PS 3-D Petroleum Systems Model of the Bighorn Basin, Wyoming*

Marcin Pankau[1], Brian Toelle[2], Ranie Lynds[3], and Penjman Tahmasebi[2]

Search and Discovery Article #11197 (2019)**
Posted February 18, 2019

*Adapted from poster presentation given at 2018 AAPG Middle East Region, Shale Gas Evolution Symposium, Manama, Bahrain, December 11-13, 2018
 DOI:10.1306/11197Pankau2019

[1]Halliburton, Houston, Texas
[2]Department of Petroleum Engineering, University of Wyoming, Laramie, Wyoming (btoelle@uwyo.edu)
[3]Wyoming State Geological Survey, Laramie, Wyoming

Abstract

This study developed a full 3-D petroleum system model of the oil- and gas-bearing Bighorn Basin of Wyoming from Precambrian to present day. The study identified thermally mature shale reservoirs that have characteristics favorable for establishing economic production and their location within the basin. These characteristics include drill depth. Previously published studies contain 1-D petroleum system models, which are limited to specific locations within the basin. This study utilized advanced 3-D modeling techniques to simulate the depositional history and thermal maturity throughout the entire basin. The project consisted of five phases – 1) structural framework construction, 2) geochemical data integration, 3) preliminary 1-D simulations, 4) 3-D predictive model simulation, and 5) calibration.

The results indicate a high degree of thermal maturity within the Permian petroleum system with high transformation ratio values. For the Cretaceous petroleum system, the results also indicate a high degree of thermal maturity and transformation ratios in the Lower Cretaceous with decreasing thermal maturity for the Upper Cretaceous formations. The cumulative erosion model indicates the majority of the erosion took place on the margins of the basin. The modeling indicates the Upper Cretaceous Frontier Formation and overlying Cody Shale are within the oil generation window over a large portion of the eastern side of the basin and are within economic drill depths.

Selected References

Burtner, R.L., and M.A. Warner, 1984, Hydrocarbon Generation in Lower Cretaceous Mowry and Skull Creek Shales of the Northern Rocky Mountain Area, *in* J. Woodward, F.F. Meissner, and J.L. Clayton (eds.), Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 449-467.

Fanshawe, J.R., 1971, Structural Evolution of Bighorn Basin: Wyoming Geological Association, 23rd Annual Field Conference Guidebook, p. 35-37

Finn, T.M., and M.J. Pawlewicz, 2014, Maps Showing Thermal Maturity of Upper Cretaceous Marine Shales in the Bighorn Basin, Wyoming and Montana: U.S. Geological Survey Scientific Investigations Map 3285, 14 p., 3 sheets, scale 1:500,000. doi.org/10.3133/sim3285

Finn, T.M., M.A. Kirschbaum, S.B. Roberts, S.M. Condon, L.N.R. Roberts, R.C. and Johnson, 2010, Cretaceous - Tertiary Composite Total Petroleum System (503402), Bighorn Basin, Wyoming and Montana: U.S. Geological Survey Digital Data Series DDS-69-V, 157 p.

Hagen, E.S., and R.C. Surdam, 1984, Maturation History and Thermal Evolution of Cretaceous Source Rocks of the Bighorn Basin, Wyoming and Montana, *in* J. Woodward, F.F. Meissner, and J.L. Clayton (eds.), Hydrocarbon Source Rocks of the Greater Rocky Mountain Region: Rocky Mountain Association of Geologists Guidebook, p. 321-338.

Hutsky A.J., C.R. Fielding, T.J. Hurd, and C.K. Clark, 2012, Sedimentology and Stratigraphy of the Upper Cretaceous (Cenomanian) Frontier Formation, Northeast Bighorn Basin, Wyoming, USA: The Mountain Geologist, v. 49, p. 77–98.

Nixon, R.P., 1973, Oil Source Beds in Cretaceous Mowry Shale of Northwestern Interior United States: American Association of Petroleum Geologists Bulletin, v. 57/1, p. 136-161.

Roberts, L.N.R., T.M. Finn, M.D. Lewan, and M.A. Kirschbaum, 2008, Burial History, Thermal Maturity, and Oil and Gas Generation History of Source Rocks in the Bighorn Basin, Wyoming and Montana: U.S. Geological Survey Scientific Investigations Report 2008-5037, 28 p.

Schrayer, G.J., and W.M. Zarrella, 1963, Organic Geochemistry of Shale - I Distribution of Organic Matter in Siliceous Mowry Shale of Wyoming: Geochimica et Cosmochimica Acta, v. 27/10, p. 1033-1046.

U.S. Geological Survey Bighorn Basin Province Assessment Team, 2010, Petroleum Systems and Geologic Assessment of Oil and Gas in the Bighorn Basin Province, Wyoming and Montana: U.S. Geological Survey Digital Data Series DDS-69-V, 8 chapters, pages variable.

Yin, P., 1997, Source Rock Maturation and Diagenetic Modeling in Badger Basin, *in* E.B. Campen (ed.), Bighorn Basin - 50 Years on the Frontier, Part II: Yellowstone Bighorn Research Association - Wyoming Geological Association - Montana Geological Society, 1997 Field Trip and Symposium, p. 41-44.

UNDER THE PATRONAGE OF HIS EXCELLENCY SHAIKH MOHAMMED BIN KHALIFA AL-KHALIFA, MINISTER OF OIL, KINGDOM OF BAHRAIN

AAPG/EAGE
SHALE GAS EVOLUTION SYMPOSIUM

11 – 13 DECEMBER 2018 • SOFITEL HOTEL, BAHRAIN

COLLEGE OF ENGINEERING & APPLIED SCIENCE, UNIVERSITY of WYOMING

DEPARTMENT of PETROLEUM ENGINEERING

3-D Petroleum Systems Model of the Bighorn Basin, Wyoming

By Marcin Pankau[1], Brian Toelle[2], Ranie Lynds[3], Pejman Tahmasebi[2]

[1] Halliburton, [2] University of Wyoming, Department of Petroleum Engineering, [3] Wyoming State Geological Survey

Abstract

This study developed a full 3-D petroleum system model of the oil- and gas-bearing Bighorn Basin of Wyoming from Precambrian to present day. The study identified thermally mature shale reservoirs that have characteristics favorable for establishing economic production and their location within the basin. These characteristics include drill depth. Previously published studies contain 1-D petroleum system models, which are limited to specific locations within the basin. This study utilized advanced 3-D modeling techniques to simulate the depositional history and thermal maturity throughout the entire basin. The project consisted of five phases – 1) structural framework construction, 2) geochemical data integration, 3) preliminary 1-D simulations, 4) 3-D predictive model simulation and 5) calibration.

The results indicate a high degree of thermal maturity within the Permian petroleum system with high transformation ratio values. For the Cretaceous petroleum system, the results also indicate a high degree of thermal maturity and transformation ratios in the Lower Cretaceous with decreasing thermal maturity for the Upper Cretaceous formations. The cumulative erosion model indicates the majority of the erosion took place on the margins of the basin. The modeling indicates the Upper Cretaceous Frontier Formation and overlying Cody Shale are within the oil generation window over a large portion of the eastern side of the basin and are within economic drill depths.

Objective

The purpose of this study was to extend the understanding of the Bighorn Basin's thermal and hydrocarbon maturation history by replicating the generation, expulsion, migration, and accumulation of hydrocarbons within the basin using 3-D petroleum systems modeling. This study determined the transformation ratios and thermal maturities of the various sources rocks within the basin, which have a direct impact on understanding the potential for unconventional reservoirs and their characteristics, such as amount of absorbed gas and secondary porosity. The results of this study can be used to help guide future exploration efforts in the basin.

Background

The Bighorn Basin is in the north-central part of Wyoming, USA, with a small portion of the basin extending into south-central Montana. The basin is bounded by a number of structural features that were used to define the basin limits used in this study. The oldest sedimentary rocks in the basin are the Cambrian Flathead Sandstone, which unconformably overlies the Precambrian basement (Fanshawe, 1971). The Paleozoic strata preserved in the basin reflect deposition on a shallow marine shelf, resulting in interbedded limestones, dolostones, and sandstones. Mesozoic strata preserves evidence of significant terrestrial and marginal marine environments, capped by deposits from an interior seaway that stretched from Canada to Mexico during the Late Cretaceous.

In 2010 United States Geologic Survey (USGS) performed an assessment of remaining undiscovered reserves in the Bighorn Basin (Roberts et al., 2010), using eleven 1-D models located in the north-central part of the basin. This project expands on previously published work by taking advantage of tools, such as full 3-D temperature, pressure, and migration modeling.

Methodology

This study was performed in five phases, which are shown in the study's Workflow Chart at right in Figure #1. These five phases were:

1. Basin Structural Framework Development
2. Geochemical and Thermal Data Integration
3. 1-D Petroleum System Model Generation
4. 3-D Predictive Petroleum System Model Generation
5. 3-D Petroleum System Model Calibration

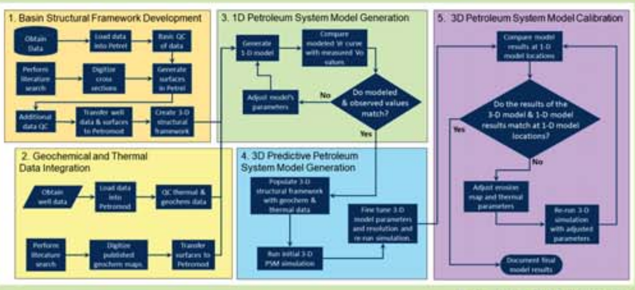

Figure #1: Workflow performed during this study

Phase #1: Basin Structural Framework Development

This phase consisted of locating publicly available data in multiple databases, downloading, reviewing, and quality controlling that data. Figure #2 shows a 3-D perspective view of the present day, topographic surface of the Bighorn Basin constructed using DEMs data as seen from the south.

A literature search was performed in order to locate any structural maps, isopach maps, cross sections (Figure #3), or published seismic lines to be used as inputs. Data from these sources were loaded into a Petrel project and reviewed for quality control purposes. A layered model of 2-dimentional surfaces for important stratigraphic horizons was created in order to approximate the present-day geometry and included characteristics such as lithology, fault locations and properties, and formation ages.

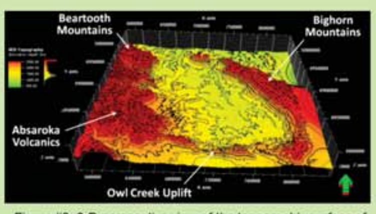

Figure #2: 3-D perspective view of the topographic surface of the Bighorn Basin as seen from the south.

Phase #2 Geochemical & Thermal Data Integration

Next a 3-D Petromod model was populated with geochemical, geological, physical and thermal data. This included: Total Organic Carbon (TOC) data, Hydrogen Index (HI) data, calculated Vitrinite Reflectance (VR) data, facies data, fault property data, erosional data, paleo-water depth data, pressure logs, temperature logs, heat flow patterns, and sediment-water interface temperature. TOC and HI maps were associated with each source rock from which PetroMod determined the kerogen type and appropriate kinetic model. Maps illustrating the distribution of the TOC, as well as HI maps were created based on the published geochemical data (e.g., Schrayer and Zarrella, 1963; Nixon, 1973; Burtner and Warner, 1984; Hagen and Surdam, 1984; Yin, 1997; Finn, 2008; and Denver Core Research Center).

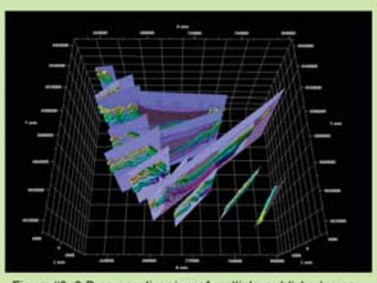

Figure #3: 3-D perspective view of multiple, published cross sections which were digitized for additional structural control.

Phase #3: 1-D Petroleum System Model Generation

Important inputs for the generation of an accurate 3D Petroleum Systems Model include heat flow and erosional data. In order to obtain valid estimates of those values, ten initial 1-D models were generated and then calibrated.

First, a forward, 1-D model was created and simulated based on the initial inputs. These initial inputs were layer thickness, lithology, TOC, HI values, and formation ages. The results were then compared to the calibration data, including temperature, pressure, and vitrinite reflectance (Ro) values. The values predicted by the initial 1-D model were then compared to the values actually measured at those locations. A good correspondence between the predicted and measured values resulted in a validated and calibrated 1-D model. If significant discrepancies existed, the parameters of the 1-D model were adjusted and another modeling run was performed until calibration was achieved. An example of one of the study's calibrated 1-D models is shown in Figure #4.

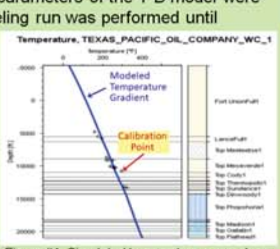

Figure #4: Simulated temperature curve along with calibration data points for the Texas Pacific Oil Company WC 1 well.

Phase #4: Predictive, 3-D Petroleum System Model Generation

Based on the results of the previous phases, a number of 3-D models were developed. Three full, 3-D predictive modeling runs were preformed, including 1) The Limited Grid Model, 2) The Extended, Fine Grid Model and 3) The Extended, Fine Grid Model with Erosion and Petroleum Generation.

For the third and final predictive 3-D model (Extended, Fine Grid Model with Erosion and Petroleum Generation), a modeling run was performed using the most geologically realistic erosion map. This erosion map featured the results of the preliminary 1-D models and was developed using the convergent gridding algorithm. As before, the model included faulting, erosion, full 3-D pressure and temperature modeling, and with a fine cell size of 100 by 200 meters. Only petroleum generation was modeled at this time. This model served as a basis for further calibration and migration modeling.

Phase #5: 3D Petroleum Systems Model Calibration

After multiple simulation runs and determination of proper inputs and methods it was necessary to calibrate the model in 3-D. Heat flow and erosion were adjusted to match Ro values actually measured at the well locations for calibrating thermal maturity. Adjusting these two characteristics resulted in a fully calibrated 3-D petroleum system model, the ultimate objective of this study.

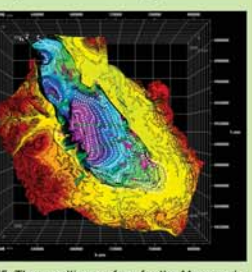

Figure #5: The resulting surface for the Mesaverde Formation (center of the basin) was combined with the topography (yellow to red) on the basin flanks.

Results

Calibrated 3-D Petroleum Systems Model

As indicated the 3-D Petroleum Systems Model was calibrated using the 1-D models and the advanced heat flow relationships. Additionally, the erosion map was fine-tuned to provide a very good relationship between simulated VR values and measured Ro values. In the process of fine-tuning the model, a new erosion map relating to the post-Eocene erosion was constructed. However, for this study the post-Eocene erosion was treated as a sum of all the erosional events that had occurred over the basin's history. Other erosional events were not calibrated due to lack of Ro data. This map is vastly different than the map published by Roberts et al. (2010), which focused only on post-Eocene erosion and indicate increasing amount of erosion from the center of the basin to the outskirts.

Within the Bighorn Basin, there are two major petroleum systems. The Cretaceous petroleum system composed of Lance Formation, Meeteetse Fromation, Mesaverde Formation, Cody Shale, Frontier Formation, Mowry Shale, Muddy Sandstone and Thermopolis Shale. The Permian-Pennsylvanian petroleum system is composed of the Phosphoria Formation and Tensleep Sandstone. Based on the results of the calibrated 3-D Petroleum Systems Model, all of these formations are thermally mature to varying degrees. Figure #6 shows the VR thermal maturity map and the Transformation Ratio map for the top of the Frontier Formation. The shades of green on the VR map indicate values between 0.6% and 1.35%, which are areas that are within the oil-generation window. The areas colored red indicate areas that are in the gas-generation window and can be seen in the basin's center.

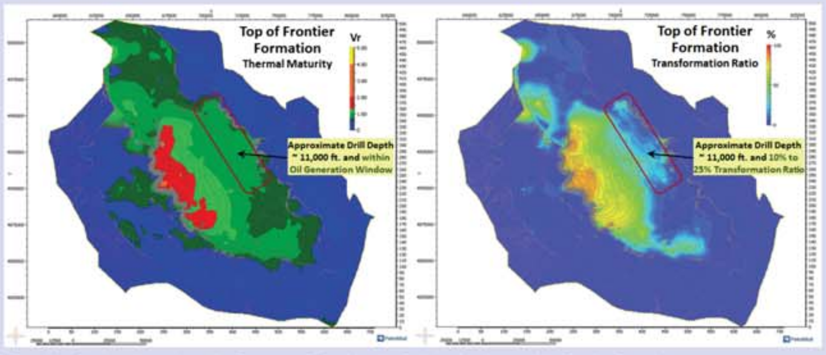

Figure #6: Calculated thermal maturity (Rv) map and Transformation Ratio Map for the top of the Frontier Formation.

Discussion

A solid structural basin framework is key to petroleum system modeling. However, it is difficult to fully capture the fine structural and stratigraphic details in a large 3-D basin model, primarily due to computational limitations. The structural framework for this study was built on a generalized stratigraphic column for the entire basin and omitted local formations that may have been present only within limited portions of the basin. Some thicker units, such as the Chugwater Formation, were treated as one without distinguishing between the units within the formation. Additionally, the framework only included the major fault systems present in the basin and thrust fault geometries were not accurately modeled due to software limitations. The structure of the basin is more complex than the model, and includes a number of smaller, local faults and greater stratigraphic variation.

The lithology of the basin was also generalized using mudlogs from existing wells. However, the mudlogs provide only a local lithology near the wellbore. Outside of that area, the lithology can vary, affect the migration pathways and leading to the formation of lithological traps. Lithology was also further simplified by using single, generalized rock type for each one of the formations. This resulted in a negative influence on the accuracy of migration modeling, completely prevented proper modeling of stratigraphic traps (which are known to occur in the Bighorn Basin).

The accuracy of the framework was affected by the gridding resolution. In this study, a resolution of 1600 grid cells in the east-west direction by 1200 grid cells in the north-south direction was used for pressure/temperature modeling. For migration modeling, the resolution was upscaled to 800 by 600 grid cells. This had the effect of decreasing computation times at the cost of resolution. The same resolution was used for geochemical/erosional maps. Generalized basin structure, combined with limited resolution, is considered the biggest source of uncertainty within this model.

However, even with these limitations the location of the modeled conventional reservoir accumulations approximates the actual field locations fairly well.

Conclusions

The results of migration modeling and the location of the modeled conventional reservoir accumulations are in general agreement with the oil and gas fields that have been located by drilling in the Bighorn Basin. Additionally, migration modeling results indicate the existence of multiple small reservoirs in the center of the basin, which, in theory, could be potential new targets for exploration. However, exploration for these reservoirs is, most likely, uneconomic due to their small accumulations and significant drill depths.

However, greater potential locating and developing unconventional reservoirs does exist within the basin where drill depths would be within economic range. Results suggest the area outlined in red in Figure #6 on the eastern side of the basin may have high potential for economic development of shale oil reservoirs. In this area the top of the Frontier Formation has a drill depth of approximately 11,000 feet. Outcrop studies (Hutsky et al, 2012) performed nearby indicate the presence of marine shales and nearshore environments of deposition within the Frontier, excellent source and reservoir rocks that should contain type II kerogens, should be in the oil generation window and within economic drill depths. Additionally, the organic-rich Cody Shale, time-equivalent to the Niobrara Formation, directly overlies the Frontier Formation. Finn (2014) indicates the Cody Shale was deposited in a marine environment. The base of this formation would also be in the oil generation window.

The area identified and outlined in red covers approximately 60 square miles and may contain shale oil resources of significant value. The Niobrara Formation in the northern DJ Basin has proven to be a prolific oil producer. It has been shown that in the Niobrara play open natural fractures have significant influence on the economics of the production. The Bighorn Basin has undergone extensive structural deformation and the presence of open natural fracture systems is highly probable. The combination of the potential for open natural fractures contained within multiple marine shales that are within the oil generation window make this portion of the Bighorn Basin highly prospective for exploration for unconventional reservoirs. Other areas within the basin and other formations are also considered prospective.

This study indicates that the potential for economic production from unconventional reservoirs, particularly shale reservoirs, within the Bighorn Basin is high and exploration boreholes are recommended. It should be noted that, at the time of this study, no horizontal wells have been drilled within the basin.

Acknowledgements

The authors would like to thank **Dean Pishko** of the University of Wyoming's College of Engineering and Applied Sciences for his support, which allowed us to present this poster at this symposium. We would also like to thank **Schlumberger** for providing the 3-D Petroleum Systems Modeling software **PetroMod** used in this study. Additionally, we would like to thank **NExT**, in particular **Kalyan Venugopal**, for the training on the **PetroMod** software we received at the beginning of this study.