THE MISSISSIPPIAN BARNETT FORMATION:

A SOURCE-ROCK, SEAL, AND RESERVOIR PRODUCED BY EARLY CARBONIFEROUS FLOODING OF THE TEXAS CRATON

Stephen C. Ruppel and Jeffery Kane

Bureau of Economic Geology
Jackson School of Geosciences
The University of Texas at Austin
Austin,. TX

ABSTRACT

The Early Carboniferous (Mississippian) was a time of crustal downwarping and flooding of southern Texas region. Mississippian facies documenting this flooding include a basal, updip, shallow to deep water carbonate succession and an overlying, downdip, deep water, fine grained siliciclastic mudrock succession. The basal carbonate succession, termed the Mississippian Limestone in the Permian Basin, includes the Chappel of the Llano Uplift and the Caballero-Lake Valley of southern New Mexico outcrops. These rocks document the margins of an extensive carbonate platform that occupied much of the western U.S. during the middle developed Mississippian. The overlying siliciclastic mudrock succession includes the Barnett formation of the Permian and Ft. Worth Basins and the Rancheria Formation of southern New Mexico outcrops. These rocks accumulated by autochthonous hemipelagic sedimentation and allochthonous mass gravity transport in low energy, below wave base, dysaerobic conditions in a platform marginal deep water basin formed on the southern margin of the Laurussian platform.

The carbonate section is poorly known and only of minor importance as a hydrocarbon reservoir in the Permian Basin. Key insights into the detailed character and architecture of these rocks are provided by analogous outcrops of the Lake Valley outcrop succession in New Mexico. The overlying Barnett mudrock succession, long recognized as a hydrocarbon source rock, is similarly poorly known but has recently attracted great attention as a target for gas exploration and development. Aspects of Barnett stratigraphy, sedimentology, mineralogy, and chemistry are inferred by comparisons to and extrapolations from better known data sets in the Ft. Worth Basin.

INTRODUCTION

The Mississippian is one of the most poorly known depositional successions in the Permian Basin. This is largely due to the fact that only small volumes of oil and gas have been produced from these rocks and there has thus been little interest in collecting data to interpret them. This has recently changed because of the successful development of the Barnett Formation in the nearby Ft. Worth Basin as a reservoir of natural gas (Montgomery, 2004; Montgomery and others, 2005). Now there is considerable interest in understanding the Barnett in the Permian Basin and it's interrelationship with overlying and underlying rocks. However, because of the historical lack of interest in these rocks, very few reports on the Mississippian of the Permian Basin, in general, and no studies of the Barnett, more specifically, have been published. Basic aspects of the system are easily defined by the abundant wireline logs that penetrate the Mississippian across the basin. However, detailed rock data (e.g., cores) needed to calibrate geophysical data and to accurately characterize facies, petrophysics, diagenesis, and depositional history are lacking. Fortunately, such data are available in adjacent basins from both outcrops and the subsurface. This report integrates existing data and models from the Permian Basin – and surrounding areas – to develop interpretations and models for the Mississippian that constitute a fundamental basis for future exploration and development activities in the Basin.

PREVIOUS WORK

Because Mississippian rocks have not until recently been of great interest to oil and gas producers in the Permian Basin, relatively little published data exist for the section. By far the most comprehensive and useful report published is the USGS study of the Mississippian of the United States (Craig and Connor, 1979). Although regional in focus, this report contains discussions of formations, age relationships, thickness, depositional environments, and structural setting for the entire Mississippian System. Included in the report are thickness and structure maps, cross sections, that provide an good overview of sedimentologic and stratigraphic relationships in the Permian Basin. Gutschick and Sandberg (1983) published a valuable analysis of the middle Osagean (Lower Mississippian) section across the U. S. primarily based on their work in western U.S. Their models are applicable over much of the U.S.

More focused studies of the Permian Basin region, however, are rare. One of the few is that by Bay (1954) who conducted a detailed stratigraphic analysis of the Mississippian section in Gaines and Andrews Counties, Texas based on wireline logs and well cuttings. Hamilton and Asquith (2000) described styles of deposition and diagenesis in the upper

Mississippian Chester Group and documented the distribution of the Barnett in Lea County, New Mexico.

Considerably more information has been published on the adjacent Palo Duro and Ft. Worth basins. Ruppel (1985) described thickness and facies variations in the Mississippian section in the Palo Duro and Hardeman basins and also published a general stratigraphic model for the Hardeman – Ft. Worth Basin areas (Ruppel 1989). Henry (1982) provided a basic analysis of the Chappel and Barnett formations in the Ft. Worth Basin area. More recently, Montgomery (2004; see also Montgomery and others, 2005) contributed an extensive summary of the Barnett in the Ft. Worth Basin.

REGIONAL SETTING

During the Mississippian, the Permian Basin area straddled the outer margin of an extensive shallow water carbonate platform that covered much of southern and western Laurussia (in what is now the central and western U.S. (Figs. 1, 2)). Because of its setting in warm tropical waters and its isolation from sources of clastic sediment input, carbonate sedimentation dominated the interior of this platform (Figs. 1 and 2). Along the western and southern margins of the platform, isolated reefs and carbonate buildups were common. The southern margin of the platform was controlled by the position of the approaching Gondwana plate (Fig. 1). Regional sedimentological data (Craig and Connor, 1979) indicate that a deep trough (the Ouachita trough) formed ahead (north) of the Gondwana plate and that by at least middle Mississippian time the outer margins of this trough were uplifted and began to shed sediment northward into the trough. The Stanley Shale of the Ouachita overthrust belt in Oklahoma, a sandstone-bearing shale succession that is rich in coarse detrital sediments (Craig and Connor, 1979), reflects near-source, outer trough sedimentation. More proximal, inner trough sediments (which formed between the carbonate platform to the north and the trough axis to the south) were characterized by siliceous muds formed by hemipelagic suspension and coarser grained carbonate detritus (transported from the carbonate platform to the north) and siliciclastic detritus (transported from the uplifted trough margin to the south) by mass gravity transport. [These sediments are represented by the Barnett Fm of the Permian and Ft. Worth Basins.] Based on studies of the western margin of the platform, Gutschick and Sandberg (1983) developed excellent models for platform margin to slope deposition that fit very well with existing evidence from the Permian and Ft., Worth Basin area (Fig. 3).

REGIONAL STRATIGRAPHY AND FACIES

As suggested above, Mississippian stratigraphy and facies development is very similar throughout most of the Permian Basin – Ft. Worth Basin region. However, there are key differences in styles and in data sets that make it worthwhile to discuss each area separately. The stratigraphic nomenclature and correlations of conventionally named Mississippian units in the Permian Basin and surrounding areas are depicted in figure 4.

Permian Basin

Stratigraphy

In general the Mississippian of the Permian Basin comprises two end-member lithologies: a carbonate dominated section updip and upsection, and a siliciclastic-rich (commonly termed “shale”) section in the southern part of the area. The basal carbonate section, which is defined and correlated by its relatively low gamma ray character is unnamed but is usually referred to as the Mississippian Lime or Limestone. The overlying high gamma ray section is commonly referred to as the Barnett Formation (Fig. 5). The basal Mississippian carbonate is underlain by the Woodford Shale in most parts of the Basin. The Barnett is generally overlain by carbonate-rich strata usually termed “Pennsylvanian Limestone” (or Lime).

Total Mississippian thickness varies widely across the Permian Basin area. A maximum thickness of more, than 2200 ft was reported by Craig and Connor (1979) in parts of Reeves and Ward counties, Texas. Most of the Mississippian section in this area is assigned to the Barnett. Figure 6 depicts the distribution and thickness of the Barnett across the region. Barnett thickness decreases northward toward the updip carbonate platform. The position of the platform margin and the updip subcrop margin of the Barnett has been defined in Gaines and Andrews counties by Bay (1954) and in Lea County by Hamilton and Asquith (2000). This change from Barnett mudrock facies to carbonates is generally well imaged by gamma ray logs (Fig. 7). Using log data, outcrop descriptions, and new descriptions from cores from this study, it is possible to define the probable position of the margin of the

Mississippian platform during the late Mississippian (Fig. 8). The line marking the platform margin also marks the approximate updip extent of the Barnett Formation.

Carbonate Facies

Very little has been published regarding the facies character of the Mississippian carbonate section in the Permian Basin area. Hamilton and Asquith (2000) showed that the upper Mississippian carbonate section in central Lea County, New Mexico was dominantly composed of ooid and crinoid grainstones. Although cores from the lower Mississippian carbonate section have not been previously reported, two cores examined during the course of this study demonstrate the wide variability in facies that exists across the region.

Core recovered from the lower Mississippian carbonate section in Gaines County (Fig. 9). illustrate marked facies diversity. The lower, low gamma ray part of the section consists of light gray to brown, coarse-grained crinoidal grainstone (Fig. 10 a,b). These rocks are well-sorted and contain extensive syntaxial cement typical of crinoid grainstones. These rocks probably represent carbonate shoal sediments deposited in a well-oxygenated, high energy setting. By contrast, the upper part of the Mississippian section in this well consists of very dark-colored, cherty mudstones and wackestones (Fig. 10 c, d) whose depositional textures suggest they were deposited in a dysaerobic low energy setting, probably below wave base.

The basal Mississippian carbonate section in the southern part of the basin differs greatly from that observed in Gaines County. Although they exhibit a similar low gamma ray signature (Fig. 11), these rocks are dark gray to black mudstones that are massive to locally laminated or burrowed (Fig. 12 a,b). The dark color of these rocks, absence of megafauna, and limited evidence of infauna indicates that they were deposited in a low energy, anoxic to dysoxic setting.

Llano Uplift

Type sections for both the basal Mississippian carbonate (Chapel Formation) and the upper Mississippian “shale” (Barnett Formation) succession are located in the Llano Uplift area of central Texas. Outcrops and newly described cores from subsurface wells in the Llano Uplift area provide key data for interpreting the Mississippian section in the subsurface elsewhere.

In outcrops, the Chappel Formation consists of light-colored, fine to coarse grained, skeletal packstone (Watson, 1980). Although ostracodes, corals, and other fossils are common, it is the abundance of crinoids, in many cases red, that distinguishes the Chappel. The thickness of the Chappel is typically only a few feet, but ranges from a few inches to more than 50 ft (in depressions in underlying Ellenburger Group (Lower Ordovician) carbonates. The Chappel is overlain by the Barnett formation which at the type section consists of 50 ft of thin bedded, black shale that contains carbonate concretions and lenses (Fig. 14a). The Barnett is typically highly petroliferous having yielded as much as 40 gallon of crude oil per ton from some outcrops in San Saba county, Texas. (Watson, 1980)

Cores of the Chappel-Barnett succession demonstrate key aspects of the two formations. In McCulloch County, Texas (Fig. 13), for example, the basal Chappel consists of 1 ft of red, skeletal packstone (Fig. 15a). Overlying rocks (which have been referred to as the Whites Crossing unit because of their facies and age (Hass, 1953) are typically coarse-grained crinoidal packstones that are locally interbedded with carbonate and siliciclastic mud (Fig. 15b,c,d,e). Although crinoidal debris dominated these rocks, other open marine fossil are locally common (Fig.15f). Whereas the basal Chappel appears to be largely indicative of in situ deposition, the Whites Crossing facies contain features (e.g., inclined bedding, slump features, poor sorting) that suggest downslope transport. The diverse fauna present in the Chappel demonstrate that these rocks were deposited in a well-oxygenated, normal marine setting typical of shallow water carbonate platforms.

The overlying Barnett in McCulloch County (Fig. 13) comprises dark gray to black siliciclastic mudstones that range from massive to thinly laminated and are locally very fossiliferous (Fig. 14b,d). The Barnett locally contains carbonate concretions (Fig. 14b) that can be seen in outcrop to have lens-like geometries (Fig. 14a). The fauna is dominated by two end-member types: thin walled brachiopods and crinoid debris (Fig. 14b,c,d). Crinoid debris (Fig. 14c) is most common at the base of the Barnett where it grades into the underlying Whites Crossing (Fig. 13). Brachiopods, which are typical of deep water forms thought have been deposited at water depths greater than 200 ft (Thompson and Newton, 1987), appear to be in situ and are associated with dark-colored mudstones (Fig. 14d). The presence of these brachiopods coupled with the absence of burrows and in situ shallow water faunas suggest the Barnett formed in dysoxic conditions in deep water.

Conodont faunas from outcrop sections of the Chappel and Barnett indicate that the Chappel is Osagean in age whereas the Whites Crossing and Barnett are much younger Meramecian deposits (Hass, 1953, 1959). This suggests that the Chappel platform was emergent prior to flooding and deposition of the Barnett.

Ft. Worth Basin

The Mississippian section in the Ft. Worth Basin differs significantly from that in the Permian Basin by lying directly on much older (Ordovician) rocks and in containing no basal carbonate (i.e., Chappel or Mississippian Limestone) section. Mississippian rocks in the Ft. Worth Basin instead overlie Viola (Middle Ordovician) or Ellenburger (Lower Ordovician) carbonates and comprise the Barnett Formation and related rocks only. Because the Barnett exhibits a high gamma ray log response it is readily definable in the subsurface (Henry, 1980). Locally the Barnett is separated into upper and lower sections by a low gamma ray interval that has been termed the Forestburg (Fig. 16). Wireline logs and core analyses show that the low gamma ray character of the Forestburg is a function of the presence of calcite. The Barnett/Forestburg section generally increases in thickness to the east and northeast toward the Ouachita overthrust. The Forestburg, however, shows no systematic areal trends in thickness.

Facies

The textures, facies, mineralogies of the Barnett and Forestburg have recently been well documented and imaged by Papazis (2005). Both units are primarily dark gray to black, laminated mudstones (Fig. 17, 18). Some mudstones are very weakly laminated to nearly massive (Fig. 17c). Most, however, display laminae composed of silt-sized grains of quartz (Fig. 18b,c) or of phosphatic peloids or skeletal debris (Fig. 18a,c,e). Agglutinate foraminifera and thin walled brachiopods like those observed in the Barnett of the Llano uplift are also common (Papazis, 2005) (Fig. 18a,d,e). The Forestburg is generally somewhat lighter in color than the Barnett reflecting its higher carbonate content (Fig. 17a). Forestburg mudstones are weakly laminated to nearly massive (Fig. 17c) but locally contain thin-walled brachiopods (Fig. 17c). Papazis (2005) reported that the Barnett is dominantly composed of quartz in the clay and silt size ranges and that clay minerals are relatively uncommon. This distinguishes Barnett mudrocks from typical shales which generally contain a high volume of clay minerals.

Synthesis of core and log data from the Ft. Worth Basin and nearby outcrops and cores from the Llano Uplift area indicates Barnett and Forestburg rocks were deposited in a restricted, low energy, deep water setting. The color and laminated character of the rocks indicates quiet water, hemipelagic sedimentation interrupted periodically by grain and/or turbid flows composed of clay to silt-size particles of quartz and/or carbonate. The limited autochthonous fauna of brachiopods and agglutinate foraminifera is characteristic of below wave base, dysaerobic conditions at depths probably greater than 200-300 meters (Thompson and Newton, 1987; Gutschick and Sandberg, 1982; Fig. 3). The Forestburg probably represents the distal tail of a platform derived, carbonate dominated, debris flow derived from the carbonate platform to the west of the Ft. Worth Basin.

MISSISSIPPIAN DEPOSITIONAL SETTING

Recent studies of cores and logs from the Permian and Ft. Worth Basins coupled with developing studies of outcrops in the Llano uplift region have provided new insights into depositional styles and facies development in the Mississippian section. It is apparent, for example, that the Barnett Formation documents an overall rise in relative sea level across the entire southern Laurussian paleocontinent during the Mississippian. In the Ft. Worth Basin area, this rise resulted in the flooding of a previously emergent carbonate platform of Ordovician rocks. It is probable that flooding was a response to downwarping of the southeastern margin of the platform associated with collisional flexure of the Laurussian plate caused by the approaching Gondwana plate (Fig. 1). In the Permian Basin area, where Mississippian deep water rocks overlie relatively deep water siliciclastics of the Woodford formation (Comer, 1991) this deepening event is less apparent.

Because of the characteristic log character of the Barnett, platform flooding is easily defined with wireline logs (i.e., these deep water mudrocks can be readily recognized by their high gamma ray character). Although the carbonate-rich intervals can similarly be defined from gamma ray logs (by their low response) carbonate facies, and thus relative water depth and depositional environment cannot. The Forestburg interval is a good example of this. Many have assumed that this carbonate-rich interval is composed of shallow water platform carbonates but as we have stated, it is instead a deep water assemblage like the Barnett but with a higher carbonate content. The succession low gamma ray (Mississippian limestone) intervals in the Permian Basin present similar difficulties of interpretation. For example, low gamma ray carbonates in the lower Mississippian in Gaines County (Fig. 7, 9) consists of crinoidal grainstones and packstone that reflect shallow water platform deposition. By contrast, low gamma ray carbonates of the lower Mississippian in Reeves County (Fig. 11) are deep water (probably slope-basin) mudstones. Low gamma ray upper Mississippian rocks in Gaines County (Fig. 9) are also deeper water, platform margin to slope mudstones and wackestones. Thus, accurate definition of Mississippian carbonate facies is thus not possible with wireline logs alone. Cores and subsurface models are needed to accurately characterize the nature and distribution of the Mississippian carbonate succession in the Permian Basin.

Important insights to Mississippian facies character and architecture are provided by correlative, analogous outcrops in the Sacramento and San Andres Mountains of southern New Mexico (Fig. 4) . The Caballero - Lake Valley Formations comprise a complex Osagean succession (Fig. 19) of carbonate grainstones, packstones, wackestones and mudstones that represent buildup, flank, interbuildup and deeper water outer ramp to slope environments (Meyers, 1975; Lane and Ormiston, 1982). The overlying Rancheria Formation (Fig. 4) consists of deeper water, laminated, locally spiculitic lime mudstones and mudstones that document major rise in relative sea level during the Meramecian (Yurewicz, 1977).

Bachtel and Dorobek (1998) reevaluated the facies distribution of the Caballero - Lake Valley - Rancheria succession and demonstrated that facies vary systematically in position and geometry when viewed in a sequence stratigraphic framework (Fig. 20). They recognized three sequences in the Caballero-Lake Valley succession each with a well defined transgressive systems tract (TST) assemblage of dark colored, low energy, deeper water mudstones and wackestones and a highstand systems tract (HST) dominated by shallow water, light-colored grainstones and packstones. Mud-rich buildups and flanking facies appear to have developed during TSTs but persisted into HSTs. The geometries of these three sequences define basinward progradation and falling sealevel. The fourth and youngest sequence contains deep water mudstones and gravity flow deposits of the Rancheria Formation. These deposits onlap the Lake Valley succession and document sea level rise. Conodont biostratigraphy shows that the Lake Valley sequences are Kinderhookian to

Osagean in age whereas the onlapping Rancheria is Meramecian (Lane, 1974; Lane and Ormiston, 1982). In updip platform areas the Rancheria succession (sequence 4 of Bachtel and Dorobek, 1998) overlies the Lake Valley succession (sequence 3) unconformably (Fig. 20) suggesting post sequence 3 lowstand exposure of the platform.

The Lake Valley succession provides a good model for understanding age and facies relationships within the Permian Basin succession. The facies succession in Gaines County area (Fig. 7. 9) represents a near platform-margin position on the shelf with the grainstones observed in core perhaps representing the HST of sequence M2 (point 1 on Fig. 20). The Mississippian succession observed in Reeves County (Fig. 11) reflects a more distal position perhaps at the downdip toe of sequence 3 (point 2 on Fig. 20). More accurate delineation of sequences, systems tracts, and facies will require more integrated core and log study of the succession.

WIRELINE LOG CHARACTER OF MISSISSIPIAN FACIES

As has been discussed, basic separation of siliciclastic and carbonate facies is a relatively straightforward matter with gamma ray logs. The forgoing discussion has also demonstrated the complexity and difficulty of defining the details of age and facies interrelationships within the carbonate section even with good quality logs. However, new studies of log response in the Barnett suggests that there are systematic differences in mineralogy within the Barnett that can be defined with conventional wireline log suites. Spectral gamma logs, for example, show changes in the abundance of potassium, thorium and uranium that indicate stratigraphic differences in the sedimentology of the Barnett. Potassium, for example, exhibits a subtle and gradual decrease in abundance upward (Fig. 21). This suggests a slight reduction in the volume or increasing maturity of siliciclastics upsection and is reflected both by the potassium curve and the CGR curves (Fig. 21). Even more interesting is the clearly lower volume of thorium present in the basal 100 ft of the Barnett. This is reflected in the thorium concentration curve and the thorium/potassium ratio curves in figure 21. Preliminary mineral modeling of these elemental changes suggests a systematic difference the clay mineral assemblage at the base of the section compared with the rest of the section (Fig. 22). The low thorium/potassium ratio suggests an assemblage of micas (or glauconite and feldspars) and illite in the lower 100 ft of the Barnett and a different assemblage of mixed layer clays in the remainder of the Barnett (upper part of the lower Barnett and the upper Barnett. These differences in sediment composition have implications for the depositional history of the Barnett and also may provide important insights into the geomechanical character of the rocks which is an important concern for reservoir development.

RESERVOIR DEVELOPMENT

Mississippian carbonate succession.

According to Dutton and others (2005) the Mississippian Platform Carbonate play is the smallest oil-producing play in the Permian Basin, having cumulative production of little more than 15 MMbbl from the five reservoirs with cumulative production of greater than 1 million barrels as of 2001. The scarcity of productive Mississippian carbonate reservoirs may be tied to the abundance of crinoidal, grain-rich facies in platform successions; these rocks typically are associated with porosity occluding syntaxial cements. Most production from Mississippian reservoirs apparently comes from more porous upper Mississippian ooid grainstones (e.g., Austin field, in Lea County, New Mexico; Hamilton and Asquith, 2000). In at least some instances, production is also developed in dolomitized intervals (e.g., Brahaney field, Yoakum County, Texas; Wright, 1979). Grimes (1982) noted that the Mississippian production at Fluvanna field, Borden County, comes from weathered chert at the top of the Mississippian section. Reservoirs are limited to the northern part of the Permian Basin corresponding to the area of shallow water platform development (Fig. 23).

Barnett Formation

The Barnett of the Ft. Worth Basin has become a prolific producer of natural gas. As of 2006, more than 1.6 TCF of gas had been produced from the Ft. Worth Basin. The Barnett succession of the Permian Basin is depositionally analogous and may contains similar facies and mineralogies. Although parts of the Mississippian section have been removed by erosion, the Barnett is present across large areas of the Permian Basin (Fig. 23). It's extent is nearly as great as in the Ft. Worth Basin and it locally attains much greater thicknesses (more than 2000 ft; Fig. 6).

Some key questions to consider in determining the potential for similar reservoir development in the Permian Basin are: (1) are Barnett facies as currently defined in the

Permian Basin truly similar?, (2) what is the nature of overlying and underlying rocks and do variations play a role in completion strategies?, (3) what is the organic matter content and thermal maturity of Barnett facies?, and (4) are they fractured? No cores are currently available to answer facies or fractures questions. However, newly initiated wireline log – based studies of the Barnett are underway to develop initial models. We are also employing rock data from cores and outcrops in the Ft. Worth Basin and Llano areas to constrain wireline log models. Regional studies are providing improved resolution on the distribution, age, and facies character of both underlying carbonate successions and overlying units. We are also conducting detailed studies of fracture character based on core data. Organic matter data are not publicly available but recent vitrinite reflectance data from Pawlewicz and others (2005) provide initial key insights into the thermal maturity of the area. In summary, a great deal more study is needed to determine the depositional, mineralogical and structural character of the Barnett in the Permian Basin. These studies will be a fundamental basis for determining the potential of the Barnett as a viable economic resource.

SUMMARY AND CONCLUSIONS

Although information on the Mississippian succession in the Permian Basin is limited, data and models from outcrops and subsurface data from adjacent areas provides an initial basis for interpreting these rocks. Carbonates dominate the Mississippian section in the northern half of the area. These rocks are part of an extensive, shallow water carbonate platform that occupied much of the western U.S. during the middle Mississippian. In the southern part of the Basin, the section is composed primarily of siliciclastic mudrocks of the Barnett Formation. These rocks were deposited in below wave base conditions in a deep water platform to slope setting. The margin between shallow water carbonate deposition to the north and deeper water, hemipelagic and gravity transport deposition to the south ran east-west across most of the Permian Basin area. A peninsular extension of the platform margin appears to have extended southward to the Llano Uplift. The platform carbonate succession (Mississippian Limestone) reaches thicknesses of about 500 ft in the north. South of the platform margin, the Mississippian Limestone thins rapidly and changes to deeper water, below wave base, carbonate mud facies. Barnett facies reach thicknesses of more than

2000 ft locally in the southern part of the Permian Basin but pinch out a short distance north of the platform margin.

Limited cores combined with data and models from outcrops in New Mexico provide constraints for interpretation of carbonate platform facies and stratigraphic architecture. However, more data are needed to accurately characterize these rocks. Core data for the Barnett are not yet available but cores and outcrops from the Ft. Worth Basin area provide keys for interpreting Barnett facies, mineralogy, and stratigraphy in the Permian Basin.. Integrated core and wireline log analysis shows great promise for providing more detailed information on the regional and local character of the Barnett in the Permian Basin as well as in the Ft. Worth Basin.

REFERENCES

Bachtel, S., and Dorobek, S.L.,1998, Mississippian carbonate ramp-to-basin in south-central New Mexico: sequence stratigraphic response to progressively steepening Outer-Ramp Profiles, Journal of Sedimentary Research, v. 68, No 6, p. 1189-1200.

Bay, T. A., Jr., 1954, Mississippian system of Andrews and Gaines counties, Texas: unpublished MS thesis, The University of Texas at Austin, 56 p.

Comer, J. B., 1991, Stratigraphic analysis of the Upper Devonian Woodford Formation, Permian Basin, West Texas and New Mexico: The University of Texas at Austin. Bureau of Economic Geology, Report of Investigations 201, 63 p.

Craig, L.C., and Connor, C. W., Coordinators, 1979, Paleotectonic Investigations of the Mississippian System in the United States, Geological Survey Professional Paper 1010, Part III..

Dutton, S. P., Kim, E. M., Broadhead, R. F., Breton, C. L., Raatz, W. D., Ruppel, S. C., and Kerans, Charles, 2005, Play analysis and digital portfolio of major oil reservoirs in the Permian Basin: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 271, 287 p., CD-ROM.

Grimes, D. N., 1982, Fluvanna field: selected oil & gas fields in West Texas: West Texas Geological Society Publication No. 82-75, p. 232–236.

Gutschick, R., and Sandberg, C., 1983, Mississippian Continental Margins on the Conterminous United States, *in* Stanley, D.J. and Moore, G.T., The Shelf break: Critical Interface on Continental Margins: Soc. Econ. Paleontologist Mineralogists Special Publication 33, p.79-96

Hamilton, D. C., and Asquith, G.B., 2000, Depositional, Digenetic, and Production Histories of Chester Ooid Grainstones in the Austin (Upper Mississippian) Field: Lea County, New Mexico, *in* DeMis, W., Nelis, M., and Trentham R.C., eds., The Permian Basin : Proving Ground for Tomorrow's Technologies, West Texas Geological Society, Publication 00-109, p. 95-105

Hass W. H., 1953, Conodonts of Barnett Formation of Texas, Geological Survey Professional Paper 243-F, p 69-94.

Hass W. H., 1959, Conodonts from the Chappel Limestone of Texas, Geological Survey Professional Paper 294-J, 44 p.

Henry, J. D., 1982, Stratigraphy of the Barnett Shale (Mississippian) and associated reefs in the northern Fort Worth Basin, in Martin, C. A., ed., Petroleum Geology of the Fort Worth Basin and Bend Arch Area: Dallas Geological Society, p. 157-178.

Lane, H. R., 1974, Mississippian of Southeastern New Mexico and West Texas; A Wedge-on-Wedge Relation: American Association of Petroleum Geologists, Bulletin, vol. 58, no. 2, p. 269 - 282.

Lane, H. R. and Ormiston, A. R., 1982, Waulsortian facies, Sacramento Mountains, New Mexico: Guide for an international field seminar, in Bolton, K. Lane, H. R., and Lemone, D. V. eds., Symposium on the Paleoenvironmental setting and distribution of the Waulsortian facies: El Paso Geological society and University of Texas at El Paso. P. 115-182.

Montgomery, S. L., 2004, Barnett Shale: A New Gas Play in the Forth Worth Basin, *in* Petroleum Frontiers, HIS Energy, v.20, No.1, 74 p.

Merrill, G. K., 1980, Preliminary Report on the Restudy of Conodonts from the Barnett Formation *in* Geology of the Llano Region, Central Texas, Guidebook to the Annual Field Trip of the West Geological Society, Publication 80-73, p 103-107.

Meyers, W. J., 1975, Stratigraphy and diagenesis of the Lake Valley formation, Sacramento Mountains, in Pray, L. C. ,ed., A guidebook to the Mississippian shelf-edge and basin facies carbonates, Sacramento and southern New Mexico region: Dallas Geological society p. 45-65. Andres Mountains

Montgomery, S. L., D. M. Jarvie, K. A. Bowker, and R. M. Pollastro, 2005, Mississippian Barnett Shale, Fort Worth basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential: American Association of Petroleum Geologists Bulletin, v. 89, p. 155-175.

Papazis, P. K., 2005, Petrographic Characterization of the Barnett Shale, Fort Worth Basin, Texas: unpublished M.S. Thesis, The University of Texas at Austin, 142 p., Appendices.

Ruppel, S. C., 1989, Summary of Mississippian stratigraphy in north and north-central Texas, *in* Mear, C. E., McNulty, C. L., and McNulty, M. E., eds., A symposium on the petroleum geology of Mississippian carbonates in north-central Texas: Fort Worth Geological Society and Texas Christian University, p. 49–55.

Thompson, J. B., and Newton, C. R., 1987, Ecological reinterpretation of the dysaerobic Leiorhynchus fauna; Upper Devonian Geneseo Black Shale, central New York: Palaios v. 2: 274-281

Watson, W.G., 1980, Paleozoic Stratigraphy of the Llano Uplift Area: West Texas Geological Society Publication 80-73, p. 27-51.

Yurewicz, D. A., 1977, Sedimentology of Mississippian basin-facies carbonates, New Mexico and West Texas; the Rancheria Formation in Cook, H. E. and Enos, P. (eds.)

Society of Economic Paleontologists and Mineralogists, Special Publication, no. 25, p. 203 - 219.

from Blakey (2004): http://jan.ucc.nau.edu/~rcb7/340Nat.jpg

Figure 1. Global reconstruction of North America region during the Late Mississippian. Note the proximity of the approaching Gondwana plate to the Permian Basin area.

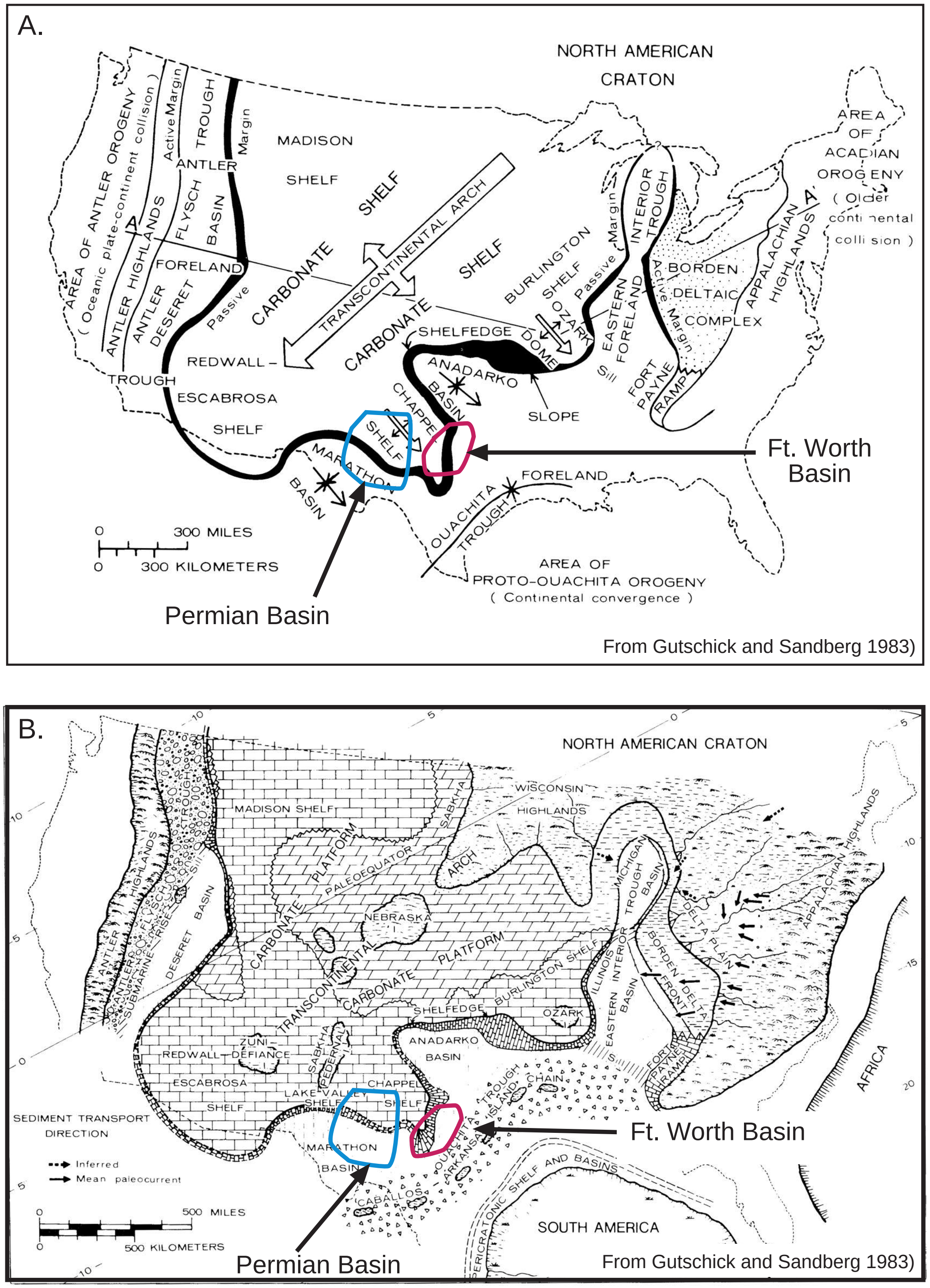
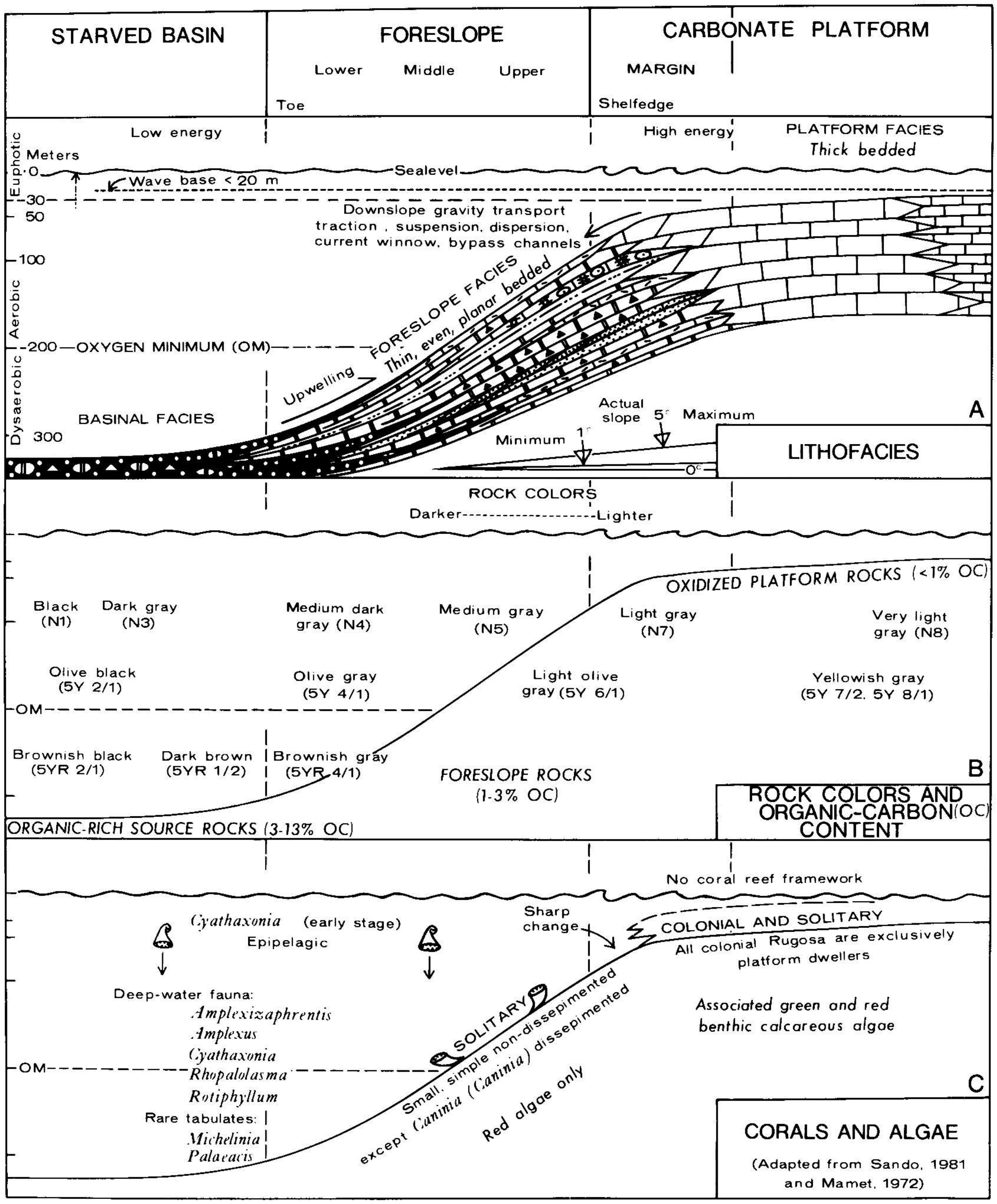
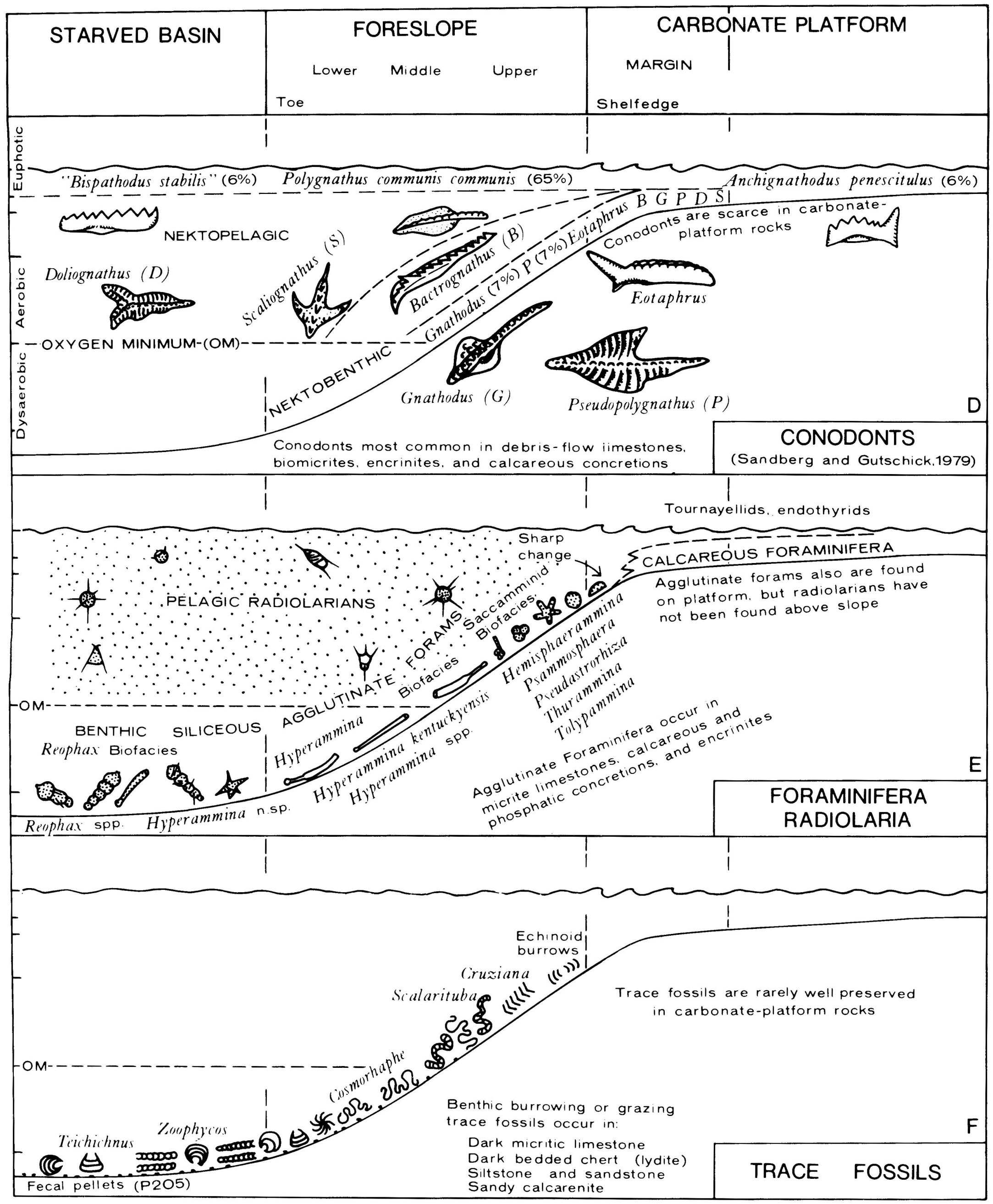


Figure 2. Paleogeography and structural features of the United States area during the Osagean (early middle) Mississippian).



From Gutschick and Sandberg 1983)

Figure 3. Models of facies and faunal development on Mississippian platforms and platform margins in western North America.



From Gutschick and Sandberg 1983)

Figure 3 (Continued). Models of facies and faunal development on Mississippian platforms and platform margins in western North America.

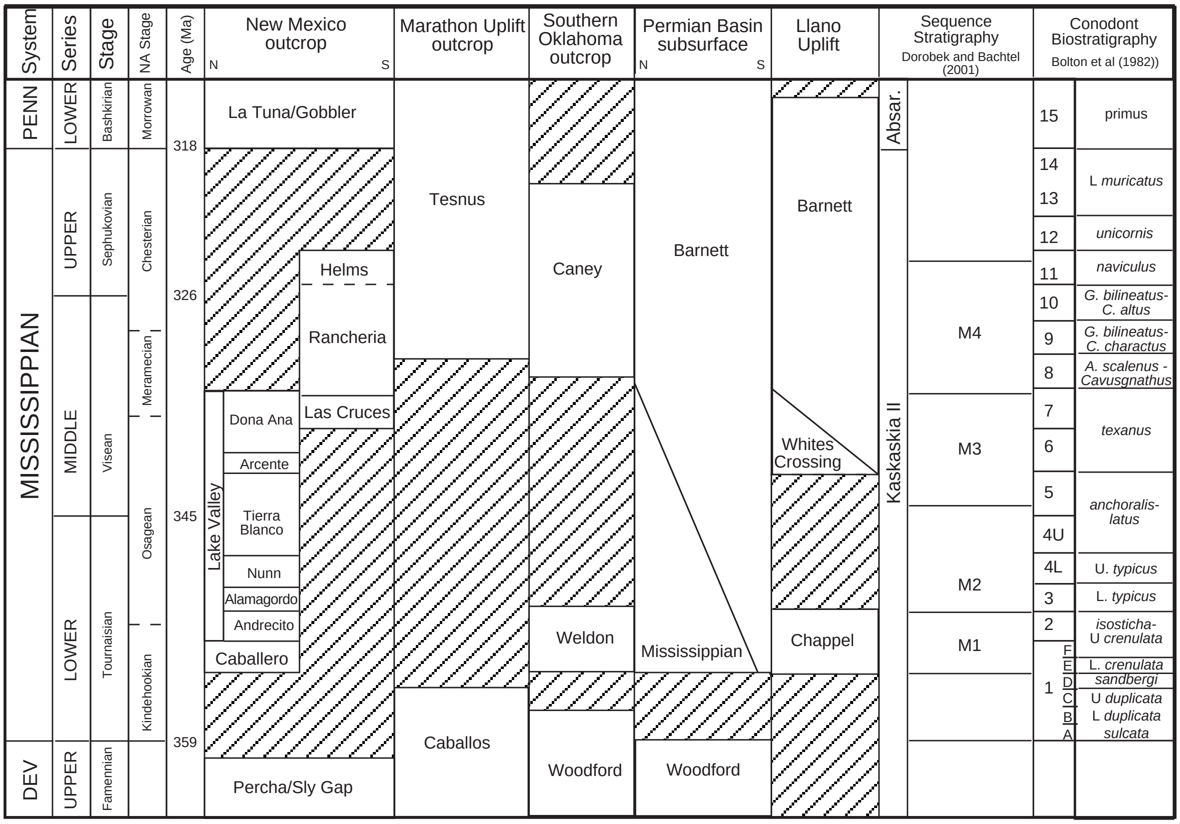


Figure 4. Chart showing stratigraphic nomenclature and correlations of Mississippian strata in the Permian Basin and adjacent areas.

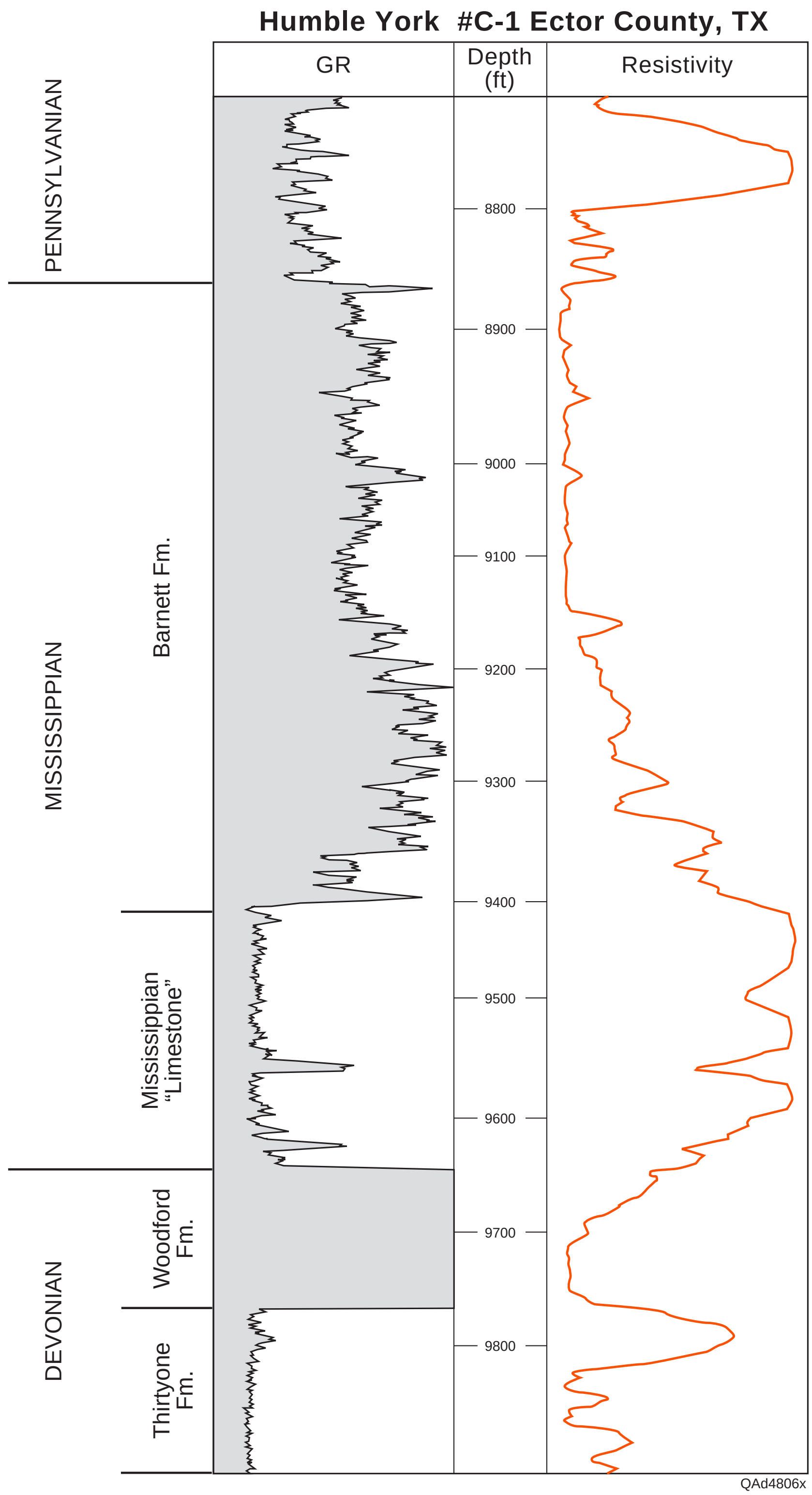


Figure 5. Typical log expression of the Mississippian section in the subsurface of the Permian Basin.

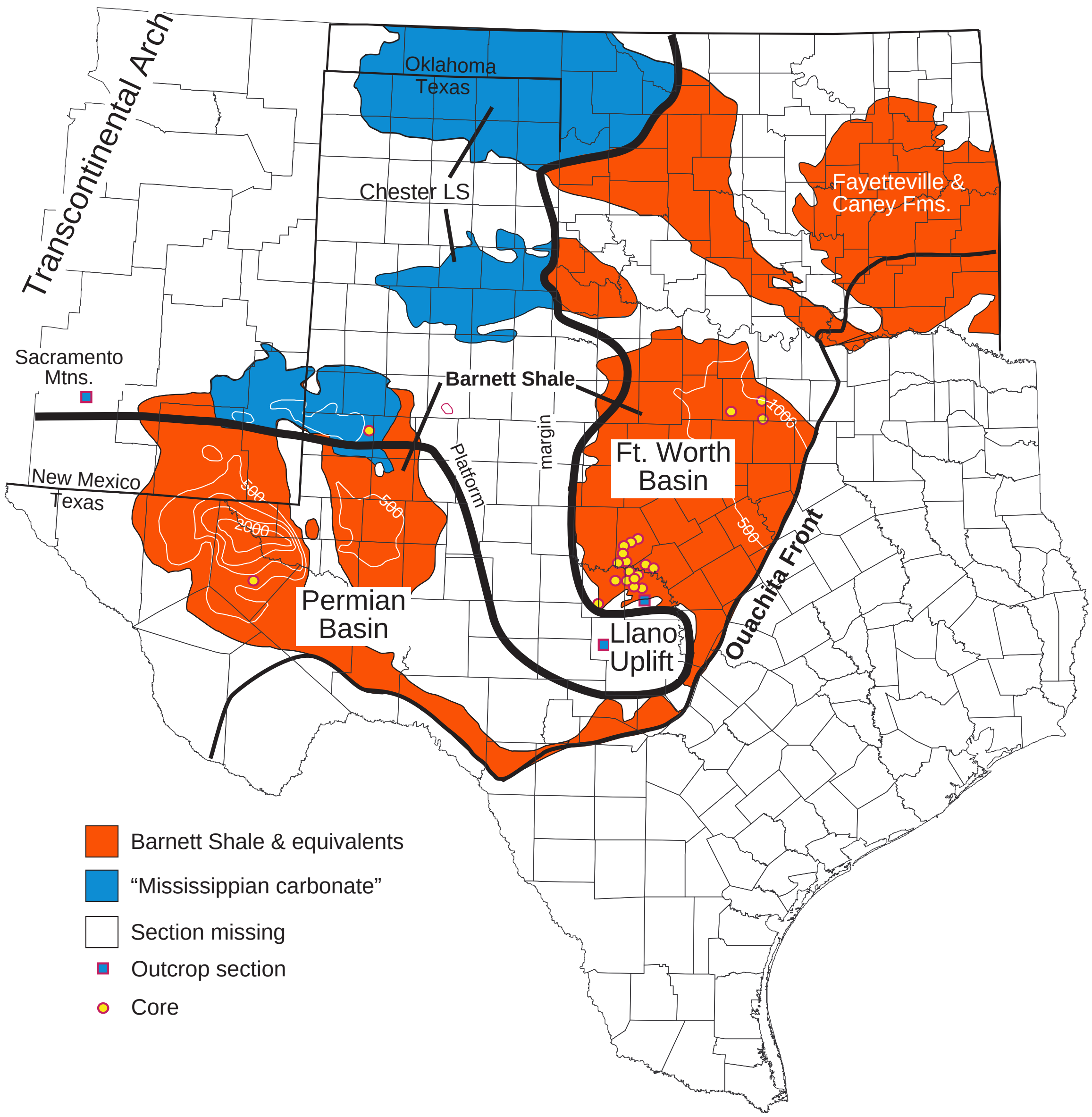


Figure 6. Distribution of Upper Mississippian rocks (outcrops and subcrops) in the southern midcontinent.

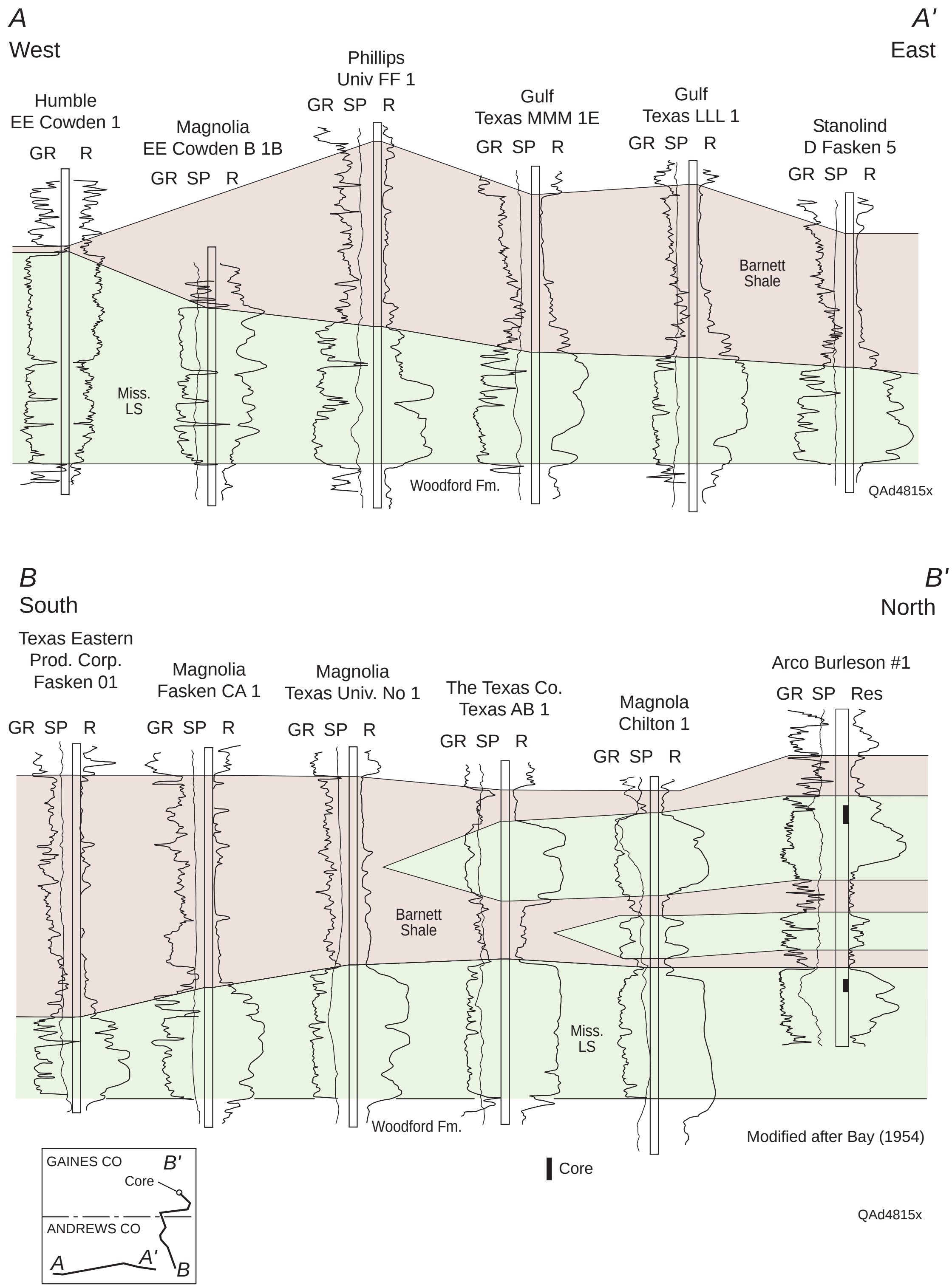


Figure 7. Cross sections showing wireline log signature and development of Barnett "shale" facies and Mississippian carbonate facies at the platform margin in the central part of the Permian basin.

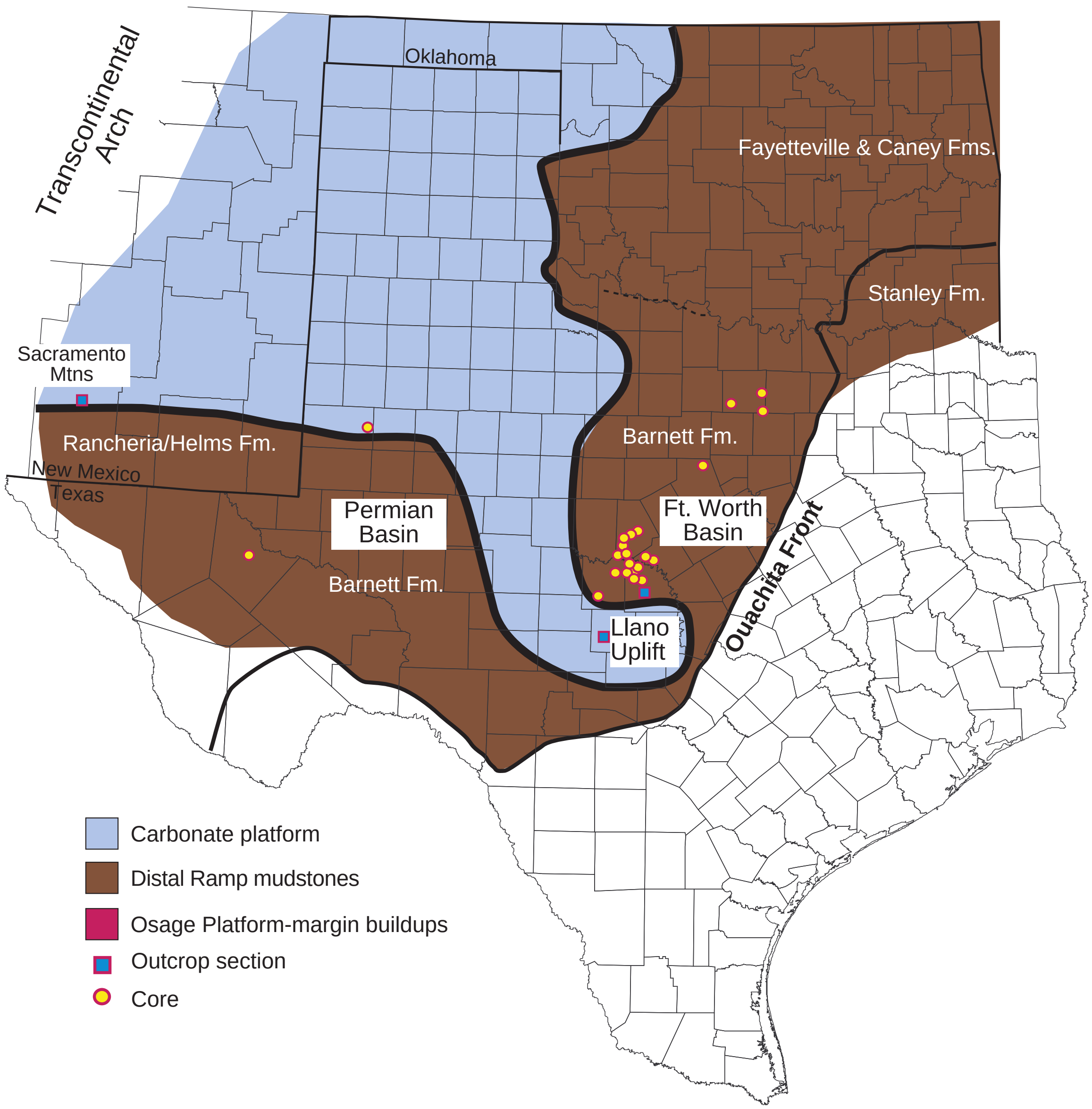


Figure 8. Paleogeography of Texas region during the Late Mississippian.

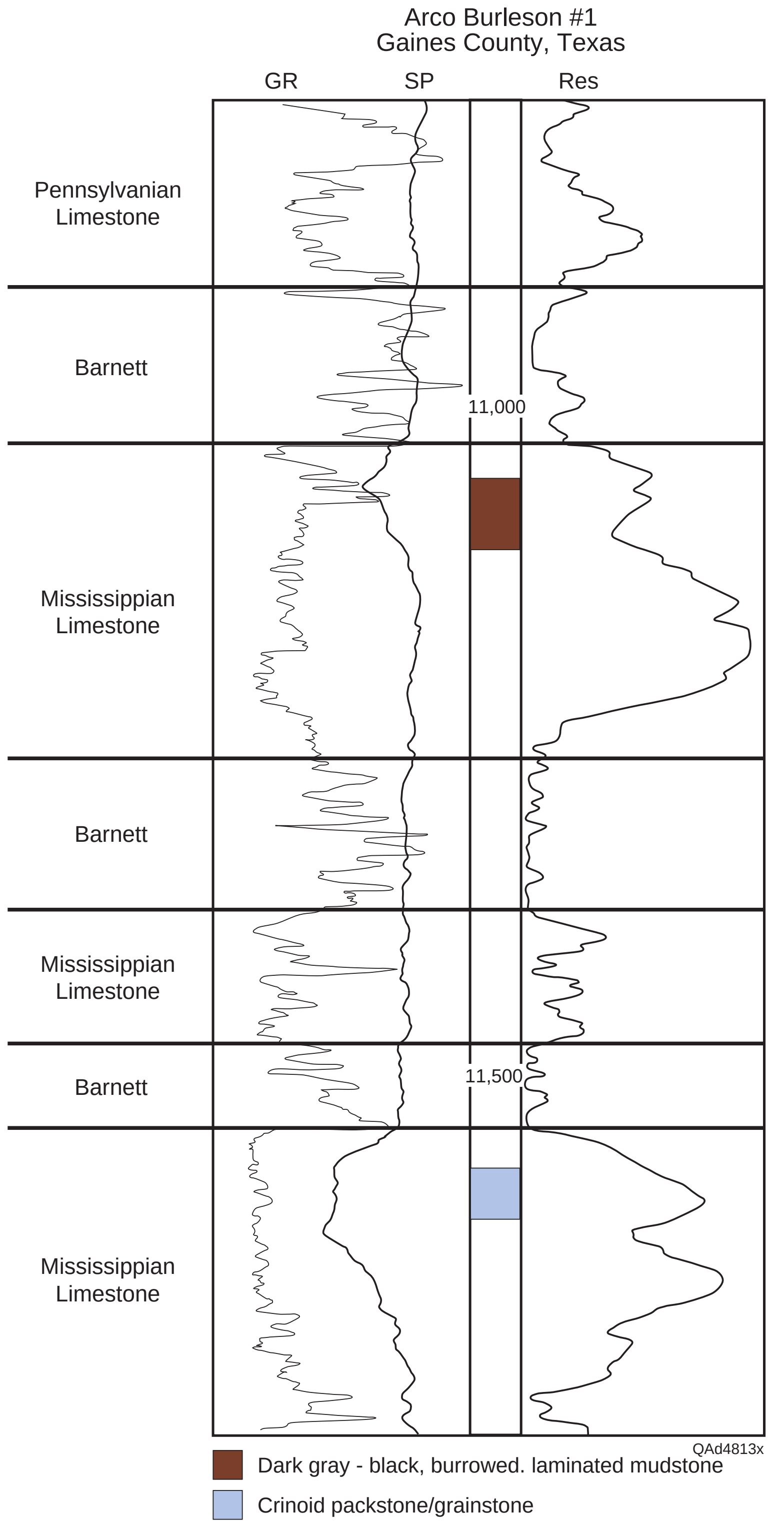


Figure 9. Typical wireline log signature from Mississippian cored well in the northern Permian Basin.

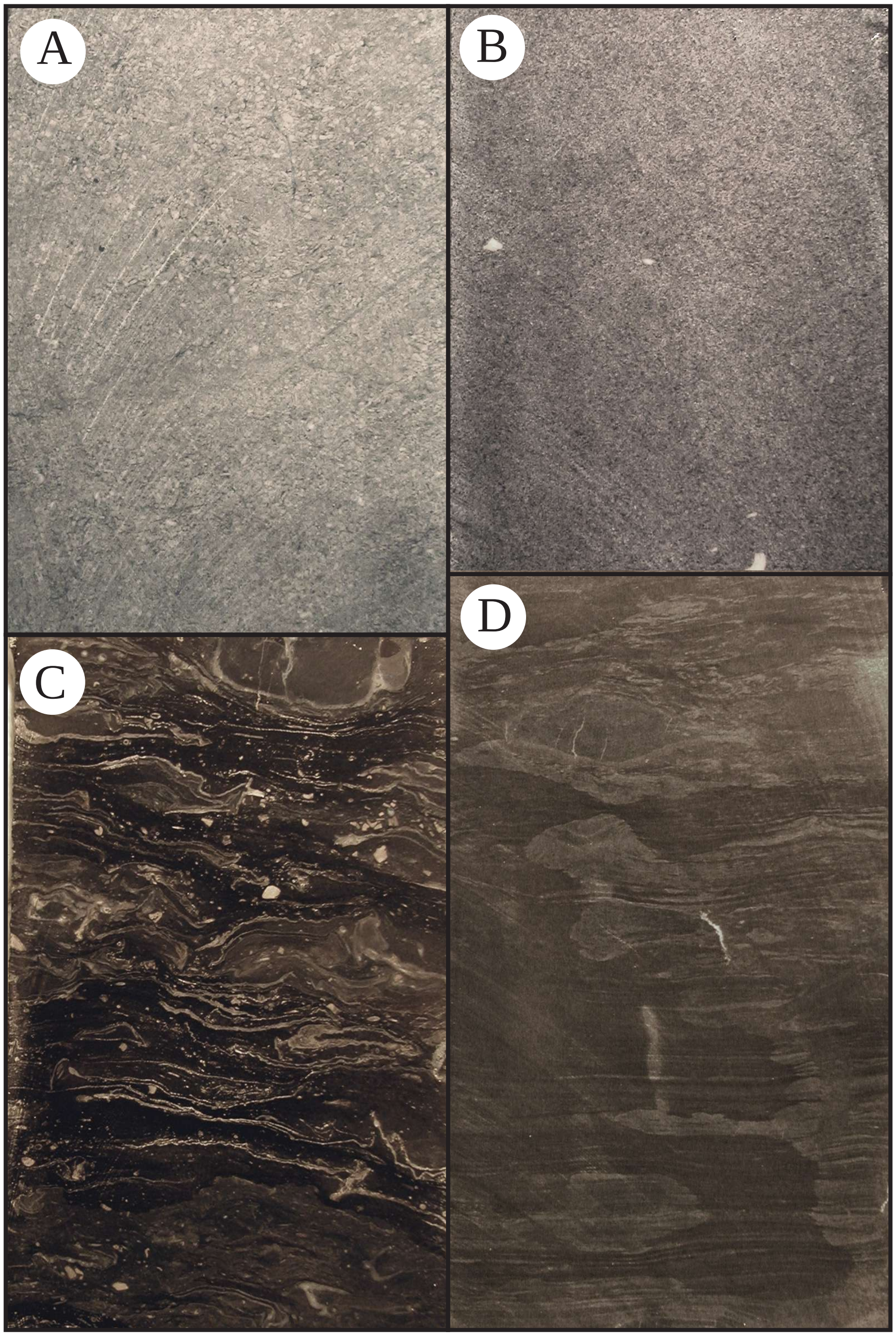


Figure 10. Slab photos of Mississippian carbonate facies succession in northern Permian Basin. Arco Burleson #1, Gaines County, Texas. A, B.. Light gray-brown, coarse grained, well sorted, crinoid grainstones of the basal Mississippian. Depths: 11562 ft (A); 11598 ft (B). C. Black skeletal wackestone containing thin-walled brachiopods and crinoid debris. Depth: 11087 ft. D. Dark-gray to black, laminated, mudstone. Depth: 11106 ft. All slabs 4.5 in wide.

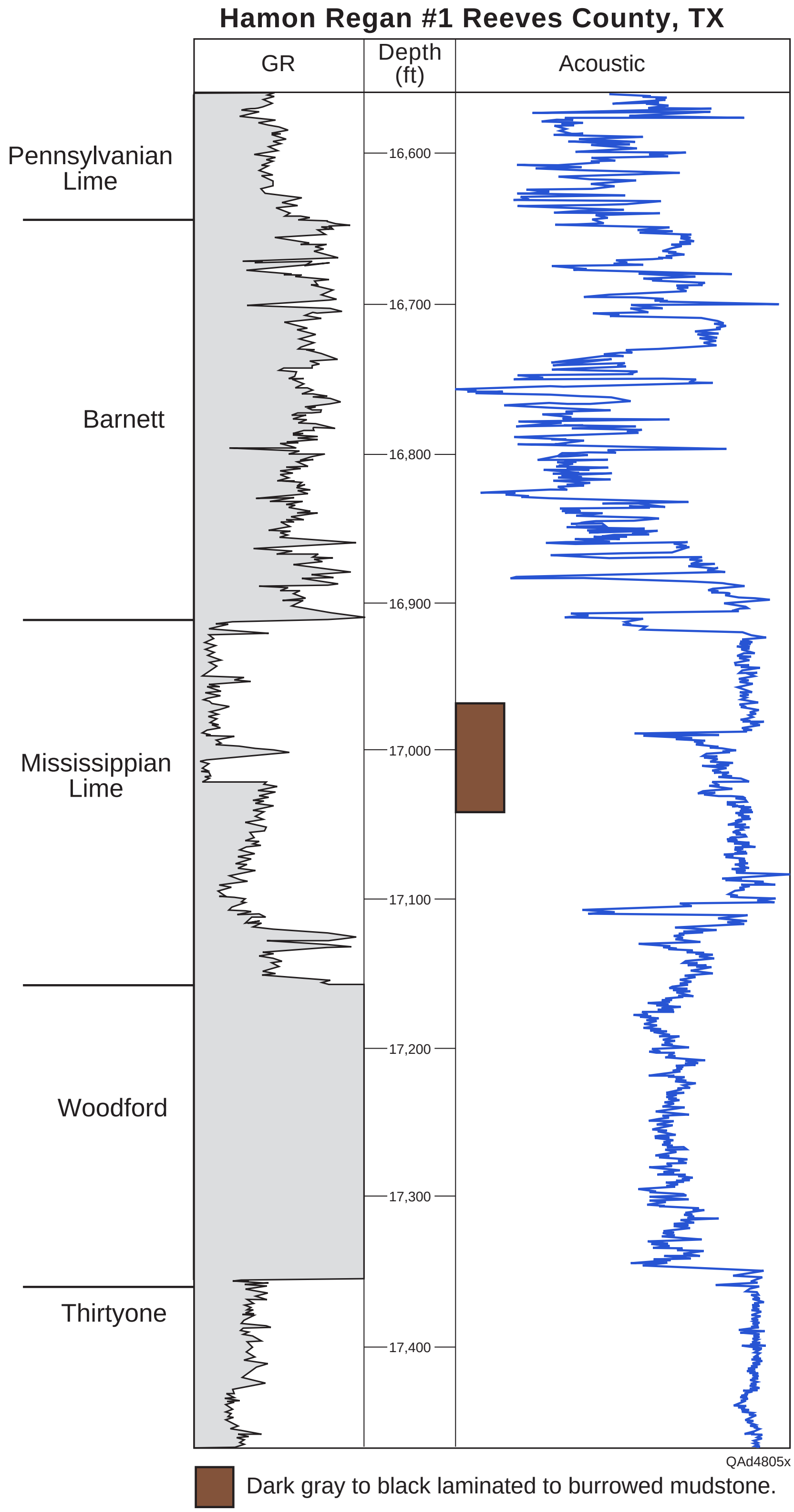


Figure 11. Typical wireline log signature from Mississippian cored well in the southern Permian Basin.

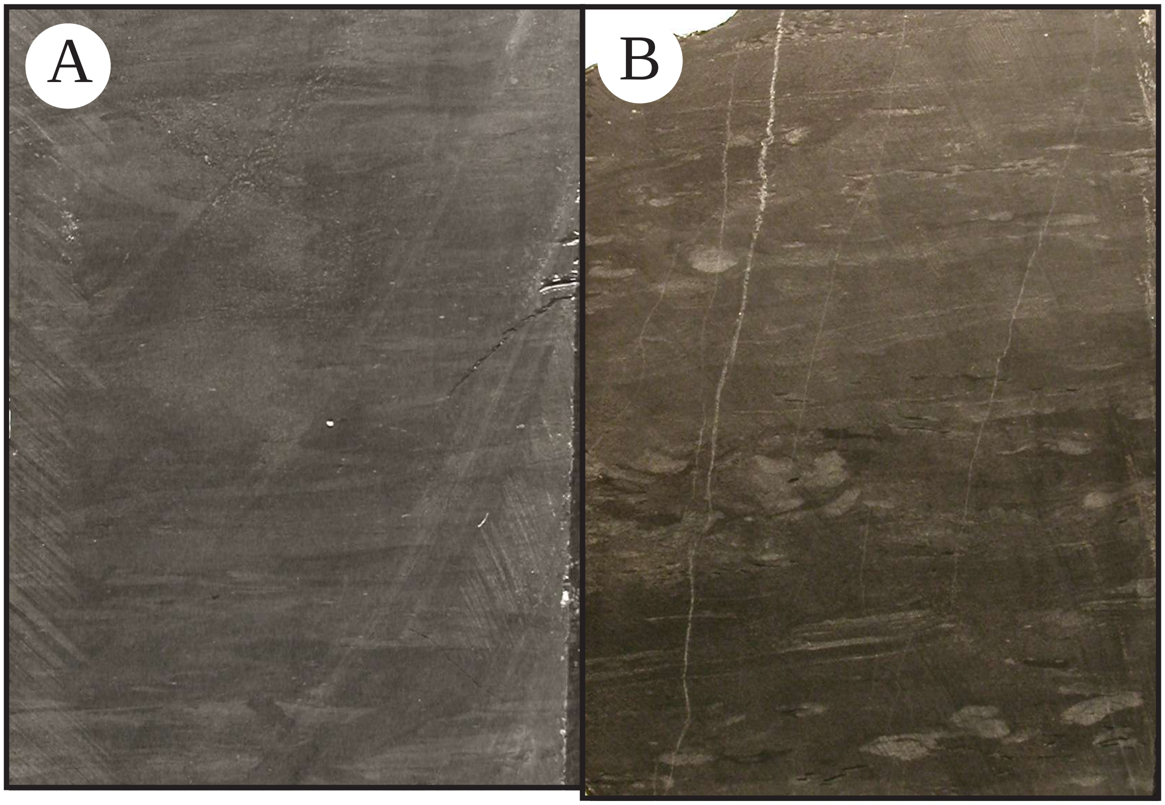


Figure 12. Slab photos of the basal Mississippian carbonate facies succession in the southern Permian Basin. Hamon Regan #1, Reeves County, Texas. A. Dark gray to black laminated to locally burrowed mudstone. Depth: 16982 ft. B. Dark gray to black burrowed mudstone. Depth: 17016 ft.

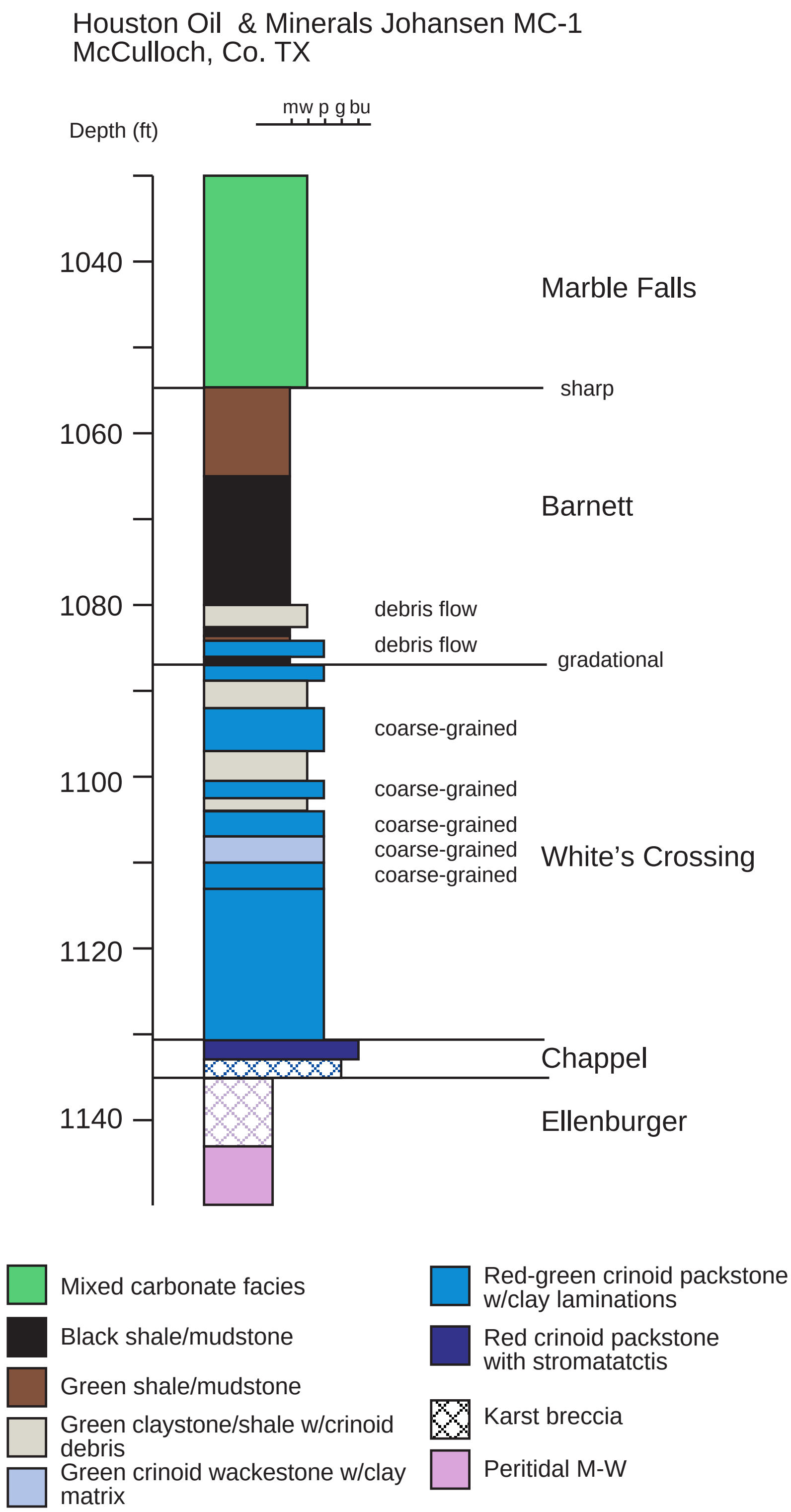


Figure 13. General facies character of Mississippian succession in the Llano Uplift area of central Texas.

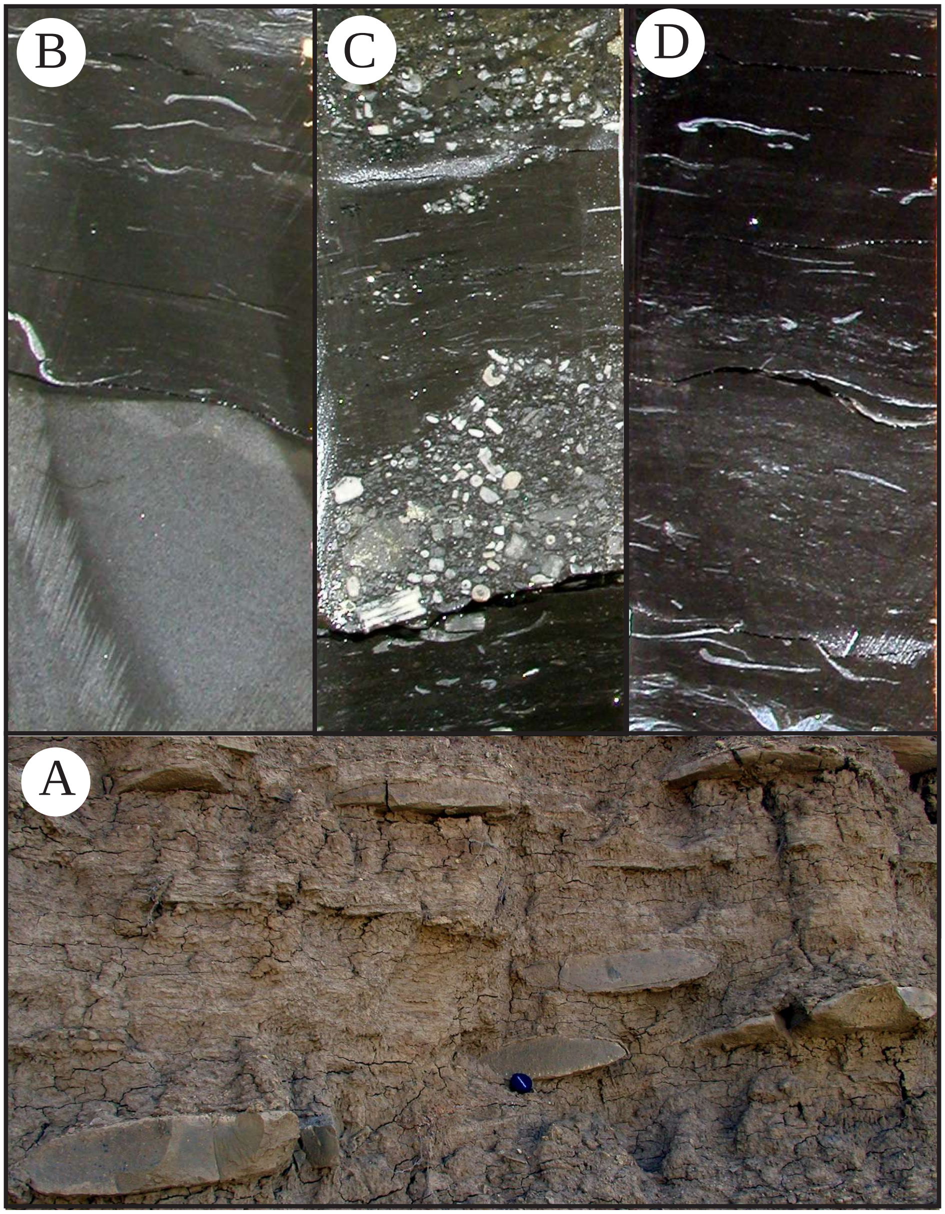


Figure 14. Slab photos of Mississippian Barnett facies succession in southwestern Ft. Worth Basin (Llano Uplift area). A. Outcrop photo showing carbonate concretion within the Barnett. Type section of Chappel Formation, San Saba County, Texas. Lens cap is 2 in diameter. B. Laminated mudstone with scattered thin-walled brachiopods overlying carbonate concretion. Depth: 1035 ft. C. Basal black mudstone with brachiopods documents in situ hemipelagic deposition, whereas overlying graded skeletal packstone to wackestone reflects debris flow. Depth: 1037 ft. D. Similar to C, showing hemipelagic sediments at bottom and top interrupted by debris flow bed. Depth: 1038 ft. B, C, and D from Houston Oil & Minerals Johanson MC-1, McCulloch County Texas.

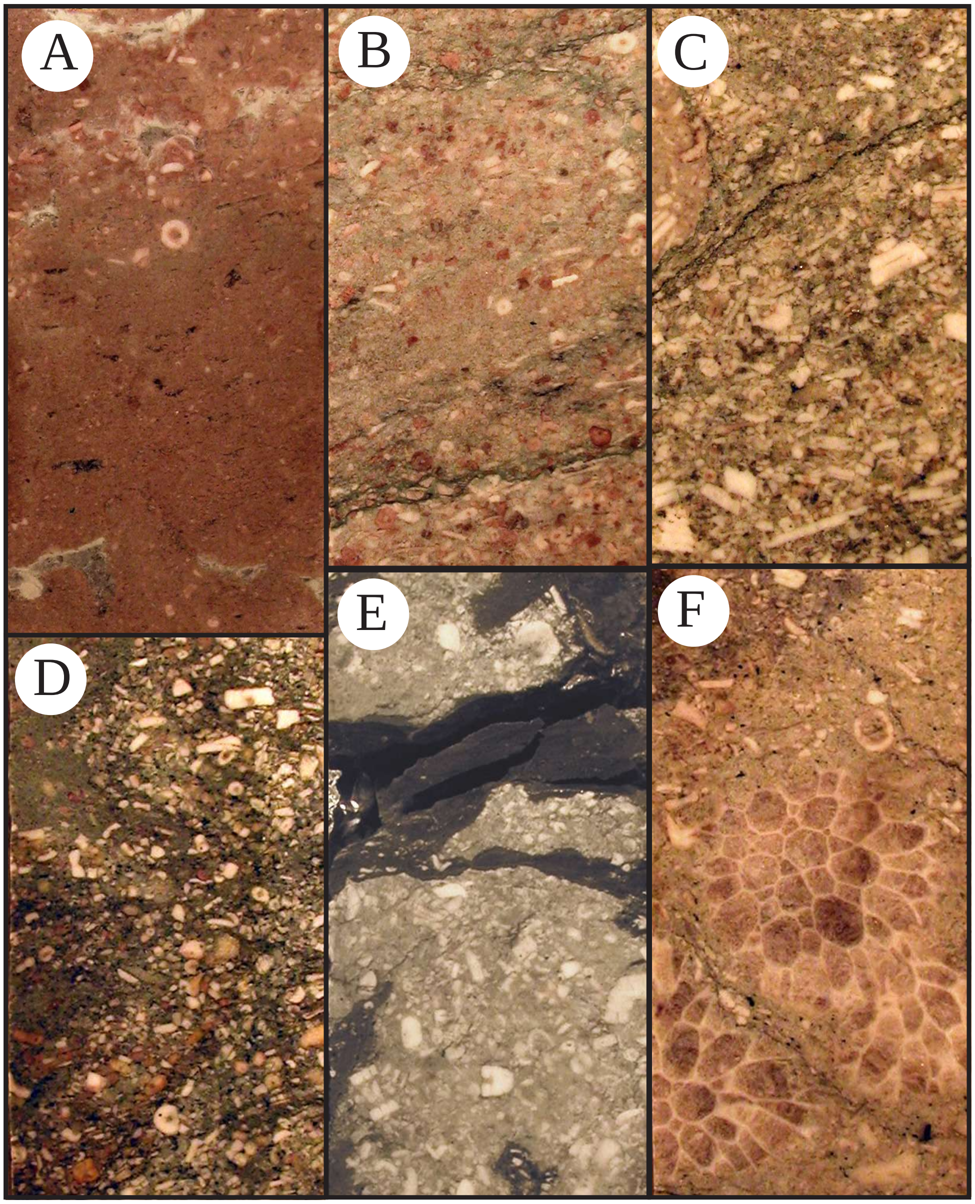


Figure 15. Slab photos of Mississippian Chappel facies succession in southwestern Ft. Worth Basin (Llano Uplift area) . Houston Oil & Minerals Johanson MC-1, McCulloch County Texas. A. Crinoidal packstone with stromatactis vugs. Basal Chappel. Depth: 1131 ft. B. Pink, poorly sorted crinoidal packstone. Depth: 1130 ft. C. Light brown, coarse-grained, poorly sorted crinoid packstone. Depth: 1110 ft. D. Brown, coarse-grained, poorly sorted crinoid packstone with green mud matrix. Depth: 1107 ft. E. Interbedded brown coarse-grained, poorly sorted crinoid packstone and black siliceous mudstone. Depth: 1098 ft. F. Coarse-grained, poorly sorted skeletal packstone. Note large corals. Depth: 1086 ft.

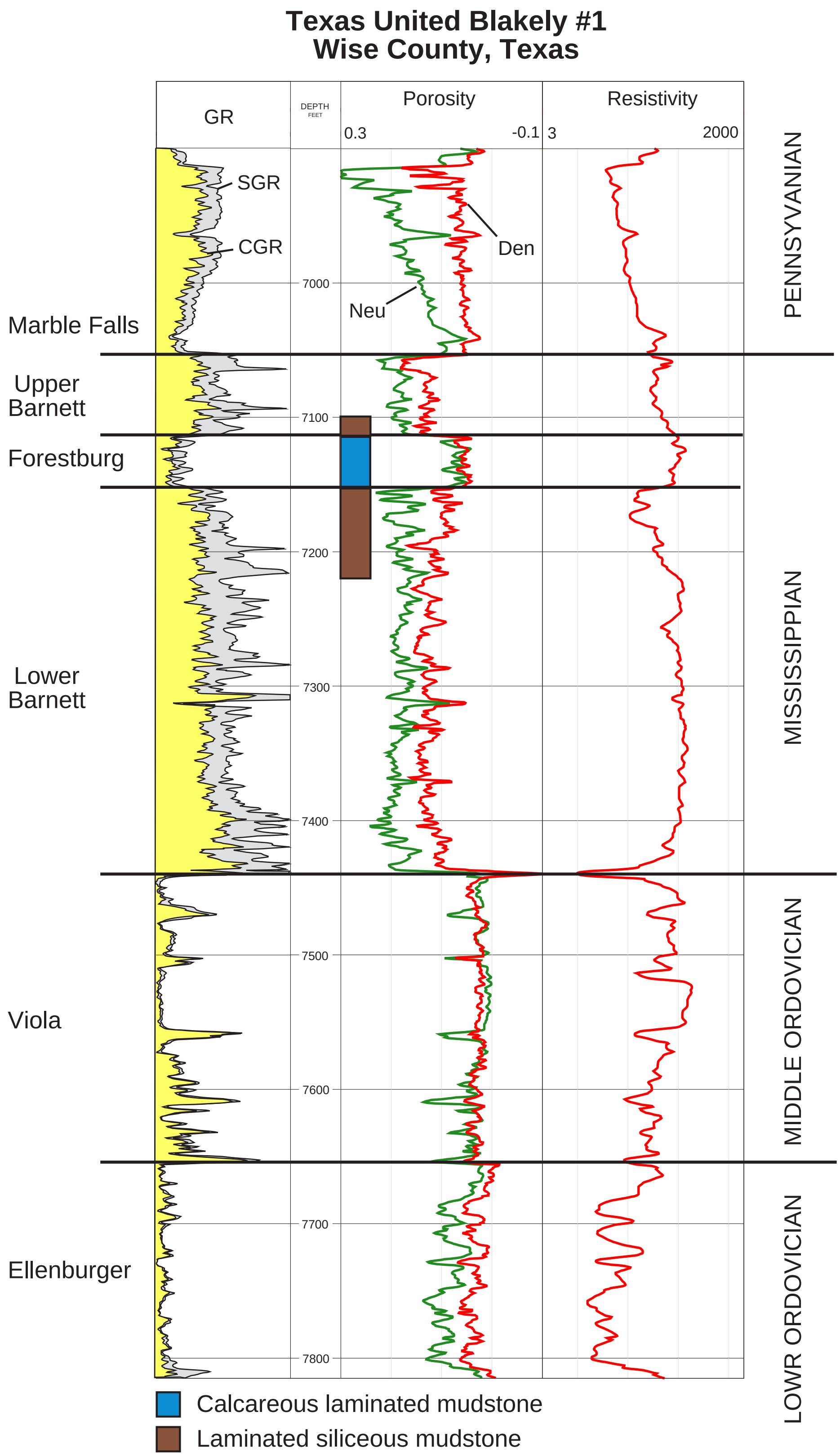


Figure 16. Typical wireline log signature of the Barnett Formation in the Ft. Worth Basin.

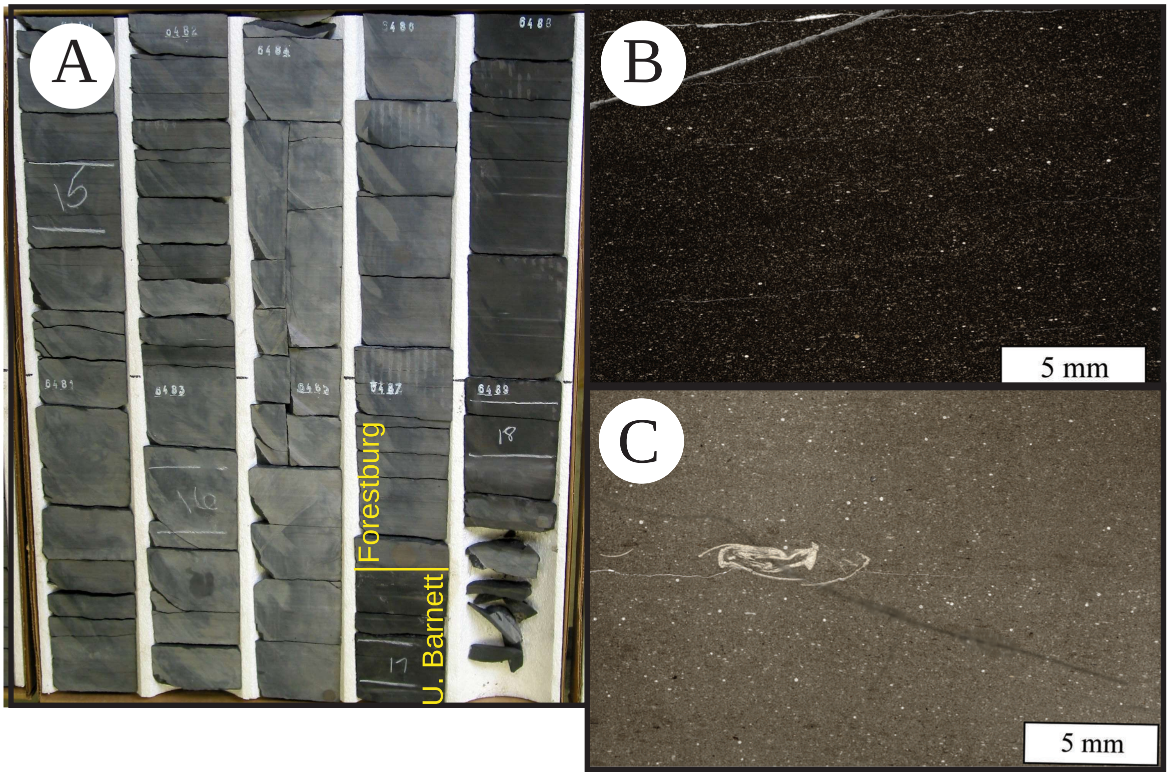


Figure 17. Photos of the Forestburg interval in central Ft. Worth Basin. A. Core slab section showing contrast in color between laminated mudstones of Forestburg and Barnett. Depth: 6480-90 ft. B. Photomicrograph of horizontally laminated mudstone with scattered silt grains. Depth: C. Photomicrograph showing graded bedding. Depth: Devon Adams SW # 7, Wise County, Texas. From Papazis (2005).

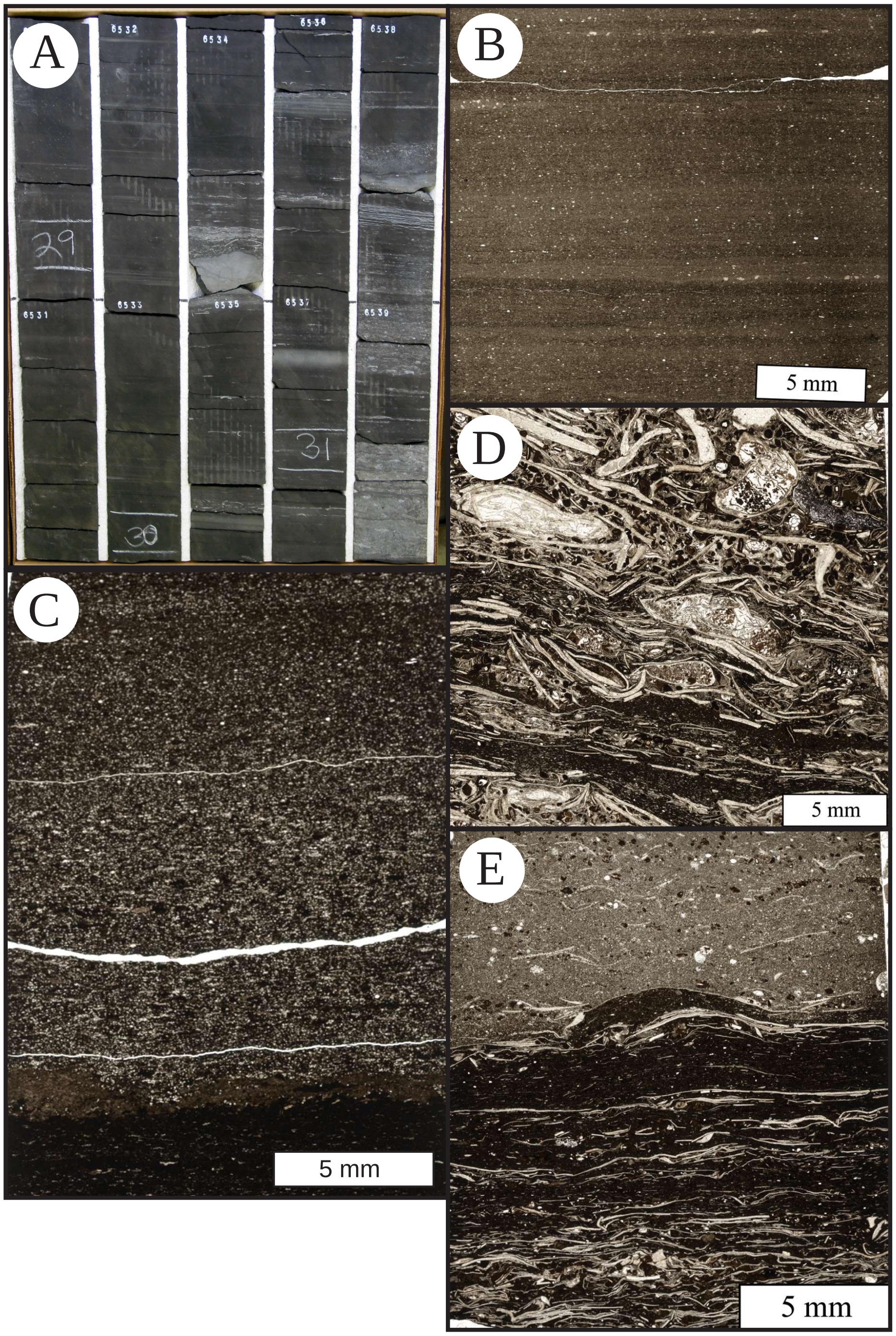
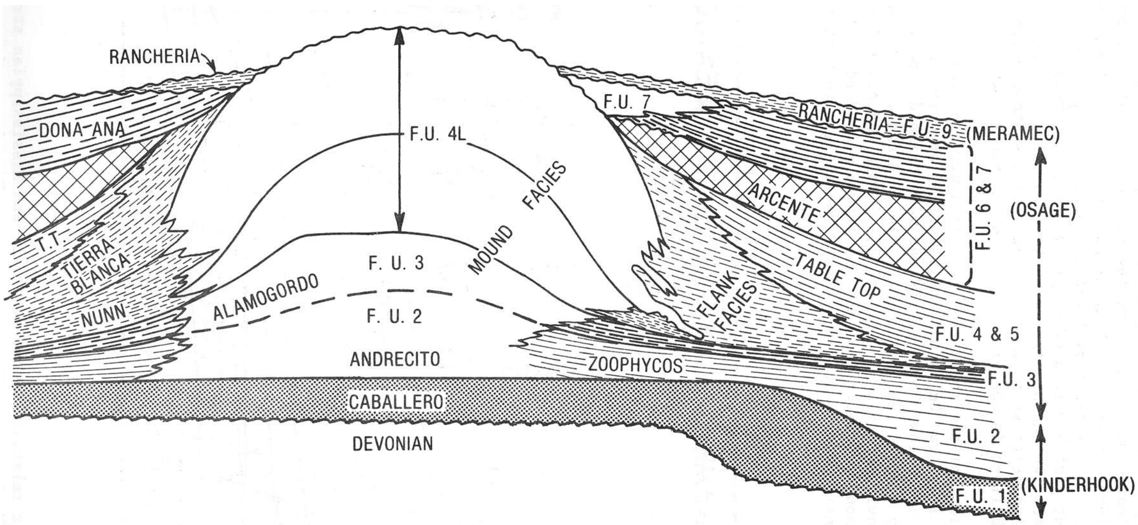


Figure 18. Photos of the Barnett Formation in central Ft. Worth Basin. A. Core slab section showing laminated mudstones and laminated skeletal wackestones of Barnett facies. Depth: 6530-40 ft. B. Photomicrograph of horizontally laminated mudstone with scattered silt grains. Depth: . C. Photomicrograph of graded bedding. Depth: . D. Photomicrograph of thin-walled deep water articulate brachiopods. Depth: . E. Skeletal wackestone (in situ deposit) overlain by skeletal calcisiltite (gravity flow deposit). Devon Adams SW # 7, Wise County, Texas. From Papazis (2005).

A.



B.

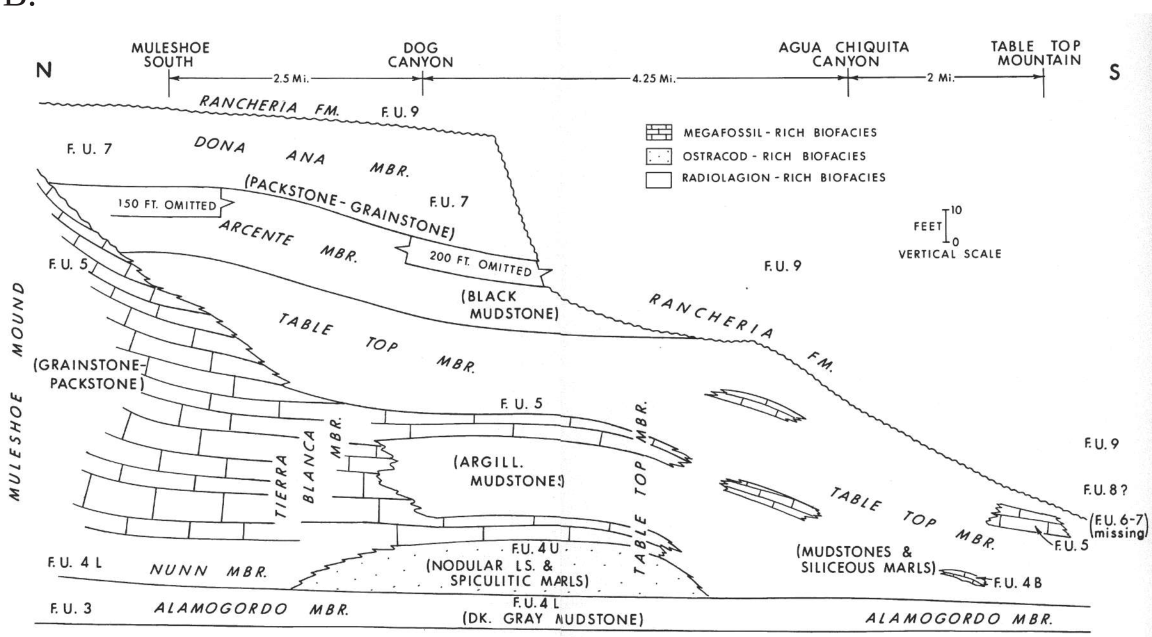
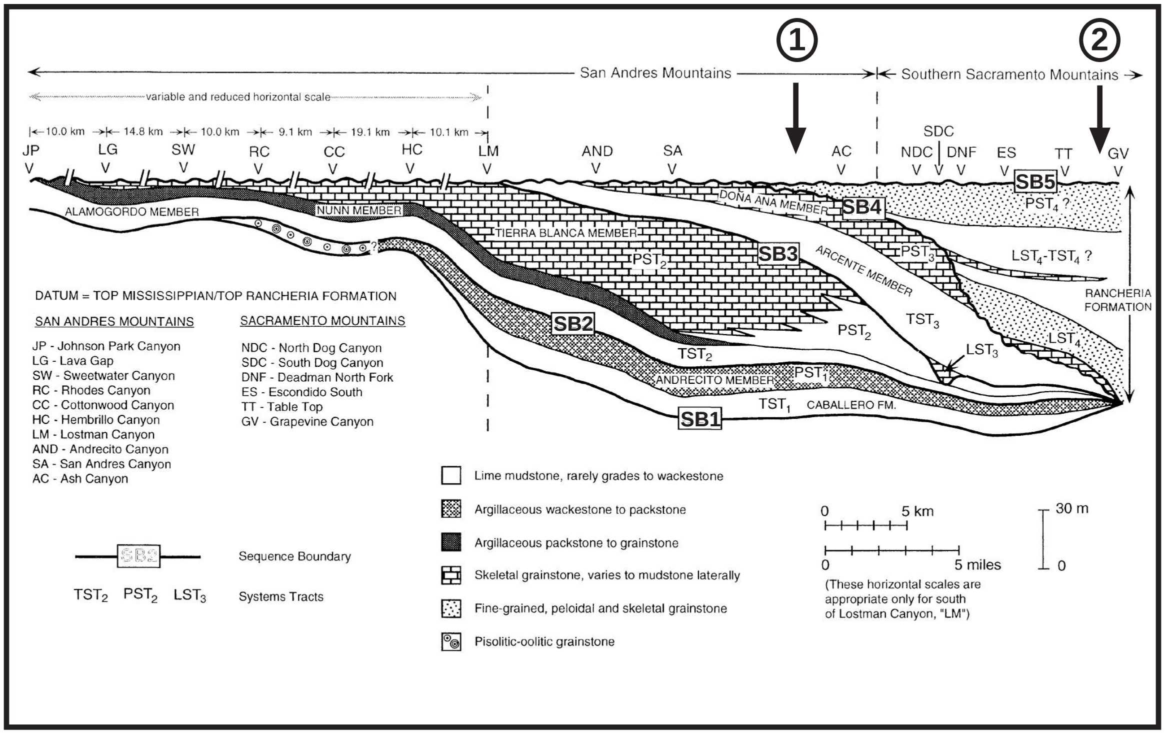


Figure 19. Stratigraphy of the Lake Valley Mississippian succession in southern New Mexico. A. Conceptual model of the architecture of the Lake Valley buildup outcrop succession. From Lane and Ormiston (1982). B. Stratigraphy and facies architecture showing downlapping Lake Valley and onlapping Rancheria. From Lane (1974).



From Bachtel and Dorobick (1998)

Figure 20. Sequence stratigraphy of the Mississippian outcrop succession in the San Andres and Sacramento Mountains of southern New Mexico. Circled numbers indicate probable depositional setting of key sections in the Permian and Ft. Worth Basins. 1. Gaines County, Texas. 2. Reeves County, Texas.

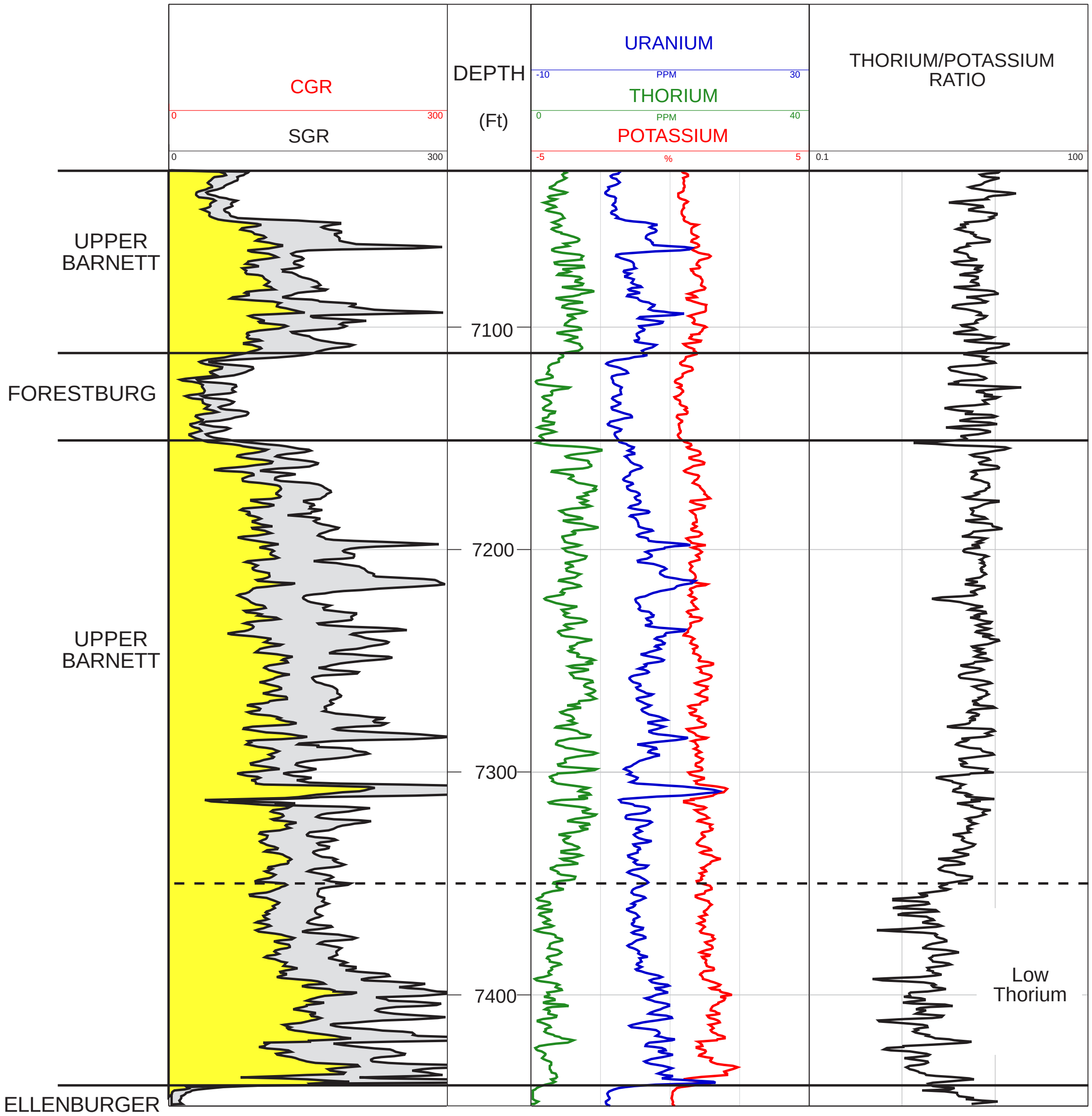


Figure 21. Spectral gamma ray log showing elemental composition of the Barnett Formation in the Texas United Blakely #1 well. Wise County, Texas. Note low thorium zone at base of lower Barnett section.

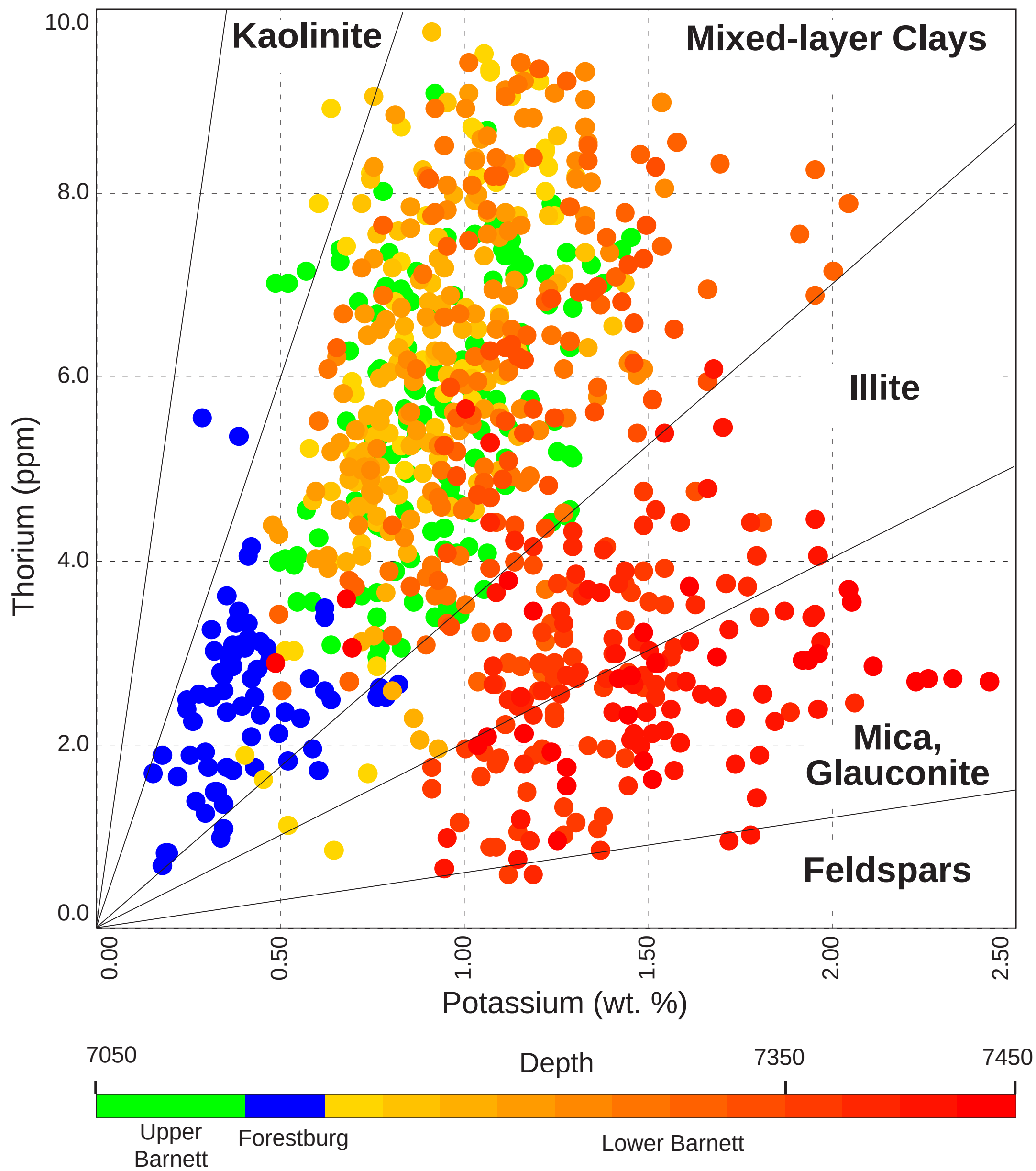


Figure 22. Crossplot of thorium and potassium content in showing systematic changes in apparent clay and feldspar composition with depth. Texas United Blakely #1, Wise County, Texas.

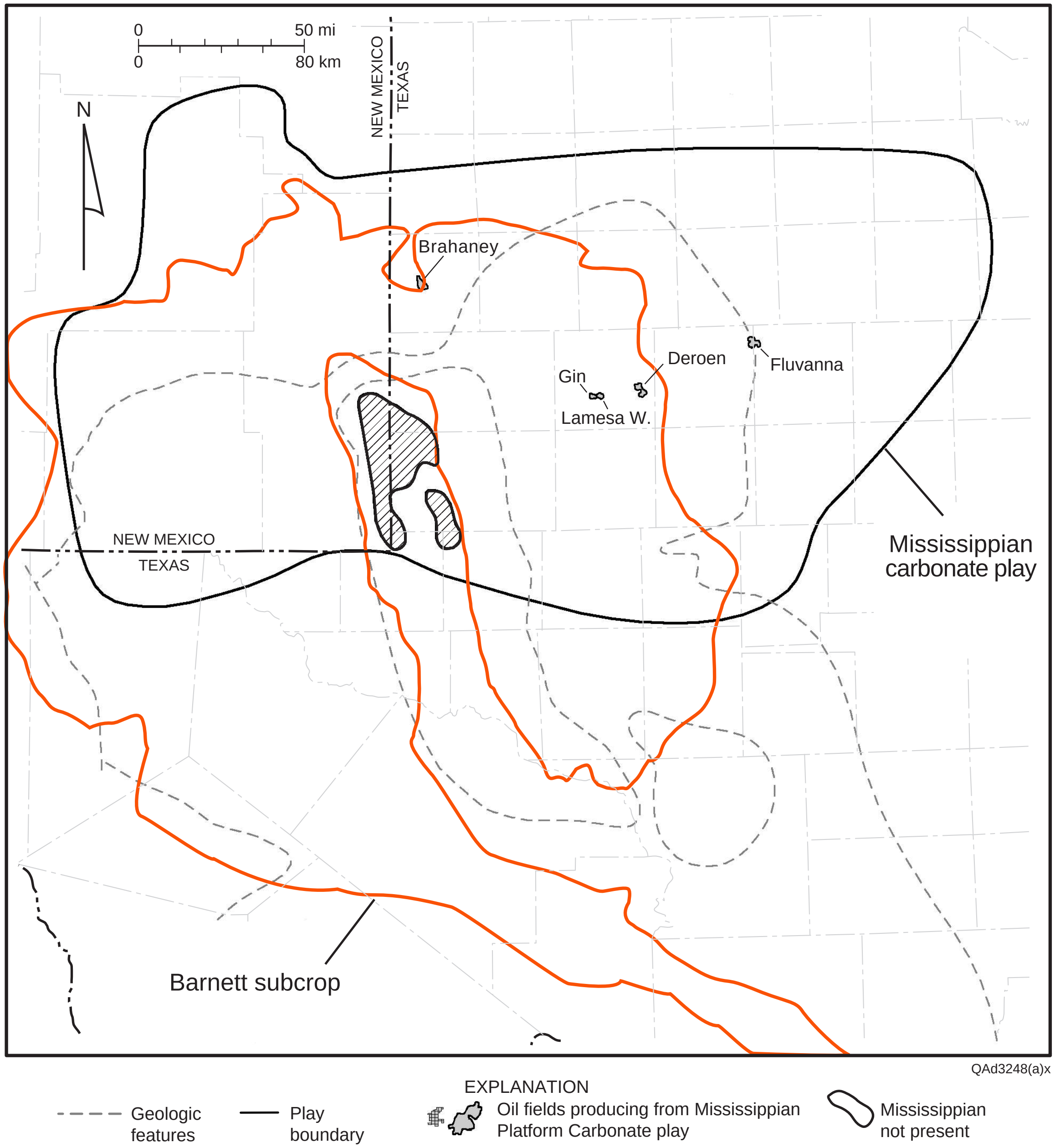


Figure 23. Map of Mississippian reservoir plays and major fields developed within the Mississippian carbonate play.