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Woodford Shale (Upper Devonian to Lower Mississippian): From Hydrocarbon Source Rock to Reservoir

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TITLE PAGE ILLUSTRATION

Close-up photo showing fissile black shale interbedded with blocky biogenic chert in the upper member of the Woodford Shale exposed along the west side of the southbound lanes of Interstate 35 on the south limb of the Arbuckle Uplift (Section 25, Township 2 South, Range 1 East).

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Woodford Shale (Upper Devonian to Lower Mississippian): From Hydrocarbon Source Rock to Reservoir

Brian J. Cardott[1] and John B. Comer[2]

ABSTRACT.—Woodford Shale (Upper Devonian to Lower Mississippian) is widely recognized as a world-class hydrocarbon source rock and since 2004 has become a commercially significant hydrocarbon source-rock reservoir for both oil and gas. This report compiles and synthesizes the research on Woodford Shale in Oklahoma and highlights the lithology, source rock attributes, and reservoir characteristics that make this formation a successful shale resource play. The Woodford Shale represents another model in the growing list of unconventional shale resources that have been successfully developed in the USA.

Woodford Shale is a fine-grained, organic-rich mudrock consisting mostly of clayey and siliceous mudrock and, less commonly, dolomitic mudrock. Basal sandstones (Misener and Sylamore members) are found in limited areas of northern and central Oklahoma and are characterized by well-sorted and well-rounded quartz grains that were locally sourced from Middle Ordovician sandstone exposed along the Ozark Uplift during the Late Devonian. Other than in these basal units, sand-sized detrital grains are notably absent from the Woodford Shale.

Woodford Shale is present throughout most of Oklahoma but is missing from the Wichita Uplift and Hollis Basin in southwestern Oklahoma and is locally absent in parts of the Arbuckle Uplift, near the central Oklahoma fault zone, and in the northwestern Cherokee Platform adjacent to the Nemaha Uplift. Woodford Shale passes from surface exposures in the Ozark Uplift, Arbuckle Uplift, and Ouachita Mountains Uplift to maximum subsea depths >16,000 ft (4,900 m), >17,000 ft (5,000 m), and >24,000 ft (7,000 m) in the Ardmore, Arkoma, and Anadarko Basins, respectively. Thicknesses in the subsurface increase from less than 25 ft (8 m) on the Anadarko Shelf and Cherokee Platform to greater than 700 ft (200 m) in the southeastern Anadarko Basin and the Marietta Basin.

Woodford Shale is informally subdivided into three members. The lower member contains plant megafossils and intermediate radioactivity, the middle member contains the most resinous spores and the least pollen as well as the highest radioactivity, and the upper member contains the lowest radioactivity and lowest total organic carbon content. All three members consist of thin beds and thin laminae that are highly variable in composition.

Quartz is commonly the dominant mineral and mostly occurs together with highly variable amounts of illite. Quartz is present as silt- and clay-sized detrital grains and as chert of biological origin. Biogenic chert forms during early diagenesis from the alteration of siliceous microorganisms (mostly Radiolaria) and intervals with high concentrations of biogenic quartz are more brittle than intervals with detrital quartz supported in a ductile clay matrix. Conventional vertical wells in Carter and Marshall Counties have produced oil at low volumes for many decades from naturally fractured, organic-rich Woodford Shale intervals composed of biogenic chert. Recent unconventional exploration and applied research confirm that the brittle biogenic chert intervals are the optimum lithology for hosting and main-

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taining both natural and induced fractures. Furthermore, a greater concentration of natural fractures occurs in the brittle chert-rich lithology and improves permeability in the Woodford Shale, resulting in better well performance.

Woodford Shale sediments were deposited over a major regional unconformity surface during a period of global warming and worldwide marine transgression. Sequence stratigraphic interpretations for the Woodford Shale are based on well log characteristics and lithology and are consistent with the global sequence established for the Late Devonian. Initial Woodford Shale deposition, including the lower and most of the middle members, has been interpreted as a transgressive system tract coincident with the global sea-level rise. The uppermost part of the middle member and the upper member have been interpreted as a highstand system tract, with the maximum flooding surface within the uppermost middle member. However, the fact that the Frasnian/Famennian boundary has been placed in each of the three members by different researchers is a cautionary tale indicating that regional correlations, including member boundaries, are poorly constrained. These correlations are not based on the well documented, high resolution biochronological data that characterize the global sequence because Woodford Shale is generally lacking in fossils.

Woodford Shale sediments were deposited in an epeiric sea that extended along a west to southwest facing passive continental margin during the Late Devonian. The widespread, blanket-like distribution and nearly uniform fine-grained lithology indicate that the entire region was one of low relief, and the absence of deltas, submarine fans, coarse clastic wedges, large clinoforms, and sand-bearing turbidites indicate that adjacent land areas were not drained by large rivers. Plate tectonic reconstructions place Oklahoma at a low southern latitude in the warm, arid southeasterly trade wind belt. An arid paleoclimate is indicated by the presence of evaporite minerals (e.g., anhydrite, gypsum, length slow chalcedony, primary dolomite), biomarkers (gammacerane), and primary sedimentary structures (syneresis cracks). In addition, extensive drought conditions are suggested by a suite of biomarkers (certain polycyclic aromatic hydrocarbons) that have been attributed to paleo-wildfires. The anomalously high organic carbon concentration characteristic of Woodford Shale is due to the combined effects of high biological productivity in the upper water column and widespread anaerobic and euxinic bottom conditions. Nutrients supporting high biological productivity were derived from a persistent zone of coastal upwelling along the Late Devonian continental margin, which is recorded by the age-equivalent biogenic chert of the Arkansas Novaculite. Upwelled nutrients were swept into the Woodford epeiric sea with the countercurrents required to maintain water balance by replacing evaporative losses and the surface water driven out of the basin by Coriolis forces. Transport of the fine-grained sediment that dominates the section was accomplished mostly by wind and by storm-generated currents. Deflation of the arid landscape, limited discharge from intermittent streams, and storm-generated runoff account for most of the terrestrial sediment contributed to the basin. These processes also contributed to eutrophication and the high biological productivity by supplying terrestrial nutrients to the basin. Recent research on the Upper Devonian Three Forks Formation of the Williston Basin, which lay at the same southern paleolatitude as Woodford Shale, documents the significance of storms in the southern tropics during the Late Devonian. The thin varve-like laminae commonly observed in Woodford Shale represent deposition of atmospheric dust from fluctuating winds and episodic fallout of fine sediment entrained along isopycnals. The presence of abraded grains of penecontemporaneous

dolomite in graded silty layers and in the basal sandstones (Misener and Sylamore members) indicates that resuspension and resedimentation were active processes throughout the region during the Late Devonian.

Woodford Shale averages >6 wt. % total organic carbon (TOC) and has a reported range between <1 wt. % and 30 wt. % TOC. Bulk organic matter is dominated by Type II (oil generating) kerogen of marine origin, which visual analyses confirm is mostly amorphous organic matter with lesser amounts of vitrinite, inertinite (semifusinite and fusinite), liptinite (e.g., *Tasmanites*), zooclasts (e.g., acritarchs), and solid bitumen. Thermal maturity based on vitrinite reflectance (VR_o) analysis ranges from marginally mature (0.49% VR_o) to post mature (6.36% VR_o). Depth of burial accounts for the thermal maturity throughout most of Oklahoma, but local high-maturity anomalies in northern Oklahoma appear to be related to high heat flow from igneous rocks at depth and to the migration of hydrothermal fluids.

Exploitation of Woodford Shale as an unconventional resource play began in Oklahoma in 2004 with the completion of vertical gas wells in the Arkoma Basin. Between August 2004 and June 2020, 5,505 wells were completed exclusively in the Woodford Shale. Seven percent of these are vertical wells and 93% are horizontal/directional wells. Based on a gas-to-oil ratio of <17,000:1, 32% are classified as oil wells. Initial potential (IP) gas rates up to 29,847 thousand cubic feet (mcf) per day and IP oil/condensate rates up to 2,505 barrels per day have been recorded. Only natural gas is produced from Woodford Shale intervals having a thermal maturity >1.67% VR_o.

The combination of an organic carbon-rich, thermally mature hydrocarbon source rock with intervals of brittle lithology make the Woodford Shale an excellent unconventional oil and gas reservoir. Recent assessments of the total undiscovered hydrocarbon resources in Woodford Shale are 29 trillion cubic feet of natural gas, 853 million barrels of crude oil, and 384 million barrels of natural gas liquids. Such large volumes remaining to be produced from this hydrocarbon source-rock reservoir document the significant commercial potential of the Woodford Shale play in Oklahoma.

INTRODUCTION

The purpose of this report is to summarize lithologic, hydrocarbon source rock, and oil and gas reservoir characteristics of the Woodford Shale in Oklahoma, to highlight the rock properties that influence crude oil and natural gas production from this hydrocarbon source-rock reservoir, and to document the history of oil and gas production from the Woodford Shale. The thermal maturity of the Woodford Shale by vitrinite reflectance is discussed and summarized for the entire state. Also presented here is an overview of the environment of deposition of Woodford Shale and the various lines of evidence that support specific conclusions about the conditions that gave rise to these widely distributed, organic-rich mudrocks. The geological and structural context for this discussion is provided by the map showing the major structural provinces in Oklahoma (Figure 1).

Woodford Shale is mostly a fine-grained rock, but with lithologic properties that vary both laterally and vertically on large (kilometer) and small (nanometer) scales. It is unusual in its high organic carbon content and widespread distribution. Woodford Shale is present throughout most of Oklahoma, and age-equivalent organic-rich rocks that include the Chattanooga Shale and the middle division and parts of the upper division of the Arkansas Novaculite are present in northeastern and southeastern Oklahoma, respectively. Age-equivalent organic-rich rocks are found throughout North America, including Woodford Shale of New Mexico and Texas; the Chattanooga Shale in the Eastern Interior of the United States; the New Albany, Ohio, and Sunbury shales of the central and eastern United States; the Antrim Shale in the Michigan Basin; the Bakken Shale in the Williston Basin; the Kettle Point Formation of Ontario, Canada; and the Pilot Shale of Utah (Conant and Swanson, 1961). Many

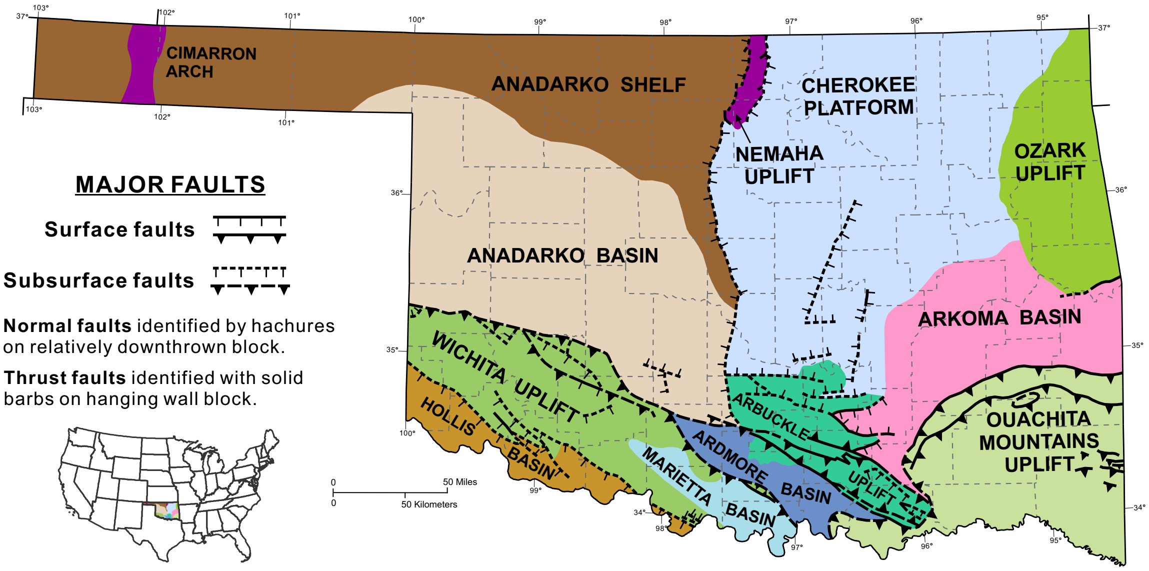

Figure 1. Map showing major geologic provinces of Oklahoma (modified from Northcutt and Campbell, 1996).

of these rocks are productive unconventional oil and gas reservoirs. Along with a review of the lithologic properties of the Woodford Shale, this report also includes discussions of the source rock parameters and reservoir characteristics relevant to the unconventional development of this resource. Also included is an overview of the history of development of hydrocarbon source-rock reservoirs in the Woodford Shale. As such, this report attempts to synthesize our current understanding of the Woodford Shale unconventional oil and gas resource in Oklahoma.

Because the Woodford Shale has been the subject of many publications, too many to be adequately covered in detail here, an update of the Woodford Shale bibliography published by Cardott (1992) is available as Appendix 1.

WOODFORD SHALE AS ROCK

Stratigraphy and Nomenclature

Taff (1902) is the earliest known usage of the term "Woodford Chert" presumably for exposures on the south side of the Arbuckle Uplift near the town of Woodford, Oklahoma, Carter County (Jordan, 1957). Gould (1925) described the Woodford type locality as the "Village of Woodford". Urban (1960) attributed the type locality to Section 27, Township 2 South, Range 1 West. The term Woodford Chert was used by Gould (1925) and Wilmarth (1938). The term "Woodford Formation" has also been used (e.g., Morgan, 1924; Wilson, 1958; O'Brien and Slatt, 1990; Comer, 1991; Cullen, 2018; Ko and others, 2018; Zoback and Kohli, 2019). The preferred term for the Woodford Formation, used in lexicons and elsewhere, is "Woodford Shale" for occurrences in both the subsurface and surface in Oklahoma (Tarr, 1955; Jordan, 1957, 1959, 1962; Urban, 1960; Hass and Huddle, 1965; Amsden, 1975, 1980; Mankin, 1987; Fay, 1997). The term Chattanooga Shale is used for stratigraphically equivalent outcrops around the Ozark Uplift in northeastern Oklahoma, in the subsurface in Kansas, and in northern Arkansas (Huffman, 1958; Wise and Caplan, 1979; Carr, 1987; Comer, 1992; Lambert, 1993; Newell and others, 2001; McFarland, 2004). The informal Misener sandstone in north-central Oklahoma is considered a basal unit of the Woodford Shale (Amsden, 1975). The Chattanooga Shale in northeastern Oklahoma is divided into the informal Sylamore sandstone (stratigraphically equivalent to the Misener sandstone) and Noel black shale members (Huffman and Starke, 1960a, 1960b; Pittenger, 1988). The middle division and parts of the upper division of the Arkansas Novaculite in the Ouachita Mountains Uplift include strata that are equivalent in age to the Woodford Shale (Hass, 1951; Hass and Huddle, 1965). Outcrops recognized and mapped as Woodford Shale also occur in the northern Ouachita Mountains Uplift (Weber, 1992; Cardott, 1994; Suneson and Hemish, 1994, p. 74).

Strata above and below the Woodford Shale vary regionally in Oklahoma (Figure 2). Woodford Shale overlies a major regional unconformity (Maxwell, 1959) and the age of the underlying strata, ranging mostly from Ordovician to late Early Devonian, is related to the extent of erosion into the pre-Woodford unconformity surface

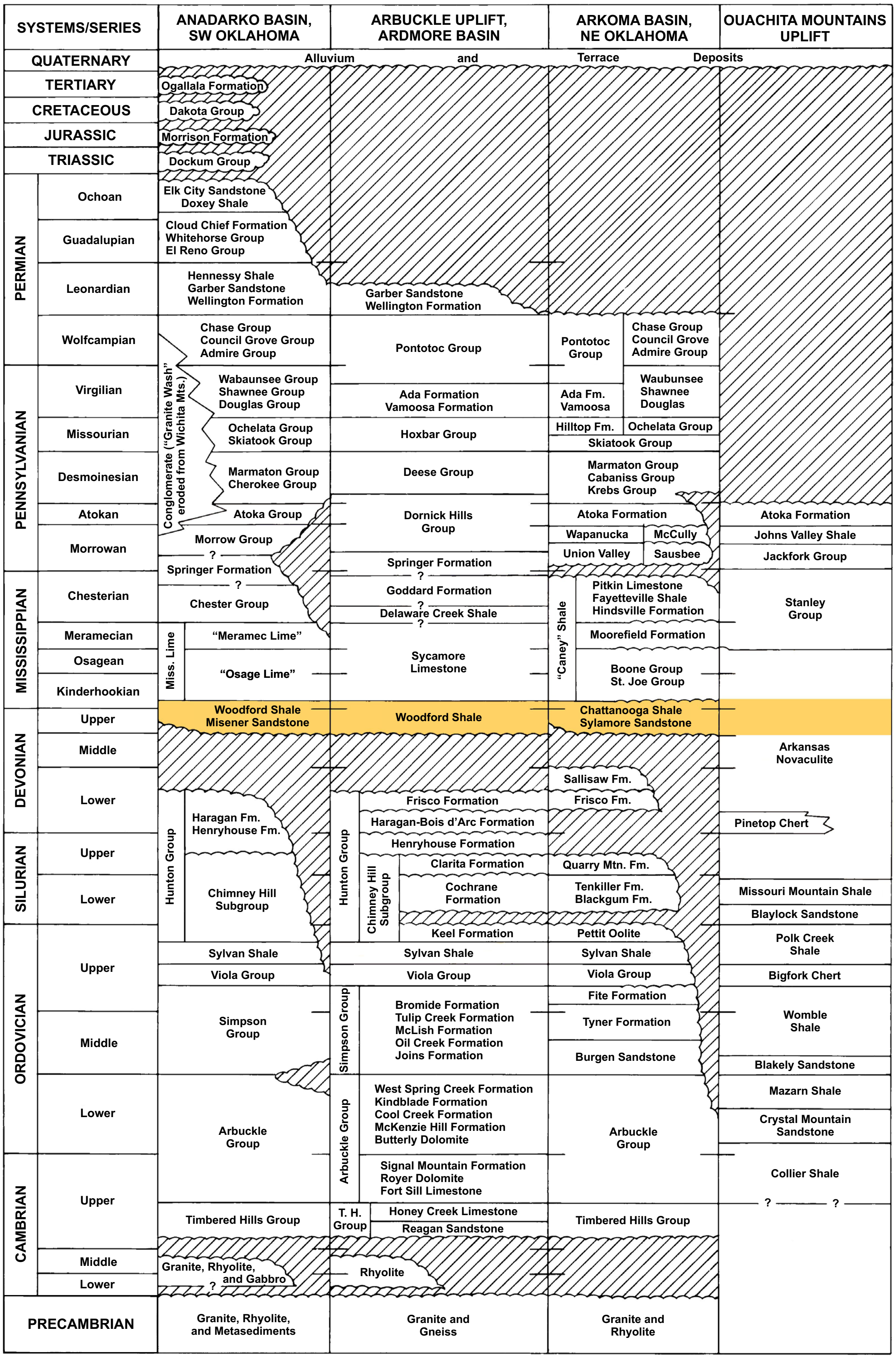

Figure 2. Generalized correlation of rock units in Oklahoma (modified from Johnson and Cardott, 1992).

(Johnson and Cardott, 1992). Small areas in northeastern Oklahoma are underlain by Precambrian granite (Tarr and others, 1965; Denison, 1981; Benson, 2014). Hunton Group carbonate formations (ranging in age from Late Ordovician to Early Devonian) underlie Woodford Shale in most of Oklahoma (Tarr and others, 1965; Amsden, 1980). Woodford Shale and age-equivalent rocks are overlain by Mississippian-age formations (Jordan and Rowland, 1959; Sutherland and Manger, 1979; Sutherland, 1981). The distribution and lithology of Mississippian-age formations vary widely in Oklahoma, resulting in differing correlations among Sycamore Limestone, Caney Shale, Osage Lime, and Meramec Lime proposed by various researchers (Higley, 2013; Gaswirth and Higley, 2013; Cullen, 2017; Miller and Cullen, 2018; Suriamin and Pranter, 2018; Milad and Slatt, 2019; Miller and others, 2019).

Age and Correlation

Based on conodont assemblages in eight Woodford Shale exposures in the Arbuckle Uplift and Ouachita Mountains Uplift in southern Oklahoma, Hass and Huddle (1965) determined that most of the Woodford Shale is Late Devonian (Frasnian-Famennian) in age and locally the uppermost part is Early Mississippian (Kinderhookian). Over and Barrick (1990), Barrick and others (1990), Over (1990, 1992), and Barrick and Meyer (2019) confirmed the Late Devonian (Frasnian) to Early Mississippian (Kinderhookian) age of the Woodford Shale in southern Oklahoma also based on conodonts. Another approach by Von Almen (1970) used microspore species to determine the Late Devonian to Early Mississippian age of the Woodford Shale.

The age of the upper Woodford Shale is problematic in outcrop and depends on where the upper boundary is picked within the gradational shale interval below the first appearance of carbonate beds in the Sycamore Limestone. Fay (1989) identified the Woodford/Sycamore boundary in the extensively studied outcrop of the Woodford Shale on Interstate-35. This well-known locality is on the south side of the Arbuckle Uplift in Section 25, Township 2 South, Range 1 East, where the Woodford Shale is exposed along the south-bound lanes of Interstate-35. The Woodford/Sycamore contact at this location is marked with Brass Marker 2 (Fay, 1989), which is 9 ft (2.7 m) below the sharp decrease in gamma-ray readings used as the upper Woodford boundary in the subsurface (Puckette and others, 2013; Milad and Slatt, 2019; Milad and others, 2020). Schwartzapfel (1990) and Kondas and others (2018) picked the boundary in outcrops at the first appearance of the laterally continuous carbonate beds of the Sycamore Limestone. Schwarzapfel (1990) and Schwartzapfel and Holdsworth (1996) suggested a later Mississippian age (Osagean-Meramecian) for the uppermost part of the Woodford Shale exposures located in the Criner Hills (between the Ardmore and Marietta Basins) and along Interstate-35 in the Arbuckle Uplift based on radiolarian and conodont faunas. Also based on conodonts, Kleehammer (1991) and Over (1992) indicated the age of the overlying Sycamore Limestone in southern Oklahoma is largely Meramecian and not older than late Osagean.

Amsden and Klapper (1972), Kirkland and others (1992), Kuykendall and Fritz (1993, 2001), and Barrick and Meyer (2019) described the basal Misener sandstone as late Middle to Late Devonian in age (Givitian to Famennian). The Sylamore sandstone, which is present in northeastern Oklahoma, is late Middle Devonian to Early Mississippian (Freeman and Schumacher, 1969, Pittenger, 1981) and the Noel shale (the upper black-shale member of the Chattanooga Shale; Amsden and others, 1967) is Late Devonian to Early Mississippian (Huffman and Starke, 1960b). Conodont analysis indicates that the middle division and parts of the upper division of the Arkansas Novaculite are Late Devonian to Early Mississippian (Kinderhookian) (Hass, 1951; Amsden and others, 1967) and an age-equivalent, lateral facies of the Woodford Shale.

Distribution

The distribution of Woodford Shale in Oklahoma is illustrated by structure and isopach maps shown in Plates 1 and 2. Plate 1 is reproduced from Evans and others (2018) and is the first Woodford Shale structure map that includes all of Oklahoma. Plate 2 is a detailed Woodford Shale isopach map reproduced from Rottmann (2000a), which represents drilled thicknesses not corrected for dip. Appendix 1 includes a bibliography of publications with previous versions of these maps. Note that the depth and thickness of age-equivalent strata within the Arkansas Novaculite in the Ouachita Mountains Uplift of southeastern Oklahoma are not included in the structure and isopach maps. The most detailed structure and isopach maps of the Woodford Shale in the Marietta Basin are in Brito (2019). Isopach maps of the Woodford Shale in the Ardmore Basin are in Party and others (2008), EIA

(2011b) and Henderson (2013).

The Woodford Shale is present throughout most of Oklahoma but is absent from the Wichita Uplift and Hollis Basin in southwestern Oklahoma and is missing in parts of the Arbuckle Uplift, is locally missing in central Oklahoma associated with the central Oklahoma fault zone, and is missing in a limited area just east of the Nemaha Uplift on the Cherokee Platform in northern Oklahoma (Plate 1). The Woodford Shale occurs at maximum subsea depths >16,000 ft (4,900 m) in the Ardmore Basin, >17,000 ft (5,000 m) in the Arkoma Basin, and >24,000 ft (7,300 m) in the Anadarko Basin (Plate 1). In general, the Woodford Shale thickens from less than 25 ft (8 m) thick in the Anadarko Shelf and Cherokee Platform to more than 700 ft (200 m) thick in the southeastern Anadarko and Marietta Basins and to 250 ft (76 m) in the Arkoma Basin (Plate 2). Houseknecht and others (2014) illustrated thicknesses as intervals of gross and net high (>150 API) gamma-ray response for the Woodford Shale in the Arkoma Basin. Mapping in the Ardmore Basin by Party and others (2008) indicated local areas in Carter and Marshall Counties where Woodford Shale thickness exceeded 400 ft (122 m). The overall basinward thickening is disrupted by numerous dendritic trends that represent incised paleovalley-fill sediments deposited during the earliest stages of Woodford deposition as marine transgression inundated the regional pre-Woodford unconformity surface (Kuykendall and Fritz, 1993, 2001; Rottmann, 2000a, b; Krumme, 2001; Blackford, 2007; Althoff, 2012; Turner and Slatt, 2016; Infante-Paez and others, 2017; McCullough, 2017; Slatt and others, 2014, 2018; Zhang and Slatt, 2019). Some local irregularities appear to be the result of Woodford deposition in karst sink holes in the underlying unconformity surface (Gupta and others, 2013; Zhang, 2016; Liborius and Sneddon, 2017; Milad, 2017; Slatt and others, 2015, 2018a; Zhang and Slatt, 2019; Slatt, 2020). Torres and others (2017) and Torres-Parada (2020) interpreted potential lacustrine (mini-basin fill) intervals above the unconformity based on seismic data, but no petrographic, geochemical, lithostratigraphic, or faunal analyses have been undertaken to confirm a lacustrine depositional environment for these deposits.

Flora and Fauna

Cardott and Chaplin (1993 and references therein) summarized the following microfossils, macrofauna, and flora found in the Woodford Shale: miospores, acritarchs, algae (*Tasmanites, Quisquilites, Foerstia*), scolecodonts, conodonts, radiolarians, sponge spicules, brachiopods (*Lingula, Productella, Spirifer, Strophomena*), arthropods (crustacean), gastropods, cephalopods (*Probleoceras, Mooreoceras*), progymnosperm *Archaeopteris* (organ genus *Callixylon*), and the gymnosperm Cordaitales (form genus *Dadoxylon*). *Calamites* (?) and *Callixylon* have been identified in the lower one-fourth of the Woodford Shale at the McAlister Cemetery Quarry (SW¼ Section 36, Township 5 South, Range 1 East) located in the Criner Hills, Carter County, Oklahoma (Kirkland and others, 1992). In addition, shrimp (Feldmann and Schweitzer, 2010), ammonoids (Becker and Mapes, 2010), and microspores (pollen) of terrestrial origin (von Almen, 1970; Molinares Blanco, 2013; Molinares Blanco and others, 2017a) have been described. Kondas and others (2018) described marine phytoplankton (acritarchs and prasinophytes), plant remains, miospores, and zooclasts (scolecodonts and animal tissues) in the Interstate-35 Woodford Shale outcrop in the Arbuckle Uplift. Ko and others (2018) recognized *Leiosphaeridia* telalginite in the Interstate-35 Woodford Shale outcrop.

Trace fossils occur locally in Woodford Shale but are more pervasive in the basal sandstones. Kirkland and others (1992) identified *Planolites*-like trace fossils in the lower part of the Woodford Shale at the McAlister Cemetery Quarry. *Planolites*, *Chondrites*, and *Paleophycus* were identified in Woodford cores from McClain, Johnston, Marshall, and Bryan Counties, mostly as horizontal traces that rarely result in total disruption of the rock fabric (Coleman and Jordan, 2018). *Schaubcylindrichnus*, *Planolites*, *Zoophycos*, *Phycosiphon*, *Chondrites*, and *Cosmoraphe* were described in mudstone cores by Kvale and Bynum (2014). In addition, *Helminthopsis* and *Paleodictyon* have been recognized during computerized tomography (CT) scanning of Woodford Shale mudstone cores (Kvale, personal communication, 10/24/2017). These traces are mostly associated with the *Zoophycos* and *Nereites* ichnofacies and they typically are produced under stressed conditions (Kvale and Bynum, 2014). Trace fossils occur mostly in lighter colored mudstones (Kvale and Bynum, 2014) and are found rarely in darker, organic-rich mudstones (Comer, 1991, 2008). *Teichichnus* (probably *T. rectus*) has been identified in a Sylamore sandstone outcrop located in Delaware County, Oklahoma, Section 14, Township 22 North, Range 22 East, by Pittenger (1981). In another study of 11 conventional 4-inch diameter cores recovered from Misener oil fields in Grant and Garfield Counties, Francis (1988) identified burrows (in 10 cores) and intensely bioturbated intervals (in 6 cores) in the Misener sandstone member, but no specific names were assigned to these trace fossils.

Lithofacies

The Woodford Shale is described as a marine, highly radioactive, carbonaceous and siliceous, fissile to blocky, dark-gray to black shale containing chert, subordinate amounts of green-greenish-gray shales, phosphate nodules, and pyrite (Cardott and Chaplin, 1993). Chert beds and phosphate nodules are predominant in the upper member in southern Oklahoma but absent in northeastern Oklahoma. Within the Arkoma Basin, the proportion of chert in the Woodford Shale increases eastward and southward (Houseknecht and others, 2014).

The anomalously high radioactivity of Woodford Shale makes it easy to identify on gamma-ray logs and numerous authors have used this feature, along with other log characteristics and lithologic variables, to divide the Woodford Shale into three informal members (Figure 3), although the boundaries of each member chosen by different authors may not be the same or correlative. In this report we also divide the Woodford Shale into three informal members (lower, middle, upper). Ellison (1950) first divided Woodford Shale in the Permian Basin into three units based on radioactivity, electric log response, and core lithology. The lower unit was calcareous and cherty and had the lowest radioactivity, the middle unit had the most resinous spores (*Tasmanites huronensis*) and the highest radioactivity, and the upper unit had few resinous spores and intermediate radioactivity (Ellison, 1950). Urban (1960) subdivided the Woodford Shale in Oklahoma into lower, middle, and upper zones based on a palynological study of the Buckhorn Creek outcrop (NE¼ Section 3, Township 2 South, Range 3 East) in the Arbuckle Uplift (Ham and others, 1990). He interpreted the depositional environment to be near-shore marine in the lower member (consistent with the occurrence of plant megafossils and vitrinite derived from woody organic matter from the progymnosperm *Archaeopteris*), distal marine in the middle member (consistent with a low pollen index of Turner and others, 2015), and near-shore marine in the upper member (Urban, 1960, supported by Turner and others, 2015). Von Almen (1970) used palynology of fifty-five Woodford Shale outcrop and core samples from seven localities in south-central Oklahoma to determine environment of deposition of three alternating palynomorph zones (Microspore-Acritarch [most regressive], Microspore-Leiosphere [intermediate], and Leiosphere [most transgressive]) in terms of distance from shore and cycles of marine transgression and regression. He reported finding all *Callixylon* (organ genus of *Archaeopteris*) wood specimens in the basal part and interpreted the wood as indicative of a near-shore marine environment of deposition.

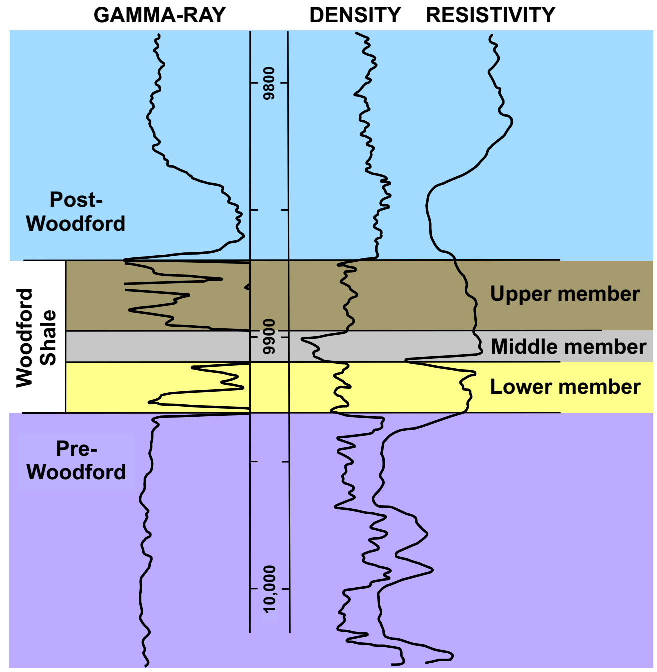

Figure 3. Electric log signatures of Woodford Shale informal members (modified from Hester and others, 1990a). Woodford Shale overall has anomalously high radioactivity, high resistivity, and low density. Within the Woodford, the lower member has intermediate radioactivity, density, and resistivity; the middle member has the highest radioactivity and resistivity and the lowest density; and the upper member has the lowest radioactivity and resistivity and highest density.

Hester and others (1990a, b) divided the Woodford Shale into three informal stratigraphic units (lower, middle, upper) based on kerogen content, gamma-ray intensity, density, and resistivity log character of ninety-nine wells in the Anadarko Basin and Anadarko Shelf. Seven cross sections demonstrated regional thinning and thickening of the units, with onlap across a positive structural trend located about 75 miles north of the Wichita Uplift that separated Woodford depocenters to the southwest (Anadarko Basin) and the northeast (Sedgwick Basin in south-central Kansas) (Hester and others, 1990a, Fig. 12, p. D12). Thinning and truncation of Woodford members across this structure indicates that contemporaneous basement flexure occurred during Woodford deposition.

The lower member has a more variable thickness distribution than the middle and upper members, reflecting deposition on an irregular, eroded, karsted, and channelized pre-Woodford unconformity surface. Woodford Shale thickens into the Anadarko Basin, but the upper member thickens toward the northeast and into the Sedgwick Basin (Hester and others, 1990a). The shift of deposition to the northeast in late Woodford time is interpreted as reflecting the transition from subsidence focused in the deep axis of the southern Oklahoma aulacogen to the early stages of foreland downwarping that culminated in Late Paleozoic (Pennsylvanian and Permian) orogeny (Hester and others, 1990a).

Lambert (1992, 1993) divided the Chattanooga (Woodford) Shale in Kansas and Oklahoma into lower, middle, and upper shale members based on geophysical-log response. Outcrop studies utilizing spectral gamma-ray profiles with uranium, thorium, and potassium readings taken every 6 in. (15 cm) and plotted full scale provide additional details used in correlation (Krystyniak, 2005; Aufill, 2007; Paxton and others, 2006; Paxton and Cardott, 2008). Most of the high gamma-ray signal is related to the occurrence of uranium and is indicative of deposition under conditions of slow sedimentation (Conant and Swanson, 1961; Paxton and Cardott, 2008, p. 32). The top of the middle member is picked above the double gamma-ray peak (Figure 4) (Paxton and others, 2006).

Caldwell (2011, 2012, 2014) and Caldwell and Johnson (2013) defined seven mudrock lithofacies (siliceous mudrock; clayey, siliceous mudrock; clayey mudrock; dolomitic, clayey mudrock; organic-poor clayey mudrock; organic-poor, clayey mudrock II; pyritic, organic-rich clayey mudrock) based on total organic carbon (TOC) and mineral content (primarily quartz, clay and dolomite) to delineate the mechanical properties, including "fracability", of the rock, and identified fifteen lithostratigraphic units within the basal, lower, middle, and upper Woodford Shale in the Anadarko Basin. The first transgression of the Woodford sea was recorded by a TOC-poor clayey mudrock basal unit. The lower and middle Woodford members contain clayey mudrock, clayey siliceous mudrock, or less common dolomitic clayey mudrock. The upper Woodford member is predominately clayey siliceous mudrock and siliceous mudrock. Furthermore, Turner and others (2015, 2016) concluded that a significant fraction of the silica in the upper Woodford is biogenically derived, while the highest concentrations of clay proxies (K and Al) occur within massive mudrock facies in the lower and middle Woodford.

Watney and others (2013) divided the Woodford Shale into lower, middle, and upper members based on biostratigraphic, petrophysical, geochemical, and sequence-stratigraphic information from a shallow core taken on the Lawrence Uplift (located on the northern flank of the Arbuckle Uplift in southern Pontotoc County). Peza and others (2014) divided the Woodford Shale into six zones. Slatt and others (2012) subdivided a Woodford Shale core from southern Oklahoma into eight lithofacies. Using

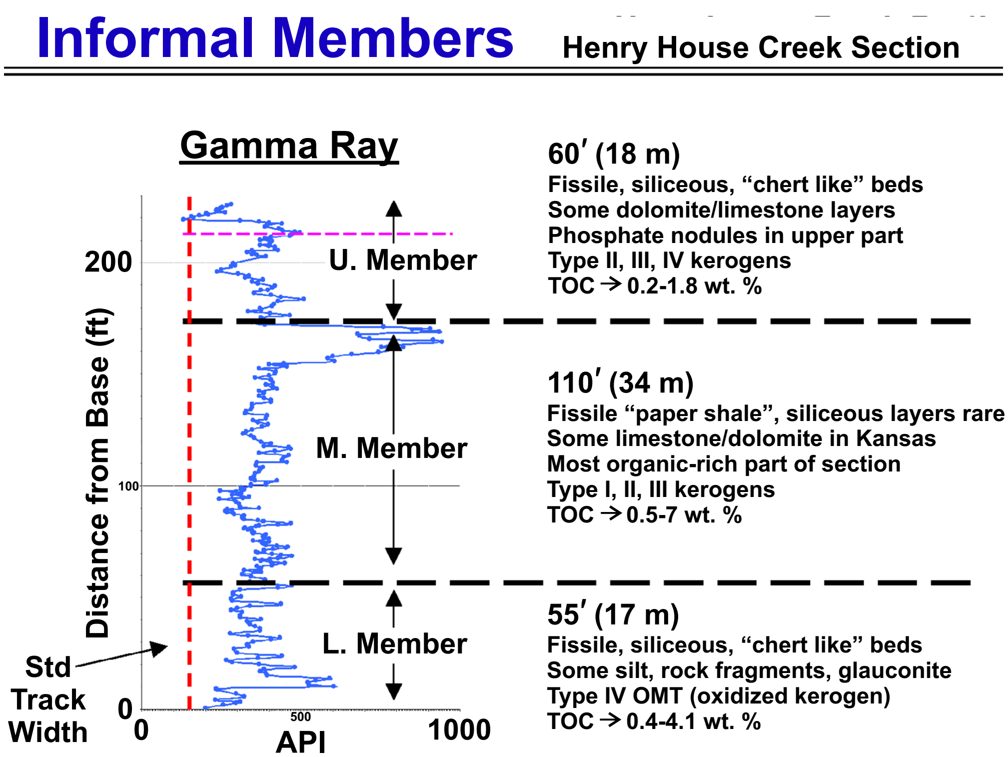

Figure 4. Vertical full-scale, gamma-ray profile of the Woodford Shale in the Henry House Creek section in the Arbuckle Uplift of Oklahoma showing delineation of informal members. Kerogen type and TOC data are from Lambert (1993). Figure is modified from Paxton and others (2006).

the three informal-member terminology, Slatt and others (2012) confirmed that the middle member had the greatest marine input and areal extent while the lower and upper members were characterized by oxic-suboxic conditions (suggestive of a near-shore marine environment). Turner and others (2015) and Turner and Slatt (2016) divided the Woodford Shale into eight lithofacies in the Wyche Farm shale pit (NE¼ Section 2, Township 2 North, Range 6 East) located in the Arbuckle Uplift; these include (1) argillaceous mudrock with detrital quartz, (2) mixed siliceous-argillaceous mudrock with thin clay lamina, (3) black to dark-gray laminated siliceous mudrock, (4) laminated siliceous mudrock with phosphatic nodules, (5) siliceous mudrock with phosphatic nodules, (6) calcareous mudrock, (7) light gray siliceous laminated mudrock, and (8) siliceous massive mudrock. Galvis and others (2018) divided the Woodford Shale in the Speake Ranch outcrop (SE¼ Section 18, Township 2 South, Range 1 West) located in the Arbuckle Uplift into seven lithofacies based on clay, quartz, and carbonate content. Laughrey and others (2017) identified five microfacies in the Woodford Shale in a well in Garvin County, Oklahoma – siliceous mudstone; silicified mudstone (most common); chert and argillaceous chert; argillaceous, siliceous dolostone; and phosphatic mudstone.

Comer (1991, 1992, 2005, 2008) recognized regional lithofacies trends in the Woodford Shale based on integrated study of the organic geochemistry and petrology of the formation (Figure 5). Siliciclastic lithofacies that contain higher proportions of detrital quartz, clay minerals (mostly illite), terrestrial (woody, Type III) organic matter, lower abundances of marine (amorphous, Type II) organic matter, and little or no biogenic silica are found mostly in northeastern Oklahoma proximal to the Ozark Uplift (Figure 5a and b) and in the western part of the southern Oklahoma aulacogen proximal to the Transcontinental Arch (Figure 5c) (Comer, 1992). Organic-rich mudstone lithofacies with little or no terrigenous organic matter, fewer and finer detrital quartz grains, lower concentrations of clay minerals, and increased amounts of biogenic silica are found mostly to the southeast in areas farthest from the paleotopographic highlands of the Transcontinental Arch and Ozark Uplift and nearer to the Late Devonian continental margin (Comer, 1992). Lithofacies change progressively from terrigenously influenced in the northwest (Figure 5c) to marine dominated in the southeast through the southern Oklahoma aulacogen (Figure 5d) and into the Ouachita Mountains Uplift (Figure 5e) (Comer, 1992) where biogenic chert composed of radiolarian tests and sponge spicules dom-

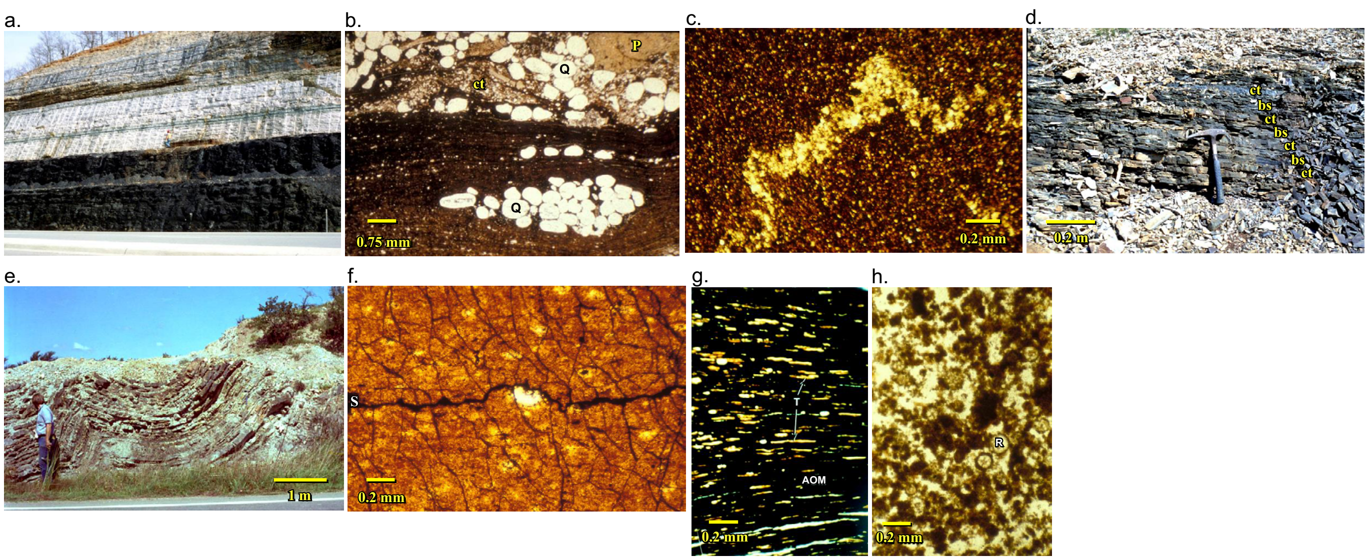

Figure 5. Outcrops and thin sections of Woodford Shale and age-equivalent rocks illustrating the changes in lithology across Oklahoma. No chert beds are present in exposures proximal to the Ozark Uplift (a and b) and none are present in cores from the western Anadarko Basin (c). Biogenic chert beds increase in abundance and thickness from west to east across the Arbuckle Uplift into the Ouachita Mountains Uplift (d-e). Photomicrographs b-c and f-h are views through a polarizing microscope using plane polarized light. (a) Chattanooga Shale is overlain disconformably by St. Joe Limestone (Lower Mississippian) along US Highway 71 at Belle Vista, Benton County, Arkansas, Section 12, Township 20 North, Range 31 West. This outcrop, which is

devoid of biogenic chert beds and generally lacks biogenic silica, is typical of the Chattanooga Shale exposed in northeastern Oklahoma. At this location a grab sample of the Chattanooga Shale contained 2.1 wt. % TOC, a mixture of marine and terrestrial organic matter, predominantly fine-grained detrital quartz and clay, and a mean random VR_o of 1.11%. Data from Comer (1992, Table 2, location AR1). (b) Sandstone lens in black shale (Comer and Hinch, 1987, Figure 3) from a grab sample of an outcrop in the Ozark Uplift at Gayler Cemetery in the type area of the Sylamore sandstone (Freeman and Schumacher, 1969), Stone County, Arkansas, Section 21, Township 15 North, Range 11 West. The interval of the Sylamore member of the Chattanooga Shale that was excavated and sampled consists of interbedded black shale and mostly medium-grained supermature quartz arenite. Quartz grains (Q) in the sandstone lens and scattered in the basal zone of the overlying bed are well rounded and represent a narrow grain-size range. Phosphate (P) and detrital chert (ct) are common in the Sylamore sandstone (Pittenger, 1981; note that samples designated as AR9 by Pittenger [1981] and by Comer [1992] are from the same suite of samples originally collected by Comer). Based on visual kerogen analysis, organic matter type in the black shale beds, which are characteristic of the Chattanooga Shale exposed in the Ozark Uplift, varies from predominantly structured material of terrigeneous origin to amorphous material of marine origin to a subequal mixture of structured and amorphous material. Black shale beds at this location have a mean TOC content of 3.5 wt. % and a mean random VR_o of 0.83%. Data from Comer (1992, Table 2, location AR9). (c) Horizontal burrow in a silty shale interval characteristic of the Woodford Shale in the western Anadarko Basin (Comer and Hinch, 1987, Figure 6a). Silt-sized components are mostly dolomite with lesser amounts of detrital quartz. This thin section was cut from core recovered from a drilled depth of 14,259 ft (4,346 m) in the Glover Hefner Kennedy No. 1 Hoffman well located in Custer County, Oklahoma, Section 1, Township 14 North, Range 16 West. Mean TOC for the cored interval of the Woodford Shale is 5.8 wt. %, mean random VR_o is 1.91%, and the organic matter is predominantly composed of structured material of terrigenous origin. Large carbonized wood fragments were observed on some bedding planes (Comer, 2008, panel 2). Data from Comer (1992, Table 2, location A16). (d) Woodford Shale in the Arbuckle Uplift on State Highway 110 two miles north of Dougherty, Murray County, Oklahoma, Section 1, Township 2 South, Range 2 East. Interbedded biogenic chert (ct) and black shale (bs). Fissile black shale beds are typically thicker than chert beds. TOC of black shale = 8.5 wt. %. Data from Comer (1992, Table 2, location OK26). (e) Arkansas Novaculite in the Ouachita Mountains Uplift at Black Knob Ridge located on State Highway 3 one mile east of Atoka, Atoka County, Oklahoma, Section 14, Township 2 South, Range 11 East. At this location biogenic chert beds are thicker (up to 8 in. [20 cm] thick) and more abundant than black shale beds. The chert beds are more resistant to weathering, stand out in relief on the outcrop, and are highly fractured as a result of the folding and thrusting that occurred during Late Paleozoic orogenesis. Mean TOC for this section is 3.2 wt. % (range = 0.1 – 11.2 wt. %). Mean random VR_o = 0.52%. Data from Comer (1992, Table 2, location OK21). (f) Naturally fractured biogenic chert from the oil-producing interval in the Woodford Shale in the southeastern Ardmore Basin, North Aylesworth field, Marshall County, Oklahoma (Comer and Hinch, 1987, Figure 5c). The fine network of fractures represents the effective reservoir porosity. The white object in the center of the slide is a recrystallized radiolarian test that was truncated by a stylolite (S). Bitumen lines the fractures and is also concentrated in the stylolite. Pale elliptical bodies scattered through this rock are radiolarian tests that have been recrystallized and deformed. This thin section was cut from a conventional core recovered from a drilled depth of 3,056 ft (931 m) in the Texaco No. 1-K Drummond well located in Section 11, Township 6 South, Range 6 East. The biogenic chert at this depth has a TOC content of 4.5 wt. %. The cored interval of the Woodford Shale contains predominantly amorphous organic matter of marine origin, a mean random VR_o of 0.46%, and a mean TOC of 7.7 wt. %. Data from Comer (1992, Table 2, location A33). (g) Highly compacted black shale bed collected from the Interstate-35 outcrop located on the south flank of the Arbuckle Uplift in Carter County, Oklahoma, Section 25, Township 2 South, Range 1 East (Comer and Hinch, 1987, Figure 7c). Opaque material is amorphous organic matter (AOM) of marine origin and the yellowish streaks are Tasmanites (T) that were flattened due to compaction. Secondary chert is absent. The mean TOC for the Woodford Shale section is 8.4 wt. % (range = 3.0 – 22.0 wt. %) and the mean random VR_o is 0.52%. Visual kerogen analysis confirms that amorphous organic matter of marine origin predominates in all of the samples collected from this outcrop. Data from Comer (1992, Table 2, location OK35). (h) Biogenic chert in the Woodford Shale. Radiolarian tests (R) are undeformed and supported in chert cement (white areas). The brownish material and dark brown clusters are amorphous organic matter of marine origin that predominate in the Woodford Shale at this location. The lack of compaction of both the radiolarian tests and the organic matter is evidence of pervasive, very early chert cementation. This thin section was cut from a cored interval at a depth of 6,264 ft (1,909 m) in the Woodford Shale in the Gulf No. 1 Schroeder well located in Oklahoma County, Oklahoma, Section 3, Township 12 North, Range 2 West. The well is in the southwestern Cherokee Platform near the boundary with the Anadarko Shelf/Basin provinces shown in Figure 1. The Woodford Shale in this core has a mean TOC of 9.3 wt. % and a mean random VR_o of 0.40%. Data from Comer (1992, Table 2, location A27).

inates the Upper Devonian section (Amsden and others, 1967; Park and Croneis, 1969; Houseknecht and others, 2014). Naturally fractured, conventional reservoirs that produce oil from the Woodford Shale are completed in the biogenic chert intervals (Figure 5f). Where black shale and biogenic chert are interbedded (e.g., Figure 5d), the end member lithologies are highly compacted, organic carbon-rich (up to 30 wt. % TOC) black shale (Figure 5g) and uncompacted, densely cemented biogenic chert (Figure 5h). Terrigenous sediment is also most common in the lower unit of the Woodford where silt- and sand-sized quartz frequently is abundant and detrital lag deposits are often observed (Amsden and others, 1967; Amsden and Klapper, 1972; Amsden, 1975; Comer, 1992). The informally recognized basal units, Misener and Sylamore sandstone members, are mostly mature quartz arenite with the quartz grains derived from the Middle Ordovician quartz arenite that was exposed in nearby outcrops along the Ozark Uplift during the Late Devonian (Amsden and Klapper, 1972; Pittenger, 1981; Francis, 1988; Krumme, 2001). The textural maturity of the quartz in these basal members (Figure 5b) is inherited, with very little modification, from the Middle Ordovician sandstone that sourced them (Amsden and Klapper, 1972; Pittenger, 1981, 1988; Francis, 1988; Kuykendall and Fritz, 1993, 2001).

Sequence Stratigraphy

Regional Studies: Several studies have applied the concepts of sequence stratigraphy to the Woodford Shale in Oklahoma (Lambert, 1993; Ali, 2015; Althoff, 2012; Amorocho Sanchez, 2013; Bernal, 2013; Bontempi, 2015; Chain, 2012; Coleman and Jordan, 2018; Galvis, 2017; Kilian, 2012; Liborius and Sneddon, 2017; Maynard, 2016; McCullough, 2014, 2017; Molinares Blanco, 2013; Peza and others, 2014; Slatt, 2013a, 2015; Slatt and Rodriguez, 2012; Slatt and others, 2015; Watney and others, 2013; Turner and others, 2015, 2016; Turner, 2016; Zhang, 2016; Jones, 2017; Brito, 2019; Philp and DeGarmo, 2020; Slatt and others, 2014, 2018a and references therein; Slatt, 2020). Figure 6 is representative of these sequence stratigraphic interpretations.

Slatt and Rodriguez (2012) provided the following time frames for Woodford Shale sea level cycles: 2nd order (~10-25 My), 3rd order (~1-3 My), and 4th order (~100,000-300,000 years). Overall, the Woodford Shale follows a 2nd order sequence (deposited over a 33 My time span) with at least eight high-frequency cycles presumed equivalent to 3rd order cycles (Slatt and Rodriguez, 2012; Slatt, 2013b, 2015). Slatt (2015) provides an overview of sequence stratigraphy of unconventional resource shales. Similar to other unconventional resource shales, Slatt (2013a, 2015) identified a basal erosional sequence boundary, transgressive system tract in the lower and most of the middle Woodford Shale members, condensed section/maximum flooding surface at the highest gamma-ray reading (plotted full scale) in the upper middle member, and highstand system tract during major sea level regression in the upper middle and upper Woodford Shale members (Figure 6). The maximum flooding surface is at the double gamma-ray peak near the top of the Woodford middle member (Turner and others, 2015, 2016; Jones, 2017; Coleman and Jordan, 2018; Slatt and others, 2018a, b). Slatt and Rodriguez (2012) indicated that the transgressive systems tract and condensed section are relatively organic rich while the highstand or regressive systems tracts are organic poor. Zhang (2016) identified seven parasequence third-order cycles in the Woodford Shale in north-central Oklahoma within ductile transgressive system tract zones and brittle highstand or regressive system tract zones.

These high-resolution stratigraphic analyses have provided invaluable insights into the complexity and variability of the Woodford Shale interval and have established a detailed framework for intrabasinal correlation, resource assessment, and exploration and development of this hydrocarbon source-rock reservoir. Also, this work has significantly advanced our understanding of the environment of deposition, relative fluctuations of sea level, sediment origins, and conditions controlling productivity and preservation of organic material. Integration of reservoir property data (e.g., porosity, pore size distribution, rock hardness, etc.) into the array of information gathered during Woodford Shale studies provides a comprehensive set of parameters with which to target exploration plays in the Woodford Shale and gives additional insights for development of other unconventional shale resources.

Global Studies: Stratigraphic sequences recognized in Woodford Shale should correlate with the global sequences established for the Late Devonian (Figure 7). While some attempts have been made to accomplish these correlations using various proxies (e.g., Paxton and others, 2006; Slatt, 2013a; Bernal, 2013; DeGarmo and others, 2016; Turner and others, 2016; Slatt and others, 2018b; Philp and DeGarmo, 2020), the lack of high-resolution biochronologic studies for Woodford Shale renders such exercises problematic. The global sequences and their

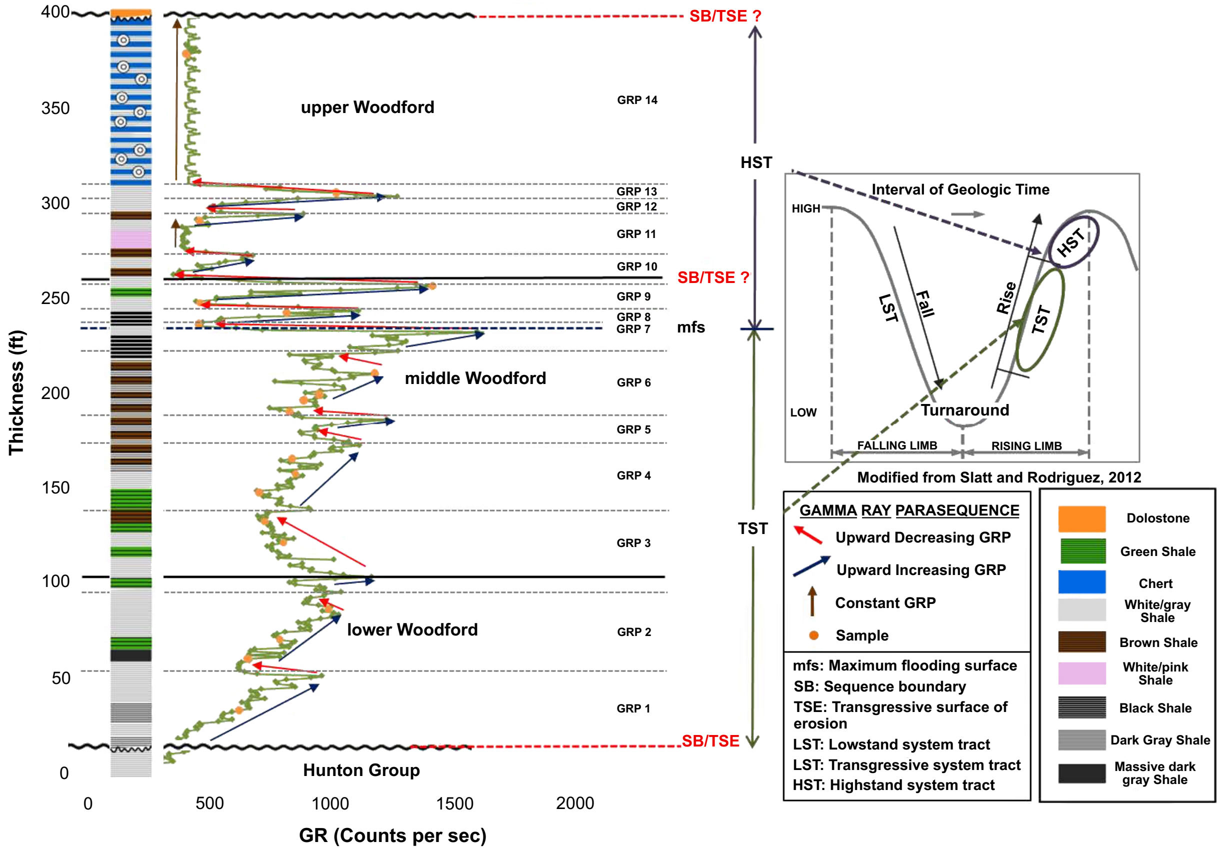

Figure 6. Interpretation of the sequence stratigraphy for Woodford Shale exposed in the McAlister Cemetery Quarry, Carter County, Oklahoma. GR = gamma-ray response in counts per second; GR is represented by the green line connecting the green dots which mark the level where the gamma-ray response was recorded. GRP = gamma-ray parasequence: fourteen parasequences (GRP 1-14) are interpreted for this section based on the rising and falling patterns in the gamma-ray response as indicated by the black and red arrows. The concentric circles in the interval at the top of the lithology column represent Radiolaria which are the dominant components of the biogenic cherts in the Woodford Shale (from Bernal, 2013).

boundaries shown in Figure 7 are the result of eustatic sea-level changes that have been well documented and correlated in Upper Devonian sections from widely separated locations around the world (Johnson and others, 1985; Sandberg and others, 1988; Sandberg and others, 2002). Researchers worldwide have undertaken intensive and detailed biostratigraphic studies that have resulted in a high-resolution biochronology for the Late Devonian primarily based on conodont zonations (Sandberg and others, 1988; Sandberg and others, 2002; Becker and others, 2016). Together with lithologic and facies analysis, these biostratigraphic studies have resulted in a consistent picture of global eustacy and have fostered an informed discussion about the conditions and events that gave rise to global changes during the Late Devonian.

Figure 7 summarizes the major events that have been correlated with both gradual and abrupt changes in sea level during the Late Devonian. These events include from oldest to youngest (1) the Taghanic onlap in the Givetian (Sandberg and others, 2002; Narkiewicz and others, 2016; Zambito and others, 2016); (2) the Amönau event in central Germany coincident with the major transgressive pulse at the beginning of the Frasnian; (3) the Alamo impact of southern Nevada coincident with abrupt global transgression; (4) the *semichatovae* transgression with abrupt deepening that carried the pelagic conodont species *Palmatolepis semichatovae* far onto shallow carbonate platforms (Sandberg and others, 2002; Becker and others, 2016); (5) the Frasnian/Famennian mass extinction, one of the five major mass extinctions of the Phanerozoic, attributed to the series of events at the end of the Frasnian comprising the Kellwasser crisis which was punctuated by periods of transgression, eustatic highstands, and abrupt and severe regression (Sandberg and others, 1988; Sandberg and others, 2002); (6) eustatic rise that coincides with post-extinction biotic radiation (Sandberg and others, 2002); (7-10) four prominent, short-lived transgressions interpreted as interglacial periods of eustatic sea-level rise (Sandberg and others, 2002) superimposed on the background of falling, then rising sea level in the Famennian attributed to the waxing and waning of glaciation at high latitude in Gondwana (Sandberg and others, 2002; Caputo and others, 2008; Isaacson and others, 2008); (11) major regression near the end of the Famennian interpreted as the climax of Famennian glaciation in Gondwana and marking the onset of biotic decline preceding the Devonian/Carboniferous mass extinction; and (12) Devonian/Carboniferous mass extinction. Events 11 and 12 encompass the Hangenberg crisis, a period of mass extinction that some argue was comparable in scale to the five greatest Phanerozoic mass extinctions (Kaiser and others, 2016).

Although the Woodford Shale sediments were deposited during and influenced by these global events, the formation lacks the floral and faunal abundance and diversity to replicate the high-resolution biochronology accomplished in other regions and to tie specific sequences or horizons to their globally recognized equivalents. However, Over (1990) maintained that the Woodford Shale in Oklahoma does contain sufficiently abundant and diverse conodont fauna to allow high resolution biostratigraphic analysis that could potentially lead to robust correlation with the global Late Devonian biochronologic sequence.

Conodont studies of a few Oklahoma localities have identified some zones that can be correlated to the global sequence (Over, 1990). The oldest Woodford conodont fauna is in the Misener and Sylamore sandstone members and is assigned to the *Polygnathus varcus* zone of late Middle Devonian (Givetian) age (Freeman and Schumacher, 1969; Amsden and Klapper, 1972). These quartz-rich units represent the earliest depositional manifestation in Oklahoma of the Taghanic onlap (Figure 7), a period of worldwide rising sea level, global warming, increased aridity, dysoxic conditions, and a global biocrisis during which extinction of Middle Devonian faunas occurred (Zambito and others, 2016). Over (1990, 2002) used conodonts to identify the Frasnian/Famennian boundary horizon in five Woodford Shale outcrops, three located in the Arbuckle Uplift, one in the Criner Hills, and one on the Lawrence Uplift (located on the northern flank of the Arbuckle Uplift in southern Pontotoc County; Ham and others, 1990). The Frasnian/Famennian boundary occurs

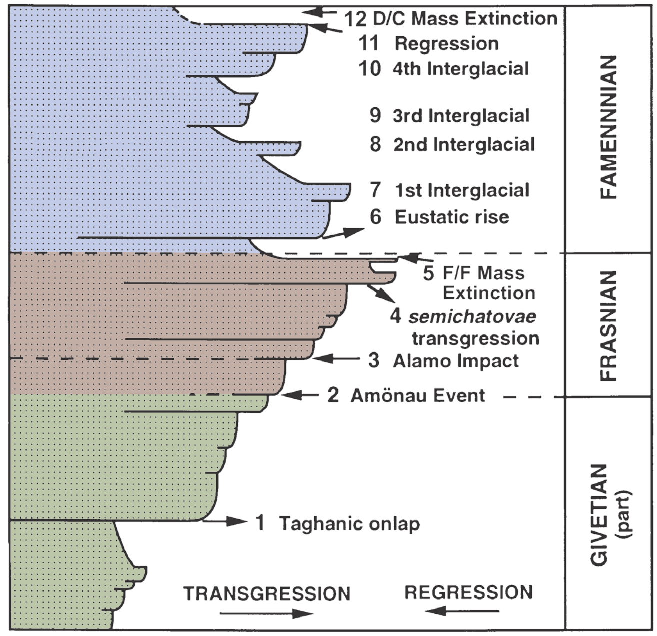

Figure 7. Late Middle to Late Devonian sea-level curve, showing positions of 12 sea-level changes, catastrophic events, and mass extinctions. D/C is Devonian-Carboniferous, F/F is Frasnian-Famennian. Modified from Sandberg and others (2002).

at the end of the Kellwasser biocrisis, a period of intense biotic decline culminating with late Frasnian mass extinction (Sandberg and others, 2002; Becker and others, 2016). The boundary horizon on the Lawrence Uplift and in the northern Arbuckle Uplift is a thin phosphate and conodont lag deposit in an otherwise continuous dark shale section (Over, 1990, 2002). The coarser grain size, accompanied by a change to more nearshore conodont biofacies, at the Woodford Frasnian/Famennian boundary indicates a drop in sea level and higher energy conditions (Over, 1990), which correlates with the abrupt regression recognized on a global scale (Figure 7, event 5). The cause of the abrupt global change from transgression to regression is still debated but may involve extraterrestrial impact, onset of glaciation centered in the southern hemisphere (Gondwana), and related environmental crises (Sandberg and others, 2002). Over (1990, 1992) used conodonts to identify the Devonian/Carboniferous boundary horizon in eight Woodford Shale outcrops, five located on the Lawrence Uplift and three in the Arbuckle Uplift. The Devonian/Carboniferous boundary occurs at the end of the Hangenberg biocrisis, a period of intense biotic decline culminating with late Famennian mass extinction (Sandberg and others, 2002; Becker and others, 2016; Kaiser and others, 2016). The boundary horizon is disconformable and associated with pelletal phosphate laminae at six localities, occurs at the top of a green shale interval at a seventh locality, and is represented by a boundary interval with no exact horizon at the eighth locality (Over, 1990, 1992). Phosphate is indicative of erosion and non-deposition and, together with the change in conodont biofacies from offshore to transitional and more nearshore fauna, indicates higher energy conditions and a lowered sea level at the Devonian/Carboniferous transition (Over, 1990, 1992), which correlates with the regression recognized on a global scale (Figure 7, event 11). The cause of the global regression in the latest Devonian is widely considered to be glaciation in Gondwana (Sandberg and others, 2002; Caputo and others, 2008; Isaacson and others, 2008; Kaiser and others, 2016; Lakin and others, 2016) which may have been triggered by significant loss of atmospheric CO_2 resulting from massive burial of organic carbon during the global deposition of black shale (Kaiser and others, 2016). Subsequent work by Nowaczewski (2011) used the conodont biostratigraphic demarcations established for the Frasnian/Famennian and Devonian/Carboniferous boundaries by Over (1990) for two outcrops in the Arbuckle Uplift (Interstate-35 and Classen Lake; Section 24, Township 1 South, Range 1 East) as benchmarks for establishing biomarker variations for the Famennian sequence.

Additional studies have used various proxies to infer correlations with the global sequences established by the detailed conodont biostratigraphy. Bernal (2013) used various proxies (e.g., radioactivity, TOC, lithology) to infer transgressive/regressive cycles and to correlate these with the global sequence for a measured section at the McAlister Cemetery Quarry located in Carter County, Oklahoma. Turner and others (2016) used chemostratigraphic proxies to place the Frasnian/Famennian boundary above an inferred maximum flooding surface in two cores and three outcrops in central Oklahoma. Philp and DeGarmo (2020) published biomarker data for the extensively studied Woodford Shale outcrop exposed in the McAlister Cemetery Quarry, Carter County, Oklahoma, and illustrated how these data tie to other proxies in identifying depositional sequences and establishing intrabasinal, regional, and global correlations. However, the fact that the Frasnian/Famennian boundary has been placed in the lower member by some researchers (Over, 1990; Cullen, 2020), uppermost middle member by Slatt (2013a, 2020) and Molinares Blanco (2019), and in the upper member by others (DeGarmo and others, 2016; Philp and DeGarmo, 2020) indicates that regional correlations, including member boundaries, are poorly constrained.

This research illustrates that a more detailed understanding of Woodford Shale sequence stratigraphy may be possible by linking lithostratigraphic, chemostratigraphic, and biomarker studies with detailed biostratigraphic studies such as those pioneered by Over (1990) and Nowaczewski (2011). The resulting chronostratigraphy would improve intra- and interbasinal correlations in Woodford Shale, including more accurate intrabasinal and regional assignment of lower, middle, and upper member boundaries. Developing the biostratigraphic chronology of the Woodford Shale and tying it directly to the various proxies would allow more detailed interpretation of the depositional environments and processes that evolved throughout the Late Devonian in Oklahoma.

Mineralogy

The mineralogy of Woodford Shale and the basal Misener and Sylamore sandstone members in Oklahoma is summarized in Table 1. Woodford Shale samples represented in Table 1 are from 25 of the locations described by Comer (1992) and these mineralogy data are previously unreported. Misener sandstone data represent cores from Grant and Garfield Counties (Francis, 1988) and Sylamore sandstone data represent outcrops from Delaware, Cherokee, and Sequoyah Counties (Pittenger, 1981). Woodford Shale mineralogy was obtained by X-ray diffraction analysis, whereas Misener and Sylamore sandstone mineralogy was determined by point counting thin sections.

An important point to emphasize here is that the Woodford Shale consists of thin beds and thin laminae that are highly variable in composition. While high resolution stratigraphic studies have become more commonplace, many analyses represent information composited over intervals greater than the scale of the variability. The mineralogy data presented in this section is particularly susceptible to homogenizing lamina-scale variations (e.g., X-ray diffraction data) and also to overestimating the significance of a small sample (e.g., thin section data). While understanding Woodford Shale variability is critical to identifying sweet spots and establishing commercial hydrocarbon production, what is most important for assessing Woodford Shale depositional processes is the larger scale lateral and vertical changes. In this context, recognizing the vertical and lateral changes in mineralogy, as well as the significance of detrital sediment grain size, is essential to developing a cogent model for the deposition of Woodford Shale.

Furthermore, when interpreting the depositional setting of the Woodford Shale, caution must be exercised in applying sequence stratigraphy models based on continental margins that are primarily influenced by large rivers discharging into the sea and dispersing large volumes of sand and mud as deltas, bars, strand plains, fans, channel-fills, and classical sand and mud turbidites. Woodford Shale consists almost exclusively of silt- and clay-sized sediments deposited across the huge expanse of epeiric seas that stretched from present-day New Mexico to Arkansas. Because there is no sedimentologic or stratigraphic evidence of large perennial rivers along this continental margin during the Late Devonian, concepts of progradation and retrogradation based on clinoform geometries and significant vertical changes in grain size (sand, silt, clay) used in the classic applications of sequence stratigraphy should be modified or abandoned for the Woodford Shale and similar mudrocks. The recognition of shoreline advance or retreat cannot be defined by seaward or landward shifts of grain size-defined packages of sediment nor by overlapping clinoforms. Shoreline shifts may not necessarily be indicated by increasing or decreasing amounts of terrestrial sediment proxies, although the general agreement of the larger scale transgression (lower and middle members) and regression (upper member) interpreted for Woodford Shale is in overall agreement with the global eustatic curve for the Late Devonian (Figure 7). In contrast to the classical sedimentation models, an increasing contribution of terrestrially derived material may result from non-riverine processes, such as tropical storms, dust storms, and less intense winds capable of eroding unconsolidated silt- and clay-sized particles from exposed land areas and widely dispersing these sediments far across the basin. The caution emphasized here is that processes deducible from stratigraphic, lithologic, and geochemical data to explain Woodford Shale deposition are fundamentally different than the processes invoked using classical sequence stratigraphy to explain deposition along more typical river- and sand-dominated continental margins. Assuming that the sequence stratigraphy fits a classical continental margin model could lead to significant misinterpretation of the conditions and environments of deposition for Woodford Shale mudrocks.

Black Shale: Semiquantitative X-ray diffraction analysis of 127 Upper Devonian black shale samples from the suite of rocks collected in Oklahoma by Comer (1992) had the following mineralogy (Table 1, Woodford Shale, gray highlight). Quartz was present in all samples, with a mean concentration of 71% and a range from 44% to 100%. Illite (listed as "clay" in Table 1 for the Woodford Shale) was also present in all samples analyzed, at least in trace amounts, with a mean concentration of 14% and a range from <1% to 32%. Feldspar, pyrite, and dolomite were present in the majority, but not all, of the samples analyzed. Feldspar was present in 83% of the samples, with a mean concentration of 2% and a range from 0% to 8%; pyrite was present in 73% of the samples, with a mean concentration of 3% and a range from 0% to 20%; and dolomite was present in 64% of the samples, with a mean concentration of 6% and a range from 0% to 43%. Calcite was detected in only 5 of the samples analyzed and phosphate (fluorapatite) was detected in only 2 samples. Chlorite (not shown in Table 1) is a minor component that was present in 78% of the samples analyzed, with a mean of 3% and a range from 0% to 8%. Other minor components found in a few samples included kaolinite (trace amounts in 5 samples), mixed-layer illite-smectite (trace amounts in 15 samples), magnesite (trace amounts in 4 samples), and anhydrite (trace amounts in 1 sample). Magnesite is found in the same samples from a subsurface cored interval containing the highest concentrations of dolomite.

Numerous additional mineralogy studies have been undertaken and the data show that quartz is commonly the dominant mineral and mostly occurs together with highly variable amounts of illite. Most mineralogy studies are limited to grab samples that indicate the mineralogy of a small part of the formation. Based on Woodford Shale grab samples, Abousleiman and others (2008), Branch (2007), Kirkland and others (1992), O'Brien and Slatt (1990), and Fishman and others (2013) reported mineral content ranging from 9 to 95% quartz, 0 to 56% dolomite, and 2 to 53% illite. The problem with grab samples is that the results depend on how the samples were collected, often selected by color (e.g., darkest shale) for hydrocarbon source rock richness instead of randomly selected.

A less biased and more representative approach to determine shale mineralogy distribution is using an electric log such as the Elemental Capture Spectroscopy (ECS) log by Schlumberger which identifies the elements present in the rock and converts element yields to mineral weight percent, thus providing the lithologic variations for the entire formation. Buckner and others (2009) and Slatt and others (2012) applied the ECS log to a shallow core of the Woodford Shale in southern Oklahoma. Slatt and others (2012, p. 386) stated that "The ECS log shows a quartz-rich upper Woodford, a more clay-rich

Table 1. Statistical summary of the mineralogy of Woodford Shale and the basal Misener and Sylamore sandstone members in Oklahoma.*

Stratigraphic Unit	Statistics	Detrital Grain Composition							Cement				Porosity (%)
		Quartz (%)	Feldspar (%)	Dolomite (%)	Phosphate (%)	Chert (%)	Calcite (%)	Clay (%)	Silica (%)	Ferroan Dolomite (%)	Calcite (%)	Pyrite (%)	
Woodford Shale	Minimum	44	0	0	0	-	-	<1	-	-	0	0	-
	Maximum	100	8	43	32	-	-	32	-	-	12	20	-
	Mean	71	2	6	0	-	-	14	-	-	0	3	-
	STDV	13	2	8	3	-	-	6	-	-	1	4	-
	n	127	127	127	127	-	-	127	-	-	127	127	-
Frequency	n+	127	105	81	2	-	-	127	-	-	6	93	-
	n-	0	22	46	125	-	-	0	-	-	121	34	-
	%+	100	83	64	2	-	-	100	-	-	5	73	-
	%-	0	17	36	98	-	-	0	-	-	95	27	-
Misener Sandstone	Minimum	3	-	0	0	-	0	0	0	0	0	0	0
	Maximum	88	-	91	13	-	3	17	9	10	23	22	14
	Mean	64	-	16	2	-	0	4	2	3	2	1	6
	STDV	20	-	22	2	-	0	4	2	3	4	3	4
	n	72	-	72	72	-	72	72	72	72	72	72	72
Frequency	n+	72	-	59	64	-	8	57	48	43	18	23	71
	n-	0	-	13	8	-	64	15	24	29	54	49	1
	%+	100	-	82	89	-	11	79	67	60	25	32	99
	%-	0	-	18	11	-	89	21	33	40	75	68	1
Sylamore Sandstone	Minimum	80	0	-	-	0	-	0	2	-	-	-	2
	Maximum	100	4	-	-	10	-	11	31	-	-	-	24
	Mean	96	1	-	-	1	-	3	13	-	-	-	9
	STDV	5	1	-	-	2	-	3	6	-	-	-	5
	n	33	33	-	-	33	-	33	33	-	-	-	33
Frequency	n+	33	21	-	-	22	-	28	21	-	-	-	33
	n-	0	12	-	-	11	-	5	12	-	-	-	0
	%+	100	64	-	-	67	-	85	64	-	-	-	100
	%-	0	36	-	-	33	-	15	36	-	-	-	0

*Statistics included are as follows: Minimum = the lowest percentage in the samples analyzed; Maximum = the highest percentage in the samples analyzed; Mean = the mean percentage in the samples analyzed; STDV = the standard deviation (1σ); n = the total number of samples analyzed. Frequency values refer to how often a given mineral is found in the samples analyzed: n+ = the number of samples in which the mineral is present; n- = the number of samples in which the mineral is absent; %+ = the percentage of samples in which the mineral is present; %- = the percentage of samples in which the mineral is absent. Woodford Shale mineralogy was obtained by X-ray diffraction analysis, hence detrital quartz grains, chert, and silica cement cannot be distinguished. Misener and Sylamore sandstone mineralogy was determined by point counting thin sections. The "clay" in Woodford Shale samples was confirmed by X-ray diffraction analysis to be illite; "clay" in the Misener and Sylamore sandstone samples represents total fine-grained material (clay matrix). Misener data represent cores from Grant and Garfield Counties; Sylamore data represent outcrops from Delaware, Cherokee, and Sequoyah Counties. Note that semiquantitative X-ray diffraction analyses are reported as weight percent and thin section point count data are reported as volume percent. Also, only the sandstones are represented in the Misener and Sylamore data sets and not the shales that are often interbedded in these members. The Misener and Sylamore sandstone data are from Francis (1988, 1991, 1992) and Pittenger (1981), respectively.

middle Woodford, and a lower Woodford of intermediate quartz and/or clay content." Major, minor, and trace elemental (chemostratigraphic) profiles of an outcrop or core, related to mineralogy and used to infer depositional environments, are possible with closely-spaced (< 1 foot) sampling intervals using a hand-held X-Ray fluorescence spectrometer (Slatt and others, 2018b). Turner and others (2015, 2016) show a decreasing trend in continental proxies (Ti and Zr) from the lower Woodford member to the top of the middle Woodford member during a transgression followed by an increasing continental proxies trend in the upper Woodford member during a regression.

A number of minor mineral components have been identified in Woodford Shale thin sections and in X-ray diffraction data or have been inferred based on elemental analysis. These include gypsum, jarosite, albite, orthoclase, ferroan dolomite, norsethite ($BaMg[CO_3]2$), gorceixite (BaAl3[PO4][PO3OH][OH]6), magnetite, witherite, barite, sphalerite, chalcopyrite, and titanium oxides (Bernal, 2013; Turner and others, 2016; Roberts and Elmore, 2018). Many of these minor minerals are diagenetic and some are indicators of hydrothermal activity (Roberts and Elmore, 2018). Woodford samples with hydrothermal minerals are from cores located in McClain and Grady Counties at the southeastern edge of the Anadarko Basin in an area intensely faulted during Late Paleozoic deformation. The Grady County, Oklahoma, core also exhibits an anomalously high vitrinite-reflectance (VR_o) value (1.5% VR_o) relative to that predicted from maximum burial depth versus VR_o for the Anadarko Basin (Roberts and Elmore, 2018). Comer (1992) also recorded a patchy distribution of anomalously high VR_o values along the Ozark Uplift in northeastern Oklahoma and suggested the likely cause was migration of hydrothermal fluids associated with the emplacement of Mississippi Valley-type lead-zinc deposits during the Late Paleozoic. Jaiswal and others (2019) proposed that warm (~60ºC–150ºC) basinal brines moving upward along faults affected rocks ranging in age from Ordovician to Pennsylvanian and may have enhanced porosity in Mississippian-age limestones in Payne County in northern Oklahoma. However, conclusions that a thermal anomaly exists in Payne County are based on two erroneous values of 1.07% VR_o in Garfield and Noble Counties and are not supported by the data presented in this report (Table 2). Some of the diagenetic phases in the Woodford Shale, including pyrite, quartz, dolomite, calcite, and apatite, developed during more than one episode of crystallization and at distinctly different times in the burial history (Roberts and Elmore, 2018). Pyrite appears to be the earliest authigenic mineral to form (Roberts and Elmore, 2018) and framboidal pyrite is the first morphology of pyrite to appear in Woodford Shale (Fishman and others, 2013). The hydrothermal indicator minerals identified by Roberts and Elmore (2018), witherite, norsethite, magnesite, saddle dolomite, gorceixite, potassium feldspar, chalcopyrite, and sphalerite, formed during the middle to late stages of diagenesis. Also, Roberts and Elmore (2018) documented dolomite pseudomorphic after gypsum and ferroan dolomite overgrowths on rounded, abraded (detrital) dolomite nuclei.

Basal Sandstones: A statistical summary of the petrographic data compiled by Francis (1988, 1991, 1992) for cores of the basal Misener sandstone from Grant and Garfield Counties is presented in Table 1. In this area the Misener sandstone is a well sorted, hybrid quartzose-carbonate succession interbedded with thinly laminated shales (Francis, 1988). Mineralogy of the sandstones varies; most are dominated by varieties of quartz (monocrystalline and polycrystalline quartz plus chert) but in some places, mostly toward the south, dolomite becomes abundant and dolomitic sandstones and quartzose dolostones are common. Generally, the Misener in this region is described as "mature, fine-grained, well sorted, well rounded, quartzose to dolomitic sandstone" (Francis, 1988, p. 60). Francis (1988) presents petrographic evidence that there is both detrital and diagenetic dolomite in the Misener. Furthermore, some of the detrital dolomite exists as rock fragments derived from older carbonate formations and some are from the re-sedimentation of dolomite that formed penecontemporaneously during the Late Devonian (Francis, 1988). Quartz grains commonly are well sorted and well rounded, and the high degree of rounding, together with the similar grain size, is cited as evidence that the quartz was derived from Simpson Group sandstone that was exposed during the Late Devonian in the Ozark Uplift to the north and east (Amsden and others, 1967; Amsden and Klapper, 1972; Francis, 1988). Accessory minerals include phosphate (as skeletal debris, nodules, lithoclasts, ooids, and overgrowths on quartz), glauconite, pyrite, and anhydrite (Francis, 1988; Kuykendall and Fritz, 2001). Clay minerals include illite, chlorite, kaolinite, and minor mixed-layer clay (possibly illite-smectite). Early and late stage calcite and ferroan dolomite cements are minor diagenetic components (Francis, 1988; Kuykendall and Fritz, 2001). Also, calcite occurs as cement in 25% of the Misener samples, where it ranges from 1% to 23% by volume. Misener sandstone porosity averages 6% and ranges from 0% to 14% (Table 1) (Francis, 1988).

The Sylamore sandstone is mostly fine-grained quartz arenite and is closely comparable to the Misener in mineralogy and texture (Table 1) (Pittenger, 1981, 1988). Quartz grains commonly are moderately to well sorted and well rounded. Chert grains are present in most samples and locally comprise up to 10% of the detrital components (Table 1). Phosphatic grains, similar to those found in the Misener, are common. Minor accessory minerals include glauconite, feldspar (mostly microcline), pyrite, and gypsum. Authigenic components include quartz (as overgrowths) and minor calcite, dolomite, feldspar overgrowths, length-slow and length-fast chalcedony, and illite (as alteration of feldspar overgrowths, pore lining, and pore filling) (Pittenger, 1981). Notably, the detrital feldspar grains are rounded with little or no alteration, suggesting, along with gypsum and length-slow chalcedony, that arid climate conditions prevailed in Oklahoma during Sylamore deposition from late Middle to Late Devonian (Pittenger, 1981).

Major differences in mineralogy between the Misener and Sylamore sandstone members documented in Table 1 appear to reflect different sediment provenance and weathering at the outcrop. Specifically, the greater abundance of feldspar in the Sylamore reflects its closer proximity to the Ozark Uplift which was emergent at the time of deposition, whereas the greater abundances of carbonates in the Misener reflects preservation in the subsurface as opposed to dissolution at the outcrop due to weathering. The absence of point-count data for chert in the Misener sandstone is an artifact of the method used by Francis (1988), in which chert is lumped together with all of the other varieties of quartz.

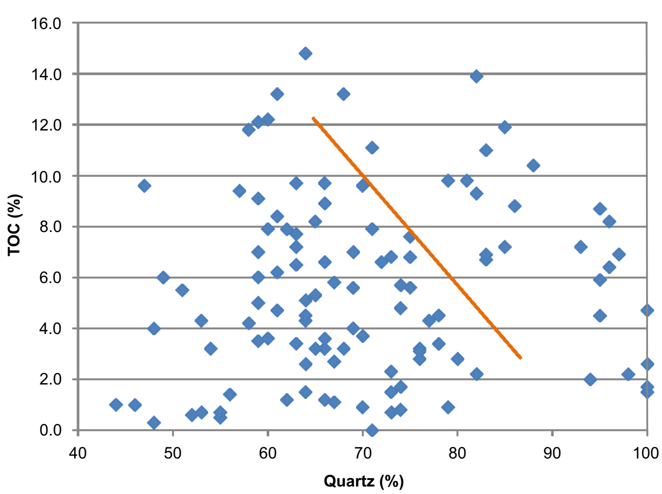

Figure 8. Graph showing relationship of quartz and total organic carbon (TOC) content of the Woodford Shale. Samples to the right of the orange line contain significant concentrations of biogenic silica and are cherty, imparting relatively more brittleness to the rock.

Chert: The middle division and parts of the upper division of the Arkansas Novaculite are equivalent in age to the Woodford Shale (Hass, 1951; Hass and Huddle, 1965), and in the frontal zone of the Ouachita Mountains Uplift this interval represents the transition from organic-rich mudstones in the west to novaculite (chert) in the Ouachita core area farther to the east (Figure 5e) (Comer, 1992, 2005). Indeed, the abundance of Radiolaria and the thickness of biogenic chert beds gradually increase from west to east across southern Oklahoma (Figure 5d-e) (Comer, 2005; Kvale and Bynum, 2014), and in the core area of the Ouachita tectonic belt almost pure radiolarian chert, with lesser amounts of sponge spicules, is the dominant facies (Park and Croneis, 1969; Lowe, 1975). Although there is significant vertical lithologic variability in Woodford Shale, in the transitional region of south-central Oklahoma where biogenic chert is interbedded with organic carbon-rich mudstone, chert is more abundant and comprises thicker beds higher in the section. This is particularly well displayed in outcrops along the Arbuckle Uplift, in the Criner Hills, and in cores from south-central Oklahoma where chert occurs as laminae (<10 mm thick), thin beds, and zones of nodules (Comer and Hinch, 1987; Schwartzapfel, 1990; Schwartzapfel and Holdsworth 1996; Kirkland and other, 1992; Kvale and Bynum, 2014; Becerra and others, 2018; Ghosh and others, 2018; Galvis and others, 2018).

Biogenic chert cannot be distinguished from detrital quartz by X-ray diffraction analysis. Consequently, a biogenic origin for the chert is confirmed by identification of siliceous microfossils (radiolarians and sponge spicules) through petrographic examination of rock samples collected from cores and outcrops (compare Figure 5b, f, and h). Lacking petrographic confirmation, biogenic chert in the Woodford may be inferred using proxy analytical data. For example, Figure 8 illustrates the relationship between TOC and total quartz content as determined by X-ray diffraction analysis. The orange line on the graph separates samples in which the quartz is biogenic chert (upper right), confirmed by petrographic analysis, from samples in which the quartz is mostly detrital (lower left). The fact that the data points are widely scattered and the separation of the two domains is not perfectly clear-cut is explained by the observation that Woodford Shale samples from the transitional region often comprise variable mixtures of detrital quartz and biogenic chert. However, the graph does suggest that, under optimum circumstances, biogenic chert intervals in the Woodford can be identified using such data. Recent chemostratigraphy data (mainly high resolution Si/Al and Si/Ti profiles) have also been used to divide the Woodford Shale into brittle vs. ductile beds, with high Si and low Al and Ti indicative of biogenic chert and low Si with high Al and Ti indicative of greater concentrations of detrital aluminosilicates (mostly clay minerals) and detrital quartz (Tréanton, 2014; Turner, 2016; Turner and others, 2015, 2016; Maynard, 2016; Reese, 2016; Zhang, 2016; Basnett, 2017; Ekwunife, 2017; Liborius and Sneddon, 2017; Becerra and others, 2018; Coleman and Jordan, 2018; and Slatt and others, 2018a, b). Detrital and biogenic quartz impart different geomechanical properties to rocks which can affect hydraulic fracturing (Slatt and others, 2018a). Intervals with high concentrations of biogenic quartz, which forms and effectively cements the rock during early diagenesis (Figure 5h), are more brittle than intervals with mostly detrital (inorganic) quartz supported in a ductile clay matrix (Turner and others, 2015; Slatt and others, 2018a).

The significance of being able to identify biogenic chert is that these beds are more competent, and therefore are more brittle, more densely fractured (Figure 5f), and more fracturable than the organic-rich mudstones (Comer, 2005; Kvale and Bynum, 2014; Becerra and others, 2018; Galvis and others, 2018; Ghosh and others, 2018). In terms of commercial reservoir potential, total quartz content is less important than the types of quartz that are present. Quartz in the Woodford Shale occurs as terrigenous clastic grains, biogenic grains (mostly Radiolaria), and diagenetic cements and replacements (Comer, 1991, 1992, 2005). The diagenetic conversion of biogenic silica (opal-A) to more stable forms of silica (opal-CT and quartz) begins rapidly after deposition (Kastner and others, 1977; Behl, 1999). Limited compaction of bedded and nodular biogenic chert, documented by uncompacted amorphous organic matter and preservation of the shape and ornamentation of radiolarian tests (Figure 5h), are evidence that the conversion of biogenic silica to quartz in Woodford Shale was an early diagenetic process (Comer and Hinch, 1987). Greater biogenic silica concentrations in the Woodford Shale increase the formation's brittleness, and zones with abundant organic-rich biogenic chert host conventionally-completed fields in Carter and Marshall Counties that have produced crude oil at low volumes for many decades (Figure 5f) (Comer and Hinch, 1987). Woodford oil fields developed using conventional completion methods include North Orr, Joiner City, Southeast Joiner City, Madill, West Caddo, Aylesworth, North Aylesworth, and Northeast Alden. Oil is produced in these fields from naturally fractured, organic-rich chert intervals within the Woodford Shale (e.g., Comer and Hinch, 1987, their figures 5 and 6c-f). Oil is also produced from naturally fractured chert intervals in the middle division of the Arkansas Novaculite at the Isom Springs Field in Marshall County, Oklahoma. Geochemical analyses have confirmed that Woodford type oil is produced in the Madill, Aylesworth, Northeast Alden, and Isom Springs fields (R. J. Harwood, 1981, personal communication; Reber, 1988, 1989) and indicate that the local, organic-rich Upper Devonian rocks are the source. Woodford Shale exposed in the McAlister Cemetery Quarry located along the Criner Hills Uplift, Carter County, Oklahoma, contains an interval of densely fractured, siliceous mudstone with bitumen lining the fractures (e.g., Kirkland and others, 1992, their figure 31b; Paxton and Cardott, 2008). Similarities with the producing intervals in naturally fractured Woodford reservoirs documented by Comer and Hinch (1987), Comer (2008) and Reber (1988, 1989) suggest that this fractured interval represents an exhumed "fossilized" Woodford Shale oil accumulation. Oil production from naturally fractured, organic-rich zones within the Woodford is compelling evidence that intervals containing significant biogenic silica are the optimum targets for hydrocarbon source-rock reservoir development.

Depositional Environment

The most detailed and comprehensive assessment of the regional depositional setting for Woodford Shale was published as a Texas Bureau of Economic Geology Report of Investigations by Comer (1991) and later summarized in an AAPG poster (Comer, 2008). The earlier publication combined stratigraphic, petrologic, and geochemical data from cores, outcrops, and well logs to construct a regional depositional model of Woodford Shale and age-equivalent formations in West Texas and southeastern New Mexico. The more recent poster included data from Oklahoma and northwestern Arkansas to support and document the relevance and consistency of the regional model to adjacent areas of the epeiric sea that occupied the Late Devonian continental margin.

Subsequent development of the Woodford Shale as an unconventional oil and gas reservoir has resulted in a significant number of new and insightful publications on the stratigraphy, lithofacies, petrology, petrography, paleontology, rock mechanics, and geochemistry of the formation (Appendix 1). The diverse data from these studies are mostly consistent with the conclusions of the earlier regional model. The following discussion is a general description of the regional depositional model along with the key data and lines of evidence that support it.

Paleogeography: The paleogeography of the southern midcontinent during the Late Devonian is illustrated in Figure 9. The expansion of an epeiric sea across the southern midcontinent of North America (Figure 9), in which fine-grained organic carbon-rich sediments were deposited, represents a period of global warming and worldwide marine transgression (Johnson and others, 1985; Sandberg and others, 2002). Plate tectonic reconstructions place Oklahoma at a low southern latitude between the wet equatorial doldrums and the wet southern temperate zone in the warm, arid southeasterly trade wind belt. The widespread, blanket-like distribution and nearly uniform fine-grained lithology of the Woodford Shale indicate that the entire region was one of low relief.

The configuration of the Woodford depositional basin in Oklahoma during the Late Devonian has been inferred from patterns of onlap (Freeman and Schumacher, 1969; Amsden and Klapper, 1972; Hester and others, 1990a; Kvale and Bynum, 2014) and local and regional variations in lithology (Pittenger, 1981; Francis, 1988; Kirkland and others, 1992; Comer, 1992, 2005, 2008; Kuykendall and Fritz, 2001; Buckner and others, 2009; Slatt and others, 2012; Kvale and Bynum, 2014; Becerra and others, 2018; Galvis and others, 2018; Ghosh and others, 2018). With the exception of the Ouachita Mountains Uplift, Arbuckle Uplift, and Wichita Uplift, which formed during tectonic

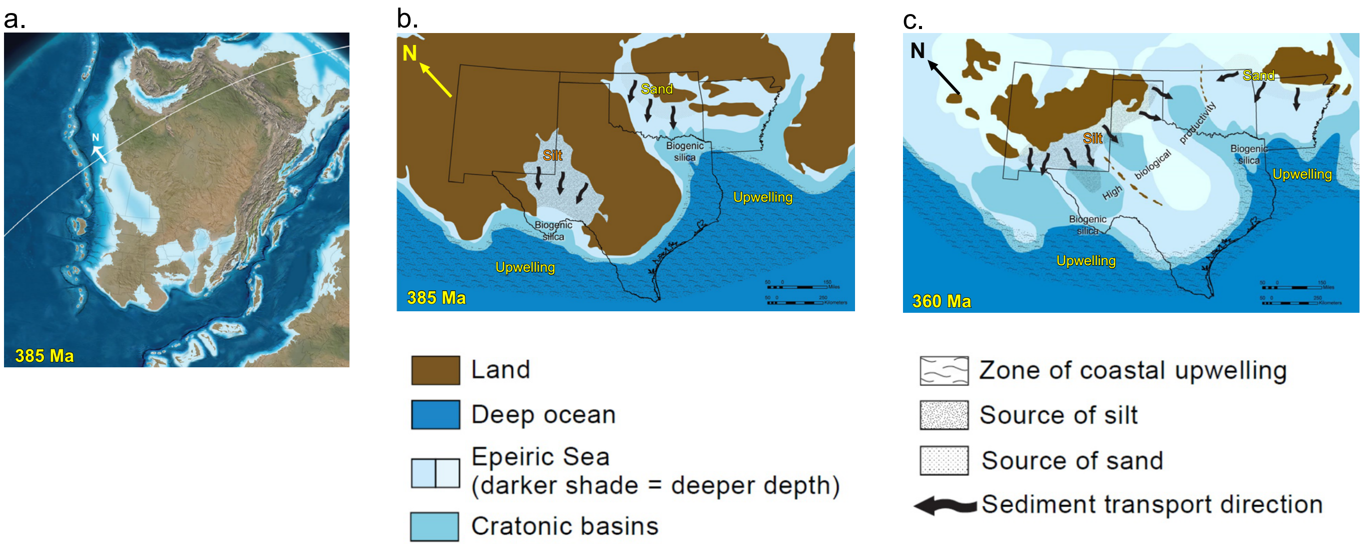

Figure 9. Paleogeography of the southern Midcontinent during the Late Devonian (Comer, 2008, modified from Blakey, 2008). Brown and green areas are emergent land masses and blue areas represent marine environments, with the darker shades of blue indicating deeper water. (a) Paleogeographic reconstruction showing North America and the orientation of the paleoequator at 385 Ma (Blakey, 2008). (b) Paleogeography of the southern Midcontinent at 385 Ma during the early stages of marine transgression. Brown areas were emergent and represent the major terrigenous sediment source areas. Deposition of the sand comprising the basal Misener and Sylamore sandstone members is shown schematically as coming from the area of the Ozark Uplift in the northeast. Silt is shown as the dominant terrigenous sediment entering the Permian Basin from adjacent land areas in west Texas and southeastern New Mexico (Comer, 1991). Areas of thick accumulations of biogenic silica are shown in west Texas and southeastern Oklahoma (Caballos and Arkansas Novaculite, respectively) and a zone of coastal upwelling is represented along the continental margin, (c) Paleogeography of the southern Midcontinent at 360 Ma during eustatic highstand. High biological productivity across the region was supported by nutrients originating from the zone of coastal upwelling along the continental margin. The middle unit of the Woodford Shale, which is the most widely distributed and most organic-rich interval, was deposited under these conditions.

deformation that began and culminated later in the Paleozoic (Suneson and Stanley, 2017), all of the modern structural elements in Oklahoma had some topographic expression during the Late Devonian (Figure 9). Relatively shallow water areas are indicated by the greater proportions and coarser grain size of terrigenous clastics in northeastern, western, and central Oklahoma (Comer, 1992). The major positive features that supplied much of the terrigenous clastic sediment to the basins were the Ozark Uplift in the northeast and Transcontinental Arch to the west. Also, the Nemaha Uplift was a positive feature based on onlap of lower Woodford facies across the structure (Kvale and Bynum, 2014), the change in lithology from more chert to the east and more clastics to the west (Kvale and Bynum, 2014), and the increase in abundance of terrigenous organic matter proximal to the uplift trend (Comer, 1992; 2005; Kvale and Bynum, 2014). The major depocenters where Woodford Shale is thickest were in the Anadarko, Marietta, and Ardmore Basins, which developed along the trend of the pre-existing southern Oklahoma aulacogen, and in the Arkoma Basin, which evolved into a classic peripheral foreland basin north of the Ouachita Mountains Uplift (Suneson, 2012). Relatively deep water is also indicated by thick accumulations of biogenic chert (Arkansas Novaculite) in the Ouachita Mountains Uplift of southeastern Oklahoma. Arkansas Novaculite represents a prolonged period of anomalously high biogenic silica productivity in a zone of coastal upwelling along the Late Devonian continental margin (Park and Croneis, 1969; Lowe, 1975). Although this continental margin was tectonically stable in the Late Devonian (Figure 9a), abrupt changes in thickness of the Woodford Shale across the Central Oklahoma fault zone associated with the Nemaha Uplift indicate that some local structural displacement did occur during Woodford deposition (Amsden, 1975, p. 10). Also, onlap, thinning, and truncation of Woodford members across a northwest-southeast trending structure located in northwestern Oklahoma (from Harper to Kingfisher Counties) indicate that contemporaneous basement flexure occurred during Woodford deposition (Hester and others, 1990a).

Paleoclimate: Diverse data from the Woodford Shale indicate the climate was warm and arid during the Late Devonian. The overall scarcity of terrestrial organic matter in the Woodford Shale suggests that land in the region supported only sparse vegetation, and the widespread predominance of fine-grained sediment and the absence of clastic wedge deposits, such as deltas and fans, indicates that nearby land areas were low relief and not drained by large rivers. The presence of anhydrite and penecontemporaneous dolomite in the basal Misener sandstone (Francis, 1988, Kuykendall and Fritz, 2001) and length-slow chalcedony, gypsum, and unaltered rounded feldspar grains that are smaller than associated rounded quartz grains in the basal Sylamore sandstone (Pittenger, 1981) also indicate that the region was arid during the Late Devonian. In addition, the presence of the biomarker gammacerane in organic carbon-rich Woodford samples (Romero and Philp, 2012) documents hypersalinity within the basin. Pyrogenic biomarkers documented in Woodford Shale imply that paleo-wildfires were widespread across the southern midcontinent during the Late Devonian (Philp and DeGarmo, 2020) and suggest that drought conditions common in arid and semiarid climates were characteristic of the region. Also, the inertinite maceral fusinite, derived from the charring of wood, is commonly observed in the Woodford Shale and is consistent with frequent paleo-wildfires (Liu and others, 2020).

Regional hypersalinity and aridity during Woodford Shale deposition is also supported by the presence of anhydrite and length-slow chalcedony in primary sedimentary structures and by penecontemporaneous detrital dolomite in fine-grained graded layers within organic-rich mudstones in the Permian Basin (Comer, 1991). Likewise, Upper Devonian (Famennian) strata in the Williston Basin, which occupied the same southern tropical zone as Woodford Shale, contain evaporites (mostly anhydrite), penecontemporaneous dolomite, mud- and clast-supported breccias, desiccation cracks, sedimentary structures indicative of rapid deposition from waning currents (graded layers and climbing ripples), and a number of other features that represent deposition in an overall arid climate that was interrupted by periodic storms and was strongly influenced by hypersaline brines (Franklin and Sarg, 2018; Garcia-Fresca and others, 2018).

Paleoceanography: Characteristic features of black shale in the Woodford, such as the high TOC content, abundant pyrite, and parallel laminae, indicate that bottom waters were stagnant and anoxic during deposition. Elevated concentrations of vanadium (V) and molybdenum (Mo), which increase in marine sediments under anoxic and euxinic conditions, document prolonged periods of sea floor stagnation during Woodford deposition (Turner and Slatt, 2016). Analysis of aryl isoprenoid biomarkers confirms that the middle unit of the Woodford Shale was deposited under persistent photic zone anoxia and euxinia, while the lower and upper units were deposited mostly under dysoxic to suboxic conditions with episodes of photic zone anoxia/euxinia (Romero and Philp, 2012; Slatt and others, 2012; Philp, 2014; Connock and others, 2018; Philp and DeGarmo, 2020). In contrast, the abundance of pelagic marine microfossils (e.g., Radiolaria and *Tasmanites*) and marine (Type II) organic matter indicates that surface waters supported a thriving marine biota. Stagnant, poorly oxygenated bottom conditions coexisting with fertile, highly productive surface waters require strong water column stratification. The presence of the biomarkers gammacerane and isorenieratane is also indicative of water column stratification (Nowasczewski, 2011; Romero and Philp, 2012). The arid climate and hypersalinity indicators imply that a persistent pycnocline developed between warm, normal-marine surface water and cold, hypersaline bottom water. Bottom anoxia developed because oxygen was rapidly consumed by decay of the large volume of organic matter and because density stratification prevented vertical mixing. Thus, Woodford Shale is the product of optimum conditions for both high primary biological productivity and effective labile organic matter preservation. This is especially evident for the middle member of the Woodford Shale because it has the highest TOC concentrations, the highest proportion of oil generative organic matter of pelagic origin, and the most persistent biomarker indicators of photic zone anoxia and both anoxic and euxinic conditions (Romero and Philp, 2012; Slatt and others 2012; Turner and Slatt, 2016).

High biological productivity over such a large geographic area for a prolonged period of geologic time requires efficient circulation of surface water and a regionally continuous supply of nutrients. Upwelling along the Late Devonian continental margin (Figure 9), documented by the thick accumulations of biogenic silica (e.g., Arkansas Novaculite), was the most likely source of nutrients. There is no evidence of large perennial rivers discharging into the basin (i.e., deltas, fans, or coarse clastic wedges) that would indicate a significant, sustained terrestrial source. The circulation model in Figure 10 shows a negative water balance required by eustatic rise with upwelled ocean water moving into the basin primarily as counter currents. Southeast trade winds, the Coriolis force, and Ekman circulation would force surface water to flow out of the basin. Net evaporation of surface water, particularly over shallow-water shelves, platforms, and shoals, would produce dense hypersaline brine that would sink to the bottom of the water column. The negative water balance from eustatic rise would be amplified

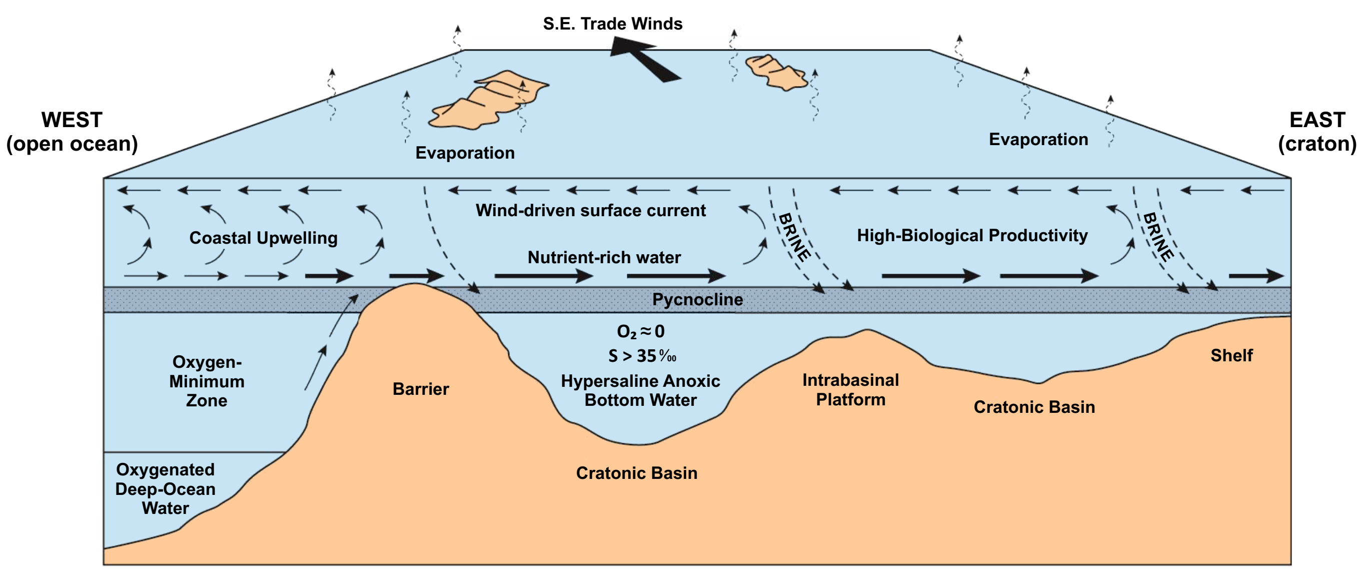

Figure 10. Block diagram illustrating water circulation during Late Devonian eustatic highstand when the middle unit of Woodford Shale was deposited (modified from Comer, 2008). Negative water balance is sustained by rising sea level and by the replacement of water lost through net evaporation and surface water outflow. Nutrients from a zone of coastal upwelling are continually swept into the epeiric sea with countercurrents and maintain high biological productivity in the upper part of the water column. Brine produced by evaporation sinks to the bottom of the water column and establishes strong density stratification and a persistent pycnocline. Anoxic and euxinic bottom conditions develop through decay of the large volume of organic-rich sediment and the absence of vertical mixing.

by the removal of surface water via wind-driven currents and evaporation, causing inflowing counter currents to be stronger than outflowing surface currents (Figure 10). The model thus provides an explanation for the continuous re-supply of nutrients required to support high biologic productivity throughout the region, even during eustatic highstand when emergent land areas were limited, low lying, and widely scattered (Figure 9c).

Depositional Processes: Figure 11 illustrates the depositional processes and resulting lithofacies for the pelagic, terrigenous, and authigenic (penecontemporaneous) sediments in Woodford Shale. The depositional model accounts for the regional continuity of almost exclusively fine-grained sediment, large contributions of pelagic marine components, absence of deltas and fans, areally and stratigraphically restricted occurrences of sandstone, graded siltstone layers, both sharp and gradational lamina and bed contacts, hybrid detrital mixtures of quartz and dolomite, presence and distribution of evaporites, high TOC concentration, widespread occurrence of undisturbed parallel laminae, interlaminated and varvelike siltstone/shale couplets, paucity of body fossils and skeletal debris, and infrequent and stratigraphically limited bioturbation. These features are interpreted to represent periods of fair weather and storm sedimentation in a strongly stratified epeiric sea along an arid passive continental margin that experienced persistent coastal upwelling (Figure 11).

Storms were likely frequent and geologically significant events because the Woodford epeiric sea was located in the tropics. Frequent storms are the most plausible mechanism for explaining the re-suspension and hybridization of fine-grained sediments and the generation of turbid bottom flows that produced fine-grained graded layers and Bouma sequences (Comer, 1991). Mechanisms known to trigger turbid bottom flows include (1) dense, sediment-laden discharge from deltas, submarine fans, and rivers in flood, (2) spontaneous slumping of rapidly deposited, unconsolidated sediment, (3) slope failure resulting from earthquakes, and (4) sediment liquefaction and autosuspension during storms (Walker, 1984). The absence of deltas, submarine fans, and coarse clastic wedges in Woodford Shale precludes the first two mechanisms. Earthquakes may have triggered some turbid bottom flows, but the subtlety of structural displacement in Oklahoma during the Late Devonian indicates that such events were weak and infrequent. Hence, storms would have been the most dominant, frequent, and powerful agents of sediment transport in the warm Late Devonian tropics. Storm-generated depositional features described in the Upper Devonian (Famennian) Three Forks Formation of the Williston Basin (Franklin and Sarg, 2018; Garcia-Fresca and others, 2018) offer corroboration for the significance of storms in the southern tropics during the Late Devonian.

During fair weather (Figure 11a), high biologic productivity in the upper water column created an abundant supply of organic carbon-rich debris. This pelagic debris, along with inorganic material suspended in the water from erosion along the shoreline, discharge of the few small intermittent rivers and streams, fallout of dust from the atmosphere, and sediment re-suspended by intrabasinal currents, slowly settled to the floor of the epeiric sea. Deposition of this diverse mixture of material was facilitated by biogenic pelletization and flocculation (Comer, 1991, 2008; Slatt and O'Brien, 2011; Bernal, 2013). These processes produced the characteristic lithofacies shown at the bottom of Figure 11a, including (1) bioturbated silty mudstone in the most hypersaline shallow-water settings, often with dolomite and occasionally with sulfate evaporates, (2) less bioturbated silty mudstone with discontinuous to lenticular laminae in areas of deeper water, and (3) black mudstone with parallel laminae, pyrite, and less silt in regions below the pycnocline. The mudstone in all three lithofacies is organic carbon-rich with the highest TOC content in mudstone deposited beneath anoxic and euxinic bottom water. Fair weather sedimentation was relatively slow and continuous.

Periods of fair-weather sedimentation shown in Figure 11a were punctuated by deposition of biogenic (mostly radiolarian) chert. Episodes of enhanced biogenic silica production and preservation are recorded as biogenic chert cyclicly interlayered with organic carbon-rich mudstone. The cause of this biogenic silica cyclicity in Woodford Shale is not well understood. In general, anomalously high concentrations of biogenic silica are interpreted as evidence of nutrient-rich water upwelling in ancient seas (Parrish and Barron, 1986; Hein and Parrish, 1987) and have been attributed to eutrophic water conditions (Racki and Cordey, 2000). Biogenic chert interlayers represent siliceous plankton blooms possibly caused by abrupt changes in upwelling that are perhaps related to climatic fluctuations and sea level changes (Racki and Cordey, 2000). Biomarker data for some of the Woodford Shale samples collected in the McAlister Cemetery Quarry suggest that a large influx of weathered and burned terrigenous organic matter supplemented surface water nutrients and contributed to eutrophication, stimulated algal

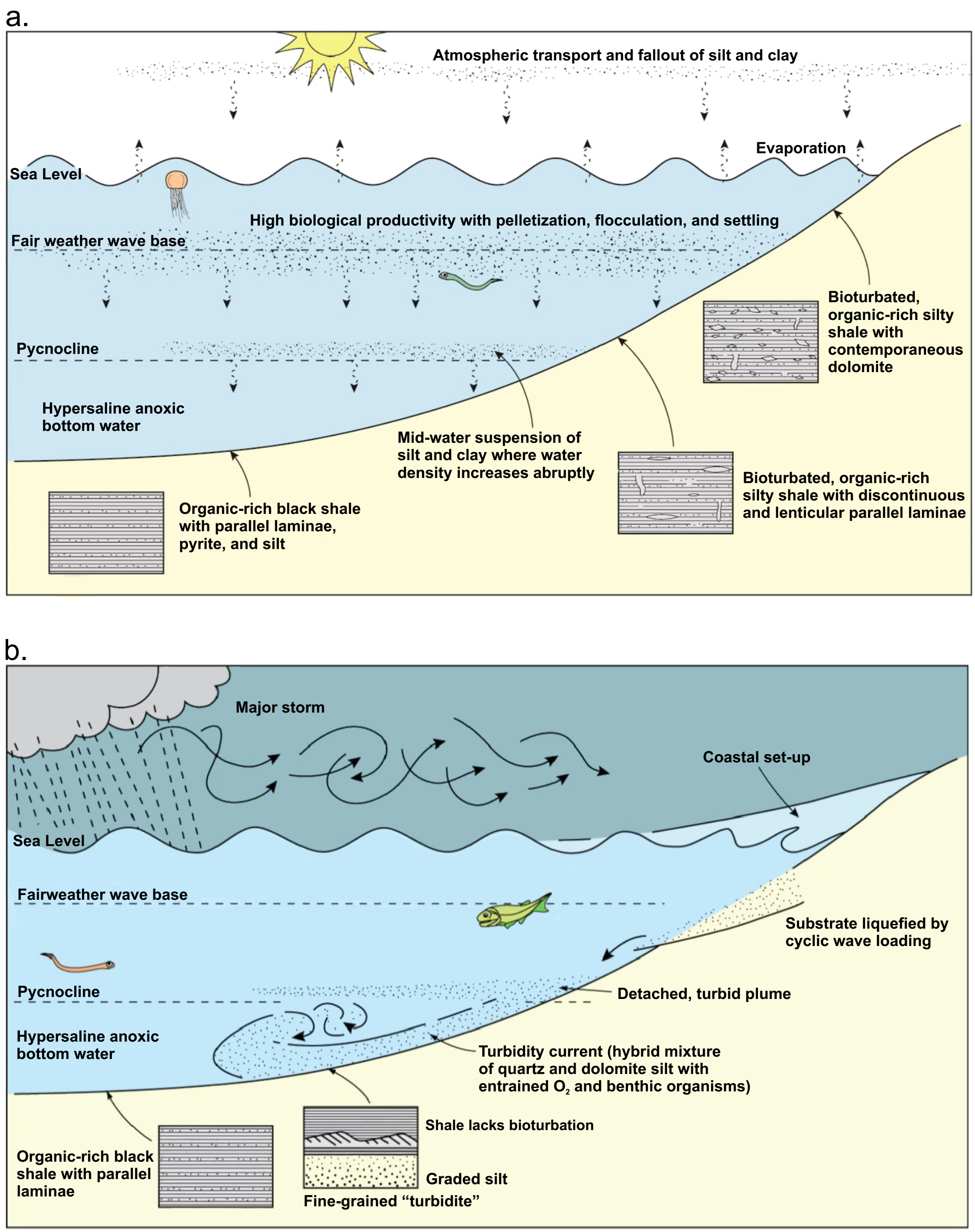

Figure 11. Schematic cross sections showing deposition of clastic detritus in the Woodford epeiric sea during the Late Devonian. (a) Fair weather sedimentation (modified from Stow and others, 2001; Comer, 2008) showing three representative Woodford lithofacies and the inferred setting in which each was deposited. (b) Storm sedimentation (modified from Walker, 1984; Comer, 2008) showing an example of a storm-generated turbidity current and resulting fine-grained turbidite.

blooms, and resulted in a period of persistent photic zone anoxia/euxinia (Philp and DeGarmo, 2020). Roberts and Mitterer (1992) suggested that the chert-black shale couplets in Woodford Shale represent pulses of high biogenic silica productivity superimposed on continuous organic carbon-rich mud deposition and that the cyclicity may have been caused by external orbital forcing (Milankovitch cycles). The increasing thickness of biogenic chert layers in Woodford Shale toward the southeast indicates that high biogenic silica productivity was sustained by nutrients supplied from the coastal upwelling occurring along the continental margin. The decrease in biogenic chert toward the northwest may simply be due to the fact that progressively less biosiliceous sediment was deposited farther from the area of highest productivity in the zone of coastal upwelling. Progressive depletion of siliceous plankton through deposition and by the attenuation of nutrient spikes would occur as upwelled water flowed and circulated farther into the basin away from the upwelling center. Also, the distal deepening of the basin toward the continental margin favors biogenic silica preservation because a deeper sea floor would be less disturbed by storms. In contrast, proximal areas would receive more terrigenous sediment, less biogenic silica because of the greater distance from the zone of coastal upwelling, and more hybrid sediments produced by autosuspension, mixing, and dilution of biogenic silica with clastic sediments during storms. The increasing abundance of biogenic chert higher in the section (Kirkland and others, 1992; Becerra and others, 2018; Ghosh and others, 2018; Galvis and others, 2018) may reflect changes in coastal upwelling (Racki and Cordey, 2000) or may record increasing dissolved silica concentrations in upwelled water with the closer approach of the Gondwana convergent margin. Elevated silica concentrations in sea water arising from volcanic and hydrothermal venting have been observed to facilitate enhanced biogenic silica productivity, and biogenic cherts from widely different locations and geological ages are associated with volcanic deposits (Racki and Cordey, 2000). The absence of beds of volcanic material in the Woodford Shale has been cited as evidence that biosilica blooms were not caused by episodic enrichment of dissolved silica from magmatic sources in or near the Woodford epeiric sea during the Late Devonian (Lowe, 1975). However, anomalously high mercury (Hg) concentrations, which are indicative of large-scale volcanism, have recently been documented in the biogenic chert beds of the uppermost Woodford Shale at the McAlister Cemetery Quarry (Cullen, 2020). These new data suggest that volcanic processes for both silica enrichment and cyclic biogenic silica deposition cannot be ruled out. A full understanding of processes controlling the cyclicity of biogenic cherts in the Woodford Shale requires further research, however, because currently available data are inconclusive.

Deposition of sediment from storm-generated currents (Figure 11b) can explain the graded siltstone layers, fine-grained Bouma divisions, detrital mixtures of quartz and dolomite, transported penecontemporaneous dolomite, bioturbation primarily in coarser-grained detrital layers, and clastic sediment bypassing of distal slopes and highs (Francis, 1988; Comer, 1991, 1992, 2008). Storms transport large volumes of sediment flushed from nearby land areas and re-suspended from unconsolidated sediment on the sea floor and in restricted shoals. Storms can generate turbid bottom flows through the action of wind-forced currents (Morton, 1981), ebb currents produced by storm surge setup (Nelson, 1982), and seaward-flowing currents caused by coastal downwelling (Swift and others, 1983). In Figure 11b, storm winds created coastal setup and cyclic wave loading liquefied the substrate, creating a dense, turbid bottom flow. Some of the finer material in this density current was diverted along the pycnocline forming a detached turbid plume, while the main denser body of the current disrupted and passed below the pycnocline (Figure 11b). The density of these storm-generated currents would have been increased by the flushing of shallow-water hypersaline environments, resulting in very dense bottom flows consisting of sediment-laden brine. Briny bottom flows would maintain their integrity below the pycnocline even in strongly stratified basins. Deposition from bottom flows resulted in turbidite-like beds (Figure 11b), which differ from classical sandy turbidites only in the fine grain size and the scarcity of bioturbation in the shale at the top of the sequence. Where present, bioturbation is best developed in the coarser, silty layers, indicating that the sea floor was briefly inhabited by organisms after deposition. This observation suggests that briny bottom flows originating in shallow-water environments transported some living benthos and entrained enough oxygen to temporarily sustain burrowing activity for a short time after sediment deposition. The horizontal trace fossils that occur along some bedding surfaces in Woodford Shale represent brief episodes during which the sea floor supported a limited benthos (Coleman and Jordan, 2018; Zou and Slatt, 2015). Ephemeral episodes of oxic-suboxic-dysoxic bottom conditions sufficient to support a limited benthos are indicated because bioturbation in Woodford Shale rarely results in total disruption of the rock fabric. Anoxia re-established quickly because oxygen was rapidly depleted by respiration of the sparse fauna, decay of organic matter, and absence of oxygen resupply. Elsewhere, organic carbon-rich black mud with parallel laminae (Figure 11b) continued to accumulate in bypassed and distal areas beyond the reach of bottom flows. Storm sedimentation was episodic and rapid.

Depositional processes represented in Figure 11 also include fallout of fine-grained particles transported to the basin as atmospheric dust (including silt- and clay-sized particles transported in dust storms and paleo-wildfire smoke clouds), fallout of fine particles entrained along the pycnocline, and the rain of pelagic debris from the upper part of the water column where biologic productivity was high. Some of the thin varve-like siltstone and shale laminae commonly observed in Woodford Shale may represent mud turbidites or storm layers too small or far from the source to produce grading and recognizable Bouma divisions, while others are likely due to episodic fallout of windblown particles and fine-grained debris entrained along the pycnocline. Entrainment of muddy water along isopycnals has been observed in nature and reproduced in flume experiments (Pierce, 1976; Rimoldi and others, 1996), and sediment plumes detached from the sea floor disperse over a much wider area than turbidity currents flowing along the sea bed (Rimoldi and others, 1996). Episodic settling of particles from muddy plumes widely dispersed along the pycnocline is a likely mechanism for producing the varve-like laminae documented in the Woodford Shale by Comer (1991, 2008) and by Kirkland and others (1992). Similar fine-grained laminae occurring in the eastern Mediterranean Sea have been attributed to this same depositional process (Maldonado and Stanley, 1978; Stanley, 1983). These observations suggest that not all terrestrial/pelagic transitions in organic carbon-rich mudstone intervals of the Woodford Shale represent transgressive-regressive cycles produced by sea level fluctuations. Some may result from episodic deposition of terrestrial components transported long distances by winds, sediment-laden currents diverted along the pycnocline, and dense bottom currents generated by storms. Based on the significance of these processes during the Late Devonian, attributing intervals of increasing terrestrial influence exclusively to transgressive-regressive cycles and sea level fluctuations would be too simplistic to capture the complexity of processes contributing to Woodford Shale deposition.

While the depositional model presented here is consistent with much of the data collected on the Woodford Shale, recent studies continue to add new high-resolution data with the goal of providing better methods for identifying zones from which hydrocarbons can be efficiently and cost-effectively produced. These data are providing more detailed information about the variations in conditions during Woodford deposition and early diagenesis and they will undoubtedly increase our understanding of the environment in which these rocks formed. Constructing a depositional model for Woodford Shale is complicated by the fact that there are no modern analogs for euxinic epeiric seas on stable cratons along arid passive continental margins adjacent to the open ocean where organic carbon-rich mud associated with abundant biogenic silica and transitioning laterally to biogenic novaculite is being deposited. In the context of understanding Earth history, continued study of these rocks will provide broad insights into the sedimentary environments possible at the Earth's surface that cannot be visited today.

WOODFORD SHALE AS HYDROCARBON SOURCE ROCK

Hydrocarbon Source Rocks in Oklahoma

Hydrocarbon source rocks are fine-grained organic-rich rocks, commonly identified as black shale (the term shale is used as a general term equivalent to mudrock and mudstone), capable of generating petroleum (Peters and others, 2010). Ulmishek and Klemme (1990) and Klemme and Ulmishek (1991) included the Woodford Shale in a list of hydrocarbon source rocks of the world.

Much of the oil generated in a hydrocarbon source rock does not migrate out of the rock. Hydrocarbon source-rock shales typically have very small pore volumes, very low permeability, and very small grains with high surface areas on which hydrocarbons are adsorbed (Hill and others, 2007). Meyer (2012, p. 72) estimated that 8 barrels of oil equivalent remains in the source rock for every barrel of crude oil in conventional reservoirs and "Speculative estimates of just how much generated oil remains in shale source rocks range between 45% and 95% depending on the geology of the formation and the quality of the estimate." Comer and Hinch (1987) calculated between 27 to 33% of the oil generated in Woodford Shale in southern and central Oklahoma was expelled from the source rock, indicating that 67 to 73% remains trapped within the formation. The recovery factor (ratio of produced hydrocarbons to total estimated hydrocarbons-in-place) of oil and gas from shale resource plays is on the order of 25% for dry gas reservoirs and 2-10% for oil reservoirs (Zoback and Kohli, 2019, p. 20). A carbon-rich pyrobitumen residue (i.e., post-oil solid bitumen) results from the thermal cracking of oil to gas (Jarvie and others, 2007). The amount of oil that is lost along the migration pathways and from surface seeps is inherently difficult to estimate.

Among the hydrocarbon source rocks identified in Oklahoma, the Woodford Shale is arguably the most important because of its distribution, thickness, and organic richness. Johnson and Cardott (1992) evaluated the available organic geochemical data of all known hydrocarbon source rocks of Oklahoma and included the Woodford Shale in the following list: Simpson Group, Sylvan Shale, Woodford Shale, Springer Formation, Morrowan, and Upper and Middle Pennsylvanian shales (Figure 2). An additional hydrocarbon source rock that was not considered is the Mississippian Caney Shale (Schad, 2004; Andrews, 2007; Cardott, 2005, 2017). The Upper Mississippian Goddard Formation and unnamed Lower Mississippian mudrocks have been recently identified as important hydrocarbon source rocks and potential hydrocarbon source-rock reservoirs (Spears, 2016; Cardott, 2017; Pearson and Philp, 2019; Symcox and Philp, 2019; Al Atwah and others, 2019). The middle division of the Upper Devonian Arkansas Novaculite in the frontal zone of the Ouachita Mountains Uplift is also a documented hydrocarbon source rock (Comer, 1992; Johnson and Cardott, 1992) and Woodford-type oil is produced from naturally fractured Arkansas Novaculite in the Isom Springs Field.

The Woodford Shale was confirmed to be a hydrocarbon source rock based on numerous oil-to-rock correlation studies dating from the 1950s (Comer, 1992 and references therein). Jones and Philp (1990) concluded that 85% of 30 oils sampled in the Pauls Valley area of the Anadarko Basin were sourced by the Woodford Shale. Wavrek (1992) correlated oils to hydrocarbon source rocks from the Ardmore and Marietta Basins and determined that, of seven oil types identified, oil type C from the Woodford Shale had the highest frequency distribution. Wang and Philp (1997, 2001) used the Woodford Shale as a reference for comparison with rock and oil samples of the Viola, Sylvan, Mississippian Lime, Springer, Chester, and Morrow as other potential hydrocarbon source rocks in the Anadarko Basin. Modeling by Gaswirth and Higley (2013) showed that 83% to 96% of the petroleum from Hunton Group reservoirs in the West Edmond field was sourced by the Woodford Shale. Based on 4D petroleum system modeling of the Anadarko Basin, Higley (2013) concluded that the Woodford Shale was an important petroleum source rock for oil in Mississippian reservoirs. Rahman and others (2017) concluded that oil production from several Woodford Shale wells in the northern Anadarko Basin included migrated hydrocarbons from a deeper, higher thermal maturity Woodford source. Wang and Philp (2019) further documented that Woodford Shale is a major source of in-situ, mixed, and migrated oil in modern unconventional oil-producing wells in north-central Oklahoma. Al Atwah and others (2019) and Atwah and others (2019) suggested a complex hydrocarbon charge history, including long-distance migration of a mixed Woodford/Mississippian source, for oils recovered from the Mississippian on the Anadarko Shelf. In a geochemical study of 172 produced oils from four different reservoir formations across 13 counties in the Anadarko Basin, Symcox and Philp (2019) concluded that much of the produced oil from STACK/SCOOP (Figure 12) Mississippian tight

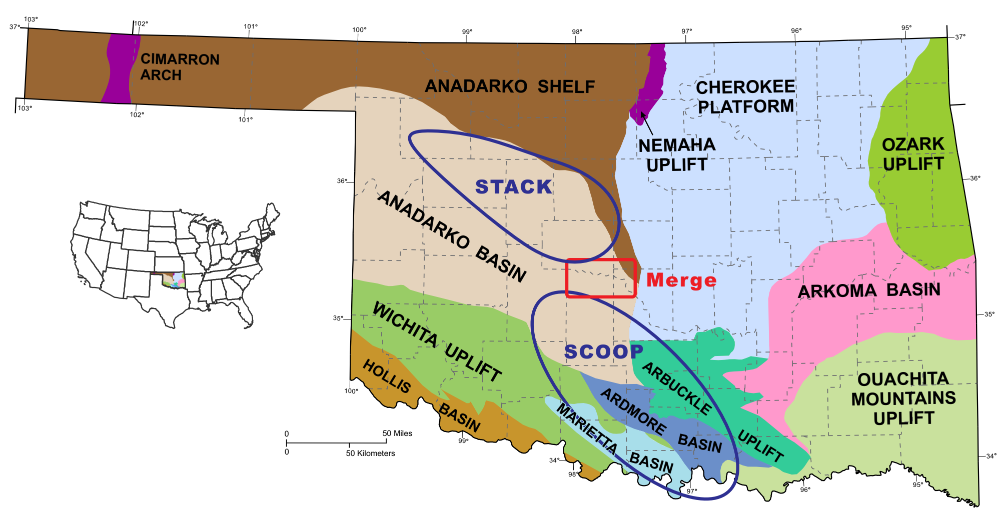

Figure 12 Generalized areas of STACK, Merge, and SCOOP plays. Modified from Haines (2017) and Milad and others (2020).

reservoirs was sourced by the Woodford Shale. Abrams and Thomas (2020) concluded that produced oils from the eastern portion of the SCOOP area may include an additional migrated charge from down dip Woodford source rocks. Wang and others (2020) identified three petroleum systems in Woodford-Mississippian tight reservoirs in central Oklahoma: Group 1 condensates in the northern Anadarko Basin were Woodford-sourced generated in-situ, Group 2 oils east of the Nemaha Uplift share Mississippian and Woodford source signatures and were probably generated in-situ, and Group 3 oils north of the Arbuckle Uplift probably migrated long distances from deeper Woodford Shale.

Comer and Hinch (1987) documented the presence of numerous small-scale oil accumulations within thermally mature intervals of the Woodford Shale and argued that these accumulations are prima facie evidence for internal migration and expulsion of hydrocarbons from this source rock. By comparing the amount of hydrocarbons in highly compacted black shale beds (Figure 5g) interlayered with uncompacted, early-cemented biogenic chert beds (Figure 5h), both containing Type-II kerogen at the same level of thermal maturity, Comer and Hinch (1987) calculated that approximately 27% to 33% of the oil generated in Woodford Shale was expelled in central and southern Oklahoma (an area of 23,000 mi^2 [60,000 km^2] with roughly 20 billion barrels of oil-in-place), thus indicating that 67% to 73% remains trapped within the formation. Comer (1992, p. 72) stated that published estimates suggest "70-85% of the oil produced in central and southern Oklahoma…originated in the Upper Devonian Woodford Shale." It is worth noting that this approach of comparing the content of early sealed chert and highly compacted black shale in interbedded intervals could also be used to test the assumption that certain metals (e.g., V, Mo, Ni) deposited with organic carbon-rich sediment remain unchanged throughout burial diagenesis and are directly indicative of oxic versus anoxic and euxinic depositional environments.

While Woodford-type oil is often produced from reservoirs in close proximity to the source rock (Reber, 1988; Wavrek, 1992; Atwah and others, 2019; Wang and Philp, 2020), long-distance migration of Woodford-sourced oils from the Anadarko Basin to Kansas is inferred based on the long distances between the fields that produce Woodford-type oil at low thermal maturity and the nearest Woodford Shale source beds which are in the main stage of oil generation (Burruss and Hatch, 1989; Newell and Hatch, 2000; Beserra, 2008; Gaswirth and Higley, 2013; Higley, 2013, 2014; Tamborello, 2020). Appendix 1 presents a bibliography on the Woodford Shale, including papers which document the Woodford Shale as a hydrocarbon source rock.

Hydrocarbon Source Rock Characterization

Hydrocarbon source rocks are evaluated based on organic matter concentration, type, and thermal maturity (Curiale and Curtis, 2016). Programmed pyrolysis is the most common method used to evaluate hydrocarbon source potential. For an explanation of programmed pyrolysis data, see Peters (1986), Peters and Cassa (1994), Peters and Rodriguez (2017), and Dembicki (2009, 2017). Thick shale intervals with as little as 0.5 wt.% total organic carbon (TOC) may be considered potential hydrocarbon source rocks (Tissot and Welte, 1984, p. 497). However, rocks with higher TOC, generally >2 wt.% TOC, are considered to be prolific source rocks with consistently greater hydrocarbon source potential, if organic matter type and thermal maturity are adequate (Jarvie, 2012a; Curiale and Curtis, 2016; Peters and others, 2016; Dembicki, 2017; Juliao and others, 2017). Oil and gas are generated from source rocks containing Types I and II kerogen. Primarily gas is generated from source rocks containing Type III kerogen. Thermal maturity relates generally to the kinetics of hydrocarbon generation, with oil (high molecular weight hydrocarbons) being generated at lower temperatures and gas (low molecular weight hydrocarbons) being generated at higher temperatures. Oil and gas are generated by breaking of bonds in kerogen, with solid bitumen (see pre-oil solid bitumen discussion below) as an intermediary between kerogen and oil, and by cracking of high molecular weight hydrocarbons as temperature increases with deep burial (Curiale and Curtis, 2016). Consequently, gas (thermogenic methane) will also be generated from oil-prone source rocks containing Types I and II kerogen during the later stages of generation at high thermal maturity. Hydrous pyrolysis experiments by Lewan (2002) indicated that, in addition to being oil generative, Types I and II kerogen generate 1.8 times as much thermogenic methane as Type III kerogen. Furthermore, co-generation of some natural gas also occurs during the generation of oil from Type I and Type II kerogens. Hydrous pyrolysis of Woodford Shale samples from the outcrop along Interstate-35 on the south flank of the Arbuckle Uplift yielded a gas/oil ratio between 1,000 and 1,600 standard cubic feet of gas per barrel of oil during the early stages of oil generation

(Lewan and Henry, 1999).

Microbial (biogenic) methane is generated by anaerobic degradation of organic matter in-situ, and microbial methane accumulations associated with coal beds and organic-rich mudstones are typically found in subsurface settings that have received meteoric water recharge (Tyler and others, 1997; Martini and others, 2008). Microbial methane has been documented in other Upper Devonian black shales in the USA, including the Antrim Shale in the Michigan Basin and the New Albany Shale in the Illinois Basin (Martini and others, 1998, 2003; McIntosh and Martini, 2008; Colosimo and others, 2016). Drake and Hatch (2021) described the Woodford Shale Biogenic Gas Assessment Unit in the Cherokee Platform Province near the Ozark Uplift at depths of 1,250 ft (380 m) or shallower where the formation is susceptible to meteoric water penetrations. Gas analysis data from Staghorn Energy LLC (personal communication, 2009) indicate that the natural gas recovered from 1,200-1,210 ft (366-369 m) from the Woodford Shale in the 1-31 Hughes Trust well (API 35-145-22973; Section 31, Township 17 North, Range 18 East) in Wagoner County, Oklahoma, is a mixture of gases of both biogenic and thermogenic origin based on the light carbon isotopic value for the methane ($\delta^{13}C$ = -52.8 per mil) and the high concentrations of C_{2+} hydrocarbons. Wagoner County is adjacent to the Ozark Uplift, and the Woodford Shale in the Hughes Trust well is in the appropriate geologic setting to receive meteoric water that entered the Woodford Shale at outcrop in the Ozark Uplift. Consequently, by analogy with Antrim Shale and New Albany Shale, microbial methane would be a likely component of the gas in this well. The thermal maturity of the Woodford Shale from the 1-31 Hughes Trust well (Oklahoma Geological Survey Organic Petrography Laboratory (OPL) 1269) is 0.94% VR_o, indicating the potential for thermogenic methane generation.

Thermal maturity terms represent the stages of hydrocarbon generation; that is, whether a given rock has reached the oil generation stage (oil window), wet-gas/condensate stage, or dry-gas (thermogenic methane) stage of hydrocarbon generation. Thermally immature hydrocarbon source rocks have not yet reached the onset of hydrocarbon generation and post-mature source rocks (which generally coincide with rocks that have undergone very low-grade to low-grade metamorphism; Teichműller, 1987; Kwiecinska and Petersen, 2004) have exhausted their hydrocarbon generating capability. The upper limit of thermogenic methane generation is ~3% VR_o (Taylor and others, 1998, p. 504; Mi and others, 2018). Furthermore, shales at thermal maturities >3% VR_o mostly have reduced gas storage and deliverability (Dembicki, 2014; Zagorski and others, 2017).

Knowing the types of hydrocarbons generated by a source rock is an important consideration in evaluating the risks and economics of a resource play. For rocks of high thermal maturity, minimum TOC "cut-off" values should be used with caution to determine hydrocarbon source potential because TOC decreases with increasing thermal maturity as organic carbon is lost during primary migration and expulsion of hydrocarbons (Hester and others, 1990a; Jarvie, 1991; Peters and others, 2016 [p. 78]; Dembicki, 2009, 2017).

Organic Carbon Concentration

Based on 251 core and 191 outcrop samples of Late Devonian strata (Woodford Shale, Chattanooga Shale, and equivalent intervals of the Arkansas Novaculite) in Oklahoma and northwestern Arkansas, Comer (1992) indicated that the TOC ranges from <1 to 26 wt.%. Burruss and Hatch (1989) reported a TOC range from 1 to 14 wt.% for the Woodford Shale in the Anadarko Basin. Higley (2014) and Higley and others (2014) contoured the Woodford TOC data of Burruss and Hatch (1989). Romero and Philp (2012) and Connock and others (2018) reported a TOC range of 3.47 to 16.90 wt.% from a Woodford Shale core at the Wyche Farm shale pit. Philp and DeGarmo (2020) reported a TOC range of 0.07 to 15.6 wt.% in the McAlister Cemetery Quarry. Carr (1987) showed a TOC range of 0.8 to 4.2 wt.% for the Chattanooga Shale (Woodford equivalent) in eastern Oklahoma/western Arkansas. Comer and Hinch (1987), Roberts and Mitterer (1992), Paxton and Cardott (2008), Fishman and others (2013), Becerra and others (2018), Slatt and others (2018a, b), Brito (2019) and Ko and others (2018) showed that TOC in Woodford Shale mudstones (up to 30 wt.% TOC; Galvis, 2017) was higher than in cherts (e.g., Figure 5g-h). These data indicate that TOC is highly variable both vertically and laterally and dependent on sample selection. Woodford Shale and age-equivalent rocks from Oklahoma and Arkansas have a mean TOC value greater than 5 wt.% (Comer, 1992, 2005, 2008). These TOC data are not normally distributed but are strongly skewed toward the high TOC values (Comer, 1992).

Infante-Paez and others (2017) used seismic inversion and attribute analysis, calibrated with well logs and cuttings, to identify TOC sweet spots in the Woodford Shale. Slatt and others (2018b) related TOC to 3D seismic surveys of the Woodford Shale to illustrate TOC content variation geographically and stratigraphically. In general, the lower and middle Woodford members have the highest TOC content while the upper Woodford member has the lowest TOC content (Slatt and others, 2012, 2018a, b; Connock and others, 2018; Brito, 2019; Philp and DeGarmo, 2020).

A positive correlation between organic carbon concentration and radioactivity was observed by Schmoker (1981) and used to derive organic-matter content from gamma-ray log API unit values for Appalachian Devonian shales. Paxton and Cardott (2008) published the range of TOC values recorded for the major gamma-ray markers (API unit maxima) of the Woodford Shale in the Henry House Creek section located in the Arbuckle Uplift (Figure 13). Houseknecht and others (2014) found that gamma-ray values >150 API units generally correlate with TOC values >2% for the Woodford Shale.

Organic petrology and programmed pyrolysis data for the Woodford Shale samples compiled for this study are presented in Table 2. The programmed pyrolysis data are compliments of GeoMark Research, Ltd. TOC ranges from 0.97 to 21.9 wt.% (Figure 14) (6.4 wt.% average, 3.2 wt.% standard deviation). Additional programmed pyrolysis data of Oklahoma Geological Survey Organic Petrography Laboratory Woodford Shale samples are in Craddock and others (2018).

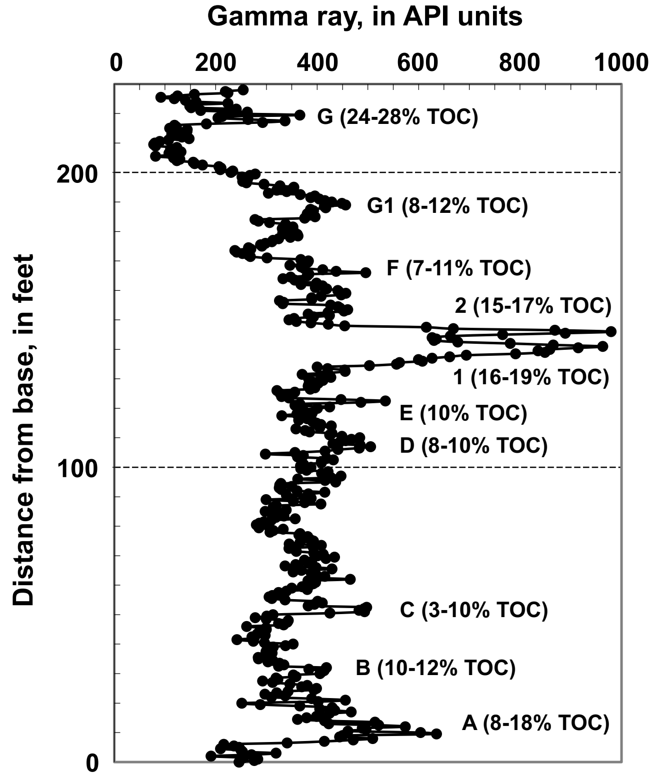

Figure 13. Range of total organic carbon (TOC) concentrations for the major gamma-ray markers of the Woodford Shale in the Henry House Creek section in the Arbuckle Uplift (from Paxton and Cardott, 2008, p. 61).

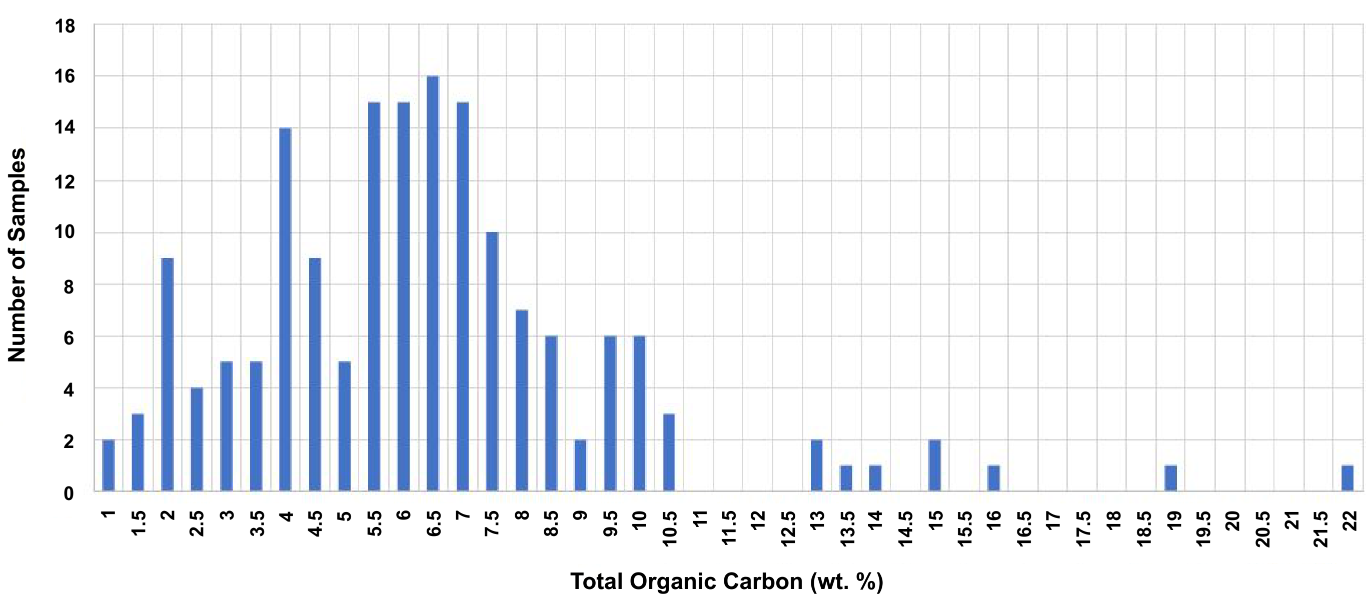

Figure 14. Histogram of total organic carbon (TOC) content for the Woodford Shale in Oklahoma (modified to nearest 0.5 wt.% from Table 2).

Organic Matter Type

Based on the quantitative analysis of C, H, and O in isolated, solvent-extracted kerogen, bulk organic matter in the Woodford Shale is predominantly Type II kerogen (oil generative) of marine origin (Figure 15) (Comer and Hinch, 1987). The van Krevelen diagram (Figure 15) illustrates how the three main types of sedimentary organic matter change with increasing thermal maturity and the fact that the compositions of all three kerogen types converge toward the lower left corner of the diagram clearly shows why kerogen typing using this method should be done using samples of low thermal maturity (Dembicki, 2017).

Programmed pyrolysis involves the temperature programmed heating of crushed rock samples in an inert atmosphere (Figure 16). Data derived from programmed pyrolysis pyrograms (including T_{max}, Hydrogen Index [HI = S_2/TOC], and Production Index [PI = $S_1/(S_1 + S_2)$]) can be used to assess both the bulk kerogen type and thermal maturity. Pseudo van Krevelen plots using data from programmed pyrolysis commonly show a significant proportion of Type I kerogen in Woodford Shale (Slatt and others, 2018b; Al Atwah and others, 2019; Atwah and others, 2020; see SR in Appendix 1). Type I kerogen is typically found in lacustrine hydrocarbon source rocks while Type II kerogen is found in marine hydrocarbon source rocks like the Woodford Shale (Vandenbroucke and Largeau,

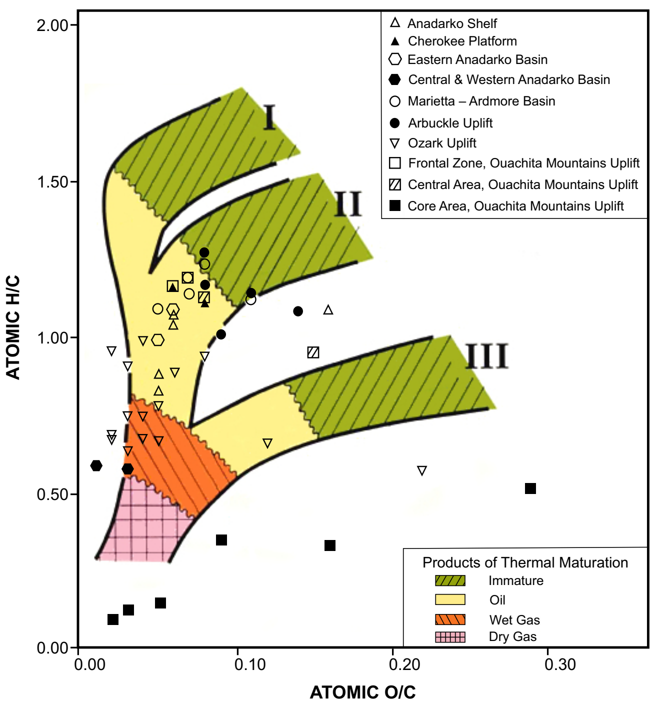

Figure 15. Van Krevelen diagram summarizing kerogen type (I, II, and III) and thermal maturity for Woodford Shale and age equivalent rocks in Oklahoma. Data points represent mean values for samples collected from individual cores and outcrops. Data points that fall below the Type III trend are post mature (core area, Ouachita Mountains Uplift) or oxidized due to weathering at the outcrop (Ozark Uplift). Samples from the core area, Ouachita Mountains Uplift were collected from outcrops in Arkansas. The frontal, central, and core area were initially recognized and described by Flawn (1959). Thermal maturity trends are from Tissot (1984). Modified from Comer and Hinch (1987).

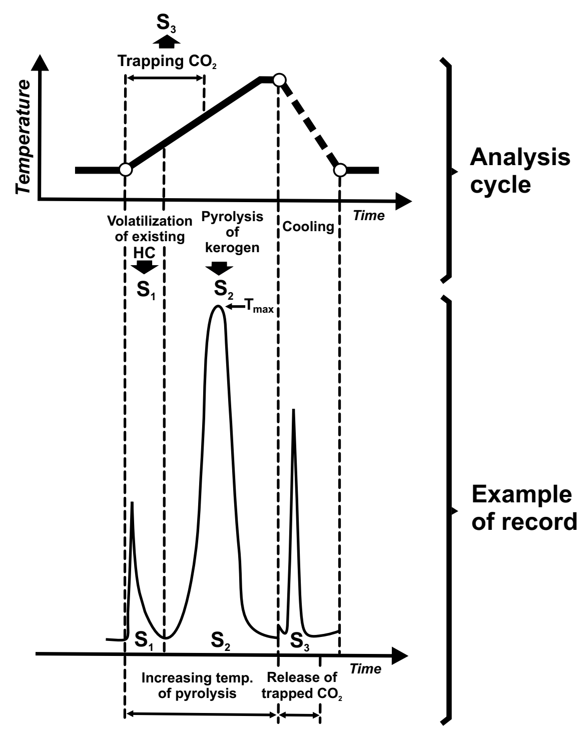

Figure 16. Example of the record produced from programmed pyrolysis. Crushed rock samples are placed in a vessel and heated in an inert atmosphere to determine the amounts of free hydrocarbons (S_1), hydrocarbons formed by cracking of organic matter (S_2), and CO_2 formed from oxygen in the organic matter (S_3). T_{max} is the oven temperature corresponding to the peak of the S_2 curve which marks the maximum rate of hydrocarbon generation from the organic matter (from Tissot and Welte, 1984, p. 510, Figure V.1.10).

2007). The Type I interpretation for the Woodford Shale depends on how the programmed pyrolysis data, such as those in Table 2, are plotted (Figure 17). The pseudo van Krevelen plot in Figure 17a suggests a significant amount of Type I kerogen, while the kerogen quality plot in Figure 17b nearly excludes Type I kerogen, similar to what was described by Philp and DeGarmo (2020). Dembicki (2009, p. 346) suggested that "if a marine source rock is plotting along the Type I kerogen trend on pseudo-van Krevelen diagrams, it likely contains Type IIS kerogen." The presence of Type IIS kerogen in the Woodford Shale has not been confirmed.

Type III kerogen of terrestrial origin is present in significant concentrations locally in the Chattanooga Shale and the Woodford Shale near the Ozark Uplift and in the Ouachita Mountains Uplift, respectively (Comer and Hinch, 1987; Comer, 1992; Burruss and Hatch, 1989; Johnson and Cardott, 1992). Type III kerogen in the Woodford Shale is also increasingly common westward along the Anadarko Basin axis and in the western part of the basin, a region proximal to the Transcontinental Arch which was a regional topographical high during the Late Devonian (Comer, 1992). Samples with higher concentrations of Type III kerogen generally have lower TOC and little or no biogenic silica, reflecting the dilution of pelagic marine sediments by terrigenous siliciclastics

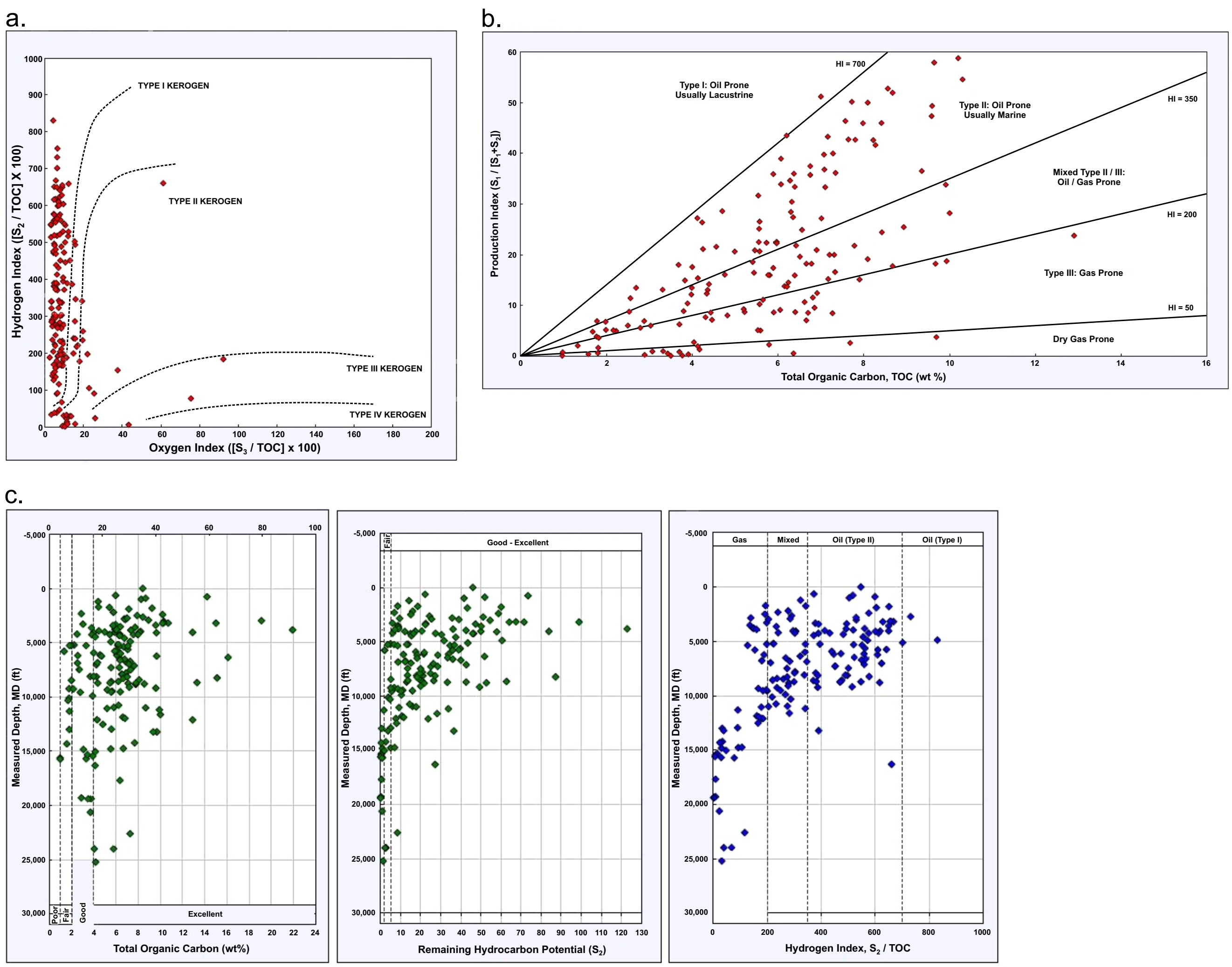

Figure 17. Programmed pyrolysis data of the Woodford Shale from Table 2. (a) Pseudo van Krevelen plot: Hydrogen Index ($[S_2/TOC] \times 100$) vs. Oxygen Index ($[S_3/TOC] \times 100$). (b) Kerogen quality plot: Production Index ($S_1/[S_1+S_2]$) vs. total organic carbon (TOC). (c) Source potential logs: total organic carbon (TOC), remaining hydrocarbon potential (S_2) and Hydrogen Index ($[S_2/TOC] \times 100$) vs depth. Programmed pyrolysis data and charts are courtesy of GeoMark Research, Ltd.

derived from the nearby emergent land areas (Comer, 1992). Comer (1992) noted that increased proportions of terrestrial organic matter are found locally along the Nemaha Uplift, indicating that it was topographically high during the Late Devonian, and Kvale and Bynum (2014) showed that lower Woodford facies onlap the structure. Kvale and Bynum (2014) also observed that Woodford sediments to the west of the Nemaha Uplift contain more bioturbated intervals and less biogenic chert than those to the east. Using palynomorph assemblages, Molinares Blanco and others (2017a) concluded the upper Woodford interval contained more terrigenous detritus than the middle Woodford.

Visual kerogen analysis of low thermal maturity Woodford Shale indicates a composition of amorphous organic matter (45-95%), vitrinite, inertinite (semifusinite and fusinite), liptinite (e.g., *Tasmanites* telalginite), zooclast (e.g., acritarch), and solid bitumen macerals (Lewan, 1987; Senftle, 1989; Cardott and Chaplin, 1993; Ascent Energy, 2006; Turner and others, 2015; Kondas and others 2018; Atwah and others, 2020). Abundant telalginite (e.g., *Tasmanites*) is an important source of oil generated in the Woodford Shale (Ko and others, 2019; Shao and others, 2020).

Scanning electron microscopy (SEM) can determine the distribution of organic matter in a shale based on atomic number observed in backscatter electron imaging, but is limited in its ability to identify organic matter type (Loucks and others, 2009; Slatt and O'Brien, 2011). SEM studies of the Woodford Shale indicate an abundance of amorphous organic matter, commonly observed to be oil-prone liptinite macerals in epifluorescent light at low thermal maturity, and a predominance of post-oil solid bitumen in reflected white light at high thermal maturity (Curtis and others, 2012; Fishman and others, 2013; Cardott and others, 2015; Ko and others, 2018).

Thermal Maturity

A wide range of organic geochemical parameters are affected by the thermal maturation of organic matter during burial and heating in the absence of oxygen in sedimentary basins. They can be used to determine the stage of hydrocarbon generation experienced by specific organic-rich rock samples. The most widely used thermal maturity parameters are acquired using programmed pyrolysis and vitrinite-reflectance petrography. Vitrinite -reflectance petrography is widely considered the "gold standard" thermal maturity parameter for shales (Curiale and Curtis, 2016; Hackley and Cardott, 2016; Gentzis and others, 2017; Jarvie, 2017; Juliao and others, 2017; Horsfield and others, 2018). As summarized by Cardott (2012b), vitrinite is a maceral derived from woody organic matter that is found only in post-Silurian-age rocks. The vitrinite-reflectance value is the percentage of incident light that is reflected from polished vitrinite particles under an oil immersion objective and reported for an average of >20 measurements. The average of a number of measurements from a fixed (non-rotating) microscope stage is referred to as the mean random value. Reflected white light microscopy was first applied to coal in 1913 (Hutton, 1995). The vitrinite-reflectance analysis was first applied to determine the rank of coals in 1932 (McCartney and Teichmüller, 1972) and applied to the thermal maturity of shales in the 1950s (Taylor and others, 1998, p. 501-505).

A number of additional parameters used to decipher thermal maturity are discussed in Dembicki (2017). Some of the more noteworthy include the following: C, H, O, H/C ratio, and O/C ratio from solvent-extracted kerogen (a plot of H/C vs O/C is known as the "van Krevelen diagram [see Figure 15]); thermal alteration index (TAI) from visual analysis of kerogen; total extractable bitumen/TOC ratio, saturated hydrocarbons/TOC ratio, and saturated hydrocarbon distribution from gas chromatography analysis of soluble bitumen extracted from source rocks. Definitions, analytical methods, and critical reviews for these parameters can be found in Jarvie (1991) and Dembicki (2017).

Thermal maturity implications for a number of these parameters obtained from analyses of samples of Woodford Shale in Oklahoma, which includes presentation of data, discussion, and contour maps, are discussed in Comer (1992; 2008). Additional data and discussion of thermal maturity parameters for Woodford Shale may be found in the references included in Appendix 1.

Programmed Pyrolysis: The Source Potential Logs for the Woodford Shale in Figure 17c illustrate decreasing TOC, oil potential (S_2), and Hydrogen Index ([S2/TOC] x 100) with increasing depth and thermal maturity. For Woodford Shale, the kerogen type and thermal maturity plot using Hydrogen Index ([S2/TOC] x 100) and T_{max} (temperature, °C, of S_2 peak) in Figure 18a shows decreasing Hydrogen Index with increasing thermal maturity (T_{max}). With increasing thermal maturity and decreasing hydrogen content, the trends for kerogen Types I and II change compositionally to merge with the trend for Type III kerogen. Consequently, it is only possible to assign kerogen Types I, II, and III, each having distinctly different assemblages of biological source materials, using rock samples of low thermal maturity (<1% VR_o).

The kerogen quality plot in Figure 18b shows increasing followed by decreasing Production Index ($S_1/[S_1 + S_2]$) with increasing thermal maturity (T_{max}). Note that kerogen typing based on programmed pyrolysis becomes less reliable at thermal maturities >1.0% VR_o as TOC, S_2 (generally <0.5 mg HC/g rock; see Table 2) and HI decrease. The kerogen composition changes due to hydrocarbon generation (Figure 17 and Figure 18) and as the residual organic matter becomes dominated by solid bitumen (Wüst and others, 2013; Curiale and Curtis, 2016; Hackley, 2017; Lewan and Pawlewicz, 2017; Yang and Horsfield, 2020).

Post-oil solid bitumen is the dominant organic matter in thermally mature shales (>0.9% VR_o; Cardott and others, 2015; Hackley and Cardott, 2016; Hackley, 2017; Liu and others, 2018). Post-oil solid bitumen forms a network, recognized under reflected white light and backscatter electron imaging, that develops secondary nanoporosity beginning at ~0.7% VR_o, which provides hydrocarbon migration pathways and accommodates methane storage (Cardott and others, 2015; Cardott and Curtis, 2018). Secondary intraorganic nanoporosity is thought to form from the escape of gases during the thermal cracking of the post-oil solid bitumen (Bernard and Horsfield, 2014).

Vitrinite Reflectance: Vitrinite-reflectance data of the Woodford Shale have been published in numerous reports: Cardott and Lambert (1985); Carr (1987); Comer and Hinch (1987); Cardott (1989, 1994); Pawlewicz (1989); Cardott and others (1990); Comer (1992); Cardott and Chaplin (1993); Paxton and Cardott (2008); Achang and others, 2017; Wang and Philp (2019); and Al Atwah and others (2019). Only vitrinite-reflectance data by

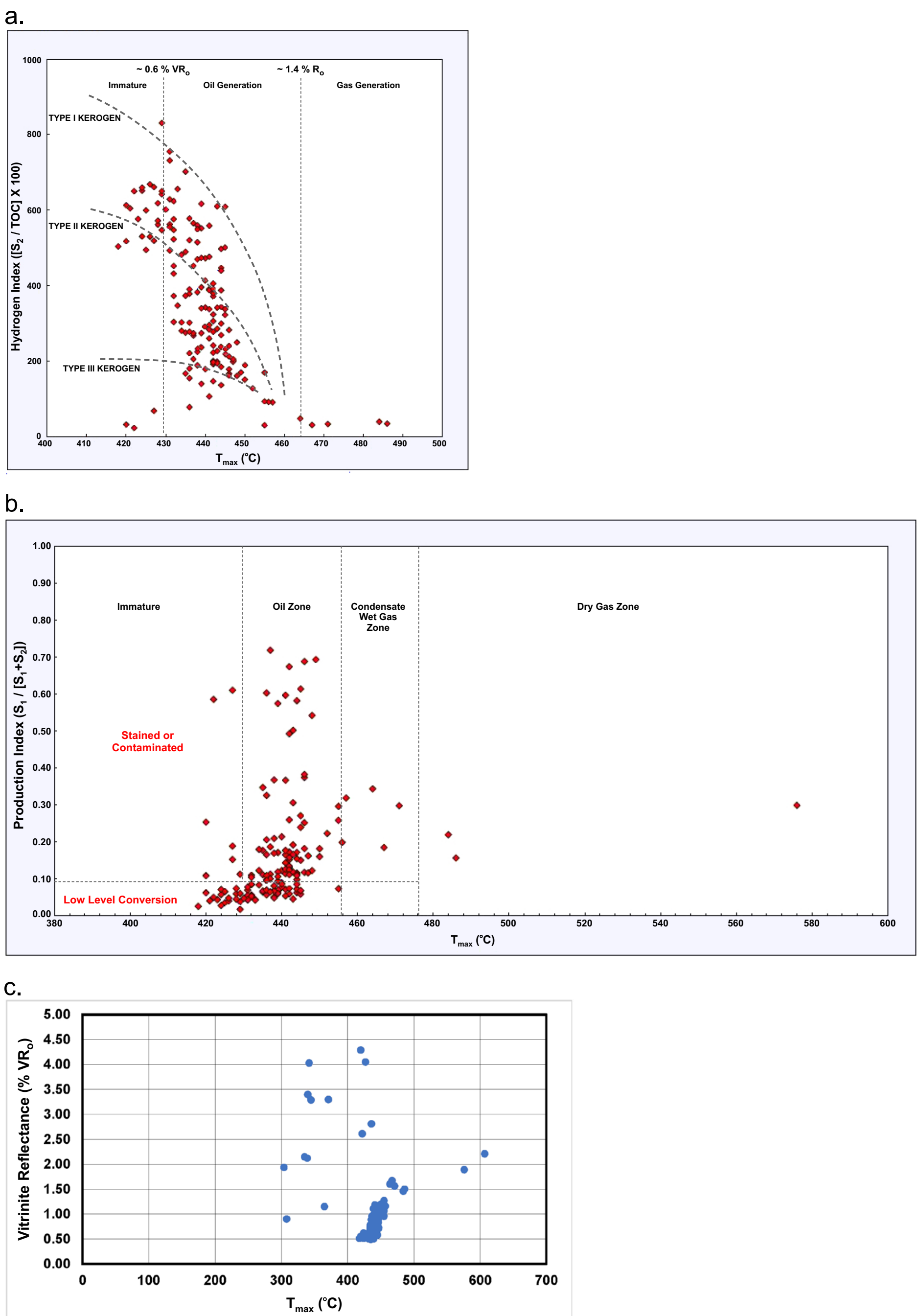

Figure 18. Programmed pyrolysis data of the Woodford Shale from Table 2. (a) Hydrogen Index ($[S_2/TOC]$ x 100) vs T_{max}. (b) Production Index ($S_1/[S_1 + S_2]$) vs T_{max}. (c) Vitrinite reflectance vs T_{max}. Programmed pyrolysis data and charts are courtesy of GeoMark Research, Ltd.

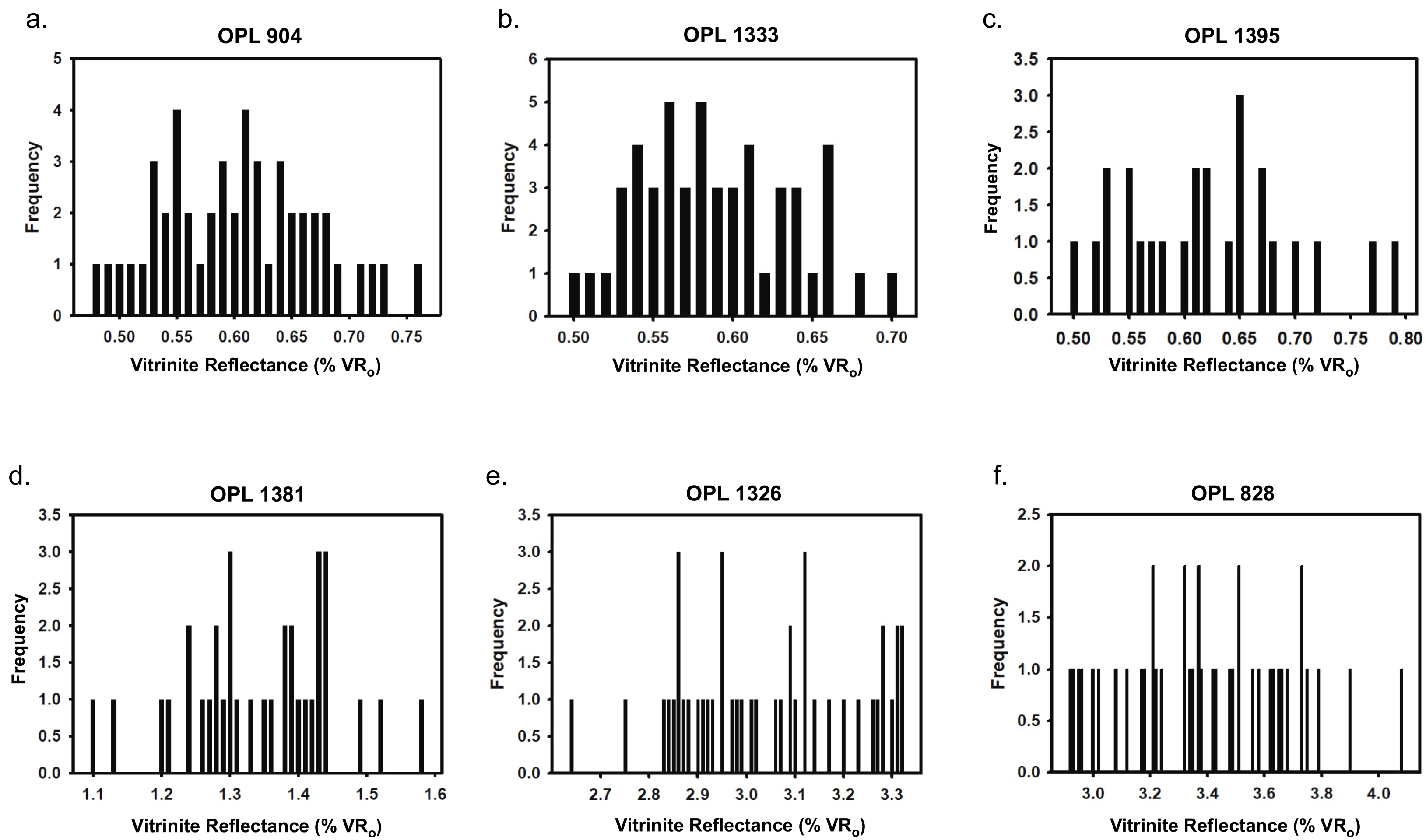

Figure 19. Examples of vitrinite-reflectance histograms. (a) OPL 904, mean 0.60% VR_o, range 0.48-0.76% VR_o; (b) OPL 1333, mean 0.59% VR_o, range 0.50-0.70% VR_o; (c) OPL 1395, mean 0.62% VR_o, range 0.50-0.79% VR_o; (d) OPL 1381, mean 1.34% VR_o, range 1.10-1.58% VR_o; (e) OPL 1326, mean 3.04% VR_o, range 2.64-3.32% VR_o; (f) OPL 828, mean 3.40% VR_o, range 2.92-4.08% VR_o.

Cardott (including Cardott and Lambert [1985] and Cardott [1989]) are used in Table 2, including some values revised by Cardott for samples OPL 107-124 that were originally analyzed by Michael Lambert in Cardott and Lambert (1985). The intent of these studies was to evaluate the thermal maturity of the Woodford Shale as a hydrocarbon source rock. More detailed studies of smaller areas would be required to evaluate whether oil or gas would most likely be commercially produced from the Woodford Shale for a given play.

In this report, data for the reflectance of vitrinite recorded in combination with other macerals (e.g., semifusinite) has the abbreviation %R_o. Since both vitrinite and bitumen reflectance values are used in this report, vitrinite reflectance is abbreviated as %VR_o and solid bitumen reflectance is abbreviated as %BR_o. Vitrinite-reflectance data (Figure 19) typically follow a normal distribution over a range of ~0.3% VR_o in the oil window and over a larger range at thermal maturities >1.0% VR_o owing to vitrinite-reflectance anisotropy (Taylor and others, 1998). ASTM (2014) provides the details for the vitrinite-reflectance analysis of shale samples. This section provides an expanded discussion of vitrinite reflectance and problems involving interpretation of this data type, because many of the confounding issues were observed in samples from the Woodford Shale and most of their resolutions were achieved by detailed analysis of Woodford samples.

Sources of error in the vitrinite-reflectance analysis discussed in Cardott (2012b) and Hackley and Cardott (2016) include the following: recycled vitrinite, caving contamination, mud additives, weathering, vitrinite-reflectance anisotropy, too few measurements, pitted-vitrinite texture, and vitrinite-like organic matter being mistaken for vitrinite (e.g., vitrinite maceral subtypes, inertinite macerals, graptolites, and solid bitumen). Photomicrographs of vitrinite, semifusinite, and solid bitumen (Figure 20) illustrate the characteristics of these macerals in reflected white light. In the present study, all of the vitrinite-reflectance analyses presented in Table 2 represent a single lithology (i.e., black shale) of Late Devonian age for which only limited older sources of recycled vitrinite were available. Caving contamination from uphole and drilling mud additives were recognized by the distinctive Woodford-type dark mineral groundmass in reflected white light using whole-rock pellets instead of kerogen-concentrate pellets (Barker, 1996). Alteration of kerogen due to present-day outcrop weathering was avoided by using well-indurated rock samples (Lo and Cardott, 1995). Quantitative vitrinite-reflectance values are identified by samples having >20 measurements; vitrinite-lean samples with <20 measurements are considered qualitative (ASTM, 2014). In rare cases, mean random vitrinite-reflectance values from regionally important vitrinite-lean Woodford Shale samples with <20 measurements are included in Table 2. Pitted-texture vitrinite values were recorded to aid in identifying the lowest-reflectance vitrinite but were not included in the reported mean value.

The two most common errors are including solid bitumen or semifusinite, which are mistakenly assumed to be vitrinite, with the vitrinite-reflectance values. Sanei (2020) provides a detailed discussion about the genesis of solid bitumen. Curiale (1986) introduced the terms pre-oil solid bitumen (defined as a thermal decomposition product derived from liptinite macerals in hydrocarbon source-rock samples that are marginally-mature to mature for oil generation) and post-oil solid bitumen (defined as a solid alteration product of a once-liquid oil that forms in the oil window, fills fractures and pores,

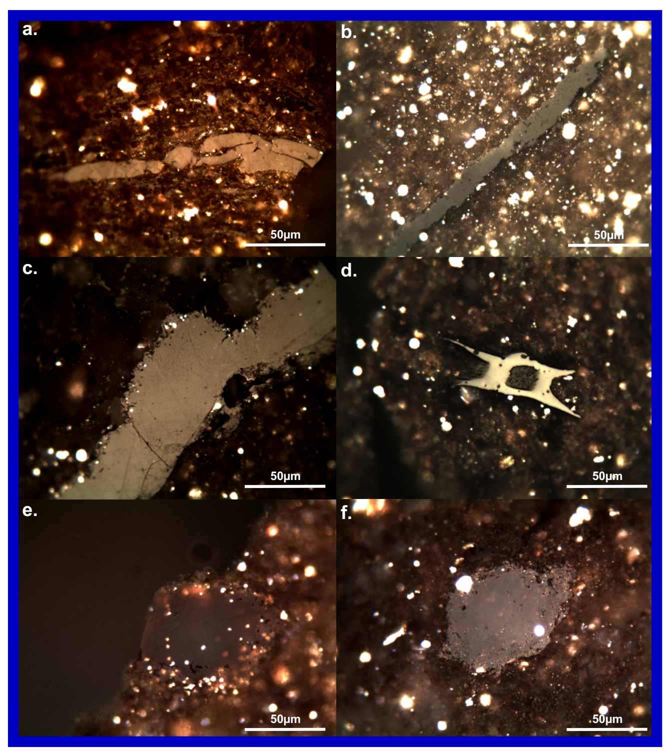

Figure 20. Photomicrographs of macerals (reflected white light; taken at 500x magnification). (a) vitrinite, OPL 1016, 0.48% VR_o; (b) vitrinite, OPL 1469, 0.58% VR_o; (c) vitrinite, OPL 1402, 1.26% VR_o; (d) semifusinite with bogen structure, OPL 1491, 2.23% R_o; (e) pre-oil solid bitumen, OPL 654, 0.30% BR_o; (f) pre-oil solid bitumen with internal reflections, OPL 603, 0.58% BR_o.

and may be an insoluble pyrobitumen) (Figure 21). Using hydrous pyrolysis experiments on the Woodford Shale, Lewan (1994) demonstrated that Type II kerogens generate (pre-oil solid) bitumen with subsequent thermal decomposition to primary oil. Pre-oil solid bitumen is often observed as irregular-shaped blobs (Figure 20e, f) and is mostly extractable in organic solvents. Hackley and others (2018, p. 233) indicated that "the 'pre-oil' solid bitumen is high viscosity organic matter rich in the heavier asphaltene and resin molecular components of petroleum, unlike a saturated hydrocarbon-rich conventional black or volatile oil." Pre-oil solid bitumen is vitrinite-like in appearance in reflected white light especially at low thermal maturity (e.g., immature to early oil generation) (Curiale, 1986; Cardott and others, 2015; Hackley and Cardott, 2016; Hackley and Lewan, 2018). Solid bitumen has been observed filling fractures in Woodford Shale outcrops and core (Comer and Hinch, 1987; Paxton and Cardott, 2008).

Hackley and others (2013) concluded that vitrinite-reflectance measurements indicating Devonian shales in the Appalachian Basin to be in the early stage of thermal maturity may erroneously include lower-reflecting pre-oil solid bitumen reflectance measurements, as explained further in Hackley and Lewan (2018). A good example of this error is in Cardott and Lambert (1985) and Cardott (1989). These authors reported a 0.47% R_o mean random value for the Jones and Pellow Oil B-2 Hall well (OPL 153; API 35-015-20258; Section 36, Township 7 North, Range 13 West) (Figure 22) located in the Wichita frontal fault zone on the north side of the Wichita Uplift (Northcutt and Campbell, 1996). Cardott (2015a) reported that the B-2 Hall well R_o value included abundant vitrinite-like pre-oil solid bitumen and corrected the

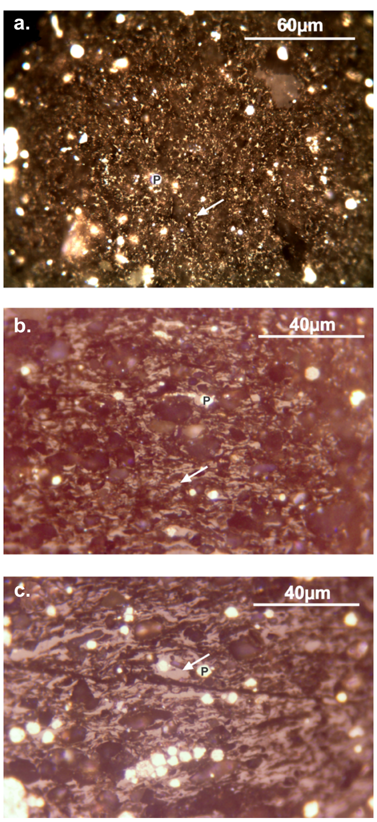

Figure 21. Photomicrographs of post-oil solid bitumen network in the Woodford Shale in reflected white light. (a) white arrow points to speckled form (~1-2 µm); pyrite (P); (b) white arrow points to wispy form (~2-5 µm); pyrite (P); (c) white arrow points to connected form (>5 µm); pyrite (P). From Cardott and others (2015, Figure 2).

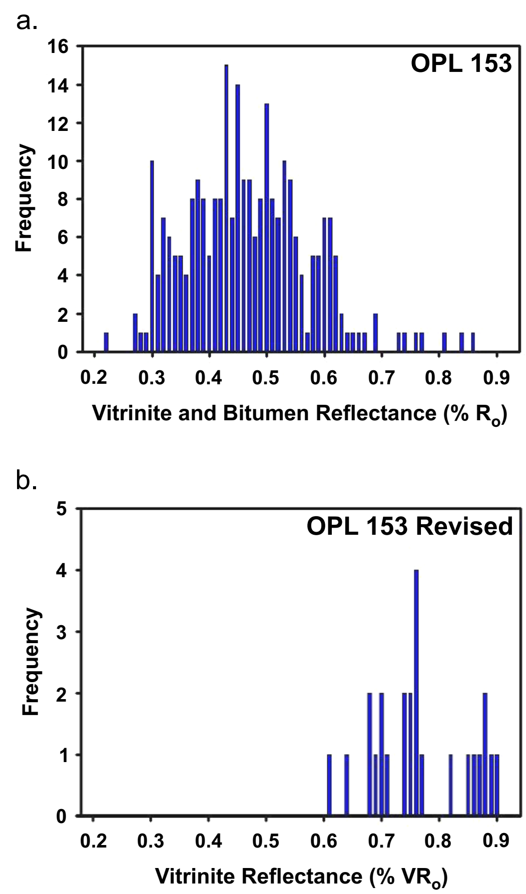

Figure 22. Reflectance histograms of OPL 153. (a) Published value in Cardott (1989) is mostly pre-oil solid bitumen reflectance (mean = 0.47% R_o; n = 262; range of 0.22-0.86% R_o); (b) Revised vitrinite-reflectance analysis (mean = 0.77% VR_o; n = 25; range of 0.61-0.90% VR_o).

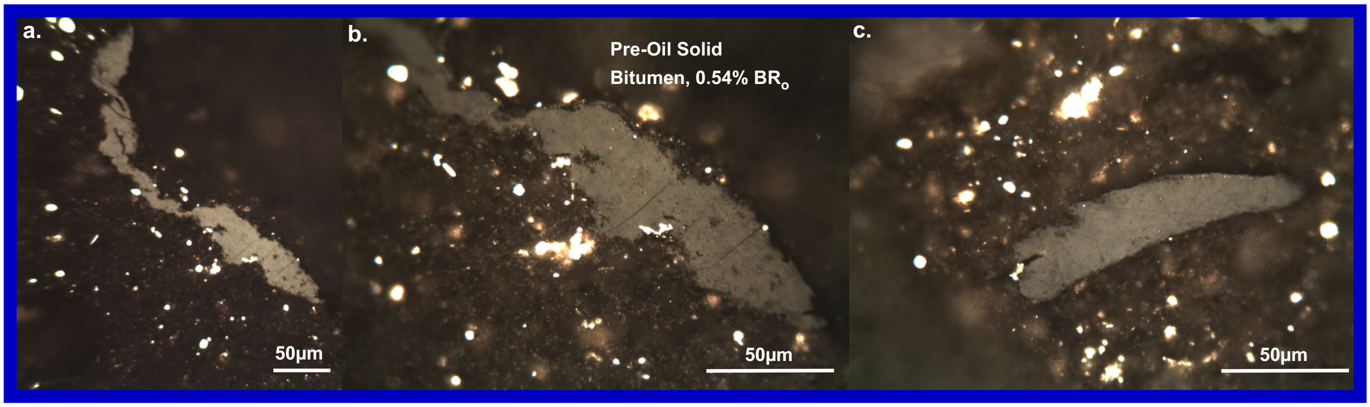

Figure 23. Photomicrographs of (a) vitrinite-like pre-oil solid bitumen taken at 200x magnification, (b) same field of view taken at 500x magnification, and (c) vitrinite (0.64% VR$_o$) from OPL 153.

measured vitrinite-reflectance value to 0.77% VR$_o$ by recounting true vitrinite. Figure 22a shows the original reflectance histogram with a wide range of reflectance values (0.22-0.86% R$_o$, 0.47% R$_o$ mean) while Figure 22b shows the re-analyzed reflectance histogram with a vitrinite-reflectance range of 0.61-0.90% VR$_o$ (mean = 0.77% VR$_o$). Macerals with reflectance values <0.60% R$_o$ were interpreted to be pre-oil solid bitumen. The 0.3% R$_o$ difference (i.e., 0.77% VR$_o$ – 0.47% R$_o$) in the means is the same difference predicted for bitumen and vitrinite reflectance means as discussed below. As an example of how pre-oil solid bitumen can appear vitrinite-like, photomicrographs of pre-oil solid bitumen and vitrinite are presented in Figure 23. Additional low thermal maturity samples that were re-analyzed to test for the inclusion of pre-oil solid bitumen reflectance values are listed in Table 2 and plotted on Plate 3.

Prior to deposition in a marine mud, any oxidation of woody organic matter in the terrestrial environment will form the semifusinite maceral (inertinite maceral group) which has a higher reflectance than the associated vitrinite maceral. In addition to a higher reflectance, semifusinite often retains the original woody structure (with curved and smooth walls known as bogen structure), aiding in its identification (Figure 20d). Erroneously including semifusinite reflectance in the vitrinite-reflectance analysis will skew the results to a higher %VR$_o$ value. Bogen structure of semifusinite and the typical range of vitrinite-reflectance values (~0.3% VR$_o$ at <1% VR$_o$) are used to exclude semifusinite reflectance values from the mean vitrinite-reflectance value. Given the many opportunities for wood to be subaerially oxidized on its path to being deposited as marine sediment, it is expected that some slightly-altered woody organic matter (recorded as semifusinite with slightly higher reflectance than vitrinite) would be encountered during the vitrinite-reflectance analysis. Vitrinite-reflectance measurements of Woodford Shale samples <1% VR$_o$ were bracketed by lower reflecting pre-oil solid bitumen and higher reflecting semifusinite macerals; measurements >1% VR$_o$ were bracketed by poorly polished (pitted-texture) vitrinite and semifusinite macerals.

The Woodford Shale is the oldest formation in Oklahoma that contains woody organic matter (i.e., vitrinite) (Wilson, 1958). Wilson (1958) and Urban (1960) indicated that fragments of Oklahoma's oldest fossil trees (*Callixylon whiteanum* wood of the Archaeopteris progymnosperm tree; Beck, 1981; Beck and Wight, 1988) are found in abundance in the lower portion of the Woodford Shale, and were deposited near shore. Kirkland and others (1992) found petrified wood in the basal section of the Woodford Shale in the Henry House Falls Quarry. The lower member of the Woodford Shale, at the start of the marine transgression, contains the most and largest (>15 µm) size vitrinite clasts. Vitrinite is rare and small (<8 µm) in the middle member of the Woodford Shale which was more distal marine. Based on biomarker analysis of the Wyche Farm core, Romero and Philp (2012) recognized a higher terrigenous input in the lower Woodford member and a predominance of marine organic matter in the middle and upper Woodford members.

Cardott and Lambert (1985) completed the first regional study of the thermal maturity of the Woodford Shale in the Anadarko Basin of Oklahoma by analyzing samples from 28 wells. Isoreflectance contours in the westernmost Anadarko Basin were modified based on published data ranging from 2.37 to 2.54% VR$_o$ for the Woodford Shale in the Union Oil Company of California 1-33 Bruner well (API 35-009-20093; Section 33, Township 11 North, Range 25 West) reported by Katz and others

(1982). Those data challenged the Time Temperature Index correlation to vitrinite reflectance by Waples (1980) who modeled a vitrinite reflectance of 4.8% VR_o for the producing horizon (Hunton Group) in the 1-33 Bruner well coinciding with the last known occurrence of dry gas. Based on 81 wells, Cardott (1989) expanded the Anadarko Basin study to include the Texas Panhandle and included 4.05% VR_o for the Woodford Shale in the Leede Oil and Gas 1-3 Green well (OPL 392; API 35-009-20566; Section 3, Township 10 North, Range 25 West). Compared to the Lone Star Producing Company 1 Bertha Rogers well (API 35-149-20020; Section 27, Township 10 North, Range 19 West), the anomalously low vitrinite-reflectance values (2.37 to 2.54% VR_o) for the 1-33 Bruner well reported by Katz and others (1982) was interpreted by Cardott (1989) to represent caving from younger formations containing vitrinite with a lower thermal maturity than the Woodford Shale. This conclusion was based on the following observations: 1) the Woodford Shale was at 27,520-27,772 ft (8,388-8,465 m) in the Lone Star 1 Bertha Rogers well (Rowland, 1974), a depth which yields a thermal maturity of 6.05% VR_o when calculated using the vitrinite reflectance versus depth regression equation in Cardott (1989); 2) vitrinite-reflectance data by James Urban for the Lone Star 1 Bertha Rogers well (in Borak and Friedman, 1981, 1982) documented caving contamination because the Ordovician- to Early Devonian-age samples from depths between ~24,000 to 31,000 ft (~7,300 to 9,500 m), which would not contain vascular plants, yielded values of 1.6-2.0% VR_o; and 3) measured vitrinite-reflectance values of the Woodford Shale (8,442-8,470 m [27,697-27,789 ft]) in the Lone Star 1 Bertha Rogers well in Price and others (1981) and Price (1997a, b) range from ~3.0 to 5.4% VR_o, consistent with the vitrinite-reflectance data from the 1-3 Green well (OPL 392; Section 3, Township 10 North, Range 25 West; 4.05% VR_o).

Lack of samples and structural complexity precluded extending the isoreflectance contours through southern Grady and northern Stephens Counties (Evans and others, 2018; Thomas, 2018; Miller and others, 2019; Abrams and Thomas, 2020). The low vitrinite-reflectance values (0.52-0.87% VR_o) for the Woodford Shale along the northern boundary with the Wichita Uplift demonstrate that Late Paleozoic deformation and uplift prevented deep burial in this part of the southern Oklahoma aulacogen.

Cardott and others (1990) reported Woodford Shale vitrinite reflectance in the Arbuckle Uplift (Ham and others, 1990) where the average value for 40 outcrop grab samples was 0.54% VR_o (mean random reflectance values ranged from 0.35-0.77% VR_o). Cardott and Chaplin (1993, their Table 3) summarized the organic geochemistry of the Woodford Shale from the Interstate-35 outcrop on the south side of the Arbuckle Uplift where the mean random vitrinite-reflectance values reported by several authors varied between 0.30-0.52% VR_o. Concerning the Interstate-35 outcrop, Cardott and Chaplin (1993, p. 29) concluded that “excluding bitumen reflectance values, the mean random (whole rock) vitrinite reflectance…is 0.50% (79 measurements with 0.43-0.66% reflectance range).” Ko and others (2018) calculated 0.49% VR_o based on programmed pyrolysis of Woodford Shale siliceous mudstone in the Interstate-35 outcrop. Based on a shallow (19 ft; 5.8 m) Woodford Shale core in the Arbuckle Uplift, Lo and Cardott (1995) reported an average of 0.51% VR_o (mean random reflectance values range from 0.46-0.55% VR_o) for unweathered samples and 0.35% VR_o for a weathered surface rubble sample in the Highway 77D Woodford outcrop (Section 30, Township 1 South, Range 2 East), about 7 miles north of the Interstate-35 Woodford outcrop. The well-indurated, very low permeability nature of the Woodford Shale protects the organic matter from weathering and sampling below the fissile zone in outcrop commonly provides unweathered samples of the Woodford Shale (Lewan, 1980). Paxton and Cardott (2008, p. 53) reported the mean random vitrinite reflectance of the Woodford Shale outcrop along Highway 77D on the north side of the Arbuckle Uplift is 0.58% VR_o (based on 26 measurements ranging from 0.48-0.72% VR_o). The low thermal maturity (0.35 and 0.42% VR_o) of outcrop samples in Cardott and others (1990) may be related either to weathering or inclusion of lower reflecting pre-oil solid bitumen reflectance values (Curiale, 1986; Cardott and others, 2015). Philp and others (1992) showed that weathering of Woodford outcrop samples had altered both hydrocarbon and stable isotopic compositions.

Cardott (2012a) prepared a Woodford Shale isoreflectance map for eastern Oklahoma (revised in Cardott, 2017). Woodford Shale thermal maturity ranges from 0.49% VR_o at a depth of 5,084 ft (1,550 m) in Lincoln County, Oklahoma, north of the Arbuckle Uplift, to 6.36% VR_o at a depth of 17,854 ft (5,442 m) in Le Flore County, Oklahoma.

The Woodford Shale vitrinite-reflectance map and data compiled for this report are in Plate 3 and Table 2. All of the reflectance measurements are for random (not maximum) orientations of vitrinite using a fixed stage, Vickers M17 Research Microscope, EG&G Gamma Scientific DR-2 Digital Radiometer, and EG&G Gamma Scientific D-46AQ Photomultiplier (circa 1980; Cardott, 1989). Mean random vitrinite-reflectance values were qualitatively evaluated using two petrographic thermal maturity indicators: (1) vitrinite reflectance equivalent (VRE) calculated from measured pre-oil and post-oil solid bitumen reflectance values, and (2) fluorescence colors of *Tasmanites* alginite. Errors can be made by either not comparing vitrinite-reflectance results to other thermal maturity indicators or assuming that vitrinite-reflectance values are suppressed.

VRE in Table 2 was calculated from regression equations in Landis and Castaño (1995) ([BR_o + 0.41]/1.09; VRE A), Schoenherr and others (2007) ([BR_o + 0.2443]/1.0495; VRE B), and Schmidt and others (2019) ([0.938xBR_o] + 0.3145; VRE C), keeping in mind that VRE is based on fewer solid bitumen reflectance values than the mean random vitrinite-reflectance value. Of significance, VRE indicates that solid bitumen was distinguished from vitrinite. Jacob (1989) measured solid bitumen reflectance from solid hydrocarbon vein deposits and noted that solid bitumen reflectance is less than vitrinite reflectance until ~1% VR_o, after which solid bitumen reflectance is higher than vitrinite reflectance. Landis and Castaño (1995) measured reflectance of both vitrinite and solid bitumen co-occurring within the shale and found solid bitumen reflectance is less than vitrinite reflectance until ~4% VR_o. Schoenherr and others (2007) combined the datasets of Jacob (1989) and Landis and Castaño (1995) to derive their equation. Combining nine published datasets, Schmidt and others (2019) noted that solid bitumen-reflectance values are lower than vitrinite-reflectance values until 4.5% VR_o.

Figure 24a compares 210 pairs of co-occurring mean random vitrinite and solid bitumen reflectance values measured in samples of the Woodford Shale from Table 2 (equation 1) (VRE = [BR_o + 0.3118]/1.0713 [coefficient of determination R^2=0.9749]; VRE D). Note that vitrinite-reflectance values <1.6% VR_o follow one trend (mostly pre-oil solid bitumen; solid bitumen reflectance is less than vitrinite reflectance). Vitrin-

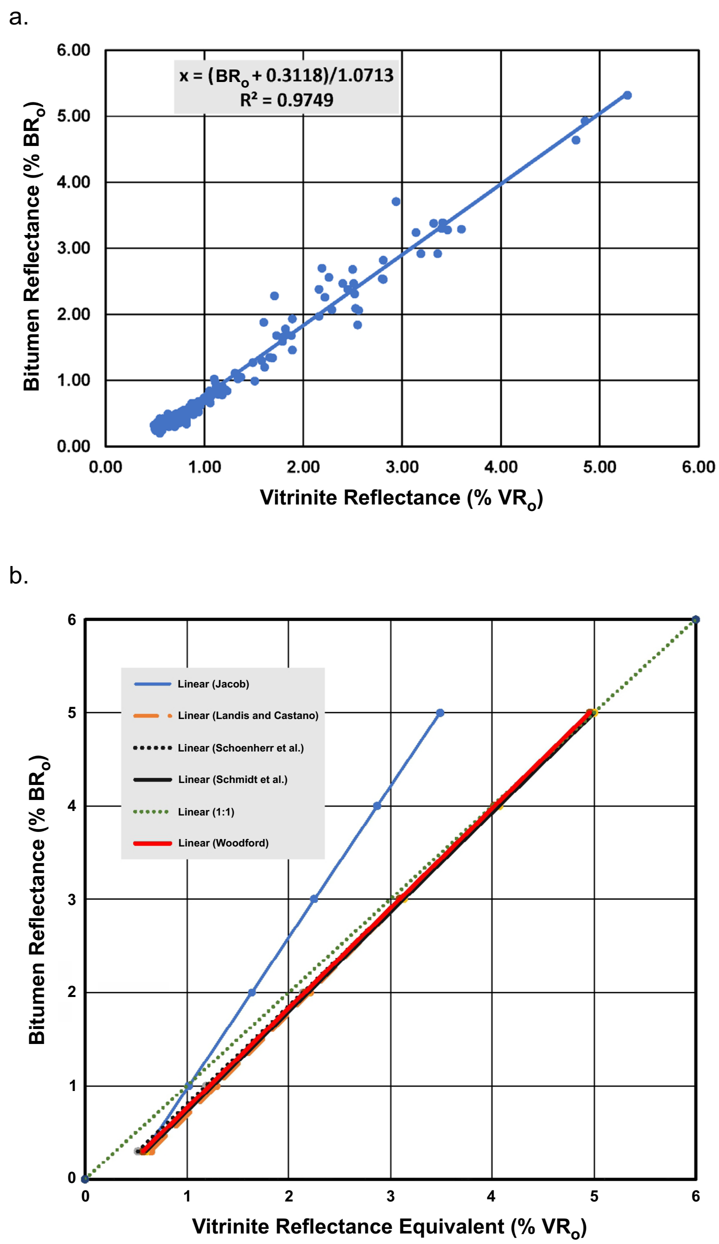

Figure 24. Measured mean random vitrinite reflectance and solid bitumen reflectance pairs. (a) Woodford Shale data in Table 2. Mean random solid bitumen reflectance values are based on fewer measurements than the mean random vitrinite-reflectance values. (b) Comparison of published vitrinite reflectance equivalent (VRE) equations: Jacob (1989) (VRE = [0.618 x BR_o] + 0.40); Landis and Castaño (1995) (VRE = [BR_o + 0.41])/1.09); Schoenherr and others (2007) (VRE = [BR_o + 0.2443]/1.0495); Schmidt and others (2019) (VRE = [0.938 x BR_o] + 0.3145); Woodford (this study) (VRE = [BR_o + 0.3118]/1.0713).

ite reflectance values >1.6% VR_o have a wider spread, mostly due to both solid bitumen and vitrinite-reflectance anisotropy, and follow a different trend (all post-oil solid bitumen; solid bitumen reflectance is slightly less than vitrinite reflectance). Mastalerz and Drobniak (2019) used 1.5% BR_o as the boundary between solid bitumen and pyrobitumen. Table 2 (VRE D) includes VRE calculated from equation 1.

Figure 24b compares published VRE equations with equation 1 for the Woodford Shale (regression line in Figure 24a). The regression line from Jacob (1989) crosses the 1:1 regression line at 1%. The other regression lines fall below the 1:1 regression line (i.e., solid bitumen reflectance is less than VRE) well into the dry gas window (4% VR_o), with solid bitumen reflectance getting closer to vitrinite reflectance equivalent with increasing thermal maturity. The regression line from equation 1 (Woodford) is closest to the regression line from Schmidt and others (2019). The slope of the Jacob (1989) regression line may be different from the slopes of the other regression lines due to inclusion of solid bitumen reflectance values from solid hydrocarbon vein deposits (asphaltite and asphaltic pyrobitumen) external to the shale.

Tasmanites alginite qualitative fluorescence colors change from green to orange with increasing thermal maturity before fluorescence is extinguished at 0.9-1.0% VR_o (Taylor and others, 1998, p. 137). Based on Table 2 for the Woodford Shale, green to greenish-yellow fluorescence corresponds to 0.49-0.74% VR_o, yellow fluorescence corresponds to 0.70-0.77% VR_o, and orange fluorescence corresponds to 0.82-0.98% VR_o (although alteration from weathering can also result in orange fluorescence; see Table 2, 0.64-0.74% VR_o).

There are two thermal maturity anomalies in the subsurface on the Woodford Shale isoreflectance map in northern Oklahoma on Plate 3 that are not consistent with the Woodford Shale structure map on Plate 1. A greater anomaly (mean random vitrinite-reflectance values >1.0% VR_o) in Osage County, Oklahoma, on the Cherokee Platform, and a lesser anomaly (>0.8% VR_o) in Garfield County, Oklahoma, on the Anadarko Shelf are suggestive of igneous hot spots affecting post-Woodford deposition. These thermal anomalies coincide with broad gravity high anomalies in residual Bouguer gravity from basement rocks related to the Mid-Continent rift system (Elebiju and others, 2011; Cardott, 2015b; Crain and Keller, 2016; Chopra and others, 2018). The variable nature of Woodford Shale thermal maturity in north-central Oklahoma is the reason for the deflection in the 0.6% VR_o isoreflectance contour between western and eastern Oklahoma. The Woodford Shale is at a thermal maturity level of 0.77% VR_o in the Devon Energy 1-33 Frank SWD well (OPL 1455; API 35-083-23957; Section 33, Township 19 North, Range 2 West) in Logan County, Oklahoma. A lower value of 0.57% VR_o reported by Cardott and Lambert (1985) and Cardott (1989) from the nearby Bobby J. Darnell 1 Kindschi well (OPL 114; API 35-083-21423; Section 14, Township 19 North, Range 2 West) is interpreted to be based on caving contamination (Table 2). Achang and others (2017) calculated 0.56% VR_o based on programmed pyrolysis of the Woodford Shale in the Sundown Energy LP 1-28 Danker well in Lincoln Co. (API 35-081-23817; Section 28, Township 14 North, Range 3 East), in agreement with nearby measured vitrinite-reflectance data.

Thermal maturity of the Woodford Shale in Oklahoma ranges from marginally mature (0.49% VR_o) to post mature (6.36% VR_o) (Table 2). Although the suggestion that early oil generation in Woodford Shale may begin at 0.35% R_o (Comer, 2005), the recognition that solid bitumen (having a lower reflectance than vitrinite) has been misidentified as vitrinite in the vitrinite-reflectance analyses in some Woodford samples most likely explains this low vitrinite-reflectance value. A higher value near 0.5% VR_o (as used by Tissot and Welte, 1984, p. 517, and Hunt, 1996, p. 334) may better represent the onset of hydrocarbon generation in the Woodford Shale. Peters and Cassa (1994) use 0.6% VR_o as the onset of commercial oil generation. Jarvie (2012b, p. 91) indicated "…thermal maturity values from about 0.60 to 1.40% R_o are the most likely values significant for petroleum liquid generation. Regardless of thermal maturity, there must be sufficient oil saturation to allow the possibility of commercial production of oil." Therefore, 0.5% VR_o may be the best estimate for the onset of oil generation in the Woodford Shale, while 0.6% VR_o should be considered the lower limit of commercial volumes of oil expulsion following oil saturation.

Hydrous pyrolysis kinetics for the Woodford Shale indicate the onset to completion of oil generation correlates to a range of about 0.6 to 1.2% VR_o (Higley, 2014, p. 26; Lewan and Pawlewicz, 2017). Formation of light alkanes (C_1 – C_5) during hydrous pyrolysis experiments of Woodford Shale samples collected from exposures on the south flank of the Arbuckle Uplift along Interstate-35 confirm the co-generation of natural gas from Woodford kerogen during the main stage of oil generation (Lewan, 1997). Total C_1 to C_5 gas concentrations of 28, 78, and

146 mmol/400 g of rock were recovered from sealed vessels after 72 hours of heating at 300, 330, and 350°C, respectively (Lewan, 1997). Even though thermogenic gas is generated concurrently with oil generation, kinetics modeling indicates that in the Woodford Shale additional thermogenic gas generation results from the cracking of oil to gas between 1.2 to 1.7% VR_o (Higley, 2014, p. 26-28). For the Woodford Shale in the Anadarko Basin, Higley (2013, p. 81) presented models to show that "Oil generation began at burial depths of about 6,000 to 6,500 ft (1,800 to 2,000 m). Modeled onset of Woodford Shale oil generation was about 330 million years ago (Ma); peak oil generation was from 300 to 220 Ma." Although Dembicki (2014) concluded that "sufficient hydrocarbon saturation to allow expulsion is usually not reached until 0.7-0.9% R_o", Comer and Hinch (1987, p. 857) suggested that expulsion may begin earlier in very organic-rich oil-prone source rocks like the Woodford Shale because they yield large enough volumes of oil in the earliest stages of oil generation to reach effective oil saturation. Anderson (2014) recommended 0.9-1.2% VR_o as the maximum liquids recovery zone. Dembicki (2014) favored a narrow range of 1.2-1.5% VR_o (typically recognized as the condensate window) for a liquids-rich play. Jarvie (2017, p. 343) concluded that "The optimum goal for highly economic oil production is in the volatile oil window" (~0.95-1.15% R_o). These studies clearly indicate that thermal maturities well into the oil window are the optimum for a liquids-rich play, but they do not preclude the possibility that highly organic-rich intervals with lower thermal maturities may result locally in an economically viable liquids-rich play because such intervals could generate a large enough volume of hydrocarbons to saturate the rock at maturities closer to the beginning of the oil window.

Thermal maturity limits for oil and thermogenic methane generation, preservation, and destruction that have been published in the literature are summarized below. The limits highlighted below have been applied to the Woodford Shale data in this report (Figure 25). Lewan and Pawlewicz (2017) suggested that 1.5% VR_o is the lower limit for significant shale-gas accumulations sourced by gas generated from oil cracking. Using data from the Barnett Shale, Jarvie and others (2005) assigned the following vitrinite-reflectance limits for core samples: immature (< 0.55% VR_o), oil window (0.55–1.15% VR_o; peak oil generation at 0.90% VR_o), condensate–wet-gas window (1.15–1.40% VR_o), and dry-gas window (> 1.40% VR_o). Approximately 3% VR_o is considered the upper limit of thermogenic methane generation (Taylor and others, 1998, pp. 128 and 504; Lewan, 2002; Lewan and Kotarba, 2014). Lewan and Pawlewicz (2017) determined that 3.3-3.9% VR_o is the end of thermogenic gas generation. Approximately 5% VR_o is considered the upper limit of thermogenic methane preservation (Houseknecht and Spötl, 1993; Lewan and Kotarba, 2014). The methane preservation limit may be related more to reservoir conditions than to methane destruction. Hunt (1996, p. 425) indicated that methane is stable at temperatures up to 550°C.

Hydrocarbon Assessment for Woodford Shale	Vitrinite Reflectance (% VR_o)
Early oil generation zone	0.40-0.60%
Commercial oil window	0.60-1.15% (peak oil at 0.90%)
Condensate—wet-gas window	1.15-1.40%
Dry-gas window	>1.40%
Thermogenic methane generation limit	3.9%

Figure 25. Hydrocarbon generation assessment for the Woodford Shale.

Figure 26a shows the thermal maturity-depth profile for all of the vitrinite-reflectance data in Table 2. In general, thermal maturity increases with increasing present depth of burial (not modeled to maximum burial depth), but the scatter is large. Woodford Shale well cuttings with the highest vitrinite reflectance measured in the Anadarko Basin (4.89% VR_o; OPL 245) at 22,526 ft (6,866 m) deep (GHK 1-18 Dugger well; Cardott, 1989) is deeper than the Woodford Shale well cuttings with the highest vitrinite reflectance measured in the Arkoma Basin (6.36% VR_o; OPL 960) at 17,854 ft (5,442 m) deep (Amoco Production Company 1 Devils Backbone well; Cardott,

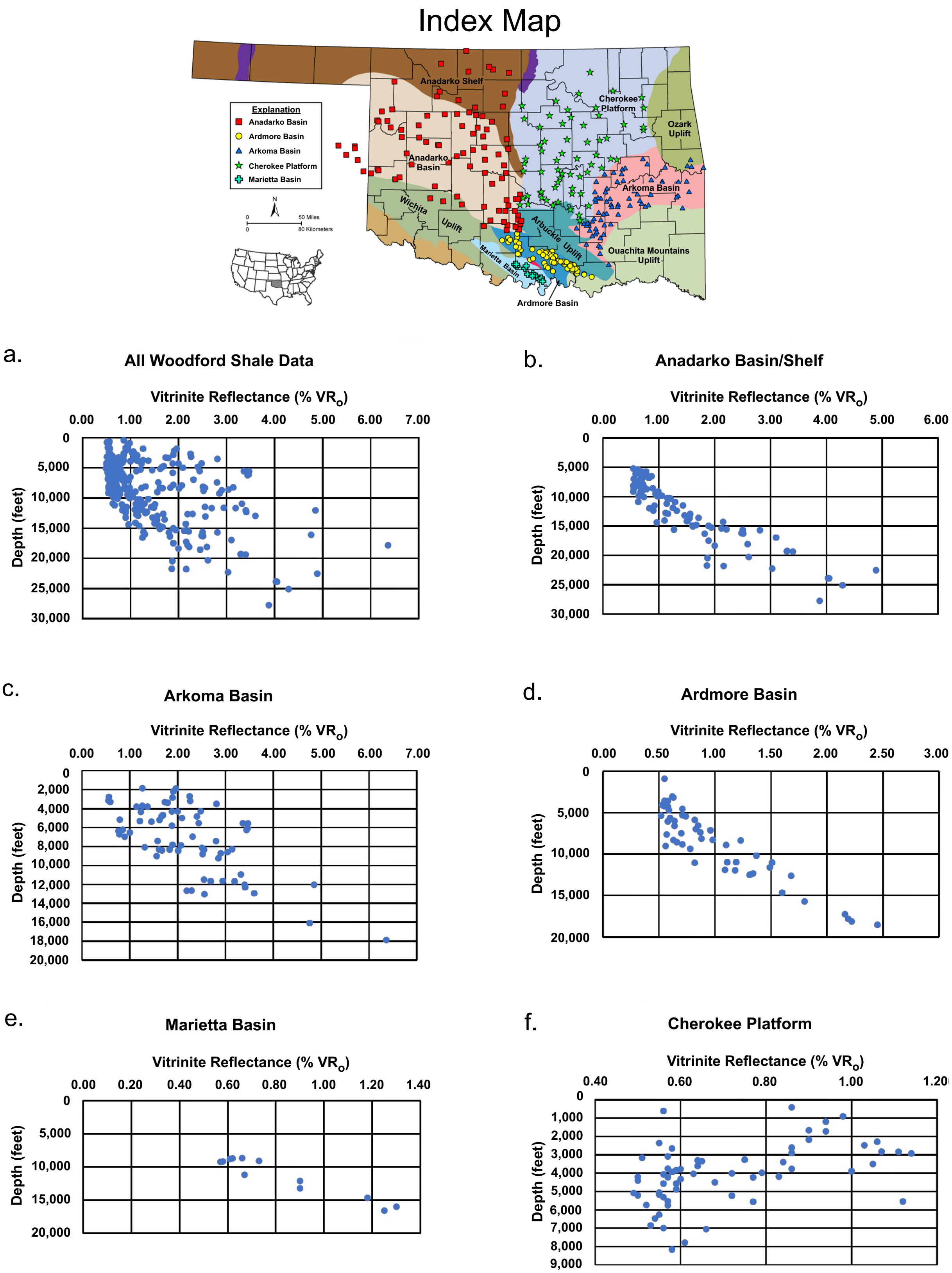

Figure 26. Woodford Shale thermal maturity profiles: (a) all data, (b) Anadarko Basin/Shelf, (c) Arkoma Basin, (d) Ardmore Basin, (e) Marietta Basin, (f) Cherokee Platform.

2012a). Figure 26b shows the thermal maturity profile for the Anadarko Basin and Anadarko Shelf with a narrow range of values, while Figure 26c shows the thermal maturity profile for the Arkoma Basin with a wider range in values. The thermal maturity of the Woodford Shale in the Anadarko Basin increases with increasing depth (Cardott, 1989; Higley, 2014), while thermal maturity of the Woodford Shale in the Arkoma Basin cuts across structure contours (Figure 27) (Cardott, 2012a) indicating that thermal maturity in the Arkoma Basin is controlled more by previous depth of burial instead of present depth of burial (Cardott, 2013b). The thermal maturity profiles shown in Figure 26d and Figure 26e follow a narrow range for the Ardmore and Marietta Basins, whereas vitrinite-reflectance values for the Cherokee Platform shown in Figure 26f are widely scattered with no obvious depth trend. The highest thermal maturities (>1.0% VR_o) on the Cherokee Platform are in Osage County, Oklahoma (associated with the thermal anomaly) and Okfuskee and Hughes Counties on the edge of the Arkoma Basin.

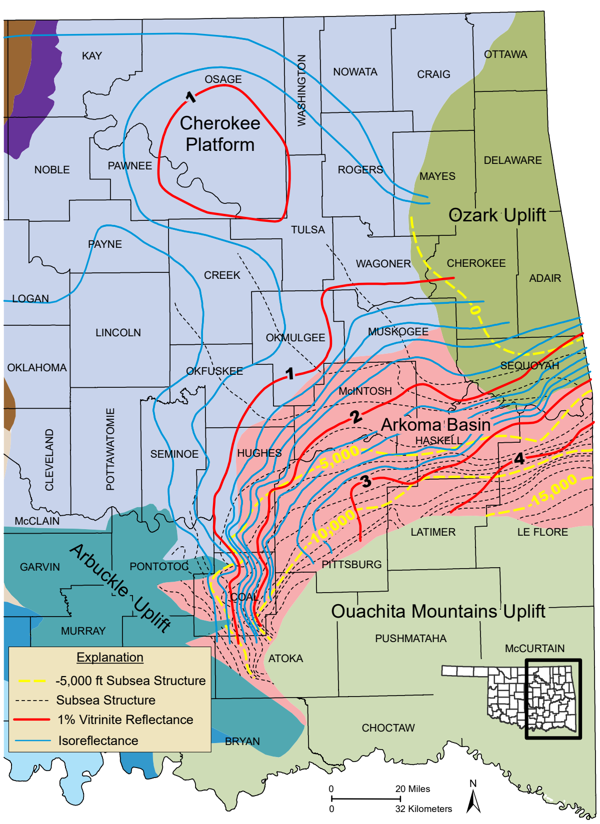

Figure 27.Woodford Shale combined vitrinite isoreflectance and structure map of eastern Oklahoma (modified from Cardott, 2012a). Vitrinite isoreflectance contours are from Plate 3.

Woodford Shale vitrinite isoreflectance contours presented in this report should be used as a qualitative thermal maturity indicator (e.g., start, middle, end of oil window; condensate window; dry gas window) and not as a "drill here" indicator because of the following factors:

1. Vitrinite reflectance of a single sample is an average — the mean of a histogram — representing many individual measurements that have a range of values.
2. Although the wide distribution of Woodford Shale well locations is adequate to estimate regional hydrocarbon source rock potential, closer spaced sampling is required for the accurate assessment of the hydrocarbon production potential for a specific play.
3. The middle and upper members of the Woodford Shale contain predominantly marine organic matter and very little vitrinite, making the statistical validity of the reflectance measurements more problematic. In contrast, the lower member typically has a significantly lower TOC content and contains the most and largest (>15 μm) vitrinite/petrified wood.
4. The vitrinite-reflectance values of a few samples in a well is extrapolated to the entire thickness of the formation even though the Woodford Shale may be up to 700+ ft (200+ m) thick (Table 2).

In summary, the thermal maturity of the Woodford Shale spans the oil, condensate, and dry-gas windows with a range of 0.49-6.36% VR_o. Significant oil expulsion commences by 0.6% VR_o. The maximum recovery of oil and condensate is achieved between 0.9-1.4% VR_o, while thermogenic methane recovery occurs from the oil window through dry-gas window (Figure 25).

WOODFORD SHALE AS RESERVOIR

Shale Resource Systems

Petroleum systems include all of the essential aspects of petroleum geology that link oil and gas in reservoirs to their hydrocarbon source rocks (generation, migration, and accumulation) (Magoon, 1988, 1992; Magoon and Dow, 1994). Shale resource systems (i.e., shale gas and tight oil) for natural gas (mostly methane), condensate (mostly propane, butane, pentane, hexane), and oil (mostly higher molecular weight hydrocarbons) are self-contained, continuous systems that encompass hydrocarbon source, migration pathway, reservoir, and seal (USGS, 1995; Schmoker, 1999, 2002; Curtis, 2002; Hill and others, 2007; Pollastro, 2007; Cardott, 2006, 2017; Breyer, 2012; Jarvie, 2012a, b; Hackley and Cardott, 2016). The term "shale gas" refers to the thermogenic or microbial gas produced from organic carbon-rich shale/mudrock. Since the term "shale oil" is typically used for the yield generated by the retorting of oil shale (i.e., immature oil-prone source rock), the term "tight oil" is used for oil produced from oil-bearing (thermally mature) shale (Boak, 2014; Boak and Kleinberg, 2020; Peters and others, 2016).

Beginning in 1981, followed by commercial success in 1999, Mitchell Energy Corporation with the help of research by the Gas Research Institute (Gas Technology Institute) and advances in drilling and completion technology (e.g., horizontal/directional drilling, multi-stage hydraulic fracture stimulation, pumping more proppant, super-extended laterals; Soeder, 2018; Zoback and Kohli, 2019) developed the Mississippian-age Barnett Shale in the Fort Worth Basin as the first commercial shale-gas reservoir in the world (Curtis, 2002; Montgomery and others, 2005; Bowker, 2007; Martineau, 2007; Steward, 2007; Stark and Smith, 2017). Other shale-gas plays were developed in the U.S. soon after the success of the Barnett Shale (Figure 28) (EIA, 2011a, 2016). As profoundly stated by Curtis (2002, p. 1937), "shale gas may represent one of the last, large onshore natural gas sources of the lower 48 states". In 2004 the Oklahoma Geological Survey hosted the "Unconventional Energy Resources in the Southern Midcontinent" symposium which focused on gas shales in Oklahoma (Cardott, 2005).

Successful shale-gas and tight-oil production is affected by both geological factors and well-completion techniques. Early on, it was determined that mechanical properties (brittle vs. ductile) are as important as hydrocarbon source potential in establishing commercial production (Cardott, 2006; Jarvie and others, 2007; Jarvie, 2012a). Slatt and others (2018a) identified six essential attributes to be used as screening criteria for successful shale resource plays: these include 1) permeable and brittle lithologies; 2) organic-rich source rock; 3) optimum thermal maturity for hydrocarbon generation; 4) adequate resource thickness; 5) oil/gas shows in wells or seeps

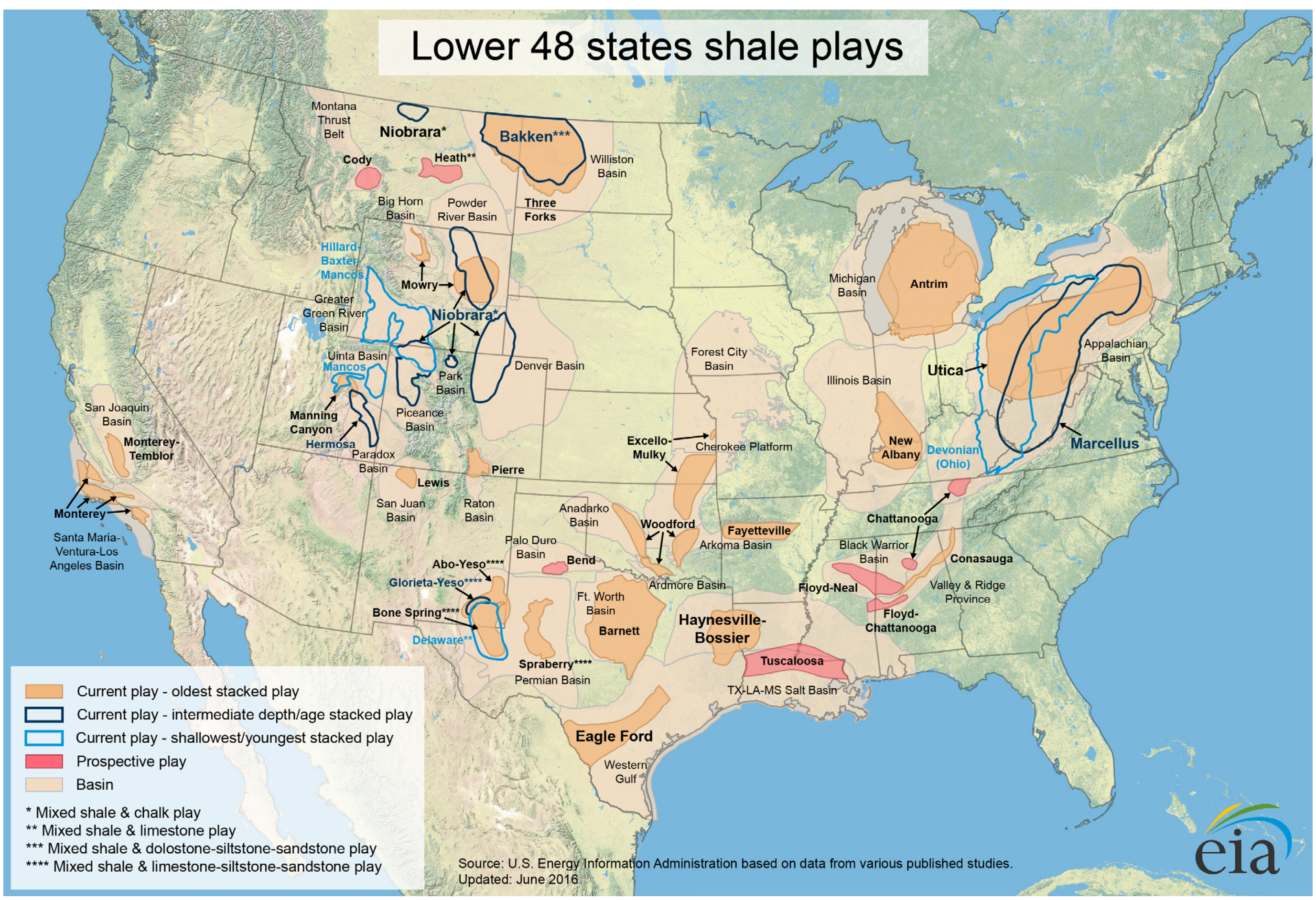

Figure 28. Map of shale resource plays in the contiguous United States. From EIA (2016).

in outcrops; and 6) lateral continuity that is regionally extensive. The following references provide further information on the characteristics of shale resource plays (Breyer, 2012; Jarvie, 2012a, 2012b, 2017; Zagorski and others, 2012, 2017; Slatt, 2013b; Bernard and Horsfield, 2014; Gentzis and others, 2017; Juliao and others, 2017; Zou and others, 2017; Horsfield and others, 2018; Soeder, 2018; Camp and others, 2019; Zoback and Kohli, 2019; Slatt, 2020). For a discussion on shale porosity and permeability, see Slatt and others (2018a).

Following the success of natural gas production from the Mississippian-age Barnett Shale in the Fort Worth Basin in Texas (Bowker, 2003, 2005, 2007; Hall, 2005; Steward, 2007; Hill and Jarvie, 2007), operators began to look at other gas shales (Cardott, 2008). The age-equivalent Caney Shale was evaluated in 2004 in the Arkoma Basin in Oklahoma (Schad, 2004). When it was determined that the ductile, clay-rich Caney Shale in the Arkoma Basin did not fracture like the Barnett Shale (Andrews, 2007), operators turned to the brittle, silica-rich Woodford Shale in the Arkoma Basin as a shale-gas reservoir target in Oklahoma. Figure 29 shows the Oklahoma gas-shale and tight-oil well completions history for the Caney Shale, Goddard/Springer shale, and Woodford Shale from 2004-2019. On an annual basis, the maximum number of 610 Woodford Shale well completions was achieved in 2014. The subsequent drop in the number of completions coincided with the global decline in oil prices.

The Woodford Shale in Oklahoma has been widely recognized as an important potential gas and oil reservoir (Comer, 2005; Haines, 2006; Kulkarni, 2011, 2012; Higley, 2011, 2013; Pickett, 2008; Torkelson, 2007; Williams, 2010). The development of the Woodford Shale as a gas and oil reservoir evolved from the foundational knowledge of its effectiveness as a regional hydrocarbon source rock and subsequent multidisciplinary studies of its mechanical properties. The combination of an excellent thermally mature hydrocarbon source rock with intervals of brittle lithology make the Woodford Shale an excellent unconventional oil and gas reservoir (Comer, 2005; Kvale and Bynum, 2014). The Woodford Shale is included in several lists of important shale-gas and tight-oil reservoirs in the USA (Cardott, 2008; Kuuskraa, 2011; Jarvie, 2012a; Hackley and Cardott, 2016; Gentzis and others, 2017; Juliao and others, 2017; Stark and Smith, 2017; Zou and others, 2017).

Houseknecht and others (2010) included the Woodford Shale Gas Assessment Unit (total undiscovered resources for F95 to F5 fractiles of 6,065-17,036 billion cubic feet of gas [BCFG; mean of 10,678 BCFG] and 34-356 million barrels of natural gas liquids [MMBNGL; mean of 142 MMBNGL]) in a petroleum assessment project of the Arkoma Basin. Higley and others (2011, 2014) included the Woodford Composite Total Petroleum System (total undiscovered resources for Woodford Shale Oil Assessment Unit for F95 to F5 fractiles of 175-730 million barrels of oil [MMBO; mean of 393 MMBO], 795-3,851 BCFG [mean of 1,963 BCFG], and 22-121 MMBNGL [mean of 50 MMBNGL]; total undiscovered resources for Woodford Shale Gas Assessment Unit for F95 to F5 fractiles of 8,806-25,998 BCFG [mean of 15,973 BCFG] and 94-336 MMBNGL [mean of 192 MMBNGL]) in an oil and gas assessment project of the Anadarko Basin. Drake and Hatch (2021) included the Woodford Shale Oil Assessment Unit (total undiscovered resources for F95 to F5 fractiles of 195-924 million barrels of oil [MMBO; mean of 460 MMBO] and 246-1,345 BCFG [mean of 644 BCFG]) and Woodford Biogenic Gas Assessment Unit (total undiscovered resources for F95 to F5 fractiles of 90-993 BCFG [mean of 416 BCFG]) in an oil and gas assessment project of the Cherokee Platform Province.

As of year-end 2019, EIA (2021) reported proved reserves of 524 million barrels of crude oil and 20.9 trillion cubic feet of natural gas for the Anadarko Basin/southern Oklahoma Woodford Shale play.

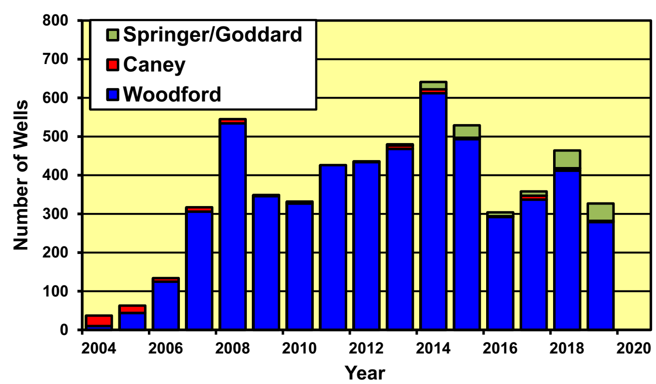

Figure 29. Histogram showing numbers of Woodford Shale, Caney Shale, and Springer/Goddard shale well completions in Oklahoma, 2004-2019.

Woodford Reservoir Characterization

Comer (1991) highlighted petrologic and geochemical data necessary for predicting potential locations and lithologies of commercial petroleum reservoirs within the Woodford Shale in the Permian Basin. Hester and Schmoker (1993) anticipated that the Woodford Shale would be an economically significant reservoir rock in Oklahoma. Some of the key geologic and technical factors that are evaluated for shale-gas and tight-oil plays are: organic matter type, quantity, and thermal maturity; mineralogy; ability to be fractured; rock thickness; depth; porosity; permeability; and reservoir pressure (Zagorski and others, 2012). Many of these factors for the Woodford Shale have been discussed in previous sections of this report. Slatt and others (2018a) suggested 75 ft (23 m) as a minimum thickness for productive wells with commercial initial potential (IP) rates. In addition to being a hydrocarbon source rock, a shale-gas or tight-oil reservoir needs to have sufficient permeability for conventional reservoir completion (e.g., Bakken Shale; Sonnenberg and others, 2017) or brittle lithology (e.g., >30% quartz or carbonate) responsive to artificial stimulation (Jarvie, 2012b; Horsfield and others, 2018). Reservoir pressure is an important aspect for hydrocarbon production. Zagorski and others (2017, p. 71) indicated that "A key parameter influencing the Marcellus play is overpressure. A near-normal or overpressure gradient is essential for effective large-scale water fracs." Al-Shaieb and others (1992, 2001) described the Woodford Shale as the basal seal of an Anadarko-Basin-wide overpressured compartment that they referred to as the megacompartment complex.

Intervals in the Woodford Shale having a biogenic silica-rich, brittle lithology are critical for hosting and maintaining natural and induced fractures. Biogenic chert intervals occur more frequently higher in the section and increase in abundance and thickness eastward from the southeastern Anadarko Basin into the Ouachita Mountains Uplift. Biogenic chert intervals possess good mechanical properties for reservoir development while intervals composed mostly of detrital clay and silt possess poor mechanical properties that inhibit reservoir development (Caldwell, 2011) (see section titled Chert above). Natural fractures are more abundant in the brittle chert-rich lithology and the natural fractures enhance the permeability developed during hydraulic fracturing in the Woodford Shale (Ataman, 2008; Badra, 2011; Bramlett, 1981; Slatt and Abousleiman, 2011; Molinares Blanco and others, 2017b). Portas Arroyal (2009) correlated potential fracture zones identified from seismic attributes with fracture zones identified on the outcrop. Natural fractures that are prevalent in siliceous and cherty facies in the Woodford may be filled with brittle authigenic minerals that promote additional brittle behavior (Roberts and Elmore, 2018). However, Woodford lithology is variable vertically and regionally. Mineral and organic variability has resulted in a complex reservoir that requires extensive study to develop the well-completion plan (Kvale and Bynum, 2014). For the purpose of well stimulation, the Woodford can be classified into four rock types: siliceous mudrock, clayey siliceous mudrock, clayey mudrock, and organic-poor clayey mudrock. Siliceous mudrock facies have stimulation success while the other facies result in failed fracturing treatments (Caldwell, 2014; Scaggs and others, 2017).

Slatt and Abousleiman (2011), Slatt (2013a) and Slatt and others (2018a) utilized high-resolution sequence stratigraphy of the Woodford Shale to identify brittle-ductile couplets (alternating chert/very siliceous shale and more clay-organic shale) to explain successful well completions. Slatt (2013a, 2015) indicated that these brittle-ductile couplets, with the brittle zone above a high TOC interval, represent the preferred target zones for successful completions. Fractures in chert beds observed in outcrop are typically oriented perpendicular to bedding (Fishman and others, 2013) and do not extend through adjacent clay-rich beds (Paxton and Cardott, 2008; Fishman and others, 2013; Slatt, 2013b; Slatt and others, 2018a, b). Slatt and others (2012) identified higher fracture density in upper Woodford quartzose lithofacies based on the Fullbore Formation MicroImager (FMI^{TM}) log and core analysis. A brittle formation may be recognized either by a high biogenic quartz and/or carbonate content or a combination of a high Young's modulus and low Poisson's ratio (Slatt, 2013a; Slatt and others, 2014; Tran and others, 2014). Commercial shale resource plays contain <40% clay minerals (Anderson, 2014).

Slatt and others (2018a) discussed the methods used to measure nanoporosity and permeability in shales. Focused and broad ion-beam milling field emission scanning electron microscopy is the preferred method to examine the size, shape, distribution, and connectivity of nanodarcy- and microdarcy-scale pores in shales. Several pore classifications have been proposed for shales (Cardott and Curtis, 2018). The most basic pore classifications include interparticle pores, intramineral pores, intraorganic pores, and fracture pores (Slatt and O'Brien, 2011; Loucks and others, 2012). Both organic and inorganic pore types can function as hydrocarbon storage sites and permeability pathways (Cardott and others, 2015; Slatt and others, 2018a). Post-oil solid bitumen forms a network in the thermally mature shale matrix and hosts intraorganic pores that provide a potential primary migration pathway for hydrocarbons (Cardott and others, 2015). Nanopores in post-oil solid bitumen are considered a dominant source of porosity in shale reservoirs (Curtis and others, 2012; İnan and others, 2018; Dong and Harris, 2020). Zagorski and others (2017) recognized intraorganic porosity as the key pore type in the Marcellus Shale.

Comer and Hinch (1987) documented 5 styles of solid bitumen accumulation completely enclosed within fine-grained, organic-rich intervals of the Woodford Shale and age-equivalent strata, including accumulations in fractures, stylolites, burrows, nodules, and sandstone lenses. Small-scale accumulations of solid bitumen within mature source rocks are evidence of effective porosity and permeability to oil. Both normal pore networks and enhanced fracture networks were judged to be the principal conduits for oil movement through the Woodford Shale (Comer and Hinch, 1987). Subsequent work by Slatt and O'Brien (2011) identified pores at both micrometer and nanometer scales in Woodford Shale, including pores up to tens of micrometers in diameter in clay floccules that may be interconnected, nanometer sized pores in organic particles that appear to be more isolated, pores between particles incorporated in sand-sized fecal pellets, pores in fossil remains (open chambers and porous walls), pores between microcrystals in grains of secondary origin, and microchannels and microfractures that often cut across bedding. While all of these pores provide space for gas and oil storage, the pore types most likely to create permeability are those developed in floccules, organic matter, microchannels, and microfractures (Slatt and O'Brien, 2011). Comer and Hinch (1987) reported a mean porosity of 3% for Woodford Shale samples and Gupta and others (2018) reported mean porosity values of 7.7% for high porosity and high TOC samples, 6.4% for intermediate porosity and TOC samples, and 3.1% for low porosity and relatively low TOC but high carbonate content. In a study of low thermal maturity Woodford Shale outcrops in the Arbuckle Uplift, Fishman and others (2013) indicated that cherts had porosities of 0.59-4.90% and permeabilities of 0.003-0.274 μD while mudstones had porosities of 1.97-6.31% and permeabilities of 0.011-0.089 μD.

Slatt and others (2018a, p. 307) stated "The orientation of a horizontal or vertical well relative to the orientation of bedding will affect the 'breakability' of a shale." Based on Woodford Shale outcrop studies of soft beds (laminated, fissile hydrocarbon source rocks) and hard beds (nonfissile, blocky zones) that combine reservoir quality (source rock capable of storing hydrocarbons) and completion quality (fracture development and efficient proppant placement), Galvis and others (2018) and Becerra and others (2018) proposed that the best horizontal drilling and completion target intervals correspond to high-frequency interbedding with 50/50 soft-to-hard ratios. Fishman and others (2013) concluded that cherts in the Woodford Shale may be important intervals of gas generation and storage. Based on three rock types identified in Woodford cores from seven wells, Gupta and others (2018) determined that rock type 1 (low density, high gamma ray, high quartz) concentrated in the upper part of the middle Woodford was the best reservoir rock. Other studies concur that the best horizontal landing zone in the Woodford Shale is the upper part of the middle Woodford Shale (i.e., brittle zone above a high TOC interval, above the maximum flooding surface (mfs); see Figure 6, GRP 7) (Slatt and Rodriguez, 2012; Caldwell and Johnson, 2013; Molinares Blanco and others, 2017a; Galvis and others, 2018; Brito, 2019). Zagorski and others (2017) found that key pay intervals in the Marcellus Shale are also associated with maximum flooding surfaces. Of six zones in the Woodford Shale (zone A at the top to zone F at the bottom), Peza and others (2014) concluded that zones C and D in the middle Woodford had the best reservoir quality (TOC, porosity, permeability). Based on an outcrop study of fracture intensity and bed thickness of brittle and ductile beds, Ghosh and others (2018) concluded that part of the upper and most of the middle Woodford members with high fracture densities and organic-rich intervals may be suitable horizontal well landing targets. Laughrey and others (2017) concluded that the middle Woodford member had the most favorable reservoir parameters and economic production potential for a well in Garvin Co. Torres-Parada and others (2018) concluded that the Woodford Shale brittle-ductile couplets between the upper portion of the middle member and the lower portion of the upper member had the best reservoir properties (i.e., porosity, permeability, thickness). Scaggs and others (2017, p. 54) stated "Optimally, the goal is to target the Woodford 'B' interval, which is characterized by high resistivity and neutron and density porosity coming together or crossing over, and lower total gamma ray (GR) than other Woodford intervals."

Even though the Woodford Shale in northeast Oklahoma is in the oil window, unconventional Woodford wells produce no oil and minor amounts of gas. Poor results are attributed to the change in Woodford Shale mineralogy in northeastern Oklahoma from biogenic quartz in the south and southwest (Figure 5d-f, h) to detrital quartz and clay proximal to the Ozark Uplift (Figure 5a-b). Dong and others (2017) indicated that siliceous intervals of authigenic (biogenic) quartz correlated with brittleness and improved fracture development and integrity, whereas laminated mudstones with detrital quartz grains supported in a clay matrix were relatively too ductile to support and maintain open fracture networks.

The methane molecule is 3.8 angstroms in size. Methane is more mobile than the larger oil molecules. Jarvie (2012b, p. 91) stated that "Although an organic-rich source rock in the oil window with good oil saturation is the most likely place to have oil, it is also the most difficult to produce, unless it has open fractures or an organic-lean facies closely associated with it." Conventional oil production from the Woodford Shale occurs in intervals with open natural fractures (Comer and Hinch, 1987). However, some researchers of unconventional resource shale plays question the importance of natural fractures. Bowker (2007) and Gale and others (2007) indicated that open natural fractures could be a detriment to gas production from the Barnett Shale if gas migrated out, brought water into the shale, or prevented new fractures from forming during hydraulic fracture treatments. Most natural fractures in the Barnett Shale had been sealed with calcite during burial diagenesis and reopened during hydraulic stimulation (Bowker, 2007; Gale and others, 2007). Concerning fracturing and faulting issues for the Marcellus Shale, Zagorski and others (2012, p. 196) stated "When and where do these features enhance production or act as detriments influencing completion effectiveness and borehole stability? Should fractured areas be targeted or avoided? Where is the distinction made?" Zagorski and others (2017, p. 76) concluded that "in highly fractured regions, it appears the higher degree of natural fracturing significantly negatively impacts well performance." For Woodford Shale, zones that produce oil from natural fractures in conventional wells are the same brittle biogenic chert lithologies as zones that produce unconventional oil because they are the most mechanically capable of supporting open fractures when stimulated (Comer, 2005; Kvale and Bynum, 2014; Becerra and others, 2018; Galvis and others, 2018; Ghosh and others, 2018). From this observation, Gupta and others (2013) correlated three elastic petrotype groups (containing high, intermediate, and low TOC) in the Woodford Shale, determined by core measurements and well logs, to seismic data in order to estimate brittle versus ductile rock properties and identify potential areas with natural fractures and high "fracability".

Gas and Oil Production from the Woodford Shale

Gas Production: The first recorded Woodford Shale gas well in Oklahoma is the Magnolia Petroleum Company 2 L.M. Bumpass well (API 35-019-76014; Section 33, Township 1 South, Range 3 West) in Carter County, Oklahoma, completed in June 1926. Most early Woodford Shale well completions are commingled with adjacent formations. A total of 22 Woodford Shale-only gas wells, most as old well workovers or recompletions, were completed in Oklahoma from 1926 to 1995. The earliest Woodford Shale oil well in Oklahoma is the Carter Oil Company 1 P. Phillips well (API 35-133-05194; Section 18, Township 6 North, Range 8 East) in Seminole County, Oklahoma, completed in March 1928. Andrews (2009, figure 9) included a map showing oil and gas Woodford Shale well completions in Oklahoma from 1934 to 2009.

In Oklahoma, gas production is reported for individual wells to the Oklahoma Corporation Commission while oil/condensate production is reported for each lease. Therefore, cumulative gas production data by well are accurate but cumulative oil/condensate production data are only accurate from single-well leases. Cumulative oil/condensate production from multiple-well leases is reported as the total from all producing wells and production from individual wells on a given lease cannot be deciphered from this total. For example, oil production is reported for a lease located in Wagoner County, Oklahoma, that includes two Woodford Shale well completions (1. Resource Development Technology 18-11R Dunkin, API 35-145-22949, Section 18-Township 17 North-Range 18 East; 2. Resource Development Technology 18-5H Clark, API 35-145-22967, Section 18-Township 17 North-Range 18 East) as well as wells completed in the Pennsylvanian-age Dutcher sand, but the Woodford Shale wells only produced gas (verified by the operator).

The modern Woodford Shale "gas-shale" play started in 2004 in the western part of the Arkoma Basin in an area where the Woodford is >100 ft (30 m) thick and in the dry gas window (>1.4% VR_o). At the time it was speculated that parts of the oil window ("black oil"; <1% VR_o) should be avoided because liquid hydrocarbons might plug the already low permeability and block the flow of methane in shale reservoirs (Cardott, 2005, 2006; Hill and others, 2007; Jarvie and others, 2007), and that the best thermal maturity for higher gas flow was

>1.4% VR_o. As operators drilled more and more wells into the oil window, it became apparent that shales could also produce oil and condensate (Boak and Kleinberg, 2016, 2020).

Woodford Shale play maps for the Arkoma, Ardmore, and Anadarko Basins are available at EIA (2011b). An Oklahoma shale-gas and tight-oil completions database (Appendix 2), based on the Oklahoma Corporation Commission 1002A completions report, contains 5,866 records of shale-gas and tight-oil completions. These are listed from oldest to youngest with geologic age and numbers of completions in parentheses, and include Sylvan Shale or Sylvan/Woodford (Late Ordovician; 22 completions), Arkansas Novaculite (Devonian-Mississippian; 3 completions), Woodford Shale (Late Devonian-Early Mississippian; 5,533 completions), Caney Shale (Mississippian; 115 completions), Caney Shale/Woodford Shale (28 completions), Barnett Shale (Mississippian; 2 completions), Goddard Formation (lower Springer shale; Late Mississippian; 160 completions), Atoka Group shale (Early Pennsylvanian; 1 completion), and Middle Pennsylvanian-age shales (Excello [1 completion]; Nuyaka/Mulky/Oakley [1 completion]). Figure 30 shows all shale-well completions (1926-2020) from the database (completion dates from June 22, 1926 to June 2, 2020). Most (94%) of the well completions are in the Woodford Shale.

Figure 31 shows the distribution of Woodford Shale gas and tight-oil wells by year from 2004-2020. Woodford Shale wells drilled in 2020 were in the Anadarko, Ardmore, Arkoma, and Marietta Basins. Figure 32 shows 5,505 Woodford Shale-only vertical and horizontal/directional wells completed in Oklahoma from 2004 to 2020. The wells plotted in Figure 31 and Figure 32 exclude Woodford Shale wells with commingled production from other formations. The earliest Woodford Shale wells drilled in the Arkoma Basin were vertical completions. Once the depth and thickness of the Woodford Shale was determined by vertical drilling, horizontal wells later became the preferred drilling method. Of the 5,505 Woodford Shale well completions from 2004-2020, 93% (5,096 wells) are horizontal/directional wells and 7% (409 wells) are vertical wells. Of the 5,505 Woodford Shale well completions from 2004-2020, 32% (1,763 wells) are classified as oil wells based on a gas-to-oil ratio <17,000:1.

Initial exploration intentionally targeting the Woodford Shale was a gas-shale play in the western Arkoma Basin. The first Woodford Shale gas-shale well (post 2003) in Oklahoma was the Newfield Exploration Mid-Continent Inc. 2-10 Lambert vertical well (API 35-121-23222, Section 10, Township 5 North, Range 12 East) completed in August 2004 in Pittsburgh County, Oklahoma, in the Arkoma Basin. The reported initial potential gas rate was 539 thousand cubic feet of gas per day (Mcfd) (cumulative gas production of 465 million cubic feet of gas (MMcf) from August 2004 to June 2020). The early gas flow rate decline from the initial potential rate in Woodford Shale gas-shale resource wells is partly related to the placement and number of proppant stages in brittle vs. ductile beds as discussed by Slatt and others (2018a).

The shallowest original (non-workover) vertical Woodford Shale well was the 51 Gas LLC 1 Frailey well (API 35-097-21712, Section 36, Township 20 North, Range 18 East) in Mayes County, Oklahoma, completed in May 2014 at a depth of 370 ft (113 m). The reported initial potential gas rate was 30 Mcfd. The Frailey well produced a cumulative gas total of 71,885 Mcf from November 2015 to November 2020. The deepest original vertical Woodford Shale well in the Arkoma Basin was the Sedna Energy 1-22 S.R. Phipps well (API 35-121-23640, Section 22, Township 3 North, Range 13 East) in Pittsburg County, Oklahoma, completed in October 2006 at a depth of 12,484 ft (3,805 m; initial potential gas rate of 10 Mcfd with no reported production).

The first horizontal Woodford Shale well in Oklahoma was the Newfield Exploration Mid-Continent Inc. 3H-9 Blevins well (API 35-121-23311, Section 9, Township 5 North, Range 12 East) in Pittsburg County, Oklahoma, in the Arkoma Basin completed in April 2005 with a true vertical depth of 7,265 ft (2,214 m). The well initially produced 462 Mcfd from an 834 ft (254 m) lateral and produced 910 MMcf from March 2005 until June 2020. The first Woodford Shale extended horizontal lateral (covering two or more sections) >10,000 ft (3,050 m) was the Newfield Exploration Mid-Continent Inc. 1H-17E Keen well (API 35-063-24256, Section 29, Township 5 North, Range 11 East) in Hughes County, Oklahoma, completed in December 2009 with a lateral length of 10,105 ft (3,080 m). The horizontal Woodford Shale well with the highest initial potential gas rate in the Arkoma Basin was the Newfield Exploration Mid-Continent Inc. 1H-12XX Payden well (API 35-121-24762, Section 24, Township 5 North, Range 13 East) in Pittsburg County, Oklahoma, completed in November 2015 at 17,863 Mcfd (cumulative gas production of 9,372 MMcf from November 2015 to June 2020). The horizontal Woodford Shale well in Oklahoma with the highest initial potential gas rate is the

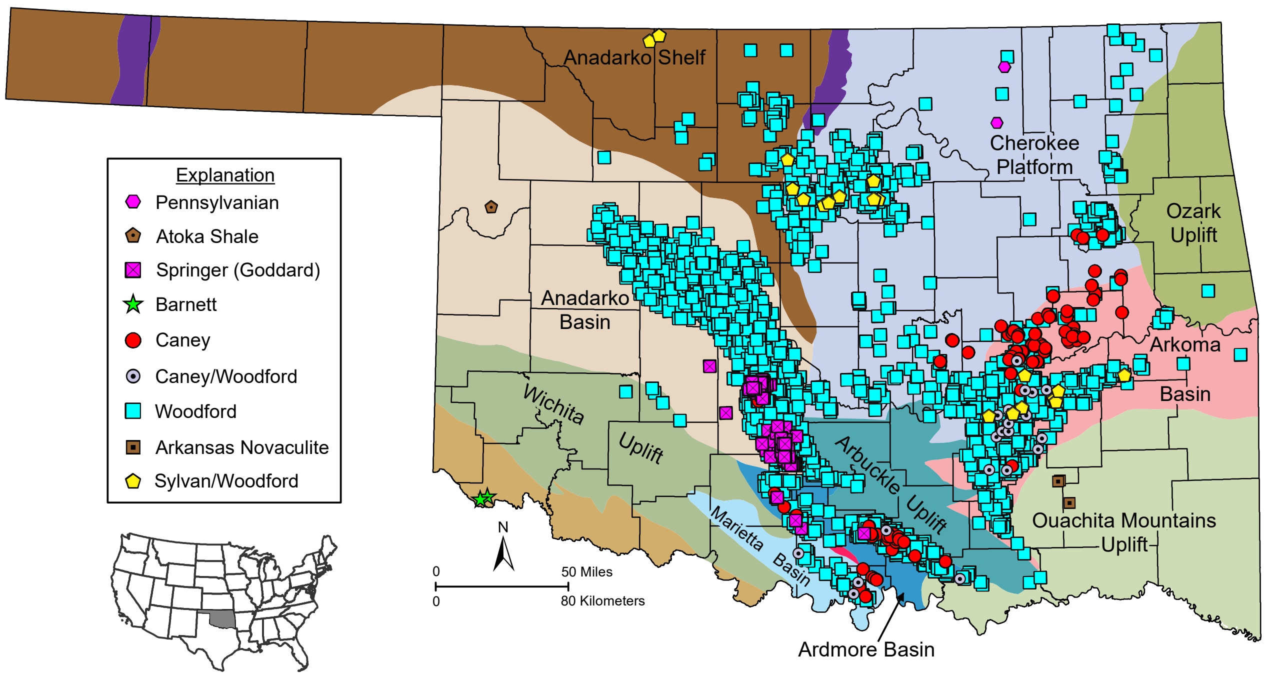

Figure 30. Geologic provinces map (Figure 1) showing Oklahoma shale-gas and tight-oil well completions (1926–2020) from data in Appendix 2.

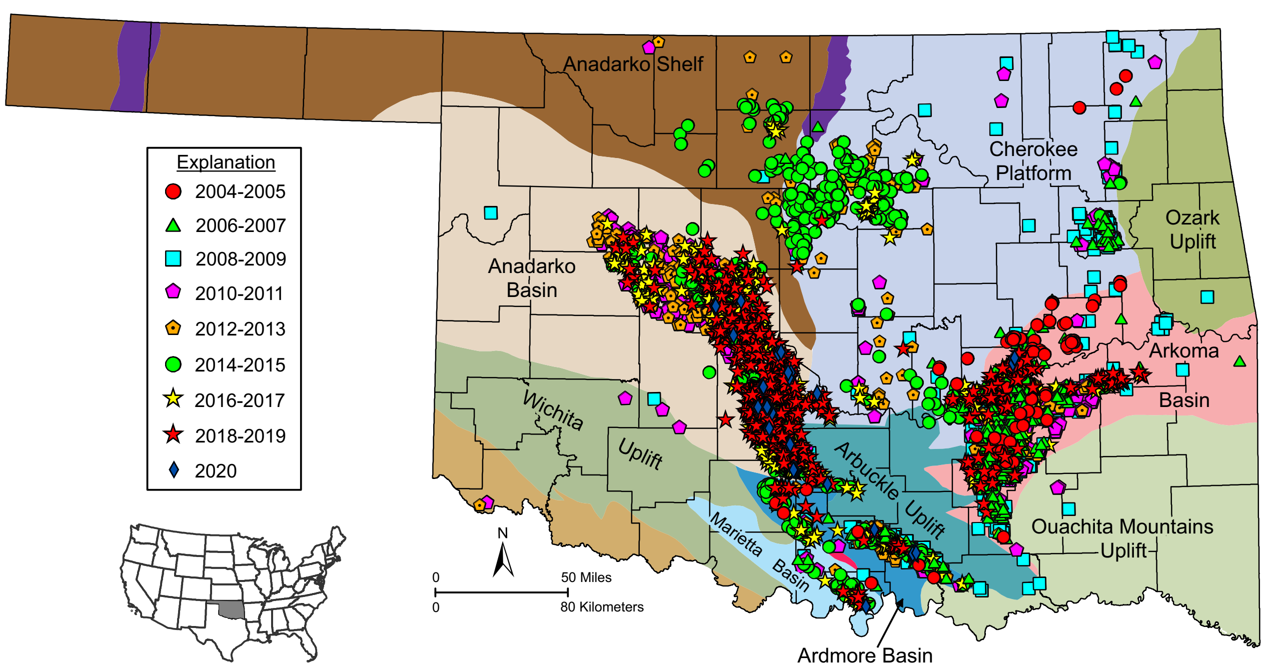

Figure 31. Geologic provinces map showing 5,505 Woodford Shale-only gas and oil well completions (2004–2020) by year from data in Appendix 2. Year 2020 wells are the top layer and older well symbols are arranged from oldest (top) to youngest (bottom).

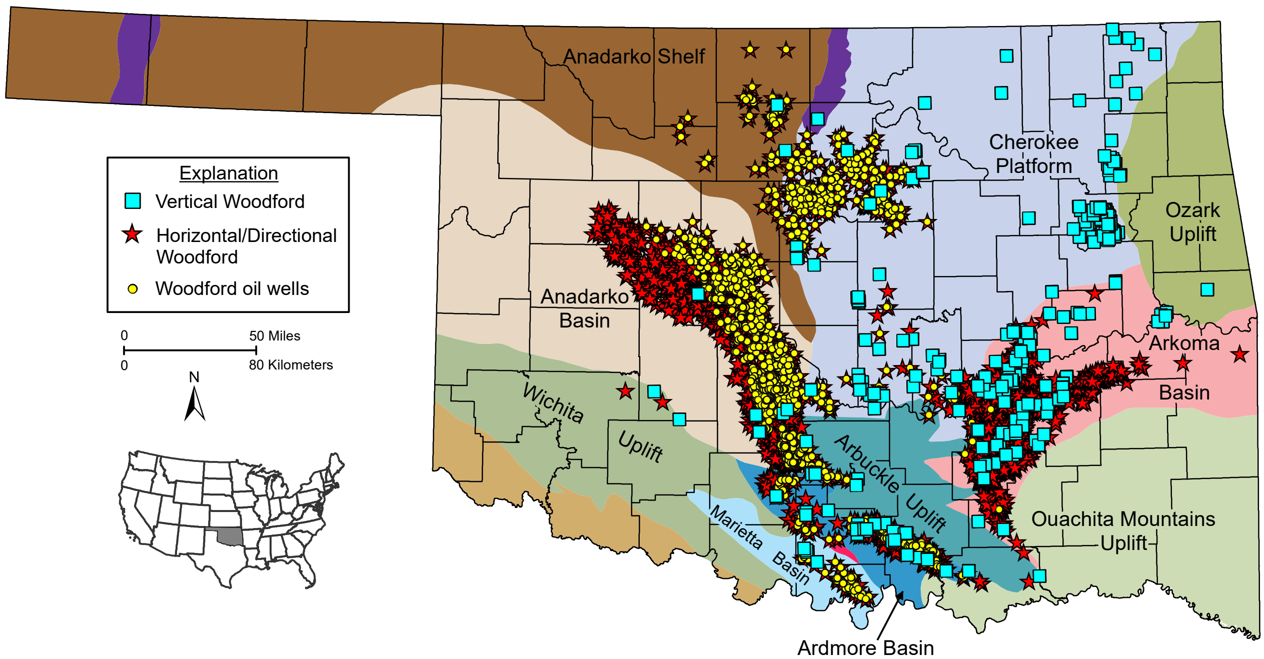

Figure 32. Geologic provinces map showing 5,505 Woodford Shale-only gas and oil well completions (2004–2020) by well type from data in Appendix 2.

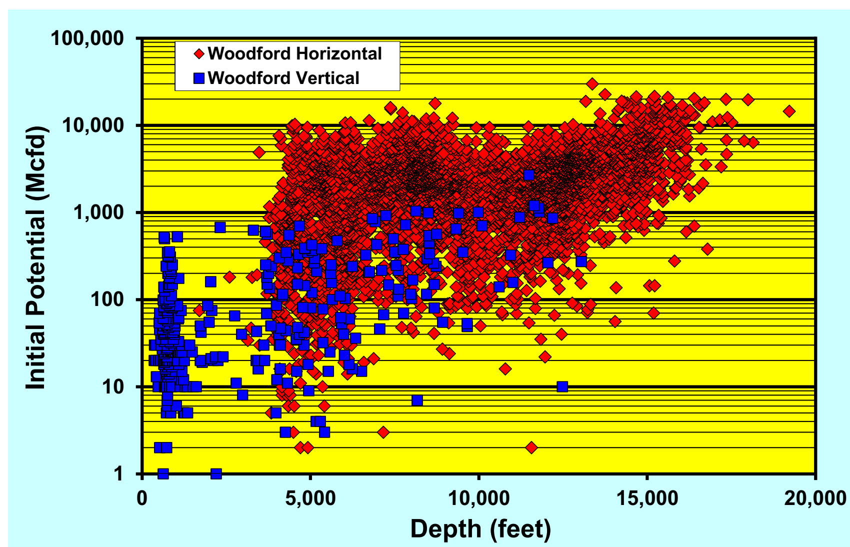

Figure 33. Chart showing initial potential gas rate vs. Woodford Shale true vertical depth (5,001 horizontal wells; 340 vertical wells) from data in Appendix 2.

Continental Resources Inc. 1-6-7XHW Simba well (API 35-011-23940, Section 6, Township 14 North, Range 12 West) in Blaine County, Oklahoma, in the Anadarko Basin completed in August 2018 with a true vertical depth of 13,371 ft (4,075 m); the well initially produced 29,847 Mcfd from a lateral of 9,818 ft (2,993 m; cumulative gas production of 14,100 MMcf from October 2018 to June 2020). True vertical depths of Arkoma Basin Woodford Shale wells range from 1,045 ft (319 m) (vertical well; Little Bear Resources 1-15 Stuber Trust well, API 35-005-20382, Section 15, Township 3 South, Range 9 East, adjacent to the Arbuckle Uplift in Atoka County, Oklahoma) to 13,810 ft (4,209 m) (horizontal well; Newfield Exploration 1H-19 Couch well, API 35-005-20430, Section 18, Township 2 North, Range 13 East; Atoka County).

Figure 33 shows initial potential gas rate vs. Woodford Shale true vertical depth (5,001 horizontal wells; 340 vertical wells) for the entire state. Initial potential gas rates range from a trace to 29,847 Mcfd for well depths that range from 368 to 19,218 ft (112 to 5,858 m). The highest initial potential gas rates were from horizontal wells. Many horizontal Woodford Shale wells include a pre-perforated liner for wellbore stability.

Oil Production: The early analog for producing oil directly from organic carbon-rich shale was the Bakken Formation in the Williston Basin. Oil production from the Bakken Formation began in the 1950s and the first horizontal Bakken oil well was drilled in the late 1980s (Nordeng, 2010). The current Bakken tight-oil play developed in Montana beginning in 2003 (Stark and Smith, 2017; Sonnenberg and others, 2017). The decline in the price of natural gas beginning in 2008 redirected operators in gas-shale plays to look for liquid hydrocarbons (oil and condensate; Kulkarni, 2012; Pickett, 2013; Pish and Killian, 2012; Stark and Smith, 2017). Hester and others (1990b) recognized the Woodford Shale as a potential "Bakken-type" horizontal target in the Anadarko Basin.

By 2007 the focus in the Woodford Shale play had shifted from gas production in the Arkoma Basin to more liquid-rich areas in the Anadarko Basin, Anadarko Shelf, Ardmore Basin, and Cherokee Platform of north and central Oklahoma (Figure 31). Caldwell (2011) showed a thickening of the Woodford Shale to more than 250 ft (76 m) thick along the eastern flank of the Anadarko Basin in western Canadian County, Oklahoma. The combination of thick shale hydrocarbon source rock in the condensate window at vertical depths less than 15,000 ft (4,600 m) led Devon Energy to develop the "Cana" play in western Canadian County, Oklahoma, beginning in 2007 with the 1-36H Hancock well (API 35-017-23972, Section 36, Township 13 North, Range 10 West; Haines, 2017). The Cana play expanded northwestward in 2009 into southern Blaine and southeastern Dewey Counties where the Woodford Shale thins from greater than 200 ft (60 m) to less than 100 ft (30 m) thick (Plate 2).

Continental Resources developed the oil- and condensate-rich South-Central Oklahoma Oil Province (SCOOP) (Figure 12) including both the Woodford Shale and Springer/Goddard shale in Carter, Garvin, Grady, and Stephens Counties, Oklahoma, beginning in 2012 (Redden, 2013; Cardott, 2017; Pickett, 2017, 2019). The SCOOP play includes the deepest horizontal Woodford Shale completion at a true vertical depth of 19,218 ft (5,858 m; Gulfport Midcon LLC 7R-12X13H Cleburne well, API 35-051-24227, Section 12, Township 4 North, Range 7 West, in Grady County, Oklahoma, completed in May 2018 with initial potential rates of 14,498 Mcfd and 2 barrels of condensate per day). The Continental Resources Inc. 1-25-24-13XH Romanoff well (API 35-051-24076, Section 25, Township 7 North, Range 5 West), in Grady County completed in April 2017, is the horizontal Woodford Shale well with the longest lateral length of 14,921 ft (4,548 m) at a true vertical depth of 10,762 ft (3,280 m) (initial potential gas rate of 1,894 Mcfd [cumulative gas production of 1.07 BCFG] and initial potential oil rate of 1,006 barrels of oil per day [bopd] [cumulative oil production of 524,870 barrels] through April 2020).

Newfield Exploration Mid-Continent Inc. developed the Sooner Trend (oil field) Anadarko (basin) Canadian Kingfisher (counties) (STACK) play (Figure 12) (including parts of the Woodford Shale Cana play) in the Meramec Lime (correlated to lower Caney Shale and upper Sycamore Limestone; Figure 2), Osage Lime (correlated to Sycamore Limestone), and the Woodford Shale beginning in 2013 (Cullen, 2017; Hart Energy, 2017; Pickett, 2014, 2017, 2019; Miller and others, 2019; Price and others, 2020). According to IHS Energy (2015, 1/23/2015 news), "The Meramec in the area is approximately 275-475 ft [84-145 m] in thickness with 3-6% porosity. The Woodford ranges from about 200 to 300 ft [60 to 90 m] thick and has porosity of 3-7%." The Meramec Lime immediately overlies the Osage/Sycamore/Woodford formations and underlies or is partly equivalent to the Caney Shale (Redden, 2015; Miller and others, 2019).

The Merge play (Figure 12) developed by Jones Energy, Inc. includes the Woodford Shale and Meramec/Sycamore in Canadian, Grady, and McClain Counties and began in 2016 between the SCOOP and STACK regions (Cullen, 2017; Stoneburner, 2017; Toon, 2017; Presley and others, 2017; Slatt and others, 2018a; Milad and others, 2020). Newfield Exploration developed the SCORE (Sycamore Caney Osage Resource Expansion) play in 2017 to test the Sycamore and Caney in the SCOOP and Osage in the STACK (Hart Energy, 2017; Presley and others, 2017).

Condensate production often begins months after the well is drilled and completed. Cardott (2012a) used liquid-hydrocarbon (including both oil and condensate) production data to differentiate between Woodford Shale wells that produce condensate and those that produce dry-gas. Production data was confirmed by the operator to be from a single well lease that was not commingled with another formation. Liquid hydrocarbon production during the first few months from higher thermal maturity (>1.4% VR_o) wells was interpreted as oil-based drilling fluid flowback. Liquid hydrocarbon samples from these wells are not available to confirm that the early production is oil-based drilling fluid. Cardott (2012a) showed that a Woodford Shale well in the Arkoma Basin (St. Mary Land & Exploration Company 3-14 Marvin well, API 35-029-20942, Section 14, Township 1 North, Range 10 East) with condensate production (verified by a condensate sample) had a vitrinite reflectance of 1.67% VR_o based on a vitrinite-reflectance analysis of cuttings samples (OPL 1373). This is the highest reported thermal maturity for a

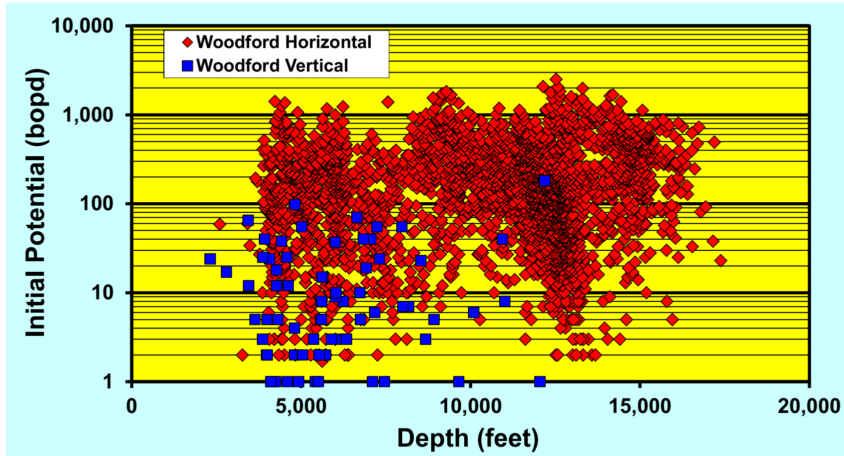

Figure 34. Chart showing initial potential oil/condensate rate vs. Woodford Shale true vertical depth (3,081 horizontal wells; 69 vertical wells) from data in Appendix 2.

Woodford Shale well that produced condensate. Jarvie and others (2007) reported a vitrinite reflectance of 1.67% VR_o for a Barnett Shale well (Mitchell Energy Corporation 2 Sims) that had condensate production (Dan Jarvie, personal communication, 3/17/2021). However, condensate production from shales with thermal maturity greater than ~1.50% VR_o is not consistent with Jarvie and others (2005) hydrocarbon generation stages nor with the hydrocarbon assessment guide presented in Figure 25. Condensate production from Woodford Shale wells in the western Arkoma Basin with thermal maturities >1.40% VR_o could be the result of migration from lower thermal maturity Woodford source rocks into higher thermal maturity Woodford reservoirs following uplift. Therefore, Woodford Shale sections with VR_o values >1.40% should be considered as potentially prospective for migrated hydrocarbons if they are in the appropriate geologic setting.

Figure 34 shows initial potential oil/condensate rate vs. Woodford Shale true vertical depth (3,081 horizontal wells; 69 vertical wells). Initial potential oil/condensate rates range from a trace to 2,505 barrels of oil per day (bopd). The well with the highest initial potential oil/condensate rate of 2,505 bopd is Newfield Exploration 5H-7X Williams (API 35-049-25040, Section 6, Township 2 North, Range 3 West, Garvin County, Oklahoma; cumulative oil production of 143,574 barrels of oil from August 2015 to May 2020). Depths of oil/condensate producing wells in Figure 34 range from 2,320 to 17,384 ft (707 to 5,299 m). The highest initial potential oil/condensate rates were from horizontal wells. Three Newfield Exploration wells (3H-7X Williams, API 35-049-25051; 1H-5XX Hays, API 35-049-25027; 5H-7X Williams, API 35-049-25040) with the highest initial potential oil rates of 2,060-2,505 bopd (44-47° API oil gravities) were in Township 2 North, Range 3 West in Garvin County, Oklahoma, from a true vertical depth of 12,139-12,572 ft (3,700-3,832 m) at an estimated thermal maturity of 1.1% VR_o (see OPL 1478).

Cardott (2013a) developed maps of well locations coded for the initial potential values together with isoreflectance contours in order to create Woodford Shale liquid hydrocarbon production maps in the context of thermal maturity. Using the same approach, Figure 35 shows initial potential oil and condensate production from Woodford Shale wells. The boundary between condensate and natural gas (black circles) wells occurs at ~1.4-1.5% VR_o. Some of the oil produced from Woodford wells having high IP oil rates >700 barrels (red stars) in north-central Oklahoma may come through fracture connections from adjacent formations. Woodford Shale wells at the peak of the oil window (~0.9% VR_o) in Wagoner County, Oklahoma, produce only natural gas (microbial and thermogenic). Assuming that the bulk organic matter is Type II kerogen (which has not been analytically confirmed), the lack of oil production from these mature source beds may be due to poor fracture development resulting from the absence of biogenic quartz as discussed above and the consequent low permeability inhibiting the flow of oil.

Reported oil gravities range from 21 to 79 API degrees. Based on Woodford Shale completion reports, 49 API degrees is the approximate boundary between oil and condensate. Figure 36 shows Woodford Shale API gravities reported by the operator to delineate oil (<49°) and condensate (≥49°). Of 2,212 Woodford oil wells reporting API gravity, 1,171 had <49° oil gravity and 1,041 had ≥49° oil gravity. For the most part, the thermal maturity limit of condensate is 1.4-1.5% VR_o. With few exceptions only natural gas is produced at higher thermal maturities.

CONCLUSIONS

Woodford Shale is both a world-class hydrocarbon source rock and a commercial unconventional oil and gas reservoir. Based on conodont and microspore assemblages, most of the Woodford Shale is Late Devonian (Fras-

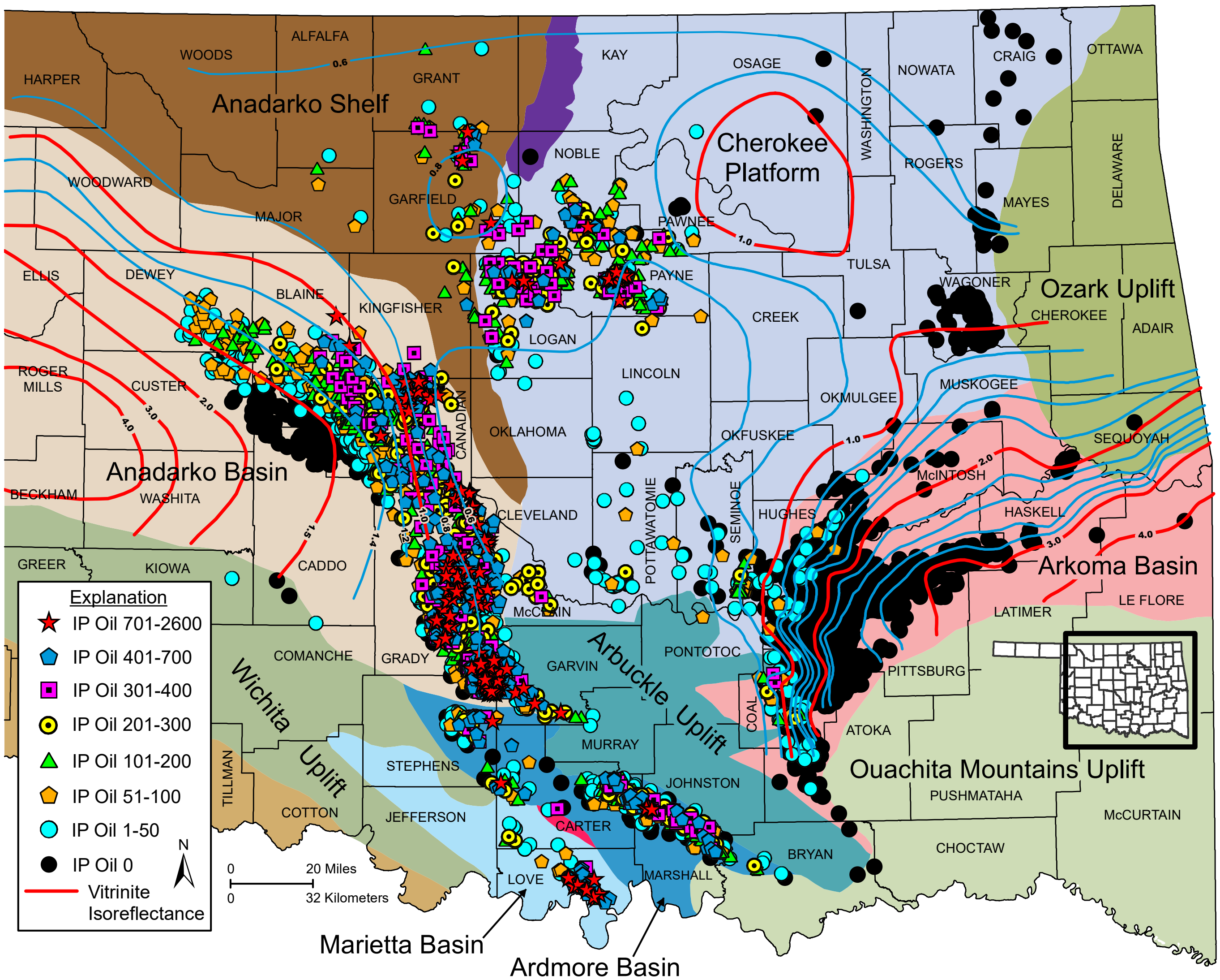

Figure 35. Geologic provinces map showing 5,505 Woodford Shale-only initial potential oil/ condensate rates from data in Appendix 2. Note that “IP Oil” in the explanation includes both oil and condensate. Vitrinite isoreflectance contours are from Plate 3.

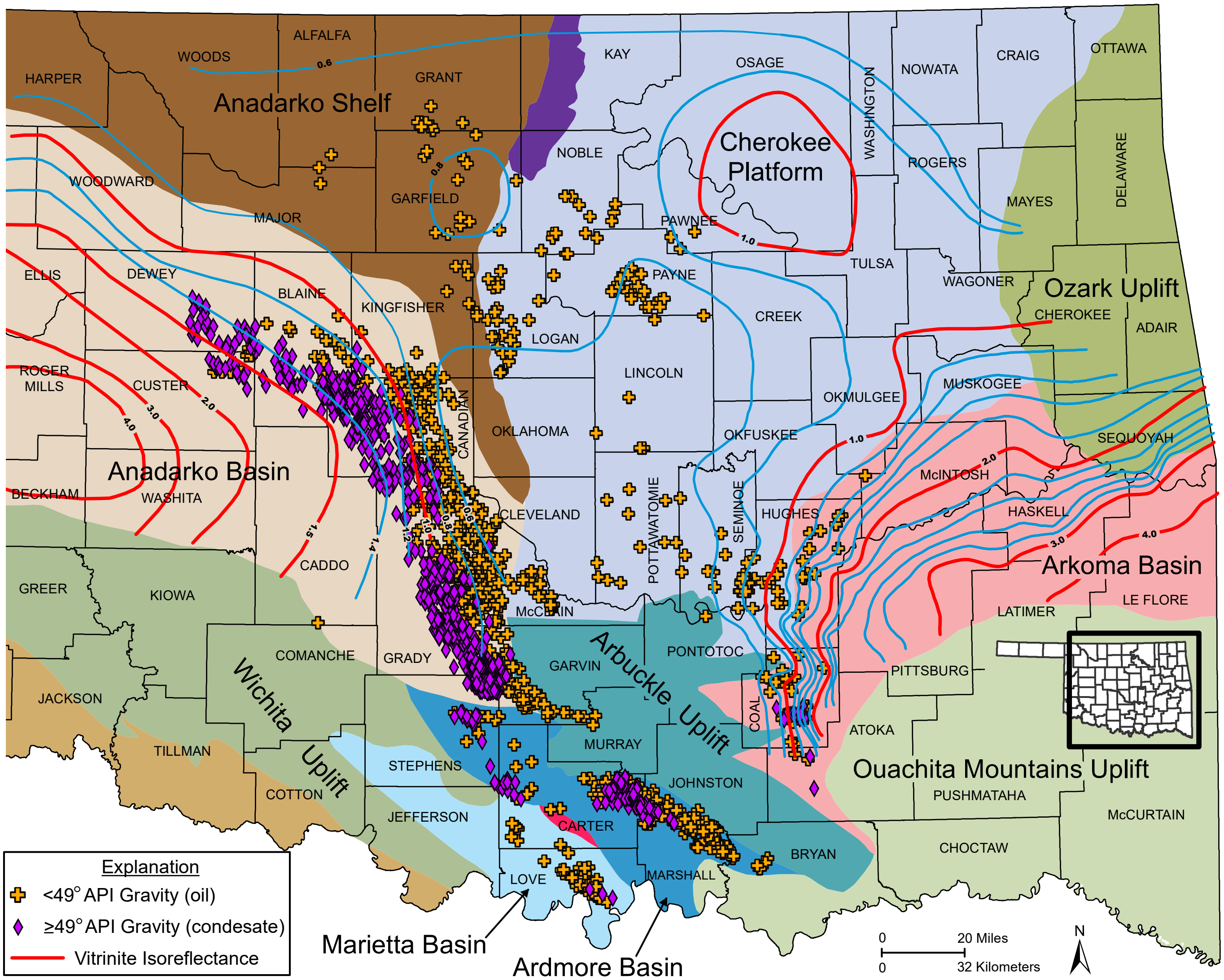

Figure 36. Geologic provinces map showing 2,212 Woodford Shale-only wells that produce oil (<49° API gravity) and condensate (≥49° API gravity) from data in Appendix 2. Vitrinite isoreflectance contours are from Plate 3.

nian-Famennian) in age and locally the uppermost part is Early Mississippian (Kinderhookian). The basal Misener sandstone is late Middle to Late Devonian in age (Givetian to Famennian) and the Sylamore sandstone, which is present in northeastern Oklahoma, is late Middle Devonian to late Kinderhookian. The characteristic Woodford Shale lithology is fine-grained, organic carbon-rich mudrock. Composition varies from clayey to siliceous mudrock with lesser amounts of dolomitic mudrock. The basal sandstones (Misener and Sylamore members) are present in limited areas of northern and central Oklahoma and consist of well sorted and well-rounded quartz grains that were derived with little modification from nearby Middle Ordovician sandstone that was exposed along the Ozark Uplift during the Late Devonian. Except for these basal units, sand-sized detrital quartz grains are notably absent from Woodford Shale.

Woodford Shale is present throughout most of Oklahoma and is locally absent in southwestern Oklahoma and parts of northern and central Oklahoma. The Woodford Shale occurs at maximum subsea depths >16,000 ft (4,900 m) in the Ardmore Basin, >17,000 ft (5,000 m) in the Arkoma Basin, and >24,000 ft (7,300 m) in the Anadarko Basin. In general, the Woodford Shale thickens from <25 ft (8 m) thick on the Anadarko Shelf and Cherokee Platform to >700 ft (200 m) thick in the southeastern Anadarko and Marietta basins, to >400 ft (120 m) in the Ardmore Basin, and to >250 ft (76 m) in the Arkoma Basin.

The anomalously high radioactivity of Woodford Shale makes it easy to identify on gamma-ray logs. Most of the high gamma-ray signal is caused by unusually high concentrations of uranium. High concentrations of uranium indicate strongly reducing conditions and slow sedimentation. Numerous authors have used the gamma-ray log, along with other log characteristics and lithologic variables, to divide the Woodford Shale into three informal members (Figures 3, 4, and 6). The lower member contains plant megafossils and has intermediate radioactivity, density, and resistivity; the middle member contains the most resinous spores and the least pollen and exhibits the highest radioactivity and resistivity and the lowest density; and the upper member has the lowest TOC, radioactivity, and resistivity and the highest density. The top of the middle member is picked above the double gamma-ray peak (Figure 4), which is recognizable over much of Oklahoma. All three members are composed of thin beds and thin laminae of organic carbon-rich mudstones that are highly variable in composition.

The depositional environment has been interpreted by a significant number of researchers as follows: near-shore marine in the lower member (consistent with the occurrence of plant megafossils and the greater abundance of vitrinite derived from woody organic matter from the progymnosperm *Archaeopteris*), distal marine in the middle member (consistent with a low pollen index), and near-shore marine in the upper member. However, the absence of tabular sand bodies (e.g., sand-dominated shoreface deposits) in the Woodford Shale prevent the identification of paleoshorelines based on traditional grain size trends, lithologic attributes, and terrestrial sediment source proxies, thus obscuring the generally applied meaning of terms such as near-shore or proximal and off-shore or distal for this stratigraphic interval. Transport of fine-grained detritus by wind and storm-generated currents, processes interpreted to have dominated during Woodford Shale sedimentation, would allow terrigenous components to spread widely across the region far from their original source. In such a setting, intervals with greater proportions of fine-grained terrigenous detritus may not be nearer to a paleoshoreline than intervals with greater proportions of marine components, a situation further complicated by episodes of resuspension and resedimentation that occurred frequently throughout the region.

Woodford Shale overlies a major regional unconformity and the age of the underlying strata, ranging mostly from Ordovician to late Early Devonian, is related to the extent of erosion into the pre-Woodford unconformity surface. Woodford Shale sequence stratigraphy includes a basal erosional sequence boundary, transgressive system tract in the lower and most of the middle Woodford Shale members, condensed section/maximum flooding surface at the highest gamma-ray reading (plotted full scale) in the upper middle member, and highstand system tract during major sea level regression in the upper middle and upper Woodford Shale members (Figure 6). This sequence stratigraphic interpretation for the Woodford Shale in Oklahoma is generally consistent with global sea level curves developed based on lithologic and high-resolution biochronological studies from many locations around the world (Figure 7). However, placement of the Frasnian/Famennian boundary in each of the three Woodford Shale members by different researchers shows that regional correlations are poorly constrained. Intraformational Woodford correlations are mostly based on electric log characteristics, lithology, and chemostratigraphic proxies and are not based on the well documented, high resolution biochronological data that characterize the global sequence because Woodford Shale is generally lacking in fossils.

A wide variety of minerals have been identified in Woodford Shale but quartz is typically the dominant mineral and mostly occurs together with highly variable amounts of illite. Quartz is present as silt- and clay-sized detrital grains and as chert of biologic origin. Biogenic chert forms during early diagenesis from the alteration of siliceous microorganisms (mostly Radiolaria), and intervals with high concentrations of biogenic quartz are more brittle than intervals with detrital quartz supported in a ductile clay matrix. Naturally fractured, organic-rich Woodford Shale intervals composed of biogenic chert are the producing zone in conventional vertical wells located in Carter and Marshall Counties that have produced oil at low volumes for many decades. Recent unconventional exploration and applied research confirm that the brittle biogenic chert intervals are the optimum lithology for hosting and maintaining natural and induced fractures. The brittle chert-rich lithology also has a greater concentration of natural fractures which improves permeability in the Woodford Shale, resulting in better well performance.

Woodford Shale sediments were deposited in an epeiric sea that extended along a west to southwest facing passive continental margin during the Late Devonian. Plate tectonic reconstructions for this time period place Oklahoma at a low southern latitude in the warm, arid southeasterly trade wind belt. Woodford Shale deposition began as the sea encroached over a major regional unconformity surface during a period of global warming and worldwide marine transgression. The widespread, blanket-like distribution of nearly uniform fine-grained sediment suggests a region of low relief, and the absence of deltas, submarine fans, coarse clastic wedges, large clinoforms, and sand-bearing turbidites indicate that adjacent land areas were not drained by large rivers. The deepest parts of the Late Devonian epeiric sea in Oklahoma coincided with the thickest accumulations of Woodford sediments in the Anadarko, Ardmore, and Marietta Basins. In contrast the onlap of Woodford sediments and the increased amounts of terrigenous detritus proximal to the Nemaha and Ozark Uplifts indicate that both were topographically high in the Late Devonian. Although the region was mostly tectonically stable, contemporaneous epeirogenic activity is indicated by the abrupt change in thickness of the Woodford Shale across the Central Oklahoma fault zone associated with the Nemaha Uplift and by the truncation of Woodford members and the shift of the locus of deposition from southwest to the northeast in late Woodford time across a northwest-southeast trending structure located in northwestern Oklahoma.

An arid paleoclimate is indicated by the presence of evaporite minerals (e.g., anhydrite, gypsum, length slow chalcedony, primary dolomite), biomarkers (gammacerane), and primary sedimentary structures (syneresis cracks). In addition, extensive drought conditions are suggested by a suite of biomarkers (certain polycyclic aromatic hydrocarbons) that have been attributed to paleo-wildfires. The anomalously high organic carbon concentration characteristic of Woodford Shale is due to the combined effects of high biological productivity in the upper water column and widespread anaerobic and euxinic bottom conditions. High biological productivity was supported by nutrients derived from a persistent zone of coastal upwelling along the Late Devonian continental margin, which is recorded as age-equivalent biogenic chert of the Arkansas Novaculite. Upwelled nutrients were swept into the Woodford epeiric sea with the countercurrents that maintained water balance by replacing evaporative losses and the surface water driven out of the basin by Coriolis forces and Ekman circulation.

The absence of large rivers constrains interpretations of the processes for transport and deposition of Woodford sediments. Given the dry, low relief setting, transport of the fine-grained sediment that dominates the section was accomplished mostly by wind and by storm-generated currents. Deflation of the arid landscape, limited discharge from intermittent streams, and storm-generated runoff would account for most of the terrestrial sediment contributed to the basin. These processes would also accomplish the transport of terrestrial nutrients into the basin and provide additional support for the persistent high biological productivity in the epeiric sea. Recent research on the Upper Devonian Three Forks Formation of the Williston Basin, which lay at the same southern paleolatitude as Woodford Shale, documents the significance of storms in the southern tropics during the Late Devonian. The thin varve-like laminae commonly observed in Woodford Shale represent deposition of atmospheric dust from fluctuating winds and episodic fallout of fine sediment entrained along isopycnals. The presence of abraded grains of penecontemporaneous dolomite in graded silty layers and in the basal sandstones (Misener and Sylamore members) indicates that resuspension and resedimentation were active processes throughout the region during the Late Devonian.

Hydrocarbon source rocks are evaluated based on organic matter concentration, type, and thermal maturity. Total organic carbon (TOC) content in the Woodford Shale ranges from <1 to 30 wt.% and averages >6 wt.%. TOC is highly variable both vertically and laterally. Bulk organic matter in Woodford Shale is predominantly Type II kerogen (oil generative) of marine origin. Visual kerogen analysis of low thermal maturity Woodford Shale indicates a composition of amorphous organic matter (45-95%), vitrinite, inertinite (fusinite and semifusinite), liptinite (e.g., *Tasmanites* telalginite), zooclast (e.g., acritarch), and solid bitumen macerals. The Woodford Shale is the oldest formation in Oklahoma known to contain woody organic matter (i.e., vitrinite). Thermal maturity of the Woodford Shale in Oklahoma ranges from marginally mature (0.49% VR_o) to post mature (6.36% VR_o). Depth of burial accounts for the thermal maturity throughout most of Oklahoma. Two thermal maturity anomalies in the subsurface on the Woodford isoreflectance map are located in northern Oklahoma. The greater anomaly (>1.0% VR_o) is in Osage County on the Cherokee Platform and the lesser anomaly (>0.8% VR_o) is in Garfield County on the Anadarko Shelf. Both are suggestive of igneous hot spots affecting post-Woodford alteration. Small thermal anomalies in northeastern Oklahoma have been attributed to the migration of hydrothermal fluids associated with the emplacement of Mississippi Valley-type lead-zinc deposits during the Late Paleozoic.

The combination of an excellent hydrocarbon source rock containing intervals of brittle lithology (biogenic chert) make the Woodford Shale an excellent unconventional oil and gas reservoir. Overall, the Woodford Shale has a brittle, biogenic silica-rich lithology important for hosting and maintaining natural and induced fractures. Biogenic silica, which becomes more dominant higher in the section, is associated with brittle geomechanical properties while fine-grained detrital quartz, clay, and silt predominant in the lower Woodford are associated with ductile geomechanical properties. Brittle-ductile couplets, with the brittle zone above a high TOC interval, represent the preferred target zones for successful completions. The best horizontal landing zone in the Woodford Shale in recent plays (e.g., SCOOP, STACK, southern Oklahoma) is the upper part of the middle member and the lower part of the upper member where the brittle zone overlies a high TOC interval above the maximum flooding surface.

There have been 5,505 Woodford Shale well completions (excluding wells commingled with other formations) from August 2004 to June 2020. The earliest Woodford Shale wells drilled in the Arkoma Basin were vertical completions that produced gas. Once the depth and thickness of the Woodford Shale was determined by vertical drilling, horizontal wells later became the preferred drilling method. Of the 5,505 Woodford Shale well completions, 93% (5,096 wells) are horizontal/directional wells, 7% (409 wells) are vertical wells, and 32% (1,763 wells) are classified as oil wells based on a gas-to-oil ratio <17,000:1. By 2007 the focus in the Woodford Shale play had shifted to more liquid-rich areas in the Anadarko Basin, Anadarko Shelf, Ardmore Basin, and Cherokee Platform of northern and central Oklahoma. Initial potential gas rates range from a trace to 29,847 thousand cubic feet per day, initial potential oil/condensate rates range from a trace to 2,505 barrels of oil per day, while total vertical depths range from 368 to 19,218 ft (112 to 5,858 m). Reported oil gravities range from 21 to 79 API degrees (49 API degrees is the approximate boundary between oil and condensate). Of 2,212 Woodford oil wells, 1,171 wells had <49° oil gravity and 1,041 wells had ≥49° oil gravity. For the most part, the upper limit of condensate production from Woodford Shale is 1.4-1.5% VR_o. Intervals with thermal maturities >1.67% VR_o produce only natural gas.

Woodford Shale is an excellent unconventional oil and gas play because it is a thermally mature, organic carbon-rich source rock with intervals of brittle lithology. Recent assessments by the U. S. Geological Survey estimated the mean total undiscovered hydrocarbon resources in Woodford Shale to be 29 trillion cubic feet of natural gas, 853 million barrels of crude oil, and 384 million barrels of natural gas liquids. This research highlights the potential for significantly increasing oil and gas production from the Woodford Shale in Oklahoma.

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