Reservoir quality and stratigraphy of the Mowry and Muddy interval of the Powder River Basin, Wyoming, USA

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Interest in the Powder River Basin (PRB) of Wyoming, Northwest USA, has been increasing in recent years, as it is a mature basin with a number of prolific stacked plays, coupled with the promise and opportunity of a few key emerging plays. The Mowry Shale is one of the emerging unconventional plays and has historically been characterized as a key source rock for the underlying Muddy Sandstone and other shallower reservoirs. Both the Mowry Shale and the Muddy Sandstone are considered underexplored and to have potentially significant potential.

Looking at these two plays in concert, the contrasts between the conventional and unconventional opportunities are clear. Despite its name suggesting otherwise, in its truest form, the Muddy Member is a fluvial estuarine sandstone and, when found, is most often clean and well sorted. The Mowry, on the other hand, is a shallow marine shale, ubiquitous however quite heterogeneous in the basis. Drilling activity suggests that the industry is struggling to understand the stratigraphic and spatial controls on exploiting the Mowry as an unconventional target. In discussing prospectivity in the Mowry and Muddy interval, a common theme is: 'We know where the Mowry is but we don't know where it's good; we know the Muddy is good but we don't know where it is.'

To address these issues, an integrated geoscience project was commissioned to study the area in order to refine the stratigraphic framework, enhance understanding of the depositional setting and review overall prospectivity in these plays. As part of the project, 1173' of core and the associated wireline logs from 14 key wells were analysed and interpreted to target specific problems. Two hundred and seventy four core piece samples were taken at approximately four' intervals and there was a concentration around key lithostratigraphic boundaries. In addition, a complementary suite of 51 field samples from outcrops in the western PRB and Wind River Basin have provided additional control and valuable analogue data to supplement the subsurface dataset. The project utilized recent-vintage 3D seismic surveys that span the western margin of the study area (Figure 1).

The primary focus of the investigation focused on the reservoir quality and internal stratigraphy of the Mowry and Muddy interval. These interpretations have been extended from initial core-based studies to the full study interval through calibration to available wireline log suites and associated petrophysical derivatives. Ultimately, the interpretations were further enhanced by calibration with elastic properties derived from pre-stack inversion of the

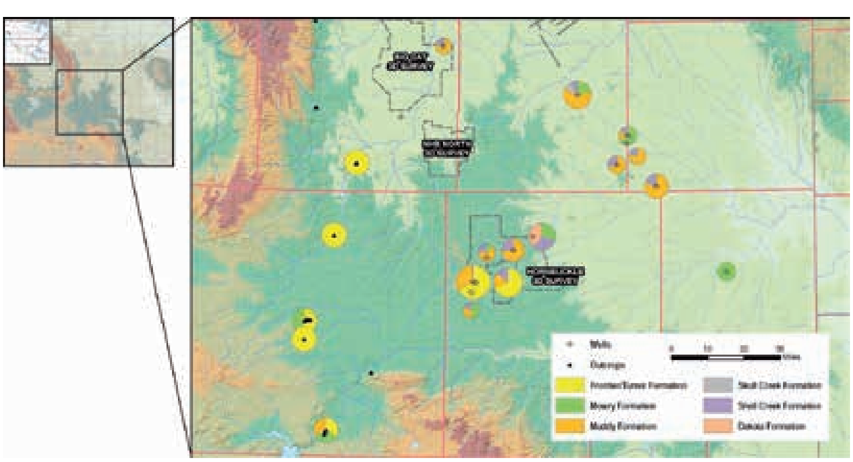

Figure 1 *Map of study area: wells analysed with formation distribution, seismic coverage and field locations.*

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seismic data and the rock-based analyses. With the seismic and well data acting as control, the interpretation was extended across the basin, allowing mapping of the extent and character of the key Mowry and Muddy Units as a means to assess exploration risk and opportunities in this evolving play.

Paleogeography and climate

The PRB is a North-South trending, westward-dipping basin that resembles an asymmetric syncline and documents three significant tectonic phases: 1) Proterozoic continental assemblage; 2) Mesozoic retro-arc foreland system; and 3) Laramide flat-slab compartmentalisation of the foreland system (Melick, 2013).

During the Mesozoic, the PRB occupied an east-central position within the Western Interior Basin (WIB) of North America. It was during this time that sedimentary basins across western North America were linked to the geodynamics of an active western continental margin (Dickinson, 2004)

The western margin of the WIB was dominated by zones of maximum subsidence, which decreased eastwards giving rise to a broad, east-central forebulge zone and backbulge basin (Miall et al., 2008). By the Mid-Cretaceous (~100 Ma), low-angled subduction was in place as far north as 60° N, evolving into a limited region of flat slab subduction during the early Upper Cretaceous (~90 Ma). It was during the Cretaceous that the WIB was flooded and drained by a series of marine transgressions. At peak flooding, the Cretaceous seaway extended from Arctic Canada and Alaska south to the Gulf of Mexico, with probable intermittent connections to the Hudson Bay region (Davis et al., 1989; Kauffman, 1984).

Mid-Cretaceous (Albian to Turonian) paleoclimatic studies suggest that precipitation rates ranged from ca. 80 to ca. 160 inches/year (White et al., 2001; Brenner et al., 2003) and up to maximum values of ca. 220 inches/year (Ufnar et al., 2008). To put this into context, the present-day precipitation range for similar latitude (45°N) in North America is ca. 33 inches/year (Barron et al., 1989). These estimates are consistent with predictions provided by a paleo-source facies prediction tool, based on global Earth Systems modelling techniques (Figure 2).

Stratigraphic framework and integrated facies analysis

The sedimentology and depositional facies of the target units was determined from detailed core studies, including 1:50 scale core descriptions. The core descriptions were supplemented by mineral composition data and textural information derived using automated mineralogical analysis performed on selected key core samples and on all the collected field samples with a Scanning Electron Microscope (SEM) (Oliver et al., 2013). To aid in the development of a robust chronostratigraphic framework, a detailed multidisciplinary biostratigraphic workflow was established using the same sample set of both core and field samples. The biostratigraphic work included detailed analysis of the microfossil and fauna assemblages primarily for the understanding of the depositional environment and subsequent stratigraphic determination. After careful investigation, involving a review of richness and preservation issues, quantitative palynology was deemed the most appropriate stratigraphic tool for the project. Very detailed interpretation and analysis of observed palynomorphs assisted in this framework and allowed for a precise tie-back to well logs for consistent chronostratigraphic timing and depositional environment determination that could be mapped across the region with the aid of seismic reservoir characterization techniques.

Facies data were used with the palynological dataset to develop a robust stratigraphic framework and depositional history for the Thermopolis to Frontier Formations. Within this framework, the muddy member of the Thermopolis Formation was subdivided into five units (A-E), with varying depositional environments (tidal inlets, sand bars, channels, mouthbars, etc.). The Mowry Formation was deposited in a shelfal setting and can be subdivided into three members (F-H) depending on different oxygenation states and variations in sediment input. The facies were

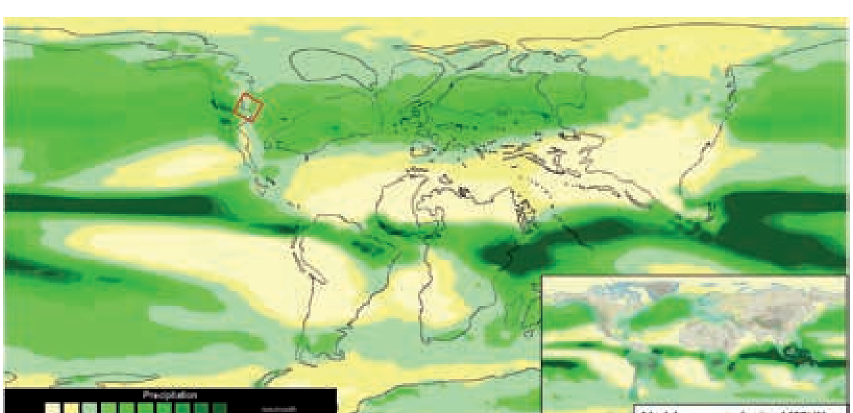

Figure 2 *Average annual precipitation in study area (red square) is > 100 inches, ten times that at the present day (inset).*

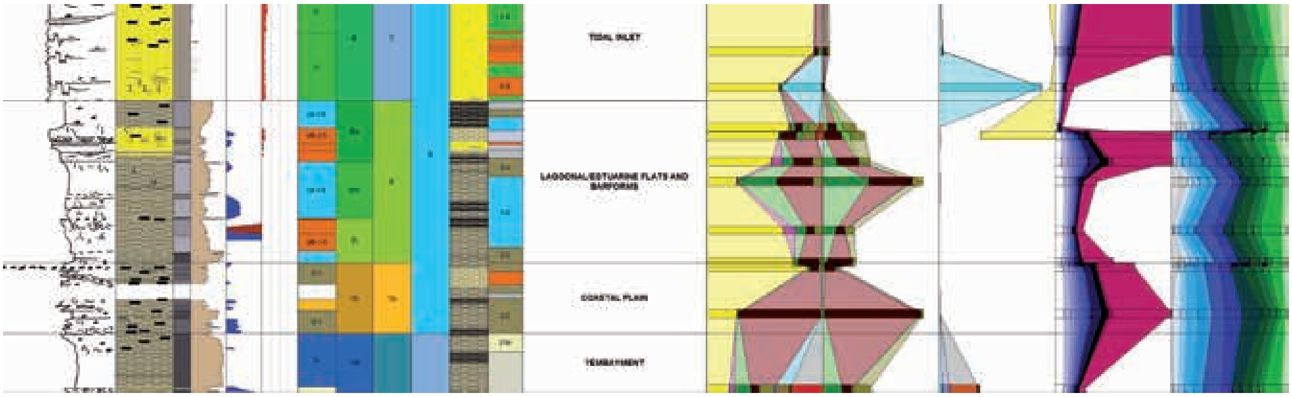

Figure 3 *Example well summary chart.*

extrapolated into the un-cored intervals using petrophysical methods (Figure 3).

The sedimentological facies were grouped into five log facies (shale, low density shale, shaly sand, unconventional sand and conventional sand) and could be separated based on elastic properties (Vp, Vs and density) and petrophysical parameters (porosity, water saturation and clay volume). Pre-stack seismic inversion and elastic lithofacies can be used to bridge the gap between sedimentological and seismic rock property interpretations (Castillo et al., 2014). Vp/Vs and acoustic impedance were the key variables that allowed interpretations to extend from the well database into the seismic volume. With a revised stratigraphic framework in place and an understanding of the lithological and facies controls on the seismic responses the seismic data could be interpreted accurately and with confidence.

A 3D geomodel was generated for the Muddy and Mowry volume in the seismic areas, populated with the inverted seismic data. The facies model created over the areas of available 3D seismic data has been used to validate extension of the more general geological model away from the well control and has been used to constrain the development of a regional-scale conception depositional model and subsequent regional mapping of key features of the target formations.

Petrography, diagenesis and reservoir quality

Detailed petrographic analysis was conducted using quantitative light microscopy augmented by SEM automated mineralogy methods to determine the key detrital and authigenic phases and the porosity and brittleness of each facies (Figure 4).

Detrital textures and phases observed in all samples reveal a texturally and mineralogically mature system with most samples being well sorted, well rounded and primarily arenaceous in composition. The most abundant authigenic cements are quartz overgrowths with localised high quantities of calcite and hematite cements. The most abundant authigenic clays are illites, with kaolinite also common. Effective porosity loss due to diagenesis has been primarily through compaction (exaggerated by ductile phases), quartz cementation and illite precipitation. Calcite and hematite cementation and kaolinite precipitation are less abundant phases but locally adversely impact effective porosity.

Rheological changes associated with the intensity of diagenetic alteration, as defined from the combined petrographic and SEM analysis show a good correlation with acoustic impedance in both the well logs and seismic data.

Overall, the Mowry Formation mudstones contain a variable but often high component of detrital silt that is primarily quartzose in origin. Elevated siliceous content in some intervals has been linked to an additional siliceous source associated with the dissolution and recrystalisation of silica from a biogenic (radiolarian) origin (Byers and Larson, 1979). This study, however, has not documented significantly elevated siliceous content and no clear evidence of a biogenic silica source could be clearly developed. Most of the silica content in the study samples is therefore considered to have either a detrital origin, associated with terrestrial input, possibly enhanced by silica sourced from the volcanics of which the bentonite layers are an obvious potential source. The latter observation is supported by the common association noted in outcrop between bentonite layers and immediately adjacent highly indurated shales.

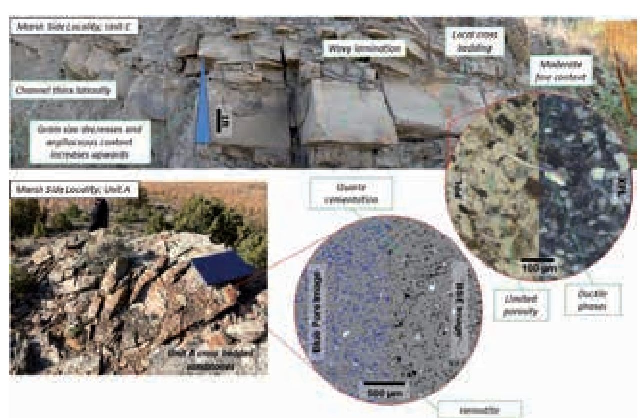

Figure 4 *Outcrop and Backscatter Electron (BSE) analysis of Units A and C.*

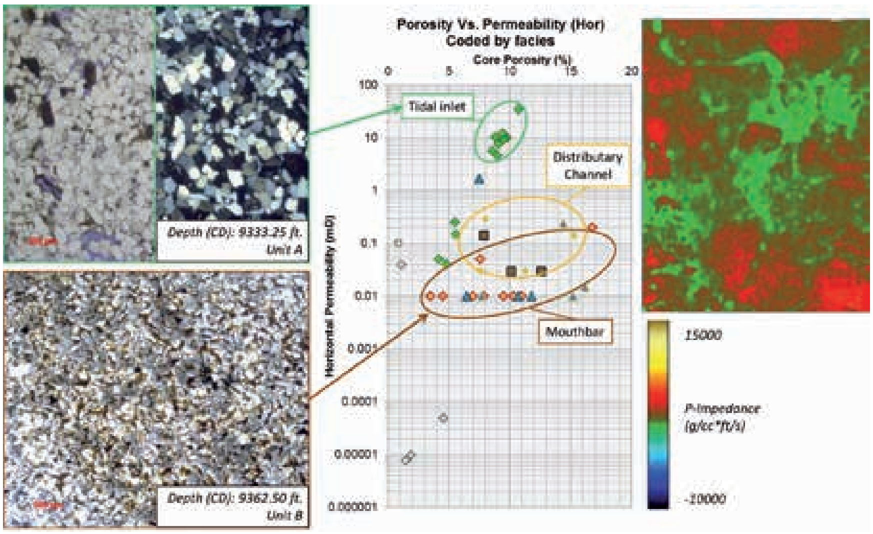

Figure 5 *Left: Thin sections from Units A and B. Centre: Core porosity vs. Permeability plot. Right: Sinuous, ribbon-form low-value features highlight tidal channel geometries on the P-impedance map.*

Integration and interpretation

The Core-Log-Seismic workflow has revealed a number of key observations and considerations when evaluating the Muddy and Mowry interval in the PRB. Facies analysis and lithological descriptions have been established for the 14 study wells, which were used to constrain and improve the petrophysical analysis and allow extrapolation into un-cored intervals. Quantitative palynology, integrated with sedimentary facies description, was used to establish a robust chronostratigraphic framework for the Albian to Cenomanian intervals. In addition, compositional changes in microplankton and miospores assemblages have provided critical information for paleoenvironmental interpretation of the studied intervals.

The Muddy Member of the Thermopolis Formations is characterised by coastal environments, in which good-quality sandy facies, such as tidal inlets, tidal sand bars and channels, are observed within the A, B and D Units respectively. In contrast, more argillaceous sandy facies, such as mouthbars, distributary channels and finer-grained channels, are observed in Units C and E. Sandy tidal facies are widely distributed, but the channels (predominantly Unit D) are highly localised. A distinct geographic boundary between the two facies can be mapped using a combination of core and seismic observations.

The tidal inlets and channel sands of Units A and D form the best-quality conventional reservoirs in the target interval, with clean stacked sand packages and textures indicating a relatively mature depositional system. Given the ribbon-form nature of the channel sands and their general easterly flow direction, broad inferences concerning their distribution can be made. However, the clear lack of significant lateral migration means that seismic data and direct mapping of channel belts is the most accurate means of mapping their distribution. In terms of reservoir quality, porosity can be shown to decrease with depth and below ca. 13,000' porosities are generally <10% (Figure 5). Quartz overgrowth cementation and compaction porosity loss due to burial diagenesis is more important in reducing porosity than clay mineral formation in these sandier facies. In contrast, argillaceous sandy facies lose porosity with depth at a greater rate and typically have porosity of <10% at depths greater than about 9000'.

The overlying Mowry Formation represents a restricted shelfal environment comprising three distinct parasequences (Members F-H) separated by bentonites resulting from discrete volcanic events. Members H and G (especially the latter) primarily comprise anoxic subtidal sheet deposits, whereas Member F consists primarily of dysoxic to suboxic subtidal sheets. Sands characteristic of transitional facies and subtidal channels were also observed, along with evidence indicative of shallow water conditions and the influence of subaqueous oxygenated flow, tidal currents, etc.

Petrophysical modelling techniques were used to accurately capture the parameters of the encountered lithologies in the study wells, including porosity, water saturation and mineralogy (clay, quartz, calcite, etc.). The results were validated against SEM data to ensure accuracy. In addition, a stable model has been created from these parameters to generate shear sonic curves, which played an important role in the subsequent geophysical and geomechanical modelling. Five lithofacies were established from the elastic logs and vetted against observations from the field and cores to help to refine the seismically constrained subsurface geomodel.

Seismic reservoir characterization processes such as deterministic pre-stack inversion and seismic lithofacies predictions (Figure 6) were carried out to integrate the petrophysical and seismic data resulting in a 3D lithology/facies model for the Muddy Member and Mowry

Formation. The seismic-based facies model was used to validate the geological model of the study area.

Finally, reservoir and source rock characteristics were assessed to identify the key play risks for the three members of the Mowry Formation, allowing generation of common risk segment maps that highlight the parts of the basin with the highest potential for the development of a shale play in the study area. Source quality risk is shown to increase in areas where fluvial input is highest, resulting in a potential clastic dilution effect that lowers absolute TOC values and is associated with an influx of type-III Kerogen that is less oil-prone. In addition, this process is associated with potentially more oxic conditions and a reduced likelihood of enhanced preservation. Early mature regions of the basin are considered a moderate risk because significant hydrocarbon generation is thought to only occur from peak oil maturity onwards and is restricted to geographically confined regions of the basin. The maturity, source quality, and reservoir risk maps have been combined to create an overall risk map, Figure 7.

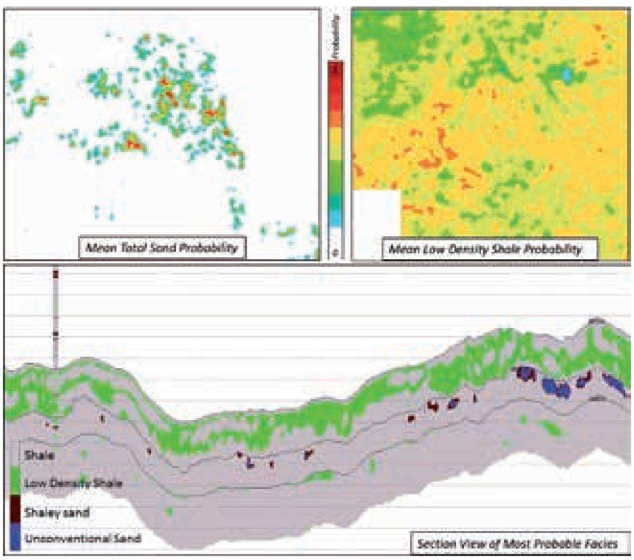

Figure 6 *Facies and fluid probability (FFP) analysis.*

Conclusion

Through a combination of core, wireline log and seismic analysis we have successfully delineated the stratigraphy of the Thermopolis to Frontier Formations of the PRB. We are able to map these units across the basin and evaluate their stratigraphic and spatial extent. We have used this framework to underpin a quantitative evaluation of the reservoir quality and source rock maturity of key units within the stratigraphy.

Whilst individual components can yield valuable information, such as core descriptions, palynology, log analysis, horizon picking, etc., it can be easy to misinterpret this data and misrepresent the key observations derived. Here, we have been able to combine classic geological disciplines with robust geophysical analysis to deliver an integrated geoscience solution.

The Mowry and Muddy interval of the PRB remains underexplored and will require significant investment to reveal its full potential. In this study, we have evaluated a number of the controlling factors on productivity and identified those regions with greater prospectivity across the basin.

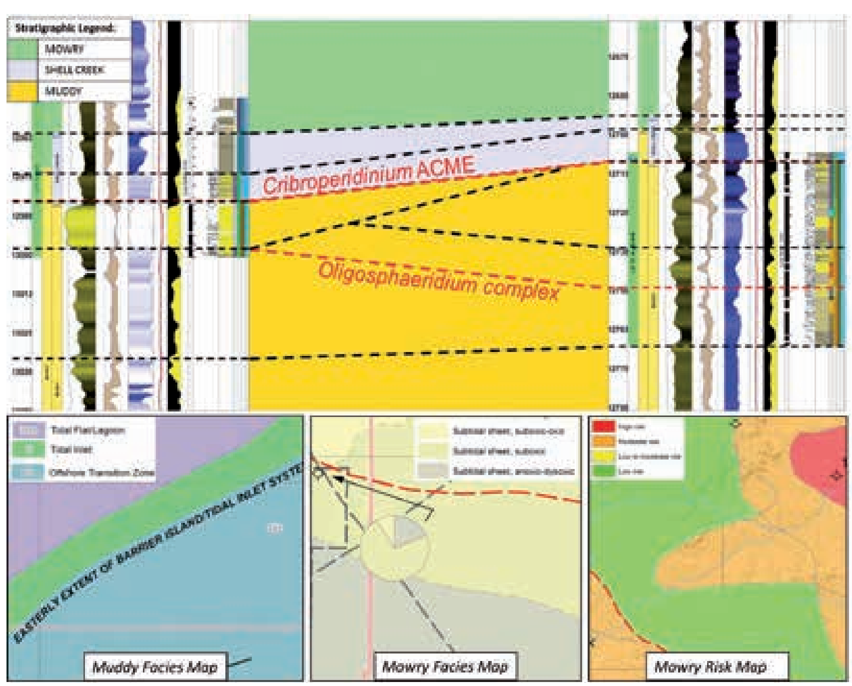

Figure 7 *Extracts from the correlation panel (top) and the facies and risk maps (bottom).*

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