Increasing CO_2 Storage Options with Injection of CO_2 in Shales

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September 23, 2021

Advanced Resources International, Inc.

Increasing CO2 Storage Options with Injection of CO2 in Shales

PROMOTING DOMESTIC AND INTERNATIONAL CONSENSUS ON FOSSIL ENERGY TECHNOLOGIES: CARBON CAPTURE AND STORAGE AND CLEAN ENERGY SYSTEMS

Prepared for:

United States Department of Energy Office of Fossil Energy and Carbon Management
and United States Energy Association

Sub-Agreement: USEA/DOE-002415-21-01

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Report Outline

Disclaimer

Acknowledgements

A portion of the information on resource characterization and reservoir modeling related to cyclic CO_2 EOR in shale oil basins is based on work previously prepared by Advanced Resources International, Inc. for the U.S. Department of Energy, National Energy Technology Laboratory (U.S. DOE/NETL).

Advanced Resources International would like to acknowledge the Enhanced Oil Recovery Institute (EORI) of Wyoming and Mr. Graeme Finley, Senior Geologist; Mr. Stephen Whitaker, Senior Geologist; and Dr. Eric Robertson, Reservoir Engineer for their preparation of Chapter 4, Mowry Shale, Powder River Basin.

Executive Summary

The US Energy Association/Advanced Resources International (USEA/ARI) study--*"Increasing CO_2 Storage Options with Injection of CO_2 in US Shales"*—has defined three new, large capacity settings for geologically storing CO_2 in shale formations—the Niobrara Shale in the DJ Basin of Colorado, the Cana-Woodford Shale in the Anadarko Basin of Oklahoma, and the Mowry Shale in the Powder River Basin of Wyoming.

These three shale formations would provide nearly 4,600 million metric tons (MMmt) of CO_2 storage capacity in basins and states where CO_2 storage capacity in saline formations is notably limited or still poorly defined. This amount of CO_2 storage is equivalent to removing over 1 billion passenger vehicles for one year,[1] or approximately every passenger vehicle in the United States for 9 years.[2]

In addition, the injection of CO_2 into these three shale formations would provide nearly 7,000 million barrels (MMB) of oil with a carbon intensity notably lower than the carbon intensity of imported oil or domestic oil produced by conventional means. Given a preferrence for consuming lower carbon intensity oil, where possible, the oil recovered by injection of CO_2 would displace higher carbon intensity supplies from imports and other sources.

Finally, the revenues from the sale of CO_2, the generation of state severance and royalty payments, and federal tax credits such as 45Q, would notably improve private industry's "business case" for CCUS while also helping maintain state and local tax revenues.

The report has been prepared by the staff of Advanced Resources International,Inc. including Mr. Vello Kuuskraa, Mr. Ryan Monson, Ms. Anne Oudinot, Mr. Brett Murray, and Ms. Joyce Frank, in collaboration with the Enhanced Oil Recovery Institute of Wyoming. We would like to acknowledge Mr. Graeme Finley, Senior Geologist; Mr. Stephen Whitaker, Senior Geologist; and Dr. Eric Robertson, Reservoir Engineer from the Enhanced Oil Recovery Institute for their preparation of Chapter 4, Mowry Shale, Powder River Basin.

[1] https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator
[2] https://www.fhwa.dot.gov/policyinformation/statistics/2019/mv1.cfm

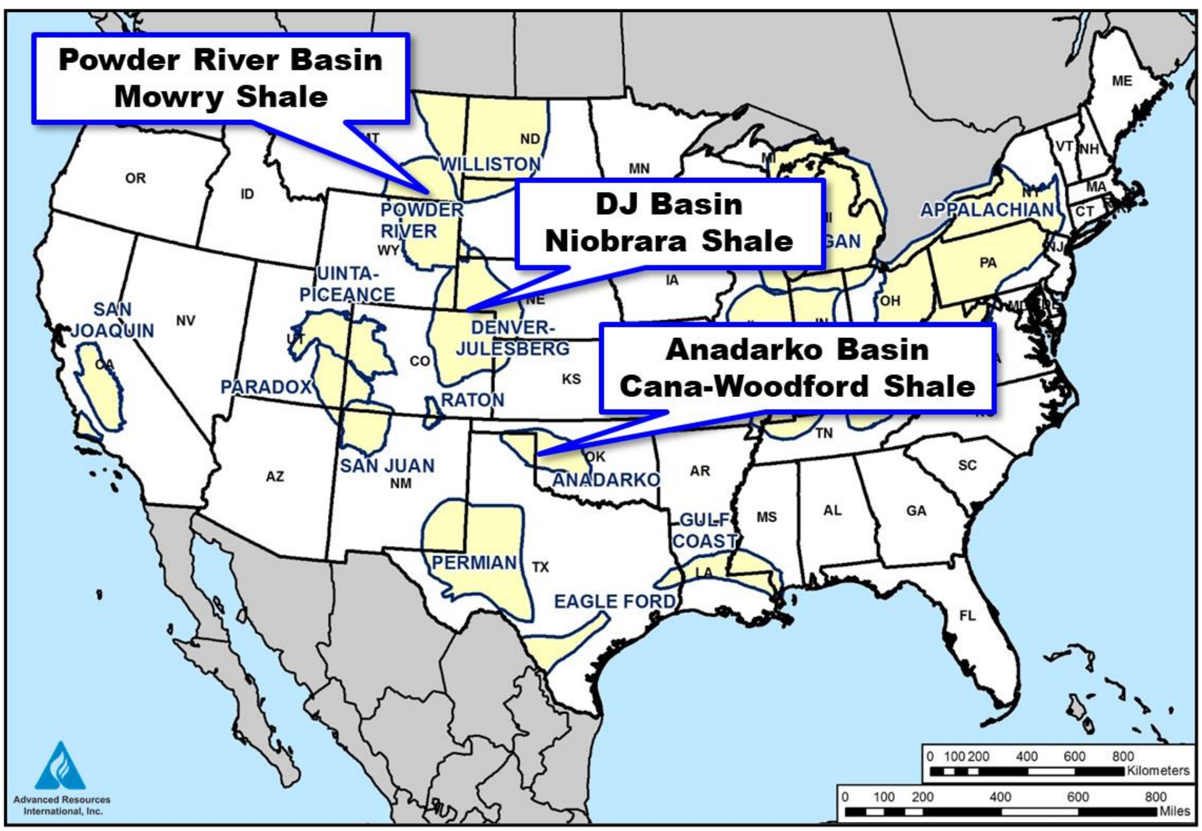
Chapter 1. Summary of Findings

1. Summary of Study Findings

Study Purpose. The purpose of the US Energy Association/Advanced Resources (USEA/ARI) study entitled-- *"Increasing CO_2 Storage Options with Injection of CO_2 in US Shales"*—is to define new settings and options for storing CO_2 in geologically favorable formations. The CO_2 storage process involves cyclically injecting CO_2 into existing production wells completed in deep shale oil formations. In addition to providing a secure geologic setting for permanent CO_2 storage, the injection of CO_2 would enable these fields to produce domestic oil with a lower carbon intensity than oil produced by conventional means.

Study Areas. The three shale CO_2 storage settings evaluated by this USEA/ARI study are the Niobrara Shale in the DJ Basin of Colorado, the Cana-Woodford Shale in the Anadarko Basin of Oklahoma, and the Mowry Shale in the Powder River Basin of Wyoming, Figure 1-1.

Figure 1-1. Location of Three Major U.S. Shale Oil Basins Addressed by the Study



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Study Methodology. The study used a five-step methodology for assessing the CO_2 storage and low carbon intensity oil recovery potential offered by the above three shale oil basins.

1. Geologic Characterization. Conducting a detailed geological characterization of each shale formation, including its areal extent, depth, thickness, porosity, and other key features.
2. Partitioning. Partitioning the area of shale deposition in each basin into geologically similar settings.
3. Study Areas. Defining a geological model for each of the geologically partitioned areas, including establishing a representative performance “type well” for each area.
4. Integrating Geology with Reservoir Modeling. Incorporating the geological model into a compositional reservoir model to calculate the volume of CO_2 that would be injected and stored and the volume of low carbon intensity oil that would be recovered with cyclic injection of CO_2 (Shale EOR).
5. Alternative Designs. Examining alternative cyclic CO_2 injection designs that would help maximize the volume of CO_2 stored in each shale formation.

Primary Study Finding. The primary study finding is that the injection of CO_2 into the shale formations in these three basins would support significant volumes of CO_2 storage along with by-product production of low carbon intensity oil. Overall, the three shale formations would provide 4,635 million metric tons (MMmt) of CO_2 storage capacity and the production of 6,953 million barrels (MMB) of low carbon intensity oil, as shown in Table 1-1.

- **The Niobrara Shale** in the DJ Basin of Colorado provides a much needed, new CO_2 storage option close to large point sources of CO_2 emissions with a storage capacity of 1,530 MMmt of CO_2 and 3,340 MMB of low carbon intensity oil recovery.
- **The Cana-Woodford Shale** in the Anadarko Basin of Oklahoma provides an alternative CO_2 storage option to the induced seismically prone Arbuckle Formation with a storage capacity of 960 MMmt of CO_2 and 1,710 MMB of low carbon intensity oil recovery.
- **The Mowry Shale** in the Powder River Basin of Wyoming adds a large-scale CO_2 storage option currently lacking in the Powder River Basin with a storage capacity of 2,145 MMmt of CO_2 and 1,903 MMB of low carbon intensity oil recovery.

The CO_2 storage volumes presented above are based on using an operating design that helps maximize the volume of CO_2 that can be stored in shales. Further discussion of this cyclic CO_2 injection and storage design and its results are provided for each of the three shale basins addressed by the study.

Table 1-1. CO_2 Storage and Low Carbon Intensity Oil Recovery from Application of Cyclic Injection of CO_2: Three Shale Basins

Three Shale Formations / Basins		CO_2 Storage with Shale EOR	Low Carbon Intensity Oil Recovery with Shale EOR	CO_2 Storage with Shale EOR*	
		(MMmt)	(MMB)	(mt/B)	(g/MJ)
▪	Niobrara Shale / DJ Basin	1,530	3,340	0.46	75
▪	Cana-Woodford Shale / Anadarko Basin	960	1,710	0.56	92
▪	Mowry Shale / Powder River Basin	2,145	1,903	1.1	180
Total/Average		**4,635**	**6,953**	**0.67**	**109**

*The conversion of metric tons per barrel oil (mt/B) uses 10^6 grams per metric ton (g/mt) and 6,120 Mega Joules per barrel (MJ/B) oil.

Additional Study Findings. Three additional findings from this study provide insights and information on pathways for improving the viability of CO_2 storage and for supporting lower carbon intensity domestic oil consumption.

1. **Supporting Consumption of Lower Carbon Intensity Oil.** According to the U.S. Energy Information Administration's (USEIA's) latest report (AEO 2021), the U.S. is projected to consume nearly 20 million barrels per day (MMB/D) of petroleum and other liquids in Year 2030, essentially the same level of oil consumption as today. If this is indeed the case, and even if new initiatives reduce petroleum demand, one of the key goals of Carbon Management will be to reduce the CO_2 footprint of oil consumption from imports and domestic oil fields to the maximum extent possible.

Life-cycle analyses (LCA) show that the carbon intensity of one barrel of oil produced by cyclic injection of CO_2 (Shale EOR) is 87 g CO_2/MJ, consisting of 11 g CO_2/MJ for traditional shale oil extraction, refining and transportation (Masnadi et al., 2018), 3 g CO_2/MJ for Shale EOR (Godec et al., 2016), and 73 g CO_2/MJ when consumed as gasoline, diesel or jet fuel.

However, an average of 109 g CO_2/MJ is stored for every barrel of oil produced with Shale EOR in these three shale basins. This CO_2 storage volume enables these three new sources of domestic oil to have a negative carbon intensity of 22 g CO_2/MJ, compared to a positive carbon intensity of 84 g CO_2/MJ for conventional oil, Table 1-2.

Table 1-2. Carbon Intensity of Alternative Sources of Oil Supply

Source of Carbon Emissions	Shale EOR Oil ($g\ CO_2/MJ$)	Other Oil Sources: Conventional Domestic Oil ($g\ CO_2/MJ$)	Other Oil Sources: Imported Oil ($g\ CO_2/MJ$)
Conventional Production (Extraction, Transport, Refining)	11	11	12
EOR Operations	3		
Combustion	73	73	73
CO2 Storage	(109)		
Total Carbon Intensity	**(22)**	**84**	**85**

2. Displacing Imports of Higher Carbon Intensity Oil. Life-cycle analyses (LCA) studies also show that U.S. oil imports have a positive carbon intensity of about 85 g CO_2/MJ (including 12 g CO_2/MJ from extraction, refining, and transportation plus 73 g CO_2/MJ from consumption) (ICCT, 2010). In contrast, the carbon intensity of oil produced by cyclic injection of CO_2 into shales (Shale EOR) is a negative 22 g CO_2/MJ for, Table 1-2.

Given that domestic oil consumption (demand) would be essentially the same, the incremental production of **negative** carbon intensity oil by cyclic injection of CO_2 in shales (Shale EOR) would displace an equivalent volume of **positive** carbon intensity oil imports, helping reduce domestic CO_2 emissions.

3. Improving the Business Case for CCUS. Shale formations provide an already developed, secure setting for storing CO_2, reducing the costs and need to develop other CO_2 storage facilities. In addition, the revenues from the sale of CO_2, the generation of state severance and royalty payments, and federal tax credits such as 45Q, would notably improve private industry's "business case" for CCUS while also helping maintain essential state and local tax revenues.

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Chapter 2. Niobrara Shale, Denver-Julesburg Basin

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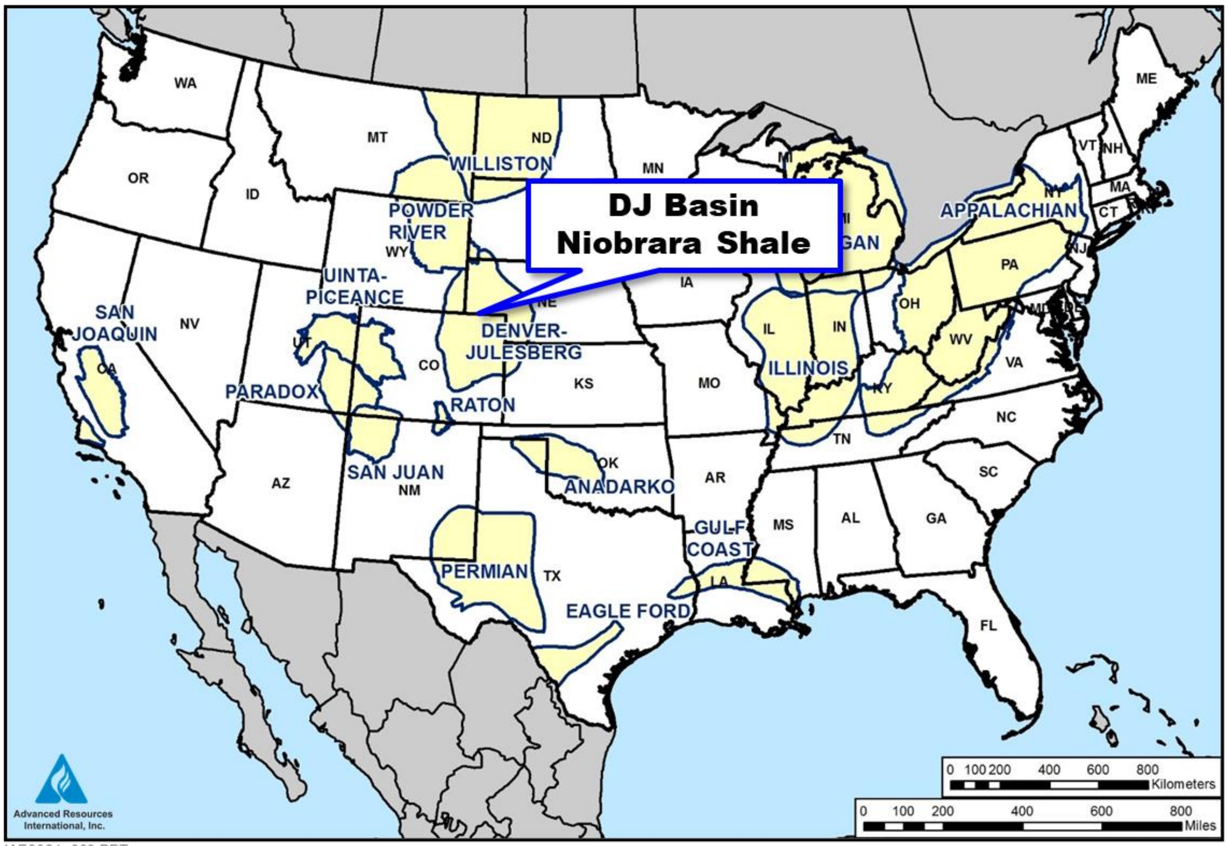
2. Niobrara Shale, Denver-Julesburg Basin

2.1 Introduction and Summary of Findings

This chapter of the Report discusses the potential for storing CO_2 and producing low carbon intensity oil from the Niobrara Shale of the Denver-Julesburg (DJ) Basin of Colorado, Figure 2-1.

Figure 2-1. Location of Niobrara Shale, DJ Basin



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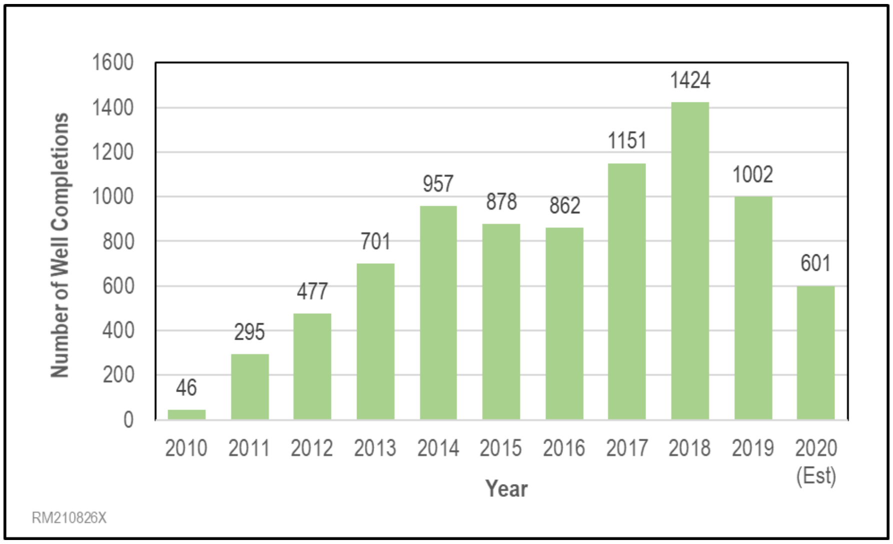
Source: Advanced Resources International, 2021.

2.1.1 DJ-Niobrara Shale Status and Development

The Niobrara Shale in the DJ Basin was originally pursued with vertical wells in areas with naturally occuring fracture networks. Today, the DJ-Niobrara Shale is developed using intensively hydraulically fractured, long horizontal (Hz) wells. The development of the DJ-Niobrara Shale has grown rapidly, from only 46 Hz well completions in 2010, to 957 Hz well completions in 2014, and peaking at 1,424 Hz well completions in 2018. With lower oil prices and a steadily maturing reource, Hz well completions in the DJ-Niobrara Shale have dropped sharply, declining to about 600 in 2020, Figure 2-2. To date, about 8,500 Hz wells have been completed and placed on production in the Niobrara Shale of the DJ Basin.

Figure 2-2. DJ-Niobrara Shale Hz Well Completions, 2010-2020



Source: Advanced Resources International's Tight Oil Database, 2021.

Shale oil production from the DJ-Niobrara Shale reached a peak of 424,000 barrels per day in 2019, before declining to 378,000 barrels per day in 2020. With active Hz rig counts remaing low, DJ-Niobrara Shale production is projected to decline further in 2021.

2.1.2 Study Findings

1. Identification of a New, Large Volume CO_2 Storage Option Close to Large Point Sources of CO_2 Emmissions. Our geological and reservoir engineering study of the Niobrara Shale in the DJ Basin of Colorado and Wyoming has defined a new, large volume CO_2 storage option close to large point sources of CO_2 emmissions in the Rocky Mountain area. The CO_2 storage capicity offered by the Niobrara Shale is estimated at 1,530 million metric tons (MMmt). In addition, the cyclic injection of CO_2 into the Niobrara Shale (Shale EOR) would provide 3,340 million barrels (MMB) of low carbon intensity by-product oil, Table 2-1.

Table 2-1. CO_2 Storage and By-Product Oil Recovery from Application of Cyclic Injection of CO_2

Shale Formations / Basins	CO_2 Storage with Shale EOR	Low Carbon Intensity Oil Recovery with Shale EOR	CO_2 Storage with Shale EOR*	
	(MMmt)	(MMB)	(mt/B)	(g/MJ)
Niobrara Shale /DJ Basin	1,530	3,340	0.46	75

*The conversion of metric tons per barrel oil (mt/B) uses 10^6 grams per metric ton (g/mt) and 6,120 Mega Joules per barrel (MJ/B) oil.

2. Recovery of Low Carbon Intensity Domestic Oil with Cyclic Injection of CO_2 in the Niobrara Shale. As presented in Chapter 1, the carbon intensity of one barrel of oil produced from the Niobrara Shale of the DJ Basin with cyclic injection of CO_2 (Shale EOR) is 87 g CO_2/MJ. However, as shown in Table 2-1, 75 g CO_2/MJ are stored for every barrel of oil produced from the Niobrara Shale, enabling this oil to have a carbon intensity of 12 g CO_2/MJ. This compares to a carbon intensity of 84 g CO_2/MJ for domestically produced conventional oil and 85 g CO_2/MJ for imported oil, Table 2-2.

Table 2-2. Carbon Intensity of Alternative Sources of Oil Supply

Source of Carbon Emissions	Niobrara Shale EOR Oil (g CO_2/MJ)	Other Oil Sources	
		Conventional Domestic Oil	Imported Oil
		(g CO_2/MJ)	(g CO_2/MJ)
Conventional Production (Extraction, Transport, Refining)	11	11	12
EOR Operations	3		
Combustion	73	73	73
CO2 Storage	(75)		
Total Carbon Intensity	**12**	**84**	**85**

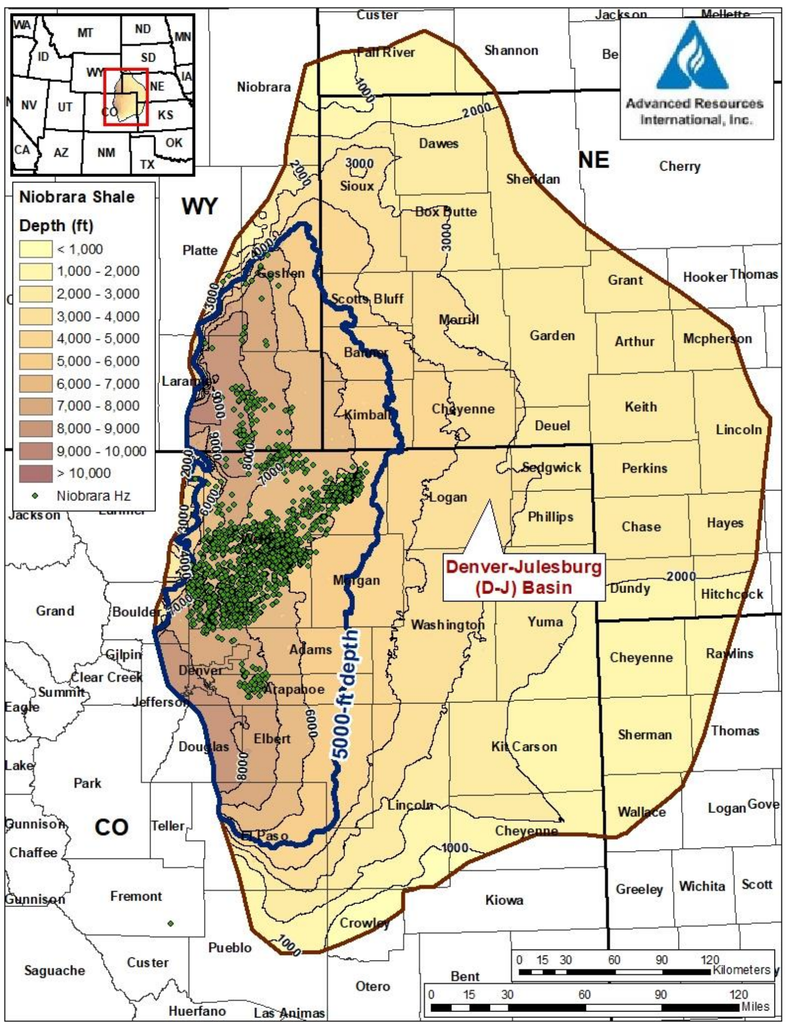
As such, the implementation of Shale EOR in the Niobrara Shale would support two key Carbon Management goals--reducing the CO_2 footprint of domestic oil consumption and adding new, economically viable options for geological storage of CO_2.

2.2 Geologic Setting of the DJ-Niobrara Shale

2.2.1 Geographic Location

The Denver-Julesburg (DJ) Basin covers portions of eastern Colorado, Wyoming and Nebraska. As shown by the blue outline in Figure 2-3, the Niobrara Shale is productive along the western edge of the DJ Basin in North-Central Colorado and Southern Wyoming. The highest quality and most intensively drilled portion of the DJ-Niobrara Shale is the Wattenberg "core" area located in central Weld County. Emerging productive areas of the Niobrara Shale are in Adams and Arapahoe Counties of Colorado and Laramie County of Wyoming.

Figure 2-3. DJ-Niobrara Shale Basin Location Map

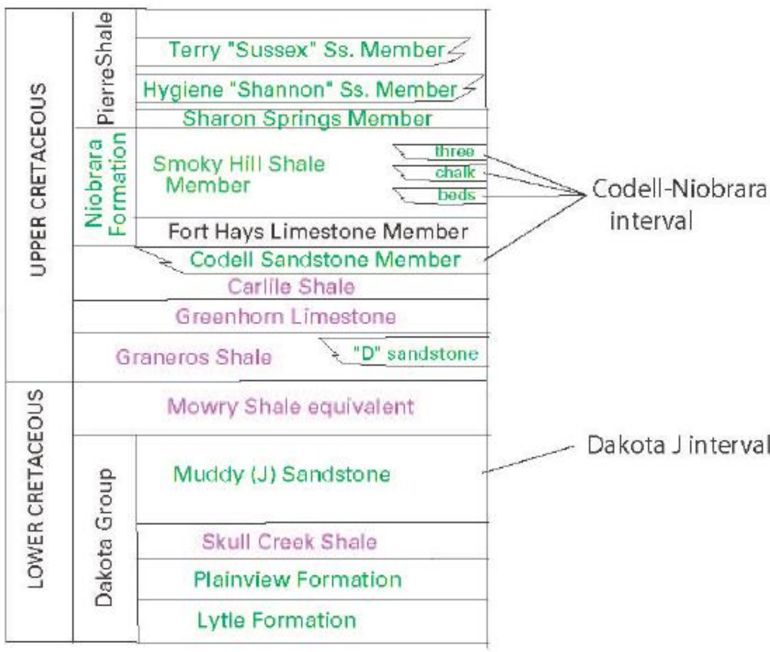


Source: Advanced Resources International.

2.2.2 Stratigraphic Column

The Niobrara Formation contains interbedded chalk, marl, shale and limestone deposited during sea-level oscillations in the Late Cretaceous (Mabrey, 2016). The Niobrara Shale is overlain by the Pierre Shale and underlain by the Codell Sandstone, Figure 2-4. The Niobrara Shale contains two members: the Smokey Hill and Fort Hays. The Smokey Hill Member, the primary target for development, contains interbedded chalks and marls (Mabrey, 2016). Although both the chalk and marl benches are reservoir rocks, the chalk intervals are the main targets for horizontal drilling and fracturing.

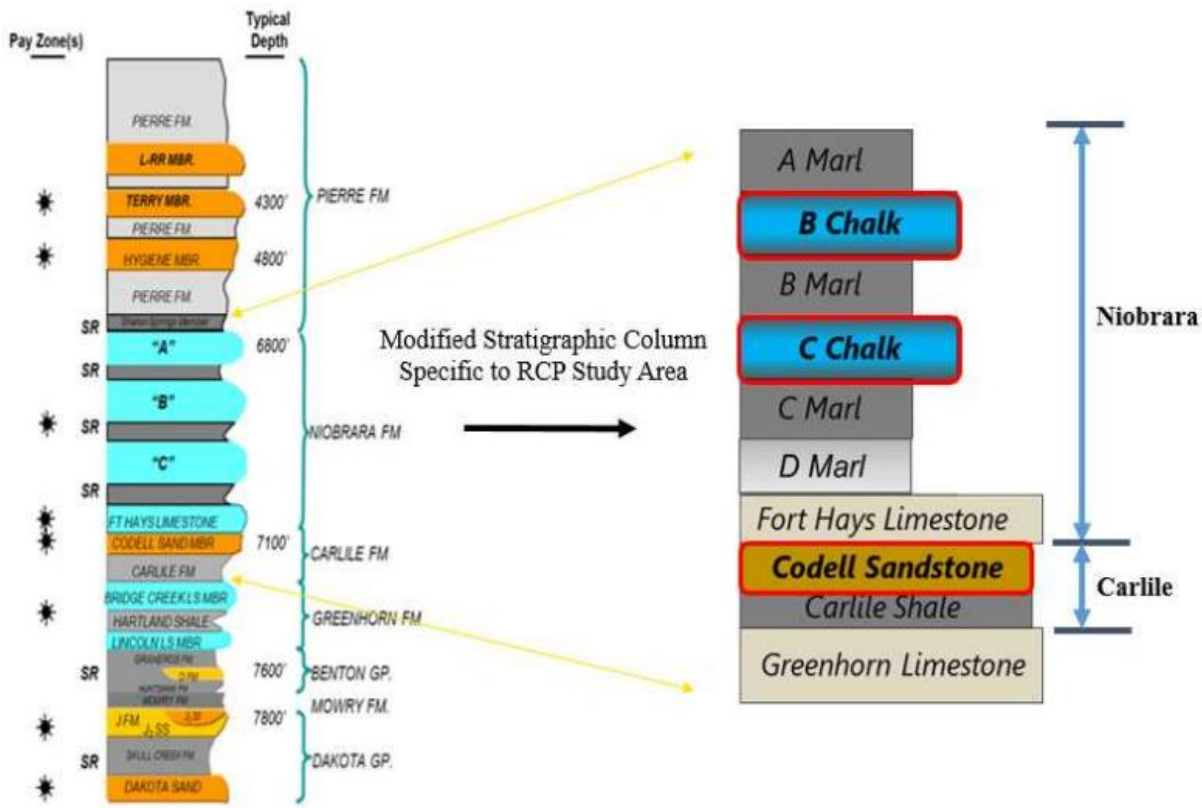
Figure 2-4. DJ Basin Stratigraphic Column



Source: Higley and Cox, 2007.

The stratigraphic column in Figure 2-5 provides a closer illustration of the separate marl and chalk benches in the Niobrara Shale. The “B” Chalk is the primary target, although the “A” Chalk and “C” Chalk can also be productive where present.

Figure 2-5. DJ-Niobrara Shale Focused Stratigraphic Column

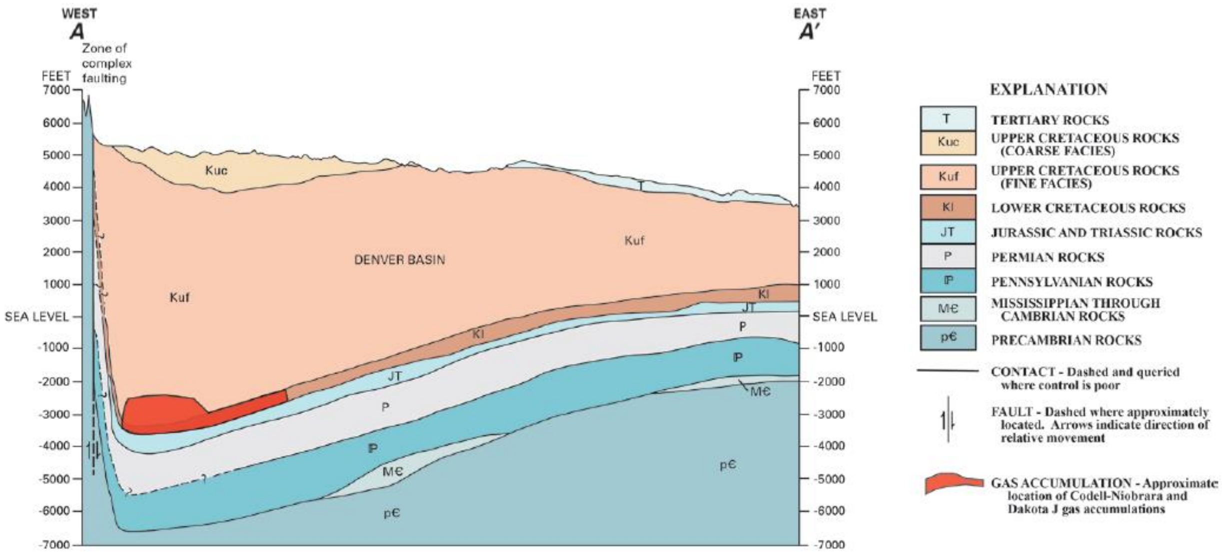


Source Ning, 2017

2.2.3 Geologic Cross-Section

The West-to-East cross-section in Figure 2-6 shows the geologic structure for the DJ Basin in east-central Colorado near the Wattenberg Field in Weld County. The Cretaceous-age Niobrara Shale is relatively shallow in the eastern DJ Basin before deeping steeply toward the west. The thrust faults of the Front Range of the Rockies border the Niobrara Shale on the west.

Figure 2-6. DJ Basin Cross-Section



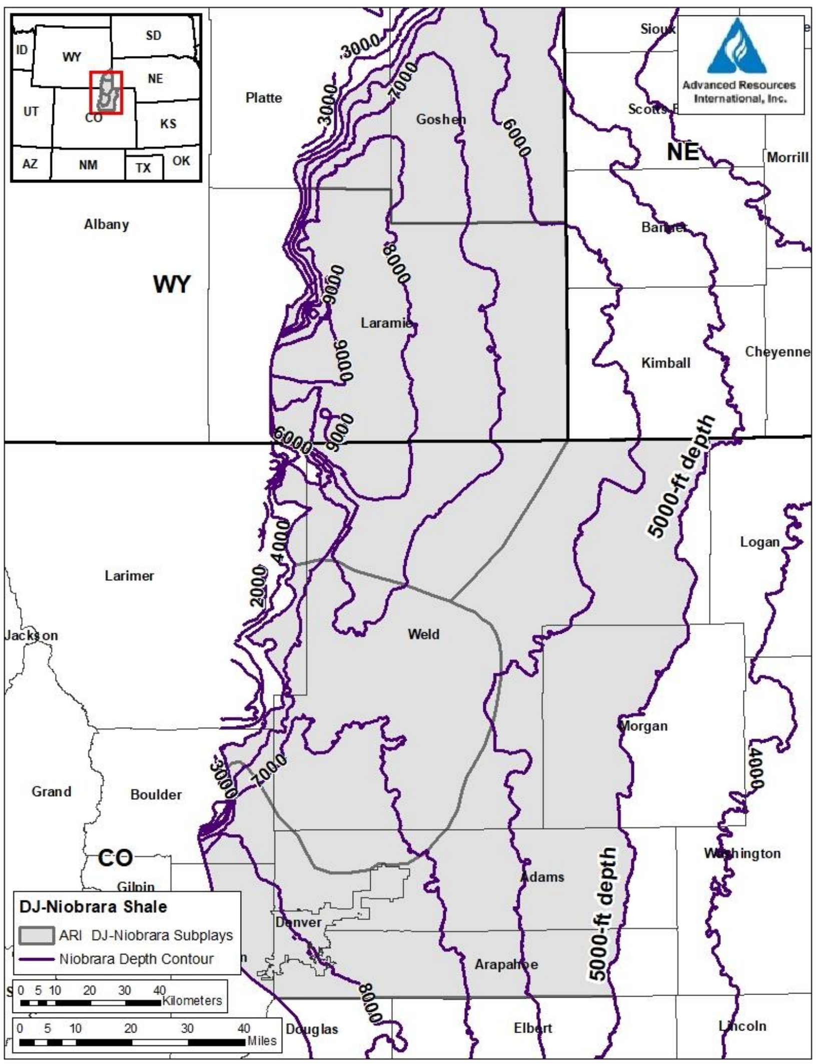
Source: Nelson and Santus, 2011.

2.3 Establishing the Essential Reservoir Properties

2.3.1 DJ-Niobrara Shale Assessment Area and Depth

The Niobrara Shale in the DJ Basin encompases a potentially productive area of over 9,000 square miles, at depths greater than 5,000 ft. Approximately half of this area has been derisked, with more of the area derisked in the Wattenberg "core" area in Weld County and less of the area derisked in the eastern and nothern extentions of the "core" area. The Niobrara Shale deepens quickly to the west, from 5,000 ft in the east to over 9,000 ft near the Front Range, Figure 2-7. The majority of hydrocarbon production occurs at depths of 6,000 to 7,500 ft.

Figure 2-7. DJ-Niobrara Shale Depth

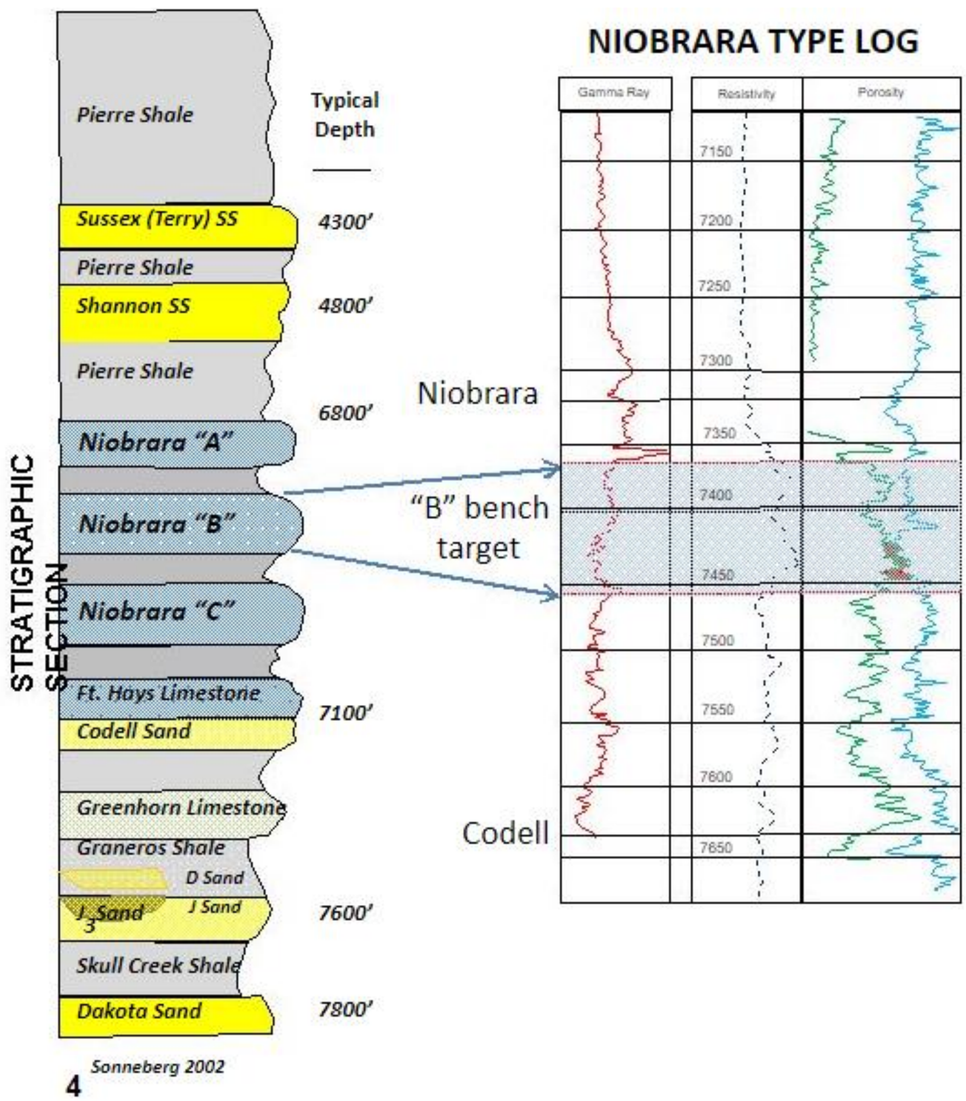


Source: Advanced Resources International, 2021.

2.3.2 DJ-Niobrara Shale Type Log

The type log for the DJ-Niobrara Shale is shown in Figure 2-8. The Niobrara "A", "B" and "C" benches are productive chalk units, each about 20-30 ft thick (Higley and Cox, 2007). Figure 2-8 highlights the Niobrara "B" bench, the currently targeted interval in the Niobrara Shale. The "B" bench is further divided into an "Upper B" and "Lower B" unit.

Figure 2-8. DJ-Niobrara Type Log



Source: Continental, 2010.

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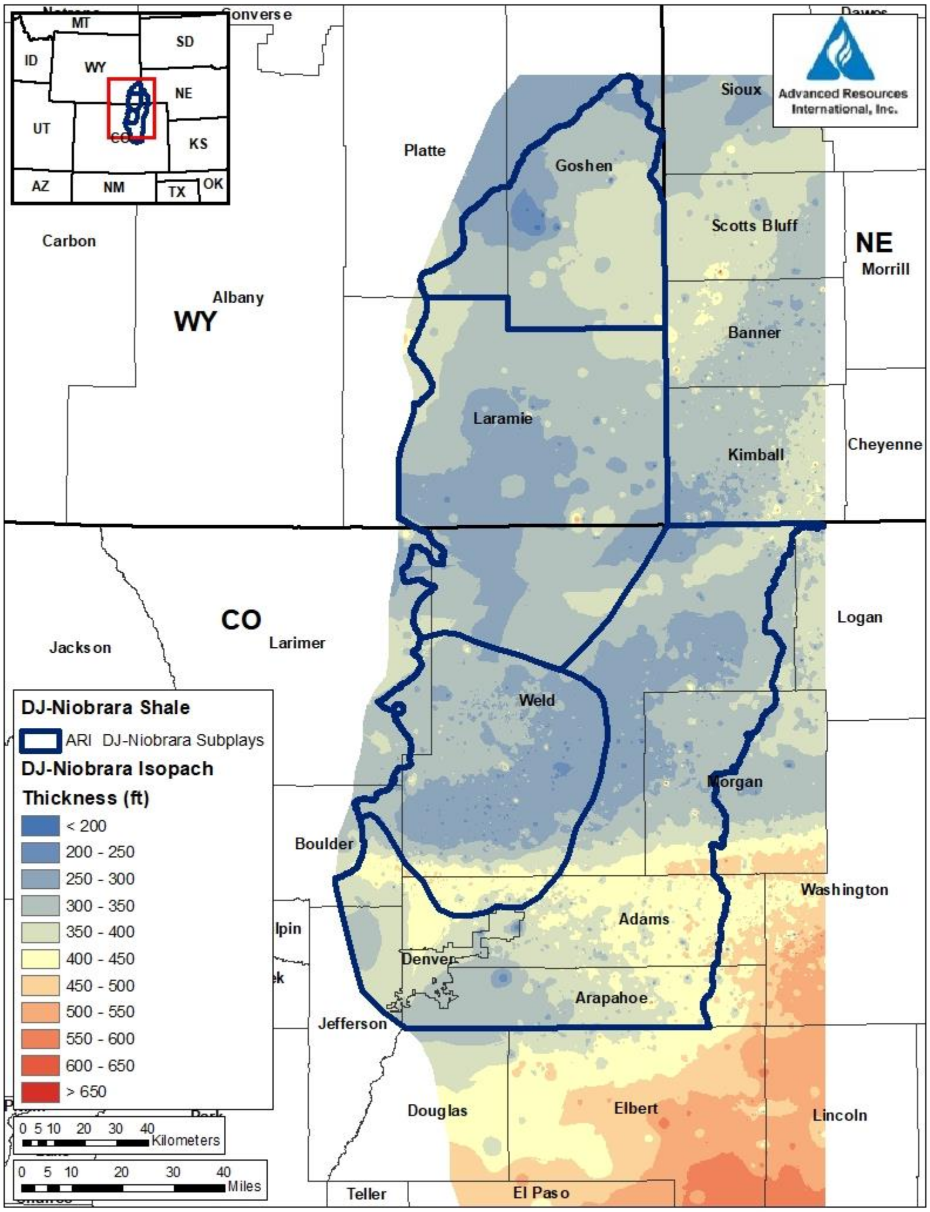
2.3.3 DJ-Niobrara Shale Thickness

The gross thickness of the Niobrara Shale in the DJ Basin ranges from about 500 ft in the southern portion of the play area to about 300 ft in the northern portion of the play area, Figure 2-9. In the highly drilled "core" area of Weld County, the Niobrara Shale is 200-300 ft thick, with a net pay of about 200 ft.

Figure 2-9. DJ-Niobrara Shale Isopach



Source: Advanced Resources International, 2021.

2.3.4 DJ-Niobrara Shale Porosity

The technical literature cites a porosity value of about 10% for the Niobrara Shale in the DJ Basin (Higley and Cox, 2007). History match and reservoir modeling work completed by Johnson in 2018 used an 8% porosity for DJ-Niobrara marl intervals and a 9% porosity for DJ-Niobrara chalk intervals. The study used porosity values for the DJ-Niobrara Shale ranging from 9% to 10.7% depending on area and rock type.

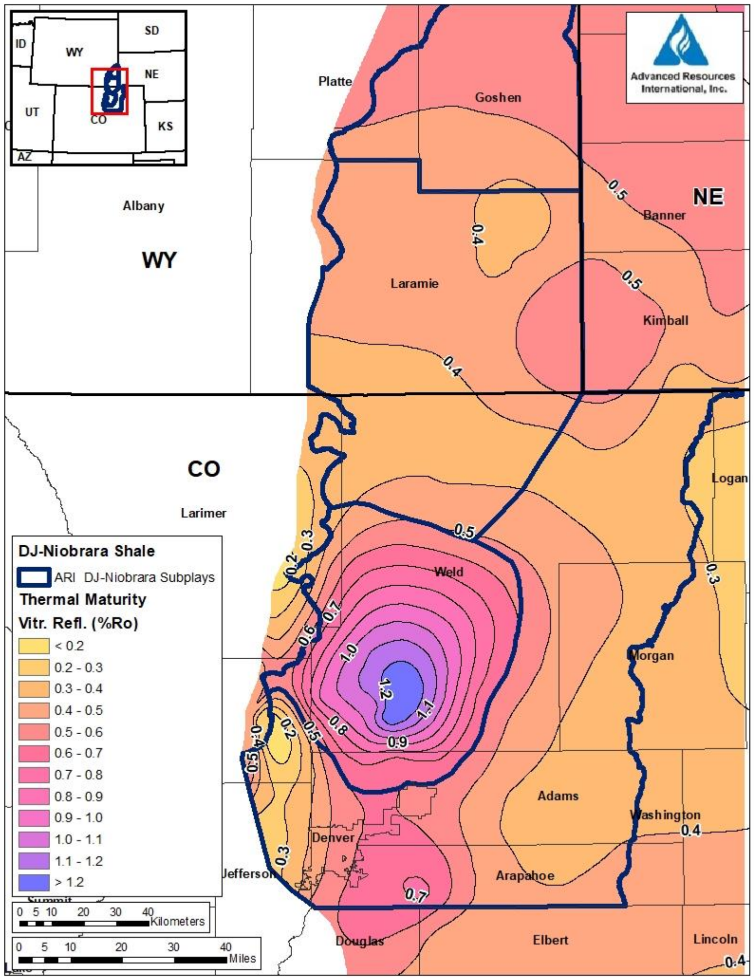
2.3.5 DJ-Niobrara Shale Oil and Water Saturations

The technical literature reports water saturations of 23% (Ning, 2017) and 33% (Johnson, 2018) for the DJ-Niobrara chalk intervals. Production data show that the majority of the water produced is flowback from fracturing and completion operations. The study used an average water saturation of 35%, with a somwhat lower value for the chalk and a somewhat higher value for the marl.

2.3.6 DJ-Niobrara Shale Thermal Maturity

The thermal maturity of the DJ-Niobrara Shale ranges from over 1% Ro in the Wattenberg "core" area to below 0.6% Ro in the Eastern and Nothern Extention areas, Figure 2-10. The Wattenburg "core" area has a high producing gas oil ratio (GOR) with lower producing GOR's in the extention areas.

Figure 2-10. DJ-Niobrara Shale Thermal Maturity



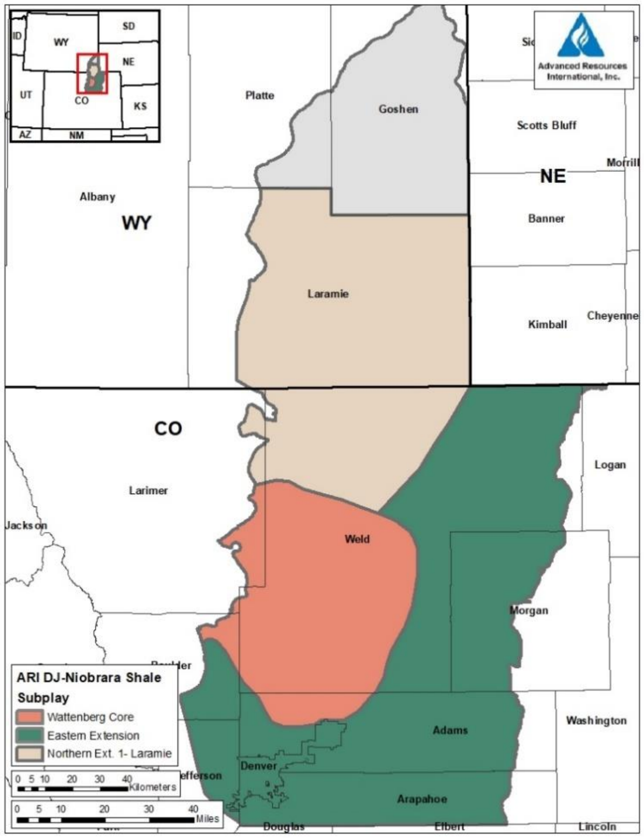
Source: Advanced Resources International, 2021.

2.4 Defining and Characterizing the DJ-Niobrara Shale Plays

2.4.1 Defining the DJ-Niobrara Plays

The Niobrara Shale in the DJ Basin has been partioned into three geologically similar resource assessment units: (1) the Wattenburg "core" area; (2) an Eastern Extension area; and (3) a Northern Extension area, Figure 2-11.

Figure 2-11. CO_2 Storage Capacity Assessment Units of the DJ-Niobrara Shale Area



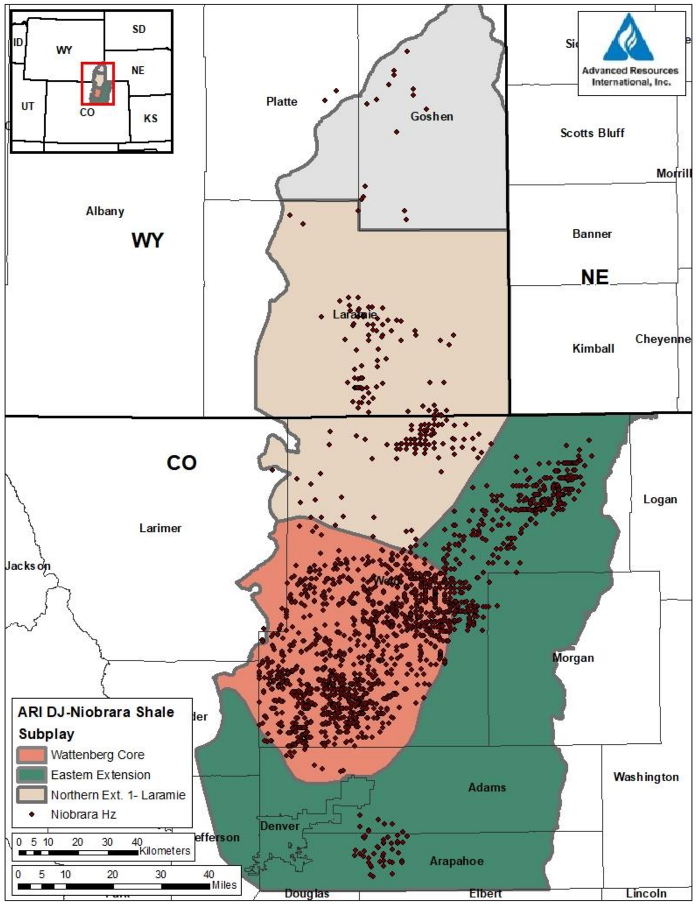
Source: Advanced Resources International, 2021.

The Wattenburg "core" area is the most highly developed partition of the Niobrara Shale, Figure 2-12. Drilling in the Eastern Extension area is largely focused in northwest Weld County and a small portion of Arapahoe County. Despite significant development in the Northern Extension area, the resource remains poorly defined. Goshen County in Wyoming has been excluded from this resource assessment due to the poor quality and limited number of wells.

2.4.2 Characterizing the DJ-Niobrara Plays

Table 2-3 provides the key reservoir properties for the three CO_2 storage capacity assessment units of the Niobrara Shale area.

Figure 2-12. Horizontal Completions in the DJ-Niobrara Shale Area



Source: Advanced Resources International, 2021.

Table 2-3. Reservoir Properties for the DJ-Niobrara Shale

Reservoir Properties	Wattenberg Core Area	Eastern Ext.	Northern Ext. 1
Total Area	1,840 mi^2	4,150 mi^2	3,070 mi^2
De-risked Area	1,470 mi^2	1,650 mi^2	1,380 mi^2
Average Depth	7,200 ft	6,000 ft	7,500 ft
Net Pay	200 ft	200 ft	200 ft
Porosity	10.7%	10.0%	9.0%
Oil Saturation	65%	65%	65%
Formation Volume Factor (RB/STB)	2.15	1.7	1.7
Producing GOR (Mcf/B)	8.1	2.5	1.7

Source: Advanced Resources International, 2021.

2.5 Constructing Representative Study Areas

The study established a geologically representative area for each of its three CO_2 storage and reource assessment units of the Niobrara Shale in the DJ Basin.

2.5.1 Representative "Core" Study Area

The key reservoir properties for the representative "core" Study Area surrounding the Wattenburg Field are shown below in Table 2-4.

Table 2-4. DJ-Niobrara Shale "Core" Study Area Reservoir Properties

Reservoir Properties	Units
Pattern Area	128 acres
Hz Well Pattern Dimensions	
▪ Length	8,500 ft
▪ Width	660 ft
Depth (to top)	7,200 ft
Net Pay	200 ft
Porosity	
▪ Matrix (Avg)*	10.7%
▪ Fracture	1.0%

Reservoir Properties	Units
Initial Oil Saturation (Avg)*	
▪ Matrix/Fracture	65% / 1%
Solution Gas/Oil Ratio	1.8 Mcf/B
Formation Volume Factor	2.15 RB/STB
Initial Pressure	4,100 psia
Temperature	240 °F
Bubble Point	3,400 psia
Formation Compressibility	1.00 E $^{-6}$/psi
Oil Gravity	41 °API

*Rock Units	Net Pay	Porosity	Oil** Saturation
Chalk	140	11.0%	67%
Marl	60	10.0%	59%
Total	200	10.7%	65%

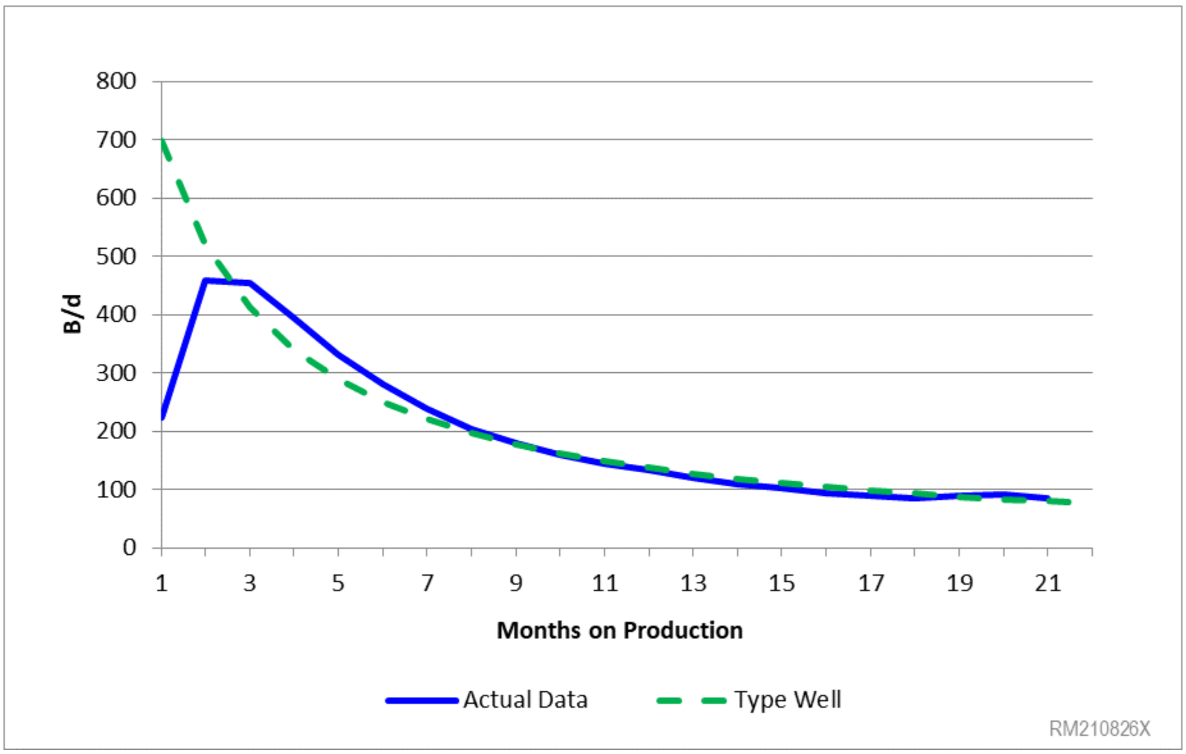
**Total Porosity and Oil Saturation is based on a weighted average of each Rock Unit.

Source: Advanced Resources International, 2021.

2.5.2 Representative Type Well for "Core" Study Area

The performance type well, shown below in Figure 2-13, represent the composite production performance of 814 horizontal (Hz) wells drilled in 2019 in the Wattenburg "core" area of the DJ-Niobrara Shale. The type well for this Study Area covers 128 acres, has a Hz lateral of 8,500 ft, a net pay of 200 ft, and an estimated gross oil recovery of 260,000 barrels. Similar "type wells" were constructed for the other two resource assesment units of the Niobrara Shale defined by this study.

Figure 2-13. DJ-Niobrara Shale "Core" Study Area Type Well Oil Production



Source: Advanced Resources International, 2021.

2.6 Reservoir Simulation

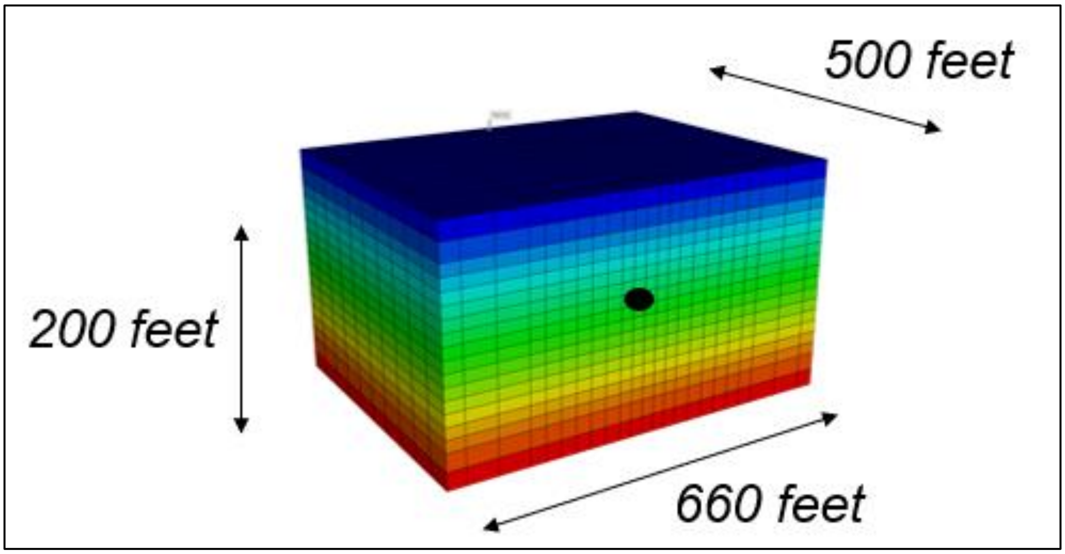
2.6.1 Model Construction

The GEM reservoir simulator from Computer Modeling Group (CMG) was utilized for the study. GEM is a robust, fully compositional, Equation of State (EOS) reservoir simulator used widely by industry for modeling the flow of three-phase, multi-component fluids through porous media. The reservoir model and grid blocks constructed to replicate the DJ-Niobrara Shale geologic and reservoir setting in the Study Area are illustrated in Figure 2-14.

The reservoir property values in Table 2-2 were used to populate the reservoir model and its 18 layers: 2 layers of 15 feet each to model 30 feet of “A” chalk, 3 layers of 10 feet each to model the “A” marl, 8 layers of 10 feet each to model the “B” chalk, 3 layers of 10 feet each to model the “B” marl, and 2 layers of 15 feet each to model the “C” chalk, Figure 2-15.

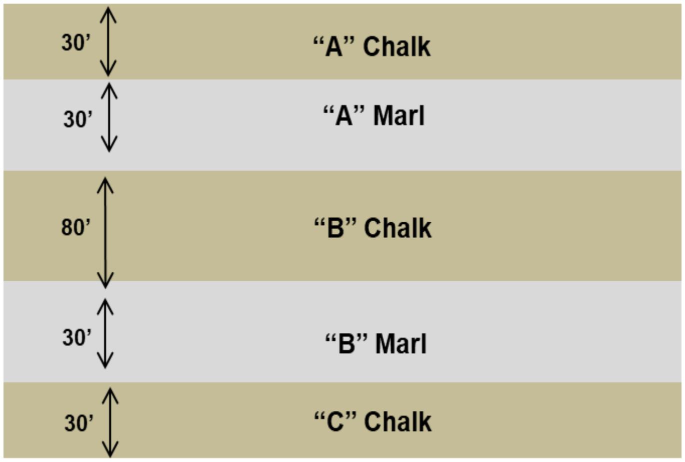
The model evaluates a 500 ft portion of the Hz well, which is 1/17th of the 8,500 ft lateral length of the “type well”. The well was completed in the center of the “B” chalk.

Figure 2-14. Reservoir Model and Grid Blocks Used for Niobrara Shale “Core” Study Area



Source: Advanced Resources International, 2021.

Figure 2-15. Reservoir Model Layers to Represent Distributed Lithology

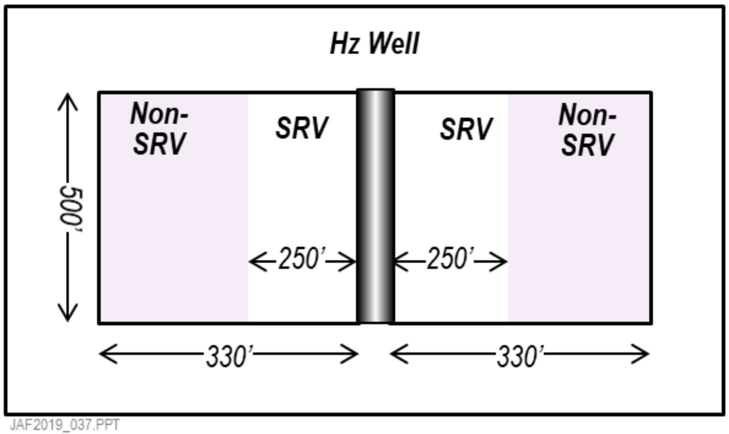


Source: Advanced Resources International, 2021.

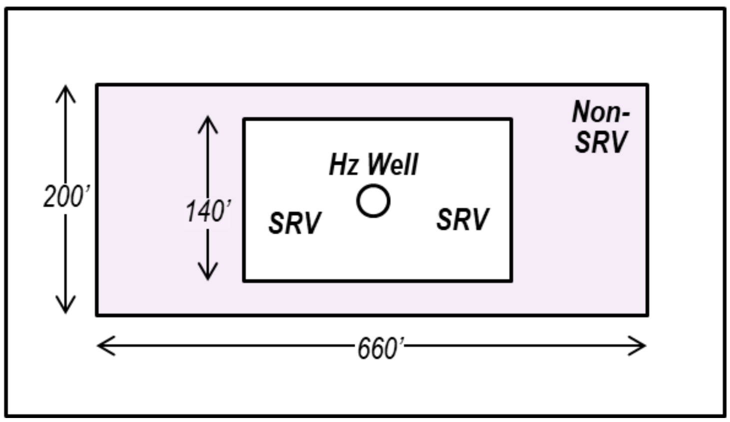
To capture the impact of the hydraulic stimulation on the performance of the horizontal well, a Simulated Reservoir Volume (SRV) was established in the model, with the dimensions and permeabilities described in Figure 2-16 and Table 2-5. Enhanced permeability was assumed in the SRV for the fracture and the matrix.

Figure 2-16. SRV Dimensions and Productivity Used to History Match Well Performance

A. SRV Dimensions, Plan View



B. SRV Dimensions, Side View



Source: Advanced Resources International, 2021.

Table 2-5. SRV and Non-SRV Permeability Used to Match Well Performance

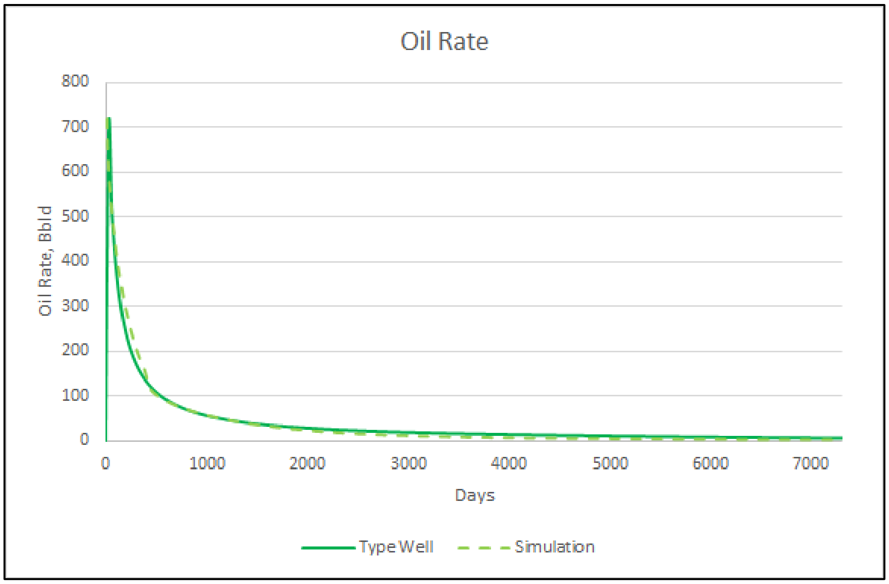
	Chalk Matrix	Marl Matrix
Non-SRV		
Horizontal	$5.6 * 10^{-3}$ mD	$5.8 * 10^{-5}$ mD
Vertical	$5.6 * 10^{-5}$ mD	$5.8 * 10^{-7}$ mD
SRV	0.14 mD	0.14 mD

Source: Advanced Resources International, 2021.

2.6.2 History-Matching Oil Production

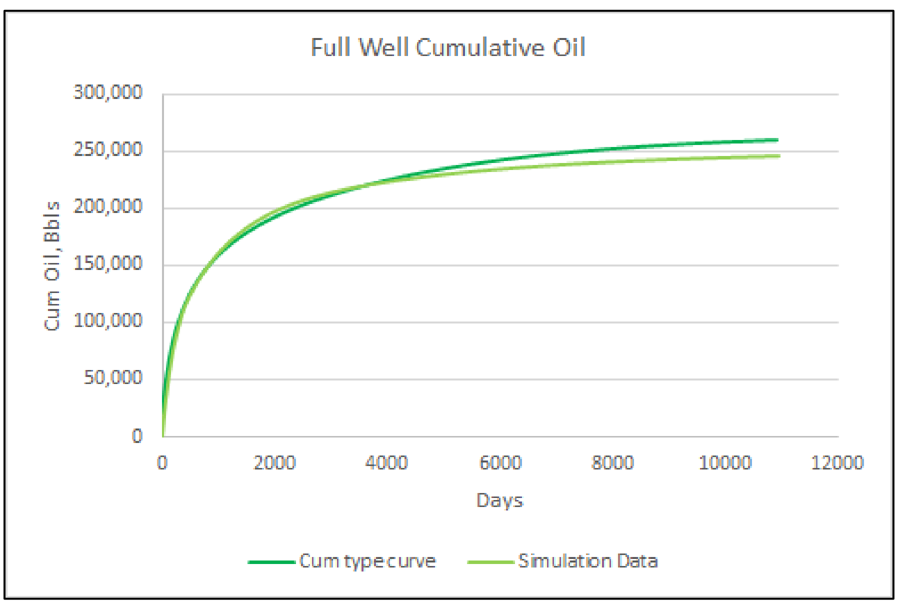
Using the DJ-Niobrara Shale reservoir properties in Table 2-4, the SRV dimensions in Figure 2-16, and the enhanced permeability values in Table 2-5, reservoir simulation achieved a good history match with the type well for the "core" Study Area (Figures 2-17 and 2-18). With an OOIP of 6.4 million barrels in the well pattern area and a 30-year history matched oil recovery of 246,000 barrels, the primary oil recovery efficiency is 3.8% of OOIP.

Figure 2-17. History Match of Oil Production



Source: Advanced Resources International, 2021.

Figure 2-18. Projection of 30 Years of Primary Production



Source: Advanced Resources International, 2021.

2.7 Performance of Cyclic CO_2 Injection

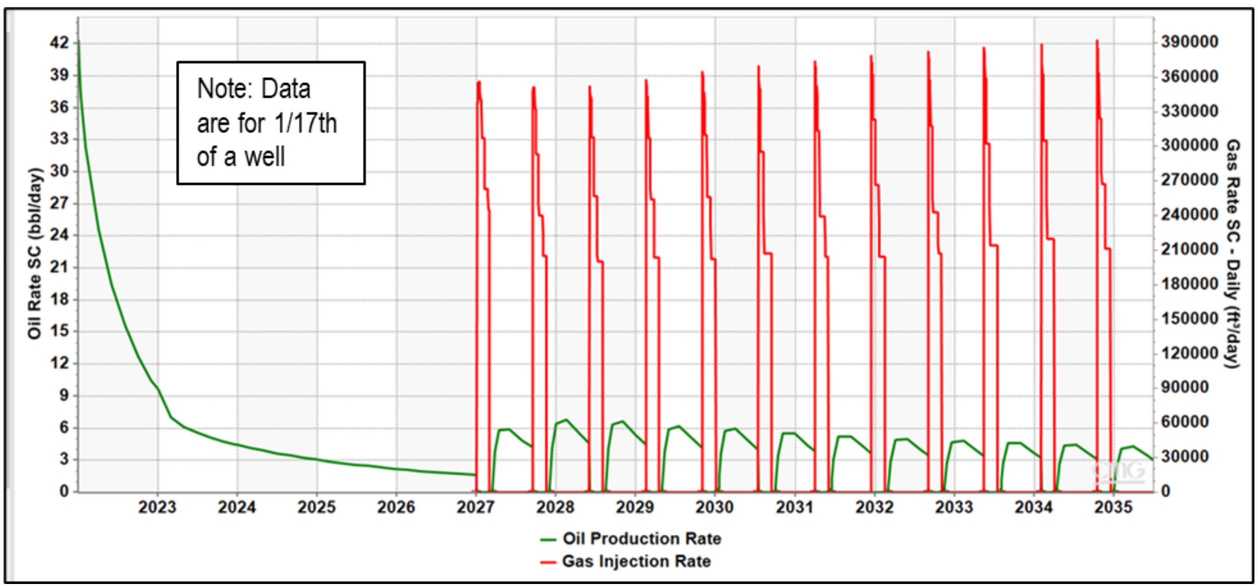
2.7.1 Performance of Cyclic CO_2 Injection

Cyclic CO_2 injection was initiated in the "core" Study Area well after five years of primary production. At this time, the Hz well had produced 193,000 barrels, equal to nearly 80% of its estimated ultimate oil recovery (EUR).

- In cycle one, CO_2 was injected at an average rate of 5,100 Mcfd for 2 months (BHP limit of 4,300 psia) to refill reservoir voidage, with a total of 303,000 Mcf of CO_2 injected.
- CO_2 injection was followed by a 2-week soak time and then followed by 6 months of production.
- Eleven additional cycles of CO_2 injection, soak and production followed.
- In the 13th and final cycle, all of the CO_2 produced during the 12th cycle was reinjected and the well was shut in. No production occurred in the 13th cycle.

Figure 2-19 illustrates the oil production and CO_2 injection data for the five years of primary production and the subsequent thirteen cycles (8.5 years) of cyclic CO_2 injection, soak and oil production from the partial, 1/17th of the total Hz well.

Figure 2-19. Cyclic CO_2 Injection Rates and By-Product Oil Production: Partial Well



Source: Advanced Resources International, 2021.

Advanced Resources International, Inc.

The 13 cycles of CO_2 injection into the Study Area well provides 134,000 barrels of incremental oil recovery (170,000 total barrels less 36,000 that would have been prouced by continuation of primary production) for an uplift factor of 1.59x over primary production, Table 2-6. Importantly, the 13 cycles of CO_2 injection also store 1,173 MMcf of CO_2. As such, the application of cyclic CO_2 injection into the DJ-Niobrara Shale would store 8.75 Mcf (0.46 metric tons) of CO_2 per barrel of oil.

Table 2-6. Cumulative Oil Production, CO_2 Injection and CO_2 Production: Study Area Well

	Cumulative Oil Production (MBbls)		**Cumulative CO_2 Injection** (MMscf)	**Cumulative CO_2 Production** (MMscf)	**Estimated CO_2 Storage** (MMscf)
	Total	**Incremental**			
End of 5-year primary	193		-	-	-
End of first cycle	208	8	303	133	170
End of 6th cycle	288	73	1,649	1,088	561
End of 12th cycle	363	134	3,307	2,397	910
End of 13th cycle	363	134	3,570	2,397	1,173

Source: Advanced Resources International, 2021.

The results from the “core” Study Area well were extrapolated to the larger Wattenberg “Core” area. Similar procedures were used to establish the CO_2 storage potential and incremental oil recovery potential for the other two Niobrara Shale resource assessment units in the DJ Basin.

2.8 Study Findings

Four major findings emerge from the study— "Increasing CO_2 Storage Options with Injection of CO_2 in Shales: Niobrara Shale, Denver-Julesburg Basin."

1. The Study Identified a Large Capacity CO_2 Storage Option in the Rockies. Cyclic injeciton of CO_2 into the DJ-Niobrara Shale provides opportunities to store 1,530 million metric tons (MMmt) of CO_2 while producing 3,340 million barrels (MMB) of low carbon intensity (12 g CO_2/MJ) oil, Table 2-7.

- **Wattenberg Core.** The Wattenberg Core Area provides CO_2 storage capacity of 450 MMmt of CO_2 with 985 MMB of low carbon intensity oil
- **Eastern Extension.** The Eastern Ext. area provides CO_2 storage capacity of 670 MMmt of CO_2 with 1,460 MMB of low carbon intensity oil.
- **Northern Extension-Laramie.** The Northern Ext. provides CO_2 storage capacity of 410 MMmt of CO_2 with 895 million barrels of low carbon intensity oil.

Table 2-7. CO_2 Storage and Low Carbon Intensity Oil Recovery from Cyclic Injection of CO_2: Niobrara Shale, DJ Basin

DJ-Niobrara Shale CO_2 Storage Assessment Area	Risked Area	Well Depth	CO_2 Storage with Cyclic Injection of CO_2	By-Product Oil Recovery with Cyclic Injection of CO_2
	(mi^2)	(ft)	(MMmt)	(MMB)
Wattenberg Core	1,470	7,200	450	985
Eastern Extension	1,650	6,000	670	1,460
Northern Ext.- Laramie	1,380	7,500	410	895
		Total	**1,530**	**3,340**

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2. The Niobrara Shale CO_2 Storage Option is Close to Large Point Sources of CO_2. Establishing a new, large capacity CO_2 storage setting is critical for commercial scale implementation of carbon capture at large, regional point sources of CO_2 near Denver, Colorado and the greater Rockies region. Identification of potential saline storage formations in the DJ Basin is nascent in development, with limited opportunities for storage explored thus far, (Hovorka et al., 2003). The DJ-Niobrara Shale offers a well-understood storage formation that would help avoid construction of long CO_2 pipelines for storing CO_2 from this area to other regions.

3. The Niobrara Oil Produced with Cyclic Injection and Storage of CO_2 Has Low Carbon Intensity. Life-cycle assessments in the technical literature enabled the study to establish that the carbon intensity of one barrel of oil produced from the Niobrara Shale of the DJ Basin with cyclic injection of CO_2 (Shale EOR) is 87 g CO_2/MJ. (Masnadi et al., 2018 and Godec et al., 2016)

As shown in Table 2-8, however, 75 g CO_2/MJ would be stored for every barrel of oil produced from the Mowry Shale, enabling this oil to have a carbon intensity of 12 g CO_2/MJ. This compares to a carbon intensity of 84 g CO_2/MJ for domestically produced conventional oil (Masnadi et al., 2018) and 85g CO_2/MJ for imported oil (ICCT, 2010), Table 2-8.

Table 2-8. Carbon Intensity of Alternative Sources of Oil Supply

Source of Carbon Emissions	Mowry Shale EOR Oil (g CO_2/MJ)	Other Oil Sources	
		Conventional Domestic Oil (g CO_2/MJ)	Imported Oil (g CO_2/MJ)
Conventional Production (Extraction, Transport, Refining)	11	11	12
EOR Operations	3		
Combustion	73	73	73
CO_2 Storage	(75)		
Total Carbon Intensity	**12**	**84**	**85**

4. Undertaking Cyclic Injection of CO_2 in the Niobrara Shale Would Improve the Business Case for CCUS. The revenues from the sale of CO_2 to the DJ-Niobrara Shale operators and the generation of state severance and royalty payments, along with federal tax credits such as 45Q, would notably improve private industry's "business case" for CCUS. It would also help maintain state tax revenues used largely for supporting education and infrastructure.

2.9 References

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Chapter 3. Cana-Woodford Shale

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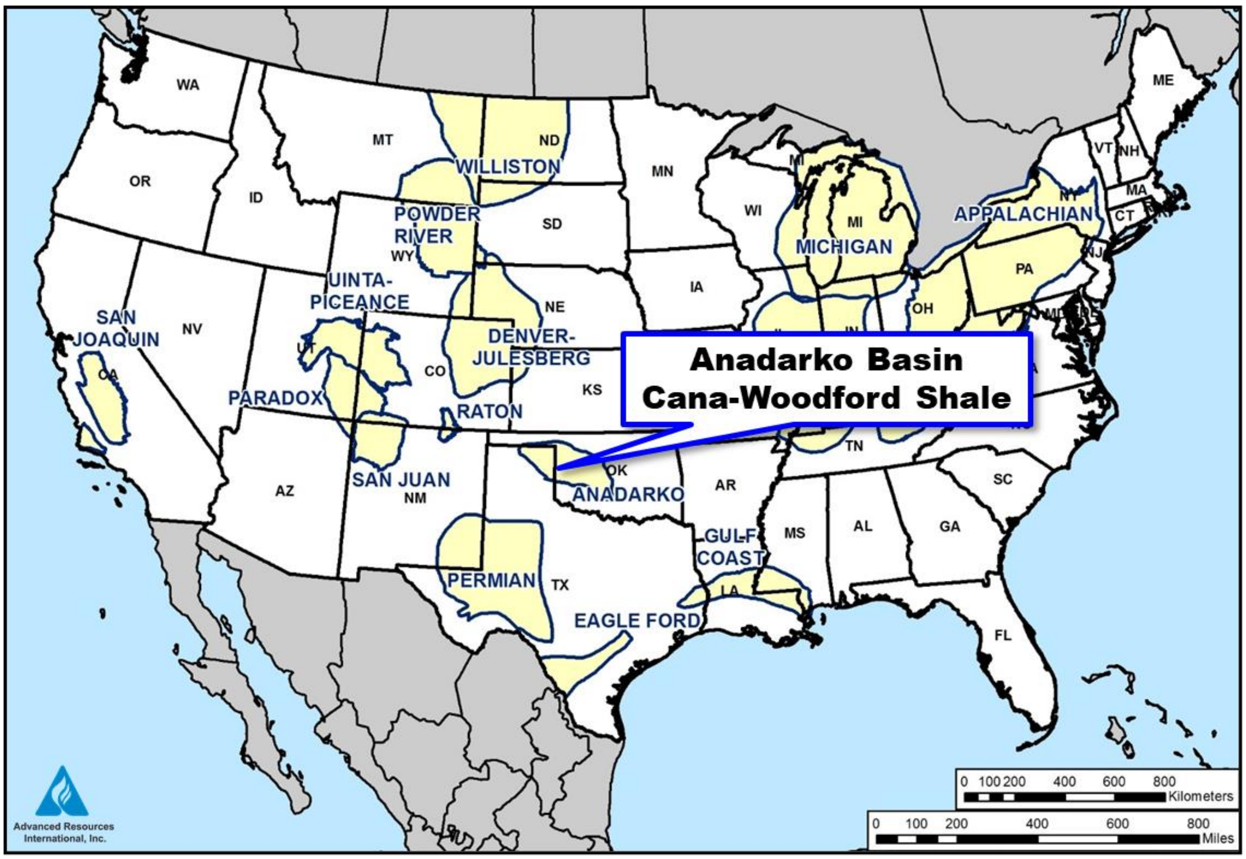
3. Cana-Woodford Shale, Anadarko Basin

3.1 Introduction and Summary of Findings

Chapter 3 of the Report addresses the potential for storing CO_2 and producing low carbon intensity oil from the Cana-Woodford Shale of the Anadarko Basin of western Oklahoma, Figure 3-1.

Figure 3-1. Location Map for Six Major U.S. Shale Oil Basins



JAF2021_032.PPT

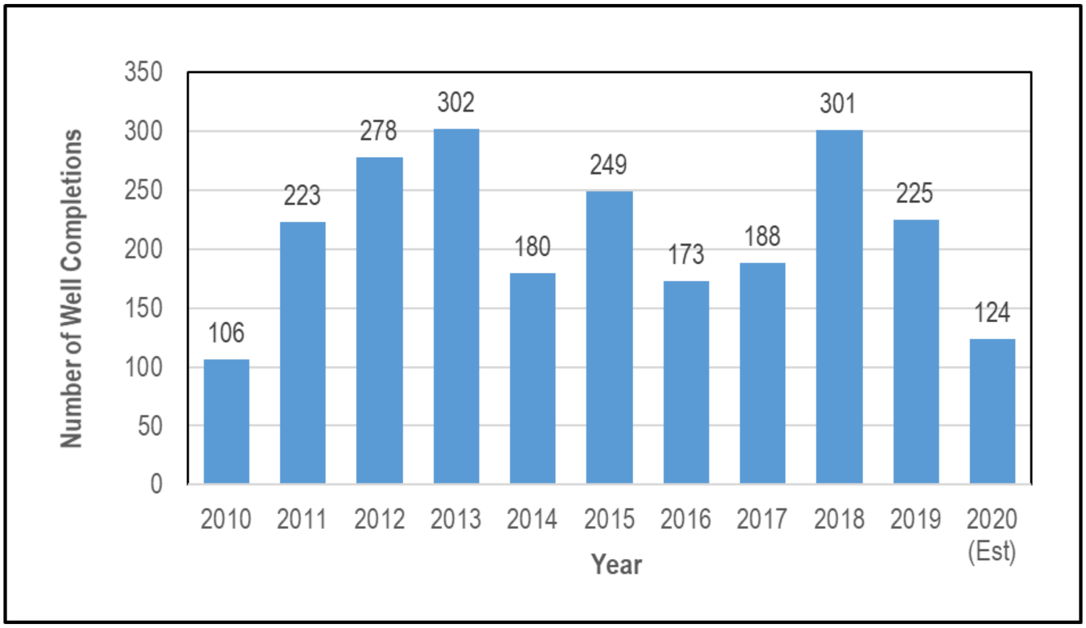
Source: Advanced Resources International's Tight Oil Database, 2021.

Advanced Resources International, Inc.

3.1.1 Cana-Woodford Shale Status and Development

The Cana-Woodford Shale of the Anadarko Basin is a rapidly maturing reource play, with nearly 2,500 wells drilled to date. From a base of about 106 horizontal (Hz) well completions in 2010, development increased rapidly, peaking at 302 Hz well completions in 2013, Figure 3-2. Since 2013, development has tended to track oil prices, with annual Hz well completions ranging from about 170 to 300. With lower oil prices and a steadily maturing reource play, Hz well completions in the Cana-Woodford Shale declined to about 120 in 2020 based on preliminary data.

Figure 3-2. Cana-Woodford Shale Hz Well Completions, 2010-2020



Source: Advanced Resources International's Tight Oil Database, 2021.

In line with lower well drilling, shale oil production from the steadily maturing Cana-Woodford Shale, providing 92,000 barrels per day in 2020, is projected to decline in 2021.

3.1.2 Study Findings

1. The Study Has Defined a New, Large Volume Option for Storage of CO_2 in the Mid-Continent Region. The study finds that 960 million metric tons (MMmt) of CO_2 could be stored in the Cana-Woodford Shale of the Anadarko Basin portion of Oklahoma using cyclic injection of CO_2 (Shale EOR), Table 3-1.

Table 3-1. CO_2 Storage and By-Product Oil Recovery from Application of Cyclic Injection of CO_2

Shale Formation / Basin	CO_2 Storage with Shale EOR	Low Carbon Intensity Oil Recovery with Shale EOR	CO_2 Storage with Shale EOR*	
	(MMmt)	(MMB)	(mt/B)	(g/MJ)
Cana-Woodford Shale / Anadarko Basin	960	1,710	0.56	92

*The conversion of metric tons of CO2 per barrel of oil (mt/B) to grams of CO2 per Mega Joule (g/MJ) uses 10^6 g/mt and 6,120 MJ/B oil.

Establishing new, large-scale CO_2 storage settings is particularly important for Oklahoma because:

- The dominant saline aquifer, the Arbuckle Formation, has already stored massive volumes of water produced from conventional oil and gas wells in the Anadarko Basin.
- The continued injection and disposal of produced water from these wells has raised the reservoir pressure in portions of this basin sufficiently to create induced seismic activity, leading to constraints on future injection of water into the Arbuckle Formation.
- The CO_2 emissions captured from power and other industrial plants in Oklahoma would require constructing long distance CO_2 pipelines to CO_2 storage sites in the Illinois Basin or the Williston Basin of North Dakota.

2. Development of the Cana-Woodford Shale with Cyclic Injection of CO_2 Would Provide an Alternative Source of Low Carbon Intensity Domestic Oil. Life-cycle assessments in the technical literature enabled the study to establish that the carbon intensity of one barrel of oil produced from the Cana-Woodford Shale of the Anadarko Basin with cyclic injection of CO_2 is 87 g CO_2/MJ. (Masnadi et al., 2018 and Godec et al., 2016) However, as shown in Table 3-1 and Table 3-2, 92 g CO_2/MJ would be stored for every barrel of oil produced from the Cana-Woodford Shale, enabling this oil to have a negative carbon intensity of 5 g CO_2/MJ.

This compares to a **positive** carbon intensity of 84 g CO_2/MJ for domestically produced conventional oil (Masnadi et al., 2018) and 85 g CO_2/MJ for imported oil, Table 3-2. (ICCT,2010)

Table 3-2. Carbon Intensity of Alternative Sources of Oil Supply

Source of Carbon Emissions	Cana-Woodford Shale EOR Oil (g CO_2/MJ)	Other Oil Sources	
		Conventional Domestic Oil	Imported Oil
		(g CO_2/MJ)	(g CO_2/MJ)
Conventional Production (Extraction, Transport, Refining)	11	11	12
EOR Operations	3		
Combustion	73	73	73
CO2 Storage	(92)		
Total Carbon Intensity	**(5)**	**84**	**85**

3. Storing CO_2 In the Cana-Woodford Shale Would Improve the Business Case for CCUS. The Cana-Woodford Shale would provide an already established, secure setting for storing CO_2 in the Anadarko Basin, reducing the costs and need to transport CO_2 emissions captured in Oklahoma to other basins. In addition, the revenues from the sale of CO_2 to the Cana-Woodford Shale field and the generation of state severance and royalty payments, along with federal tax credits such as 45Q, would notably improve private industry's "business case" for CCUS while also helping maintain state tax revenues.

* * * * * * * * * *

The implementation of cyclic injection and storage of CO_2 in the Cana-Woodford Shale of the Anadarko Basin would support key Carbon Management goals-- adding new, economically viable options for geological storage of CO_2 and reducing the CO_2 footprint of domestic oil consumption by providing lower carbon intensity oil that would **displace** the consumption of higher carbon intensity oil from imports or other sources.

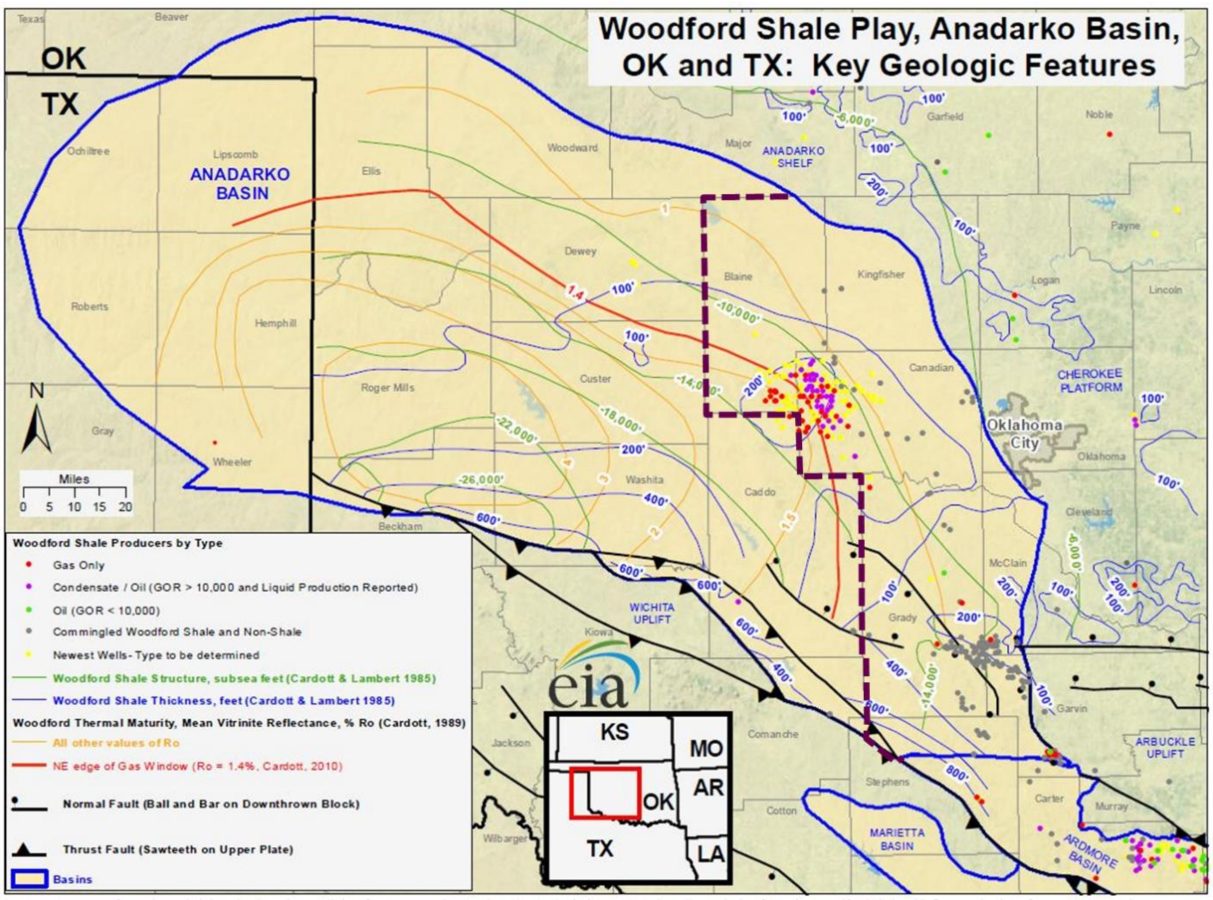
3.2 Geologic Setting of the Cana-Woodford Shale

3.2.1 Anadarko Basin Geographic Location

The Cana-Woodford Shale, located in west-central Oklahoma, produces oil and gas from the eastern portion of the Anadarko Basin, as shown by the dashed play ouline on Figure 3-3.

The “core” (highest quality) area of the Cana-Woodford Shale is located in Canadian County, hence the name Cana-Woodford. Other shale producing counties in this basin include Blaine and Kingfisher in the north, as well as Grady, McClain and Garvin counties in the south. In the deep, western portion of the play area, the Cana-Woodford Shale is predominantly a dry natural gas prospect. In the less thermally mature central and eastern portions of the shale deposit, the Cana-Woodford Shale transitions into a wet gas/condensate and oil prospect.

Figure 3-3. Cana-Woodford Shale Play Location Map

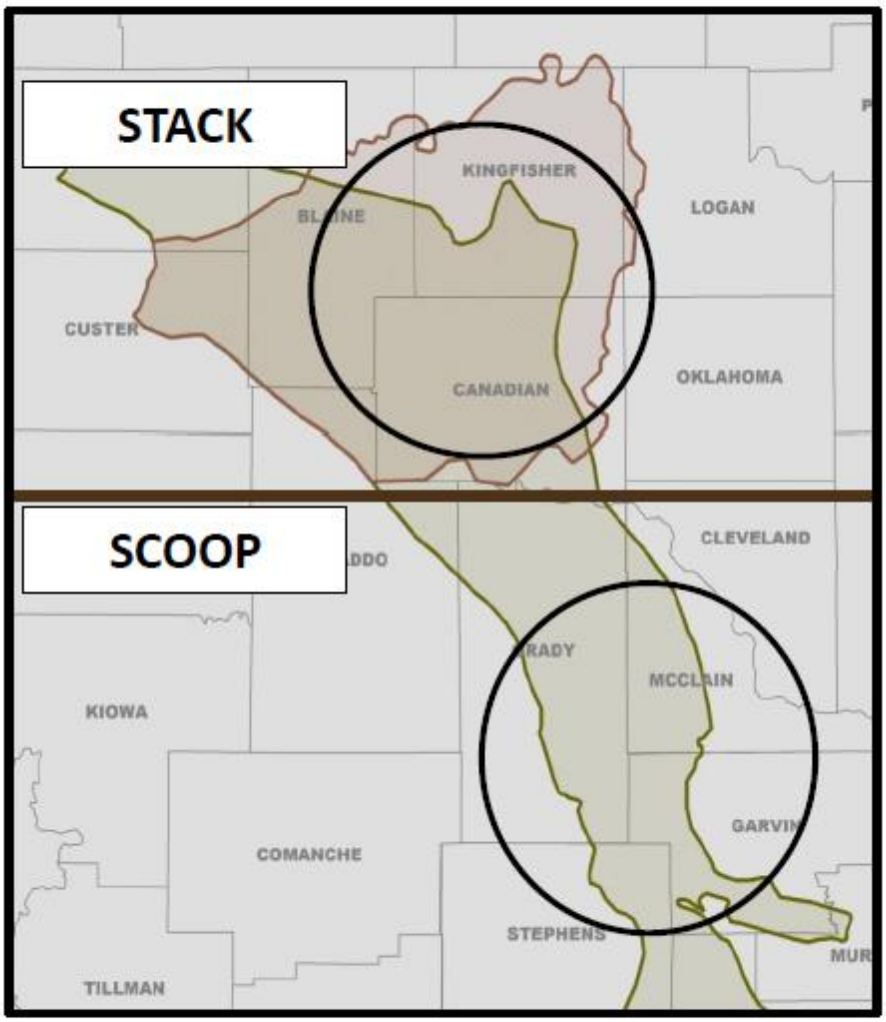


Source: Advanced Resources International, modified from U.S. EIA, 2011.

Advanced Resources International, Inc.

Industry refers to the northern producing counties of the Cana-Woodford Shale as the "STACK" (Sooner Trend, Anadarko Basin, Canadian and Kingfisher counties). The southern producing counties of the Cana-Woodford Shale are called the "SCOOP" (South Central Oklahoma Oil Provence), Figure 3-4. The SCOOP area includes notable portions of Grady, McClain, Stephens and Garvin counties.

Figure 3-4. STACK and SCOOP Areas of the Cana-Woodford Shale in the Anadarko Basin



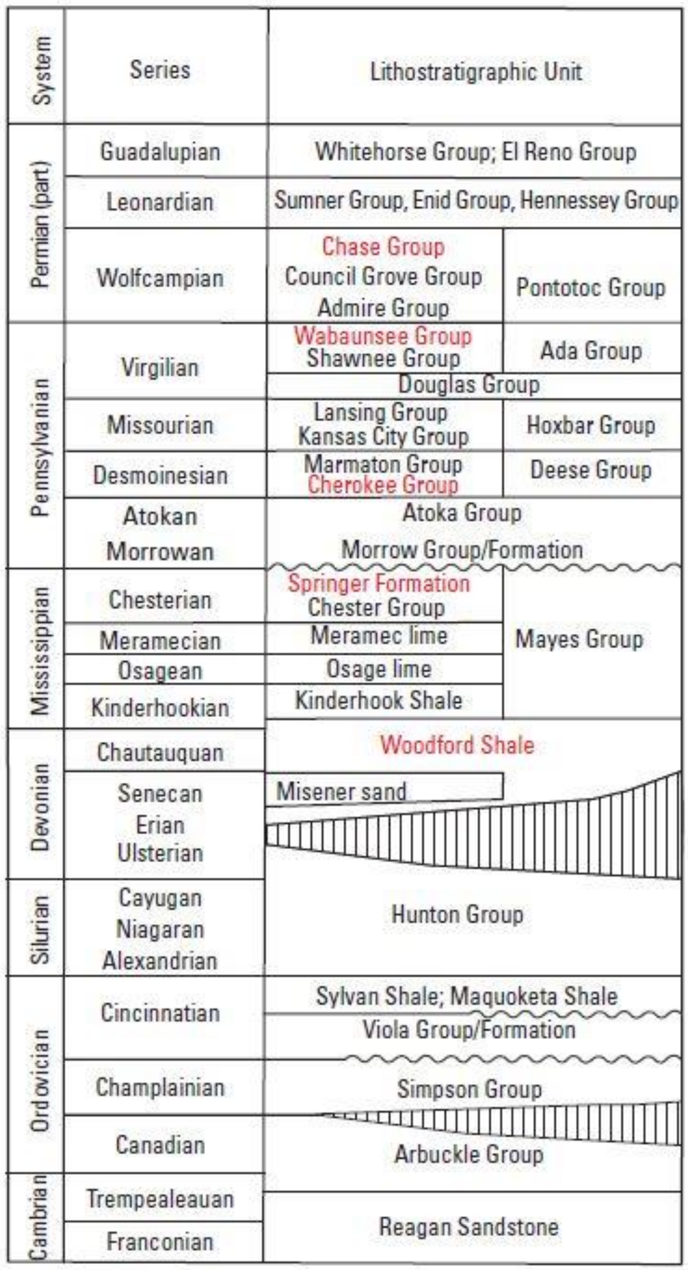
Source: Newfield Exploration, 2015.

Advanced Resources International, Inc.

3.2.2 Cana-Woodford Shale Stratigraphic Column

The Cana-Woodford formation is an Upper Devonian to Lower Mississippian marine shale deposit. It underlies the Meramec formation and overlies a regional unconformity and the Hutton formation, as shown by the Anadarko Basin stratigraphic column, Figure 3-5.

Figure 3-5. Anadarko Basin Stratigraphic Column



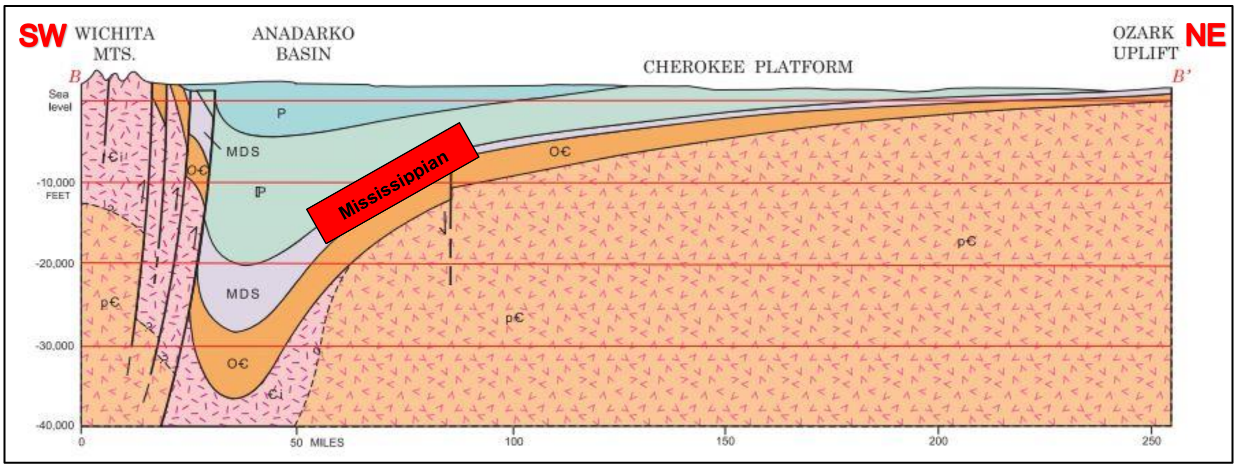
Source: Gianoutsos, 2014

Advanced Resources International, Inc.

3.2.3 Geologic Cross-Section

The SW-NE trending cross-section in Figure 3-6 shows the geologic structure for the area. The Mississippian and Devonian Cana-Woodford Shale in the Anadarko Basin deepens steeply to the west where it is partly over-thrusted by the Wichita Mountain Uplift. This stuctural setting helps explain the rapid east-to-west change in the depth and related thermal maturity of the Cana-Woodford Shale in the Anadarko Basin.

Figure 3-6. Anadarko Basin Cross-Section



Source: Johnson, 2008

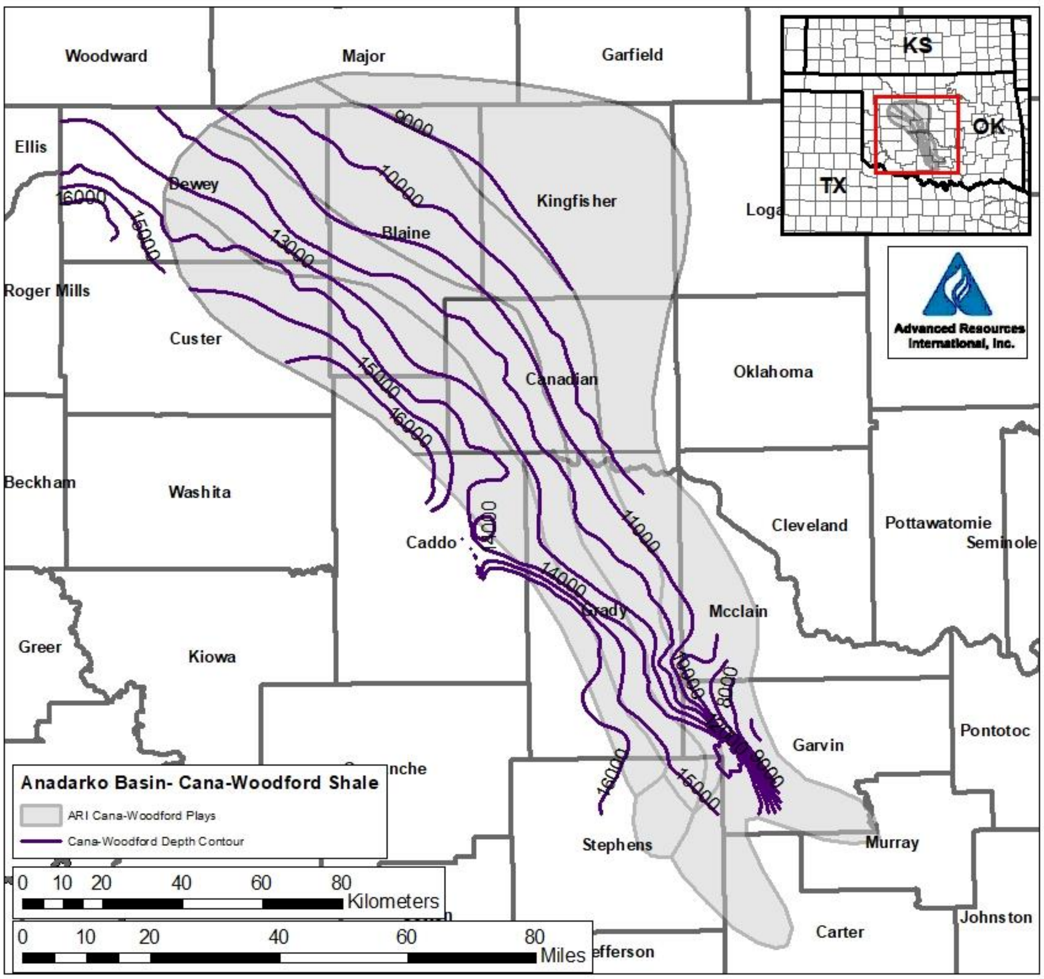
3.3 Establishing the Essential Reservoir Properties

3.3.1 Cana-Woodford Shale Assessment Area and Depth

The Cana-Woodford Shale encompasses an area of over 5,000 square miles, with the oil-dominant portions of the shale extending across approximately 3,200 square miles.

The Cana-Woodford Shale play ranges in depth from 8,000 ft near its north-eastern edge to over 15,000 ft along its south-western edge, Figure 3-7. Over-pressuring (up to 0.65 psi/ft) of the Woodford Shale begins at depths greater than 9,000 ft.

Figure 3-7. Cana-Woodford Shale Depth



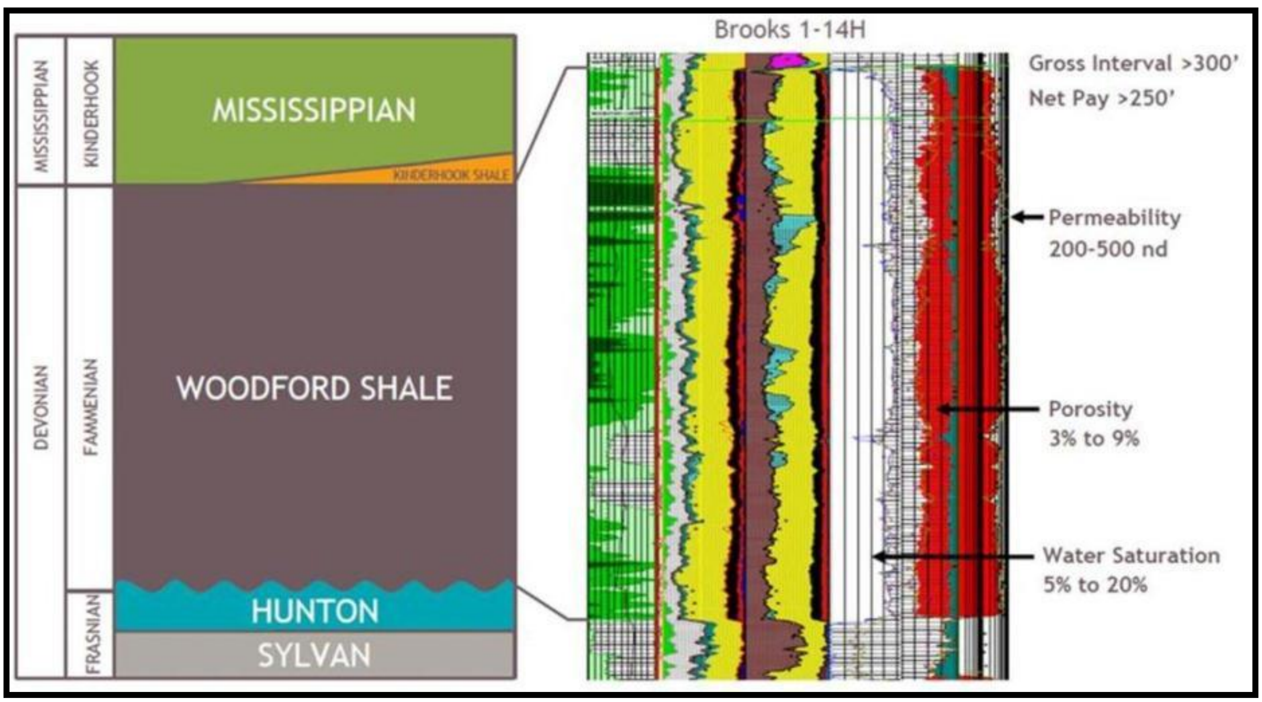
Source: Advanced Resources International, 2021.

In the condensate/wet gas "core" area of the nothern STACK area, the depth of the Cana-Woodford Shale ranges from 11,500 ft to 13,500 ft. In the eastern, oil dominant regions of the STACK, the depth of the Cana-Woodford Shale ranges from 8,000 ft to 10,000 ft. In the southern SCOOP area, the depth to the top of the Cana-Woodford Shale, in the oil dominant areas of eastern Grady, McClain, and Garvin counties, ranges from 9,000 to 12,000 ft.

3.3.2 Cana-Woodford Shale Type Log

The type log for the Cana-Woodford Shale in the "core" area of Canadian County is shown in Figure 3-8. Here the Cana-Woodford Shale has 250 ft of net pay within a gross interval of over 300 ft. Additional data show that Cana-Woodford Shale becomes thinner in the southeast to a low of about 100 ft. Porosity of the Cana-Woodford Shale in this type-log ranges from 3% to 9% while permeability ranges from 200 to 500 nano-darcies.

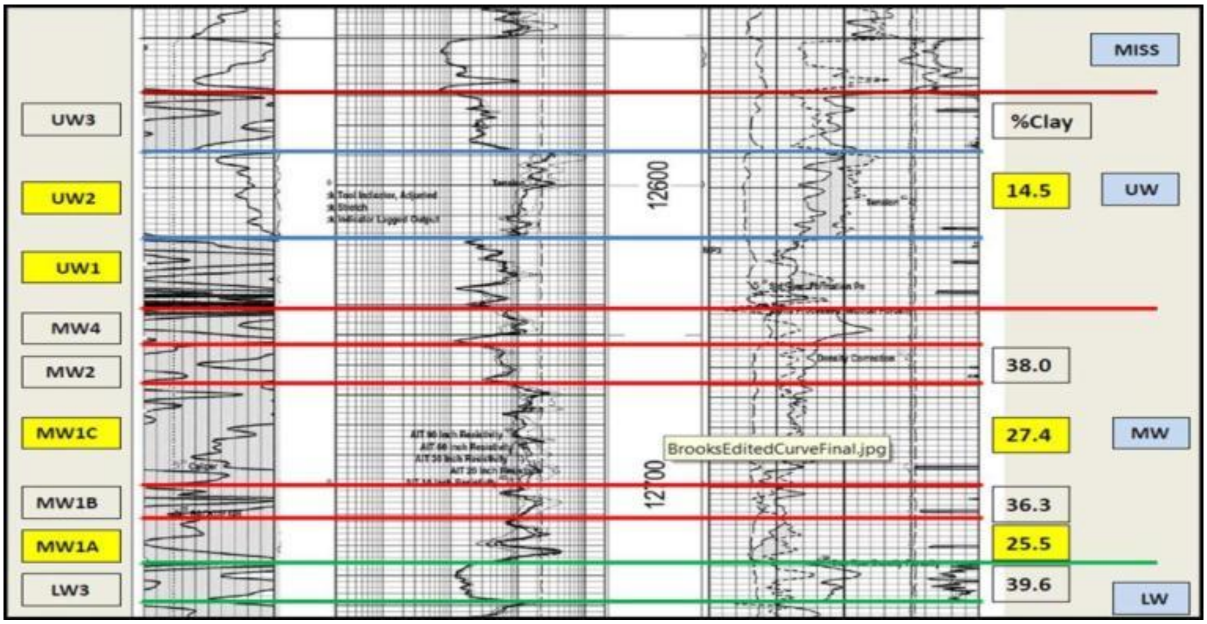
Figure 3-8. Cana-Woodford Shale Core Area Type Well Characteristics



Source: Devon, 2012.

Core data from the Cana-Woodford Shale show that the Upper Cana-Woodford has relatively lower clay content of about 14% to 15% while the Middle and Lower Cana-Woodford has considerably higher clay content that ranges from 26% to 40%, as shown by the well log on Figure 3-9. Total organic carbon (TOC) of the Cana-Woodford Shale ranges from 5% to 6.5% throughout the play area. Operators tend to target the Upper Cana-Woodford because of its lower clay content (Caldwell, 2013).

Figure 3-9. Cana-Woodford Shale Core Area Well Log

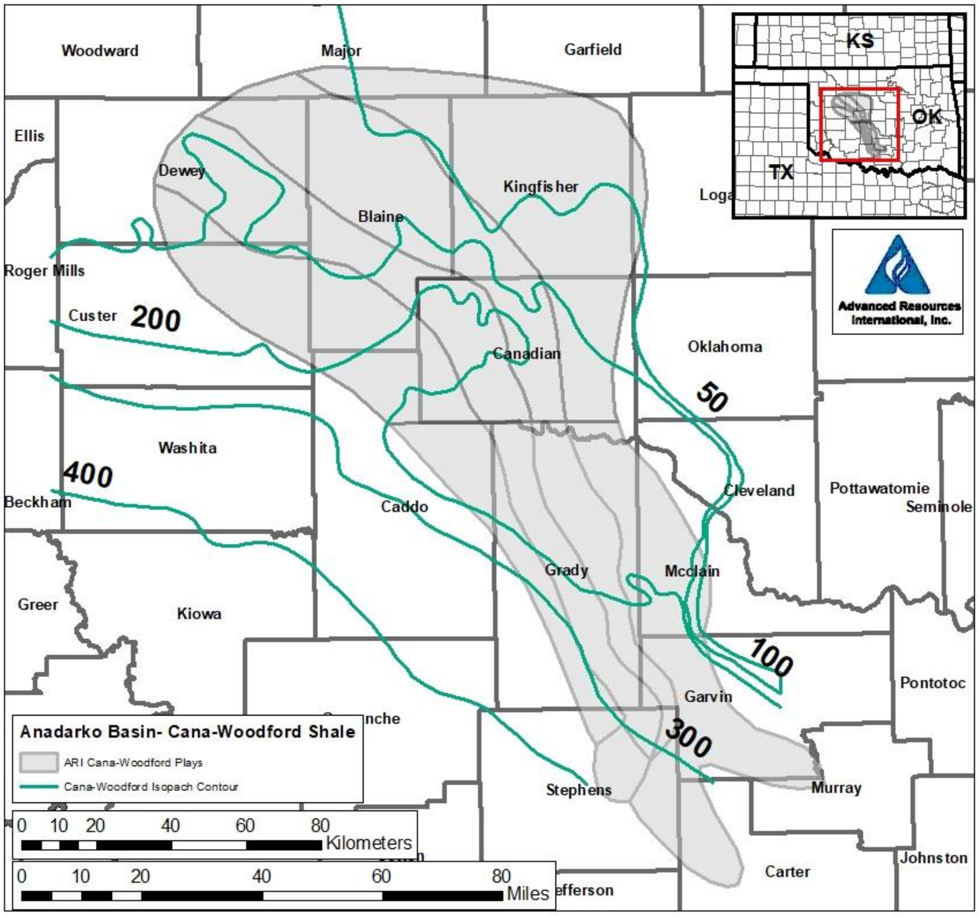


Source: Cimarex, Caldwell, 2013.

3.3.3 Cana-Woodford Shale Thickness

The shale formation is approximately 200 to 300 ft thick in the highly drilled west-central “core” area of Canadian County, Figure 3-10. The net thickness of the Cana-Woodford Shale in the oil dominant areas of eastern Canadian and Kingfisher counties ranges from 75 ft to 175 ft. The Cana-Woodford Shale in the SCOOP area is generally thicker than in the STACK area. For example, in Grady County the net shale thickness ranges from 150 ft to 350 ft.

Figure 3-10. Cana-Woodford Shale Isopach



Source: Advanced Resources International, 2021.

3.3.4 Cana-Woodford Shale Porosity

Based on industry published information, the porosity of the Cana-Woodford Shale ranges from, 6% to 9% in the condensate/wet gas core area in Canadian County and is somewhat higher, ranging from 7% to 10%, in the eastern, oil dominant portions of the play (Continental, 2010).

3.3.5 Cana-Woodford Shale Oil and Water Saturations

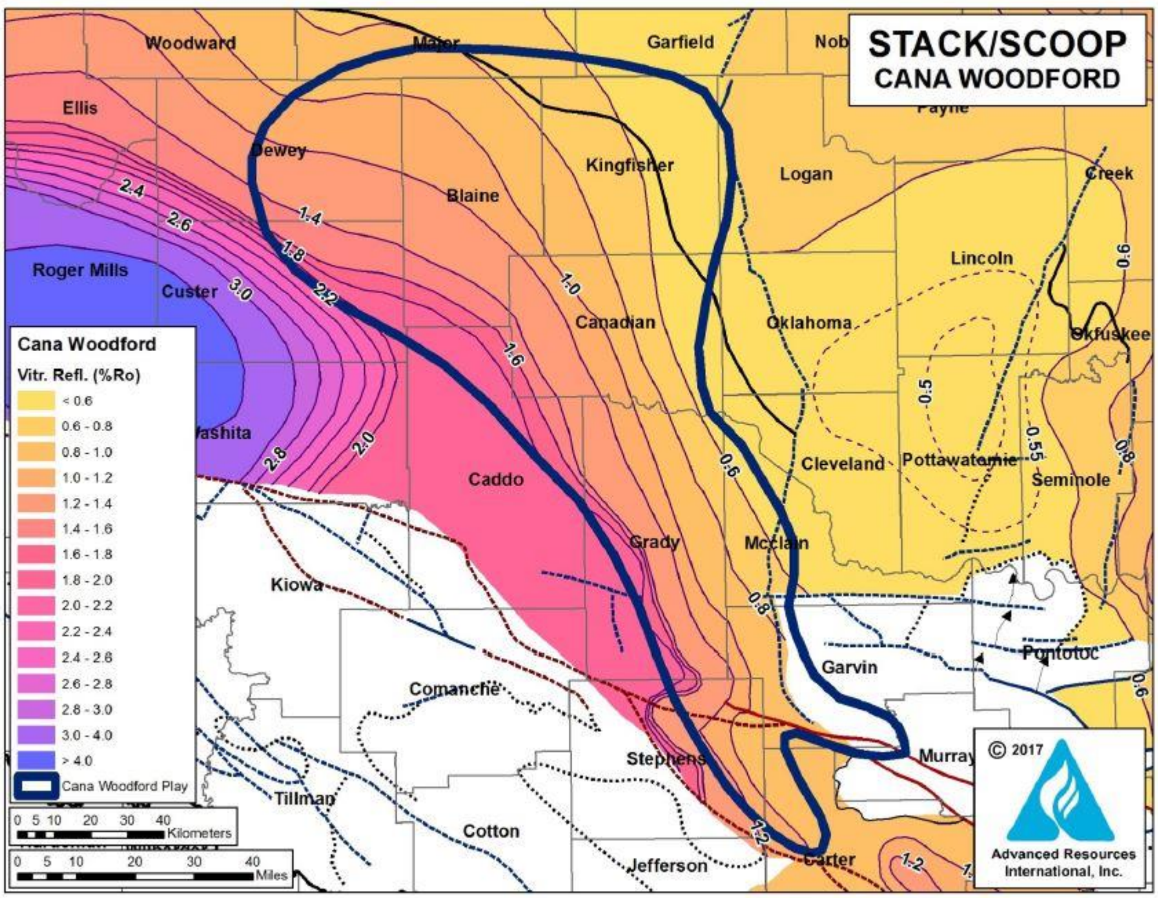
Information on the oil saturation of the Cana-Woodford Shale is scarce in the technical literature. Particularly challenging is establishing if oil saturations change across the oil dominant plays. Based on published research and independent reservoir modeling of the Cana-Woodford Shale, the initial mobile oil saturation is estimated to range from 53% to 64%, with an average of 60% (Ryan, 2017).

3.3.6 Cana-Woodford Shale Thermal Maturity

The diverse thermal maturity of the Cana-Woodford Shale has created three distinct settings: (1) a dry gas area; (2) a wet gas/condensate area; and (3) an oil area. Vitrinite reflectance (thermal maturity) is highest in the deep, western portions of the Cana-Woodford Shale play area, with lower thermal shale maturities observed to the east.

Dry gas production occurs in nothern Caddo and western Grady counties. Condensate/ wet gas production is prevalent in central Canadian, Blaine, Grady, and Stephens counties. The oil dominant area is located in eastern Canadian, northern Blaine, Kingfisher, McClain and Garvin counties, Figure 3-11.

Figure 3-11. Cana-Woodford Shale Thermal Maturity



Source: Advanced Resources International, 2021.

3.4 Defining and Characterizing the Cana-Woodford Shale Resource Assessment Area

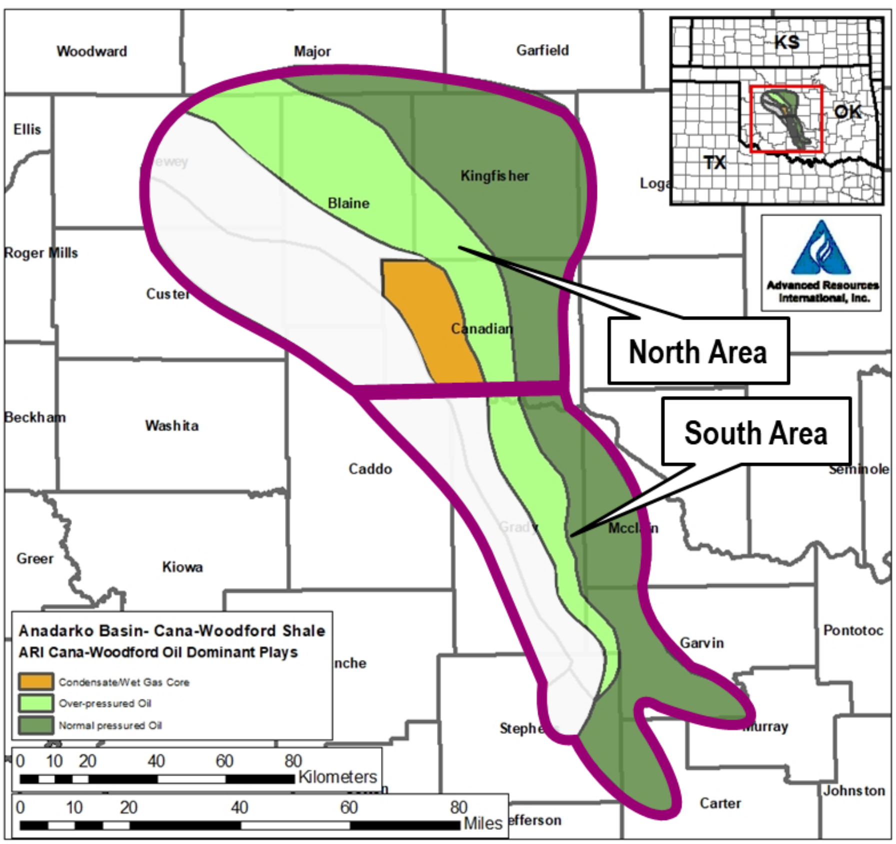
3.4.1 Defining the Cana-Woodford Plays

The center of activity in the Cana-Woodford Shale is the condensate/wet gas "core area" of west-central Canadian County, with the oil-dominant plays to the east and south of this area steadily becoming more active.

For the Cana-Woodford Shale oil dominant play areas, the normally-pressured and over-pressured oil plays can be defined by their gas-oil ratios (GORs). The core and over-pressured areas are characterized by realaively high GORs (8 to 13 Mcf/Bbl); the normally pressured areas have lower GORs (5 to 6 Mcf/Bbl).

The location of the northern and southern oil dominant plays of the Cana-Woodford Shale in the Anadarko Basin are shown on Figure 3-12.

Figure 3-12. Cana-Woodford Shale Oil Dominant Areas



Source: Advanced Resources International, 2021.

3.4.3 Characterizing the Oil Dominant Plays

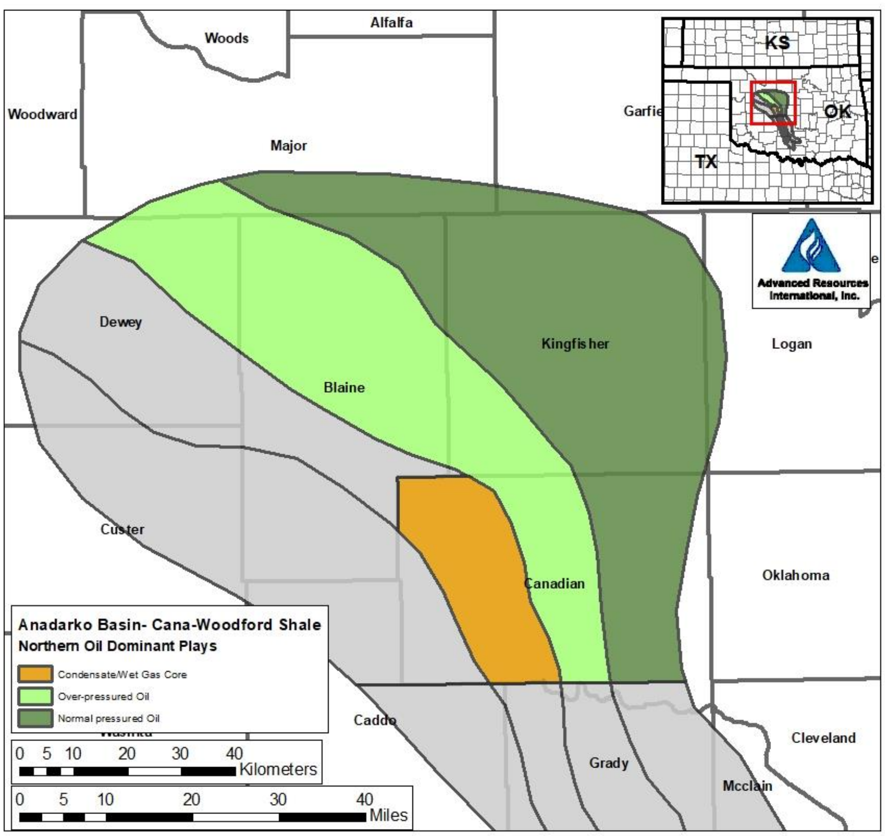
Three reource assessment units were defined for the northern STACK area and two resource assessment units were defined for the southern SCOOP area. For each resource assessment unit, the study assembled representative volumetric and other reservoir properties essential for estimating CO_2 storage capacity.

3.4.4 Northern Cana-Woodford Shale Area

The CO_2 storage capacity assessment for the Northern Cana-Woodford Shale extends across 2,000 square miles in Canadian, Blaine, and Kingfisher counties. Most of the drilling has occurred in Canadian County, the location of the “core” area of the Cana-Woodford Shale.

The Northern Cana-Woodford Shale Area is partitioned into three hydrocarbon assessment units: (1) a “core” area; (2) an over-pressured area; and (3) a normally-pressured area, Figure 3-13. Table 3-3 provides the key reservoir properties for the three CO_2 storage capacity assessment units of the Northern Cana-Woodford Shale area.

Figure 3-13. CO_2 Storage Capacity Assessment Units of the Northern Cana-Woodford Shale Area



Source: Advanced Resources International, 2021.

Table 3-3. Reservoir Properties for Estimating CO_2 Storage Capacity for the Northern Cana-Woodford Shale

Reservoir Properties	Core Area	Over-Pressured Area	Normally Pressured Area
Total Area	255 mi^2	750 mi^2	975 mi^2
Risked Area	205 mi^2	600 mi^2	780 mi^2
Average Depth	12,250 ft	9,800 ft	8,250 ft
Net Pay	250 ft	150 ft	100 ft
Porosity	6.5%	7.5%	7.5%
Oil Saturation	60%	60%	60%
Formation Volume Factor (RB/STB)	2.30	1.96	1.68
Solution GOR (Mcf/B)	13.3	8.4	5.8

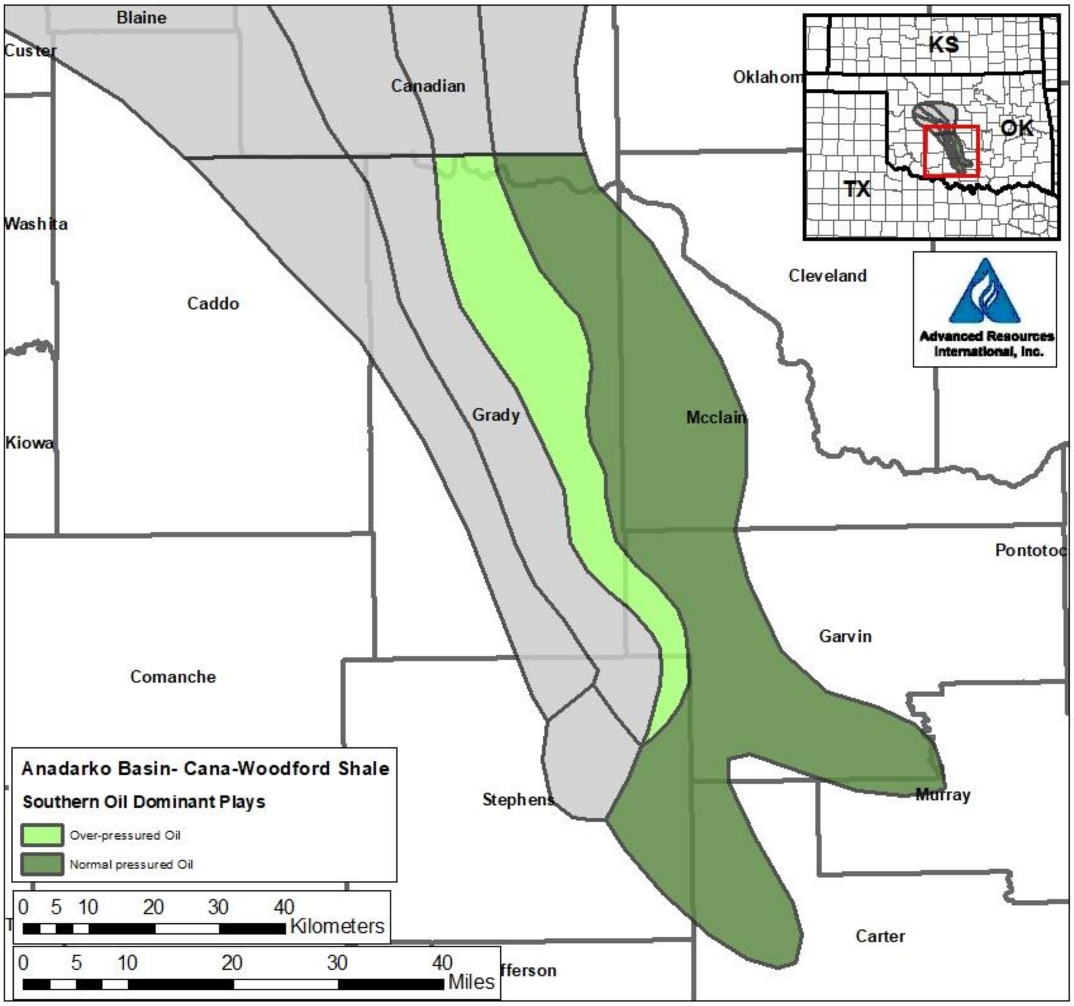
Source: Advanced Resources International, 2021.

3.4.5 Southern Cana-Woodford Shale Area

The CO_2 storage capacity assessment for the Southern Cana-Woodford Shale extends across 1,200 square miles, in Grady, McClain, Stephens and Garvin counties. The Southern Cana-Woodford Shale is partitioned into two CO_2 storage capacity assessment units: (1) an over-pressured area; and (2) a normally-pressured area, Figure 3-14.

Table 3-4 provides the key reservoir properties for the two CO_2 storage capacity assessment units of the Southern Cana-Woodford Shale area.

Figure 3-14. CO_2 Storage Assessment Units of the Southern Cana-Woodford Shale Area



Source: Advanced Resources International, 2021.

Table 3-4. Reservoir Properties for Estimating CO_2 Storage Capacity for the Southern Cana-Woodford Shale

Reservoir Properties	Over-Pressured Area	Normally Pressured Area
Total Area	320 mi^2	925 mi^2
Risked Area	260 mi^2	740 mi^2
Average Depth	13,500 ft	12,000 ft
Net Pay	200 ft	150 ft
Porosity	7.5%	7.5%
Oil Saturation	60%	60%
Formation Volume Factor (RB/STB)	2.25	2.05
Solution GOR (Mcf/B)	6.1	6.1

Source: Advanced Resources International, 2021.

3.5 Constructing Representative Study Areas

3.5.1 Representative Study Area

A geologically representative Study Area was etablished for each of the five CO_2 storage assessment units of the Cana-Woodford Shale, defined above. The key reservoir properties for the Southern Normally Pressured Shale Study Area are shown in Table 3-5.

Table 3-5. Cana-Woodford Shale Southern Normally Pressured Shale Study Area

Reservoir Properties	Units
Pattern Area	160 acres
Hz Well Pattern Dimensions	
▪ Length	9,100 ft
▪ Width	660 ft
Depth (to top)	12,000 ft
Net Pay	150 ft

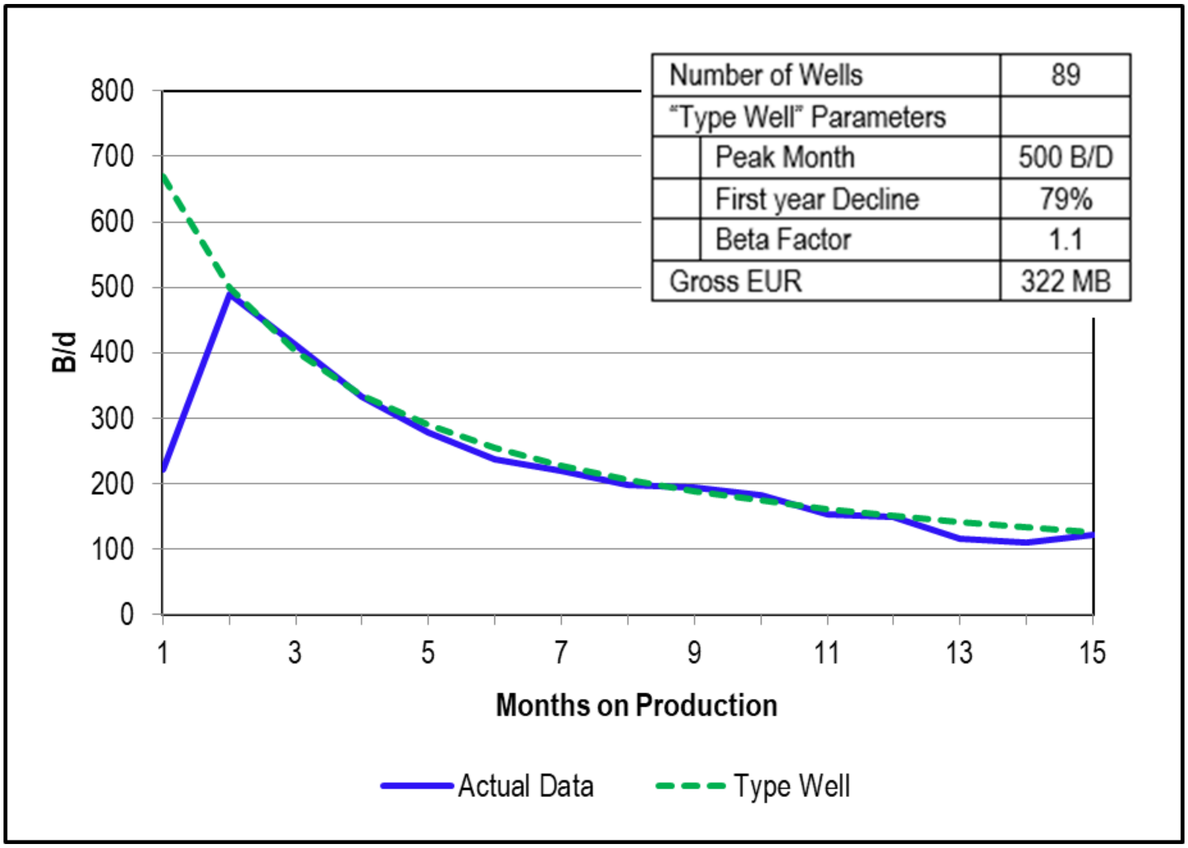
Reservoir Properties	Units
Porosity	7.5%
Oil Saturation	60%
Saturation Gas/Oil Ratio	6.1 Mcf/B
Formation Volume Factor	2.05 RB/STB
Pressure	6,000 psi
Temperature	240 °F
Oil Gravity	44 ° API

Source: Advanced Resources International, 2021.

3.5.2 Type Well for Southern Normally Pressured Shale Study Area

The "type well" for the Southern Normally Pressured Shale Study Area, Figure 3-15, represents the composite performance of 89 horizontal (Hz) wells drilled in 2019. The "type well" for this Study Area has a spacing of 4 wells per section (4 wells per 640 acres), a Hz well lateral of 9,100 ft, and an estimated gross primary oil recovery of 322,000 barrels.

Figure 3-15. Southern Normally Pressured Shale Study Area Type Well



Source: Advanced Resources International, 2020.

Similar "type wells" were constructed for each of the remaining four resource assesment units of the Cana-Woodford Shale defined by this study.

3.6 Performance of Cyclic CO_2 Injection

3.6.1 Performance of Cyclic CO_2 Injection

To estimate the volumes of CO_2 storage and incremental oil recovery, the study drew on previously modeled CO_2 storage and incremental oil recovery factors prepared for the Bakken Shale, Wolfcamp Shale and Eagle Ford Shale (Kuuskraa et al., 2020) and the Niobrara Shale in this report. These modeling studies provided a weighted average uplift factor of 1.59x (over primary oil recovery) for incremental oil recovery.

In the previous modeling studies of cyclic CO_2 injection, the CO_2 produced in the final (12^{th}) cycle, after being seperated from the produced oil, was vented and thus not stored. However, reinjecting the CO_2 produced in the 12^{th} cycle and then closing the well would enable significant volumes of additional CO_2 to be stored. Under this modified design, the weighted average CO_2 storage factor for the Cana-Woodford Shale would increase to 0.56 mt of CO_2 stored per barrel of incremental oil produced. Our initial assessment shows that the collection of 45Q tax credits for this addition volume of CO_2 storage would make this altenative CO_2 storage design cost-effective.

For additional information on GEM reservoir modeling and the assumptions used to calculate the oil recovery uplift and CO_2 storage from injection of CO_2 into the Wolfcamp Shale, Bakken Shale and Eagle Ford Shale, please refer to the USEA's previous report on storing CO_2 in domestic shale oil formations (Kuuskraa et al., 2020).

3.7 Study Findings

The study, "Increasing CO_2 Storage Options with Injection of CO_2 in Shales: Cana-Woodford Shale, Anadarko Basin", has produced four significant findings.

1. The Study Has Defined a New, Large Volume Geologic Option for Storing CO_2. The major finding is that the injection of CO_2 into the Cana-Woodford Shale leads to storage of 960 million metric tons (MMmt) of CO_2 and incremental recovery of 1,710 million barrels (MMB) of low carbon intensity oil. As shown the Northern and Southern areas of the Cana-Woodford Shale of the Anadarko Basin, Table 3-6.

- **Northern Shale Area.** The 1,585 square mile Northern Shale Area, called the STACK by industry, provides a CO_2 storage capacity of 515 million metric tons (MMmt) of CO_2 with 915 million barrels of by-product oil recovery.
- **Southern Shale Area.** The 1,000 square mile Southern Shale Area, called the SCOOP by industry, provides a CO_2 storage capacity of 445 MMmt of CO_2 with 795 million barrels of by-product oil recovery.

Table 3-6. CO_2 Storage and By-Product Oil Recovery from Application of Cyclic Injection of CO_2: Cana-Woodford Shale of the Anadarko Basin, Oklahoma

Cana-Woodford Shale Area	Risked Area	Well Depth	CO_2 Storage with Cyclic Injection of CO_2*	By-Product Oil Recovery with Cyclic Injection of CO_2*
	(mi²)	(ft)	(MMmt)	(MMB)
1. Northern Shale Area				
▪ Core Area	205	12,250	85	155
▪ Over-Pressured	600	9,800	200	355
▪ Normally-Pressured	780	8,250	230	405
		Sub-Total	**515**	**915**
2. Southern Shale Area				
▪ Over-Pressured	260	13,500	130	235
▪ Normally-Pressured	740	12,000	315	560
		Sub-Total	**445**	**795**
Cana-Woodford Shale Area Total			**960**	**1,710**

* Based on reservoir modeling of Bakken, Midland, Eagle Ford, and Niobrara Shales.

2. The Newly Defined CO_2 Storage Option is Essential for Supporting Large-Scale Implementation of CCUS in Oklahoma. The geologic characterization and reservoir modeling of the Cana-Woodford Shale in the Anadarko Basin identified an additional large-scale CO_2 storage setting important for Oklahoma:

- The dominant saline aquifer in the Anadarko Basin, the Arbuckle Formation, has already stored massive volumes of water produced from conventional oil and gas wells in the region.
- The continued injection and disposal of produced water from these wells has raised the reservoir pressure in portions of this basin sufficiently to create induced seismic activity, leading to constraints on injection of water into the Arbuckle Formation.
- Without the CO_2 storage capacity offered by the Cana-Woodford Shale, a significant portion of the CO_2 emissions captured from power and other industrial plants in the Oklahoma portion of the Anadarko Basin would need long distance CO_2 pipelines linked to storage sites in the Illinois Basin or the Williston Basin of North Dakota.

3. Use of Cyclic CO_2 Injection for the Cana-Woodford Shale Would Provide and Alternative Source of Low Carbon Intensity Domestic Oil. Life-cycle assessments in the technical literature enabled the study to establish that the carbon intensity of one barrel of oil produced from the Cana-Woodford Shale of the Anadarko Basin with cyclic injection of CO_2 is 87 g CO_2/MJ. (Masnadi et al., 2018 and Godec et al., 2016) However, as shown in Table 3-7, 92 g CO_2/MJ would be stored for every barrel of oil produced from the Cana-Woodford Shale, enabling this oil to have a negative carbon intensity of 5 g CO_2/MJ. This compares to a positive carbon intensity of 84 g CO_2/MJ for domestically produced conventional oil (Masnadi et al., 2018) and 85 g CO_2/MJ for imported oil, Table 3-7. (ICCT, 2010)

Table 3-7. Carbon Intensity of Alternative Sources of Oil Supply

Source of Carbon Emissions	Cana-Woodford Shale EOR Oil (g CO_2/MJ)	Other Oil Sources	
		Conventional Domestic Oil	Imported Oil
		(g CO_2/MJ)	(g CO_2/MJ)
Conventional Production (Extraction, Transport, Refining)	11	11	12
EOR Operations	3		
Combustion	73	73	73
CO2 Storage	(92)		
Total Carbon Intensity	**(5)**	**84**	**85**

4. Storing CO_2 with Cyclic Injection of CO_2 in the Cana-Woodford Shale would Improve the Business Case for CCUS in Oklahoma. The Cana-Woodford Shale would provide an already established, secure setting for storing CO_2 in the Anadarko Basin, reducing the costs and need to develop a new CO_2 storage facility or to transport CO_2 captured in Oklahoma to other basins.

In addition, the revenues from the sale of CO_2 to the Cana-Woodford Shale field and the generation of state severance and royalty payments, along with federal tax credits such as 45Q, would notably improve private industry's "business case" for CCUS while also helping maintain essential state revenues.

3.8 References

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Chapter 4. Mowry Shale, Powder River Basin

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Acknowledgements

A portion of the information on resource characterization and reservoir modeling related to cyclic CO_2 EOR in shale oil basins is based on work previously prepared by Advanced Resources International, Inc. for the U.S. Department of Energy, National Energy Technology Laboratory (U.S. DOE/NETL).

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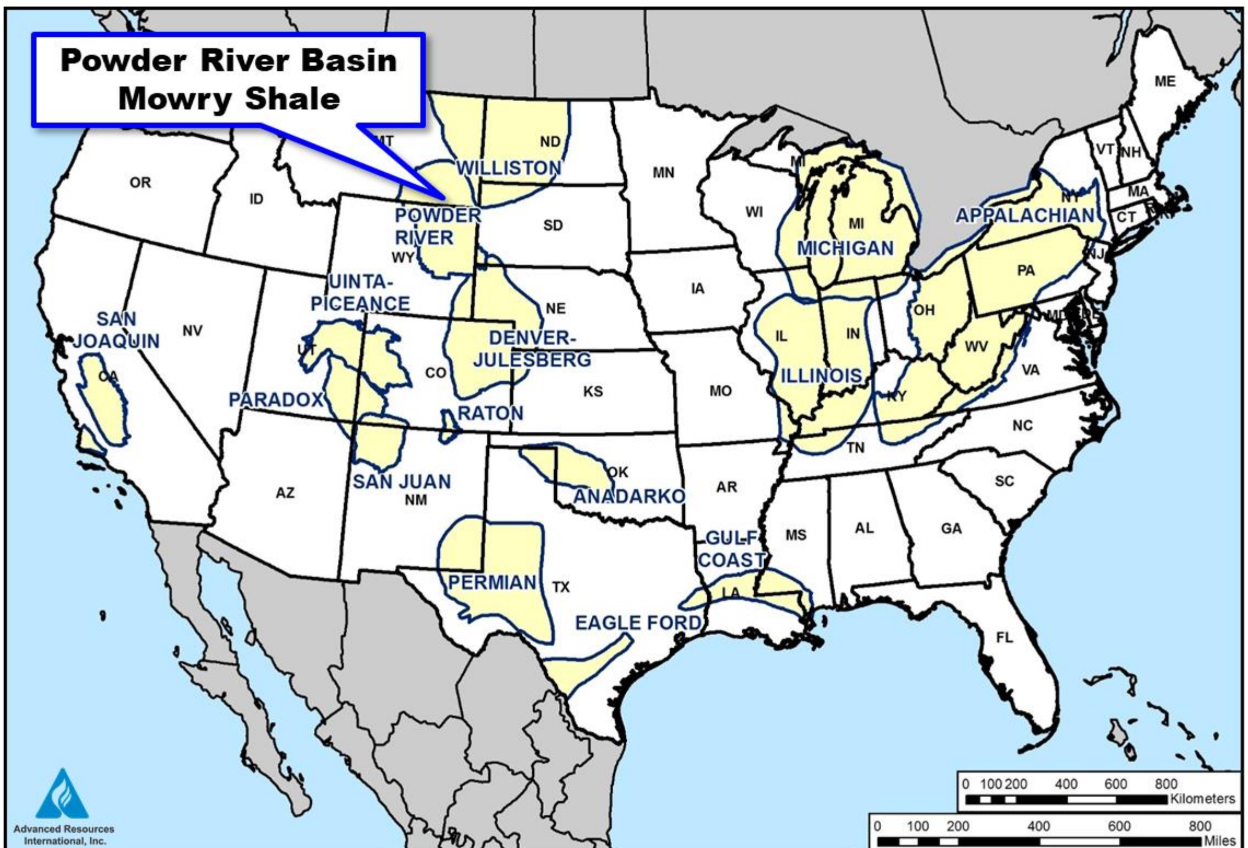
4. Mowry Shale, Powder River Basin

4.1 Introduction and Summary of Findings

Chapter 4 of the Report discusses the potential for storing CO_2 and producing low carbon intensity oil from the Mowry Shale of the Powder River Basin in Wyoming and Montana, Figure 4-1. Chapter 4 was prepared by the Enhanced Oil Recovery Institute (EORI) of Wyoming and has been incorporated into the overall USEA Report by Advanced Resources International.

Figure 4-1. Location Map for Six Major U.S. Shale Oil Basins



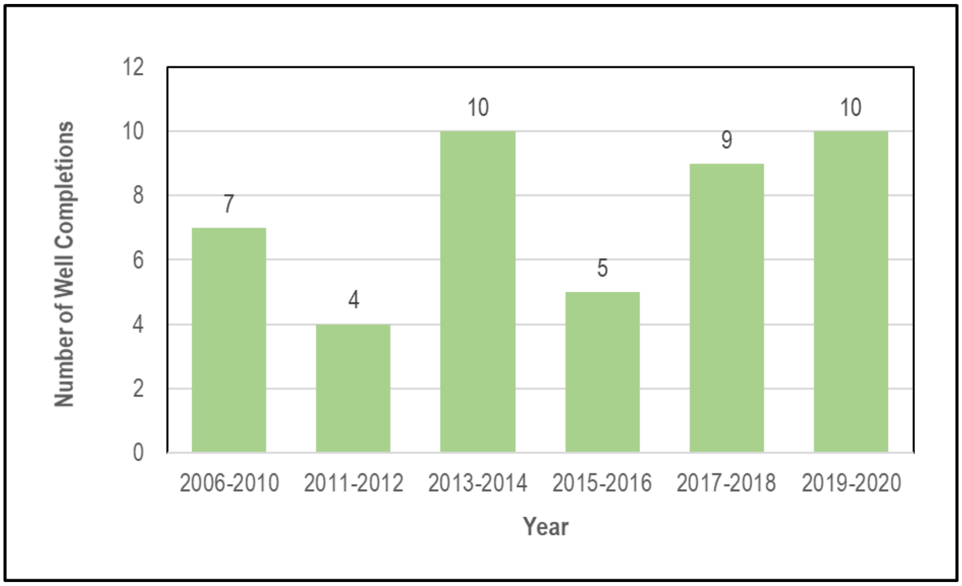
JAF2021_030.PPT

Source: Advanced Resources International, 2021.

4.1.1 Mowry Shale Status and Development

The Mowry Shale is an emerging resource play in the Powder River Basin. Since 2006, there have been 45 horizontal (Hz) wells completed in the Mowry Shale, with 11 Hz well completions prior to 2013, 24 Hz well completions between 2013-2018, and 10 Hz well completions in the past two years (2019 and 2020), Figure 4-2. Despite limited activity to date, a number of operators continue to view that, with continued progress in well drilling and completion technology, the Mowry Shale has the potential to become a significant, economically viable resouce play.

Figure 4-2. Mowry Shale Hz Well Completions, 2006-2020



Source: Advanced Resources International's Tight Oil Database, 2021.

Shale oil production from the Mowry Shale increased modestly from 50 barrels per day in 2010 to 970 barrels per day in 2018, before jumping to 2,760 barrels per day in 2019. This large increase in recovery was a result of drilling of new, more productive wells with longer lateral lengths. As of the end of year 2020, the Mowry Shale was producing at approximately 2,600 barrels per day.

4.1.2 Study Findings

1. The Study Has Defined a New, Large Volume CO_2 Storage Option Essential for Wyoming and the Rockies. The geological and reservoir engineering study prepared by EORI shows that the Mowry Shale in the Wyoming portion of the Powder River Basin offers a new, large capacity CO_2 storage option estimated at 2,145 million metric tons (MMmt), Table 4-1.

Table 4-1. CO_2 Storage and By-Product Oil Recovery from Application of Cyclic Injection of CO_2

Shale Formations / Basins	CO_2 Storage with Shale EOR	Low Carbon Intensity Oil Recovery with Shale EOR	CO_2 Storage with Shale EOR*	
	(MMmt)	(MMB)	(mt/B)	(g/MJ)
Mowry Shale / Powder River Basin	2,145	1,903	1.1	180

*The conversion of metric tons per barrel oil (mt/B) uses 10^6 grams per metric ton (g/mt) and 6,120 Mega Joules per barrel (MJ/B) oil.

Prior work by EORI and the School of Energy Resources of the University of Wyoming has shown that the Powder River Basin lacks an established saline formation for storing commercial scale volumes of CO_2. Much of the water currently produced as part of oil and gas recovery in this basin is reinjected into the formation from which it was produced. Alternatively, the produced water is injected into the very deep (18,000 ft) and costly to drill aquifer in the Madison Formation for which the CO_2 storage capacity is yet to be established.

2. Pursuit of the Mowry Shale with Cyclic Injection of CO_2 Would Provide An Alternative Source of Low Carbon Intensity Domestic Oil. Life-cycle assessments in the technical literature enabled the study to establish that the carbon intensity of one barrel of oil produced from the Mowry Shale of the Powder River Basin with cyclic injection of CO_2 is 87 g CO_2/MJ. (Masanadi et al., 2018 and Godec et al., 2016) As shown in Table 4-1, 180 g CO_2/MJ would be stored for every barrel of oil produced from the Mowry Shale, enabling this oil to have a negative carbon intensity of 93 g CO_2/MJ compared to a positive carbon intensity of 84 g CO_2/MJ for domestically produced conventional oil (Masnadi et al., 2018) and 85 g CO_2/MJ for imported oil (ICCT, 2010), Table 4-2.

Table 4-2. Carbon Intensity of Alternative Sources of Oil Supply

Source of Carbon Emissions	Mowry Shale EOR Oil (g CO_2/MJ)	Other Oil Sources: Conventional Domestic Oil (g CO_2/MJ)	Other Oil Sources: Imported Oil (g CO_2/MJ)
Conventional Production (Extraction, Transport, Refining)	11	11	12
EOR Operations	3		
Combustion	73	73	73
CO2 Storage	(180)		
Total Carbon Intensity	**(93)**	**84**	**85**

3. Using Cyclic Injection of CO_2 in the Mowry Shale Would Improve the Business Case for CCUS in Wyoming. A large capacity storage option in the Powder River Basin would reduce the need and costs to transport the CO_2 captured from power and other industrial plants in this basin to other basins. In addition, the potential revenues from the sale of CO_2 to the Mowry Shale oil fields and the generation of state severance and royalty payments, along with federal tax credits such as 45Q, would notably improve private industry's "business case" for CCUS. This activity would also help to maintain state tax revenues used largely for supporting education and infrastructure in the state of Wyoming.

* * * * * * * * * *

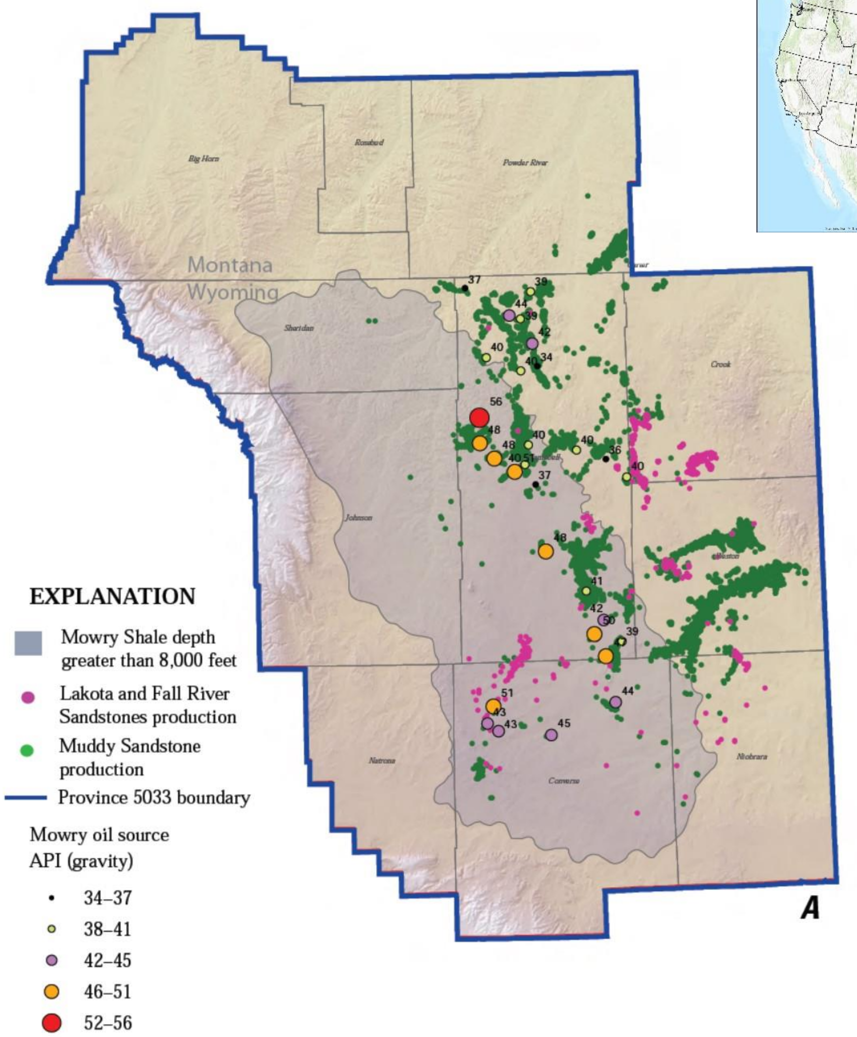
The implementation of cyclic injection and storage of CO_2 in the Mowry Shale of the Powder River Basin would support key Carbon Management goals-- adding new, economically viable options for geological storage of CO_2 and reducing the CO_2 footprint of domestic oil consumption by providing lower carbon intensity oil that would **displace** the consumption of higher carbon intensity oil from imports and other sources.

4.2 Geologic Setting of the Mowry Shale

4.2.1 Powder River Basin Geographic Location

The Powder River Basin, located in northeastern Wyoming and southeastern Montana, encompasses a vast 34,000 square mile area. The Mowry Shale is an emerging tight (shale) oil play within this basin with potential to provide a significant new setting for both geologic storage of CO_2 along with low carbon intensity oil supplies. So far, the great majority of the tight oil development has occurred in the southern portion of the basin, primarily in Converse and Campbell counties, Figure 4-3.

Figure 4-3. Mowry Shale Play Location Map



Source: Anna, 2009.

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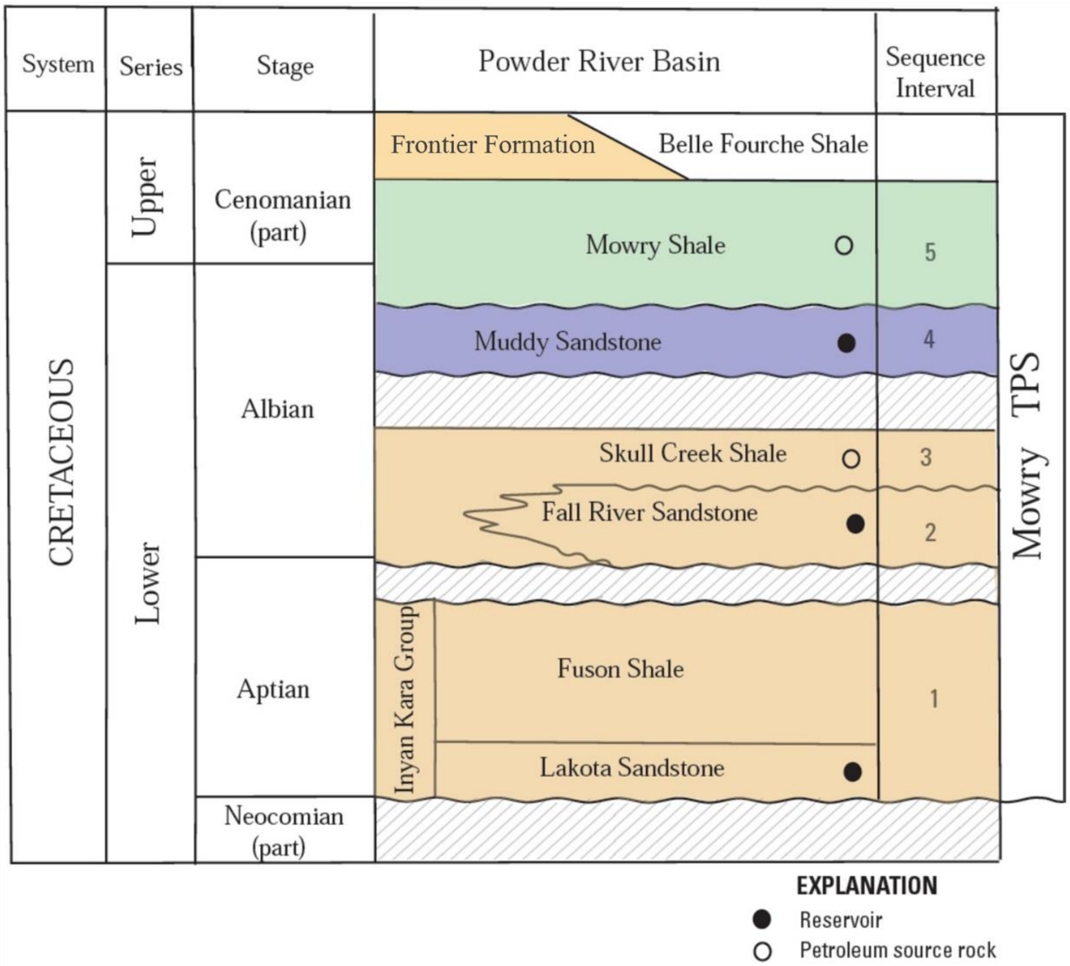
4.2.2 Mowry Shale Stratigraphic Column

The Mowry Shale is a Lower Cretaceous marine shale deposit. It underlies the Belle Fourche Shale Member of the Frontier formation and overlies the Shell Creek and Muddy Formations, as shown by the stratigraphic column for the Powder River Basin, Figure 4-4.

Figure 4-4. Powder River Basin Stratigraphic Column

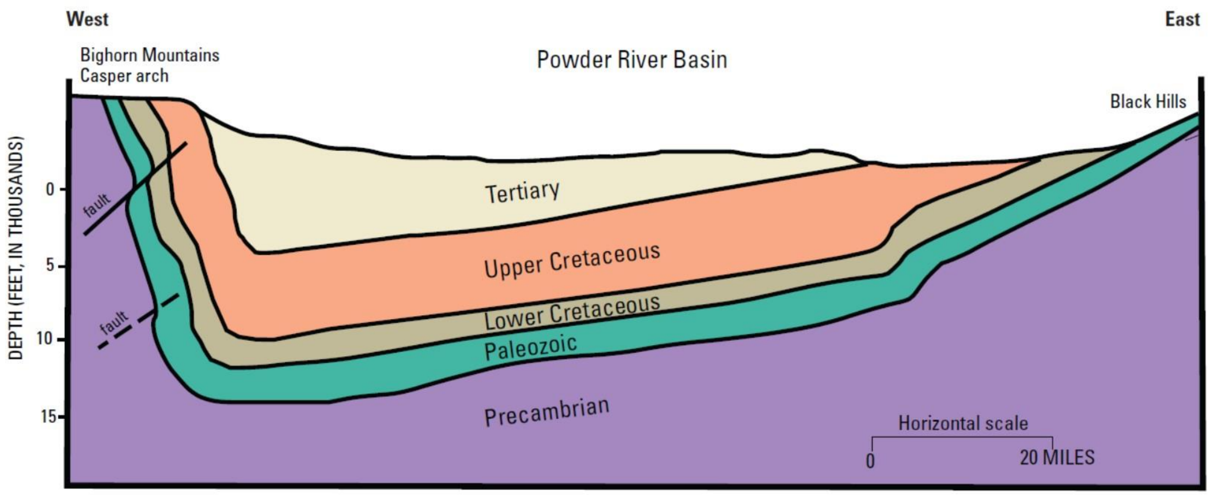


Modified from Anna, 2009

4.2.3 Geologic Cross-Section

The west-to-east trending cross-section in Figure 4-5 shows the geologic structure for the Powder River Basin. The basin is asymetrical with the eastern side of the basin exhibiting shallow, monoclinal dip until it reaches the off-centered basin axis, at which point, the basin dips steeply as it climbs to the Casper Arch and Big Horn Mountains. The Mowry Shale is present throughout most of the basin.

Figure 4-5. Powder River Basin Cross-Section



Source: Anna, 2009

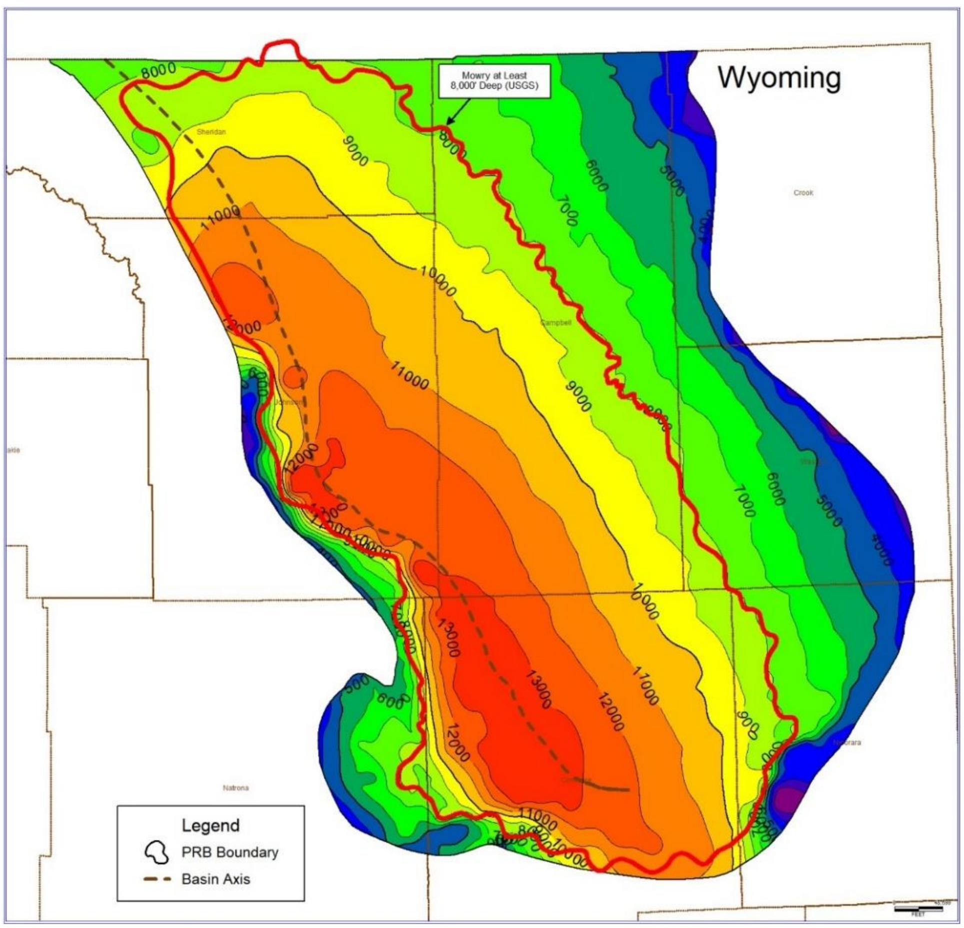
4.3 Establishing the Essential Reservoir Properties

4.3.1 Mowry Shale Assessment Area and Depth

The Mowry Shale assessment in the Powder River Basin focuses on the Wyoming portion of the basin, in Campbell, Converse, Crook, Johnson, Natrona, Niobrara, Sheridan and Weston counties. The assessment area comprises 3,748 square miles, with approximately 2,260 square miles currently derisked, Figure 4-6.

The Mowry Shale reaches a maximum depth of over 13,000 ft along the basin axis in Campbell, Converse and Johnson counties, gradually becoming shallower to the north in Sheridan County and even shallower to the east until it outcrops in eastern Crook and Weston counties. Over-pressuring of the Mowry Shale begins at depths greater than 8,000 ft, as delineated by the red outline on Figure 4-6.

Figure 4-6. Mowry Shale Depth



Source: EORI, 2021

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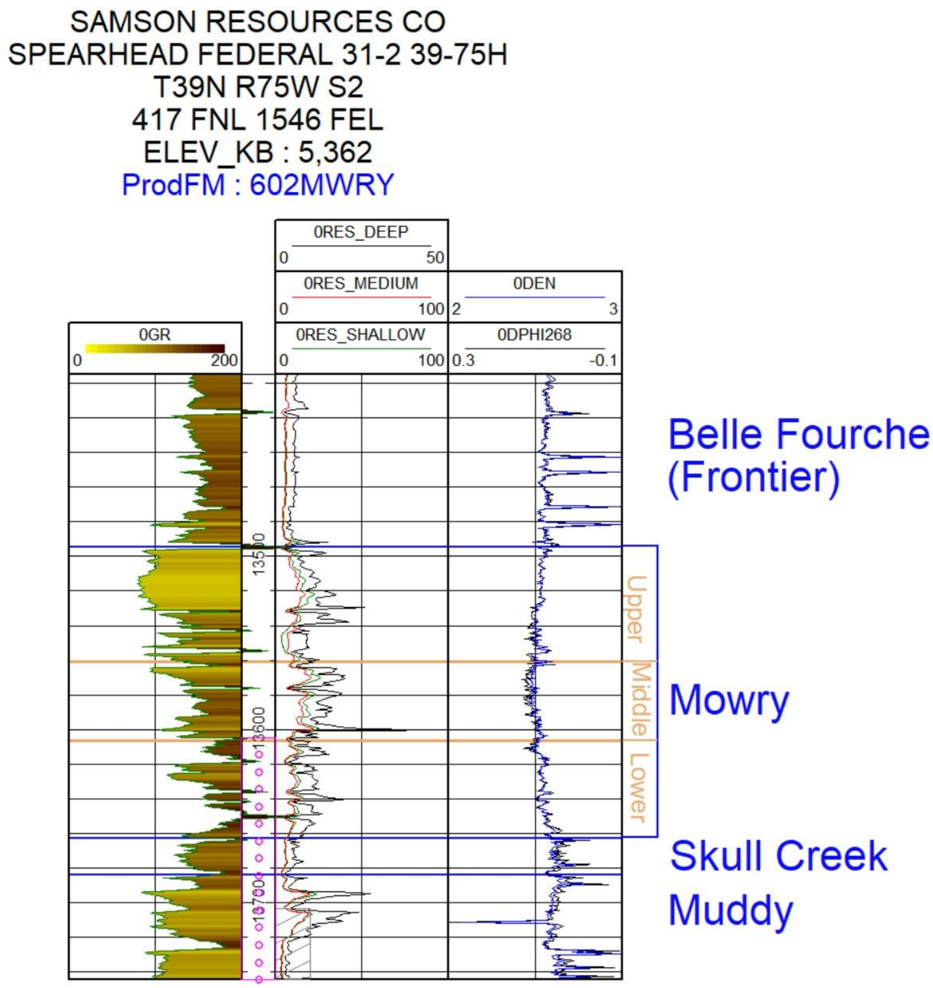
4.3.2 Mowry Shale Type Log

A type log for the Mowry Shale is shown in Figure 4-7. Here the Mowry Shale is 168 ft thick with a net pay of 46 ft (defined as the thickness of the Middle Mowry). Porosity of the Mowry Shale in this type-well ranges from 7% to 10%. The very high gamma ray spikes on the 0GR curve in Figure 4-7 denote bentonites. Bentonite is prolific within the Mowry Shale and many of the thicker betonites (6 inches to 1 foot thick) can be mapped across extenive portions of the Powder River Basin. These bentonites act as buffers that prevent hydraulic fractures from effectively reaching the Mowry Shale intervals above and below the Middle Mowry, which is currently the primary horizontal drilling target.

Figure 4-7. Mowry Shale Type Well



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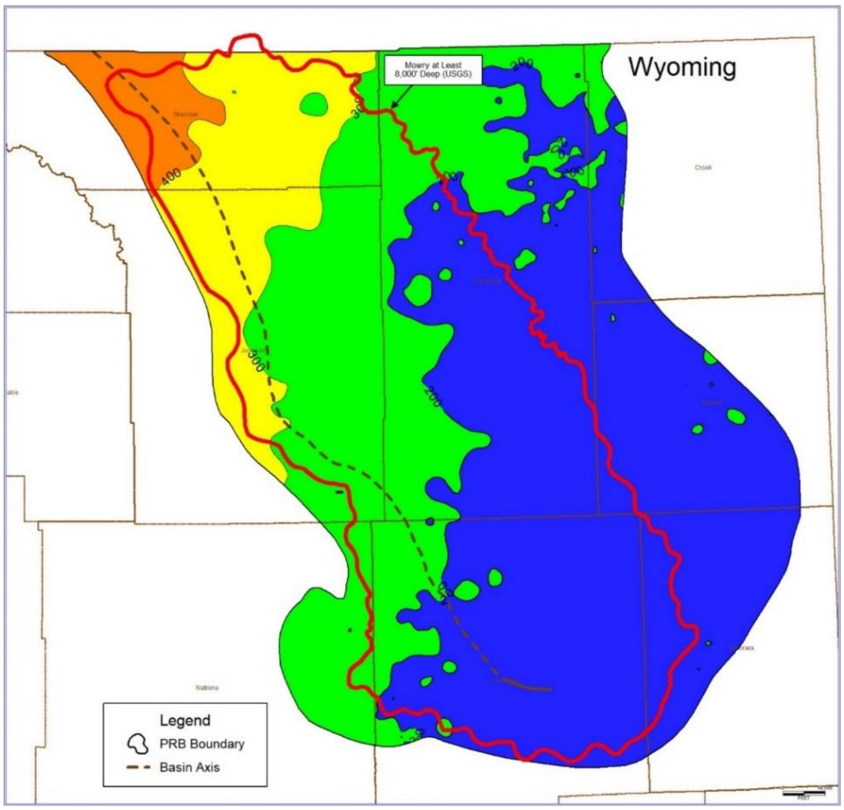
4.3.3 Mowry Shale Thickness

The Mowry Shale thickens across the basin from about 200 ft on the southeast to 400 ft on the northwest, Figure 4-8. Current drilling activity in the Mowry Shale is focused on the sorthern part of the Powder River Basin where the total Mowry Shale interval is somehwat thinner, at about 200 ft, but is thermally more mature. The Middle Mowry in this area is typically 60 to 70 ft thick.

Figure 4-8. Mowry Shale Thickness



4.3.4 Mowry Shale Porosity

Detailed information on the porosity of the Mowry Shale is scarce in the technical literature. Challenges to establishing porosity values in the organic portions of the Mowry Shale include identifying porosity formed by the conversion of kerogen to hydrocarbon (generally only seen by scanning electron microscopy), erroneous porosity calculations from geophyiscal logs due to clay bound water in the formation, and the presence of natural fractures. Porosity tends to be higher in the more thermally mature areas and lower in the less thermally mature areas. The study used a porosity of 7% for the Middle Mowry geologic model.

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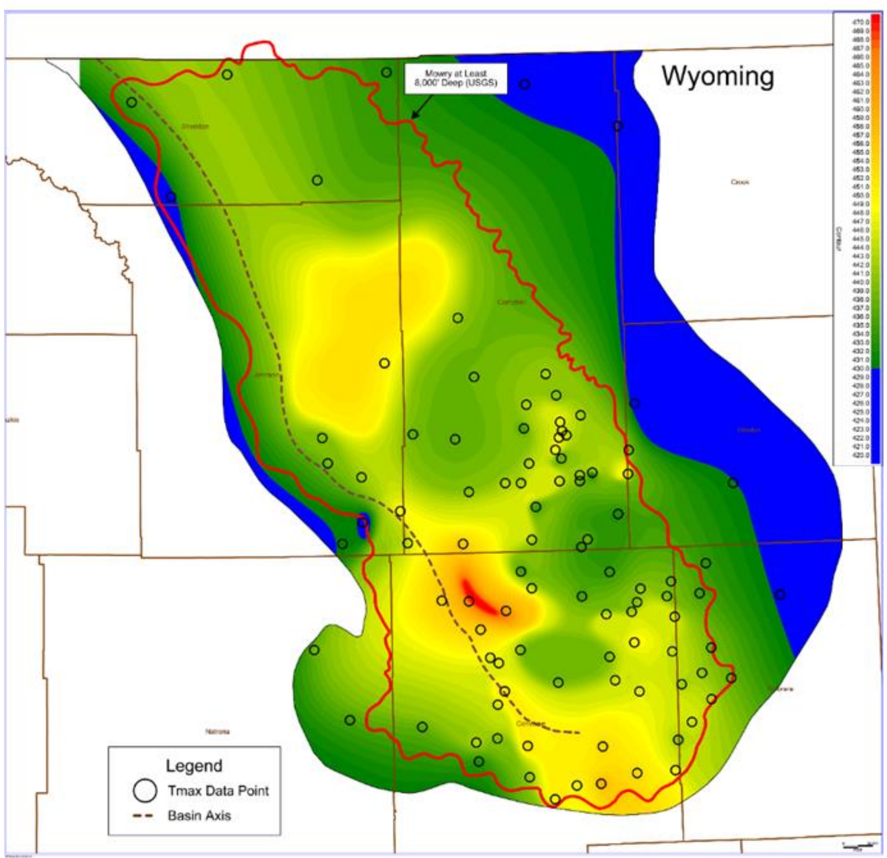
4.3.5 Mowry Shale Oil and Water Saturations

Many factors affect the determination of oil saturation in the Mowry Shale. The mixed porosity-type nature of the Mowry Shale provides the first complication. Porosity from kerogen alteration is likely oil-wet, while intergranular porosity can be oil or water-wet. Additionally, the presence of fractures introduces a third scale of porosity that can be either oil- or water-wet. The study used a value of 90% oil saturation for the Mowry Shale geological model.

4.3.6 Mowry Shale Thermal Maturity

The diverse thermal maturity of the Mowry Shale has created two distinct hydrocarbon settings: (1) a wet gas/condensate area; and (2) an oil area. T_{max} (℃), a measure of thermal maturity, is highest at three "hot spots" located just east of the basin axis, with lower thermal maturities observed as depth decreases to both the west and east. These thermal "hotspots" and potential higher well productivity settings are illustrated on Figure 4-9.

Figure 4-9. Mowry Shale Thermal Maturity



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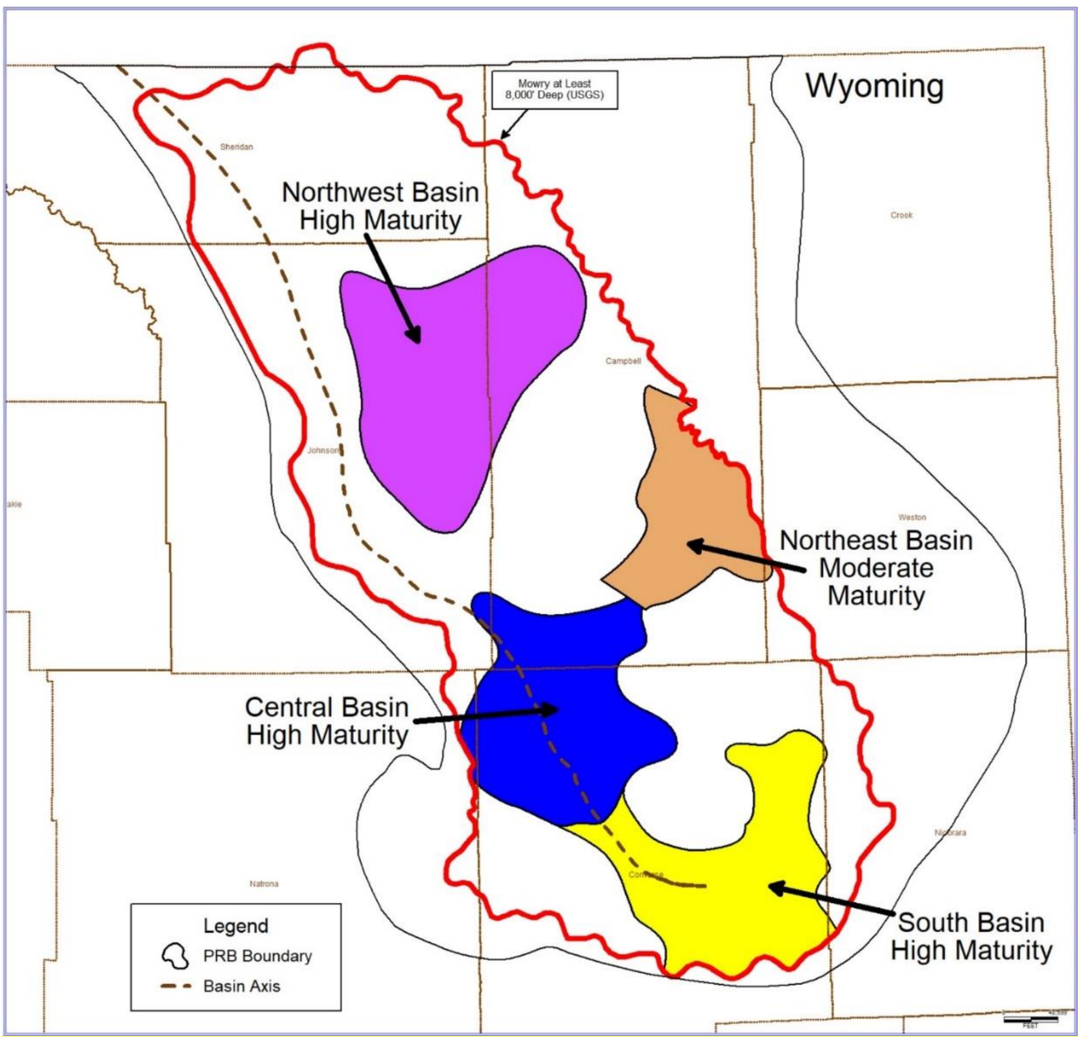
4.4 Defining the Mowry Shale Resource Assessment Units

Four resource assessment units were defined for the Mowry Shale, Figure 4-10. Most of the activity to date has been in the condensate and wet-gas prone Central Basin High Maturity reource assessment unit (blue). The Northeast Basin Moderate Maturity assessment unit (brown) is oil prone. The other two high thermal maturity areas, the South Basin assessment unit (yellow) and the Northwest Basin assessment unit (purple), are condensate and wet-gas prone. A risk factor was applied to each of the four resource assessment units to account for still limited information on the areal extent of each of these resource assessment units within the Powder River Basin.

Figure 4-10. CO_2 Storage Capacity Assessment Units of the Mowry Shale



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4.5 Constructing Representative Study Areas

4.5.1 Representative Study Areas

The next step of the study involved establishing a representative Study Area for each of the four resource assessment units of the Mowry Shale in the Powder River Basin. The key reservoir properties for the four Mowry Shale resource assessment units and Study Areas, defined above, are provided in Table 4-3.

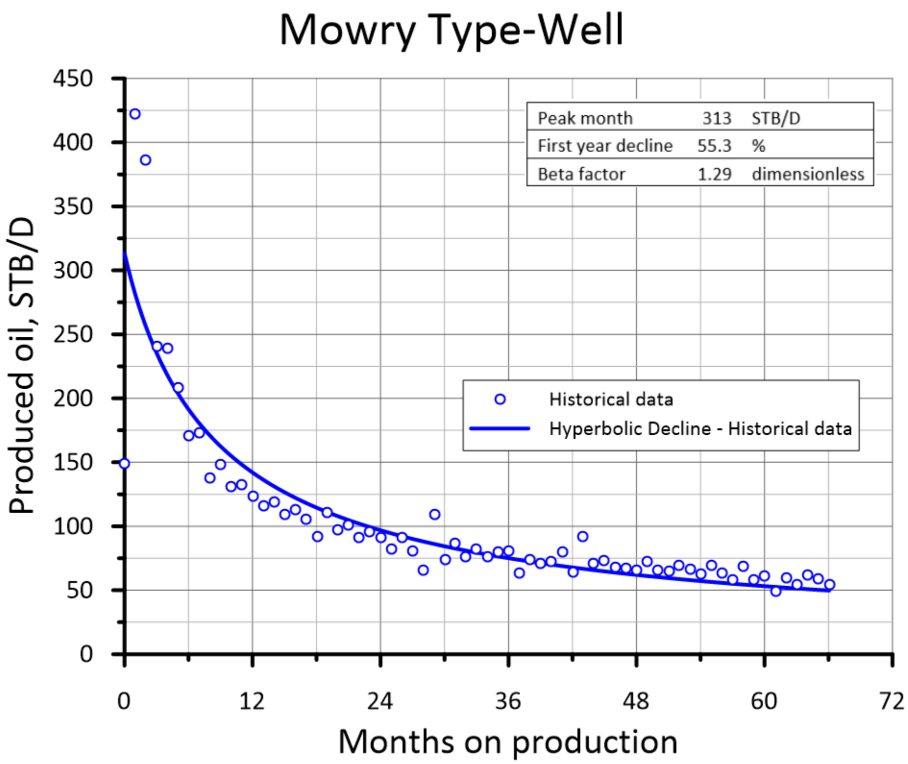
Table 4-3. Reservoir Properties for Estimating CO_2 Storage Capacity for the Mowry Shale

Reservoir Properties	Central Basin High Maturity	Northeast Basin Moderate Maturity	Northwest Basin High Maturity	South Basin High Maturity
Total Area	989 mi^2	553 mi^2	1,252 mi^2	954 mi^2
Risk Factor	0.85	0.40	0.50	0.60
Risked Area	841 mi^2	221 mi^2	626 mi^2	572 mi^2
Net Pay Thickness (Middle Mowry)	65 ft	65 ft	65 ft	65 ft
Porosity	7.0%	7.0%	7.0%	7.0%
Oil Saturation	90%	90%	90%	90%
Hz Well Length	3,865 ft	3,865 ft	3,865 ft	3,865 ft
Frac half-length	100 ft	100 ft	100 ft	100 ft
Number Frac Stages/Well	28	28	28	28
Distance Between Wells	1,760 ft	1,760 ft	1,760 ft	1,760 ft
Hz Well Spacing	3 wells/section	3 wells/section	3 wells/section	3 wells/section
Initial Pressure	7,000 psi	7,000 psi	7,000 psi	7,000 psi
Oil Gravity	46 °API	46 °API	46 °API	46 °API

4.5.2 Type Well for Study Area

The “type well”, shown in Figure 4-11, represents a high quality Mowry Shale oil producer located in the Central Basin High Maturity resource assessment unit. Because the Mowry Shale play has yet to be “unlocked,” the study expects that future wells implemented with advanced technology will perform as well, or possibly better, than this type well.

Figure 4-11. Mowry Type Well Used in Model



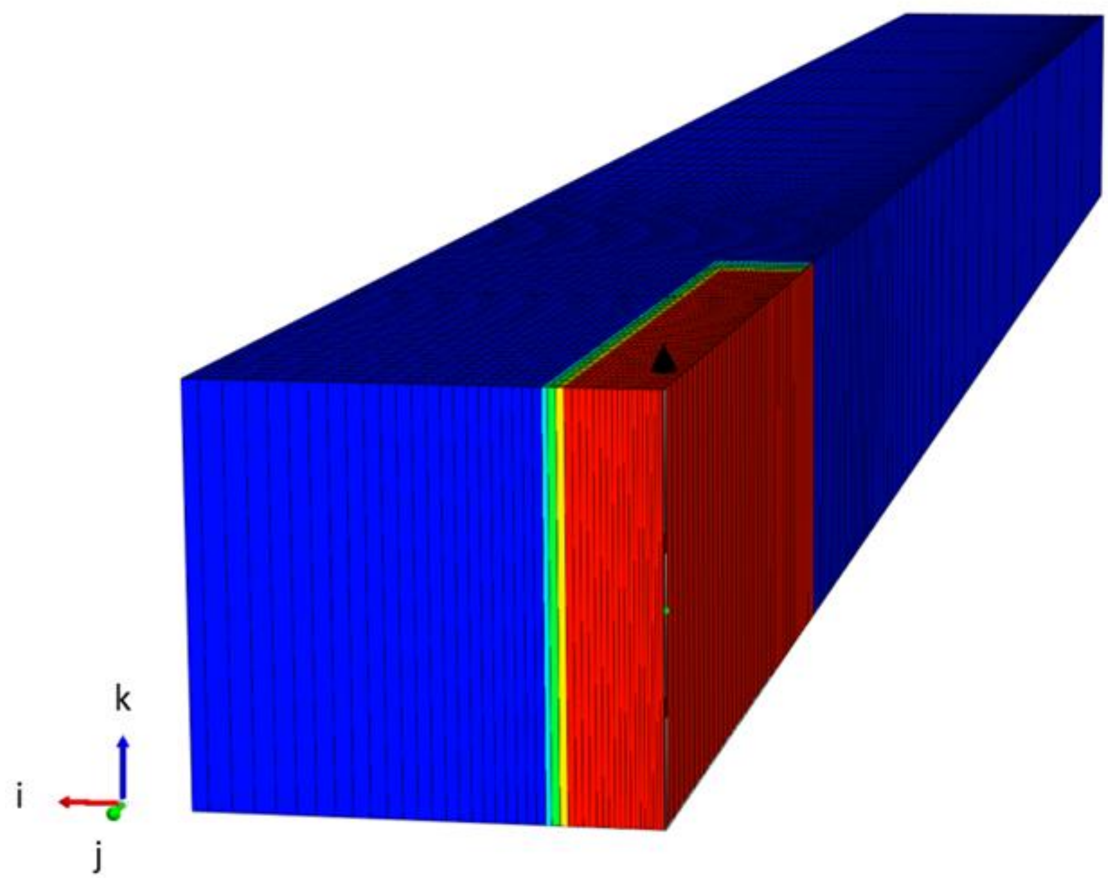
4.6 Reservoir Simulation

4.6.1 Mowry Shale Model Construction

CMG-GEM (Computer Modeling Group) was used by EORI as the numerical reservoir simulator for the study. CMG-GEM is a robust, fully compositional, Equation of State (EOS) reservoir simulator used widely by industry for modeling CO_2 injection and oil recovery processes. The reservoir model and grid blocks constructed to replicate the Mowry Shale geologic and reservoir setting in the Central Basin Study Area are illustrated in Figure 4-12.

The model has 3,375 grid blocks and is designed to take advantage of symmetry (1/4th of one fracture stage out of 28 fracture stages used in the total well or 1/112 of an entire well) to minimize the number of grid blocks in the model. The reservoir model was populated with the key reservoir and fluid property values for the Central Basin Study Area, shown previously in Table 4-3.

Figure 4-12. Reservoir Model and Grid Blocks Used for Mowry Shale Study



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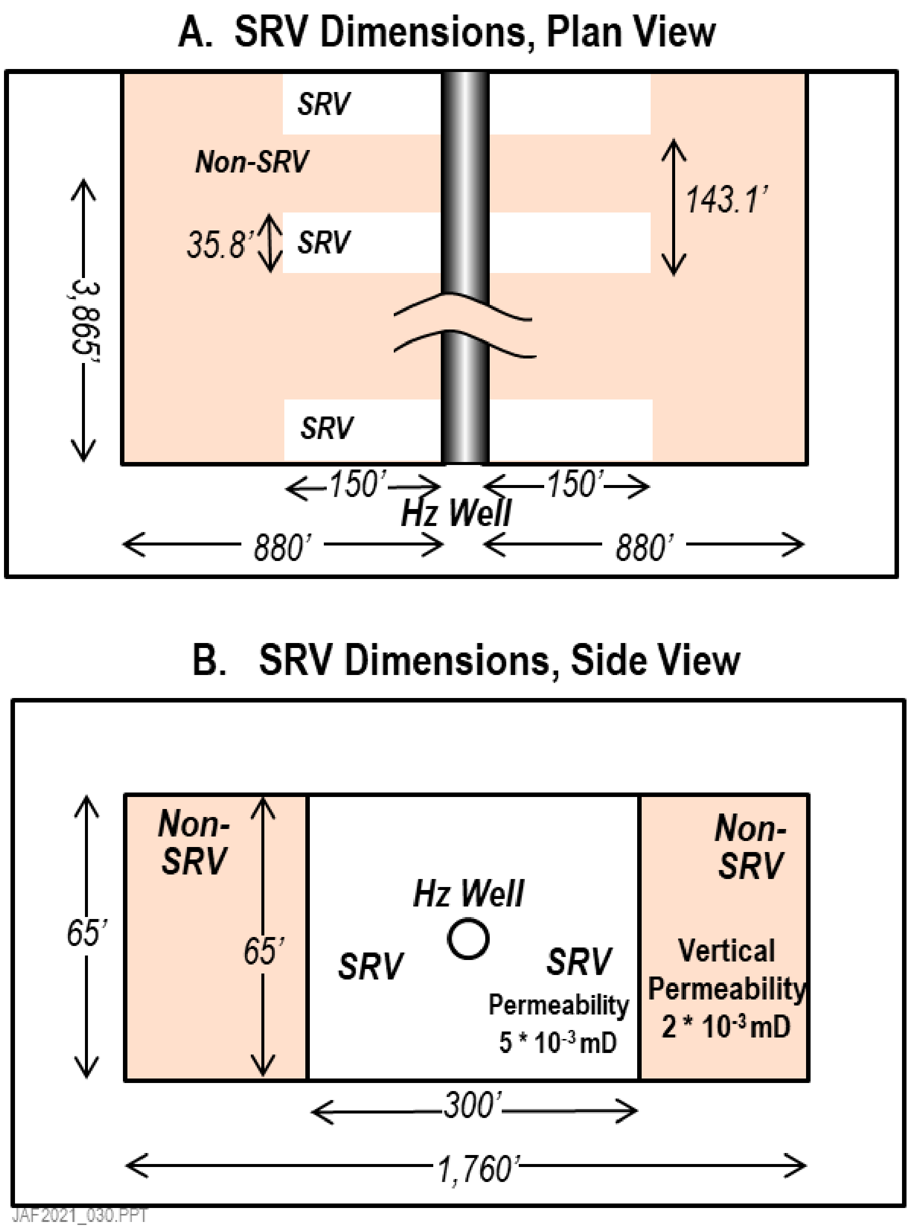
To capture the impact of hydraulic stimulation on the performance of the Mowry Shale horizontal well, a Stimulated Reservoir Volume (SRV) was established in the model (shown as the red grid blocks in Figure 4-12). Figure 4-13 provides information on the SRV dimensions and enhanced permeability value derived from the history match of the Central Basin Study Area Mowry Shale type well.

Figure 4-13. SRV Dimensions and Permeability Used to History Match Well Performance.



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4.6.2 History-Matching Oil Production

Figure 4-14 shows the history match of oil production for the Mowry Shale type well in the Central Basin High Maturity Study Area. The history match was achieved by using the porosity and initial oil saturation values provided in Table 4-3 and the dimensions and permeability values of the SRV and non-SRV portions of the reservoir model provided previously in Figure 4-13.

Primary oil production for the type well is projected to be 301,000 barrels. Figure 4-15 provides the cumulative oil production for a 1/112 segment of the well, as evaluated by the reservoir model. With an original oil in-place (OOIP) of 4,670,000 in the 213-acre well drainage area, the well has a primary recovery efficiency of 6.4% of OOIP.

Figure 4-14. History Match of Monthly Oil Production

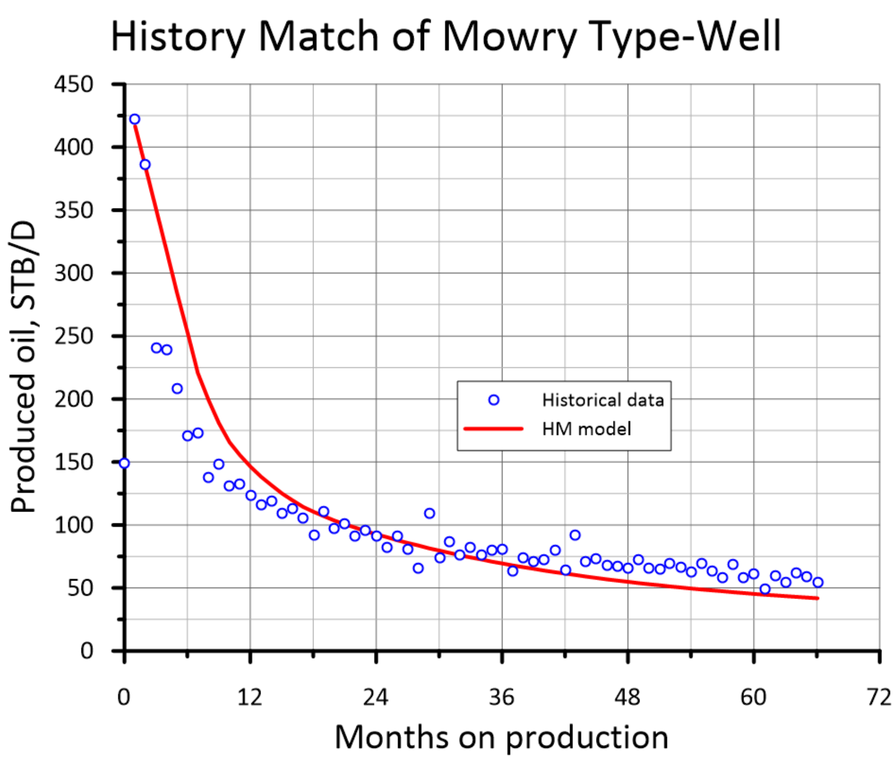
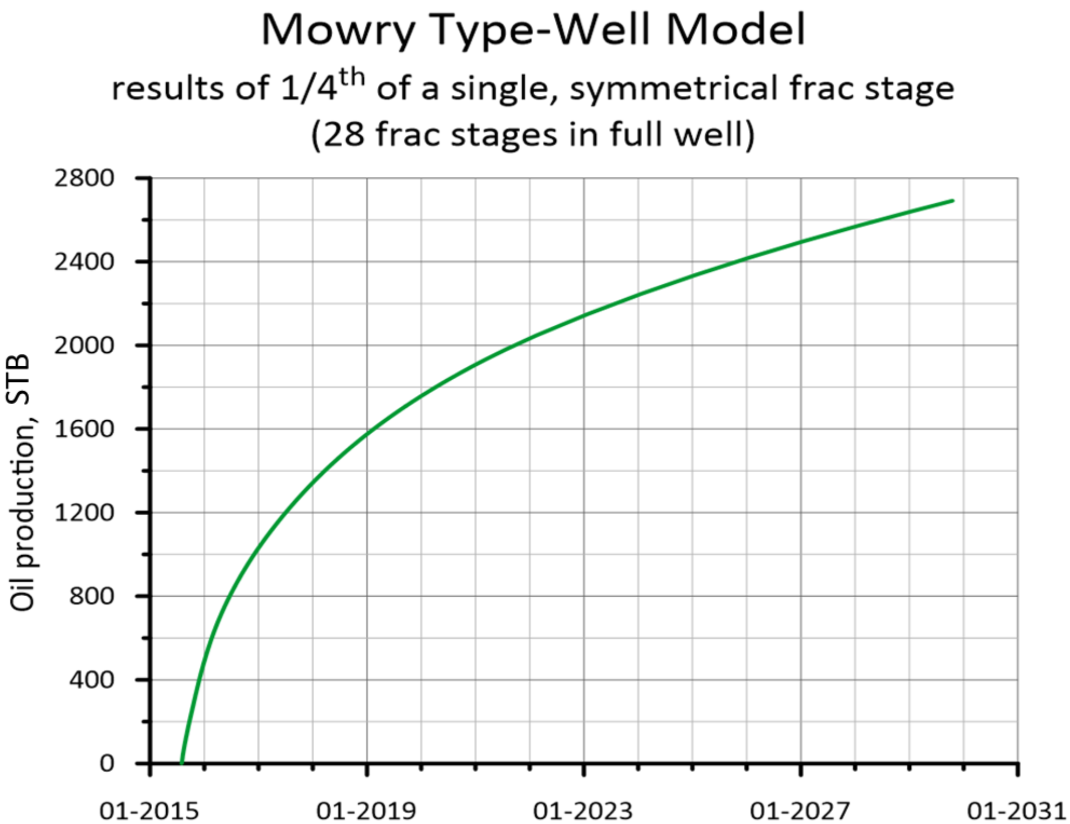


Figure 4-15. Projection of 13.5 Years of Primary Production



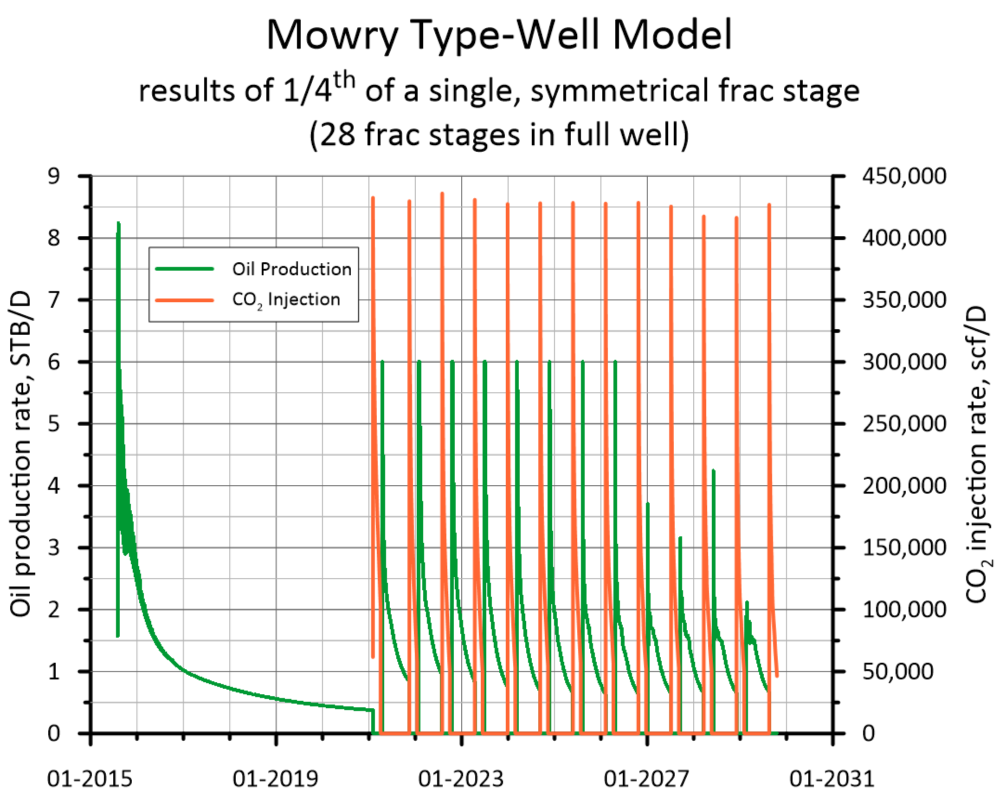
4.7 Performance of Cyclic CO_2 Injection

Cyclic CO_2 injection was modelled beginning after five years of primary production. At this time, the Hz well had produced 215,000 barrels, equal to about 70% of its estimated ultimate oil recovery (EUR).

- In cycle one, CO_2 was injected at a maximum pressure of 7,000 psia for 2 months to refill reservoir voidage, with a total of 1,361 MMcf of CO_2 injected.
- CO_2 injection was followed by a 2-week soak time and then by 6 months of production.
- Eleven additional cycles of CO_2 injection, soak and production followed.
- At the end of the 12th cycle, a 13th round of CO_2 was injected and the well shut in, with no subsequent production of CO_2 or by-product oil allowed.

Figure 4-16 illustrates the oil production and CO_2 injection data for the five years of primary production, the subsequent twelve cycles (8.5 years) of cyclic CO_2 injection, soak and oil production, and the thirteenth cycle of CO_2 injection for the 1/112 portion of the Hz well.

Figure 4-16. Primary Production and Enhanced Oil Recovery from Cyclic CO_2 Injection



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The 13 cycles of CO_2 injection provides 281,000 barrels of incremental oil recovery (367,000 total barrels less 86,000 barrels that would have been produced by continuation of primary production) along with 5,142 MMcf of CO_2 storage. As such, cyclic injection of CO_2 stores about 21 Mcf of CO_2 (equal to 1.1 metric tons of CO_2) for every barrel of incrementally produced oil. The 281,000 barrels of incremental oil provides a 1.93x uplift to primary oil production for the Study Area well,Table 4-4.

Table 4-4. Cumulative Oil Production, CO_2 Injection and CO_2 Production: Study Area Well

	Cumulative Oil Production (MBbls)		**Cumulative CO_2 Injection** (MMscf)	**Cumulative CO_2 Production** (MMscf)	**Estimated CO_2 Storage** (MMscf)
	Total	**Incremental**			
End of 5-year primary	215		0	0	0
End of first cycle	253	26	1,361	279	1,083
End of 6th cycle	429	164	6,084	2,583	3,501
End of 12th cycle	582	282	11,412	6,269	5,142
End of 13th injection (storage)	582	281	12,283	6,269	5,968

The results from the Study Area well were extrapolated to the larger Central Basin High Maturity area. Similar procedures were used to establish the CO_2 storage potential and incremental oil recovery potential for the other three Mowry Shale resource assessment units in the Powder River Basin.

4.8 Study Findings

Four significant findings have emerged from the study—"Increasing CO_2 Storage Options with Injection of CO_2 in Shales: Mowry Shale, Powder River Basin."

1. The Study Has Defined a New, Large Volume Geological CO_2 Option for Storing CO_2. The geological and reservoir engineering study prepared by EORI shows that the Mowry Shale in the Wyoming portion of the Powder River Basin offers a new, large CO_2 storage option with a capacity of 2,145 million metric tons (MMmt). A closer look at the CO_2 for storage capacity for each of the four Study Areas of the Mowry Shale of the Powder River Basin is provided below and in Table 4-5.

- **Central Basin.** The 841 square mile Central Basin High Maturity area provides a CO_2 storage capacity of 798 million metric tons (MMmt) of CO_2 with 708 million barrels of by-product oil recovery.

- **Northeast Basin.** The 221 square mile Northeast Basin Moderate Maturity area provides a CO_2 storage capacity of 210 MMmt of CO_2 with 186 million barrels of by-product oil recovery.

- **Northwest Basin.** The 626 square mile Northwest Basin High Maturity area provides a CO_2 storage capacity of 594 MMmt of CO_2 with 527 million barrels of by-product oil recovery.

- **South Basin.** The 572 square mile South Basin High Maturity area provides a CO_2 storage capacity of 543 MMmt of CO_2 with 482 million barrels of by-product oil recovery.

Table 4-5. CO_2 Storage and By-Product Oil Recovery from Application of Cyclic Injection of CO_2: Mowry Shale of the Powder River Basin, Wyoming

Mowry Shale Partition	Risked Area	Well Depth	CO_2 Storage with Cyclic Injection of CO_2	By-Product Oil Recovery with Cyclic Injection of CO_2
Central Basin High Maturity	841 mi^2	13,000 ft	798 MMmt	708 MMB
Northeast Basin Moderate Maturity	221 mi^2	9,000 ft	210 MMmt	186 MMB
Northwest Basin High Maturity	626 mi^2	10,500 ft	594 MMmt	527 MMB
South Basin High Maturity	572 mi^2	12,000 ft	543 MMmt	482 MMB
Total	**2,260 mi^2**		**2,145 MMmt**	**1,903 MMB**

2. The Study Established a Much-Needed CO_2 Storage Option for Enabling the Use of CCUS by the Power and Industrial Plants of Wyoming. Establishing a new, large capacity CO_2 storage setting is critical for large scale implementation of CCUS in the Powder River Basin of Wyoming as well as for the greater Rocky Mountain Region.

There is currently no dominant saline formation viable for large scale storage of CO_2 in the Powder River Basin. Production of water from oil and gas development is currently injected back into the formation from which it was produced, or it is injected into the aquifer in the Madison Limestone. The Madison Limestone in the Powder River Basin is very deep (18,000 ft) and poorly defined in terms of its permeability and continuity, creating risks and uncertainty to using the Madison Limestone for large scale CO_2 storage.

3. Pursuit of the Mowry Shale with Cyclic Injection of CO_2 Would Provide an Alternative Source of Low Carbon Intensity Domestic Oil. Life-cycle assessments in the technical literature enabled the study to establish that the carbon intensity of one barrel of oil produced from the Mowry Shale of the Powder River Basin with cyclic injection of CO_2 (Shale EOR) is 87 g CO_2/MJ. (Masnadi et al., 2018 and Godec et al., 2016)

As shown above in Table 4-1, however, 180 g CO_2/MJ would be stored for every barrel of oil produced from the Mowry Shale, enabling this oil to have a **negative** carbon intensity of 93 g CO_2/MJ. This compares to a **positive** carbon intensity of 84 g CO_2/MJ for domestically produced conventional oil (Masnadi et al., 2018) and 93 g CO_2/MJ for imported oil (ICCT, 2010), Table 4-6.

Table 4-6. Carbon Intensity of Alternative Sources of Oil Supply

Source of Carbon Emissions	Mowry Shale EOR Oil (g CO_2/MJ)	Other Oil Sources	
		Conventional Domestic Oil	Imported Oil
		(g CO_2/MJ)	(g CO_2/MJ)
Conventional Production (Extraction, Transport, Refining)	11	11	12
EOR Operations	3		
Combustion	73	73	73
CO_2 Storage	(180)		
Total Carbon Intensity	**(93)**	**84**	**85**

4. Use of Cyclic CO_2 Injection for the Mowry Shale Would Notably Improve the Business Case for CCUS for Wyoming. The Mowry Shale would provide a secure setting for storing CO_2 in the Powder River Basin, reducing the costs to transport the CO_2 captured from power and other industrial plants in this basin to other basins.

In addition, the revenues from the sale of CO_2 to the Mowry Shale fields and the generation of state severance and royalty payments, along with federal tax credits such as 45Q, would notably improve private industry's "business case" for CCUS while also helping to maintain state tax revenues used largely for supporting education and infrastructure in Wyoming.

4.9 References

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