THE WRISTEN OF THE PERMIAN BASIN: EFFECT OF TECTONICS ON PATTERNS OF DEPOSITION, DIAGENESIS, AND RESERVOIR DEVELOPMENT IN THE LATE SILURIAN

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ABSTRACT

Rocks of the Upper Silurian Wristen Group display a range in facies and depositional style that contrasts markedly with the more homogeneous character of the underlying Middle to Lower Silurian Fusselman Formation. The Wristen contains distinct (1) shallow-water platform (Fasken Formation) and (2) deeper water, outer platform to slope carbonate facies (Frame and Wink Formations) that document crustal downwarping of the southern margin of the Laurentian paleocontinent during the Middle Silurian.

Deeper water facies of the Frame and Wink Formations dominate the more southerly areas of the Wristen subcrop in the Permian Basin and consist of nodular mudstones and wackestones (Wink) and carbonate debris flows and shales (Frame). Wristen platform facies are assigned to the Fasken Formation and include platform-margin carbonate buildup successions and a complex variety of middle to inner platform facies ranging from small carbonate buildup facies to skeletal wackestones and packstones to tidal-flat complexes.

Hydrocarbon reservoirs are restricted to the Fasken Formation; more than 1.2 billion barrels of oil has been produced. A large volume of oil (more than 1.8 billion barrels) remains as a target for improved characterization of reservoir facies and architecture. The models and data presented here provide an important basis for better understanding of this complex depositional system.

INTRODUCTION

The Silurian of the Permian Basin constitutes a thick section (as much as 2,000 ft) of carbonate platform, platform-margin, and slope rocks. Most of this section (locally as much as 1,800 ft) is assigned to the Upper Silurian Wristen Group (fig.1), from which more than 1.2 billion barrels of oil had been produced as of 2000 (Dutton and others, 2005). Despite the economic significance of this reservoir play, relatively little detailed information exists regarding its stratigraphy, lithology, and reservoir character. This report documents the depositional and diagenetic history of the Wristen on the basis of available data and describes the controls on reservoir development, distribution, and heterogeneity.

PREVIOUS WORK

Early stratigraphic studies of Silurian rocks in West Texas (Jones, 1953; Galley, 1958) generally subdivided the Silurian and Devonian section in the Permian Basin into three parts: a lower Fusselman Formation, an overlying, unnamed “Silurian/Devonian” (or “Siluro-Devonian”) carbonate section, and an uppermost Woodford Formation. Wilson and Majewske (1960) recognized some the distinctive differences between Silurian and Devonian depositional units, and McGlasson (1967) published a very accurate characterization of the basic architecture and character of these units. Hills and Hoenig (1979) formally named the component depositional units within the Siluro-Devonian. They assigned the term “Wristen” for the post-Fusselman/pre-Devonian part of the section. They further subdivided the interval locally into an upper Frame Member and a lower Wink Member. Ruppel and Holtz (1994) elevated the Wristen to group rank and the Frame and Wink to formation status. They also defined the Fasken Formation to represent the extensive oil-bearing succession of platform carbonates in the Wristen Group (fig. 1). Canfield (1985) presented an excellent analysis of the Frame and Wink facies. Barrick (1995) demonstrated, on the basis of conodont biostratigraphy, that the Wristen Group is dominantly Wenlockian to Pridolian (Late Silurian) (fig. 1). Ruppel and Holtz (1994) also provided detailed documentation on the extent and geological character of the Wristen, along with information on the reservoir attributes of producing Wristen fields in the Permian Basin.

REGIONAL SETTING

The Late Silurian (Wenlockian to Pridolian) was a period of significant global variability in terms of climate, sea level, and ocean chemistry. During the Late Ordovician and Early Silurian, icehouse conditions, caused by episodic advance and retreat of glacial ice in Gondwana (what is now Africa and South America), prevailed. This setting is well documented by numerous globally correlative unconformities in Early Silurian platform deposits (Caputo, 1998). Glaciation diminished during the Middle Silurian, and by the end of the period a greenhouse climate appears to have prevailed. Global paleogeographic reconstructions indicate that during the Silurian the U.S. Midcontinent was part of a broad, subtropical platform that occupied much of the western part of the Laurentian paleocontinent (fig. 2). In the Early Silurian, the area of the Permian Basin was bordered on the south by the Iapetus Ocean. Continuing collision between the Baltic and Laurentian plates along this margin during the Late Silurian resulted in closure of the Iapetus by the beginning of the Devonian. Deposits of the Wristen Group reflect the interplay between climatic, eustatic, and global tectonic drivers in the Permian Basin area during the Middle and Late Silurian.

In contrast to the underlying Late Ordovician to Early Silurian Fusselman Formation, which displays relatively widespread facies continuity indicating deposition on a regionally extensive, more-or-less flat platform, Wristen Group rocks display regional systematic variations in facies that document major tectonic downwarping and drowning of the platform in the Permian Basin area (Ruppel and Holtz, 1994; Ruppel and Hovorka, 1995). This downwarping of the distal part of the platform appears to have begun during the early Wenlockian (fig. 3B). Drowning is indicated by the shift from extensive shallow-water platform deposition reflected in the underlying Fusselman. A tectonic mechanism is implicated by the absence of evidence of a major world-wide eustatic rise event at this time (McKerrow, 1979; Johnson and others, 1998). Differential subsidence is documented by the rapid shift to outer platform and slope deposition in the southern part of the Permian Basin area while shallow-water platform conditions were maintained in the north. Successions in Oklahoma and the Illinois Basin show similar facies and subsidence patterns (Becker and Droste, 1978; Amsden and Barrick, 1988; Droste and Shaver, 1987). Further support for a tectonic subsidence event comes from a subsidence analysis of the Illinois Basin succession by Heidlauff and others (1986). Downwarping of the Fusselman platform in Texas, and equivalent successions in Oklahoma and the Illinois Basin, may have been a product of foreland deformation along the southern margin of the North American plate associated with plate convergence and the closing of the Iapetus Ocean. Walper (1977) suggested that convergence of the North American and South American/African plates began as early as the Late Ordovician.

Drowning of the southern part of the platform was associated with the deposition of deep-water ramp/outer platform sediments of the Wristen Group (Wink and Frame Formations). These rocks contrast with the shallow-water platform Wristen Group deposits (Fasken Formation) that accumulated in the northern part of the area (fig. 3C). Deeper water Wink and Frame deposits document a classic drowning succession with outer ramp nodular wackestones and mudstones of the Wink Formation being overlain by more distal, deeper water, carbonate mudstones and shales of the Frame Formation. The increasing abundance of skeletal debris, in many cases in the form of carbonate turbidites, upward and northward in the Frame section attests to the aggradation of the Fasken platform to the north and downslope transport of platform material southward into the basin. Despite the evidence of basinward transport of platform-derived carbonate detritus, however, facies geometries in the Fasken and Frame Formations indicate that relatively little progradation occurred during Middle to Late Silurian Wristen Group deposition. Platform-margin buildups in the Fasken, for example, exhibit predominantly aggradational geometries and are confined to a relatively narrow belt through central Andrews County (Ruppel and Holtz, 1994; Ruppel and Hovorka, 1995).

The Middle to Late Silurian was punctuated on the Wristen platform by episodic rise and fall of relative sea level similar to that which affected Fusselman deposition. This cyclicity is reflected in both repetitive, upward-shallowing facies stacking patterns, recording sea-level rise and selectively leached cycle tops, associated with sea-level fall. Although Middle to Late Silurian eustasy is presently poorly defined, evidence from the Wristen platform succession suggests a record similar to that observed in the Early Silurian (Ruppel and Holtz, 1994).

Sedimentologic and stratigraphic relationships between the Wristen Group and overlying Lower Devonian Thirtyone Formation suggest that a major rise in relative sea level or major change in ocean chemistry or circulation occurred in West Texas and New Mexico in Early Devonian time (Ruppel and Holtz, 1994). Relative rise is suggested by the distinctly deeper water character of basal Thirtyone Formation chert-rich deposits compared with immediately underlying Wristen Group carbonates rocks. This is especially apparent in central Andrews

County (Andrews South field, for example), where deeper water Thirtyone chert deposits overlie Fasken reef successions (F. J. Lucia, personal communication, 1992; Canter and others, 1992; D. Entzminger, personal communication, 2005). A similar relationship is observed farther basinward where basal Thirtyone shales, and carbonate-chert mudstones of pelagic origin, sharply overlie more proximal deep-water deposits of the Frame Formation. The causes of this relative rise in sea level are uncertain. Evidence of global sea-level rise at this time is equivocal (cf., Vail and others, 1977; McKerrow, 1979). It seems more likely that deepening at the Silurian-Devonian boundary in West Texas may be in part related to a second pulse of foreland deformation associated with the continued convergence of the Laurentian and Gondwanan plates and the closure of the Iapetus Ocean.

FACIES AND SEDIMENTOLOGY OF THE WRISTEN GROUP

The Wristen Formation was designated by Hills and Hoenig (1979) for Silurian rocks overlying the Fusselman and underlying Devonian rocks assigned to the Thirtyone Formation (fig. 1). Hills and Hoenig (1979) divided the formation into a basal Wink Member, an overlying Frame Member, and an unnamed “carbonate facies” (which is laterally equivalent to the Wink and Frame). Because of the importance of the unnamed carbonate unit in terms of its thickness and importance as a major hydrocarbon-producing reservoir interval, Ruppel and Holtz (1994) assigned the name Fasken Formation to this unit. They also elevated the Wink and Frame Members to formation status and the Wristen to group status (fig. 1).

Studies of the Fusselman Formation suggest that the contact between the Wristen Group and the underlying Fusselman Formation is unconformable. Preliminary studies of the conodont faunas across this boundary (Barrick, 1995) indicate, however, that the unconformity does not represent a major hiatus. This conclusion is supported by regional data that suggest a short-duration exposure event (Amsden and Barrick, 1988).

The Wristen is overlain by the Lower Devonian Thirtyone Formation, except where the latter has been removed by erosion. This contact is commonly sharp, but it is unclear whether it represents a hiatus. Recent biostratigraphic studies have in fact shown that the top of the Frame Formation is Early Devonian in age (Barrick, 1995). This age assignment implies that the Fasken (the apparent updip equivalent of the Frame) is also of Early Devonian age at its top. Although some authors have suggested a major sea-level fall the end of the Silurian from world-wide data (for example, Vail and others, 1977; Johnson and others, 1998), data from the Frame appear to contradict this notion. There is abundant evidence of karsting within the Fasken, but these features are usually developed where the Thirtyone has been removed. So it seems more likely that karsting of the Fasken is a younger event (perhaps Middle Devonian).

The Wristen subcrop margins are controlled by postdepositional erosion on the west (Baldonado and Broadhead, 2002), north, and probably east. Wristen rocks are thickest in western Gaines and Andrews Counties, Texas, and southeastern Lea County, New Mexico. According to Canter and others (1992) the Wristen reaches a maximum thickness of more than 1,500 ft in southeastern Lea County, New Mexico (fig. 4).

Wink Formation

Distribution and Age

The Wink Formation overlies the Fusselman across most of the southern half of the Silurian subcrop area (fig. 5). The Wink is relatively easily definable using gamma-ray wireline logs in this area where it and the Frame Formation underlie the Thirtyone Formation (Hills and Hoenig, 1979). Northward in central Andrews County, the Wink is difficult to distinguish from the Fasken Formation (fig. 5). In the mapped area (fig. 6) the Wink ranges from less than 50 ft in the southeastern part of the area to about 300 ft in the north where it grades into the Fasken.

On the basis of conodonts, Barrick (1995) showed that the Wink is Early Upper Silurian (Wenlockian) in age and equivalent to the Clarita Formation in Oklahoma (Amsden, 1980).

Facies

Hills and Hoenig (1979) defined the Wink as a gray limestone. Examination of cores indicates that these rocks are characteristically nodular-bedded, gray, lime wackestones and mudstones (fig. 7; Ruppel and Holtz, 1994). Thin-walled brachiopods and ostracodes are locally common, but other skeletal allochems are rare. The Wink contains small volumes of terrigenous clay and silt, which, as is apparent on gamma-ray logs (fig. 8), generally increase upsection as it grades into the siltier and more argillaceous Frame Formation. Canfield (1985) divided the Wink into a lower limestone section composed of skeletal packstones and wackestones and an upper dolostone unit dominated by silt-bearing wackestones.

Depositional Setting

Nodular wackestones and mudstones of the Wink Formation (fig. 7) represent deposition in outer platform, probably below-wave-base, conditions. These deposits document the beginning of drowning of the extensive shallow-water Fusselman platform during the Middle Silurian. As discussed earlier, this drowning was associated with the formation of a well-developed, platform-to-basin topography whose geometry controlled deposition for much of the remainder of the Silurian and the Early Devonian (Ruppel and Holtz, 1994).

Subsurface Recognition and Correlation

In cores, the Wink is usually readily distinguishable from the underlying Fusselman by its darker colored, more mud-rich, commonly nodular character and its sparser faunal content. The lighter colored Fusselman typically contains abundant pelmatozoan ossicles and much more grain-rich texture. The contact between the Wink and the Fusselman is also relatively easily defined on wireline logs. In most areas, the base of the Wink consists of a shaly mudstone whose high gamma-ray character makes recognition and correlation of this contact straightforward (fig. 8). The upper contact of the formation is more problematic. The upward-deepening nature of the Wink is marked on logs by a gradual upward increase in gamma-ray log response, reflecting an increase in mud-donated facies and shale. The base of the overlying Frame is typically placed at the first occurrence of high-gamma-ray shales and mudstones (fig. 8).

Frame Formation

Distribution and Age

The Frame Formation (in part, the "Silurian shale" of some earlier workers) overlies the Wink and exhibits essentially the same distribution pattern as the latter (fig. 9). The unit can be recognized as far north as central Andrews County, where it grades into the Fasken Formation (fig. 5). It reaches maximum thicknesses of about 700 to 800 ft in this area (fig. 9). Like the Wink, the Frame is thinnest in the southeast.

Graptolite data (Decker, 1952) suggest that the Frame is probably equivalent to the Henryhouse Formation (Hunton Group) in Oklahoma and the Texas Panhandle (Amsden, 1980).

As mentioned, new conodont data (Barrick, 1995) show that the Frame ranges in age from Late Silurian to Early Devonian (Ludlovian-Lochkovian) (fig. 1).

Facies

According to Hills and Hoenig (1979) the Frame is largely shale in the type area in Pecos County. In much of the subcrop area, however, the unit consists of greenish-brown, argillaceous lime mudstone and wackestone (fig. 10d); fragments of pelmatozoans and pentamerid brachiopods are locally common, along with ostracodes and trilobites (Ruppel and Holtz, 1994). Also common, are rocks containing interlaminated mudstone and skeletal packstone-grainstone; some grain-rich intervals display normal graded bedding (fig. 10a,b). Less common are breccias and conglomerates but locally present (fig. 10d).

Depositional Setting

The muddy texture and general scarcity of skeletal remains in Frame Formation rocks indicate that they were formed in deep water, below wave-base conditions, probably representative of a slope or basinal setting. Beds of graded and laminated skeletal debris represent gravity flows of shallow-water skeletal sands derived from the Fasken shallow-water carbonate platform to the north (Ruppel and Holtz, 1994). Mapping of shale/carbonate fractions in the Wristen (McGlasson, 1967; Hills and Hoenig, 1979) suggests that the deepest part of the basin during Frame deposition probably lay along a north-trending axis through Pecos County, where predominantly shales accumulated. Areas surrounding this central basin received sand- to silt-sized carbonate detritus derived from surrounding areas of carbonate platform development.

Subsurface Recognition and Correlation

The Frame is distinctly different from either the underlying Wink or the updip Fasken. Because of the presence of clay-rich mudstones and shales, the Frame exhibits a high but variable gamma-ray response in most distal settings (fig. 8). In more proximal areas near the Fasken platform, the Frame contains platform-derived debris and interbedded shallower water deposits. Even in these settings the Frame tends to be distinguished from the overlying Fasken or Devonian Thirtyone Formations by its relatively higher gamma-ray response (fig. 5).

Fasken Formation

In their original definition of the Wristen Formation, Hills and Hoenig (1979) referred to the thick, predominantly carbonate unit that constitutes the post-Fusselman Silurian in the northern part of West Texas and New Mexico as simply the “carbonate facies” of the Wristen Formation. Recognizing the importance of this unit, which contains all of the known hydrocarbon resources in the Wristen, Ruppel and Holtz (1994) named this unit the Fasken Formation. They designated three co-type sections for the Fasken in wells in Andrews County, Texas. All of these wells have long cored intervals and comprehensive suites of wireline logs that illustrate some of the significant lithologic diversity that characterizes this rock unit.

Distribution and Age

The Fasken, as defined by Ruppel and Holtz (1994), consists of most of what has historically been referred to as the Siluro-Devonian carbonate section in the Permian Basin. The Fasken is typically underlain by the Frame Formation but also represents the northern, updip, shallow-water platform facies equivalent of the Frame Formation (fig. 5). The gradational lateral contact between the two units runs generally east-west through central Andrews County, Texas (fig. 4). Ruppel and Holtz (1994) showed that the Wink undergoes similar facies change to the north and may also be best considered in part a deeper water facies equivalent of the Fasken (fig. 5).

Where separable from the underlying Fusselman, the Fasken exhibits an east-to-west thickening trend. The unit reaches thicknesses of more than 1,500 ft in extreme western Andrews County and eastern Lea County, New Mexico (Canter and others, 1992; Ruppel and Holtz, 1994) and thins to less than 200 ft in Dawson County. Thickening trends are clearly defined by the total Fasken isopach map (fig. 11). Throughout most of the region, the Fasken is overlain by the Woodford Formation. Locally, where the Woodford has been removed by late Paleozoic erosion, the Fasken is overlain by Pennsylvanian/Permian clastics and carbonates.

The age of the Fasken Formation is imprecisely known. Recent conodont studies have shown that the Wristen Group ranges from Middle Silurian (Wenlockian) to Early Devonian (Barrick, 1995). This is consistent with previous interpretations that the Fasken (“Siluro-Devonian” of many earlier workers) contains a Middle Silurian–age (Niagaran) fauna. Part of the shallow-water platform succession that is assigned to the Fasken in this report has also yielded Lower and Middle Devonian fossils (Wilson and Majewske, 1960). These isolated occurrences apparently document outliers or remnants of the eroded Thirtyone Formation carbonate platform facies. The shallow-water platform Fasken succession is probably represented in part by the Henryhouse Formation in Oklahoma. Although much of the Henryhouse is interpreted as deeper water (Barrick, 1995), the shallower water *Kirkidium* facies of the Henryhouse contains facies very similar to those of the Fasken, as does the Bois D'Arc Formation (a facies of the overlying dominantly deep-water Haragan Formation) A strikingly similar succession of Late Silurian–age (Ludlovian to Pridolian) platform and platform-margin carbonates also exists in the Illinois Basin (Becker and Droste, 1978; Droste and Shaver, 1982, 1987).

Facies

The Fasken Formation comprises a highly diverse assemblage of carbonate lithofacies. The unit can be subdivided into two general facies complexes: (1) platform-margin skeletal wackestones to grainstones and boundstones and (2) interior platform mudstones to pellet and skeletal wackestones to grainstones (Ruppel and Holtz, 1994).

A typical outer platform and platform-margin succession is illustrated in the type section for the Fasken Formation near the Hutex field area in southeastern Andrews County (fig. 12). The base of the cored interval in this well contains dark-colored skeletal wackestones that contain poorly sorted skeletal debris including stromatoporoids, corals, and pelmatozoans (fig. 13). These rocks pass upward into a section of wackestones that contain more abundant and larger fragments of stromatoporoids and corals (including *Halysites*). Stromatoporoids comprise both broken hemispherical forms that display all orientations and thin, laminate stromatoporoids in growth position (fig. 13a,b,c). Overlying these rocks are pelmatozoan/stromatoporoid packstones (fig. 13d). Pelmatozoan debris is well sorted, but stromatoporoids are variable in size throughout the unit. Locally, these deposits are interbedded with beds and lenses of ooid grainstone. These rocks are succeeded by a thin interval of relatively well sorted coral/bryozoan rudstone that exhibits considerable interparticle porosity (fig. 14a). The Fasken is capped in this section by coral framestone composed of small stick corals, bryozoans, and relatively uncommon stromatoporoids. These deposits contain geopetal cavities filled with sediment and, less commonly, cement (fig. 14c,d). Locally, these buildups are capped by ooid grainstone. Fasken platform-margin buildups in Texas and New Mexico are similar to well-described outcropping Silurian buildups in the Illinois Basin in terms of both facies patterns and fauna (Lowenstam, 1948, 1950; Ingels, 1963; Wilson, 1975).

Across most of the Wristen platform, especially in the northern part of the area (Gaines County and northward), major buildup successions are less common (Ruppel and Holtz, 1994). In these areas, Fasken facies comprise diverse assemblages of shallow-water platform carbonate facies. The upper Fasken is typically composed of upward-shallowing, shallow subtidal to tidal-flat cycles (fig. 15). The basal subtidal facies in these cycles, which average 15 to 20 ft in thickness, are composed of skeletal wackestones containing stromatoporoids, corals, mollusks, and brachiopods (fig. 16a). Tidal-flat caps are laminated and mud rich and locally contain fenestral pores (fig. 16b). The lower Fasken contains a series of boundstone-capped cycles composed generally of more mud-dominated rocks at the base and increasingly grain-dominated deposits upward (fig. 17). Capping boundstones in these 30- to 35-ft-thick cycles are thin and, in some instances, are overlain by silt/clay-filled karst solution pit deposits. In a second core succession, less than 1 mi away, the facies are strikingly different. Here the Fasken is composed of a cyclic succession of upward-shallowing, subtidal to tidal-flat carbonates (fig. 17). Cycles show evidence of early dolomitization and porosity retention much like those of the Permian Clear Fork, San Andres, and Grayburg platform successions. Some of these cycles, which are more variable in thickness than boundstone-capped cycles, exhibit karst/solution profiles in their upper parts that contain collapse breccia and infilling, green mudstone/siltstone. Porosity is typically highest below karsted tidal-flat caps and generally decreases downsection (Ruppel and Holtz, 1994).

Depositional Setting

Fasken facies successions are typical of those found on shallow-water carbonate platforms. The margins of the Middle to Late Silurian Wristen platform are well defined by the change from platform facies of the Fasken to outer platform to slope, clay-rich facies of the Frame and Wink (figs. 3, 18). North and west of this margin, the outer part of the platform is marked by the presence of organic reef complexes (fig. 12). Because of the limited availability of cores through these complexes, understanding of their paleoenvironmental setting and facies geometries is greatly facilitated by comparisons with the well-exposed, outcropping Silurian reefs of the Illinois Basin of Indiana and Illinois (Lowenstam, 1948, 1950; Ingels, 1963).

Like their Illinois Basin counterparts, Fasken Formation buildup deposits (e.g., fig. 12) typically overlie basal mudstones and sparse wackestones (Ruppel and Holtz, 1994). These mud-rich rocks are gradational to proximal Frame Formation deposits in facies and depositional setting and accumulated in a below-wave-base setting on the outer ramp. Overlying silt-sized skeletal packstones and wackestones represent the first indication of reef-influenced sedimentation. Thin, delicate, laminar stromatoporoids also indicate accumulation below fair-weather wave base (fig. 13b,c). Blocks and clasts of hemispherical stromatoporoids and corals common in these rocks document erosion and downslope transport from adjacent, shallow-water portions of the buildup complex, presumably due to storm activity (fig. 13b,d). Such debris beds are relatively uncommon in Illinois Basin buildups (Wilson, 1975). Pelmatozoan grainstones and packstones in Fasken buildup complexes (fig. 13d) represent skeletal debris derived from reef-top dwelling organisms. Such flanking encrinites are ubiquitous in Silurian, as well as other Paleozoic, buildup successions (Wilson, 1975). These encrinites, which may account for more than half of each buildup, can accumulate either above or slightly below wave base. Coral/bryozoan rudstones encountered in the upper parts of many Fasken buildup successions (fig. 14a) represent reef rubble produced by active erosion of the upper proximal reaches of the reef complex and deposited in relatively shallow water. Similar rubble beds have been documented at the tops of other Silurian buildups (Lowenstam, 1948). Coral framestone, which forms the top of some successions (fig. 14c), represents growth of the reef into wave base and the development of extensive and diverse reef faunas. Subsequent vertical growth of these buildups produces shoaling and lateral and basinward progradation of the reef complex (Wilson, 1975). Ooid grainstones encountered at the tops of some sections document aggradation, shoaling, and the end of buildup growth. By analogy with well-studied structures in Indiana and Illinois, depositional relief on Fasken platform-margin buildups may have reached as much as 130 to 220 ft (Wilson, 1975). On the basis of data from Silurian outcrops in the Illinois Basin, Ingels (1963) developed a model of buildup architecture that may be representative of platform-margin buildups in the Fasken. As this model shows (fig. 19A), the buildup complex is dominated by flanking debris; core boundstones are volumetrically minor. These features and the general dimensions of this model seem to fit well with the known data on Fasken platform-margin successions like those in the Magutex and Hutex field areas (fig. 12).

Buildups are also common in the Wristen inner platform. However, these features are smaller in terms of both vertical relief and lateral dimensions (Ruppel and Holtz, 1994). Like smaller, inner platform buildups in the Illinois Basin (fig. 19B), Fasken shallow-platform buildups rarely contain framestone but are more typically dominated by skeletal wackestone. These rocks reflect lower energy deposition on the inner platform and suggest that platform-margin buildups acted as a partial baffle to wave energy. It should be emphasized, however, that there is no indication that any continuous shelf-margin rim was developed along the platform margin. Tidal-flat successions are locally developed across the platform probably associated with local paleotopographic highs. Sedimentation in the inner platform was in part controlled by episodic rise and fall of relative sea level. This is apparent from patterns of facies stacking and diagenesis (see below) in both tidal-flat and shallow-water subtidal sequences and somewhat deeper water, more grain-rich, buildup-associated sequences developed on the outer parts of the platform (figs. 15 and 17).

Diagenesis

The most apparent products of diagenetic alteration of the Fasken Formation are (1) dolomite and (2) karst-related, solution features. Examination of these features in the Fasken suggests that these two products are process related.

Previously published maps displaying the distribution of limestone versus dolostone in the Fasken Formation suggest the section is entirely dolostone (McGlasson, 1967, his fig. 8; Wright, 1979, his fig. 10). This interpretation is misleading, for although dolostone is present throughout most of the Fasken, limestone is also present in many sections (for example, figs. 12, 15, and 17). Because virtually all of the hydrocarbon production from the Fasken comes from dolomitized intervals, an appreciation of the distribution and origins of dolomite in these rocks is critical. Both matrix-replacive dolomite and pore-filling dolomite cement are common. Much of the dolomite is associated with hiatuses caused by relative-sea-level lowstand. Dolostone is most abundant below cycle tops, especially those that display solution or karst features, and decreases downsection (fig. 15). Although the timing of dolomitization cannot be unequivocally demonstrated, much of the dolomite may have formed soon after leaching (that is, penecontemporaneously). Additional dolomite may have been precipitated at subsequent successive, lowstand events, fluid access being gained by karst pipes and channels.

Dolostones at the top of the Fasken section retain little or no original structure or texture. These rocks, which are overlain by the Upper Devonian Woodford Formation, may have undergone multiple episodes of postdepositional leaching and diagenesis during the more than 20 million years represented by this regional Middle Devonian hiatus. These multiple episodes of overprinting diagenesis have resulted in a wide variability in pore development at the top of the Fasken; solution vugs and molds are especially common.

Throughout the remainder of the Fasken inner platform section where fabric-retentive dolomite is dominant, porosity is composed of skeletal molds (for example, fig. 16a) and less common interparticle (largely intercrystalline) pores. However, where multiple episodes of leaching and dolomitization have occurred and fabric has been destroyed, vuggy and intercrystalline pores similar to those observed at the top of the section are common.

Solution-collapse and karst breccia horizons are common in the Fasken (Ruppel and Holtz, 1994). Some of these features appear to have formed associated with exposure at individual intraformational Fasken lowstands. However, many may be related to longer duration, post-Fasken lowstand events. For example, at Emerald field (Gaines County, Texas), karst features are found immediately below the Wristen a few feet below the overlying Woodford. This succession of cave-roof and cave-fill features was most likely formed during the Middle Devonian (Entzminger and Loucks, 1992). Cave-fill breccias of this sort are typically composed of poorly sorted, polymict clasts in a matrix of silt, glauconite, and carbonate mud (fig. 16c). Breccia zones may be found as much as 100 ft below the top of the Fasken. These karst features are probably very similar in origin and age to those developed in the Fusselman in the Franklin Mountains of West Texas and New Mexico (McGlasson, 1967).(Note that outcrop Fusselman sections are equivalent to both Wristen and Fusselman subsurface units.)

Subsurface Recognition and Correlation

Fasken facies associations are distinctly different from those of the Wink or the Frame, so these units are easily distinguished in cores. Wireline log distinction is also usually obvious. The shallow-water carbonates of the Fasken usually display a low gamma-ray response that contrasts with the typically much higher gamma-ray values in the laterally equivalent Frame and underlying Wink caused by the presence of clay-rich carbonate mud (fig. 5).

Distinction of the Fasken from the Devonian Thirtyone Formation is locally problematic, especially along the updip subcrop limit of the latter where chert is relatively minor. Gamma-ray signatures in both are generally low, making distinction problematic. An understanding of the areal extent of the two formations is perhaps the best guide to their separation. In actuality, the two only coexist along a narrow band in southern Andrews County.

Where the Wink and Frame are absent (north and west of the Fasken/Frame facies transition area), the Fusselman is difficult to distinguish from the overlying Fasken Formation (fig. 5).

Sequence Stratigraphy of the Wristen Group

Core studies demonstrate that the Wristen Group in the Permian Basin is at least locally cyclic. As discussed above, some Fasken core successions reveal patterns of cyclicity and facies stacking that resemble middle Permian carbonate platform successions, which were also formed in transitional icehouse-greenhouse conditions, in terms of cyclicity and facies stacking patterns. However, documentation of the cycle- and sequence-scale stratigraphy of the Wristen remains scanty.

Two efforts have been made to develop a subregional sequence-stratigraphic framework for the Wristen (Canter others, 1992; Baldonado and Broadhead, 2002). However, both of these studies relied on wireline log correlations, none of which was supported by rigorous log calibration to cores, seismic, outcrops, or other depositional models. Experience with the Wristen and other carbonate platform successions in the Permian Basin illustrates that wireline logs are not a reliable basis for correlation unless used in conjunction with and closely calibrated to cores and outcrop models. Further work is needed before a useable sequence stratigraphy of the Wristen can be developed. Global studies of Middle and Upper Silurian stratigraphy suggest that the Wristen Group may constitute as many as four depositional sequences (fig. 4). Considering the potential impact of sea-level rise/fall events on depositional facies architecture and diagenesis, an improved understanding of the sequence stratigraphy of the Fasken is crucial to developing improved models for reservoir development in the Permian Basin.

Reservoir Development

Wristen platform reservoirs are assigned to the Wristen Buildups and Platform Carbonate play (Dutton and others, 2005). All of these reservoirs are productive from carbonates of the Fasken Formation of the Wristen Group. According to Dutton and others (2005), 85 reservoirs have produced more than 1 million barrels from this play through 2002. Total production from the play, as of 2000, stands at 889 million barrels (Dutton and others, 2005).

Reservoir Distribution

Wristen Group reservoirs are restricted to the northern part of the area where the Fasken Formation subcrops (fig. 20); the deeper water equivalent Frame and Wink Formations of the Wristen are not productive. The Woodford forms the top seal and probable source for nearly all of these reservoirs. Reservoirs are developed in two settings: (1) in platform-margin buildup successions along the Wristen platform margin in central Andrews County (for example, Magutex, Hutex, and Fullerton fields) and (2) in highly diverse shallow-water facies in the interior of the Wristen platform. In both instances, the reservoirs are predominantly localized over structural traps and sealed by the Woodford Formation.

Porosity Development

Porosity in Fasken Formation reservoirs is a function of both original depositional setting and diagenesis. In platform-margin buildups (for example, at Magutex and Hutex fields), two main styles of porosity development exist. Primary, intergranular porosity is observed locally in buildup grainstones (both skeletal and ooid grainstones) on the outer platform (fig. 14a,b). In inner platform, nonbuildup successions, porosity is typically moldic and intercrystalline, associated with leaching of allochem-rich intervals. As is the case with the Fusselman, leaching seems to be due to multiple exposure events both during and after Fasken deposition. Porosity development in many reservoirs is clearly related to these exposure events (for example, Fullerton field), as probably is dolomitization. Porosity in such reservoirs is commonly composed of moldic and intercrystalline pores whose distribution is in most cases controlled by original depositional facies.

The Fasken is also productive from reservoirs that exhibit more fabric-destructive diagenesis similar to that which is common at the top of the Fusselman Formation. Like the

Fusselman, porosity in these reservoirs is typically composed of vugs and intercrystalline pores in dolomite. This type of reservoir development is usually restricted to the top of the Fasken section (e.g., Little Lucky Lake field, Chaves County, New Mexico). These leached zones are the result of exposure, and in most cases later dolomitization, following Fasken deposition and are locally developed in both platform-margin buildup successions and inner platform sequences. In some cases, dissolution associated with the post-Wristen unconformity affects the Fasken to depths of many tens to hundreds of feet (for example, Fullerton field). In many instances the result of this dissolution is the development of solution-cavity and cave successions similar to those documented in Lower Ordovician Ellenburger reservoirs (Kerans, 1988; 1989; Loucks, 1999, 2003). Reservoirs in which dissolution has penetrated deep in the section are commonly those situated on major structural highs.

Traps, Seals, and Sources

Most Wristen reservoirs are formed by simple or fault-modified anticlinal closure. Examples of this structure include essentially all of the larger fields—for example, Fullerton, Hutex, Magutex, and Breedlove. In nearly all documented cases, productive Fasken reservoirs are overlain by the Upper Devonian Woodford Shale. This finding suggests that where the Woodford has been removed by erosion, younger strata have proved ineffective top seals. Studies of source rocks and reservoir oil character suggest that Fasken reservoir oil was sourced from the overlying Woodford (Williams, 1977). This interpretation also implies that Fasken productivity is tied directly to the presence of the Woodford.

Opportunities for additional resource recovery

Ruppel and Holtz (1994) determined that Fasken (Wristen Group) reservoirs contain more than 750 million barrels of remaining mobile oil. This large remaining oil resource is a function of the low average recovery efficiency (28%) characteristic of the play and the fact that the Fasken is one of the most poorly known carbonate reservoir successions in the Permian Basin. The low recovery efficiency indicates that the Fasken possesses a great deal of geological heterogeneity. Unfortunately, the data needed to define this heterogeneity are severely limited. The relative scarcity of cores and the absence of detailed outcrop or reservoir studies make construction of effective models for the distribution, geometry, and character of reservoir facies difficult. There is great potential for markedly increasing the hydrocarbon recovery from existing Fasken fields and defining areas of probable untapped accumulation once detailed geological studies become available. The Fasken succession represents perhaps the most ignored plays in the Permian Basin. As such, it offers possibly the highest potential return on characterization and investment of all the reservoir plays in the basin.

SUMMARY AND CONCLUSIONS

The Wristen Group of the Permian Basin comprises a diverse assemblage of dominantly carbonate facies that reflect (1) the reshaping of the southern margin of the Laurentian paleocontinent by forces associated with the closing of the Iapetus Ocean and (2) high-frequency sea-level rise and fall events associated with waning but still active glaciation in Gondwana. The Wristen consists of two broad paleotopographic realms: a southern region characterized by fine-grained, deeper water carbonate mudstones and shales (Wink and Frame Formations), and (2) a northern shallow-water platform carbonate (Fasken Formation). All of the known hydrocarbon production in the Permian Basin has come from shallow-water platform facies of the Fasken Formation. Fasken rocks display considerable diversity ranging from platform-margin carbonate-buildup successions to interior platform tidal flats. Porosity development is a function of depositional textures and overprinting diagenesis, including dolomitization and karsting. Although the basic elements of Fasken facies and rock-fabric diversity can be defined from existing core investigations, additional, more detailed, rock-based studies are needed to adequately characterize reservoir architecture and controls of porosity and permeability development if more effective methods for the recovery of the remaining oil in these reservoirs are to be developed.

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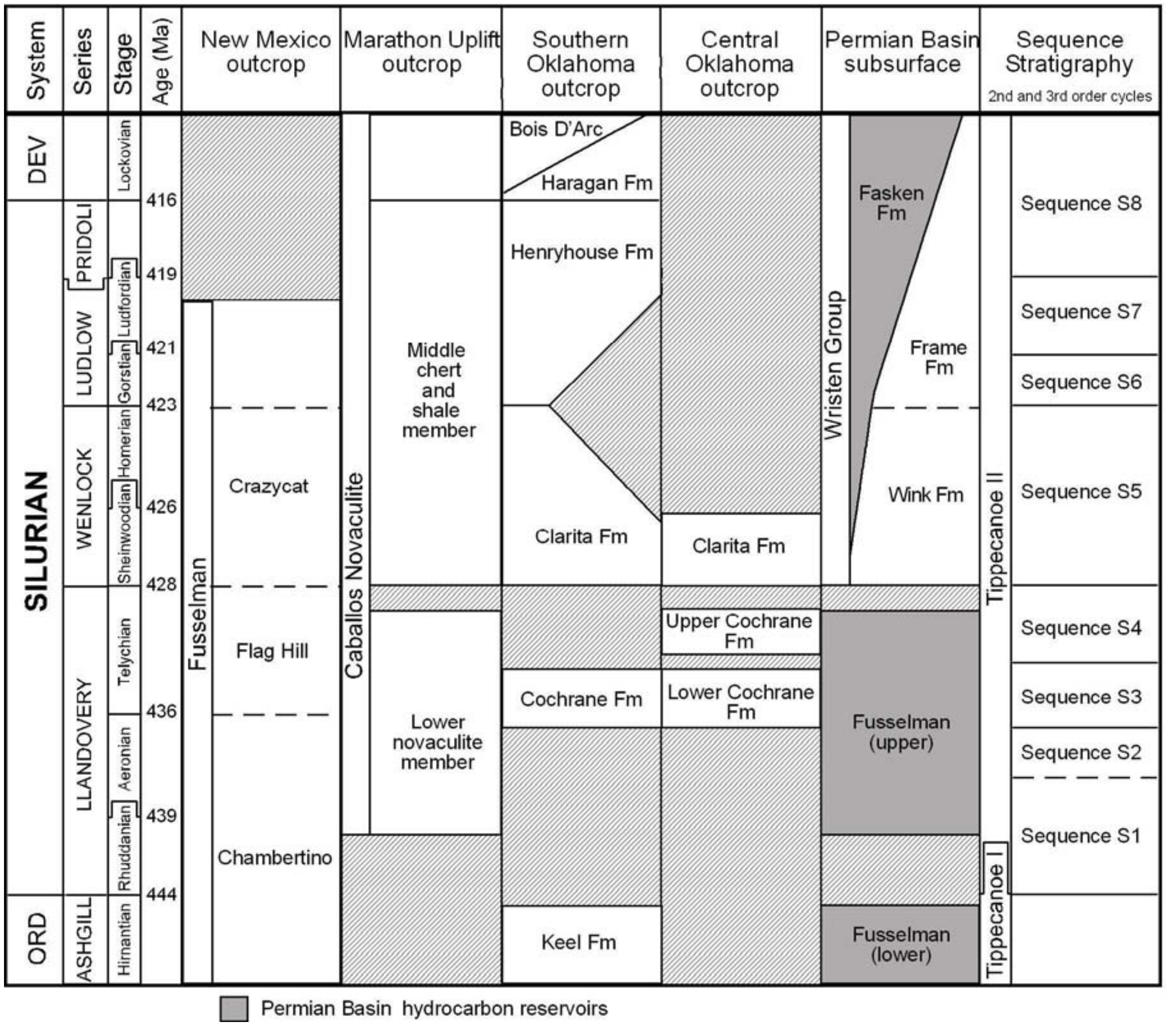
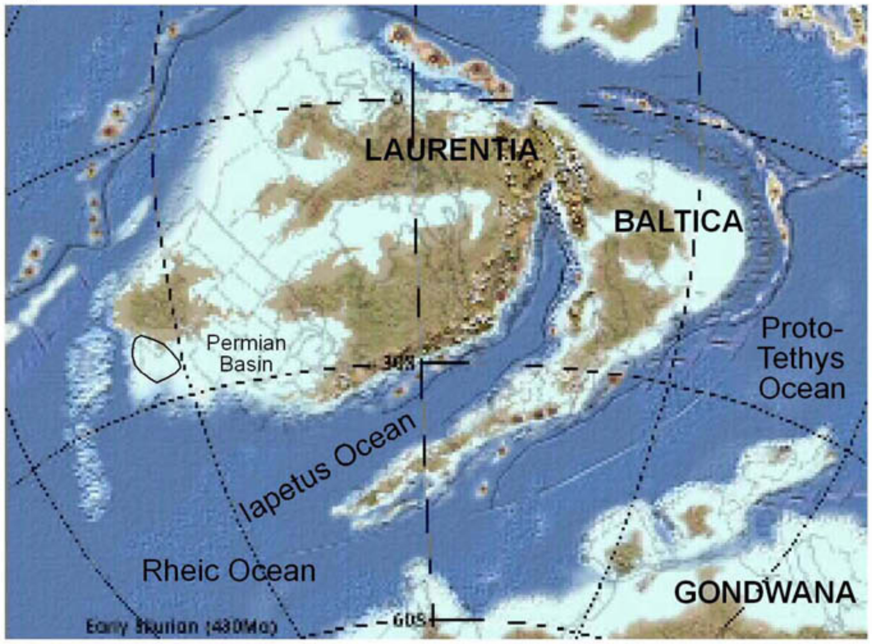


Figure 1. Correlation of Silurian Devonian strata in West Texas with successions in Oklahoma and New Mexico. Age dates are from International Stratigraphic Chart (2004).

A.



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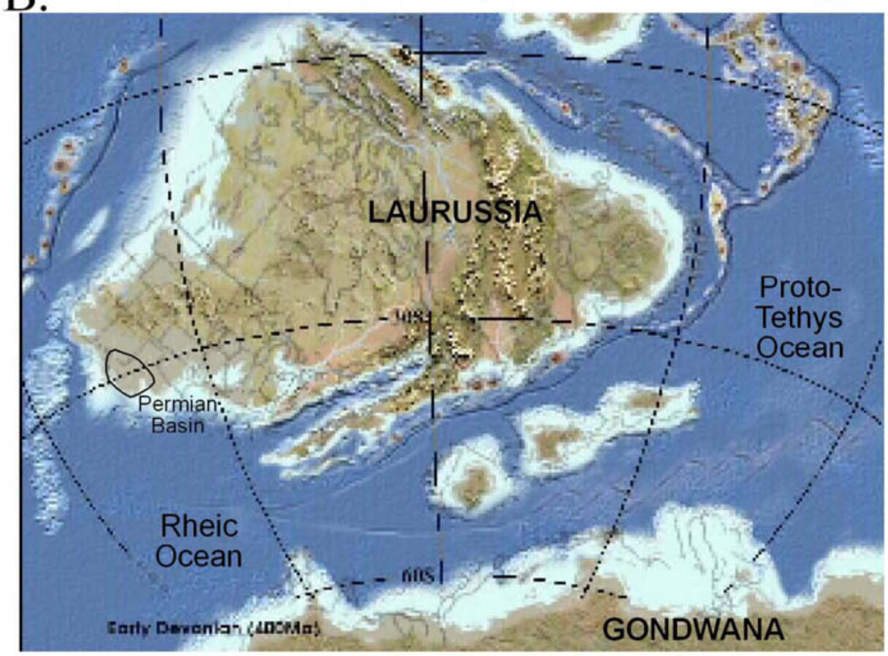
B.



from Blakey (2004): http://jan.ucc.nau.edu/~rcb7/400NAt.jpg

Figure 2. Global reconstruction of the U.S. Midcontinent during the Silurian. The extensive carbonate platform that characterized the southern margin of Laurentia and (the Permian Basin area) during the Early Silurian (A) was downwarped to form a well-defined southfacing ramp during the Middle Silurian (B) associated with plate collision and the closing of the Iapetus Ocean. From Blakey (2004).

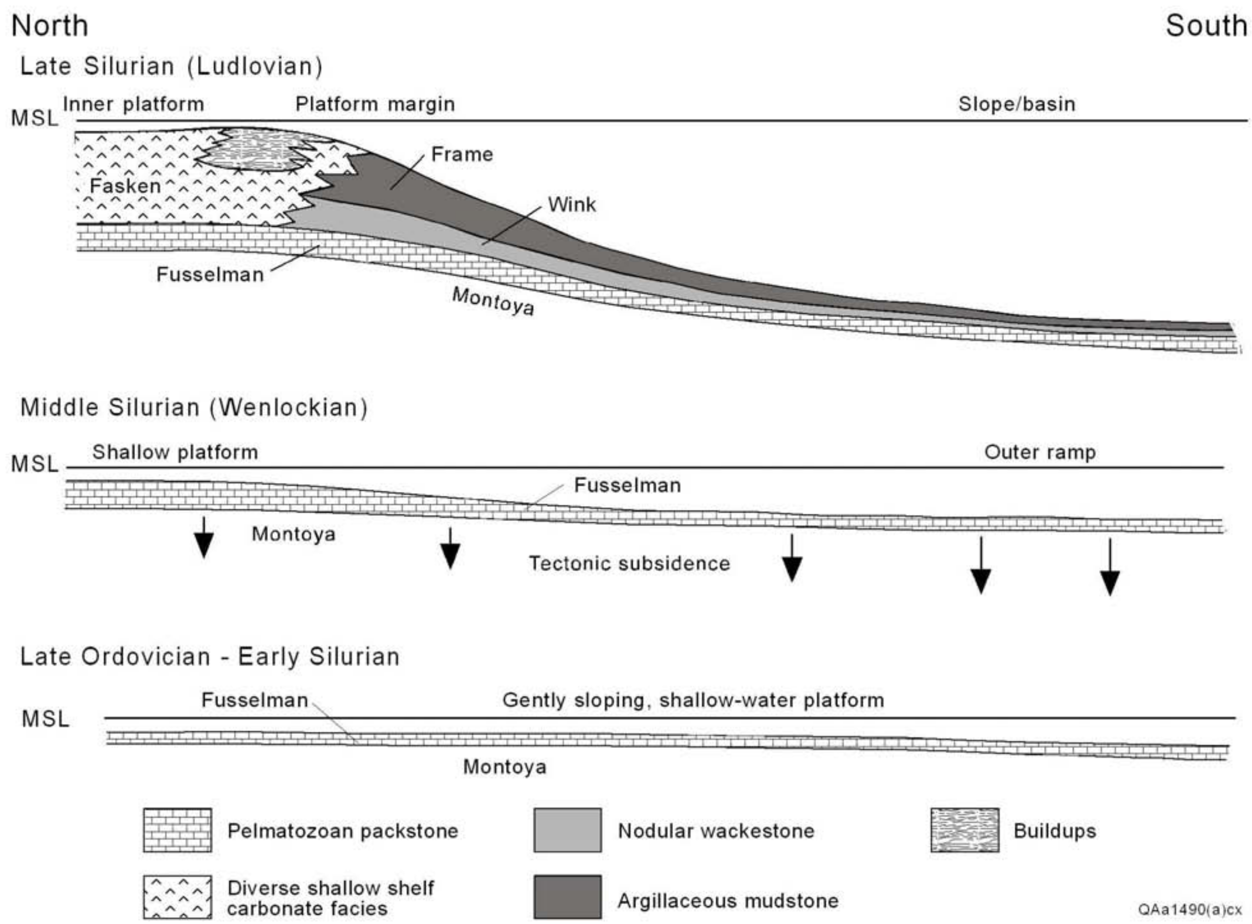


Figure 3. Diagrammatic dip cross section illustrating the depositional history and architecture of the Wristen Group in the Permian Basin.

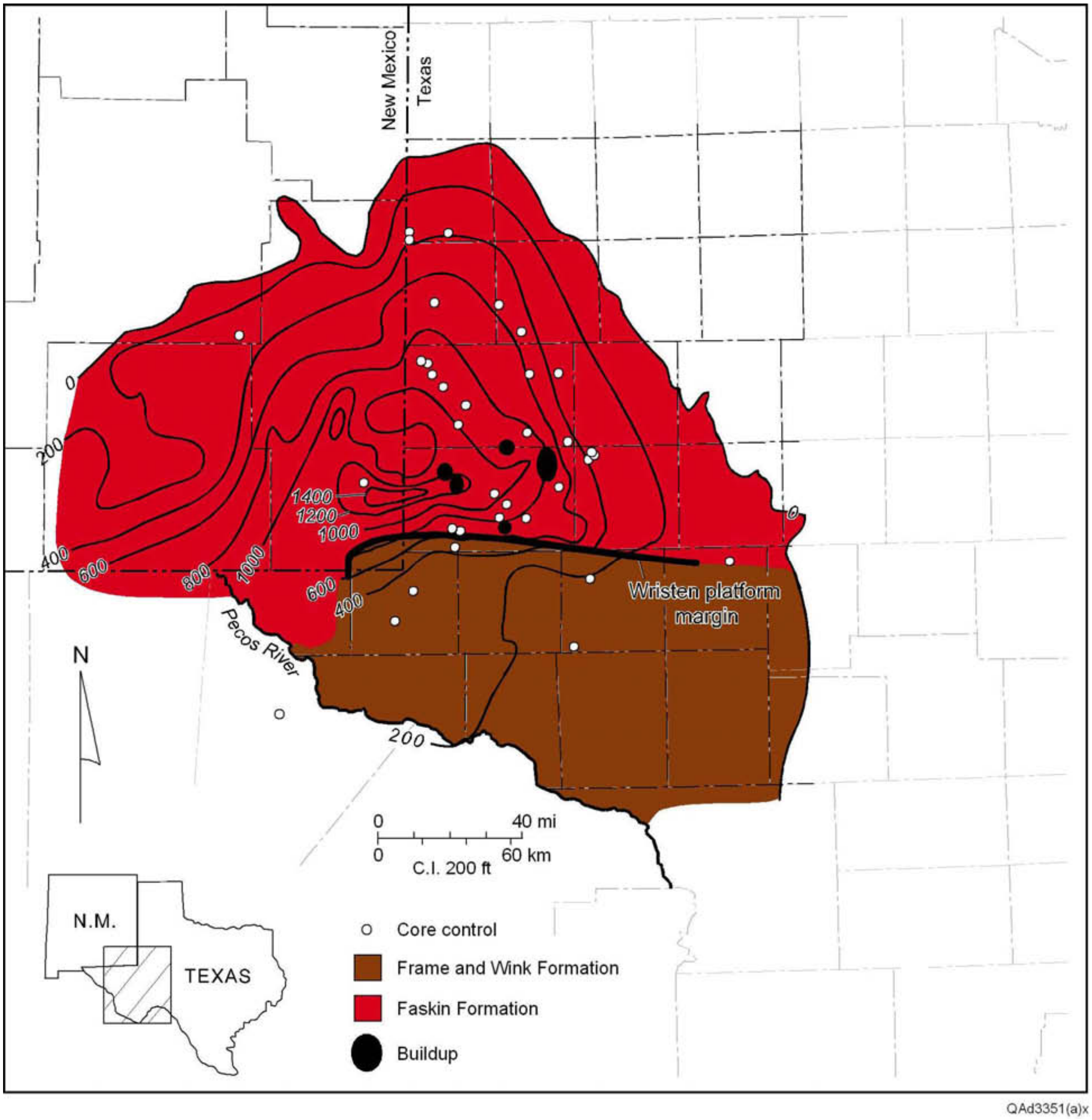


Figure 4. Thickness and distribution of the Wristen Group. South of central Andrews County, the Wristen is composed of slope and basin mudstones and wackestones of the Frame and Wink Formations. North of this line, which defines the general position of the Wristen platform margin, the Wristen comprises a diverse assemblage of shallow-water platform carbonates herein assigned to the Fasken Formation. Note that carbonate buildups are common in the Fasken Formation in several areas, especially along and just landward of the platform margin in Andrews County. The Wristen Group is thickest along the Texas/New Mexico border in Andrews and Gaines Counties.

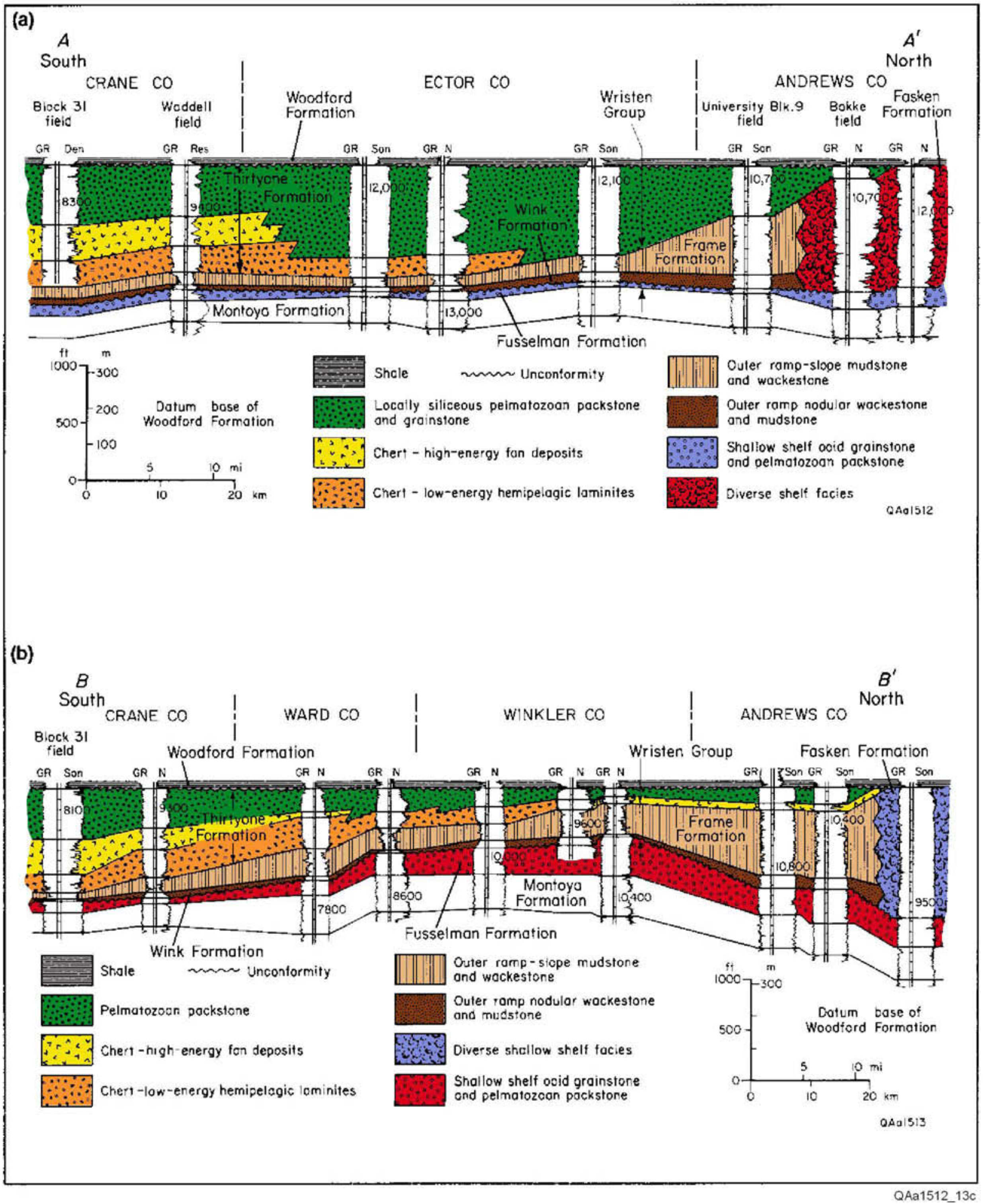


Figure 5. Dip cross sections showing general stratigraphy of the Wristen Group and overlying and underlying strata in West Texas. Lines of section shown in fig. 4.

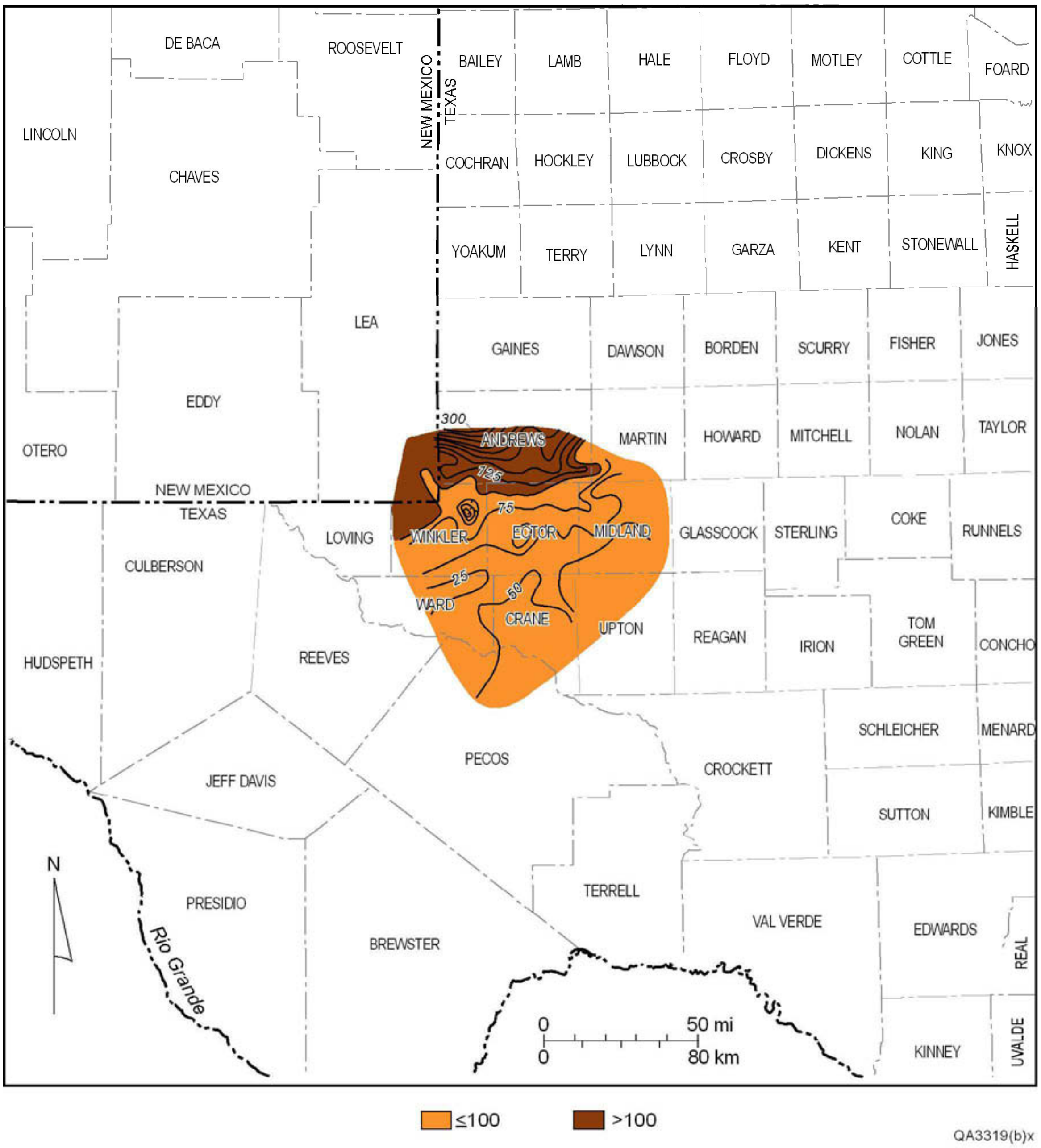


Figure 6. Thickness of the Wink Formation. Neither the Wink nor the Frame Formation is readily separable from the Fasken Formation north of the Wristen platform margin in central Andrews County.

Figure 7. Slab photograph of nodular wackestone, Wink Formation. These wackestones contain scattered fragments of trilobites, thin-walled brachiopods, and ostracodes and locally grade into mudstone. Austral Oil Co., University No. 1, Andrews County, Texas. Depth: 12,030 ft. Slab is 8 cm wide.

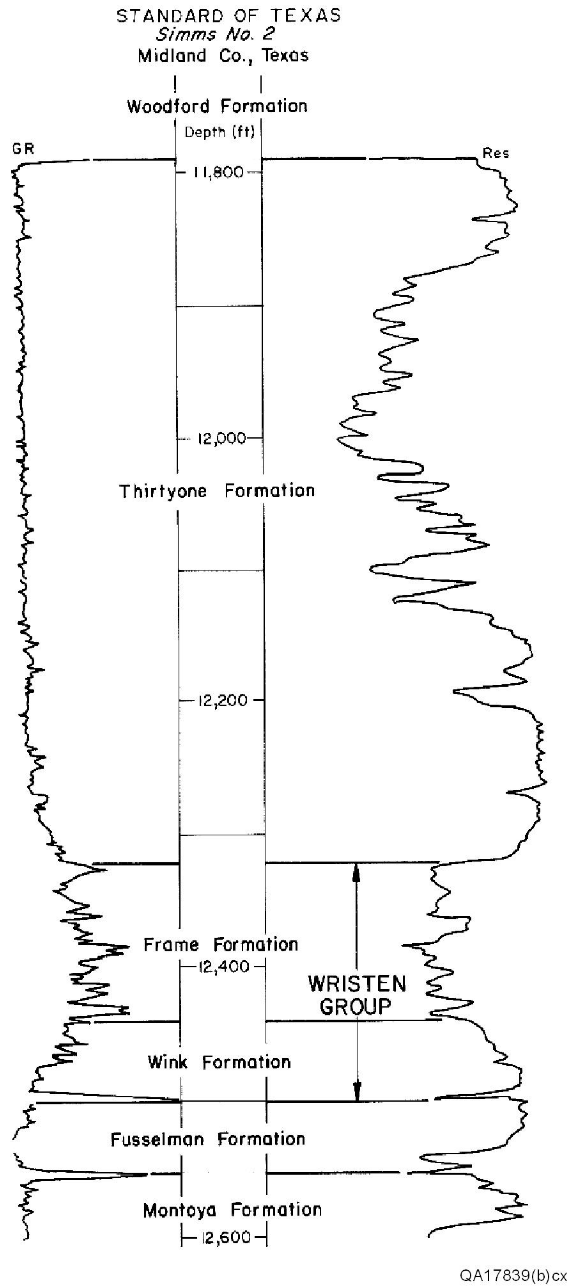


Figure 8. Typical wireline signature of the Wristen Group in the southern, deeper water part of its subcrop area. Shallow-water platform Fasken Formation deposits are not present in this area; instead, the deeper water facies of the Wink and Frame Formations are typically overlain by the Thirtyone Formation.

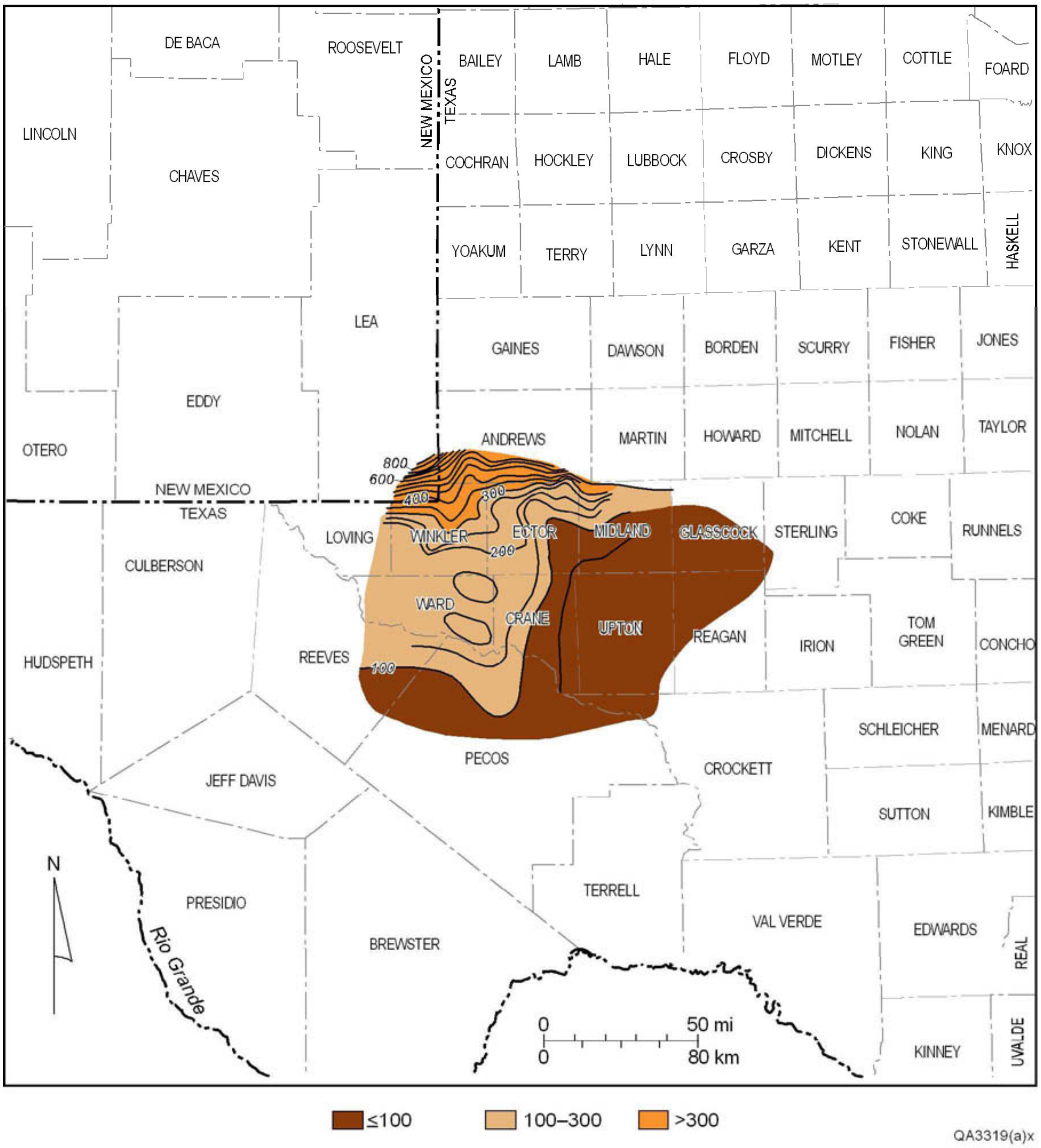


Figure 9. Thickness of the Frame Formation. Neither the Wink nor the Frame Formation is readily separable from the Fasken Formation north of the Wristen platform margin in central Andrews County.

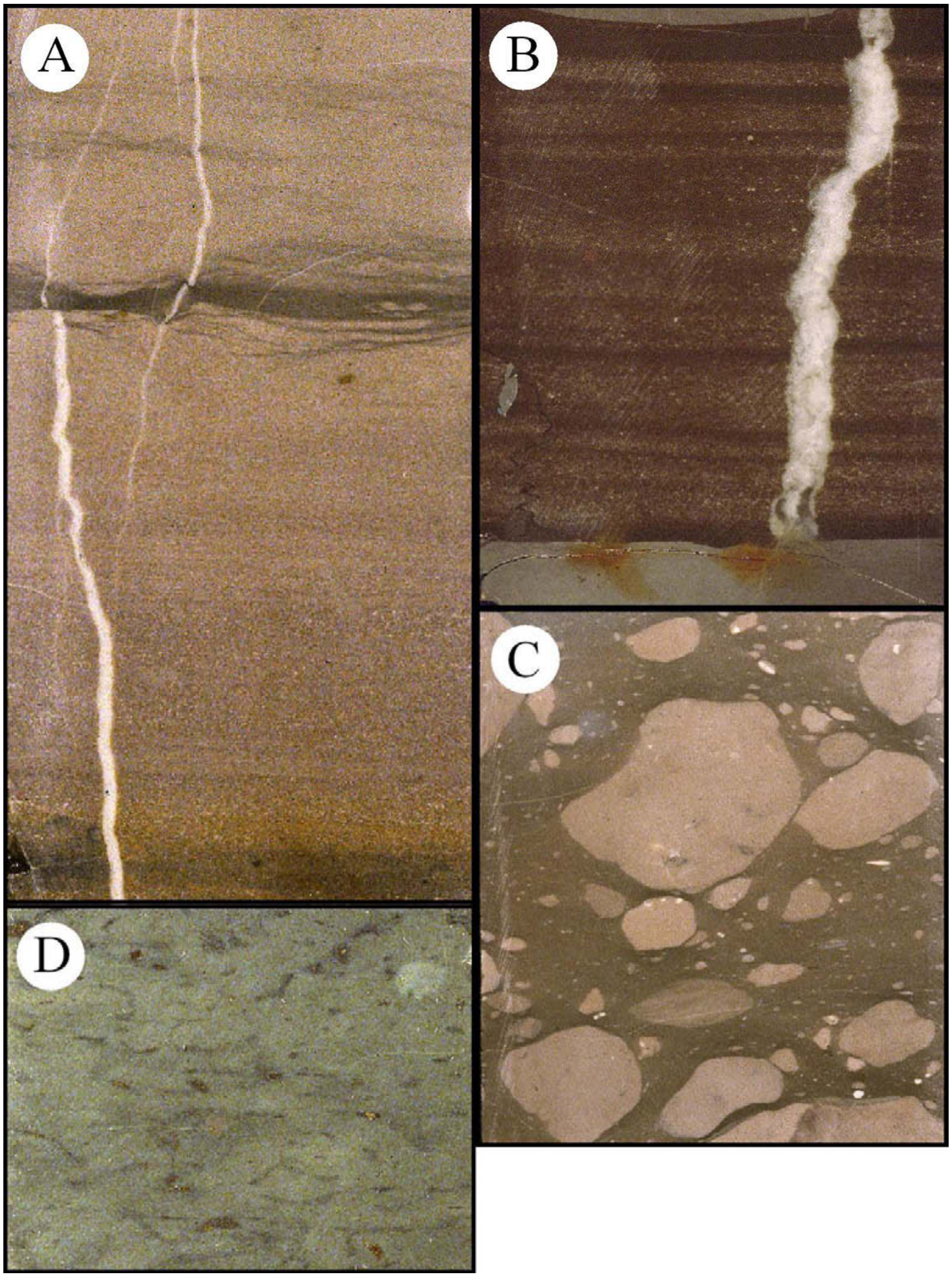


Figure 10. Typical outer ramp - slope facies of the Frame Formation (Wristen Group). A. Calcarenite displaying normal (upward-fining) graded bedding. Amoco Unit #74, Three Bar field, 8198 ft, Andrews County, Texas. B. Laminated skeletal calcarenite composed of grain-rich (packstone) and mud-rich (mudstone) layers. Shell McCabe #2, 9221 ft Emperor Field, Winkler County, Texas. C. Burrowed silty mudstone. Shell McCabe #2, 9221 ft Emperor Field, Winkler County, Texas. D, Mudstone containing clasts of skeletal packstone. Shell McCabe No. 2, Emperor Field, Winkler County, Texas. Slabs are 3 in (8 cm) wide.

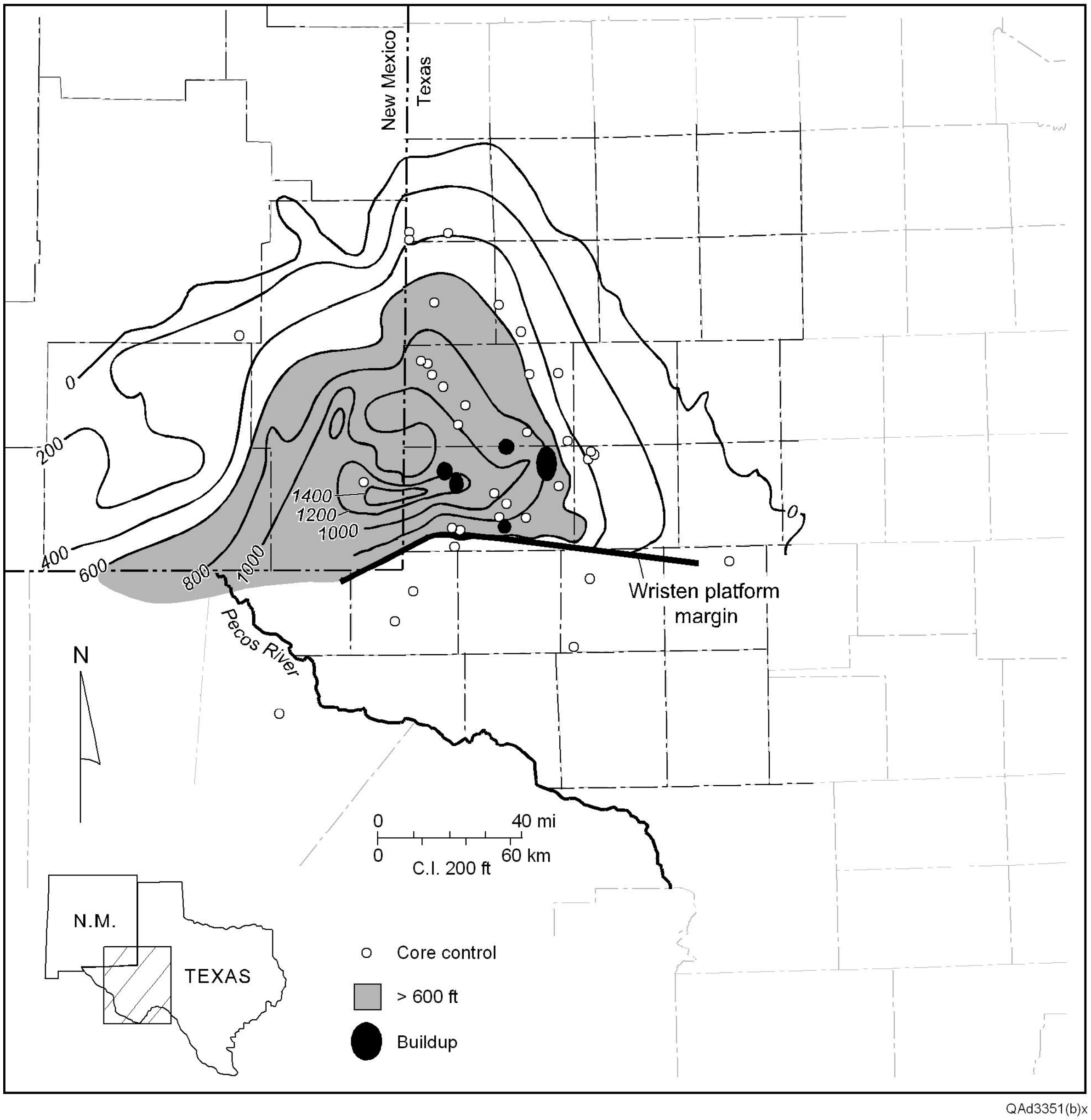


Figure 11. Thickness and distribution of the Fasken Formation. The formation thickens to more than 1,500 ft in extreme western Gaines and Andrews Counties, Texas, and southeasternmost Lea County, New Mexico. Northeastward thinning in the northern part of the area is due to truncation of the Silurian section by Middle Devonian (pre-Woodford) erosion.

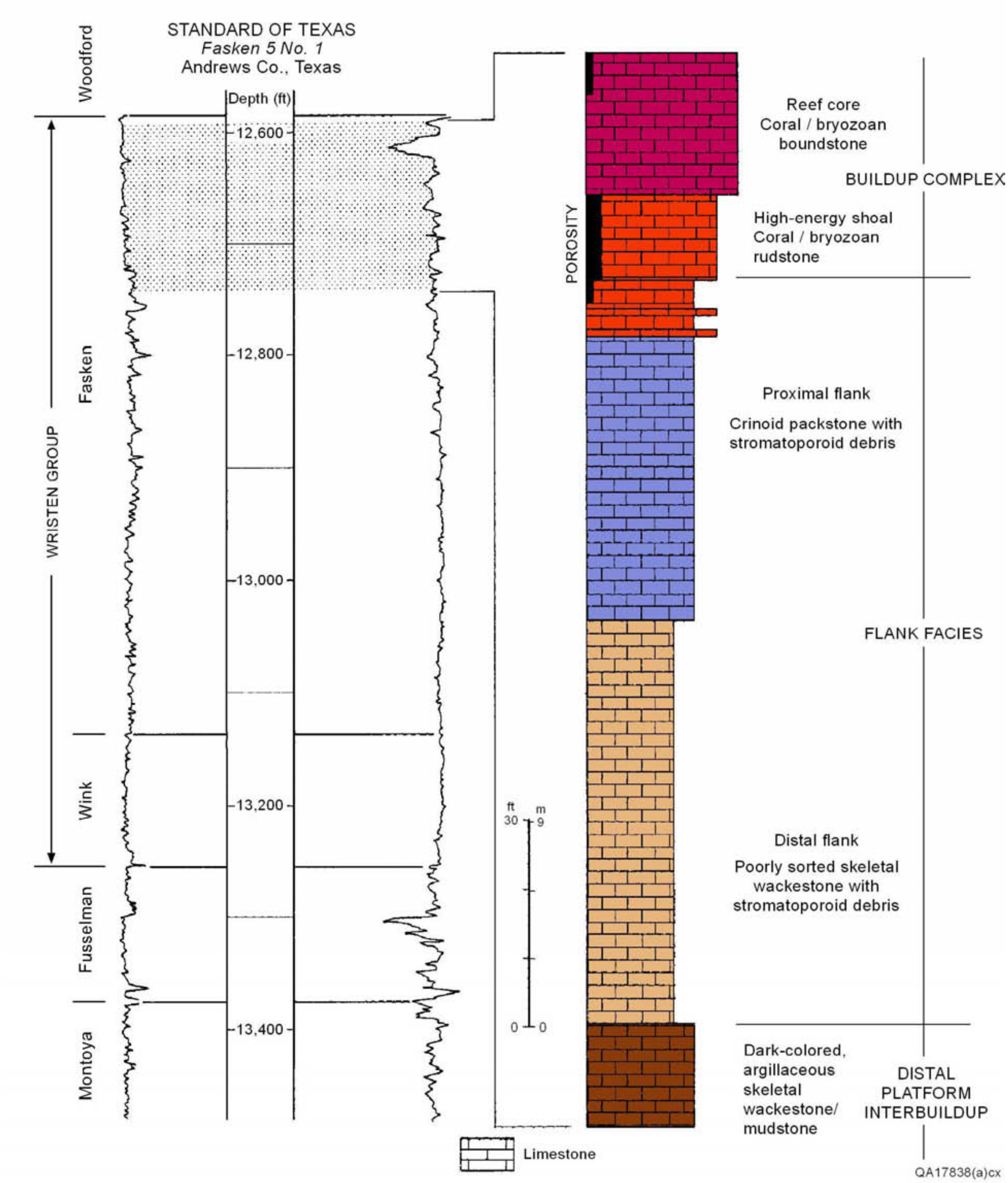


Figure 12. Fasken platform-margin buildup succession. Standard of Texas, Fasken 5 No. 1, Andrews County, Texas.

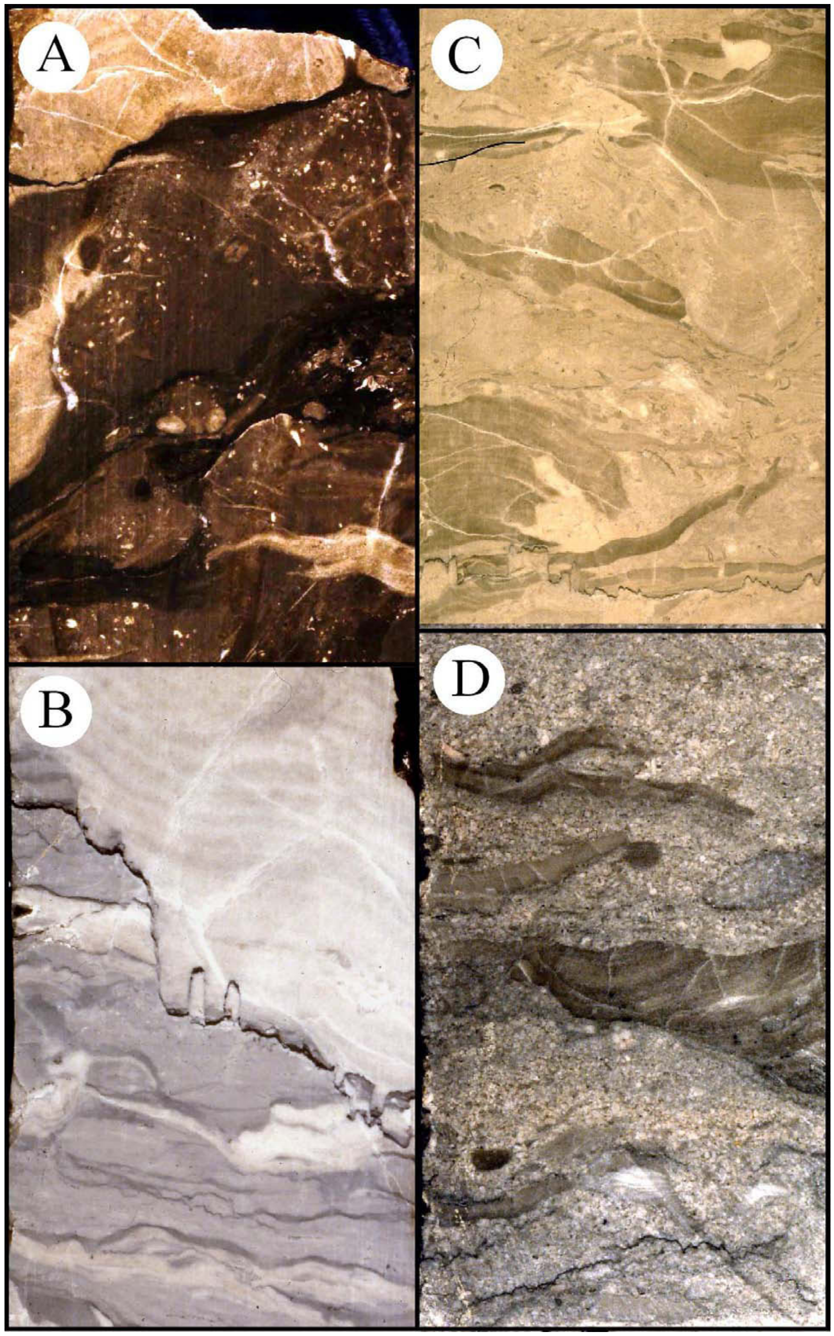


Figure 13. Distal facies of typical Fasken buildup successions. A. Skeletal wackestone containing rotated stromatoporoids typical of distal, outer-platform to slope deposits. Depth: 12740 ft. B, C. These mud supported rocks contain poorly sorted fragments of bryozoans, stromatoporoids, pelmatozoans, and corals (*Halysites*) transported downslope along buildup margins. Note some stromatoporoids are in growth position. Depth: 12632 (B) and 12731 (C). D. Pelmatozoan/stromatoporoid packstone containing a matrix of moderately well-sorted pelmatozoan debris and large clasts of hemispherical stromatoporoids. Depth: 12,629 ft. All slabs from Standard of Texas, Fasken 5 No. 1, Andrews County, Texas. Slabs 3 in (8 cm) wide.

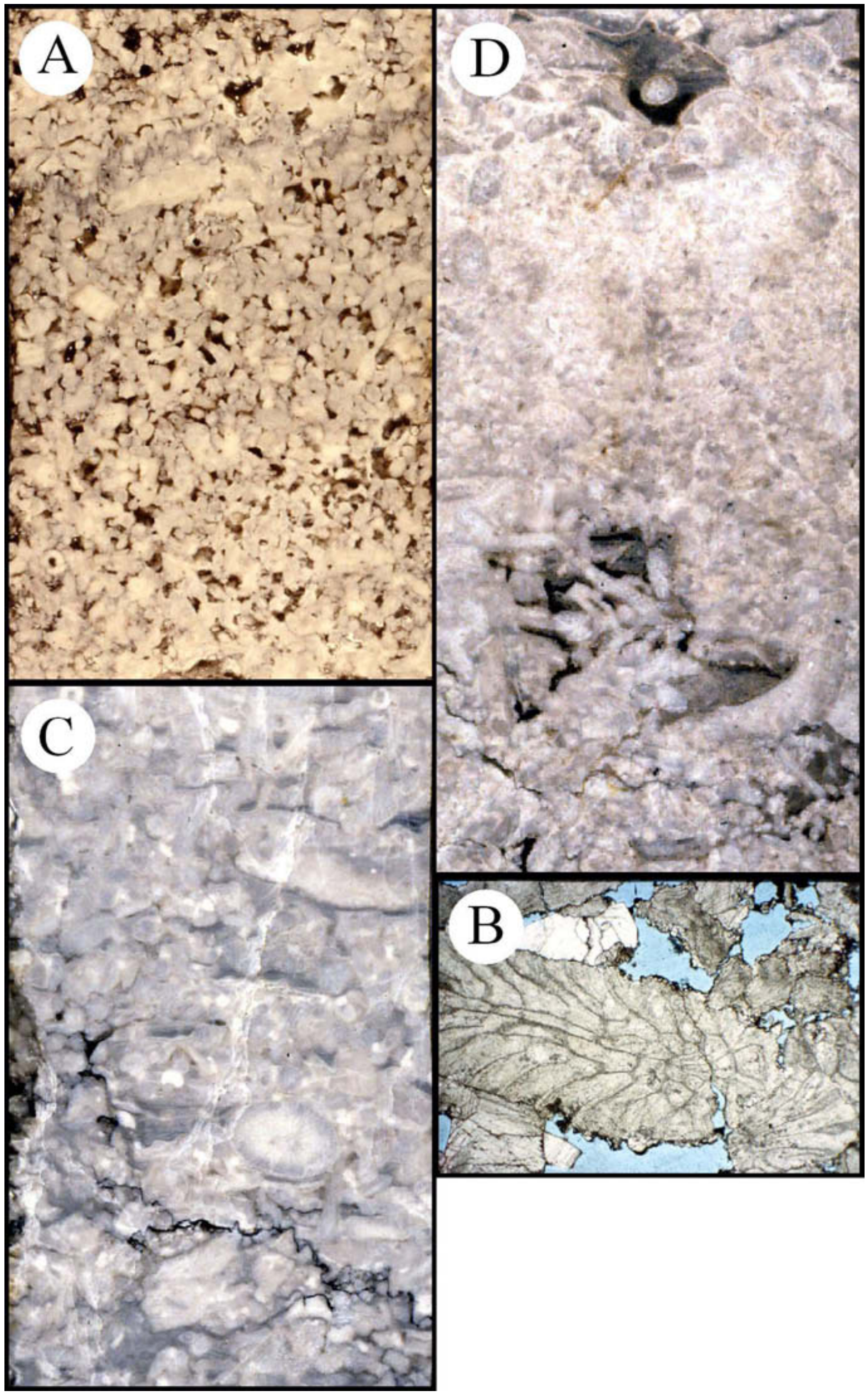


Figure 14. Proximal facies of typical Fasken buildup successions. A. Coral/bryozoan rudstone, Fasken Formation. These stick corals and ramose bryozoans were deposited as a coarse, high energy lag, at the tops of Fasken carbonate buildup successions. Depth: 12,620 ft. B. Thin section photomicrograph of A. Note the well-developed primary, intergranular porosity. C. Coral boundstone. Fauna is dominated by ramose corals and stromatoporoids. These deposits commonly exhibit numerous sediment-filled geopetals but are generally are non-porous. Depth: 12,597 ft. D. Bryozoan boundstone. Note local shelter porosity. Depth: 12 599. All slabs from Standard of Texas, Fasken 5 No. 1, Andrews County, Texas. Slabs 3 in (8 cm) wide.

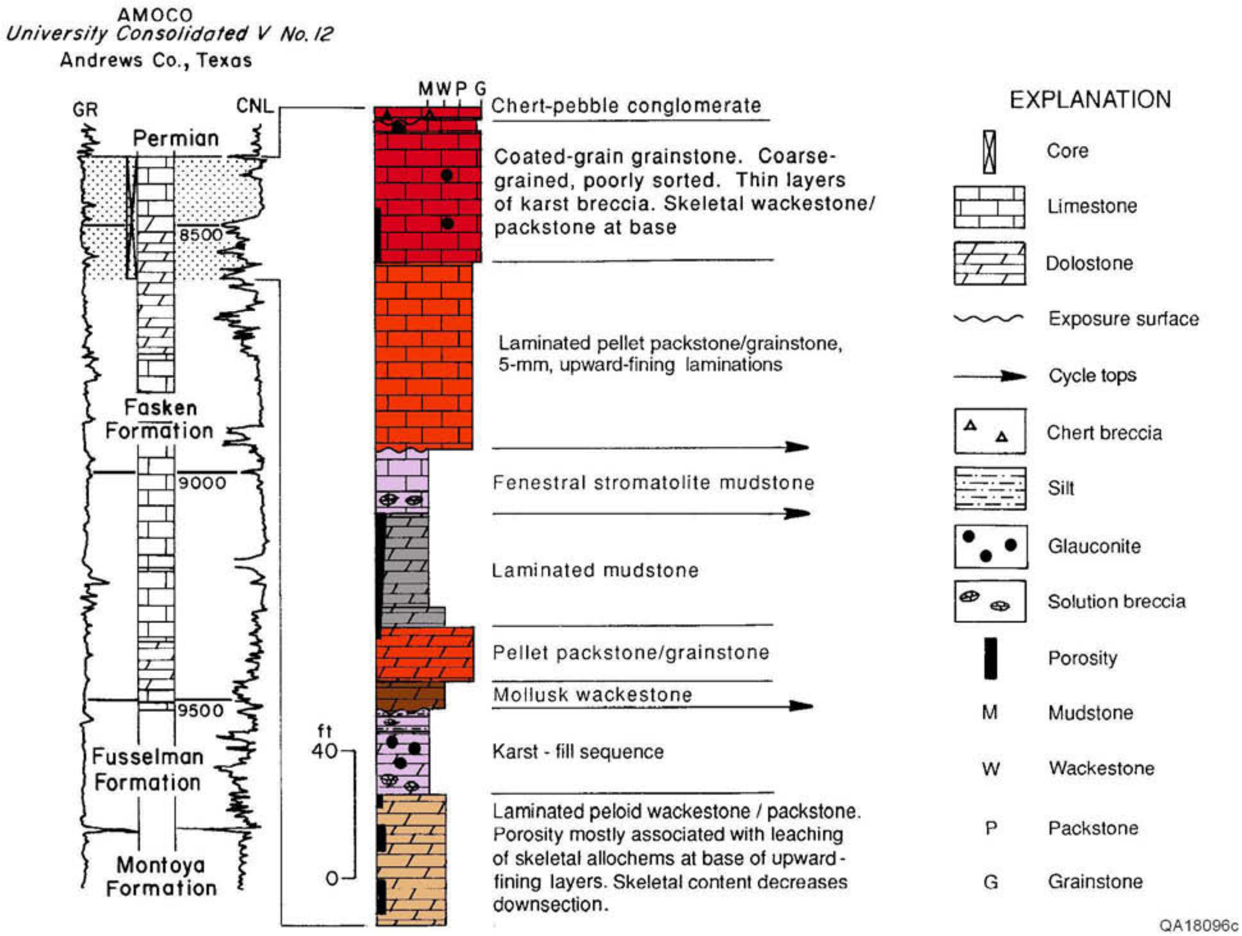


Figure 15. Upper Fasken Formation tidal flat succession, Fullerton field. In this well, the Fasken comprises a succession of tidal flat deposits punctuated by exposure and karsting. Note that porosity is most commonly developed beneath karst fills suggesting that porosity formation is controlled by leaching due to punctuated sea level fall. Amoco, University Consolidated, V, No. 12, Andrews County, Texas.

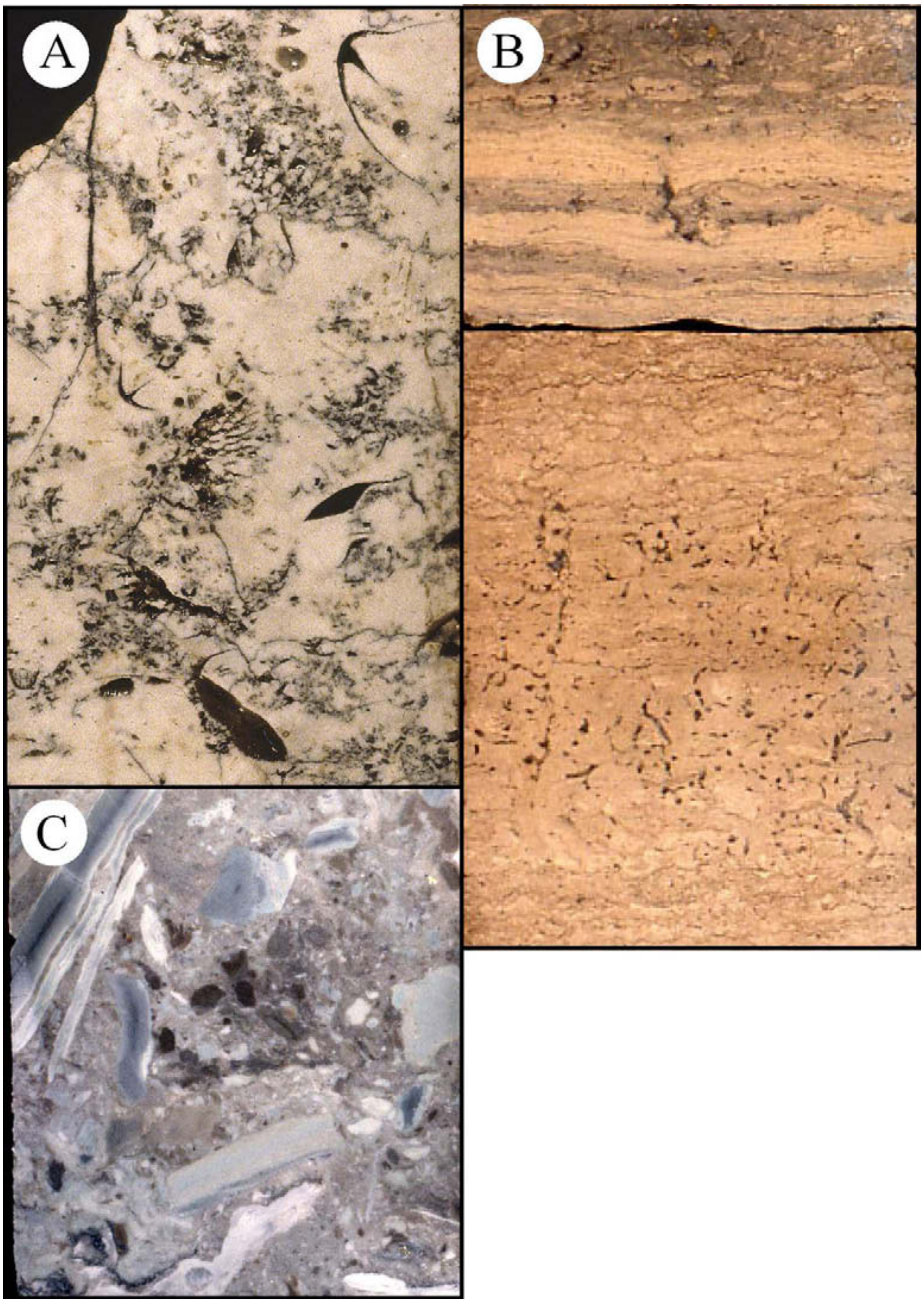


Figure 16. Facies of the Fasken inner platform. A. Subtidal skeletal wackestone. Skeletal debris consists principally of brachiopods, corals, and mollusks. Skeletal moldic pores like these typify the Fasken of the inner platform. Tex-Sin field, Texas. Texas Crude Oil Company, Chilton "B," No. 9-1, Gaines County, Texas. Slab is 8 cm wide. B. Laminated peritidal facies. These rocks define cycle tops and are typically dolomitized. Amoco University Consolidated V # 12, Fullerton field, Andrews County, Texas. Depth 8490 ft. C. Karst breccia. North Robertson field, Texas. Exxon Co., USA, Fee B-14, Gaines County, Texas. Depth: 9,748 ft. All slabs are 3 in (8 cm) wide.

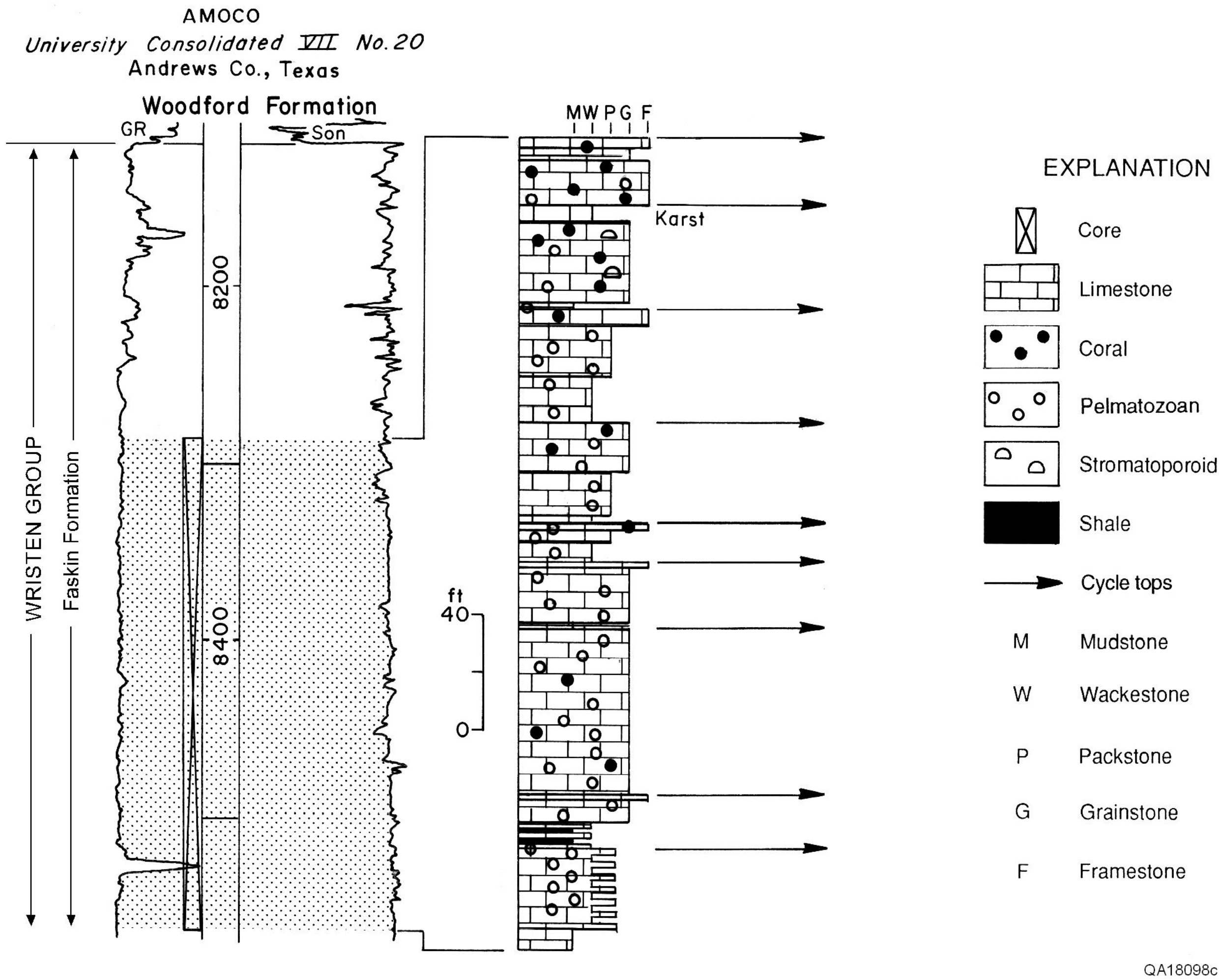


Figure 17. Lower Fasken Formation, buildup-capped, middle platform successions, Fullerton field. In this well, the Fasken is composed of a succession of aggradational, upward-shallowing sequences capped by carbonate buildups. The tops of many cycles exhibit evidence of exposure and dissolution or karsting. Very little porosity is evident. Amoco, University Consolidated, VII, No. 20, Andrews County, Texas

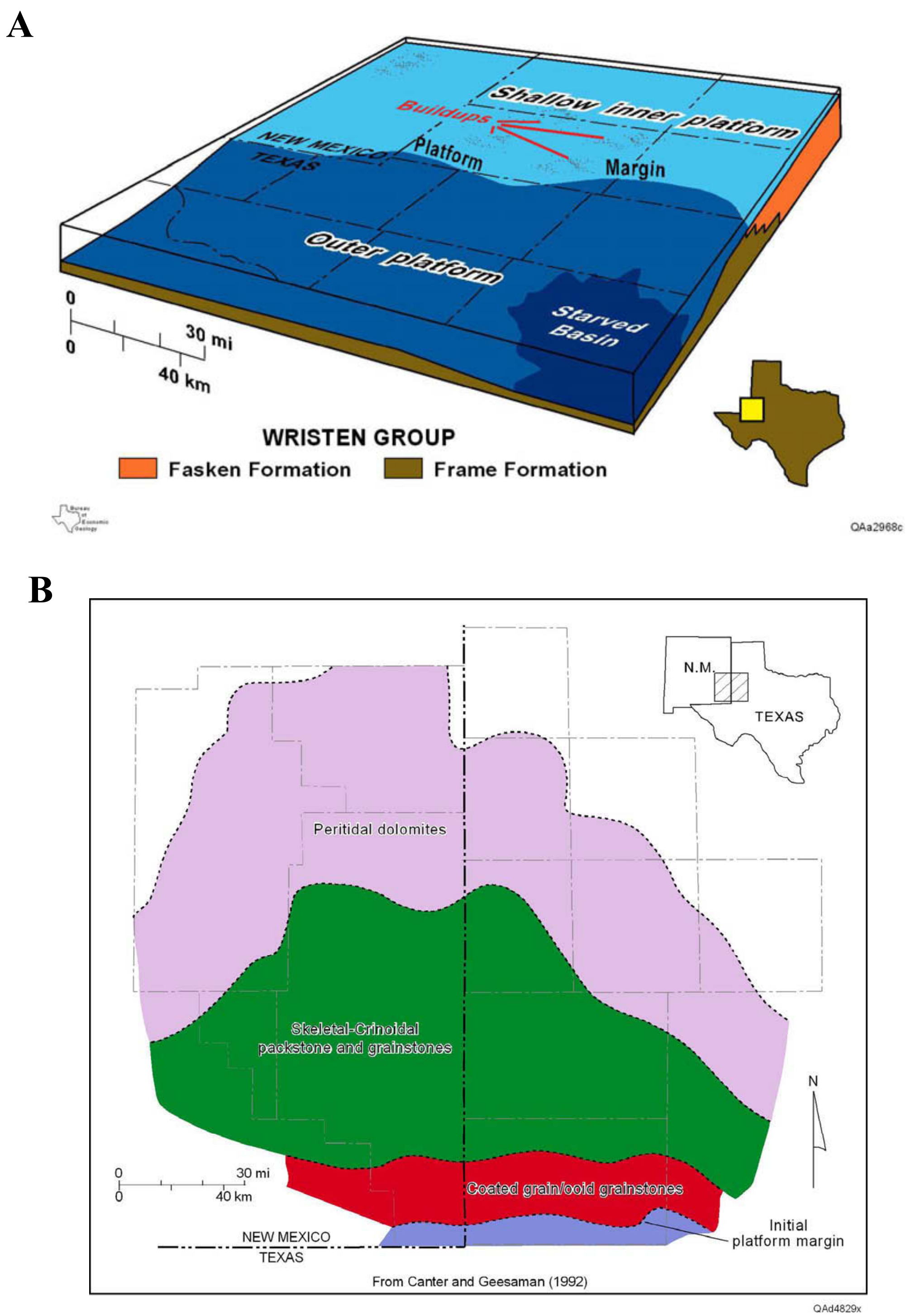
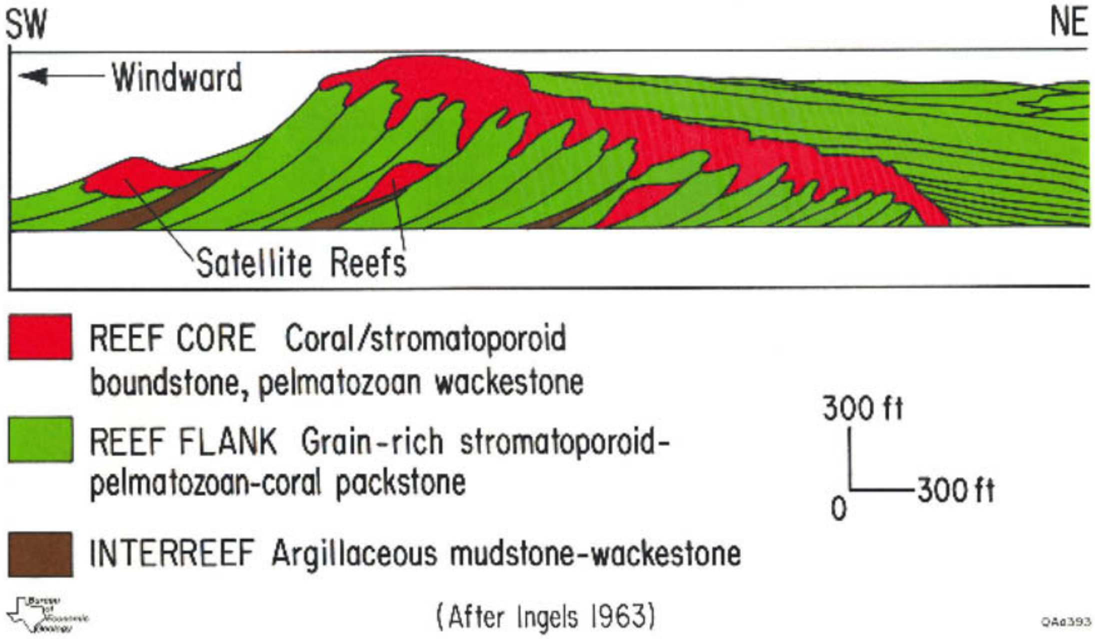


Figure 18. Paleogeographic reconstructions of Wristen Group depositional environments during the middle Silurian. A. General regional model depicting northern platform and southern, outer platform – basin. Platform rocks comprise Fasken platform-margin buildup successions and inner platform shallow subtidal to tidal-flat sediments. Coeval, argillaceous mudstones of the Frame Formation and underlying Wink Formation were deposited south of the platform margin in a slope/outer platform setting. From Ruppel and Holtz, 1994. B. Reconstruction on northern platform area showing east-west striking facies belts and general northward shallowing of facies tracts. From Canter and others, 1992.

(a)



(b)

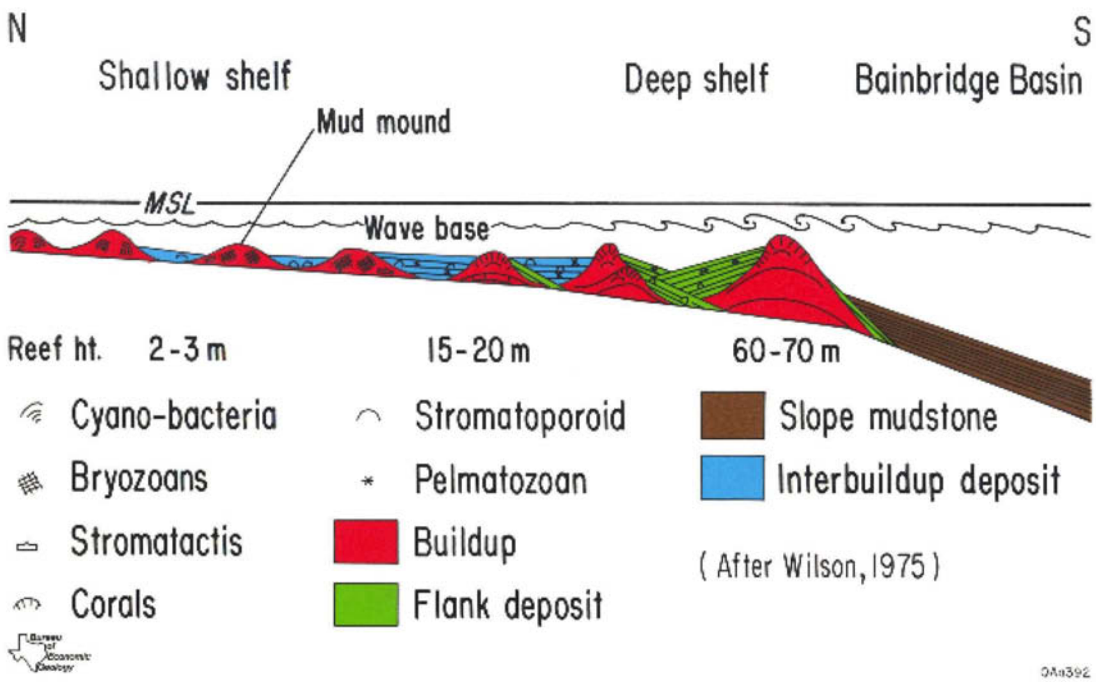


Figure 19. Models for Fasken buildup development. A. Model for platform margin buildup development based on Silurian outcrops in the Illinois Basin. From Ingels (1963). B. Platform interior buildups based on subsurface data from the Illinois Basin. From Wilson (1975).

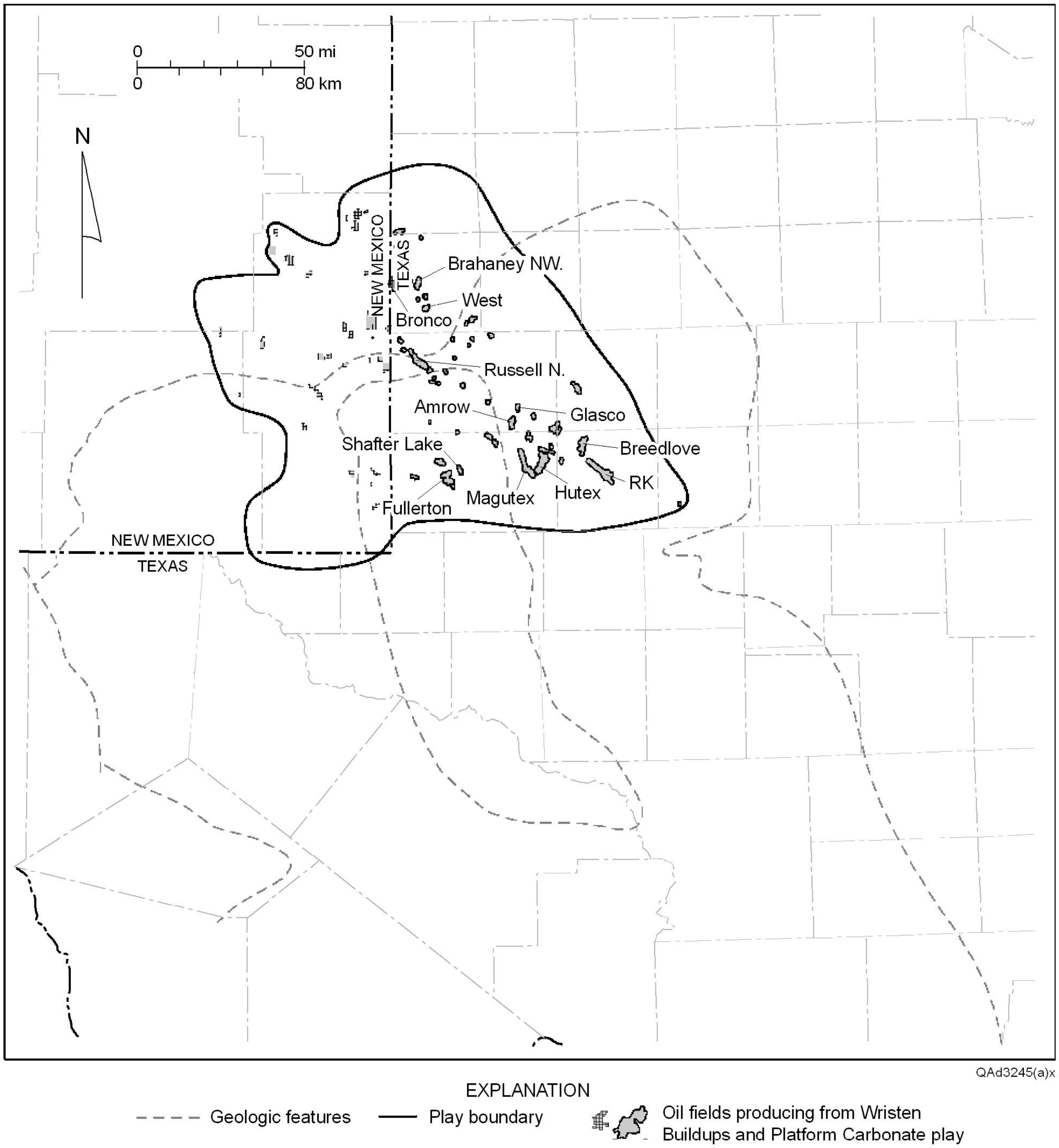


Figure 20. Map of the Permian Basin area showing distribution of reservoirs of the Wristen Buildups and Platform Carbonate play that have produced more than 1 million barrels of oil (from Dutton and others, 2005).