosity and 0.010 md permeability). C. Example of calcite-cemented, fusulinid-bioclastic-intraclastic grainstone (sample depth 8,884 ft: 2.3 percent porosity and 0.010 md permeability). Note that leached moldic grains are also occluded by cement. D. Typically well cemented, tight, fusulinid grainstone characteristic of the Virgilian (sample depth 8,883 ft: 1.9 percent porosity and 0.010 md permeability).

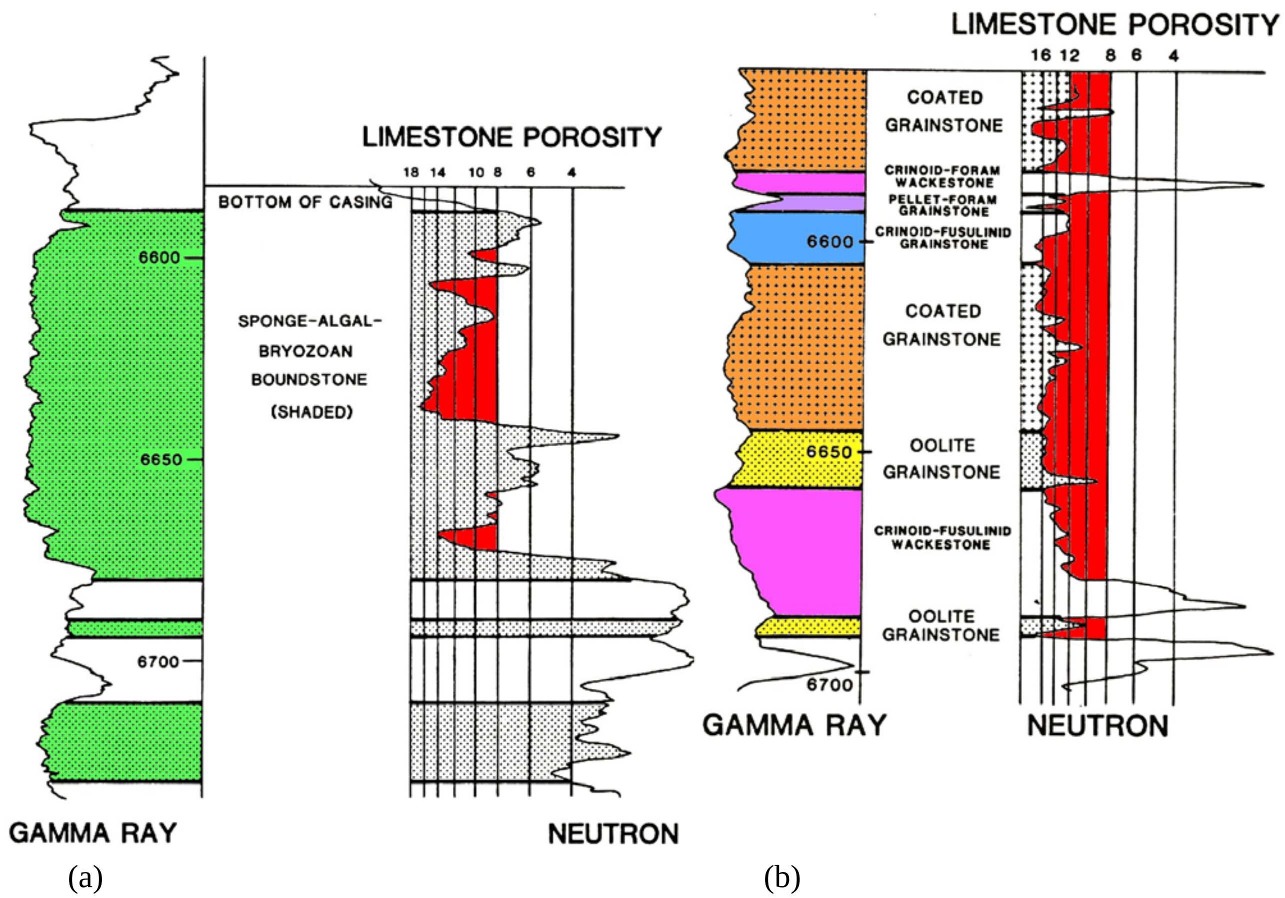
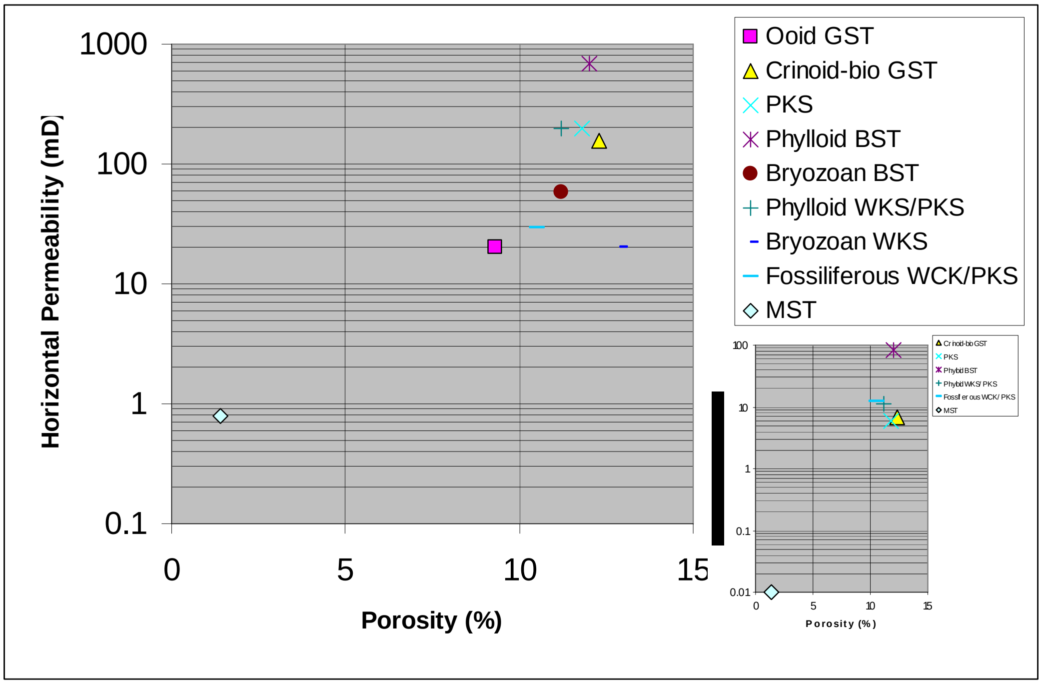


Figure 51. Facies versus wireline-log signature for (a) well 19-6 and (b) well 34-6 at SACROC field, Scurry County, Texas. Note that gamma-ray logs are similar for both wells; however, facies and associated porosity quality and extent are very different.



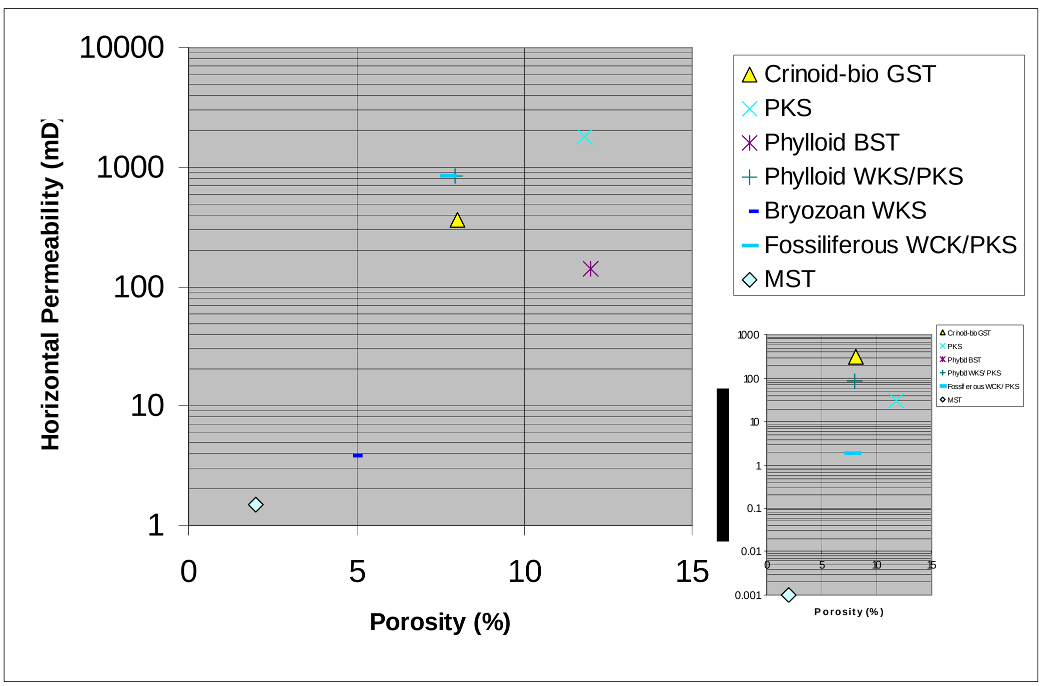
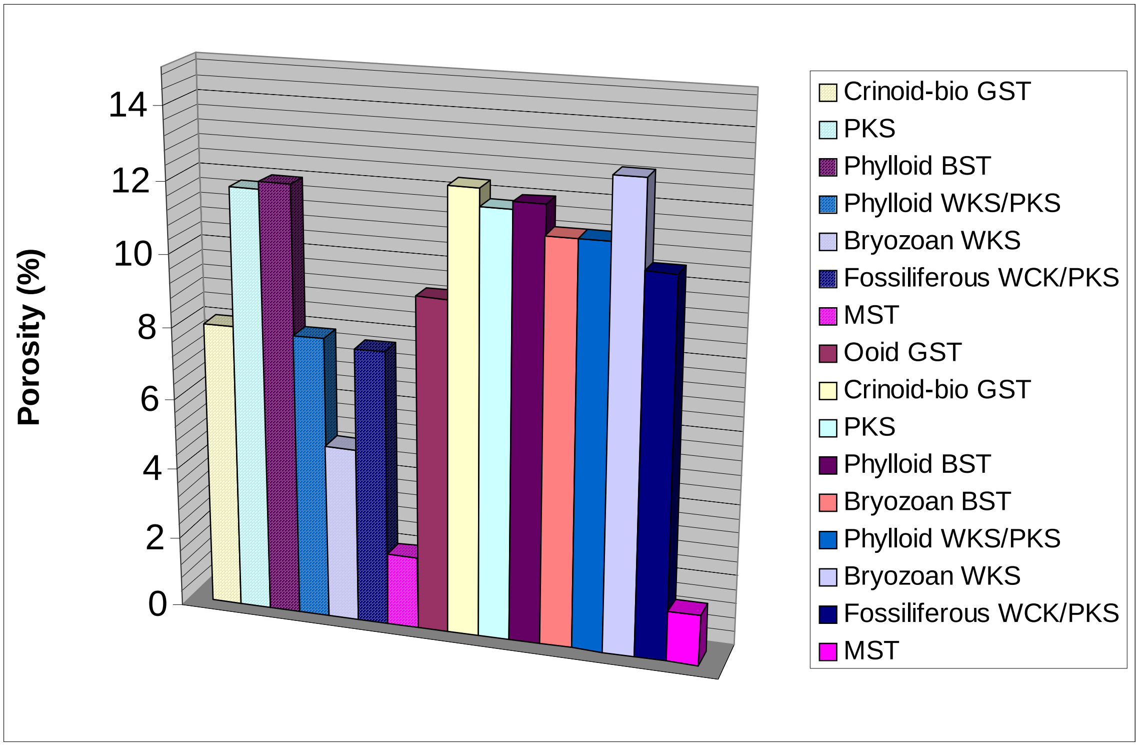


Figure 52. (Top) Porosity and permeability relationship to limestone facies at Reinecke field (data from Saller and others, 2004). Inset comprises a subset of the facies and is vertical permeability. Note that the best reservoir facies in both plots is phylloid algal boundstones. (Bottom) Porosity and permeability relationship to dolomitized facies at Reinecke field (data from Saller and others, 2004). Inset comprises a subset of the facies and is vertical permeability. Note that the best reservoir facies in using horizontal permeability is packstone, whereas crinoidal-bioclastic grainstone has the best vertical permeability.



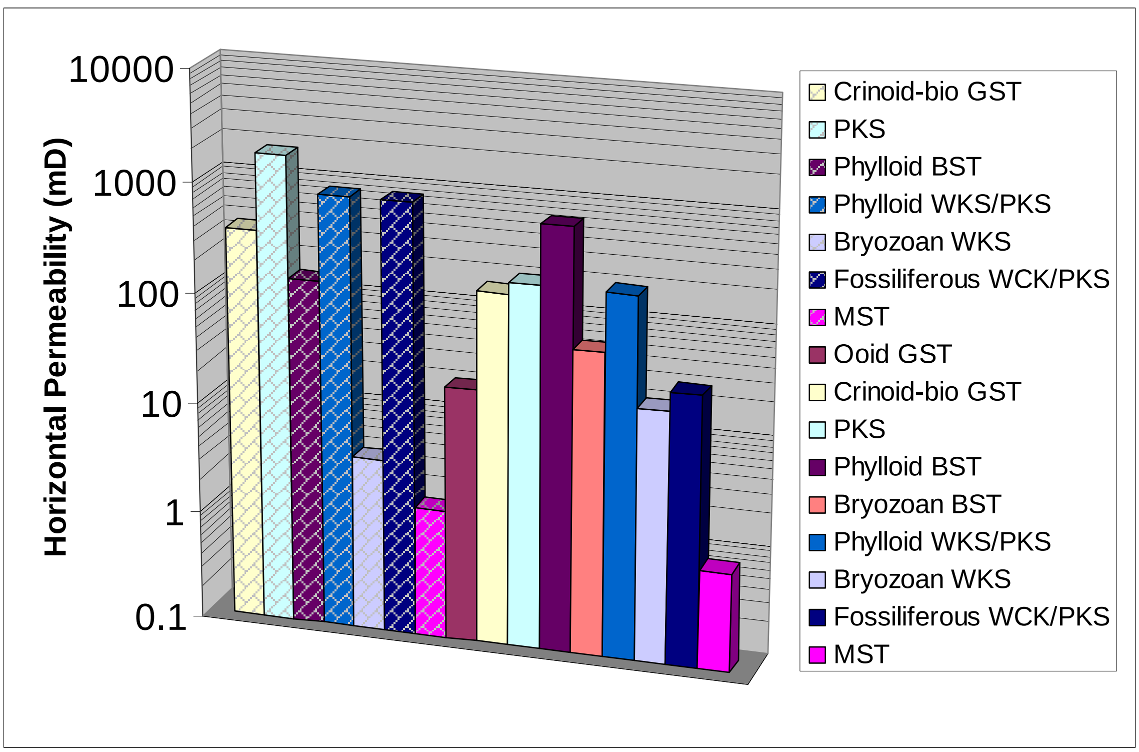


Figure 53. Bar charts comparing porosity and horizontal permeability between undolomitized (no fill pattern) and equivalent, dolomitized (fill pattern) facies at Reinecke field. Data from Saller and others (2004).

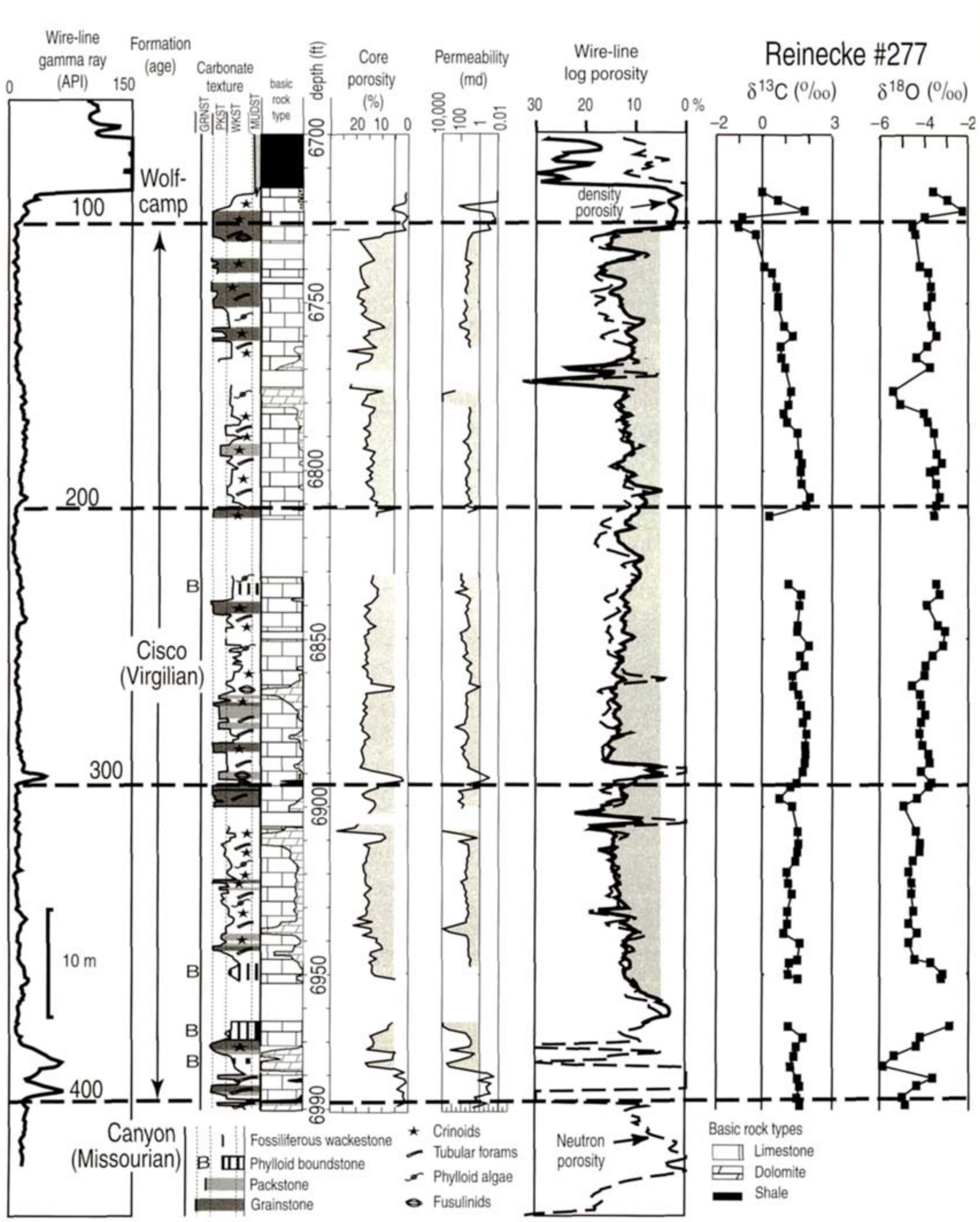


Figure 54. Single type well example from Reinecke field (after Saller and others, 2004). Note that wireline-log porosities are above 10 percent for the entire interval.

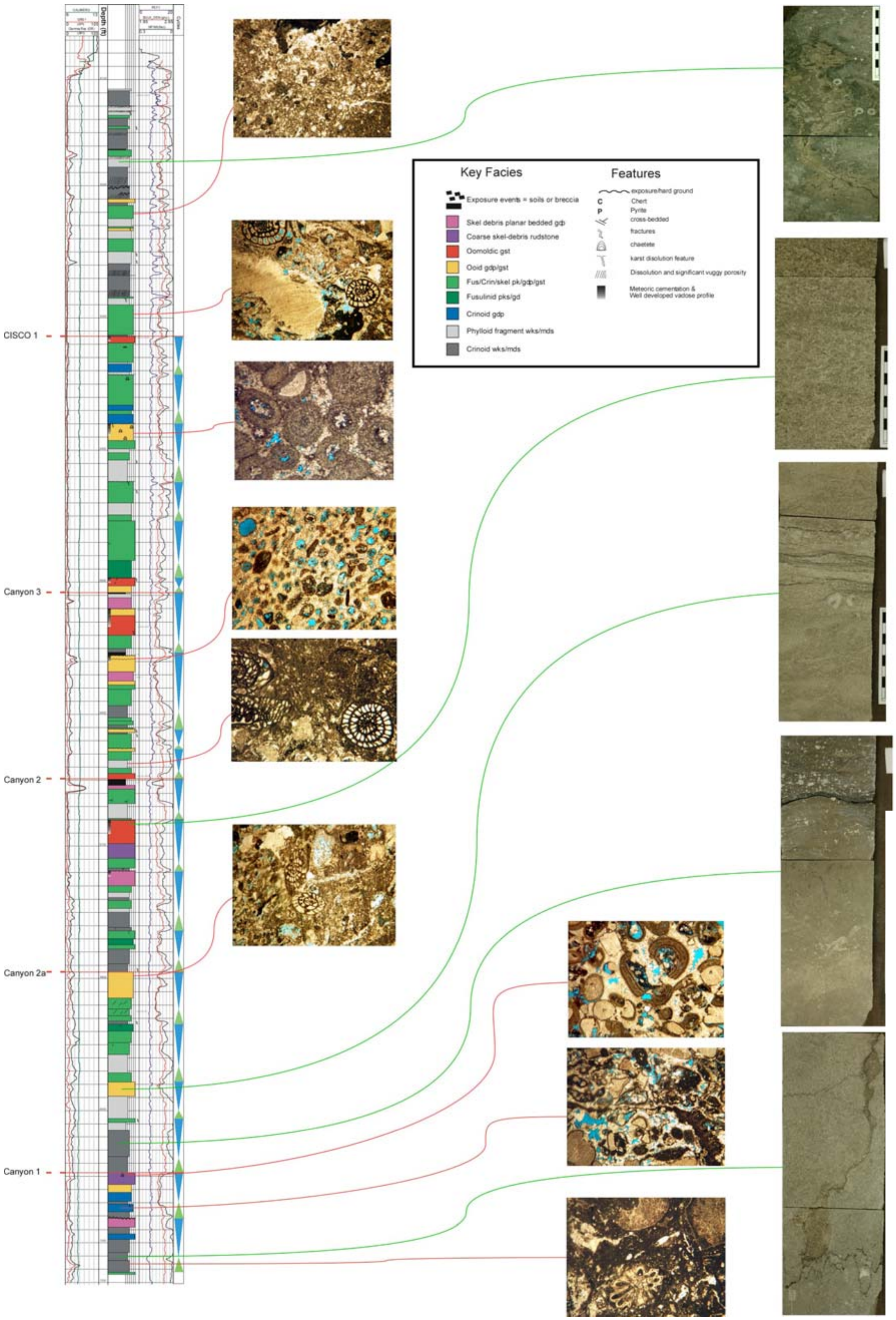


Figure 55. Type well log and facies for crestal grain-rich succession at SACROC. Note numerous transgressive and regressive cycles in green and blue. Core photos and photomicrographs both illustrate facies variability and differences in pore type, as well as potential permeability.

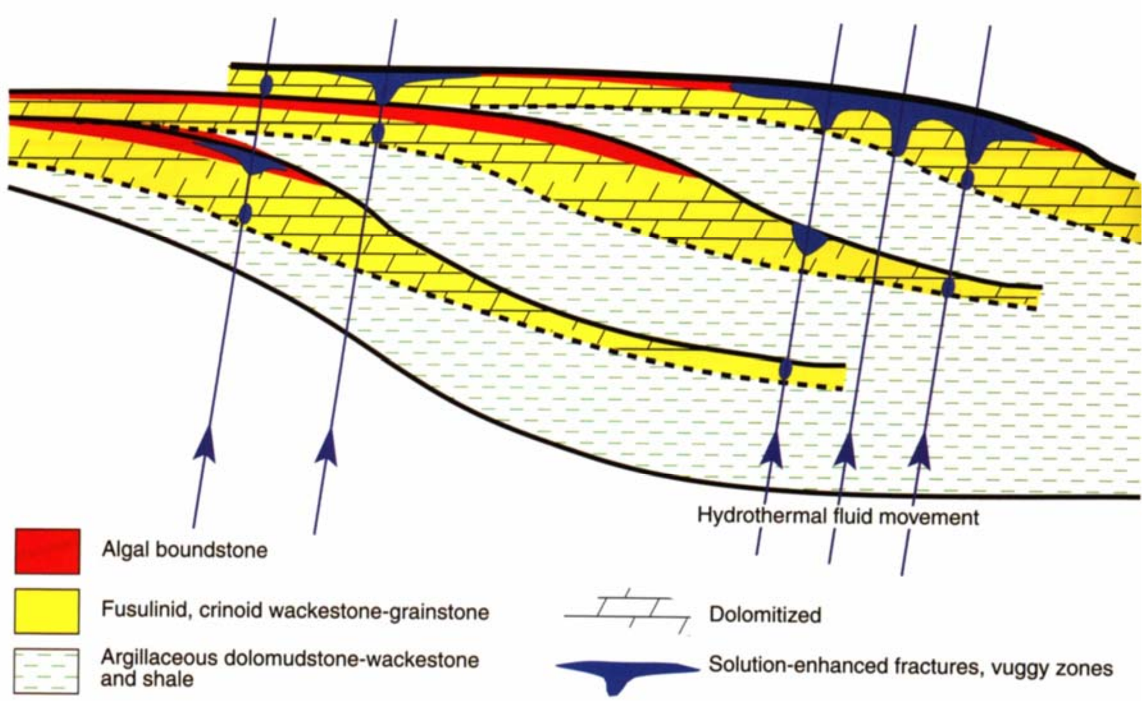


Figure 56. Conceptual dolomitization model for Missourian and Virgilian succession at Dagger Draw, Northwest Shelf. Dolomitization is thought to be diagenetically late, and fluids migrated into the succession from below via faults and fractures. After Tinker and others (2004).

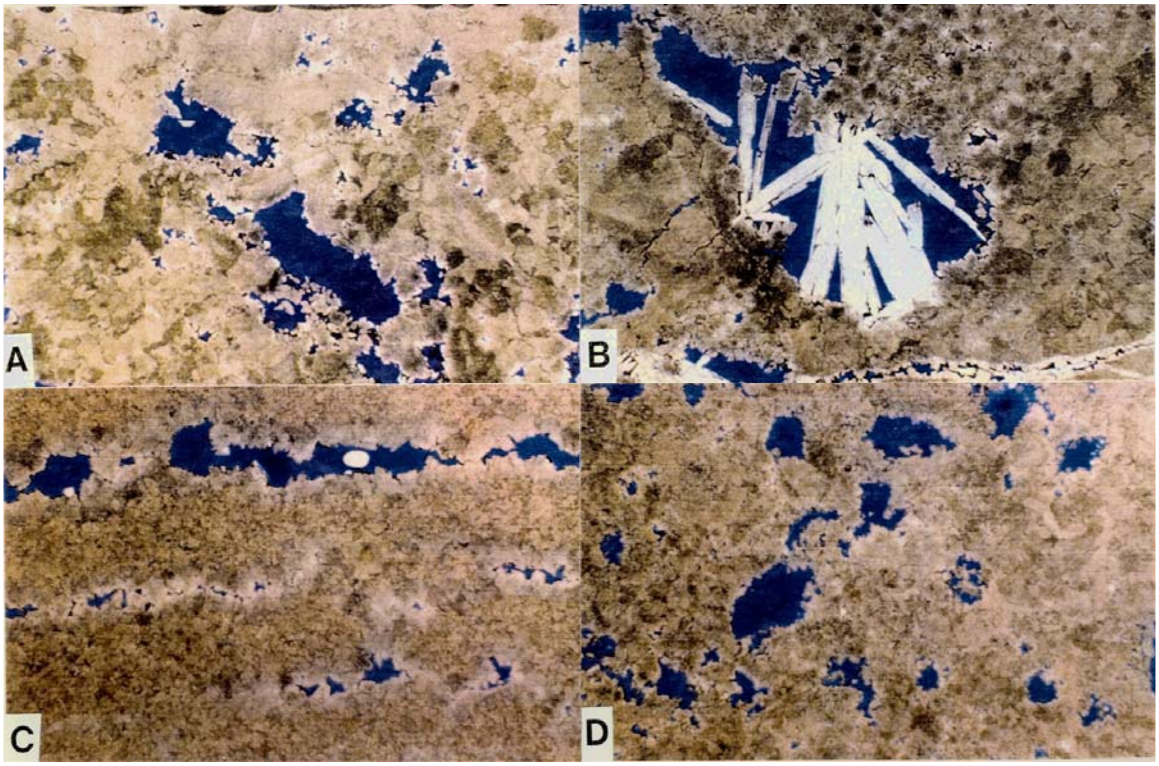


Figure 57. Thin-section photomicrographs of porosity (blue) and texture of the dolomitized facies (after Tinker and others, 2004). A. Fabric-destructive dolomitization of a possible packstone with irregular-shaped pores, possibly originally moldic and primary intergranular. All pores are technically intercrystalline now. B. Large, possibly solution enhanced pore in dolomitized wackestone packstone. Large pore partly occluded by barite cement. C. Dolomitized mudstone, which may have been originally algally laminated. Pores well connected horizontally but weak vertically. Texture commonly called zebra dolomite. D. Dolomitized packstone with moldic pores after leached bioclasts.