

THE MIDDLE-UPPER ORDOVICIAN SIMPSON GROUP OF THE PERMIAN BASIN: DEPOSITION, DIAGENESIS, AND RESERVOIR DEVELOPMENT

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ABSTRACT

Middle Ordovician Simpson Group rocks were deposited in greenhouse conditions during a period of overall sea-level rise and marine transgression following an extensive hiatus and development of an irregular karst topography on the underlying Lower Ordovician Ellenburger carbonates. Simpson Group production is from three sandstone units in the middle of the group, each sourced from eroding highs to the north and east and transported to the cratonic margins by eolian and fluvial processes. These sandstones represent lowstand and/or early transgressive deposits of three third-order sequences; nonreservoir shales and clay-rich carbonates deposited during maximum flooding, and normal marine and restricted carbonates deposited during highstand comprise the balance of the sequences. Carbonate sequences are present above and below these three reservoir-bearing sequences, for a total of five third-order Simpson Group sequences within Sloss's second-order Tippecanoe I sequence.

The three sandstone members of the Simpson Group—the Connell, Waddell, and McKee—occur at the base of the Oil Creek, McLish, and Tulip Creek Formations, respectively, from oldest to youngest. The Simpson Group also includes the underlying Joins and overlying Bromide carbonate formations. Simpson rocks were deposited during the Rangerian to middle Turinian stages of the Whiterockian and early Mohawkian series (North American) of the Middle to Upper Ordovician.

Productive sandstones are quartz rich and typically 20 to 50 ft thick. Pore-filling carbonate cements and pore-lining clays commonly reduce porosity. The Simpson play has limited production in the Permian Basin of Texas and New Mexico compared with that in

Oklahoma. In both areas, production is primarily from structural traps; despite favorable depositional conditions, stratigraphic traps have not been widely explored. The Simpson has an important nonreservoir role in Permian Basin production because its organic-carbon-rich shales are the likely source of the Ordovician oil found in many Central Basin Platform area reservoirs, including the Lower Ordovician Ellenburger. The Simpson is thickest in Pecos and Reeves Counties in Texas and thins to the north and east, being absent over all but the southeasternmost part of New Mexico and at the eastern edge of the Permian Basin region.

INTRODUCTION

The Simpson Group is a thick Middle to Upper Ordovician carbonate and clastic succession present in two distinct depocenters in the southwestern U.S.: (1) West Texas and southeastern New Mexico and (2) southern Oklahoma. This study focuses on the Texas/New Mexico depocenter but employs observations and models from Oklahoma as analogs. Simpson Group thickness reaches a maximum of more than 2,000 ft in Pecos County and more than 2,500 ft in Reeves County in West Texas. It thins to the west, north, and east, becoming absent in Roosevelt County, New Mexico, and Cochran, Terry, Dawson, Howard, Glasscock, and Reagan Counties, Texas.

Simpson Group production is relatively low, given its thickness. As a reservoir play in Texas and New Mexico, the Simpson Group comprises 19 reservoirs having individual cumulative production greater than 1 MMbbl of oil through 2000. Cumulative production from these reservoirs totaled only 103.2 MMbbl (Dutton and others, 2005; fig. 1). Production comes from three sandstone intervals that are quartz rich and typically 20 to 50 ft thick. These sandstones are separated by nonreservoir intervals composed of mostly green shales (Galley, 1958). However, these organic-carbon-rich Simpson shales are significant because they are the likely source of the Ordovician oil found in many Central Basin Platform area reservoirs, including the Lower Ordovician Ellenburger. The Simpson Group is also significant because it overlies a major hiatus in the Lower Ordovician and records a unique Middle Ordovician depositional environment in which both clastics and carbonates were deposited during a period of overall sea-level rise.

This report presents a synthesis of previous work and data from a new core study. Additional core descriptions and new regional and local wireline-log correlations will be needed

to fully establish a comprehensive sequence stratigraphic framework for the Middle to Upper Ordovician Simpson Group in Texas and New Mexico. Such a framework will not only provide a basis for new strategies in tapping this underexplored play, particularly through stratigraphic traps, but will also improve our understanding of a relatively unknown unique depositional setting and time.

PREVIOUS WORK

Decker and Merritt (1931) defined five formations within the Simpson Group in Oklahoma. These formation names were later applied to Texas and the productive sandstones named as members by Cole and others (1942). From oldest to youngest, the formations are the Joins, Oil Creek, McLish, Tulip Creek, and Bromide (fig. 2). Sandstones are present at the base of the Oil Creek, McLish, and Tulip Creek Formations in both Texas/New Mexico and Oklahoma but only defined formally in Texas (as the Connell, Waddell, and McKee sandstone members, respectively [fig. 2]; Wright, 1965). Simpson formation names are used consistently in Oklahoma, Texas, and New Mexico in outcrop and the subsurface, with one exception: in the Marathon Uplift region of Texas, the Woods Hollow Formation is equivalent to the Simpson Group.

A wealth of state survey and regional geologic association reports and field-trip guides on the Texas and New Mexico Simpson Group depocenter in the region known as the Permian Basin were published from 1950 to 1965. These reports typically describe known outcrops and subsurface penetrations in the context of lithostratigraphy and the developing nomenclature for early exploration and production. Descriptions of the Simpson Group are contained within early regional summaries by Jones (1953), Herald (1957), Galley (1958), Barnes and others (1959), and Gibson (1965). More recent compilations, for example Wright (1979) and Frenzel and others (1988), are mostly restatements of earlier interpretations with minor updates. Newer data and interpretations have been brief (abstracts and short transactions) and narrow in scope.

In contrast to those of Texas and New Mexico, Simpson Group reservoirs are significant contributors to total production in the southern Oklahoma depocenter. Accordingly, this succession has been the subject of numerous reservoir-specific early investigations reported in special volumes, such as the 1965 *Tulsa Geological Society Symposium on the Simpson*, as well as more modern reports—for example, Candelaria and others (1997), O'Brien and Derby (1997),

and Bosco and Mazzullo (2000). Simpson and Viola (Montoya-equivalent) Group reservoirs account for much of Oklahoma's production, and three Simpson Group fields have more than 500 MMbbl oil or 3.5 Tcf gas in place (Northcutt and Johnson, 1997). Most studies of the Simpson Group in Oklahoma invoke parallelism with the equivalent sandstones of West Texas (subsurface Permian Basin and Sierra Diablo region outcrops) but fail to cite specific examples. Candelaria and others (1997) published one of very few reports that established a sequence stratigraphic context for the formations and members in either depocenter. These authors noted the importance of establishing such a framework to provide a better understanding of stratigraphic traps for future exploration.

REGIONAL SETTING

Globally, the Ordovician was a time of one supercontinent, Gondwana, and three major terranes; present-day North America was the Laurentian terrane (Cocks and Torsvik, 2004). Laurentia was stable during this time—staying in a transequatorial position throughout the Ordovician with little rotation or movement (Cocks and Torsvik, 2004).

Global plate reconstructions by Blakey (2004) indicate that present-day West Texas and southeastern New Mexico were located near 30°S during the Middle Ordovician (fig. 3). Regional highs were the Canadian Shield in northeastern North America and the Pedernal Massif in the present-day southwestern U.S. (Blakey, 2004). Mountain building was occurring along the northeastern coast of the present day U.S. and Canada as part of the Taconic Orogeny, resulting in narrowing of the Iapetus Ocean to the east of Laurentia (Blakey, 2004).

The Middle and Upper Ordovician are included as part of the Tippecanoe I second-order supersequence set (Sloss, 1988) of the Tippecanoe first-order megasequence (Sloss, 1963), which spans the Middle Ordovician to the Lower Devonian (fig. 2). This was a time of greenhouse climate conditions, when glaciation was relatively minor and sea-level changes were relatively low amplitude and frequent (Read and others, 1995). The boundary with the earlier Sauk megasequence is characterized by a major unconformity in the North American cratonic interior and lacuna at the cratonic margins (Sloss, 1988). The boundary between the Upper Ordovician and the Lower Silurian (Tippecanoe II supersequence set) is an indistinct disconformity, likely related to Gondwana continental glaciation (Sloss, 1988).

Expression of the Sauk–Tippecanoe unconformity ranges from a completely removed underlying Sauk megasequence on higher parts of the craton, such as central Idaho, to a nearly fully preserved underlying section in marginal basins, such as the Appalachian Basin (Sloss, 1963). Other areas with significant pre-Tippecanoe erosion include the Sweetgrass Arch (in northwestern Montana and southern Alberta, Canada), Wyoming Shelf, Wisconsin Arch, Kankakee Arch (in Indiana and Illinois), and Ozark Dome (in Arkansas and Oklahoma) (Sloss, 1963).

Exceptionally clean quartz sandstone is typical of the early transgressive leg of the Tippecanoe megasequence and provides a sharp contrast to the underlying Sauk carbonates, readily identifying the Sauk-Tippecanoe sequence boundary. In some areas, carbonates were deposited prior to the clastics, such as in the subsiding basins of the south-central U.S.—in Oklahoma and north Texas, West Texas, the Mississippi Valley, and the Illinois Basin (Sloss, 1988). Regularly interbedded quartz sand, marine shale, and minor carbonate followed deposition of carbonates in Oklahoma (Sloss, 1988) and West Texas (Frenzel and others, 1988) depocenters.

Marine transgression most likely occurred across the entire western craton, including the Transcontinental Arch, and onlapping sandstones were deposited during continued overall sea-level rise, punctuated by minor sea-level fall. Sandstones were subsequently eroded on cratonic highs and preserved in lows. Evidence of this scenario is the absence of shorelines or depositional limits in preserved strata (Sloss, 1988) and, in a New Mexico example, lack of a known shoreline or nearshore deposits (Kottlowksi, 1970). As a result, later Middle Ordovician carbonates rest unconformably on the underlying Sauk in some areas without a basal clastic zone (Sloss, 1963). A similar situation is present along the Appalachian cratonic margin. Early Tippecanoe sandstone is not present along the margin; instead, Tippecanoe limestones rest unconformably on Sauk dolostones (Sloss, 1963). By contrast, both clean quartz sandstones and carbonate were deposited along the passive Cordilleran margin, but shale content greatly increases to the west, indicating a shelf-to-slope transition (Sloss, 1988).

The Transcontinental Arch was a significant regional topographic high during the Middle Ordovician and it, along with the Canadian Shield, has been invoked as the source of the clean quartz sandstone of the Simpson in West Texas and Oklahoma (Sloss, 1988). The Pedernal

Massif in central and north-central New Mexico was also a regional high and supplied sediment for Simpson sandstones and siltstones in southeastern New Mexico (Kottlowski, 1970).

A local extension of the Transcontinental Arch, called the Texas Arch (fig. 4), was present during the Middle to Late Ordovician (Wright, 1979) and acted as a boundary between the two primary Simpson Group depocenters. These depocenters in Oklahoma and West Texas have been described as having similar depositional patterns (Suhm and Ethington, 1975), despite being at least partly separated by this broad (600 × 250 mi), low-relief feature (Wright, 1979). The Texas Arch was the dominant positive topographic feature in the Permian Basin region during Simpson time. There is no evidence that the Central Basin Platform was a positive feature during deposition of the Simpson (Frenzel and others, 1988); it formed later during the late Mississippian (Tai and Dorobek, 2000).

This Simpson Group depocenter has historically been referred to as the Tobosa Basin (Wright, 1965). However, the mechanism for development of this basin has not been fully explained, leaving open the possibility of alternate interpretations. The idea of a “basin” may have originated from thickness maps showing thickening toward a central point. Perhaps the most widely available Simpson Group isopach map was originally drafted by Galley (1958) and then republished with some updates by Frenzel and others (1988). This map shows a central thick of more than 2,000 ft in Ward, Reeves, and Pecos Counties and gradual, even thinning to a zero line in north-central Texas and all but southeastern New Mexico. In contrast, a map with documented well control and faults published by the Texas Water Development Board (1972) and presented in simplified format (recontoured without faults) in figure 4, portrays irregular thickness variations. Some of these variations occur across faults, indicating structurally thickened strata, whereas others may be due to deposition on an irregular surface or postdepositional erosion.

Because the Simpson Group was deposited when sea level rose in the Middle Ordovician and marine transgression ended the period of exposure and karstification of the underlying Ellenburger (Kerans, 1988), local thickening may be explained by the irregular accommodation provided by the karsted surface. Thinning is also apparent over preexisting structures (for example, at Midland Farms field in Andrews County), where much of the basal Joins Formation thins on structure (Mears and Dufurrena, 1984).

A significant unconformity also exists between the Simpson Group and the overlying Montoya Group (fig. 2), suggesting that postdepositional erosion may have occurred. Outcrop studies in the Beach and Baylor Mountains indicate that the Montoya directly overlies the Oil Creek Formation, and a distinct unconformity exists between the two (Suhm and Ethington, 1975). This unconformity suggests that the McLish, Tulip Creek, and Bromide Formations were either removed through erosion or never deposited in this area. This truncation occurs progressively from SSW to NNE in a correlation section of subsurface wells in West Texas (fig. 5; Wright, 1965). Postdepositional erosion also took place along the eastern and western extents of the Simpson Group (Gibson, 1965). Whereas many published cross sections (fig. 5) show all Simpson Group formations and members thinning equally, it is more likely that thinning was accomplished through irregular accommodation, erosion, and/or nondeposition. The apparent uniform thinning shown in figure 5 is in the direction of the Texas Arch (fig. 4), a local arm of a regional high during the Tippecanoe sequence. Evidence of subaerial erosion of the uppermost Simpson (Bromide Formation) has been documented at Midland Farms field in Andrews County (Mears and Dufurrena, 1984). These local thinning trends are consistent with widespread erosion of the Simpson Group and equivalent rocks on major arches at the first-order sequence boundary between the Sauk and Kaskaskia sequences (Sloss, 1988).

Finally, structural complexity may be responsible for localized thickening shown on isopach maps in Ward, Reeves, and Pecos Counties (fig. 4). At Waha field in this area, overturned and therefore apparently thickened and repeated Simpson sections were encountered in a vertical well bore and verified by 3-D seismic (Hardage and others, 1999). Fault-thickened Simpson Group strata were also observed at Midland Farms field in Andrews County (Mears and Dufurrena, 1984).

FACIES AND SEDIMENTOLOGY OF THE SIMPSON GROUP

Biostratigraphy and Age

Recent conodont biostratigraphy indicates that Simpson Group rocks were deposited during the Rangerian to middle Turinian stages of the Whiterockian and early Mohawkian series (North American) of the Middle to Late Ordovician (fig. 2). This level of precision has not always been possible: Early Simpson Group biostratigraphy was based on graptolites in the Marathon region outcrops in southwestern Texas, and the succession was dated simply as Middle

Ordovician (Jones, 1953). More precise modern biostratigraphic correlations (using graptolites, trilobites, and conodonts) are now typically possible at the third-order sequence scale (Ross and Ross, 1992) in localized areas. Because the Simpson Group consists of dominantly nonmarine or marginally marine rocks with rare or poorly preserved diagnostic fossils, however, biostratigraphic correlation across North America remains difficult (Ross and Ross, 1992) despite extensive faunal studies (Sweet and others, 1971).

Derby and others (1991) presented what is perhaps the most comprehensive report of conodont work in the Simpson. These authors synthesized more than 20 years of work on Simpson outcrops in southern Oklahoma to define specific conodont zones for the lithostratigraphic formations. Comparison of this synthesis with that of Webby and others (2004) provides a basis for placing the Simpson in a global chronostratigraphic framework (fig. 2). The species-based conodont zonation developed by Webby and others (2004) (fig. 2) now appears to be the standard, rather than the previously proposed numbered zones established by Sweet and others (1971). It is reasonable to assume that these zones are also applicable to West Texas/New Mexico, given the facies similarity between the two depocenters and absence of any published modern studies stating otherwise. The Marathon Uplift succession has also been recently reevaluated using graptolite biostratigraphy. Biostratigraphy in this area has been especially challenging because seemingly noncorrelative graptolite faunas in this area are a function of deeper water depths and different water mass vs. graptolite faunas elsewhere in North America and the world (Goldman and others, 1995). In addition, a significant hiatus occurred between deposition of the Simpson-equivalent Woods Hollow Formation and the overlying Montoya-equivalent Maravillas Formation. These findings were used to define the position of Marathon equivalents in figure 2.

General Facies and Thickness

Rocks of the Simpson Group are composed of interbedded shale, limestone, and sandstone. The Joins and Bromide Formations are sandy carbonates; intervening formations are clay-rich carbonates and shales, each with a basal sandstone member. Sandstones make up only approximately 5 percent of the total thickness of the Simpson Group in West Texas and southeastern New Mexico. This sandstone volume increases toward the apparent source of the

siliciclastics to the northwest: a Precambrian granitic and metamorphic outcrop in New Mexico and the Pedernal Massif in southern Colorado (Wright, 1965).

Simpson Group outcrops in West Texas analogous to the subsurface Permian Basin have been described in the Baylor, Beach, and Sierra Diablo Mountains in Culberson County and in the Marathon Uplift and Solitario regions in Brewster and Presidio Counties in southwest Texas (Jones, 1953; Wilson, 1954; Wright, 1965, 1979; Suhm and Ethington, 1975). This work is primarily lithostratigraphic and biostratigraphic. Early workers described the Baylor and northeastern Sierra Diablo outcrops as consisting of sandstone, dolomite, and green and dark shale with a maximum total Simpson Group thickness of 137 ft in the Baylor Mountains (Jones, 1953; Wright, 1965). Several descriptions of the facies making up Simpson Group formations and members in the subsurface have also been published. These include a summary of various core descriptions from subsurface wells by Wright (1965) and a focused study of the McKee sandstone in several cores from Crane, Andrews, and Lea (New Mexico) Counties by Bosco and Mazzullo (2000).

Simpson Group thickness is highly variable throughout West Texas and New Mexico. A summation of the maximum ranges (from Wright, 1965) for each formation yields a maximum Simpson Group thickness of 1,650 ft. However, the total thickness of 400 to 320 ft reported in a study of cuttings from Midland Farms field wells in Andrews County (Mears and Dufurrena, 1984) is probably more typical of fields outside the thickest part of the depocenter.

Joins Formation

Distribution and Age

The Joins Formation is Middle Ordovician (Whiterockian North American Stage), according to age and conodont relationships in Pope (2004) and Webby and others (2004) (fig. 2). Distribution is likely irregular, given that it was deposited on the karst topography of the underlying Ellenburger; partial infilling relationships between the Joins and the underlying El Paso/Ellenburger Groups support this hypothesis (Suhm and Ethington, 1975). The Joins appears to be present in both Oklahoma and West Texas/New Mexico, given conodont biostratigraphic correlations (Suhm and Ethington, 1975).

Facies

The Joins is composed of slightly shaly limestone that grades into dolostone (Wright, 1965). The fine crystalline dolostone facies is argillaceous (silty to sandy), pale-orange, and thin to medium bedded, and it contains trilobites and brachiopods (Suhm and Ethington, 1975). Both lithofacies contain frosted quartz grains and clasts of the Ellenburger (cherty dolostone) below. In addition, the basal Joins Formation is glauconitic and contains thin beds of shale and sandstone in some areas (Wright, 1965).

Depositional Setting

Given the similarity in facies between the Texas/New Mexico and Oklahoma depocenters, a depositional model proposed for Arbuckle Mountain outcrops in Oklahoma should also be applicable to the Simpson Group in Texas and New Mexico. Denison (1997) interpreted the Joins to have been deposited during relatively low sea level, with early shallow marine conditions and subaerial exposure in some areas, followed by a transition to terrigenous conditions.

Subsurface Recognition and Correlation

The Joins exhibits a high gamma-ray response and reverse or positive spontaneous potential typical of shales and other clay-rich facies (figs. 6, 7). These log characteristics are markedly different from those of the underlying Ellenburger carbonate. Because it was deposited on the irregular Ellenburger topography, regional correlation is often not possible, although widely published Simpson Group cross sections show it to be regionally present and correlative (fig. 5).

Formations with a Basal Sandstone Member:
Oil Creek, McLish, and Tulip Creek

The middle three Simpson Group formations each contain a basal sandstone member overlain by mud-rich carbonate and shale strata. From oldest to youngest (with basal sandstone member) these are the Oil Creek Formation (Connell Sandstone Member), the McLish Formation (Waddell Sandstone Member), and the Tulip Creek Formation (McKee Sandstone Member) (fig. 2).

Distribution and Age

Classic lithostratigraphic correlation sections depict all three formations areas present over much of the subsurface (fig. 5, cross-section locations in fig. 4); however, it is likely that the section is incomplete in many areas owing to erosion or nondeposition. For example, only the Oil Creek Formation is present in the Beach and Baylor Mountain outcrops, where a distinct unconformity separates the Oil Creek from the overlying Montoya carbonate (Suhm and Ethington, 1975). This observation implies that the rest of the Simpson Group (McLish, Tulip Creek, and Bromide) was removed by erosion or not deposited in this area. All three formations are Middle Ordovician (Whiterockian North American Stage) according to age and conodont relationships (Pope, 2004; Webby and others, 2004) (fig. 2).

Facies

The Oil Creek Formation is composed primarily of green, and locally red, shale with thin limestone interbeds; the Connell Sandstone Member consists of medium to coarse, well-rounded, calcareous sandstone in the subsurface and is locally iron rich and interbedded with red and gray shale (Wright, 1965). In Beach and Baylor Mountain outcrops, this sandstone is fine to coarse grained and contains frosted rounded quartz grains with variable amounts of dolomite cement and quartz overgrowths (Suhm and Ethington, 1975) and, locally, thin beds of light-colored dolostone. These authors noted that the Connell resembles equivalent Midcontinent sandstones in containing 95 percent or more quartz and well-sorted, rounded, frosted grains. Overlying the Connell, the Oil Creek Formation comprises a series of brownish-gray dolostone and argillaceous dolostone intervals that range from 20 to 45 ft in thickness, exhibit very fine crystal size, and contain local stromatolites, chert, and vugs (Suhm and Ethington, 1975).

The McLish Formation consists of gray-green shale interbedded with sandy limestone and fine-grained sandstone; medium-coarse grained calcareous sandstones make up the Waddell Member at the base of the McLish Formation in the subsurface (Wright, 1965). Shale dominates the section north of Ward and Crane Counties, and shaly limestone dominates the subsurface elsewhere outside of the main producing area.

Rocks of the Tulip Creek Formation are primarily thinly bedded, green shale thinly interbedded with limestone in the subsurface. Two sandstone layers separated by green shale and sandy limestone characterize the McKee; the sandstones are medium to coarse, white, green, or

red in color, and they contain phosphate, as well as abundant frosted quartz (Wright, 1965). The basal McKee Member comprises sandstone, muddy sandstone, and sandy mudstone lithologies in cores from Andrews and Crane (Texas) and Lea (New Mexico) Counties (Bosco and Mazullo, 2000). The sandstones are subquartzose to quartzose (50–100 percent quartz) quartz arenites (<2 percent feldspar) that are fine to fine grained and moderately well sorted. Deformed rounded mudstone lithoclasts of varying sizes are present locally. Four distinct McKee facies were observed in conventional cores in Andrews and Crane Counties, Texas, and Lea County, New Mexico: (1) green-yellow laminated very fine to fine-grained muddy quartzose sandstones with bioturbation and abundant clay and occasional phosphate grains; (2) sandstones similar to those in 1 but containing common carbonate, phosphate, clay and lithoclasts, as well as scattered fossils; (3) dark-colored, laminated, very fine to medium-grained muddy sandstone and sandy mudstone with abundant fossils and common phosphate grains; and (4) laminated, very fine grained, quartzose, yellow-brown sandstones with rare green-brown mudstone interlaminae, bioturbation, and common fossils (Bosco and Mazzullo, 2000).

A new core description conducted during this study provides additional insight into the McKee sandstone member of the Tulip Creek Formation (fig. 8). Four distinct facies and a range of grain sizes and structures were observed, including (1) massive crossbedded, tan, locally bioturbated sandstone (fig. 9a); (2) mixed carbonate and shale with carbonate lenses (fig. 9b) (3) finely laminated gray carbonate and green-gray shale with bioturbation, roots, and limited sand (fig. 10a); and (4) green-black carbonaceous shale (fig. 10b). All four facies occur over a relatively short section of core (core in fig. 11 and corresponding log and core description in fig. 8).

Depositional Setting

A depositional model proposed for the Simpson Group in the Arbuckle Mountain outcrops in Oklahoma (Denison, 1997) appears applicable to the Simpson Group in West Texas. This model proposes that basal Oil Creek, McLish, Tulip Creek, and Bromide Formation sandstones were formed by the reworking of clean eolian sands from terrigenous sources during marine transgression. During sea-level highstand, a peritidal carbonate platform developed, accounting for the deposition of the carbonate units in the upper parts of each formation. This model is consistent with outcrop observations in West Texas: the Connell sandstone was

interpreted to have been deposited in high-energy shoreface and nearshore environments on the basis of observations from Beach Mountain outcrops (Suhm and Ethington, 1975).

Diagenesis

Simpson Group sandstones are exceptionally clean. However, carbonate cementation is locally common and can reduce porosity and permeability. Cementation ranges from absent to pervasive in all three sandstone intervals (Wright, 1965). Detrital clays (dominantly illite) and authigenic cements—carbonate, clay, and quartz—are also present in McKee sandstone cores from Andrews and Crane (Texas) and Lea (New Mexico) Counties (Bosco and Mazullo, 2000). The clays are grain lining, and the carbonate cements are pore filling in these cores. These authors demonstrated that bioturbation and mineralogy are systematically related to color in these sandstones. Brown and yellow sandstones are typically clay free and contain authigenic quartz cement. Gray sandstones contain large amounts of micritic mud and carbonate cement. Green sandstones contain glauconite and illite (lighter variations contain less clay and are friable). Red sandstones owe their color to hematite-rich clay. In addition to detrital clays, white and black phosphatic grains are also present in the McKee sandstone (Wright, 1965).

Subsurface Correlation

Published literature on modern subsurface wireline correlations and seismic interpretation in the Simpson is sparse. Given the mixed lithology of the Simpson—including carbonate, sandstone, and shale—both types of correlation present challenges.

Most published wireline correlations date to the discovery of the major Simpson Group fields (1965 or earlier) and as such are based on spontaneous-potential–resistivity wireline logs (fig. 7). Modern gamma-ray–neutron-porosity wireline logs are available from fields with production above and below the Simpson, such as at Dollarhide field (fig. 6), but the Simpson is typically not correlated on these logs in published cross sections.

Not only does the mixed lithology present challenges in seismic interpretation, but the complexity of structures involving the Simpson Group can also further distort imaging of this succession. Seismic data at Waha field in Reeves and Pecos Counties show that complex faulting and overturned strata can be misleading when Simpson Group horizons are picked. Hardage and

others (1999) observed that Simpson beds were overturned, highly faulted, and folded, resulting in apparent thickening and repeat sections in vertical well bores.

Published gamma-ray–neutron type logs characterize the sandstone members as having a low gamma response and high neutron response (fig. 6), and the mixed carbonate and shale parts of the formations as having a mixed gamma response and low neutron response. Early electric logs show upward-coarsening relationships (normal or negative spontaneous potential) in Connell, Waddell, and Oil Creek type logs at productive fields (fig. 7) but lack truly diagnostic log character in correlation sections (fig. 5).

Bromide Formation

Distribution and Age

Like the McLish and Tulip Creek Formations, the Bromide Formation is absent owing to erosion or nondeposition in the Beach and Baylor Mountain outcrops, where a distinct unconformity separates the Oil Creek from the overlying Montoya carbonate (Suhm and Ethington, 1975), but it is present in much of the subsurface (Wright, 1965). The Bromide is Middle to Late Ordovician (Whiterockian to Mohawkian North American Series) in age, according to conodont relationships portrayed by Pope (2004) and Webby and others (2004) (fig. 2).

Facies and Depositional Setting

The Bromide Formation comprises massive fossil-rich limestone that is thinly interbedded with green shale and sandstone in the subsurface; the limestone is increasingly sandy and shaly away from the Central Basin Platform, to the south, southeast, and west (Wright, 1979). During Bromide time, marine transgression was more extensive than during earlier Simpson deposition (Oil Creek, McLish, and Tulip Creek), resulting in shallow subtidal to supratidal marine conditions and less deposition of eolian sand (Denison, 1997).

Subsurface Recognition and Correlation

Because of similarities between lithologies of the Bromide and those of the underlying upper Tulip Creek, the base of the Bromide is difficult to characterize on wireline logs. In contrast, the top of the Bromide is readily defined on wireline logs; the clean, low-gamma-ray

wireline response of the overlying Montoya Formation is distinct from the higher gamma-ray response of the Bromide. A type log from Block 31 field in Crane County (fig. 7a) shows that the Bromide has resistivity higher than that of the underlying Tulip Creek. However, this difference is less distinct in many wells (figs. 5, 7b). On gamma-ray–neutron logs from Dollarhide field (fig. 6), the Bromide shows the expected response for a primarily carbonate section with low radioactivity and high apparent neutron porosity. Interbedded shale and sandstone are also distinct (high radioactivity, low neutron) on these logs.

Woods Hollow Formation

The Woods Hollow Formation consists of Simpson Group-age outcrops in the Marathon Uplift and Solitario regions of southwestern Texas (Jones, 1953) (fig. 2). In the Marathon region, these rocks are green-black shale with thinly interbedded siltstone and limestone, and they contain scattered conglomerate boulders; in the Solitario region, these rocks are green-black shale and thin-bedded sandstone (Wright, 1965, 1979; Wilson, 1954). The Woods Hollow Formation was deposited in deeper water than the Simpson Group. Graptolite-brachiopod-pelagic trilobite assemblages characteristic of deep-water conditions typify Marathon-area outcrops as compared with the shallow-water corals, bryozoans, sponges, calcareous brachiopods and nektonic-benthic trilobites reported in West Texas and Oklahoma outcrops (Wilson, 1954). Information from these outcrops is useful in understanding regional paleogeography but not as relevant to Simpson Group production in the subsurface Permian Basin owing to marked differences in facies.

Sequence Stratigraphy of the Simpson Group

It is important to keep in mind that Simpson Group formations and members are lithostratigraphic units defined in outcrop, not chronostratigraphic units. Several authors have recognized the time-transgressive nature of Simpson formations and members in Oklahoma, where subsurface data and interpretations are more abundant owing to the greater economic significance of Simpson reservoirs there. Statler (1965) published an early sequence stratigraphic interpretation (fig. 12) that was then incorporated into the model proposed by Candelaria and others (1997) (fig. 13). Candelaria and others (1997) presented perhaps the most complete description of Simpson formations and members in terms of third-order sequences. This

sequence stratigraphic framework developed for Oklahoma is likely applicable to the West Texas subsurface, given the similarities in depositional setting.

The five Simpson Group lithostratigraphic formations have been interpreted to represent four (fig. 13) or five third-order sequences suggested by sea-level curve (fig. 2). These sequences represent the early parts of the second-order Tippecanoe I sequence (Middle and Upper Ordovician) and the first-order Tippecanoe megasequence (Middle Ordovician to Lower Devonian) (Sloss, 1988).

The Simpson Group was deposited on the Lower Ordovician Ellenburger, following a hiatus during the Rangerian stage of the Middle Ordovician, and it was typically overlain by the Upper Ordovician Montoya Group, following a hiatus during the Chatfieldian stage (fig. 2). The basal Simpson unconformity is both a first- and second-order sequence boundary, and the upper unconformity is a third-order sequence boundary (fig. 2). Locally, both the base and top of the Simpson Group are composite unconformities. In southern New Mexico, for example, the Simpson Group was deposited on Precambrian basement (Lower Ordovician Ellenburger absent), and in the Central Basin Platform and Reagan uplift areas the Simpson Group is overlain by Pennsylvanian and Lower Permian strata (Upper Ordovician-Mississippian absent and Simpson somewhat eroded) (Wright, 1965).

Sea-level fluctuations defining third-order sequences in the Ordovician were given for North America and Europe by Ross and Ross (1992) (sea-level curve in fig. 2). These cycles, lasting 1 to 8 million years, were associated with sea-level changes typically of 66 to 328 ft (Ross and Ross, 1992). An idealized Ordovician cratonic sequence consists of a transgressive sandstone base followed by a maximum flooding condensed section, early highstand normal marine limestones, and late highstand restricted carbonate and evaporate (Schutter, 1992). Sandstones represent sequence bases in this area, consisting of quartz arenite (arkosic where filling irregular lows) deposited by eolian to coastal processes. Green marine shales or evaporites are locally present with these sandstones. Organic-rich green, pyritic, or brown shales were commonly deposited next. Normal marine conditions followed during maximum flooding, with deposition of bioturbated subtidal wackestones and packstones. High-energy grainstone shoal facies were locally deposited next, followed by peritidal laminated and fenestral lime mudstones, dolostones, and evaporites during later highstand, with evidence of subaerial exposure and possible karst.

Candelaria and others (1997) subdivided the Simpson Group into four third-order sequences on the basis of Oklahoma subsurface data (fig. 13). In their mode, the Joins represents the first of these third-order sequences (fig. 2, O5) and differs in style from the successive sequences in that carbonate was deposited throughout the sequence (with some minor basal clastics). These authors documented many 3- to 10-ft-thick fourth- or fifth-order sequences in the Joins, each consisting of sandy siltstone overlain by coarse calcarenite and generally becoming increasingly sand dominated up section in Arbuckle Mountain outcrops.

By contrast, the overlying three Simpson Group sequences contain basal sandstones overlain by shale and much less carbonate. Simpson strandline fluvial and eolian sandstones were deposited initially during sea-level lowstands and were then reworked into a series of widespread, back-stepping, shoreface complexes representing the transgressive systems tract during sea-level rise (Candelaria and others, 1997). Alternatively, the sandstones may represent only the transgressive systems tract without initial fluvial or eolian deposits (Schutter, 1992). In either case, increased clastic input from eroding regional highs was essential to the carbonate to clastic facies change from the underlying Joins and restricted Ellenburger carbonate.

The Oil Creek Formation comprises the first sandstone-based Simpson sequence (Candelaria and others, 1997); the basal Oil Creek sandstone (equivalent to the Connell member in the Permian Basin) represents both a lowstand wedge and a transgressive shoreface complex in this area (fig. 13). The top of O6 (*polonicus* zone, fig. 2) is represented by a hiatus across New Mexico, Texas, and Oklahoma. The next sequence is composed of the McLish Formation (Candelaria and others, 1997); basal McLish sandstones (equivalent to the Waddell member in Texas/New Mexico) comprise transgressive shoreface complexes (without prior lowstand deposition) (fig. 13), suggesting an overall decrease in accommodation in this area (fig. 2, O7).

Both the Tulip Creek Formation and its basal sandstone (McKee member in the Permian Basin) (fig. 2, O8) and the Bromide Formation (fig. 2, O9) comprise the third sandstone-based sequence (Candelaria and others, 1997). The basal sandstone is again interpreted to represent the transgressive systems tract only. This grouping of both the Tulip Creek and Bromide into one sequence is consistent with the interpretation of Statler (1965), but not the sea-level curve given by Ross and Ross (1992) (fig. 2), which suggests two sea-level rise-and-fall events during this time.

Insights into the Tulip Creek cyclicity are provided by core from the McKee member in Pecos County. Cycles within the McKee section here are upward fining (fig. 8). Cycle bases are typically bioturbated, followed by high-energy planar, crossbedded, massive sandstone (facies 1, fig. 9a). Cycles fine into mixed carbonate and shale (facies 2, fig. 9b), finely laminated carbonate and shale (facies 3, fig. 10a) and, in some cases, green carbonaceous shale (facies 4, fig. 10b). These cycles shallow consistently upward, as shown by an upward decrease in high-energy planar crossbeds and an increase in bioturbation. Unfortunately, core coverage is too limited for interpretations to be made about larger scale sequence stratigraphic patterns.

However, sequence stratigraphic interpretations of the Simpson Group have been established in Oklahoma, and the similarity of facies stacking patterns between the Texas and Oklahoma depocenters suggests that it is reasonable to extrapolate the sequence stratigraphic model established by Candelaria and others (1997) to the Texas succession. This approach implies that the Connell sandstone of sequence O6 represents both lowstand and stranded transgressive shoreface deposits. The Waddell and McKee members represent transgressive shoreface deposits of sequences O7 and O8, respectively (fig. 2). Whereas the general ideas presented by Candelaria and others (1997) describe the facies observed in the Texas/New Mexico depocenter, as well as that of Oklahoma, several variations are apparent from wireline-log patterns and cores from Permian Basin successions.

Log patterns in the Texas/New Mexico depocenter depict a single, thin, upward-coarsening sandstone typical of transgressive deposits picked as the Connell member and representing the base of sequence O6 (fig. 2). In Crane and Pecos Counties at Abell, Block 31, and McKee fields (fig. 7a), there is no evidence of the blocky, sharp-based pattern typical of lowstand deposits, such as those described by Candelaria and others (1997). The Connell sandstone is not definable in the logs from fields farther north (Keystone field in Winkler County, TXL field in Ector County, or Martin field in Andrews County). Log patterns do show, however, thin, upward-coarsening sandstone at Keystone and Martin (fig. 7b). The section at TXL field, a bit farther to the east, appears shaly throughout the interval and may have been deposited in a more distal shelf setting.

Similarly, in the next sequence (O7), logs from wells in the Texas/New Mexico depocenter indicate a thin, upward-coarsening sandstone at the base of the sequence. This sandstone is called the Waddell member and is present at both Bell and McKee fields in Pecos

and Crane Counties and at Martin field in Andrews County (fig. 7b). Two thicker, upward-coarsening sandstones also called the Waddell member are present at Block 31 (fig. 7a), Keystone, and TXL fields. These patterns are consistent with the Candelaria and others (1997) interpretation of transgressive deposits at the base of this sequence in the depocenter.

Log patterns and core descriptions in the Texas/New Mexico depocenter suggest that not one but two (Candelaria and others, 1997) successive Simpson Group sequences were then deposited. The first, sequence O8, mimics the previous sequence, containing two upward-coarsening to serrate sandstones at the base of the sequence. These sandstones are assigned to the McKee sandstone and are present in most Texas/New Mexico fields (fig. 7). These log-defined facies patterns can also be interpreted as transgressive deposits, an interpretation that is compatible with the Candelaria and others (1997) model. The next younger sequence, O9, shows even greater marine transgression, with a decrease in clastic input and better development of marine carbonates. It is difficult to ascertain the presence of a sequence boundary without cores, but sea-level curves suggest a marked decrease, followed by increase, in sea-level change at this boundary (fig. 2).

Reservoir Development

Simpson Group reservoirs are developed in the three sandstone members: the Connell, Waddell, and McKee. Each succession has highly variable thickness and continuity. Increasing thickness trends from north to south (eastern Lea County, NM, to eastern Ward County are 20 to 70 ft for the Connell, 20 to 120 ft for the Waddell, and 100 to 175 ft (central Winkler County) for the McKee (Wright, 1979). The maximum thickness of the McKee sandstone in the Permian Basin has been recently reported as approximately 230 ft (Bosco and Mazzullo, 2000). These data suggest that a total of 420 ft of gross sandstone could be encountered in the Simpson Group if the maximum thickness of each sandstone member occurred in the same location in the Permian Basin. Conversely, a minimum Simpson gross sandstone thickness could be as little as 140 ft in the Permian Basin and even less where the Simpson has been eroded. The Simpson Group as a whole is more sandstone dominated in Oklahoma and Arkansas: gross sandstone thickness is more than 400 ft in south-central Oklahoma and more than 300 ft thick in western Arkansas (Holden, 1965).

Reported maximum thicknesses for the entire reservoir-bearing formations (sandstone members and overlying shale) in the subsurface Permian Basin are 280 ft (Oil Creek), 475 ft (McLish), and 400 ft (Tulip Creek) (Wright, 1979). The nonreservoir Bromide and Joins Formations reach a maximum thickness of 375 and 120 ft in the subsurface Permian Basin, respectively (Wright, 1965). The Woods Hollow Formation is 180 to 500 ft thick in the Marathon region and 340 to 400 ft thick in the Solitario region (Wilson, 1954; Wright, 1965, 1979).

Reservoir Distribution

Simpson Group production in West Texas and southeastern New Mexico was developed in the Waddell sandstone in Sand Hills field in Crane County in 1936. This field (fig. 1) remains one of the top three producers in terms of cumulative production (Dutton and others, 2005). The first McKee sandstone production occurred soon after, in 1938, in Pecos County, and Connell sandstone production began in 1948 in Crane County (Wright, 1965). Production is developed in the Waddell sandstone in Crane, Ector, and Pecos Counties; in McKee sandstones in Andrews, Crane, Ector, Lea (New Mexico), Pecos, and Winkler Counties; and in Connell sandstones in Andrews, Crane, Ector, Lea (New Mexico), Pecos, and Terrell Counties (Wright, 1979).

As a reservoir play in Texas and New Mexico, the Simpson Group comprises 19 reservoirs with individual cumulative production greater than 1 MMbbl of oil through 2000 that totaled only 103.2 MMbbl of cumulative production (Dutton and others, 2005). The top three fields accounting for most of this production include, in descending order, Running W field in Crane County (25.3 MMbbl), Hare field in Lea County (New Mexico) (17.2 MMbbl); and Sand Hills field in Crane County (13.1 MMbbl) (fig. 1). All other Simpson fields have produced less than 10 MMbbl of cumulative production, and only two have produced more than 50 MMbbl. All of these fields were discovered prior to 1965. Note that the Simpson Group is present west, east, and south of the production-based play area and especially thick to the west (play area defined by Dutton and others, 2005, and shown in fig. 1; Simpson thickness shown in fig. 4).

Porosity Development

Simpson Group clastic reservoirs are composed of extremely mature quartz sandstones with primary porosity (Schutter, 1992). Porosity varies from 7 percent at Connell Block 31 to

16 percent at Martin McKee (Tyler and others, 1991). Permeability averages 45 md in Crawar Waddell (Wojcik, 1990) and 164 md in Running W Waddell field (Galloway and others, 1983).

Reservoir quality is controlled by grain size, thickness, degree of carbonate cementation, and interbedded silts or shales. The McKee member has the best reservoir quality of the three Simpson Group sandstones. It is the coarsest, thickest, and cleanest in the Central Basin Platform area (Wright, 1965). Porosity in the Connell sandstone is generally high, but permeability decreases locally where sandstone grades into sandy shale (Wright, 1965). Permeability reduction in the Waddell sandstone has also been observed locally where silt is present (Wright, 1965). Pore-filling carbonate cements and pore-lining clays can commonly reduce porosity (Galley, 1958). No regional or stratigraphic patterns of cementation or clay presence have been reported.

Traps, Seals, and Sources

Oil was trapped in the producing sandstones of the Simpson Group along the postdepositionally folded and faulted structures of the Central Basin Platform, with Simpson shales providing the seal (Dutton and others, 2005). High-angle faults on the flanks of the anticlines also contributed to trap formation, as observed at Teague McKee field. Anticlinal structural traps are responsible for reservoir accumulation in the following fields (and formations): Block 31 (Connell) in Crane County, TXL (Waddell) in Ector County, and Warren (McKee) in Lea County, New Mexico (Wright, 1965).

Other reservoirs produce where Simpson Group sandstones are truncated by erosion along the flanks of anticlines underneath a major regional unconformity. The seal is provided by overlying post-Simpson rocks, mainly Pennsylvanian and Permian shales and carbonates (Gibson, 1965; Wright, 1979; Galloway and others, 1983). The unconformity was formed during major late Paleozoic uplift that formed the Central Basin Platform and the smaller structures associated with Simpson traps. The top-producing Running W field in Crane County (fig. 1) produces where the Waddell sandstone has been erosionally truncated and overlain by Permian rocks (Galloway and others, 1983). Permian strata similarly seal both Connell and McKee sandstones at Hare field in Lea County, New Mexico (Wright, 1965)—another top producer (fig. 1). Crawar Waddell field produces from a north-south-trending anticline that is bound on the east by a northwest-southeast-trending reverse fault (Wojcik, 1990).

The only documented purely stratigraphic traps in the Simpson Group are at Abell field (Crane and Pecos Counties), owing to an updip decrease in porosity in tilted Waddell reservoir sandstones, and at Tucker field (Crane County), where Waddell sandstones become increasingly shaly and therefore less permeable updip.

Each producing sandstone interval in the Simpson Group has its own oil-water contact, suggesting sealing and in situ generation of hydrocarbons by intervening shales (Williams, 1977). Where both Ellenburger and Simpson reservoirs are productive along the postdepositionally folded and faulted structures of the Central Basin Platform region, similarities in oil character also suggest a common source (Wright, 1965, 1979).

Simpson Group shales are considered primary pre-Permian source rocks (Williams, 1977). The source capabilities of the Simpson Group are supported by the presence of Ordovician oil in Ellenburger reservoirs where overlain by Simpson shales and the lack thereof in Ellenburger reservoirs where the Simpson Group is absent. The area of productive Ellenburger reservoirs, in the Central Basin Platform and southwestern Midland Basin regions, coincides with the thickest deposition of the Simpson Group, suggesting that the superjacent Simpson Group shales provided the hydrocarbon source (Gibson, 1965). The oil-prone relationship between total organic carbon (TOC) and total hydrocarbons in Simpson Group shales in both west Texas and Oklahoma, compared with the lack of such a relationship in Ellenburger samples, lends additional support to the idea that Simpson Group shale sourced Ordovician reservoirs (Katz and others, 1994). Simpson Group shales reached the oil window of hydrocarbon generation in the Late Permian and may have generated and expelled 180 to 540 Bbbl of oil for migration into Central Basin Platform reservoirs (Katz and others, 1994).

Opportunities for Additional Resource Recovery

Simpson Group exploration strategies have focused almost exclusively on structural traps. However, extensive stratigraphic traps are likely in this depositional setting. Thus, the Simpson Group may contain a distributed but potentially significant remaining resource. Simpson Group stratigraphic traps may have been created in three systems tracts: (1) lowstand sandstones, (2) transgressive shoreface sandstones, and (3) aggradational carbonate shoal facies and progradational carbonate banks (Candelaria and others, 1997).

Stratigraphic traps are underexplored relative to structural Simpson Group traps (Candelaria and others, 1997) and have potential for future exploration. To accomplish such exploration, new regional and detailed wireline correlations using gamma-ray–neutron logs in a sequence stratigraphic framework will be necessary. Whereas wireline logs are widely available because of extensive underlying Ellenburger production, cores and core data are sparse and discontinuous. Once stratigraphic traps are identified, Simpson Group production could be accomplished through low-cost recompletion of existing Ellenburger wells.

SUMMARY AND CONCLUSIONS

The Middle Ordovician Simpson Group contains a highly varied mixture of both reservoir and nonreservoir rocks that have been poorly examined owing to its relatively low contribution to Permian Basin production. Simpson rocks were deposited in greenhouse conditions during the early transgressive leg of the Tippecanoe megasequence, following an extensive hiatus and development of a karst topography on the underlying Lower Ordovician Ellenburger carbonates of the Sauk megasequence. Simpson production is from three sandstone units in the middle of the group, each sourced from eroding highs to the north and east and transported to the cratonic margins by eolian and fluvial processes. These sandstones represent lowstand and/or early transgressive deposits of three third-order sequences; nonreservoir shales and clay-rich carbonates deposited during maximum flooding and normal marine and restricted carbonates deposited during highstand compose the balance of the sequences. Most published interpretations for West Texas and New Mexico are based on lithostratigraphic analysis and therefore do not depict the true reservoir geometry of these irregularly distributed reservoir sandstones. Modern sequence stratigraphic interpretations are sparse and are generally based on Simpson Group rocks in Oklahoma, where production is more significant. New regional and detailed wireline correlations using gamma-ray–neutron logs and development of a sequence stratigraphic framework are necessary for a better understanding of the remaining potential of Simpson Group sandstones. Not all sandstones are likely present in all areas owing to their depositional setting facies changes up- and downdip, and many of the remaining traps are likely stratigraphic and therefore subtle. However, there are several reasons to reconsider the Simpson Group: reservoir quality is generally adequate; the sandstones, although thin, can be stacked; source rock is present within the group; and reservoir sandstones are well sealed. Extensive

production of the underlying Ellenburger also means that wireline-log data are abundant, and Simpson production could be accomplished through low-cost recompletions of existing Ellenburger wells.

REFERENCES

- Barnes, V. E., Cloud, P. E., Jr., Dixon, L. P., Folk, R. L., Jonas, E. C., Palmer, A. R., and Tynan, E. J., 1959, Stratigraphy of the pre-Simpson Paleozoic subsurface rocks of Texas and southeast New Mexico: University of Texas, Austin, Bureau of Economic Geology Publication 5924, v. I–II, 836 p.
- Blakey, R. C., 2004, Regional paleogeographic views of earth history, sedimentation, tectonics, and paleogeography of the North Atlantic region, Mid-Ordovician: Northern Arizona University, <http://jan.ucc.nau.edu/~rcb7/470NAt.jpg>.
- Bosco, M. J. and Mazzullo, J., 2000, Lithology and cyclicity in Middle Ordovician McKee Sandstone Member (Tulip Creek Formation, Simpson Group) in the Tobosa Basin, Southeast New Mexico and West Texas, *in* Johnson, K. S., ed., Marine clastics in the southern Midcontinent, 1997 Symposium, Oklahoma Geological Survey Circular 103, p. 53–64.
- Candelaria, M. P., Handford, C. R., and Reed, C. L., 1997, Sequence model for the Simpson Group of the southern mid-continent: key to a new stratigraphic play, *in* Johnson, K. S., ed., Simpson and Viola groups in the southern Midcontinent, 1994 Symposium, Oklahoma Geological Survey Circular 99, p. 218–223.
- Cocks, L. R., and Torsvik, T. H., 2004, Major terranes in the Ordovician, *in* Webby, B. D., Paris, F., Droser, M. L., and Percival, I. G., eds., The great Ordovician biodiversification event: Columbia University Press, p. 61–67.
- Cole, C. T., Cordry, C. D., and Hemphill, H. A., 1942, McKee and Waddell sands, Simpson Group, West Texas: American Association of Petroleum Geologists Bulletin, v. 26, no. 2, p. 279–282.
- Decker, C. E. and Merritt, C. A., 1931, The stratigraphy and physical characteristics of the Simpson Group: Oklahoma Geological Survey Bulletin 55, p. 5-49.

- Denison, R. E., 1997, Contrasting sedimentation inside and outside the southern Oklahoma aulacogen during the middle and late Ordovician, *in* Johnson, K. S., ed., Simpson and Viola groups in the southern Midcontinent, 1994 Symposium, Oklahoma Geological Survey Circular 99, p.39–47.
- Derby, J. R., Bauer, J. A., Miller, M. A., Creath, W. B., Repetski, J. E., Dresbach, R. I., Ethington, R. L., Loch, J. D., Stitt, J. H., Sweet, W. C., McHargue, T. R., Taylor, J. F., Miller, J. F., and Williams, M., 1991, Biostratigraphy of the Timbered Hills, Arbuckle, and Simpson Groups, Cambrian and Ordovician, Oklahoma: a review of the correlation tools and techniques available to the explorationists: Oklahoma Geological Survey Circular 92, p. 15–41.
- Dutton, S. P., Kim, E. M., Broadhead, R. F., Breton, C. L., Raatz, W. D., Ruppel, S. C., and Kerans, C., 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.
- Frenzel, H. N., Bloomer, R. R., Cline, R. B., Cys, J. M., Galley, J. E., Gibson, W. R., Hills, J. M., King, W. E., Seager, W. R., Kottlowski, F. E., Thompson, S., III, Luff, G. C., Pearson, B. T., and Van Sicken, D. C., 1988, The Permian Basin region, *in* Sloss, L. L., ed., Sedimentary cover—North American Craton, U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. D-2, p. 261–306.
- Galley, J. D., 1958, Oil and gas geology in the Permian Basin in Texas and New Mexico, *in* Weeks, L. G., ed., Habitat of oil—a symposium, Tulsa, Oklahoma: American Association of Petroleum Geologists, p. 395–446.
- Galloway, W. E., Ewing, T. E., Garrett, C. M., Jr., Tyler, N., and Bebout, D. G., 1983, Atlas of major Texas oil reservoirs: The University of Texas at Austin, Bureau of Economic Geology, 139 p.
- Gibson, G. R., 1965, Oil and gas in southwestern region—geologic framework, *in* Young, A., and Galley, J. E., eds., Fluids in the subsurface environment: American Association of Petroleum Geologists Memoir 4, p. 66–100.

- Goldman, D., Bergström, S. M., and Mitchell, C.E., 1995, Revision of the Zone 13 graptolite biostratigraphy in the Marathon, Texas, standard succession and its bearing on Upper Ordovician graptolite biogeography: *Lethaia*, v. 28, no. 2, p. 115–128.
- Hardage, B. A., Pendleton, V. M., and Asquith, G. B., 1999, 3-D seismic interpretation of deep, complex structures in the Delaware Basin, West Texas: The University of Texas at Austin, Bureau of Economic Geology Geologic Circular 99-1, 42 p.
- Herald, F. A., 1957, Occurrence of oil and gas in West Texas: University of Texas, Austin, Bureau of Economic Geology Publication 5716, 442 p.
- Holden, F. T., 1965, The Simpson Group of the Arkoma Basin, Oklahoma and Arkansas, *in* Herndon, T. and Schramm Jr., M. W., eds., Symposium on the Simpson: Tulsa Geological Society Digest, v. 33, p. 134–143.
- Jones, T. S., 1953, Stratigraphy of the Permian Basin of West Texas: West Texas Geological Society Publication 53-29, 63 p.
- Katz, B. J., Robison, V. D., Dawson, W. C., and Elrod, L. W., 1994, Simpson-Ellenburger petroleum system of the Central Basin Platform, West Texas, U.S.A., *in* Magoon, L. B., and Dow, W. G., eds., The petroleum system; from source to trap: American Association of Petroleum Geologists Memoir, v. 60, p. 453–461.
- Kerans, C., 1988, Karst-controlled reservoir heterogeneity in Ellenburger Group carbonates of West Texas: American Association of Petroleum Geologists Bulletin, v. 72, p. 1160–1183.
- Kottlowski, F. E., 1970, Influence of the Pedernal uplift on sedimentation, *in* Basins of the Southwest, v. 1, Symposium of the 10th Annual Meeting Southwest Section of American Association of Petroleum Geologists, February 7–9, 1968, Wichita Falls, Texas: West Texas Geological Society Publication 70-68, p. 21–40.
- Mears, C. E. and Dufurrena, C. K., 1984, Pre-Leonardian geology of Midland Farms field area, Andrews County, Texas, *in* Transactions, Southwest Section AAPG, 1984 Convention, Midland, Texas: West Texas Geological Society Publication 84-78, p. 111–123.

- Northcutt, R. A. and Johnson, K. S., 1997, Major Simpson and Viola oil and gas reservoirs in Oklahoma, *in* Johnson, K. S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 Symposium: Oklahoma Geological Survey Circular 99, p. 48–57.
- O'Brien, J. E., and Derby, J. R., 1997, Progress report on Simpson and Viola correlations from the Arbuckles to the Ozarks, *in* Johnson, K. S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 Symposium: Oklahoma Geological Survey Circular 99, p. 260–266.
- Pope, M. C., 2004, Cherty carbonate facies of the Montoya Group, southern New Mexico and western Texas and its regional correlatives: a record of Late Ordovician paleoceanography on southern Laurentia: *Palaeogeography, Palaeoclimatology, Palaeoecology* 210, p. 367–384.
- Read, J. F., 1995, Part 1. Overview of carbonate platform sequences, cycle stratigraphy and reservoirs in greenhouse and ice-house worlds, *in* Read, J. F., Kerans, C., and Weber, L. J., eds., Milankovitch sea level changes, cycles and reservoirs on carbonate platforms in greenhouse and ice-house worlds: SEPM Short Course Notes 35, p. 1–102.
- Ross, J. R., and Ross, C. A., 1992, Ordovician sea-level fluctuations, *in* Webby, B.D., and Laurie, J. R., eds., Global perspectives on Ordovician geology: Proceedings of the Sixth Annual International Symposium on the Ordovician: University of Sydney, Australia, July 15–19, 1991, p. 327–335.
- Schutter, S. R., 1992, Ordovician hydrocarbon distribution in North America and its relationship to eustatic cycles, *in* Webby, B. D. and Laurie, J. R., eds., Global perspectives on Ordovician geology: Proceedings of the Sixth Annual International Symposium on the Ordovician, University of Sydney, Australia, July 15–19, 1991, p. 421–432.
- Sloss, L. L., 1963, Sequences in the cratonic interior of North America: *Geological Society of America Bulletin*, v.74, no. 2, p. 93–113.
- Sloss, L. L., 1988, Tectonic evolution of the craton in Phanerozoic time, *in* Sloss, L. L., ed., *Sedimentary cover—North American Craton, U.S.*: Boulder, Colorado, Geological Society of America, *The Geology of North America*, v. D-2, p. 25–51.

- Statler, A.T., 1965, Stratigraphy of the Simpson Group in Oklahoma, *in* Herndon, T., and Schramm, M. W., Jr., eds., Symposium on the Simpson: Tulsa Geological Society Digest, v. 33, p. 162–210.
- Suhm, R. W., and Ethington, R. L., 1975, Stratigraphy and conodonts of Simpson Group (Middle Ordovician), Beach and Baylor Mountains, West Texas: American Association of Petroleum Geologists Bulletin, v. 59, p. 1126–1135.
- Sweet, W. C., Ethington, R. L., and Barnes, C. R., 1971, North American Middle and Upper Ordovician conodont faunas: Geological Society of America Memoir 127, p. 163–193.
- Tai, P. C. and Dorobek, S. L., 2000, Tectonic model for late Paleozoic deformation of the Central Basin Platform, Permian Basin region, West Texas, *in* DeMis, W. D., Nelis, M. K., and Trentham, R. C., eds., The Permian Basin: proving ground for tomorrow's technologies: West Texas Geological Society Publication 00-109, p. 157–176.
- Texas Water Development Board, 1972, A survey of the subsurface saline water of Texas, v. 1, 113 p.
- Tyler, N., Bebout, D. G., Garrett, C. M., Jr., Guevara, E. H., Hocott, C. R., Holtz, M. H., Hovorka, S. D., Kerans, C., Lucia, F. J., Major, R. P., Ruppel, S. C., and Vander Stoep, G. W., 1991, Integrated characterization of Permian Basin reservoirs, University Lands, West Texas: targeting the remaining resource for advanced oil recovery: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 203, 42 p.
- Webby, B. D., Cooper, R. A., Bergstrom, S. M., and Paris, F. 2004, Stratigraphic framework and time slices, *in* Webby, B. D., Paris, F., Droser, M. L., and Percival, I. G., eds., The great Ordovician biodiversification event: Columbia University Press, p. 41–47.
- Williams, J. A., 1977, Characterization of oil types in the Permian Basin: text of talk presented to Southwest Section, American Association of Petroleum Geologists, Abilene, Texas, March 7, 1977.
- Wilson, J. L., 1954, Ordovician stratigraphy in the Marathon folded belt, West Texas: American Association of Petroleum Geologists Bulletin, v. 38, no. 12, p. 2455–2475.

- Wojcik, R., 1990, Crawar (Waddell), *in* Grace, R. M., ed., Oil and Gas Fields in West Texas Symposium, v. 5: West Texas Geological Society Publication 90-86, p. 71–72.
- Wright, W. F., 1965, Petroleum geology of the Simpson Group, West Texas and Southeast New Mexico, *in* Herndon, T. and Schramm, M. W., Jr., eds., Symposium on the Simpson: Tulsa Geological Society Digest, v. 33, p. 62–73.
- Wright, W. F., 1979, Petroleum geology of the Permian Basin: West Texas Geological Society Publication 79-71, 98 p.
- Young, S. A., Saltzman, M. R., and Bergström, S. M., 2005, Upper Ordovician (Mohawkian) carbon isotope ($\delta^{13}\text{C}$) stratigraphy in eastern and central North America: regional expression of a perturbation of the global carbon cycle: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 222, p. 53–76.

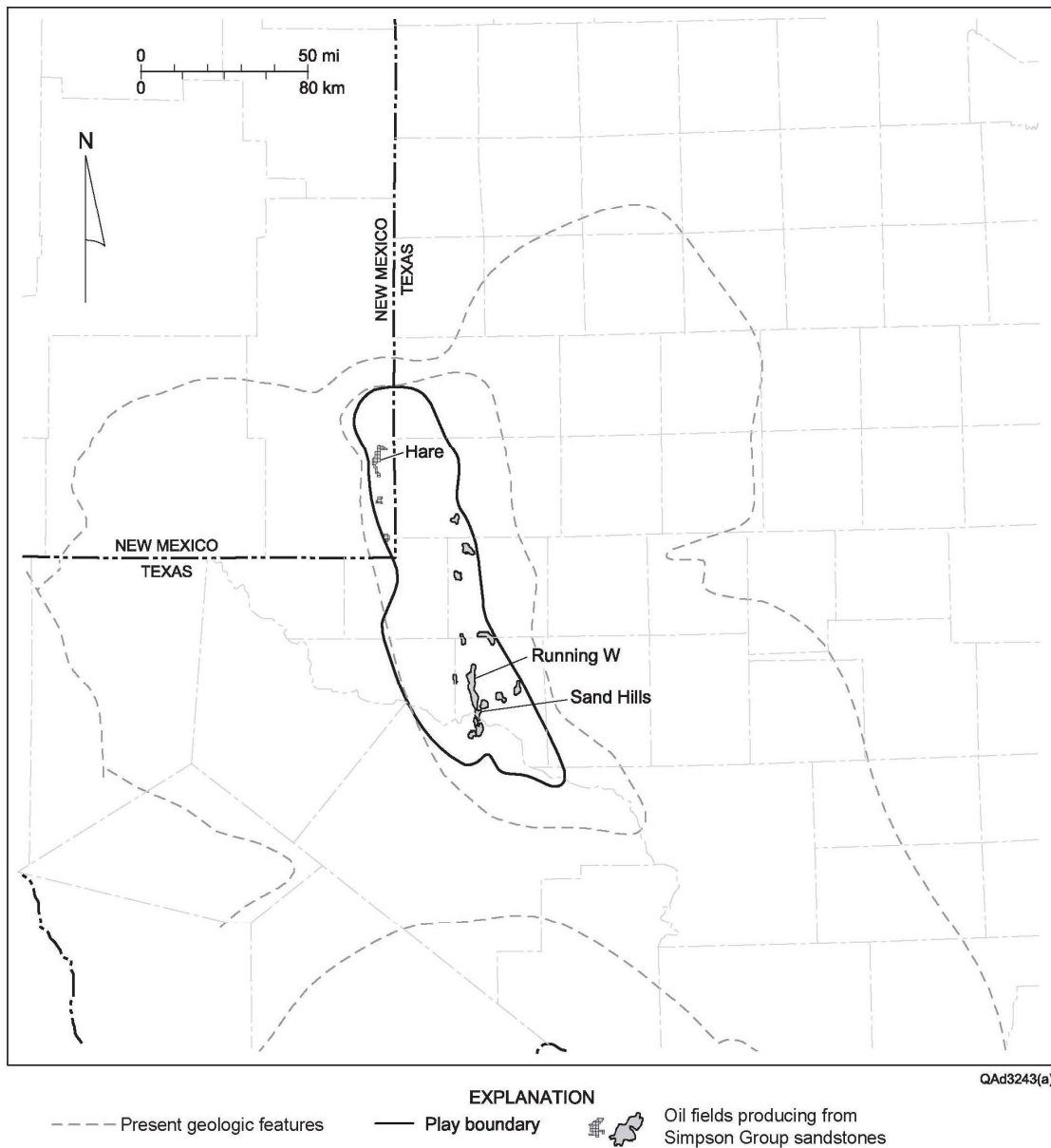


Figure 1. Location map showing Simpson fields with production greater than 1 MMbbl, top three cumulative producing fields, and present geological features. Modified from Dutton and others (2005).

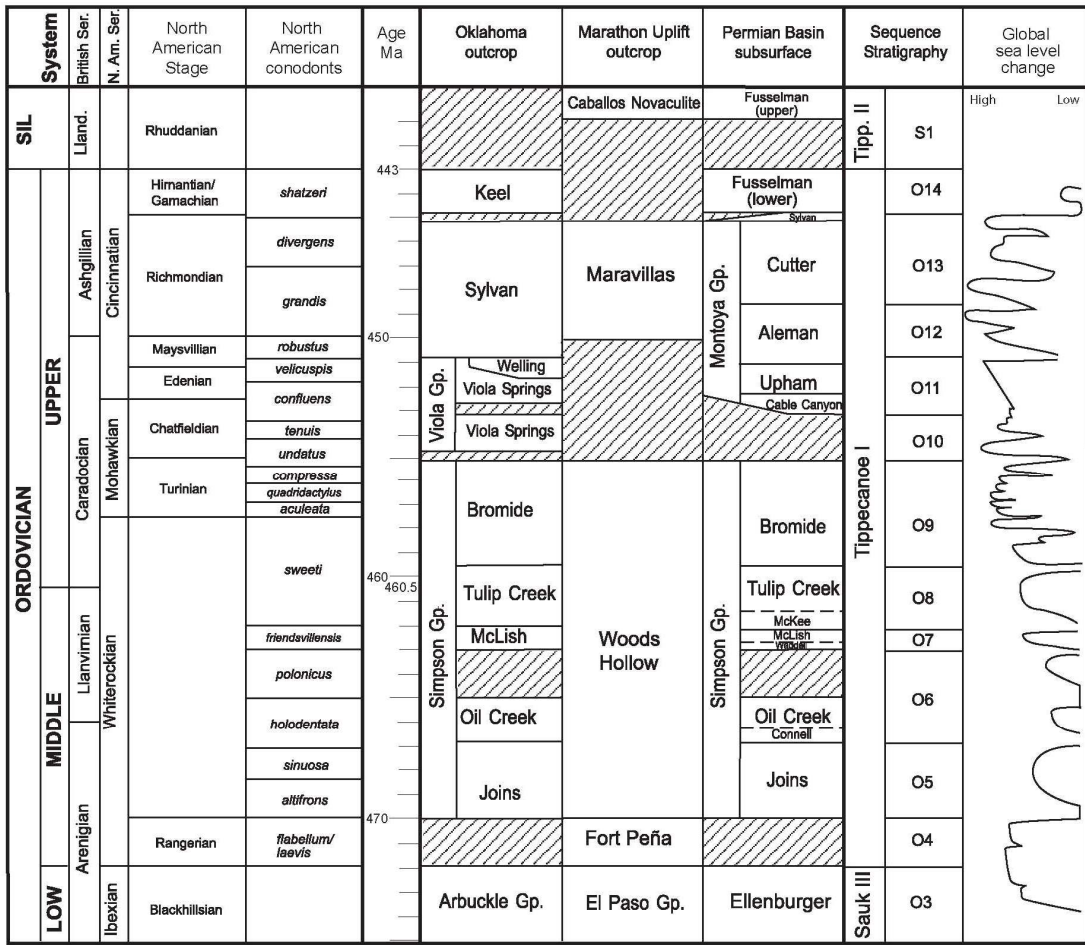
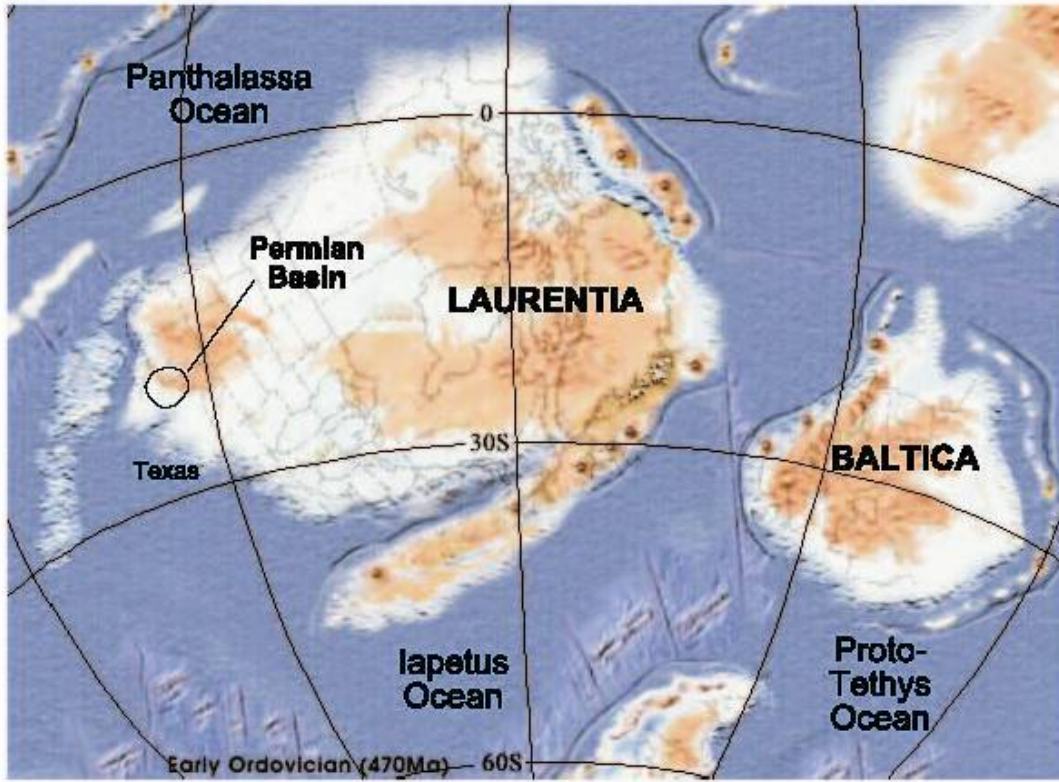


Figure 2. Stratigraphic column. Data sources include Webby and others (2004) (North American stages, conodonts, and time scale); Young and others (2005) and Derby and others (1991); Goldman and others (1995); Pope (2004); Sloss (1988, 1963); and Ross and Ross (1992).



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

Figure 3. Global plate reconstruction for Ordovician (Blakey, 2004).

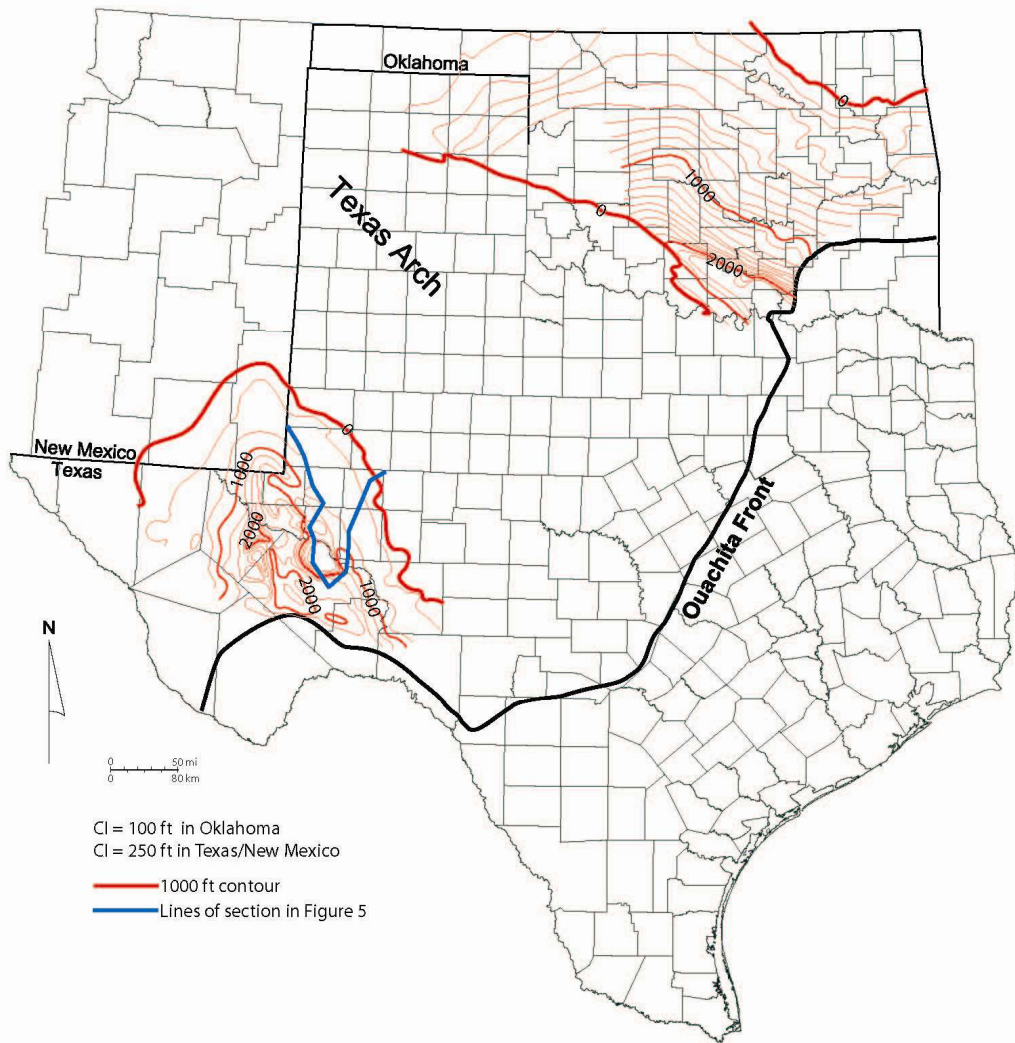


Figure 4. Thickness map of Simpson Group modified from Texas Water Development Board (1972), Frenzel and others (1988), and Northcutt and Johnson (1997). Thousand-foot contour lines and locations of figure 5 cross sections shown in heavy red and blue lines, respectively. Note that contour interval is 100 ft for Oklahoma and 250 ft for Texas and New Mexico.

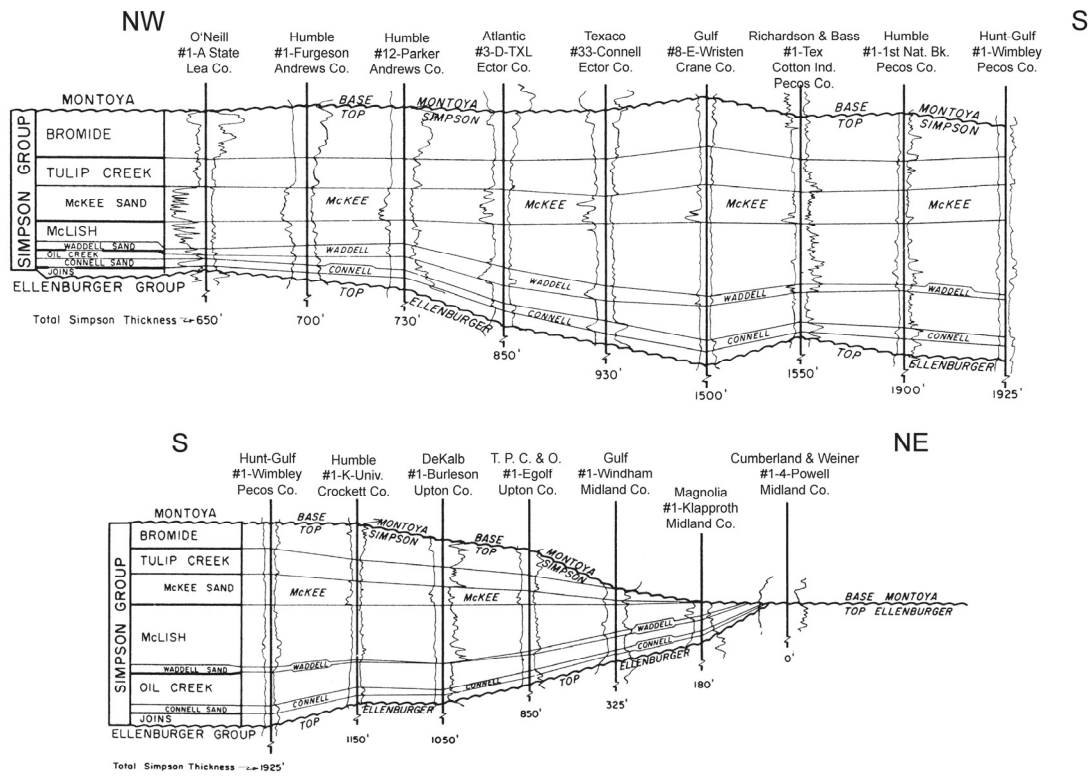
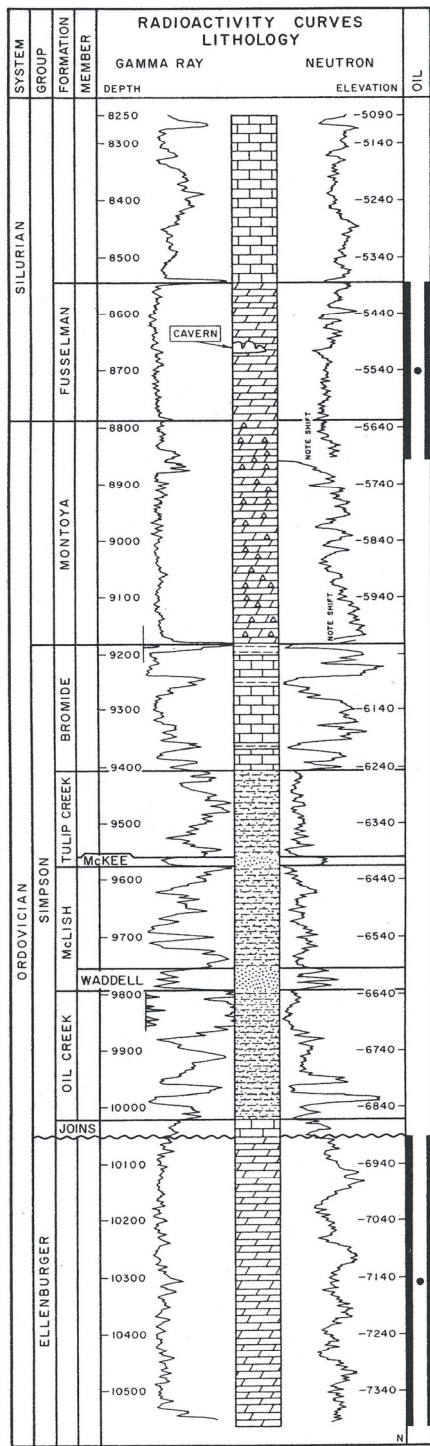


Figure 5. Cross sections showing thickness trends of Simpson Group (Wright, 1965). Cross-section locations shown in figure 4.



EXPLANATION

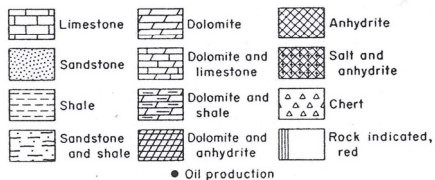


Figure 6. Type wireline log with gamma-ray neutron logs and lithology, Dollarhide field, Andrews County, Texas, and Lea County, New Mexico (Herald, 1957).

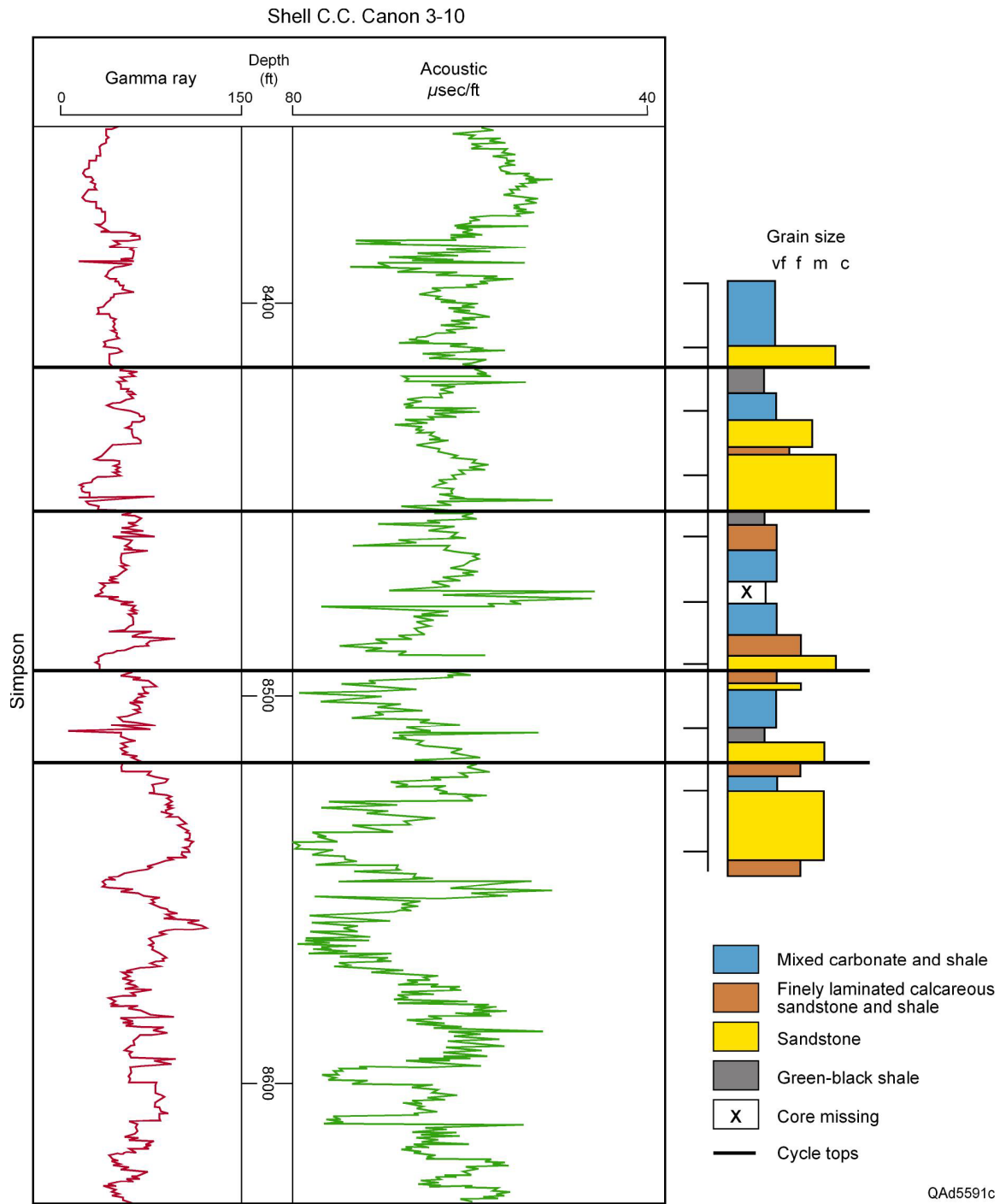


Figure 8. Core description and interpreted cycles from section assigned to McKee Member, Tulip Creek Formation, Shell C.C. Cannon 3-10 well, Pecos County, Texas.

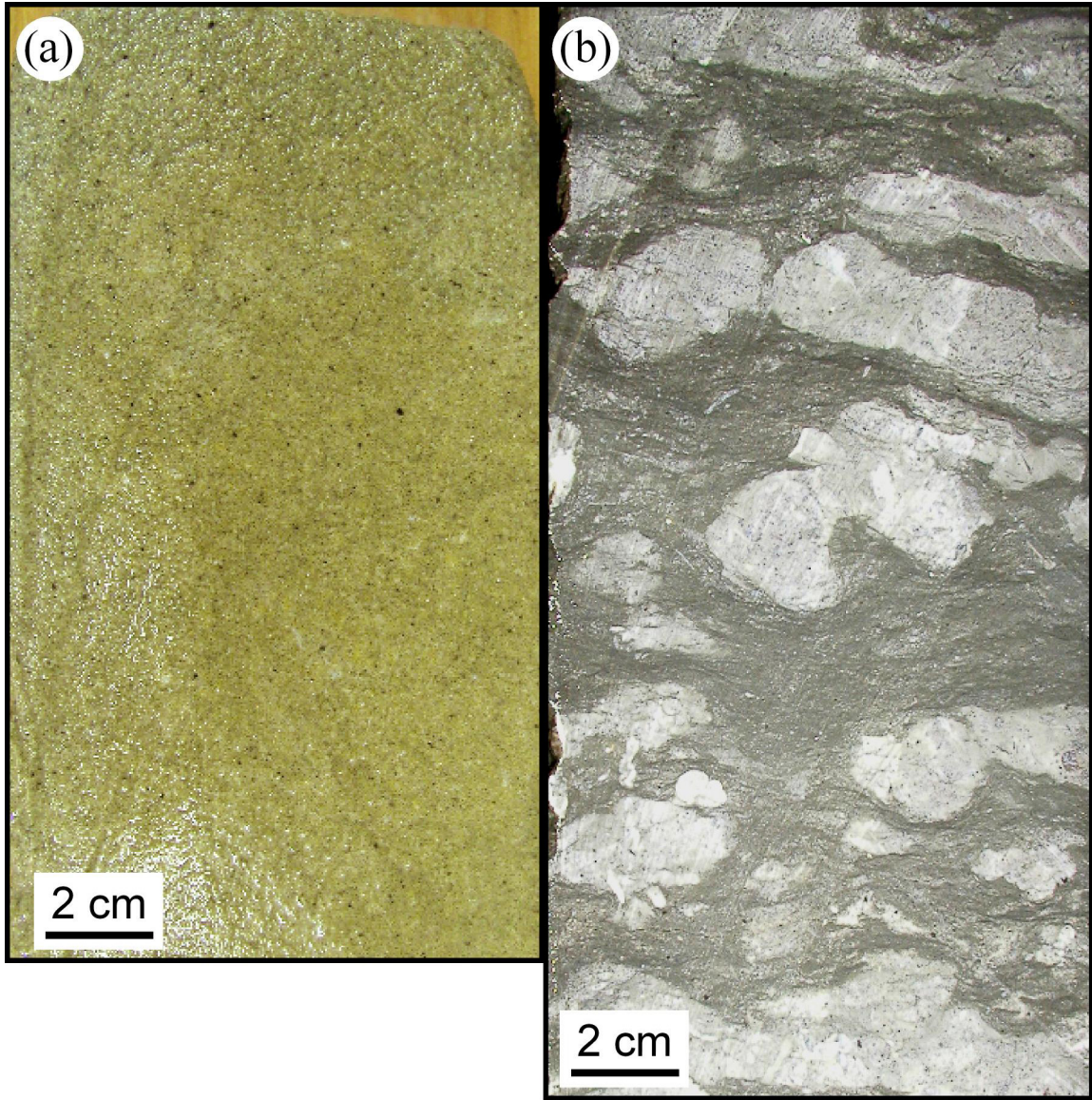


Figure 9. Core photos of McKee Member, Tulip Creek Formation, Shell C.C. Cannon 3-10 well, Pecos County, Texas. Slab width is approximately 4 inches. (a) Facies 1: massive crossbedded tan sandstone with some bioturbation. Depth: 8,483 ft. (b) Facies 2: mixed carbonate and shale with carbonate lenses. Depth: 8,464 ft.

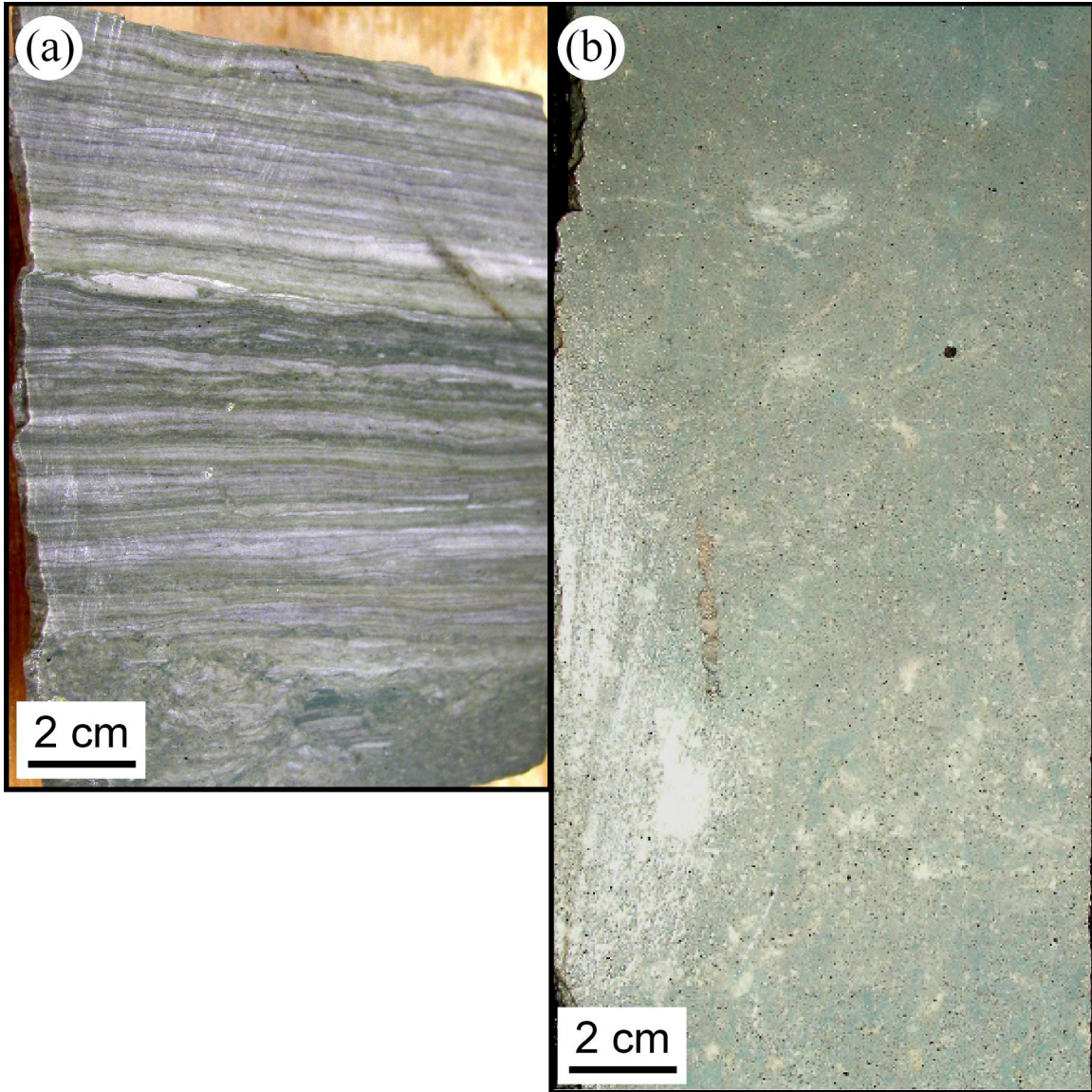


Figure 10. Core photos of McKee Member, Tulip Creek Formation, Shell C.C. Cannon 3-10 well, Pecos County, Texas. Slab width is approximately 4 inches. (a) Facies 3: finely laminated gray carbonate and green-gray shale with bioturbation, roots, and minor sandstone. Depth: 8,501 ft. (b) Facies 4: green-black carbonaceous shale. Depth: 8,479 ft.



Figure 11. Photo of core from 8,412 to 8,464 ft (described in fig. 8), Shell C.C. Cannon 3-10 well, Pecos County, Texas. Slab width is approximately 4 inches. Core depth increases from left to right.

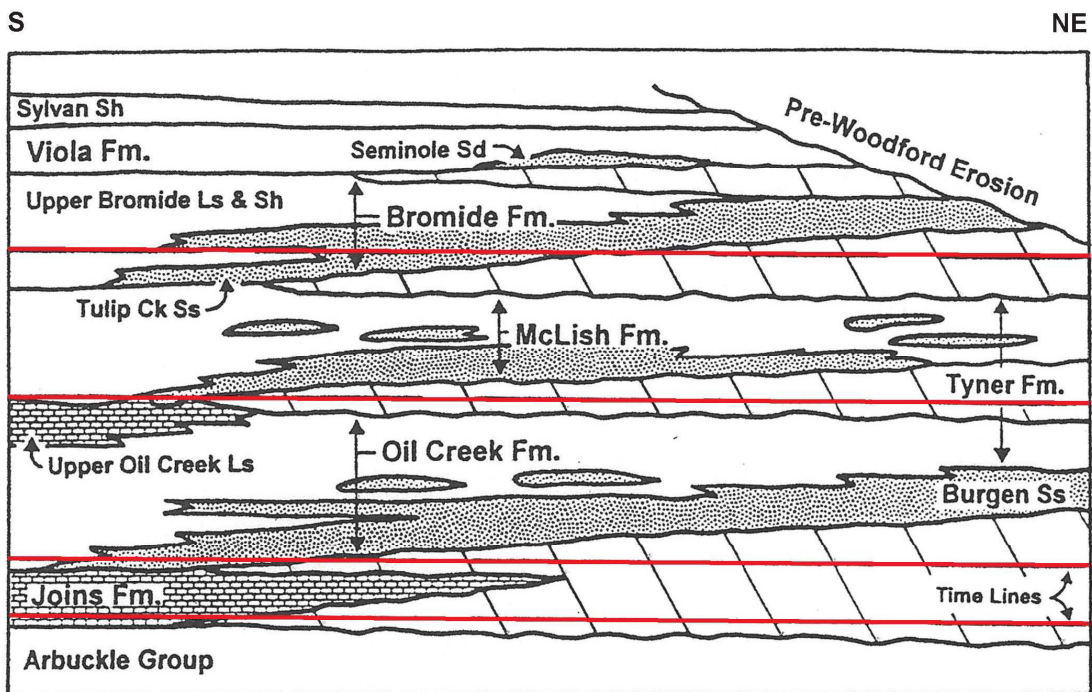


Figure 12. Simpson Group sequence stratigraphic model for Oklahoma constructed by Statler (1965). Figure as modified by Candelaria and others (1997). Red lines highlight timelines.

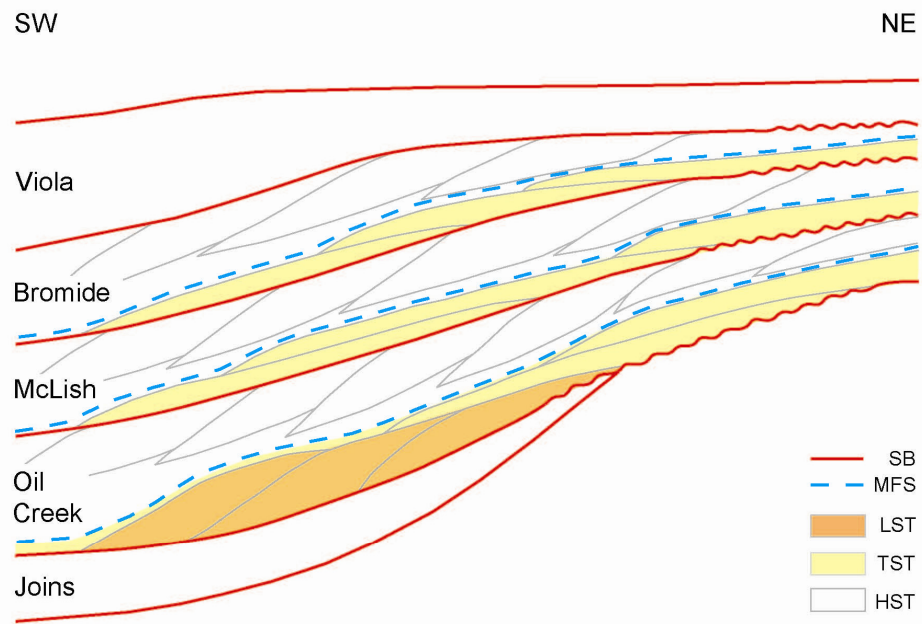


Figure 13. Simpson Group sequence stratigraphic model for Oklahoma production redrafted from Candelaria and others (1997). Note that this model focuses only on the productive area and does not show up- or downdip facies changes.