Sedimentation & Subsurface Characterization of the Lower Cretaceous Muddy Sandstone & Upper Cretaceous Shell Creek & Mowry Shales in the Powder River Basin, Wyoming

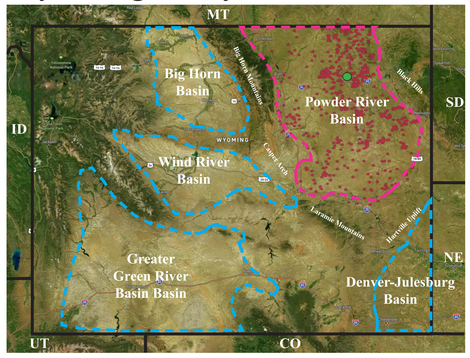
Chase Chavez, Xiangyang Xie, Bo Henk

Department of Geological Sciences, Texas Christian University, TX 76129

Abstract

Foreland basins comprise some of the most prolific hydrocarbon producing reservoirs and source rocks in the North American Rocky Mountain region. One of these major producing basins is the Powder River. Located in Northeastern Wyoming and extending into Southeastern Montana, the Powder River Basin (PRB) is one of Wyoming's largest and most active hydrocarbon producing basins. The basin comprises various Mesozoic and Paleozoic strata with productive conventional and unconventional plays. Various studies have been done on both Mesozoic and Paleozoic stratigraphy within the basin. Historically, Cretaceous age stratigraphy has been well studied within the basin. With continual industry innovations in the collection, development, and processing of subsurface geological data, more refined understanding of the PRB's Cretaceous age stratigraphy is ongoing in both academia and industry. The research in this study focuses on the Lower Cretaceous Muddy Formation and Upper Cretaceous Shell Creek and Mowry Shale intervals at basin scale, and the implications for tectonic and eustatic evolution prior to the formation of the PRB controlling sedimentation and infilling of the three formations. The Muddy being an older conventional reservoir and the Mowry a more recent unconventional play, the collection and utilization of accumulated digitized well log data from Enverus Prism with Petrel Software allows an effective approach for pursuing the goals of this study. In addition, an in-house core analysis of the Muddy and Shell Creek Formation intervals provides a calibration and refinment for producing structure, isochore, and net sand maps for the basin to be used in generating sedimentation and infilling interpretations. Additionally, well logs with correlated Paleozoic stratigraphy from the United States Geological Survey (USGS), were used to generate PRB subsidence curves for multiple well locations throughout the basin to compare with maps and figures produced in Petrel. To further enhance sedimentation interpretations, Muddy interval sands U-Pb detrital zircon analysis was conducted and compared with prior detrital zircon and subsidence work done in the western neighboring Big Horn Basin (BHB) and it's equivalent Muddy interval by May et al, 2013.

Wyoming Study Area



Study Area Boundary
Basin Boundary
Well Data Location
Apache Federal 1-20

Figure 1. Map of major Wyoming basins and Powder River Basin (PRB) study area, with distribution of well data used in project. Modified from Enverous Prism.

The Powder River Basin

Encompassing an area larger than 34,000 mi2 (54,718 km2), the PRB is located in northeastern Wyoming and extends across the state line into southeastern Montana (Fig. 1) (Fox and others, 1991). The PRB is one of the smaller basins produced by the Laramide Orogeny that resulted in the break-up of the Western Interior Basin (WIB) (Miall and Catuneanu, 2019). Formation of the basin is associated with the development of the Cordilleran Orogen and Sevier thrust belt, and both the initiation and termination of the WIB (Miall and Blakey, 2019).

The PRB is the largest of the successor basins created from the break-up of the WIB. Uplifts define the borders of the basin, which include the Laramie Mountains to the south, the Casper Arch to the southwest, the Hartville Uplift to the southeast, the Black Hills to the east, the Bighorn Mountains to the west, and the Miles City arch to the north across the Wyoming state line into Montana. Within the central part of the PRB, a minor northeast trending structure known as the Belle Fourche arch is present. Overall, the basin has a northwest-southeast trending axis and is asymmetric. Strata within the basin generally have a steep dip along the western margin and shallow towards the eastern (Lichtner and others, 2020).

Muddy Sandstone

Deposited during the regressive stage of the 1st sequence cycle of the Cretaceous, the Skull Creek Cycle of the Western Interior Seaway (WIS), is the Muddy Formation (Fig. 2). The formation is comprised of both sandstone and mudstone due to the dominant nearshore, fluvial, and estuarine depositional environments formed during a regressive low-stand of the WIB (Lichner and others, 2020). In the PRB, the Muddy typically is divided into upper and lower intervals. The lower being dominantly fluvial and estuarine, with the top being of marine bar deposit origin (Slack, 1981). Historically, the Muddy has served as one of the original hydrocarbon producing conventional reservoirs in the PRB.

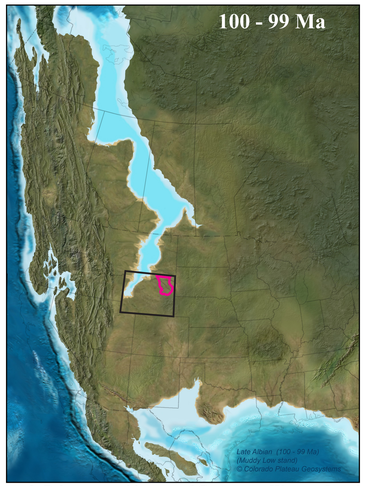


Figure 2. Paleogeographic map of Cretaceous Western Interior and relative sea position during Muddy Sandstone deposition. Modified from Blakey.

Shell Creek & Mowry Shales

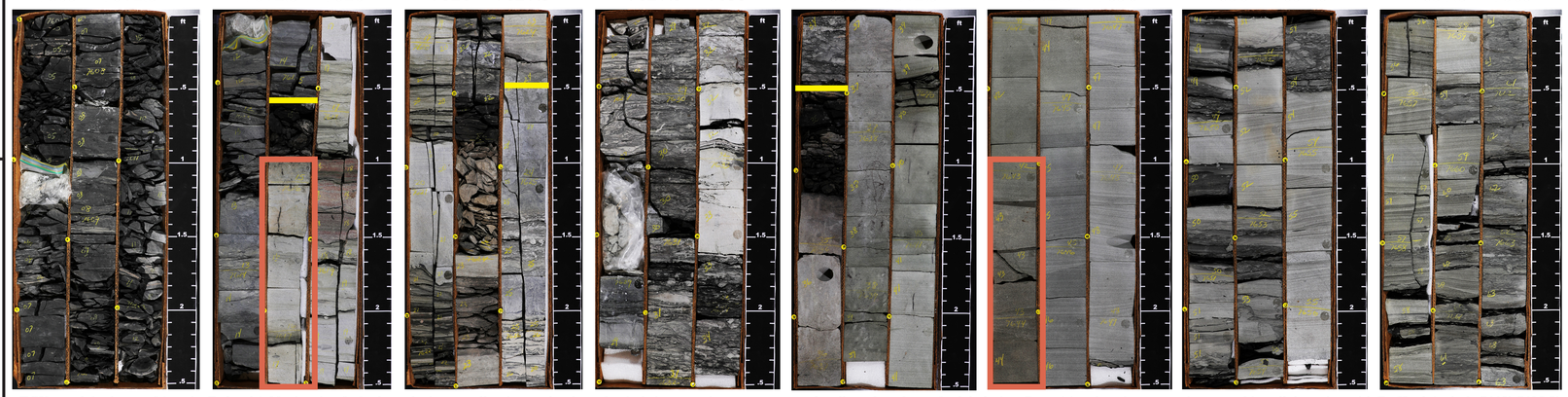
Conformably overlying the Muddy Sandstone is the transgressively deposited Shell Creek Shale (Fig. 3). Described as a "soft black shale," this unit is "commonly silty" and contains multiple bentonite beds (Eicher, 1962). It is commonly combined with the Mowry Shale interval in most prior studies. The Mowry was deposited during the transgressive phase of the 2nd sequence cycle of the WIS in the Cretaceous. With one of the highest Total Organic Carbon (TOC) average percentages of the Cretaceous shales, the Late Albian to Early Cenomanian Mowry serves as a major source rock for the Muddy Formation, as well as Upper Cretaceous reservoirs in the PRB (Momper and Williams, 1984; Dolton and others, 1990; Rahman and others, 2016; Hart and others, 2019, Lichtner and others, 2020). In the PRB, the Mowry is distally deposited, with marine deposits primarily consisting of mudstones (Bohacs et al., 2005; Hankins, 2021). Interbedded bentonites are also present throughout the unit with the top of the formation being marked with a regionally extensive clay spur.

Figure 3. Paleogeographic map of Cretaceous Western Interior and relative sea position during Shell Creek and Mowry Shale deposition. Modified from Blakey.

Subsurface Methods

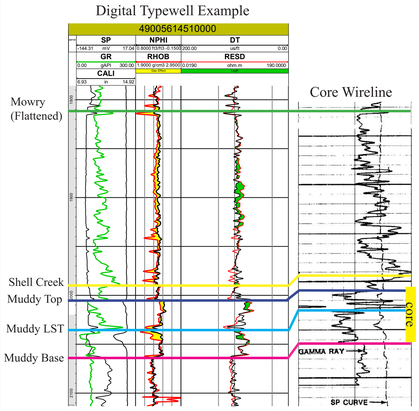
Apache Federal 1-20 Core

Detrital Zircon Sample
Facies Boundary



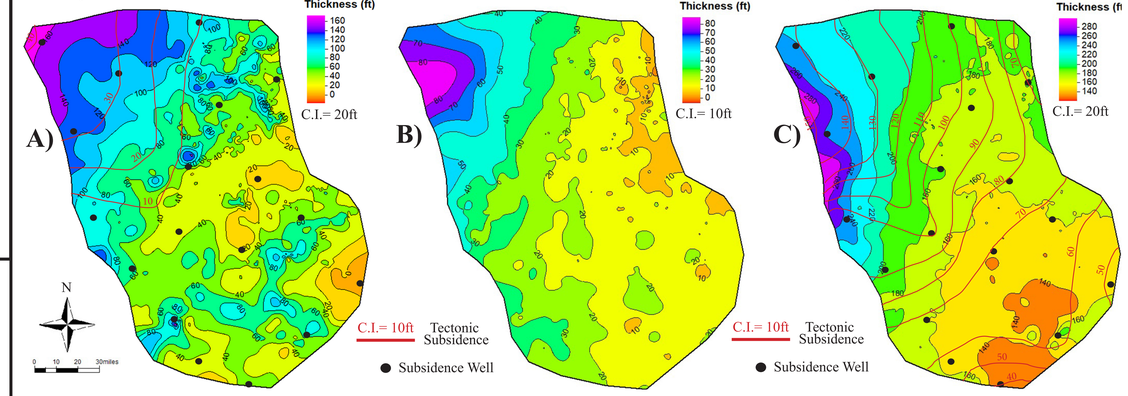
TCU core lab photos of Apache Federal 1-20, showing facies boundaries as well as intervals where detrital zircon grains were processed, collected, and sent for lab dating. Depositional environments intepreted in collaboration with Bo Henk include 7665'-7635.5' coastal, 7635.5'-7625.5' open bay, 7625.5'-7615.5' estuarine/distributary, and 7615.5'- 7605' distal marine. The coastal facies represent the regressive low-stand phase of the formation and the open bay the start of the trangressive phase before maximum flooding.

Well Log Data



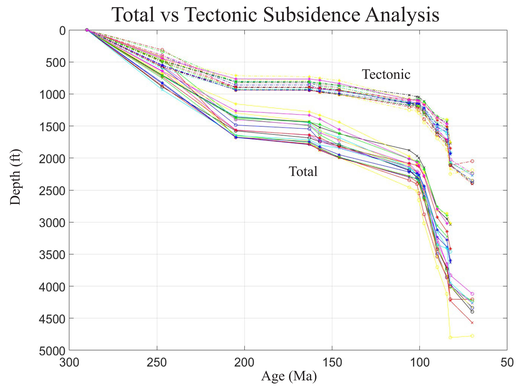
Digitized typewell example from Enverus Prism dataset, displayed in Petrel and tied with wireline raster log of Apache Federal 1-20. This outlines the process for extrapolating log curve signatures across the basin for mapping.

Products & Results



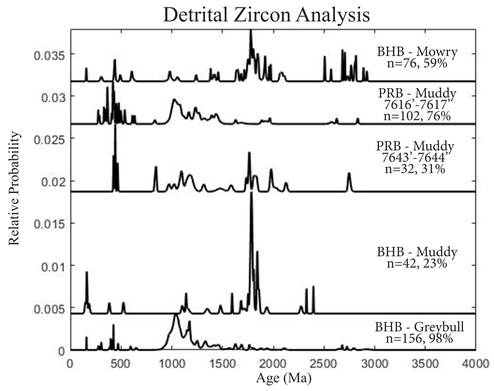
Isochore maps of Muddy Sandstone (A), Shell Creek Shale (B), and Mowry Shale (C) thicknesses generated in Petrel from well log corelations. Overlayed is the contoured tectonic subsidence decompaction for the Muddy sandstone and combined Shell Creek and Mowry Shales produced from the Matlab subsidence analysis plot. Shell Creek and Mowry thickness trends are an increasing thickness towards the northwest part of the basin, and thinning towards the southeast. The Muddy sandstone thins in the central part of the basin, over the structure known as the Belle Fourche Arch. Surrounding this structure are various valley fills and a northwest prograding marginal marine system.

Total vs Tectonic Subsidence Analysis



Subsidence analysis plot produced in Matlab using decompaction and back-stripped tectonic subsidence (Xie and Heller, 2009). Formation age inputs start at 247 Ma and end at 70 Ma. Correlations used for formation thickness inputs are from the USGS's published PRB electric log cross-sections, done by James E. Fox in 1993. A total of 18 wells were used for PRB regional subsidence analysis.

Detrital Zircon Analysis



Composite detrital zircon age >120 Ma probability distribution plot of Greybull, Muddy, and Mowry intervals from the Big Horn Basin (BHB), as well as Powder River Basin (PRB) Muddy Sandstone samples from core (May et al, 2013). Additionally provided are the total grains >120 Ma (n) and their percentages of the bulk total analyzed for the basin and interval. Dating by Jackson School of Geosciences Quardrapole ISP-MS lab.

Conclusions

• Tectonic Evolution

During Muddy deposition in the WIB, very little tectonic subsidence was occurring in the central to southern half of the basin area. However, in the northwestern side of the PRB, a slight influence can be observed. This transitions to a more prominent impact during the Shell Creek and Mowry Shale depositional timing, with an increasing decompaction thickness and gradient from the southeast to the northwest of the basin. The Muddy most likely reflects the minor impacts of the Sevier thrust belt deformation in the PRB area of the WIB, that becomes more prominent during the timing of the Shell Creek and Mowry Shale deposition.

• Basin Infilling

Muddy sandstone detrital zircon dates reflect dominant western source signatures in comparison with the western neighboring Big Horn Basin. PRB Muddy dates resemble Greybull from the BHB, an older formation that was deposited during the initial filling of the WIB by the WIS. This indicates that the two different formations shared a similar depositional pattern from the west until an evolutionary change occurred somewhere between the two basins during the Muddy timing, resulting in the BHB to be supplied by more western sources while the PRB maintained a stronger eastern. A slight variation in sample intervals from the well core can be also be observed, possibly indicating an adjustment period of sediment controls during the transition of the low-stand phase to the transgressive deposits at either a local or regional scale within the PRB. The Shell Creek and Mowry Shales overprint the Muddy with a consistent increasing thickness variations southeast to northwest. This leads to the assumption the Muddy Sandstone within the PRB was infilled by western sourced sediments within available accommodation created from the start of Sevier subsidence and eustatic regressive and transgressive changes. Lastly, A combination of increased tectonic subsidence with high-sea level and sediment supply would produce the current trends observed with the Shell Creek and Mowry Shales during basin infilling.

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