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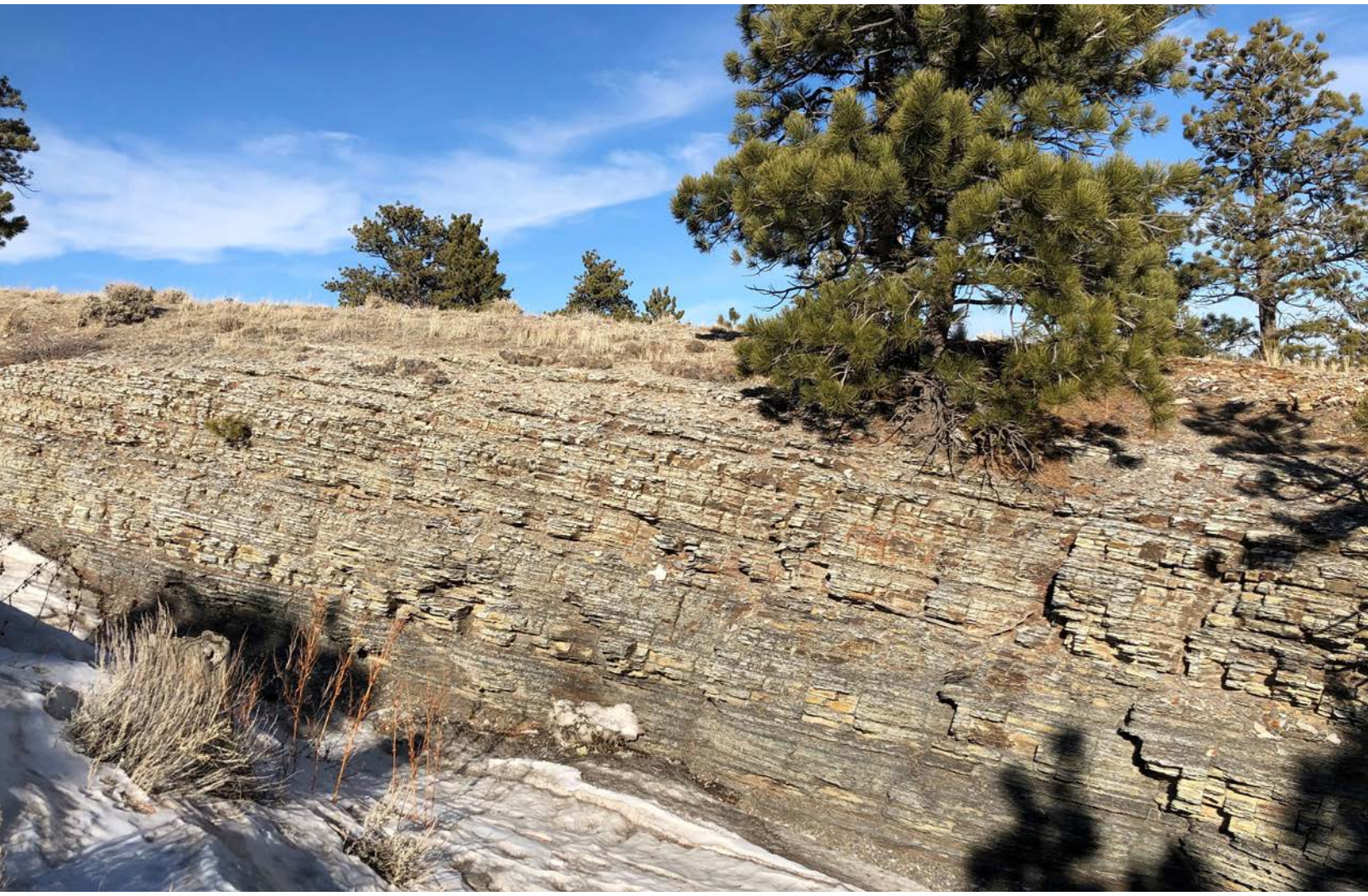

Report on Mowry Shale Thermal Maturity Mapping in the Powder River Basin, Wyoming

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Enhanced Oil Recovery Institute

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Cover Photo: Mowry Outcrop, Hwy 284 West of Casper, Wyoming.

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Introduction

The Enhanced Oil Recovery Institute (EORI) has completed a map (Figure 1) of thermal maturity of the Mowry Shale in the Powder River Basin (PRB). Thermal maturity, the degree to which the total organic carbon in a formation has been transformed from kerogen to producible hydrocarbons due to heat and pressure, is an important measure for not just the quality of a source rock, but also helps for delineating areas more favorable for unconventional drilling.

There is a dearth of published Mowry maturity maps available for the PRB and this publication endeavors to provide a detailed map based on a large, public data set covering the Wyoming portion of the PRB. Additional data, currently held confidential by operators in the basin, would be of benefit to future iterations of this map.

Vitrinite Reflectance vs Pyrolysis

The most prevalent methods for determining the thermal maturity of a source rock are vitrinite reflectance and pyrolysis. Vitrinite reflectance, usually performed on drill cuttings, is a measure of the light reflected from the surface of vitrinite particles in organic-rich rock (American Association of Petroleum Geologists, 2015). The results are reported as % R_o. The process for determining R_o traditionally uses a trained observer to perform a point-count analysis of shiny kerogen (organic matter), however a photo spectrometer may be used. This methodology can be susceptible to errors such as inconsistency in point-counting (human error) or the presence of up-hole cavings in the measured sample.

Pyrolysis is the decomposition of organic material via heating of the rock sample in the absence of oxygen. T_{max}, obtained from pyrolosis (aka Rock-Eval or source rock analysis), is the temperature at which maximum hydrocarbon generation occurs. The empirical data returned by the pyrolysis process, which is performed on core (not drill cuttings), consists of four peaks (S1 through S4), recorded as volatile organics escaping as the temperature increases. The first peak, S1, measures the free hydrocarbons present as the start of pyrolysis (proxy for how much hydrocarbon has already been generated). The second peak, S2, represents the volume of hydrocarbons that were generated during pyrolysis. The temperature at which the peak hydrocarbon generation occurs during S2 is T_{max}, which is reported in degrees Celsius. Peaks S3 and S4 measure the CO_2 produced during hydrocarbon generation and the residual carbon left in the sample after the rock has generated all the

hydrocarbons of which it is it is capable (American Association of Petroleum Geologists, 2015).

The EORI believes T_{max} to be the best measure of thermal maturity to map for the Mowry due to its empirical, lab-derived nature (pyrolosis) and the amount of available T_{max} coverage across the PRB. Additionally, while some of the publicly available R_o data is directly measured, much of the available R_o data for the Mowry in the basin is calculated from measured T_{max} values.

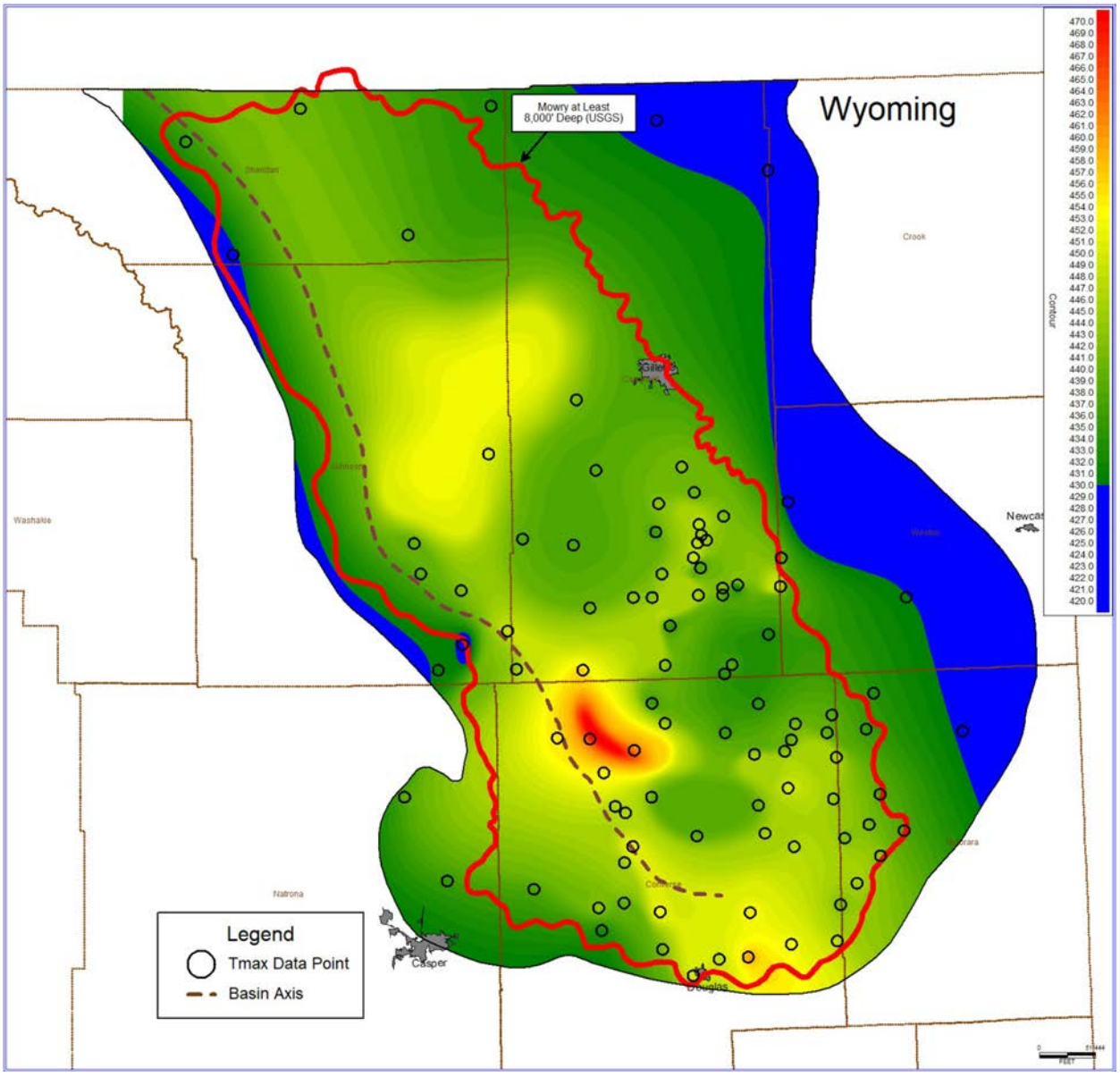

Figure 1: Map of Mowry Maturity (T_{max} in °C) in the Powder River Basin, Wyoming.

Data sources

Thermal maturity data were obtained from two principal sources; the United States Geological Survey (USGS) Core Research Center and Table 2 of Modica and Lapierre's 2012 publication "Estimation of Kerogen Porosity as a Function of Thermal Transformation." Combining these two datasets provided 98 wells with T_{max} measurements in the Mowry. Most of the wells are concentrated in the southern part of the PRB (where the rocks are more mature), but there is reasonably good data coverage across the basin. Where multiple measurements of T_{max} within the Mowry were taken in a single well, the average for all values of T_{max} was used.

Mapping Methodology

T_{max} data were imported into IHS Petra geologic mapping software. Petra was used to create computer generated grids of the T_{max} data using the Minimum Curvature gridding algorithm. These grids were then modified via hand-drawn control contours to give a more geologically realistic feel to them. In the northern part of the basin, where there was a paucity of T_{max} data, Mowry formation temperature data obtained from geophysical well logs were used to influence the maturity map's contours.

In his 2009 study, Lawrence O. Anna reconstructed the burial depth of the Mowry in the PRB and determined that the Mowry likely started sourcing hydrocarbons at a burial depth of 7,000' and began generating significant hydrocarbons where it is at least 8,000' deep. Anna's delineation of where the Mowry is currently at least 8,000' deep is commonly used within the oil and gas industry as a proxy for Mowry thermal maturity and was included on the map for reference.

The 8,000' current burial depth extent has additional implications on the productivity of the Mowry. An interval of overpressure begins at a depth of 8,000' in the PRB (Surdam, Jiao, De Bruin, & Bentley, 2010). Overpressure is a key attribute in making horizontal shale plays economic, as tight shale reservoirs need anomalously high pressure to drive production. Surdam et. al. (2010) identified that clay diagenesis exists at present-day depths of 8,000' in the PRB. The diagenesis caused smectite (a swelling clay) to convert to the more stable illite, resulting in increased sealing capacity of shales (i.e., Mowry Shale) below 8,000'.

Observations

Based on the map, the following observations have been made:

- Nearly all of the Mowry presently deeper than 8,000' is currently generating hydrocarbons based on the T_{max} data.
- The highest T_{max} values lie to the east of the present-day basin axis suggesting the basin has shifted slightly since the Mowry began generating hydrocarbons.
- The often-cited Mowry deeper than 8,000' line (Anna, 2009) does not contain the entirety of Mowry hydrocarbon generation in the PRB, but it still plays an important role in demarcating the over-pressured Mowry and related clay diagenesis.

- It should be noted that the southern high maturity anomaly is often referred to as being "dry gas" but neither the T_{max} data nor publicly available production data support that reference; it should be considered "wet gas" given that liquid hydrocarbons are produced with the gas.

Kerogen Type and Hydrocarbon Generation Windows (T_{max})

Kerogen (organic matter) type plays a significant role in which kinds of hydrocarbons are generated and at what temperature each phase (oil, condensate, dry gas) begins to generate. Individual sources utilize different thermal maturity cutoffs for hydrocarbon generation windows. The following table summarizes two of those sources:

Generation Window	Humble1 (Core Data) T_{max} (°C)	AAPG2 T_{max} (°C) Type 2 Kerogen	AAPG T_{max} (°C) Type 3 Kerogen
Immature	<428	<435	<435
Oil	428-455	435-455	435-465
Condensate	455-475	Not Reported	Not Reported
Dry Gas	>475	>455	>465

[1] (Humble Geochemical Services Division)

[2] (American Association of Petroleum Geologists, 2015)

The Mowry Shale is a hybrid of Type II and Type III kerogen (Davis, Byers, & Pratt, 1989). Based on the hybrid Type II/III kerogen type, the EORI has adopted the following hydrocarbon generation windows (modified from Humble Geochemical Services Division and American Association of Petroleum Geologists, 2015) and color scheme for our map:

EORI T_{max}	Hydrocarbon Generation Window	Map Color
<430 °C	Immature	Blue
430-450 °C	Oil	Dark green to light green
450-470 °C	Condensate	Yellow to red
>470 °C	Dry Gas	Not present on map

Acknowledgements

This work was funded by the U.S. Department of Energy, Office of Fossil Energy, Project No. DE-FE0031779. EORI would like to thank the DOE project manager, Richard Baker, for his support for this project. The EORI would also like to thank Goolsby, Finley and Associates, LLC. for compiling the Mowry T_{max} and Mowry formation temperature data, a large task, to be sure.

Disclaimer

The map contained in this report is intended to serve as a publicly available map of Mowry thermal maturity across the Powder River Basin. Users of this map should be aware that it contains interpretations of data, and that there are risks that come with those interpretations. The EORI does not warrant the use of this map for any purpose other than to serve as a guide in the user's own interpretations.

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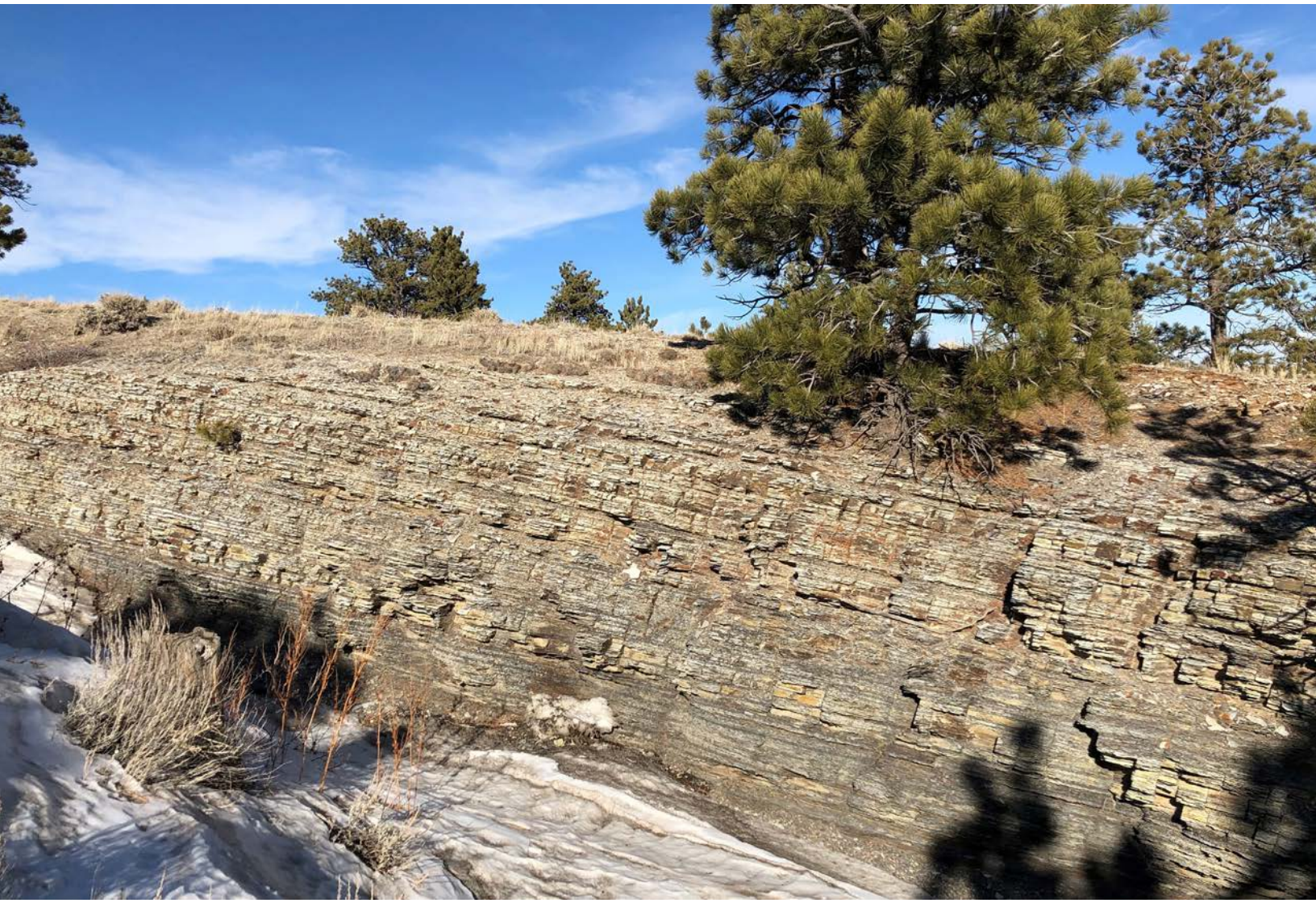

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