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U.S. Energy Information Administration

Permian Basin

Wolfcamp and Bone Spring Shale Plays

Geology review

July 2019

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Introduction

This document contains updated information and maps for the Wolfcamp and Bone Springs plays of the Permian Basin. The geologic features characterized include contoured elevation of the top of formation (structure), contoured thickness (isopach), paleogeography elements, and tectonic structures (such as regional faults and folds), as well as play boundaries, well location, and initial wellhead production of wells producing from January 2005 through September 2018.

These geologic elements are documented and integrated into a series of maps. The Permian Basin maps consist of layers of geologic and production information that users can view either as separate thematic maps (such as Figure 1) or as interactive layers of the U.S. Energy Mapping System. Data sources include DrillingInfo Inc. (DI), a commercial oil and natural gas well database, the United States Geological Survey (USGS), Texas Bureau of Economic Geology, EIA reports, peer-reviewed research papers, and academic theses.

Currently, EIA has access to well-level data, including more than 20,000 well logs from the Permian Basin, which are used for map construction. This report contains the Wolfcamp play section, including subsections on the Wolfcamp A maps in the Delaware Basin. EIA will add spatial layers for structure, thickness, and production maps as well as corresponding report sections describing major plays of the Permian Basin in the future as additional maps are created.

Permian Basin

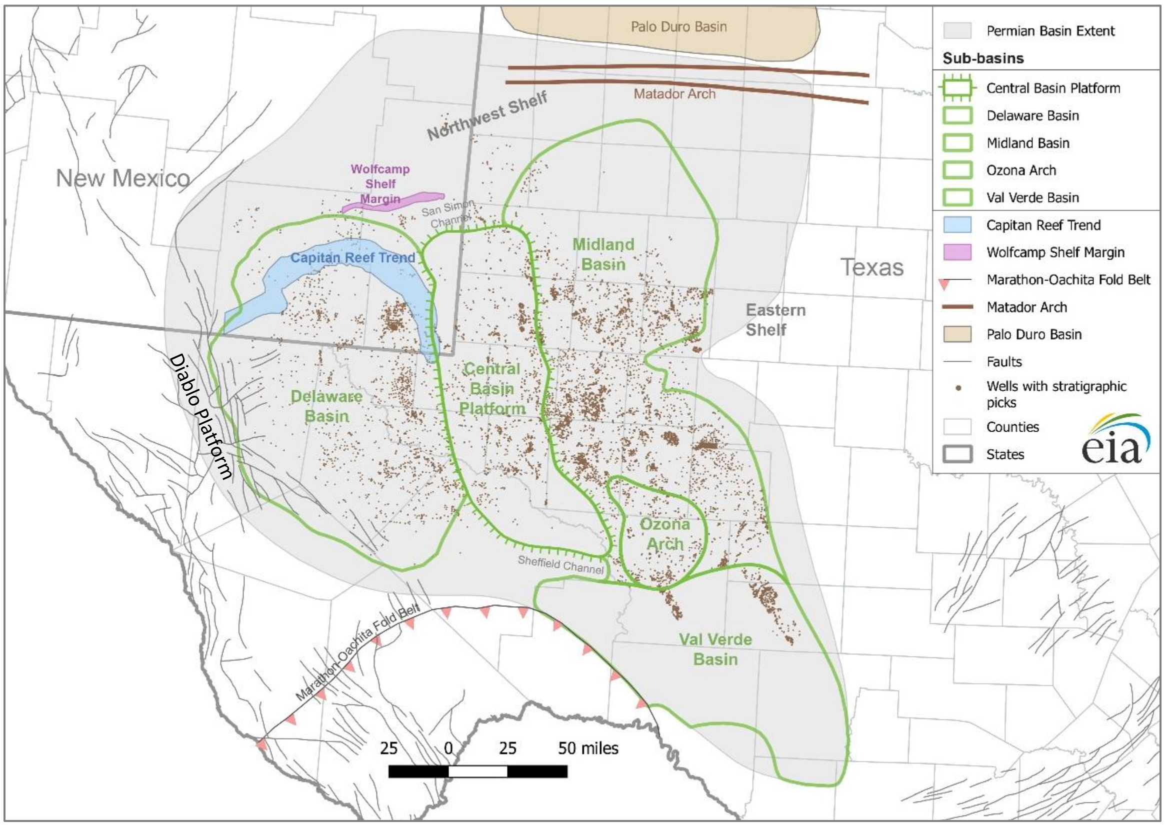
The Permian Basin of West Texas and Southeast New Mexico has produced hydrocarbons for about 100 years and supplied more than 33.4 billion barrels of oil and about 118 trillion cubic feet of natural gas as of September 2018. Implementing hydraulic fracturing, horizontal drilling, and completion technology advancements during the past decade has reversed the production decline in the Permian, and the basin has exceeded its previous production peak in the early 1970s. In **2018**, it accounted for more than 35% of the total U.S. crude oil production and about 9% of the total U.S. dry natural gas production. For **2017**, EIA estimates remaining proven reserves in the Permian Basin to exceed 8 billion barrels of oil and 27 trillion cubic feet (Tcf) of natural gas, making it one of the largest hydrocarbon-producing basins in the United States and the world (EIA, 2018).

Regional tectonic setting and geologic framework

The Permian Basin is a complex sedimentary system located in the foreland of the Marathon–Ouachita orogenic belt. It covers an area of more than 75,000 square miles and extends across 52 counties in West Texas and Southeast New Mexico. The Permian Basin developed in the open marine area known as the Tobosa Basin in the middle Carboniferous period approximately 325 million–320 million years ago (Galley, 1958). The ancestral Tobosa Basin was formed by an asymmetric structural flexure in the Precambrian basement at the southern margin of the North American plate in late Proterozoic time (Beamont, 1981; Jordan 1981). During consequent phases of basin development, sediments eroded from the surrounding highlands and were deposited in the basin (Brown et al., 1973; Dorobek et al., 1991).

The Permian Basin is now an asymmetrical, northwest to southeast-trending sedimentary system bounded by the Marathon-Ouachita orogenic belt to the south, the Northwest shelf and Matador Arch to the north, the Diablo platform to the west, and the Eastern shelf to the east (Gardiner, 1990; Ewing, 1991; Hills, 1985). The basin is comprised of several sub-basins and platforms: three main sub-divisions include the Delaware Basin, Central Basin Platform, and the Midland Basin (Figure 1).

Figure 1. Major structural and tectonic features in the region of the Permian Basin



Source: U.S. Energy Information Administration based on DrillingInfo Inc., U.S. Geological Survey.

The tectonic history of the Midland and Delaware Basins is mostly affected by uplift of the Central Basin Platform and, to a less degree, by the thrusting of the Marathon-Ouachita orogenic belt. The main phase of the basin differentiation occurred during Pennsylvanian and Wolfcampian time because of the rapid subsidence in the Delaware and Midland Basins and the uplift of the Central Basin Platform, as shown by sudden changes in thickness and lithology of Pennsylvanian to Permian strata. In the fault zone surrounding the Central Basin Platform, Strawn carbonates unconformably overlie lower to middle Paleozoic strata. This alignment is a stratigraphic indicator that the fault zone along the Central Basin Platform perimeter was tectonically active during late Pennsylvanian time. Because of deferential movements of basement blocks, uplift of the Central Basin Platform created differential subsidence and variable basin geometry in the adjacent Delaware and Midland Basins. This stage of tectonic activity lasted until the end of the Wolfcampian time, when the fast deformation and subsidence in the sub-basins stopped. However, basin subsidence continued until the end of the Permian (Oriel et al., 1967; Robinson, K., 1988; Yang and Dorobek, 1995).

The Delaware Basin is bounded to the north by the Northwestern shelf, to the south by the Marathon - Ouachita fold belt, to the west by the Diablo Platform, and to the east by uplifted areas of the Central Basin Platform separating the Delaware and Midland Basins. An echelon pattern of high angle faults with a large vertical displacement are detected along the boundaries of the Central Basin Platform, which itself is an uplifted, fault-bounded structural high that is primarily carbonate in composition and is highly faulted.

The Midland Basin is bounded to the east by the Eastern shelf through a series of north-south trending fault segments and to the north by the Northwest shelf. Southward, Midland Basin formations thin out into the Ozona Arch, an extension of Central Basin Platform, which separates the Delaware and Midland Basins (Figure 1).

Regional Stratigraphy

The age of sedimentary rocks underling the Permian system in West Texas to Southeast New Mexico ranges from Precambrian to Pennsylvanian. Typically, the oldest rocks immediately underlie Permian rocks in uplift areas such as the Central Basin Platform and the Ozona Arch. Pennsylvanian rocks are common across the Delaware and Midland Basins and on the Northwestern and Eastern shelves.

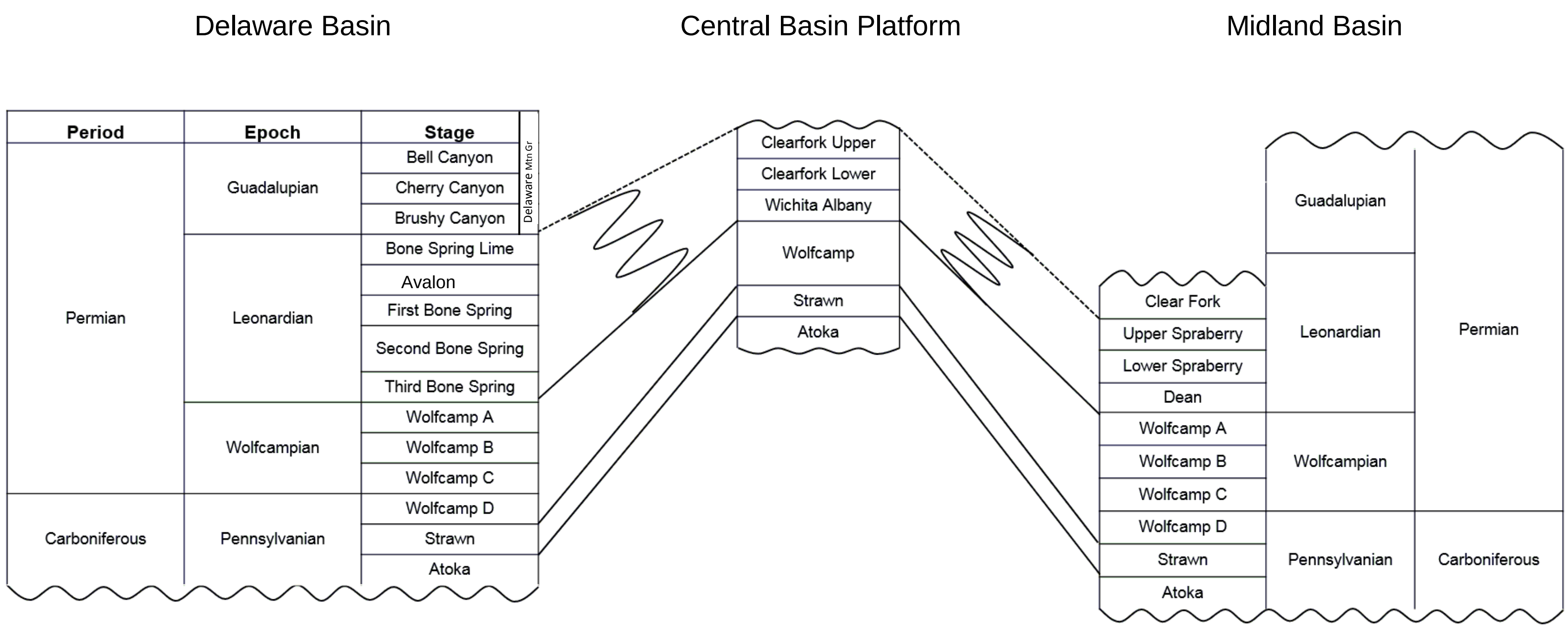
Representative stratigraphic sections of all Paleozoic systems are present and reach a maximum combined thickness in excess of 29,000 feet in the Val Verde Basin and in the southern part of the Delaware Basin. The older Paleozoic systems (Cambrian through Devonian) are found in sedimentary rocks accumulated in the ancestral Tobosa Basin, an extensive stable marine depression. The Tobosa Basin extended through the entire present day Permian Basin region. Pennsylvanian and Wolfcampian times are characteristic of a period of transition, indicated by structural deformation, differential movements, increased clastic sedimentation, and development of contemporary tectonic elements. The Permian time is mostly characterized by a long period of sedimentation ending with cessation of tectonic activity (Oriel et al., 1967; Robinson, K., 1988).

Regional stratigraphic relationships for upper Carboniferous to upper Permian strata in the Permian Basin are shown on a generalized stratigraphic schema (Figure 2) and three geologic cross sections (Figures 3–5). These cross sections indicate differences in basin geometry and the effects of differential uplift of the Central Basin Platform.

Upper Pennsylvanian and Wolfcampian strata spread across the entire Permian Basin; the thickest accumulations, however, are located in the central and southern parts of the Delaware Basin. As shown on Cross Section A (Figure 3), this stratigraphic interval quickly thins out to the Central Basin Platform, in contrast with the more gradual thickness decrease toward the western part of the Delaware Basin and eastern part of the Midland Basin.

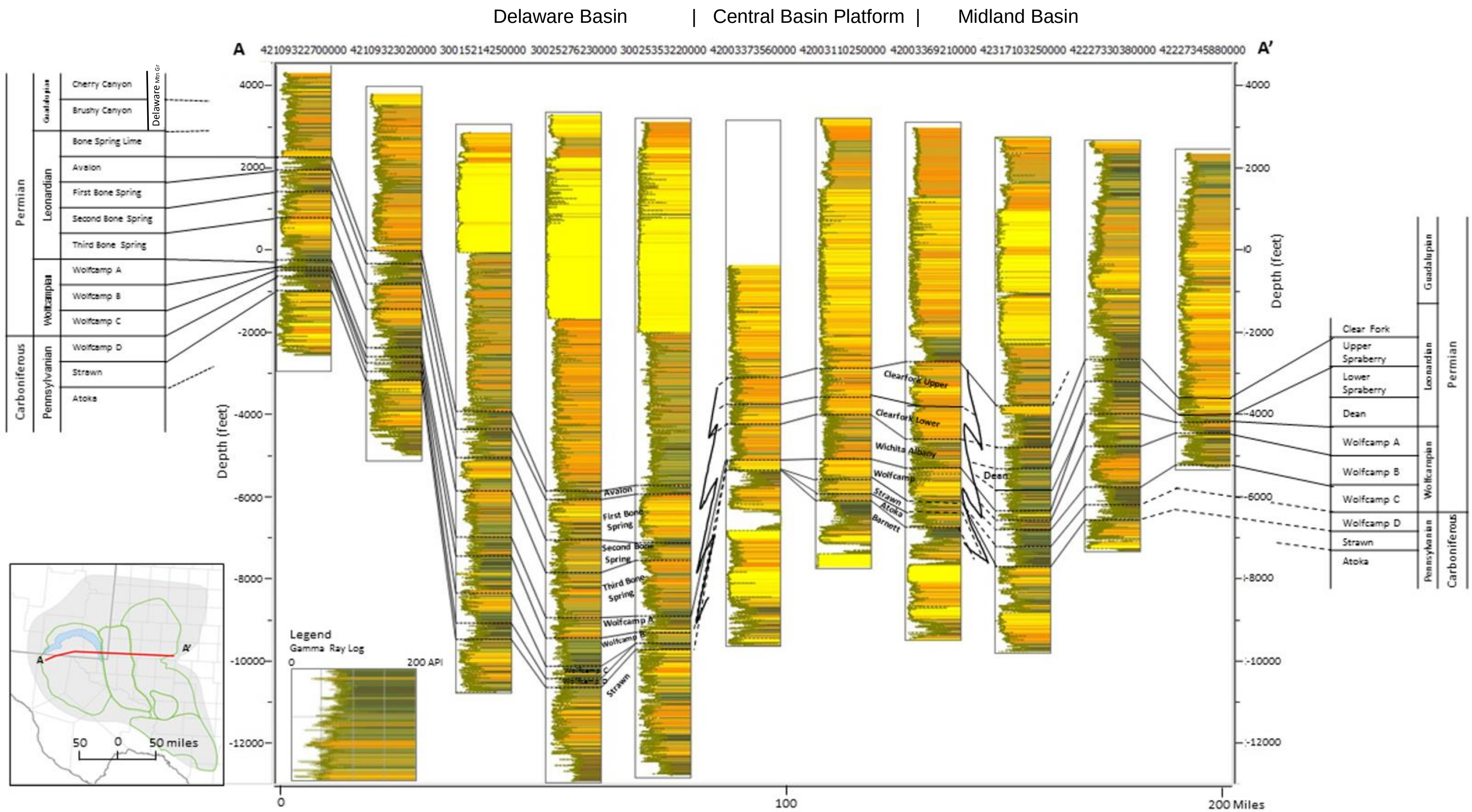
Upper Carboniferous Pennsylvanian rocks that range in thickness from 0 feet to 3,000 feet generally occur in the depth between 5,000 feet and 15,000 feet. Pennsylvanian formations, including Atoka, Strawn, and Cisco, predominantly consist of limestone, shale, and minor quantities of sandstone and

Figure 2. Generalized stratigraphic schema of upper Carboniferous through upper Permian intervals for the Permian Basin



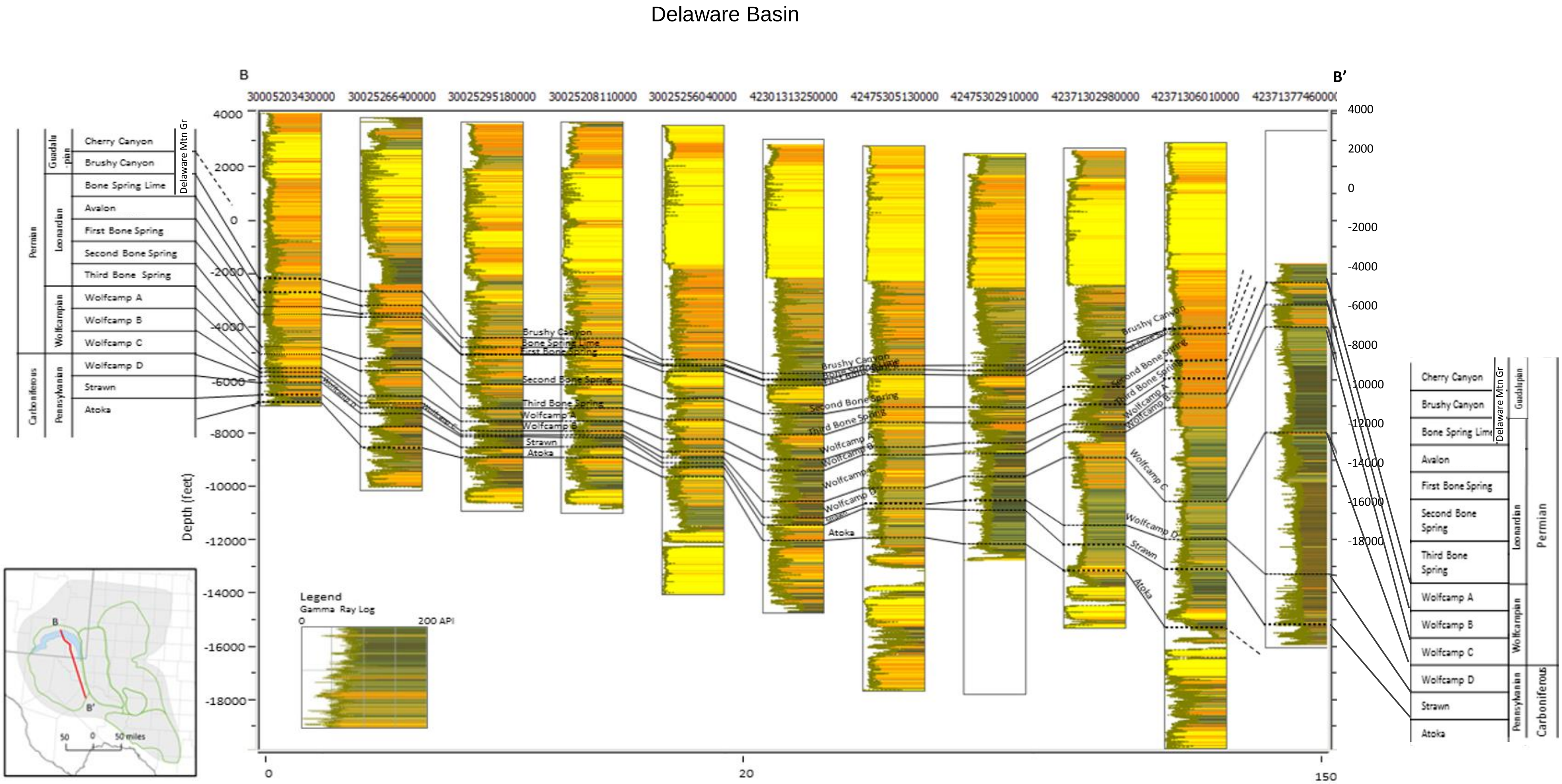
Source: U.S. Energy Information Administration based on DrillingInfo Inc., U.S. Geological Survey.

Figure 3. East to west geologic cross sections through the Permian Basin



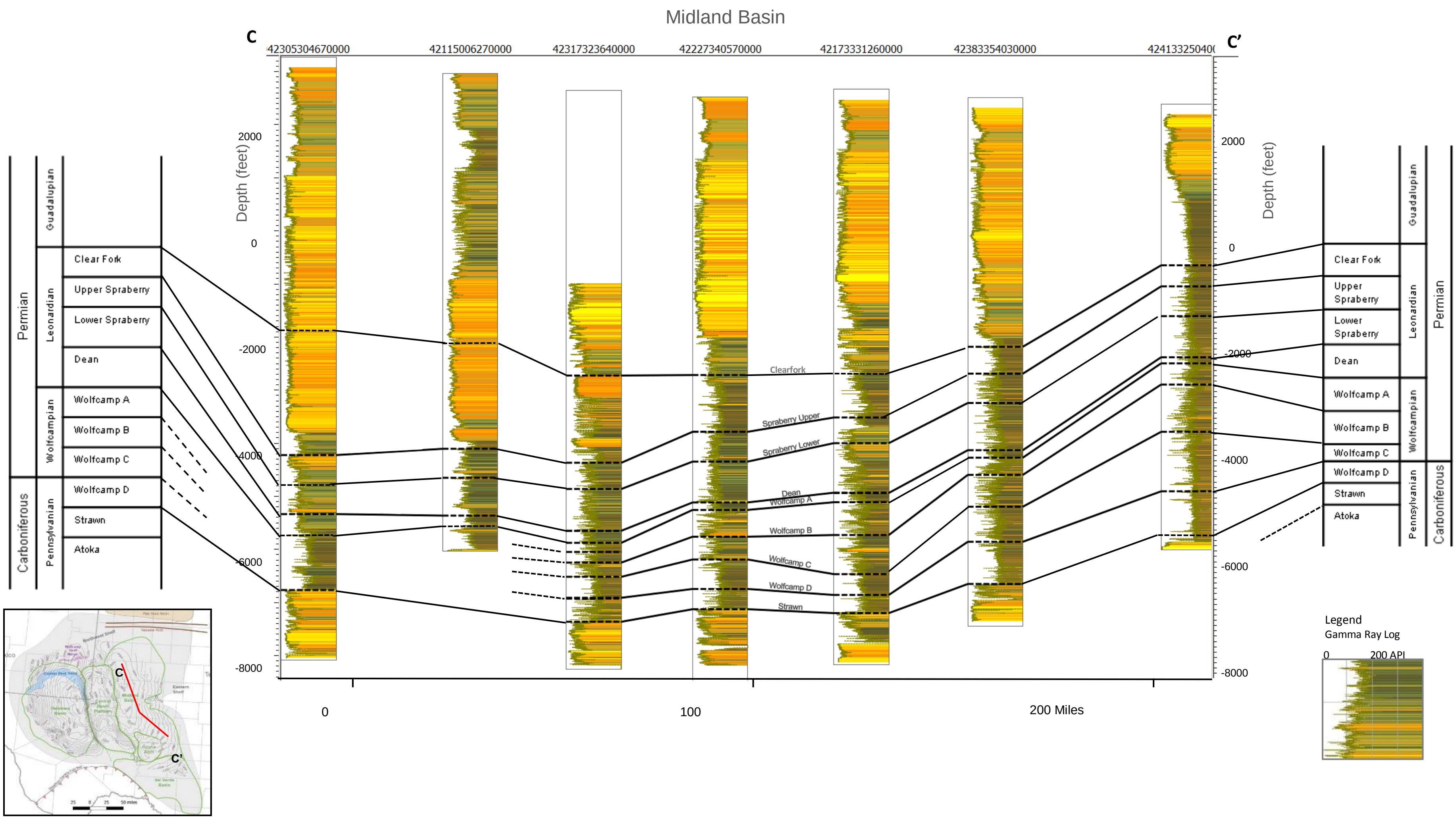
Source: U.S. Energy Information Administration based on DrillingInfo Inc., U.S. Geological Survey.

Figure 4. North to south geologic cross sections through the Delaware Basin



Source: U.S. Energy Information Administration based on DrillingInfo Inc., U.S. Geological Survey.

Figure 5. North to south geologic cross sections through the Midland Basin



Source: U.S. Energy Information Administration based on DrillingInfo Inc., U.S. Geological Survey.

siltstone. An extensive development of reef facies accounts for a large percentage of the limestone deposits in shallow peripheral areas of the Delaware and Midland Basins (Dolton et al., 1979; Hills, 1984).

Permian rocks are extremely heterogeneous, generally grading upward from a clastic-carbonate sequence into an evaporate sequence. Guadalupe, Leonard, and Wolfcamp series consist of limestone interbedded with shale and a subjugated amount of sandstones (Oriel et al., 1967; Robinson, K., 1988). The cessation of tectonic activity and transition to stable marine basin fill-in stage influenced the depositional environment in Early Permian time. Clastic sediments were deposited in the Delaware and Midland Basins surrounded by peripheral reefs and carbonate shelves that graded shoreward into evaporitic lagoons.

However, compared to the corresponding strata in the Delaware Basin, upper Cretaceous to upper Permian strata of the Midland Basin are overall thinner with no significant changes in thickness or lithology. Lithofacies within these stratigraphic units are also relatively uniform or alter gradually across the basin with some thickening adjacent to the boundary of the Central Basin Platform. Pennsylvanian to Wolfcampian strata in the peripheral areas of the Midland Basin consist mainly of carbonate facies that grade toward the basin into shale and fine-grained siliciclastic[1] facies. In the central part of the basin, thick Wolfcampian shales overlie shallow water carbonates of the Strawn limestone (Oriel et al., 1967; Robinson, K., 1988).

Paleogeography and depositional environment

Paleogeographic reconstructions of the Late Carboniferous (346 Ma[2]), Middle Pennsylvanian (305 Ma), and Early Permian (280 Ma) exhibited at Figure 6 show present-day New Mexico, Oklahoma, and Texas as one open, marine area (Figure 6 c) that developed into a semi-enclosed epicontinental sea (Figure 6 b and a) (Brown et al.; Blakey, 2011).

During much of Pennsylvanian time, the Permian Basin formed as a semi-enclosed depression; however, it was not until the Wolfcampian (Early Permian) that a carbonate shelf and margin developed around the edges of both the Delaware and Midland Basins. These accumulations of carbonates formed after the end of intense tectonic movement and widespread siliciclastic sedimentation, which began during the Early Pennsylvanian. By the early Leonardian, this ramp-type shelf was already developing a series of barriers along its seaward edge, becoming a more distinct rimmed margin. The development of this marginal rim influenced depositional environments on the shelf, creating the intrinsic lateral facial changes observed in the Leonardian and Guadalupian rocks behind the shelf edge. From the late Wolfcampian through Guadalupian (Late Permian), the Midland and Delaware Basins were principally sites of siliciclastic accumulation, whereas the platforms and shelves were sites of carbonate deposition (Figure 6). A major change in large-scale basin configuration occurred during the Guadalupian. During the middle Guadalupian, the Eastern shelf, Midland Basin, and Central Basin platform ceased to be areas of

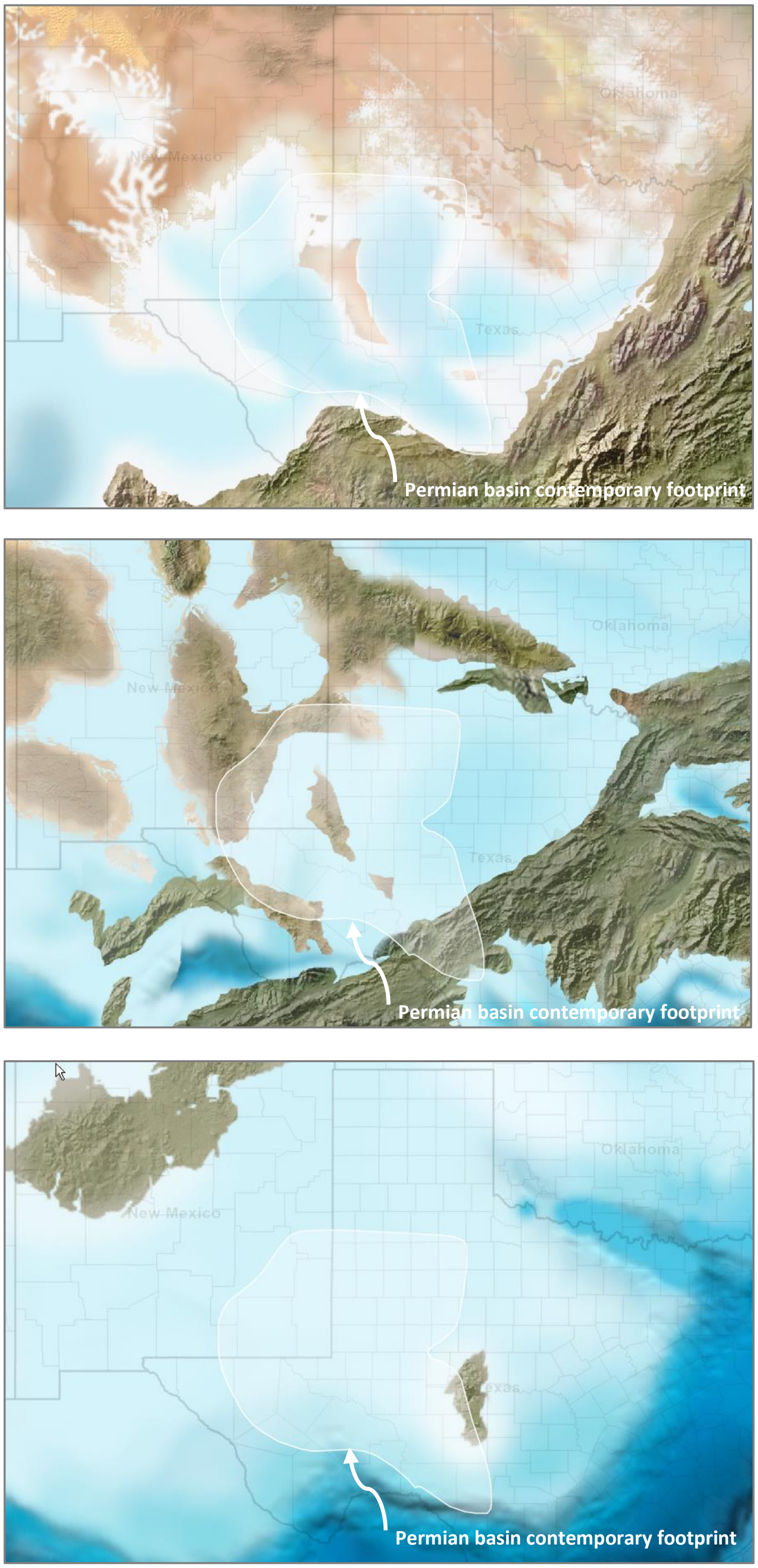
[1] Siliciclastic rocks are composed of terrigenous material formed by the weathering of pre-existing rocks, whereas carbonate rocks are composed principally of sediment formed from seawater by organic activity. Siliciclastic rocks consist of clastic, silicic components (mostly quartz, feldspars, and heavy minerals).
[2] *Ma* is the abbreviation for mega-annum (a million years) in Latin.

Figure 6. Paleogeographic reconstructions exhibiting the southern part of North America. a) Early Permian (280 Ma); b) Middle Pennsylvanian (305 Ma); c) Early Carboniferous (345 Ma). Modified after Blakey (2011)

a)

b)

c)



intense fine-grained siliciclastic and carbonate accumulation and instead became sites of cyclic deposition of sandstone, anhydrite, and halite (Oriel et al., 1967; Robinson, K., 1988; Yang and Dorobek, 1995).

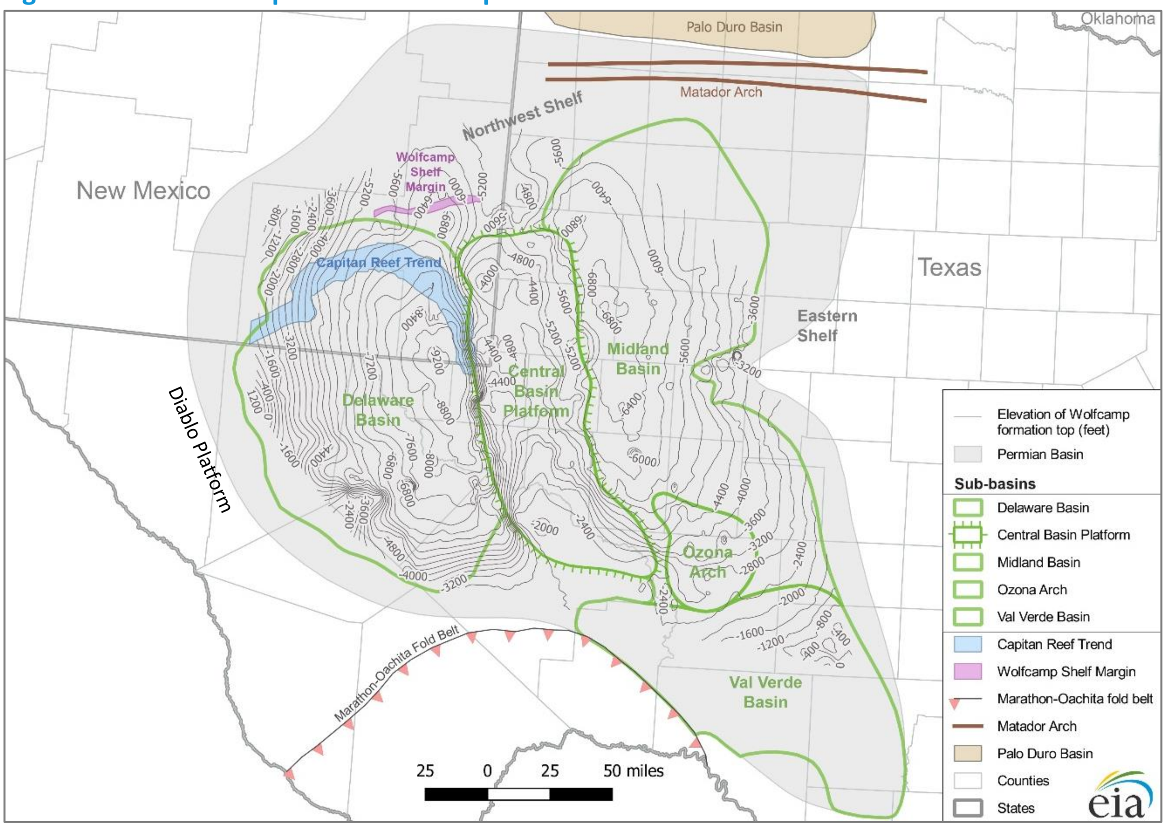
Wolfcamp formation

The Wolfcamp Shale, a Wolfcampian-age organic-rich formation, extends in the subsurface in all three sub-basins of the Permian Basin (Delaware Basin, Midland Basin, and Central Basin Platform) and is the most prolific tight oil and shale gas-bearing formation contained within. The Wolfcamp Shale is divided into four sections, or benches, known as the Wolfcamp A, B, C, and D. The Wolfcamp D is also known as the Cline Shale. The most drilled targets to date are the A and B benches.

The four benches of the Wolfcamp formation each display different characteristics in terms of lithology, fossil content, porosity, total organic content, and thermal maturity. Overall, basement tectonics patterns influence Wolfcamp structure and thickness (Gaswirth, 2017).

Structure map of the Wolfcamp formation

Figure 7. Structure map of the Wolfcamp formation



Source: U.S. Energy Information Administration based on DrillingInfo Inc., U.S. Geological Survey.

USGS estimates undiscovered, continuous, hydrocarbon resources of only the Wolfcamp formation in the Midland Basin to be in excess of 19 billion barrels of oil, 16 trillion cubic feet of natural gas, and 1.6 billion barrels of natural gas liquids (NGL), making it one of the largest hydrocarbon plays in the United

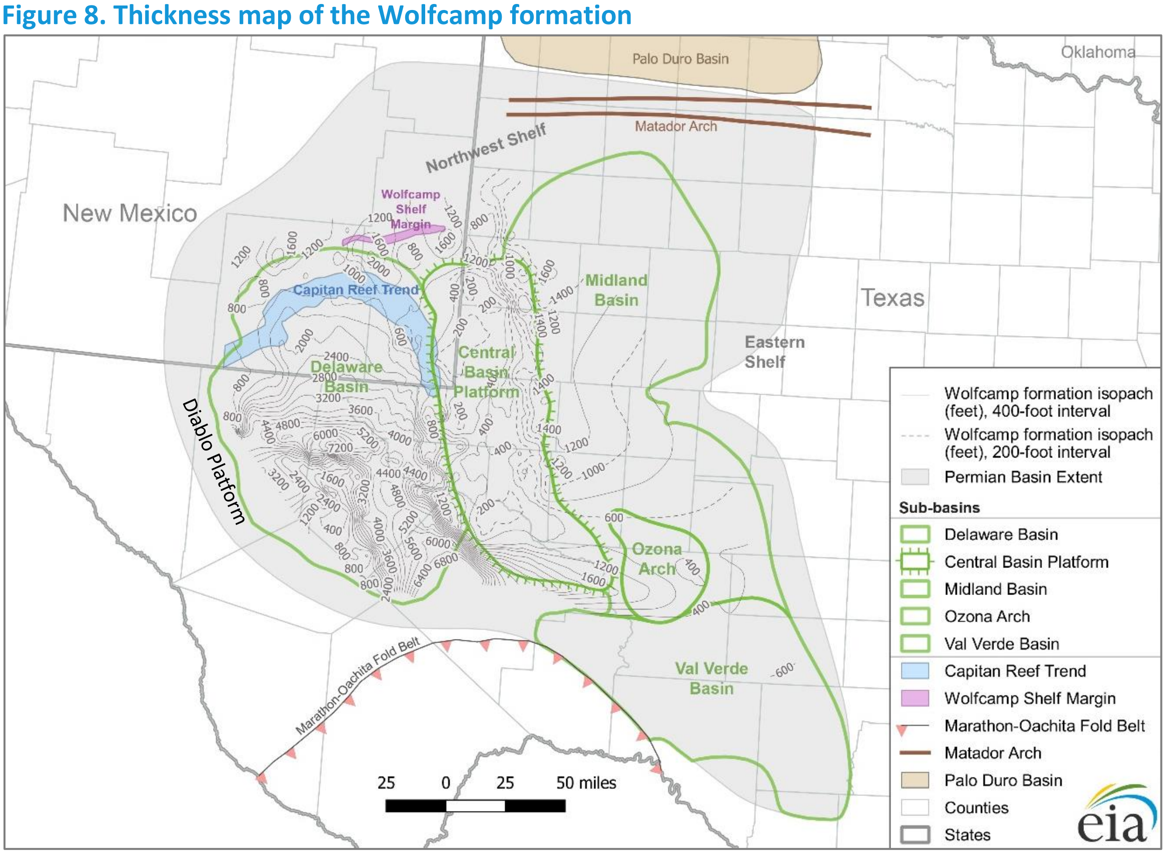
States (Gaswirth, et al., 2016). Like other continuous plays, key geologic and technical criteria that control play boundaries and productivity include thermal maturity, total organic carbon (TOC), formation thickness, porosity, depth, pressure, and brittleness.

EIA constructs contoured elevation maps of subsea depth to the top of a geologic formation (also called structure maps) from point-measurement depth referenced to sea level (well observations) for the formation in the subsurface. These elevation measurements provide the third dimension for characterizing the depth or elevation of a reservoir on an otherwise two-dimensional map. DrillingInfo Inc. provides these stratigraphic picks, or formation depths, based on well log interpretation from 7,730 wells. Subsea depth of Wolfcamp in the Delaware Basin varies from 0 feet in the west to -9,500 feet subsea in the central areas, and in the Midland Basin, it varies from -2,000 feet subsea in the east along the Eastern Shelf to -7,000 feet subsea along the basin axis near the western basin edge (Figure 7).

Thickness map of the Wolfcamp formation

Thickness maps (isopachs) show spatial distribution of the formation thickness across the formation footprint. Thickness values are used, in combination with reservoir petrophysical properties such as porosity and thermodynamic parameters (reservoir temperature and pressure), to calculate resource volumes, such as oil-in-place and natural gas-in-place estimates.

Figure 8. Thickness map of the Wolfcamp formation



Source: U.S. Energy Information Administration based on DrillingInfo Inc., U.S. Geological Survey.
Note: To the east of the Central Basin Platform, stratigraphic picks for the Wolfcamp formation top are available, although stratigraphic picks for the Wolfcamp formation bottom are very limited.

The isopach map for the Wolfcamp formation is constructed from subsurface point measurements from 2,040 individual wells that include both depth to the top and to the base of the Wolfcamp formation. The Wolfcamp thickness varies between 200 feet to 7,050 feet across the Permian Basin. As the isopach map demonstrates (Figure 8), thickness ranges from about 800 feet to more than 7,000 feet thick in the Delaware Basin, from 400 feet to more than 1,600 feet thick in the Midland Basin, and from 200 feet to 400 feet in the adjacent Central Basin Platform.

Regional stratigraphy and lithology of the Wolfcamp formation

The Wolfcamp formation deposited during late Pennsylvanian through late Wolfcampian time is distributed across the entire Permian Basin. The Wolfcamp formation is a complex unit consisting mostly of organic-rich shale and argillaceous carbonates intervals near the basin edges. Depth, thickness, and lithology vary significantly across the basin extent. Depositional and diagenetic processes control this formation heterogeneity. Stratigraphically, the Wolfcamp is a stacked play with four intervals, designated top-down as the A, B, C, and D benches (Gaswirth, 2017). Porosity of the Wolfcamp Formation varies between 2.0% and 12.0% and averages 6.0%; however, average permeability is as low as 10 millidarcies[3], which requires multistage hydraulic fracturing. Figures 3–5 show the regional stratigraphy of the Permian interval, including representation of Wolfcamp benches.

Total organic carbon content of the Wolfcamp formation

Large amounts of organic material that accumulated in the deep, poorly oxygenated areas of the Delaware and Midland Basins later converted to hydrocarbons. Analytical results from well core samples indicate that TOC content in the Wolfcamp formation ranges from less than 2.0% to 8.0% (Ward, et al., 1986; Kvale and Rahman, 2016). Wolfcamp lithological facies vary significantly across the Permian Basin. The carbonate turbidites[4] originated from the Central Basin Platform, whereas the siliciclastic - dominated turbidites derived from surrounding highlands. The carbonate turbidites display TOC values ranging from 0.6% to 6.0%, whereas the siliciclastic turbidites generally exhibit less than 1.0%. The interbedding, non-calcareous mudstones contain as much as 8.0% TOC. Analytical results of oil samples produced from Wolfcamp reservoirs also demonstrate that these oils were generated from mostly marine type II kerogens with a contribution from type III kerogens (Kvale and Rahman, 2016; Gupta et al., 2017). Known good source rocks typically contain mostly 2.0% TOC or higher. As such, the Wolfcamp formation has sufficient TOC content compared with other low permeability plays.

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[3] A darcy (or darcy unit) and millidarcy (md or mD) are units of permeability, named after Henry Darcy. They are not SI units, but they are widely used in petroleum engineering and geology. Like some other measures of permeability, a darcy has dimensional units in length. The darcy is referenced to a mixture of unit systems. A medium with a permeability of 1 darcy permits a flow of 1 cubic centimeter per second of a fluid with certain viscosity under a pressure gradient of 1 atmosphere per centimeter acting across an area of 1 square centimeter.

[4] A turbidite is a sedimentary bed deposited by a turbidity current, which is a type of sediment gravity flow responsible for distributing vast amounts of clastic sediment into the deep ocean. Turbidites are deposited in the ocean floor below the continental shelf by underwater avalanches, which slide down the steep slopes of the continental shelf edge. When the material comes to rest in the ocean floor, sand and other coarse material settle first, followed by mud, and eventually the very fine particulate matter.

Wolfcamp play boundaries

In the Delaware Basin Wolfcamp play, boundaries are controlled by the main tectonic features of the Permian region (Figures 9 and 10). The play boundaries are outlined to the south by the Marathon-Ouachita fold and thrust belt, to the north by the Northwest shelf, and to the west by the Diablo Platform, and the southern play boundary traces the western margin of the Central Basin Platform. The changes in depth and thickness along the play boundaries reflect the amount of differential movements that set off subsidence within the Delaware Basin and the uplift of the surrounding highlands. EIA's analysis of the well log and productivity suggests the best reservoir quality corresponds to the Upper Wolfcamp areas with the following characteristics:

- Thickness is more than 1,000 feet
- Subsea depth to the formation top is more than 3,000 feet
- Neutron porosity ranges from 4.0% to 8.0%
- Density ranges from 2.60 g/cm^3 to 2.85 g/cm^3
- Estimated total organic carbon ranges from 1.0% to 8.0%
- Deep resistivity ranges from 10 Ohm-meter to 80 Ohm-meter

Wolfcamp formation benches

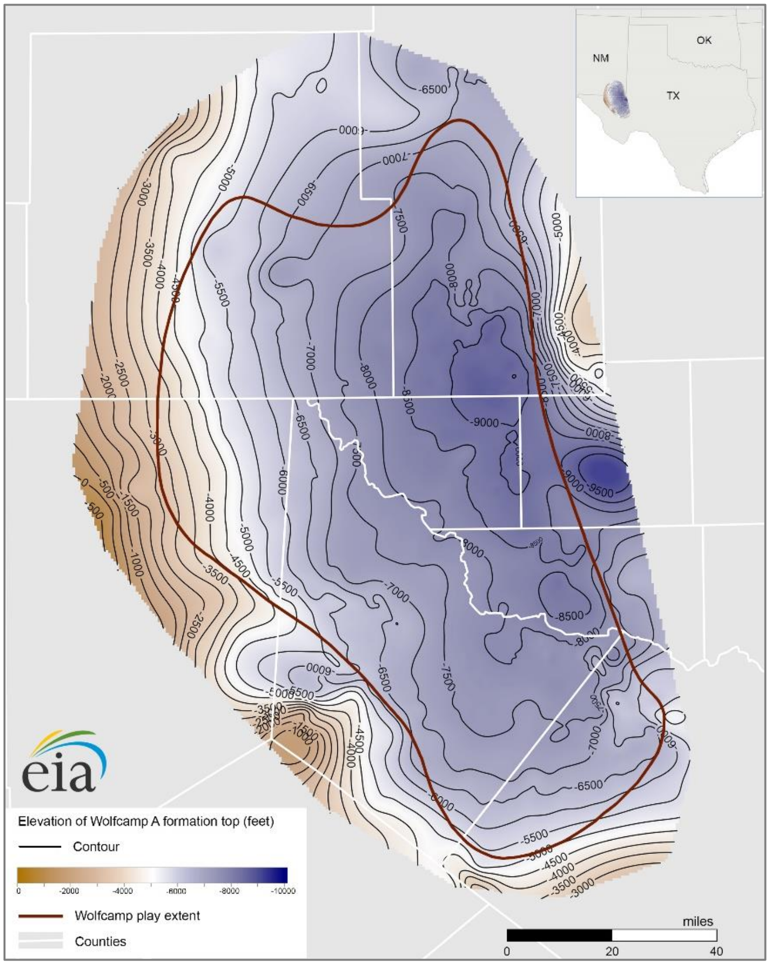
Most of the current drilling activities in the Delaware and Midland Basins target Upper Wolfcamp (A and B benches) rather than Lower Wolfcamp (C and D benches), which is more natural gas prone and more mature. The Upper Wolfcamp sections are comprised of two main facies: shallow water fine-grained calcareous turbidites that are often interbedded with dolomite and deep-water turbidites and mudstones that represent the distal accumulation (Thompson et al., 2018; Gupta et al., 2017). Distal turbidites and mudstones of Upper Wolfcamp are the thickest and have the best reservoir quality.

Structure and thickness maps of Wolfcamp A in the Delaware Basin

EIA constructed the Wolfcamp structure map in the Delaware Basin from subsurface point measurements (well observations) of the depth to the formation top. These stratigraphic picks include well log interpretations from 2,020 wells drilled in the Delaware Basin. Subsea depth of Wolfcamp in the Delaware Basin varies from 0 feet in the west to -9,500 feet in the Central Basin areas (Figure 9).

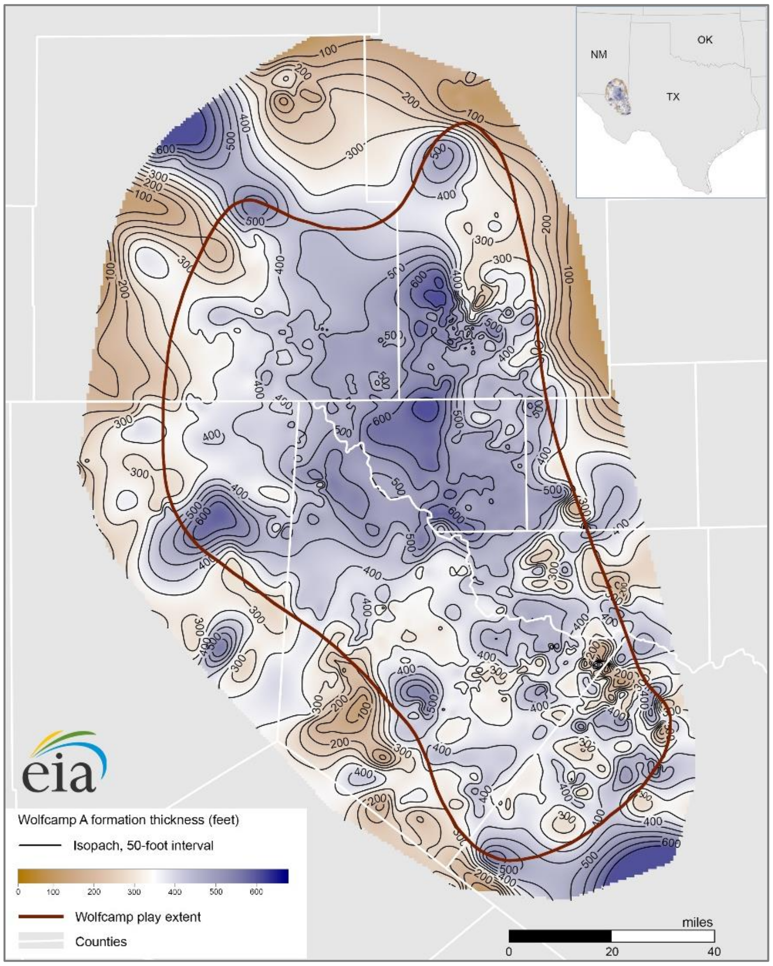
EIA constructed the Wolfcamp A thickness map from subsurface point measurements from 1880 wells that include both depth to the top and to the base of the Wolfcamp A bench. Thickness ranges from about 100 feet to more than 700 feet thick in the Delaware Basin (Figure 10).

Figure 9. Structure map of Wolfcamp A (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Figure 10. Thickness map of Wolfcamp A (Delaware Basin)



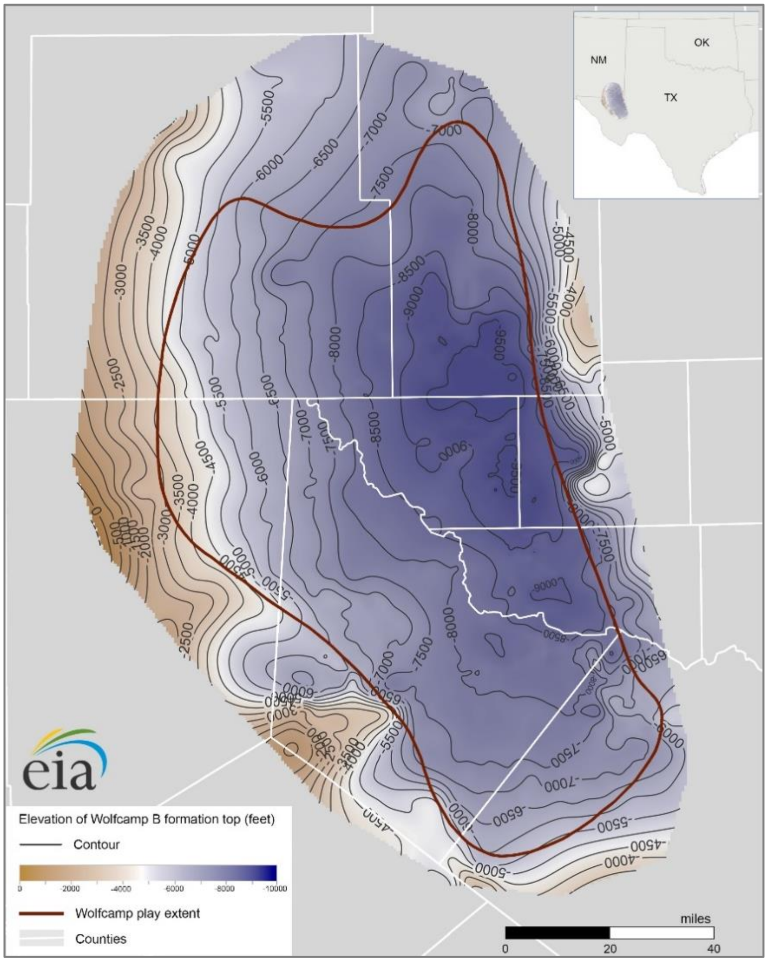
Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Structure and thickness maps of Wolfcamp B in the Delaware Basin

EIA constructed the Wolfcamp structure map in the Delaware Basin from subsurface point measurements of the depth to the formation top. These stratigraphic picks include well log interpretations from 1,422 wells. Subsea depth of Wolfcamp B in the Delaware Basin varies from 0 feet in the west to -10,000 feet in the Central Basin areas (Figure 11).

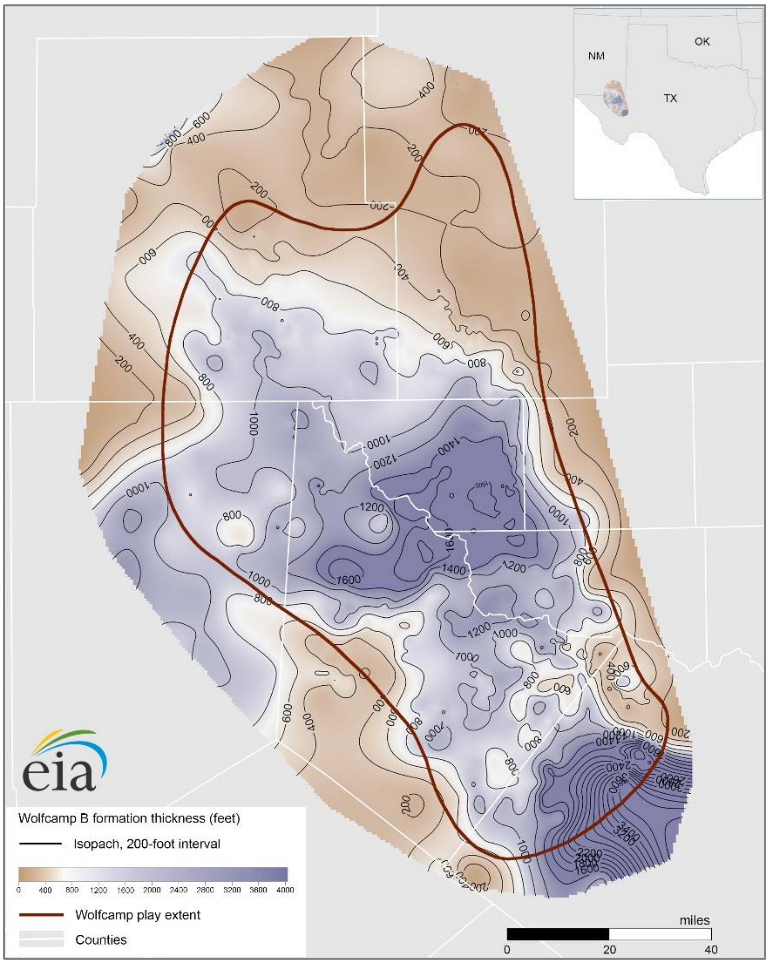
EIA constructed the Wolfcamp B thickness map based on stratigraphic picks from 1193 wells that include both depth to the top and to the base of the Wolfcamp B bench. Thickness ranges from about 150 feet to more than 1800 feet thick across the Delaware Basin, with the exception of the southeast area, where thickness of Wolfcamp B is more than 4000 feet (Figure 12).

Figure 11. Structure map of Wolfcamp B (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Figure 12. Thickness map of Wolfcamp B (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Bone Spring formation

The Leonardian (Middle Permian) Bone Spring formation of the Delaware Basin extends in subsurface under southeastern New Mexico and a part of West Texas. The Leonardian Bone Spring formation is characterized by a succession of calcareous, siliciclastic, and carbonaceous marine deposits associated with significant production of oil, condensate, and dry gas in the Delaware Basin.

In the Bone Spring formation, main depositional processes are defined as a variety of gravity-driven sediment flows that resulted in turbidites with some pelagic layers. Distal flows deposited fine-grained silty shales often with carbonate cements. More proximal flows produced an accumulation of turbiditic silts and fine-grained sandstone and shales along with pelagic shales. Carbonate cementation is often presented across observed lithologies (Montgomery, 1997[1,2]). The Bone Spring formation had produced hydrocarbons from conventional wells long before it became an unconventional target. These conventional wells targeted sandy layers within the Bone Spring interval. During the past decade, the Bone Spring formation has been developed as an unconventional play. In its 2018 report, the U.S. Geological Survey (USGS) estimated undiscovered, continuous, hydrocarbon resources in the Delaware Basin Bone Spring and Avalon assessment units as follows: 14 billion barrels of oil, 32 trillion cubic feet of natural gas, and 2.3 billion barrels of natural gas liquids; and 2.7 billion barrels of oil, 27.5 trillion cubic feet of natural gas, and 2.8 billion barrels of natural gas liquids, respectively (Gaswirth et al., 2018).

Regional stratigraphy and lithology of the Bone Spring formation

The Bone Spring formation directly underlies the Brushy Canyon formation of the Delaware group (Guadalupian) and overlies the Wolfcamp formation. The Bone Spring formation consists of alternating carbonate and sandstone layers representing the slope and basinal equivalent of Abo-Yeso and Wichita-Clear Fork carbonate accumulated along the Northern Shelf margin (Montgomery, 1997[1,2]).

Subdivisions of the Bone Spring include members, labeled respectively, from the top to bottom: Bone Spring Lime, Avalon, Frist Bone Spring Carbonate, Frist Bone Spring Sand, Second Bone Spring Carbonate, Second Bone Spring Sand, Third Bone Spring Carbonate, and Third Bone Spring Sand. In this succession, the upper unit of each member is represented by carbonate, and lower unit is represented by sandstone, historically called as 'sand'. In addition, the Avalon shale was identified within the First Bone Spring Carbonate. The Avalon is divided further into three informal intervals: Lower Avalon, Middle Avalon, and Upper Avalon. Lower and Upper Avalon are generally considered to be mudstone-rich intervals separated by the more carbonate-rich Middle Avalon (Montgomery, 1997[1,2]).

In this study a generalized stratigraphic schema (Figure 4) includes the following subdivisions of the Bone Spring formation from top to bottom: Avalon, Frist Bone Spring, Second Bone Spring, and Third Bone Spring. The Leonardian Bone Spring formation of the Delaware Basin shows a distinct transition from slope to basin floor deposits. These rocks were primarily deposited by slope and deepwater re-sedimentation of carbonate and clastic detritus delivered from carbonate-dominated platforms surrounding the Delaware Basin. The formation is divided into thick successions of carbonate and clastic members that reflect the history of relative sea level fluctuation during the Leonardian time. The siliciclastic sediments were transported to the basin during relative sea level lowstands. However, the effects of sea level on sedimentation and facial distribution can be complex, so a drop in the sea level can shift carbonate development basinward (Saller, et al., 1989).

Reservoirs in the Bone Spring are the product of complex interactions among depositional processes, diagenesis, and structural deformation. Main basin structures at the Bone Spring level are a result of differential movements on basement blocks during the Permian period. Initiation of structural features development began in the Pennsylvanian time, when the Central Basin Platform was raised. Tectonic activity, including reactivation of basement faults, continued but decreased during the Permian period so that by the end of the Leonardian time (top of Bone Spring) and into the early Guadalupian series (lower Brushy Canyon), structure development continued to influence depositional environment.

Total organic carbon content of the Bone Spring formation

The Bone Spring formation is a hybrid shale-oil system with high total organic carbon source rocks interbedded with organic-poor sandy layers. Shale members contain some organic matter, but the total organic carbon (TOC) content is usually on the lower end for a typical source rock, about 1% to 5%. Geochemical data indicated TOC from Bone Spring formation samples ranges from 0.99% to 4.17%, and the residual hydrocarbons left in the rock range from 0.26 milligram/gram (mg/g) to 1.38 mg/g. Measured vitrinite reflectance[5] from the selected samples averages 0.62 %Ro. This value belongs to the

[5] Vitrinite reflectance is a measure of the percentage of incident light reflected from the surface of vitrinite particles in a sedimentary rock. It is expressed as %Ro. Results are often presented as a mean Ro value based on all vitrinite particles measured in an individual sample.

beginning of the oil generation window. Analytical results show that most of the samples are oil prone Type II kerogen,[6] which is primarily marine organic matter (Jarvie et al., 2001; Stolz et al., 2015).

Bone Spring and Avalon play boundaries

By the 1980s, the Bone Spring formation had become a major conventional target with wells targeting mostly sandstone members (Jackson et al, 2014). The Bone Spring formation had not been a prolific conventional reservoir, but by the year 2000, more than 65,000 million barrels (MMb) of oil were produced from the Bone Spring play. With the introduction of hydraulic fracturing and horizontal drilling, production has increased considerably, and it is now one of the fastest developing unconventional plays in the United States. Between 2008 and 2019, more than 4,000 horizontal wells have been drilled in the Bone Spring formation.

The Bone Spring formation is a very attractive unconventional target because it has many pay zones, high TOC, and large formation thickness (average of 3,000 feet). In the mid-2000s, much of the exploration was in the *Wolfbone* interval where the well is landed at the base of the Third Bone Spring Sandstone so that both the Bone Spring and underlying Wolfcamp formations can be stimulated. However, many horizontal wells are often stacked targeting other intervals in the First, Second, and Third Bone Spring members. Starting in 2012, Avalon shale was designated as an emerging unconventional play. In the Bone Spring formation, interval porosity for productive wells varies from 8% to 20% in the sand layers and from 1% to 4% in the mud layers, but all layers have very low permeability at an average of less than a few millidarcies (Jackson et al, 2014). Recent advances in completion techniques have increased the oil recovery factor to as high as 34%.

The Bone Spring formation has been described as a hybrid shale oil system with organic-rich source rocks alternated with organic-lean reservoir intervals (Jarvie et al., 2001). The Bone Spring formation consists of interbedded siliciclastic, carbonate, and shale rocks of up to 4,000 feet. The formation is divided into different larger sandstone and carbonate intervals with the sandstone members in the base of each interval labeled as the First, Second, and Third Bone Spring. In addition, the Avalon shale was identified within the First Bone Spring Carbonate.

The Bone Spring play produces oil and associated gas from carbonate debris flows and turbidite reservoirs throughout the 3,500-foot section, where organic-rich layers of shale or carbonate are interlaminated with organic-lean sandstone or carbonate layers (Dutton et al, 2005). The reservoirs of the Avalon shale play consist of hundreds of feet of dark, organic-rich siliciclastic mudstones interbedded with carbonate-rich turbidite deposits. The reservoir quality of this unconventional hydrocarbon system is generally controlled by carbonate content. Increased carbonate content is related to lower productivity than in neighboring mudstones. The lowest reservoir quality is associated with mainly grainy carbonate facies, and the highest reservoir quality is associated with siliceous mudstones. Accordingly, the better reservoirs are found where muddy deposits are thickest and dominate carbonate debris flows (Montgomery, 1997[1,2]; Walsh, 2006; Hurd et al., 2018).

In the Bone Spring and Avalon plays of the Delaware Basin, boundaries are constrained by the main tectonic features of the Permian region (Figures 9 and 10). The play boundaries are outlined to the south by the Marathon-Ouachita fold and thrust belt, to the north by the Northwest shelf, and to the west by

[6] Kerogen is the portion of naturally occurring organic matter in a sedimentary rock. Typical organic constituents of kerogen are algae and woody plant material. Kerogens are described as Type I, consisting of mainly algal marine kerogen and highly likely to generate oil; Type II, mixed terrestrial and marine source material that can generate waxy oil; and Type III, woody terrestrial source material that typically generates gas.

the Diablo Platform, and the southern play boundary traces the western margin of the Central Basin Platform. The changes in depth and thickness along the play boundaries reflect the amount of differential movements that set off basement sinking within the Delaware Basin and the uplift of the surrounding platforms.

EIA's analysis of the well log and productivity suggests the best reservoir quality corresponds

(1) to the Bone Spring areas with the following characteristics:

- Thickness is more than 1,000 feet
- Subsea depth to the formation top is more than 1,500 feet
- Neutron porosity ranges from 4.5% to 16.5%
- Density ranges from 2.54 grams per cubic centimeter (g/cm^3) to 2.70 g/cm^3
- Estimated total organic carbon ranges from 1.0% to 8.0%
- Deep resistivity ranges from 15 ohmmeter to 75 ohmmeter

(2) and to the Avalon areas with the following characteristics:

- Thickness is more than 150 feet
- Subsea depth to the formation top is more than 500 feet
- Neutron porosity ranges from 4.0% to 17%
- Density ranges from 2.52 g/cm^3 to 2.70 g/cm^3
- Estimated total organic carbon ranges from 4.0% to 8.0%
- Deep resistivity ranges from 15 ohmmeter to 75 ohmmeter

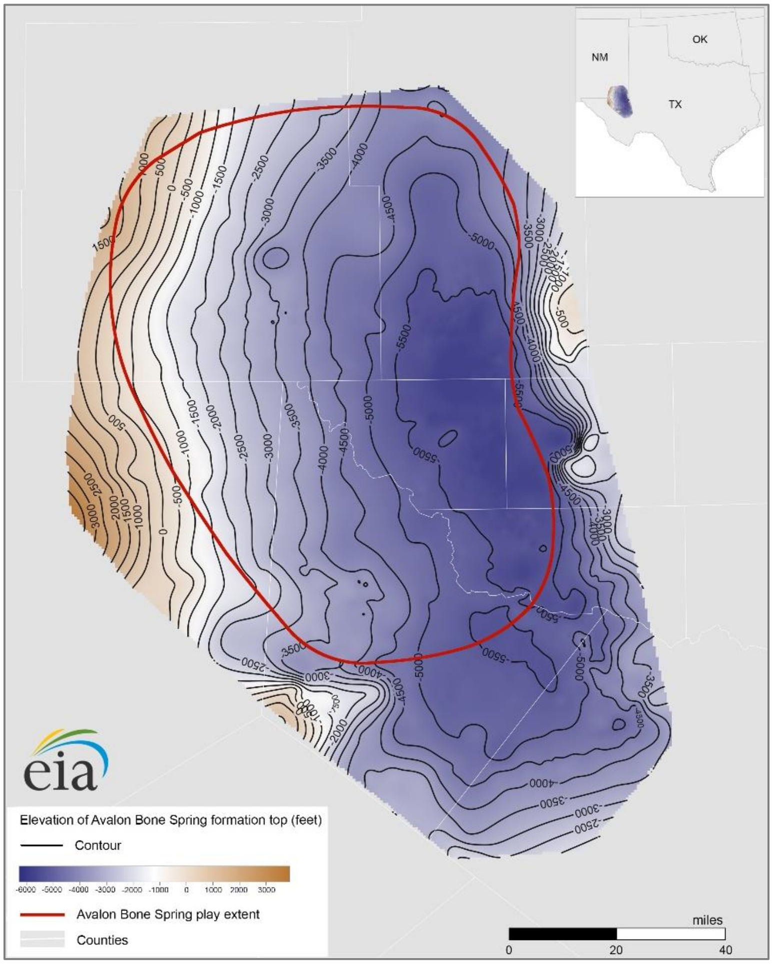
Bone Spring formation members

The Avalon, First Bone Spring, and Second Bone Spring intervals are widespread throughout the entire Delaware Basin, but they exhibit maximum development along the Basin's northern slope. Along the margin of the Central Basin Platform, they are silty and clay rich. In contrast, during deposition of the Third Bone Spring, a depocenter was located in the northeastern part and in the central part of the Delaware Basin next to the Central Basin Platform. Structural, thickness, and facies analysis indicates a similar northern source for many carbonate-debris flow units (Montgomery, 1997[1,2]; Stolz et al., 2015).

Structure and thickness maps of Bone Spring–Avalon

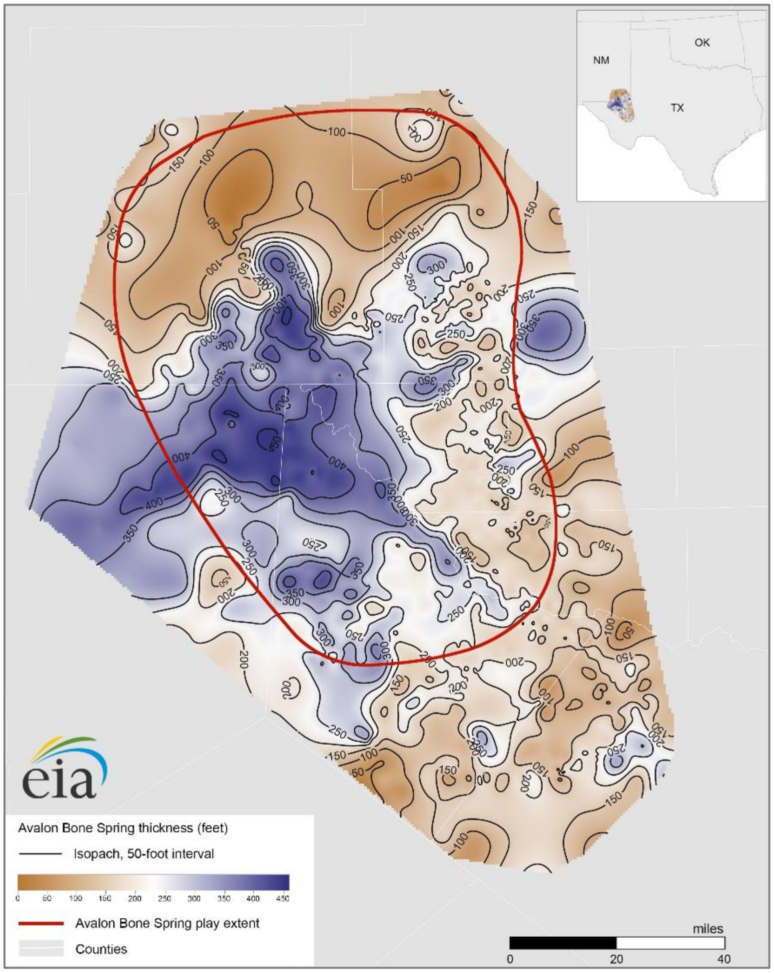
The Avalon shale play consists of organic-rich mudstones interbedded with fine-grained carbonate strata. EIA constructed Avalon Bone Spring structure and thickness maps in the Delaware Basin from subsurface point measurements (well observations) of the depth to the formation top and base. These stratigraphic picks include well-log interpretations from 520 wells. Subsea depth of Avalon in the Delaware Basin ranges from 0 feet in the west to -5,500 feet in the eastern part of the Basin in areas next to the Central Basin Platform (Figure 13). The Avalon ranges from 50 feet to 500 feet in thickness (Figure 14).

Figure 13. Structure map of Avalon Bone Spring (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Figure 14. Thickness map of Avalon Bone Spring (Delaware Basin)

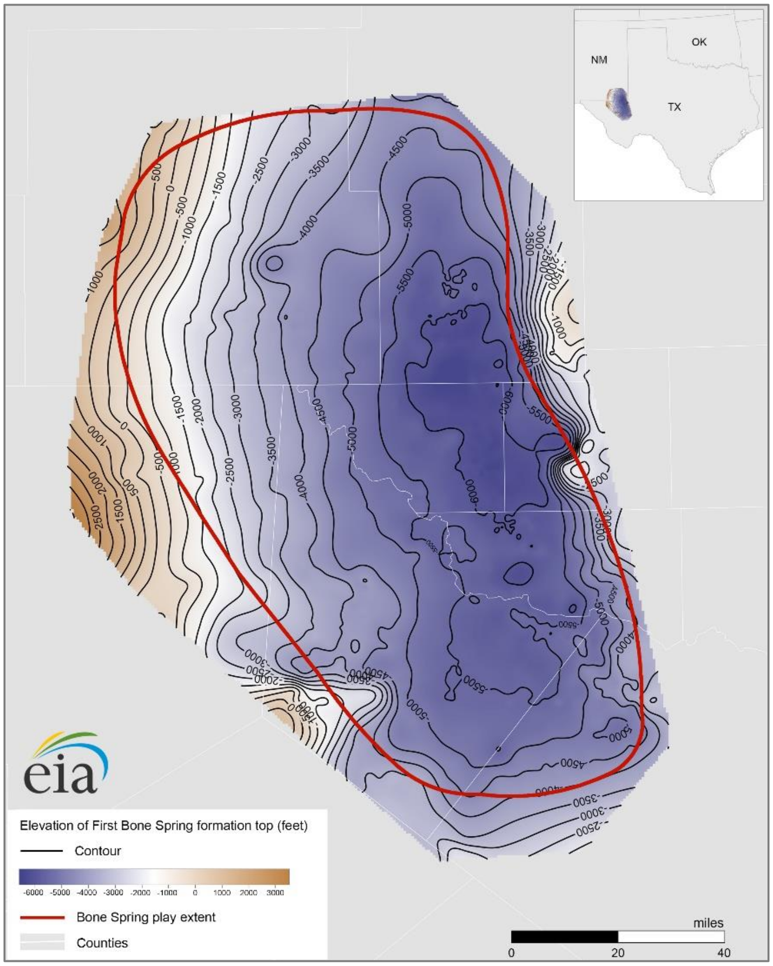


Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Structure and thickness maps of First Bone Spring

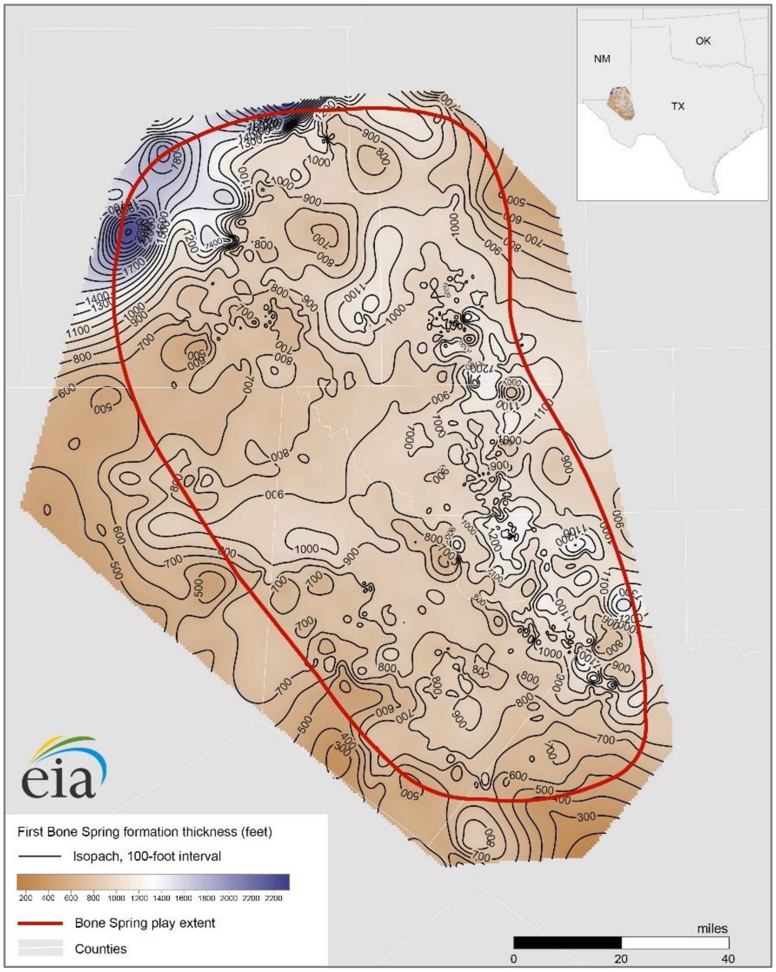
EIA constructed First Bone Spring structure and thickness maps in the Delaware Basin based on stratigraphic picks from 650 wells. Subsea depth of First Bone Spring in the Delaware Basin varies from 0 feet in the west to -6,000 feet in the eastern part of the Basin in areas next to the Central Basin Platform (Figure 15). Thickness ranges from about 250 feet to more than 1,200 feet thick across the Delaware Basin, with the exception of the northwest area, where thickness of First Bone Spring is more than 2,000 feet (Figure 16).

Figure 15. Structure map of First Bone Spring (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Figure 16. Thickness map of First Bone Spring (Delaware Basin)

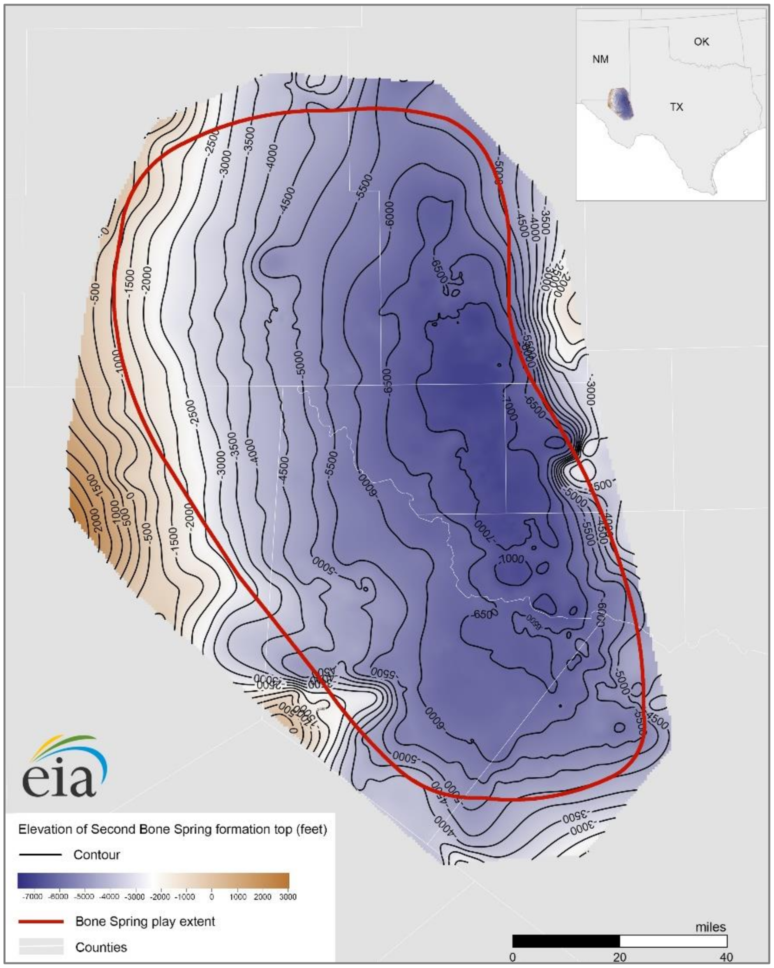


Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Structure and thickness maps of Second Bone Spring

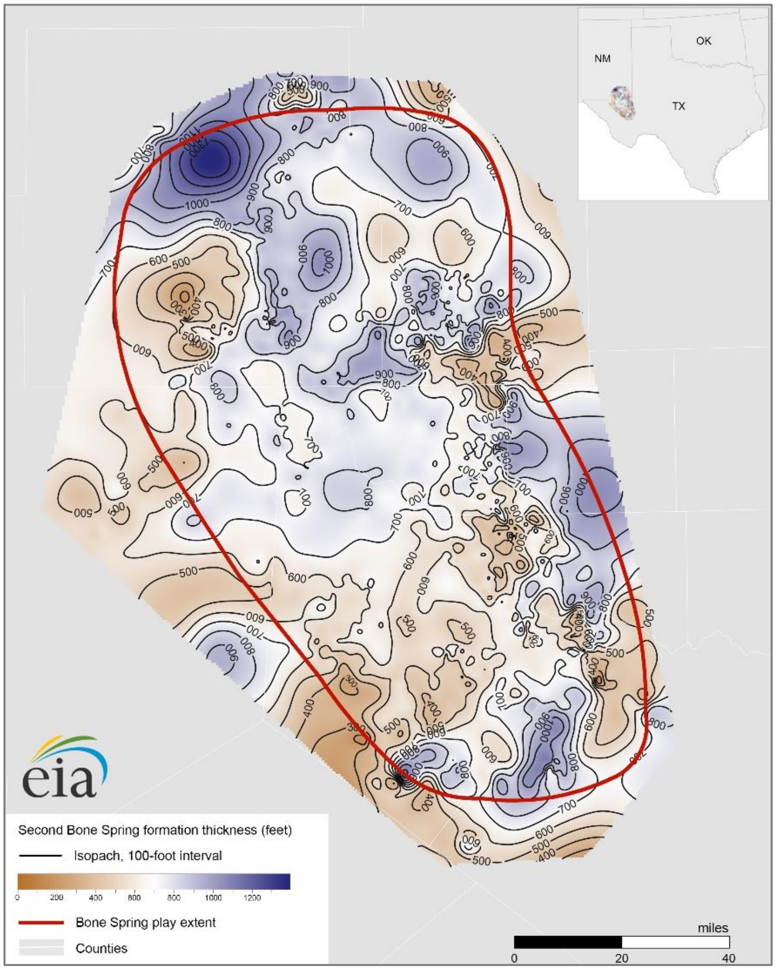
EIA constructed Second Bone Spring structure and thickness maps in the Delaware Basin by using subsurface point measurements from 720 wells. The subsea depth of Second Bone Spring in the Delaware Basin ranges from 0 feet in the west to -7,000 feet in the eastern part of the Basin in areas next to the Central Basin Platform (Figure 17). The Second Bone Spring ranges from 250 feet to more than 1,000 feet in thickness (Figure 18).

Figure 17. Structure map of Second Bone Spring (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Figure 18. Thickness map of Second Bone Spring (Delaware Basin)

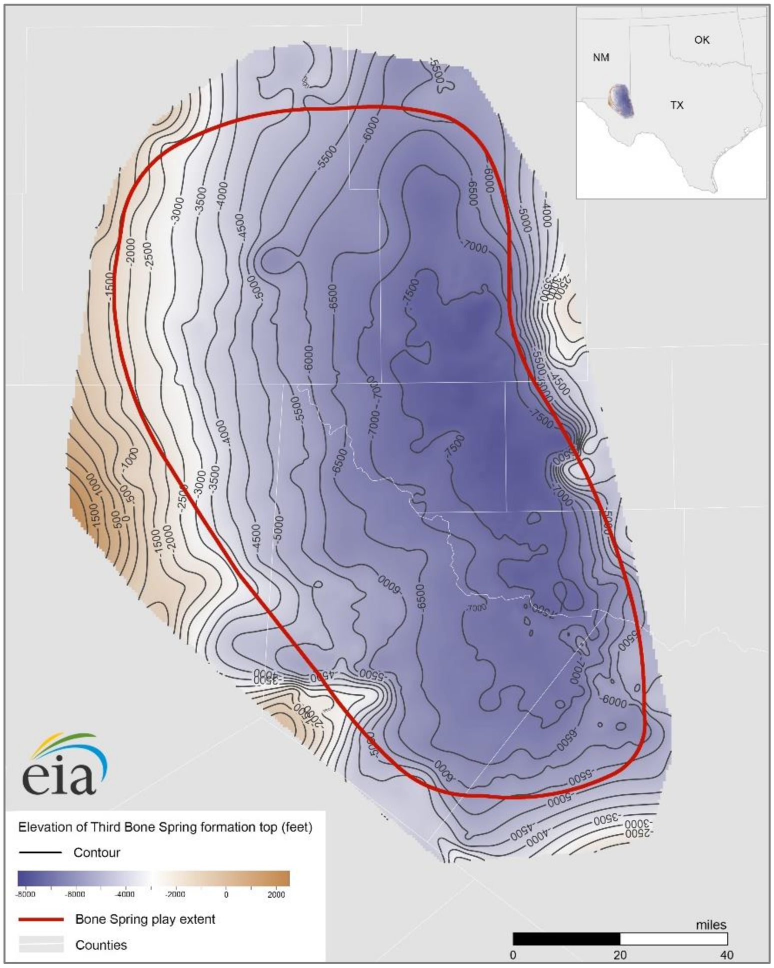


Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Structure and thickness maps of Third Bone Spring

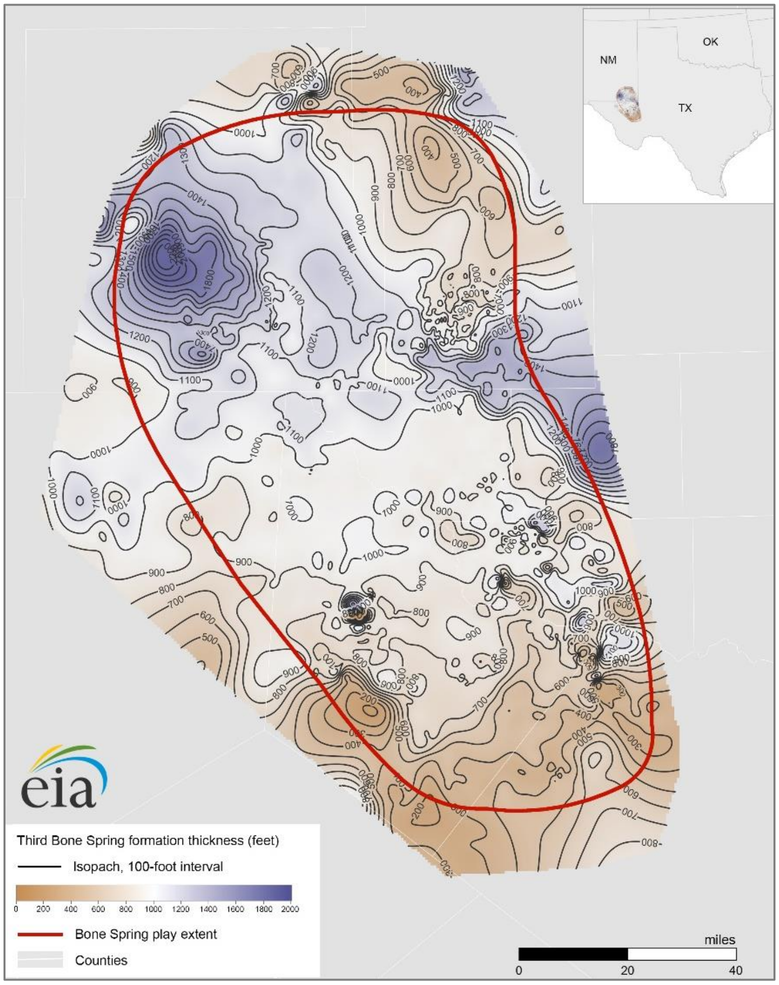
EIA constructed Third Bone Spring structure and thickness maps in the Delaware Basin based on stratigraphic picks from 1,050 wells. Subsea depth of Third Bone Spring in the Delaware Basin ranges from 0 feet in the west to -7,500 feet in the eastern part of the Basin (Figure 19). Thickness ranges from about 200 feet to more than 1,200 feet thick across the Delaware Basin, with the exception of the northwest area and the area in the middle part of the basin next to the Central Basin Platform, where the thickness of First Bone Spring exceeds 2,000 feet and 1,000 feet, respectively (Figure 20).

Figure 19. Structure map of Third Bone Spring (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

Figure 20. Thickness map of Third Bone Spring (Delaware Basin)



Source: U.S. Energy Information Administration based on DrillingInfo Inc.

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