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Predicting Reservoir Heterogeneity in The Upper Cretaceous Frontier Formation in The Western Powder River Basin – An Integrated Stratigraphic, Sedimentologic, Petrophysical, and Geophysical Study.

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Summary

Understanding how stratigraphic and sedimentologic heterogeneity is reflected in wireline logs and seismic attributes is crucial to predict areas of better reservoir development in tight oil plays. This study explores the predictive capability of an integrated geologic, petrologic, petrophysical and geophysical model based on detailed facies analysis of thirteen sediment cores expanded over 400 wireline log suites and 440 square miles of 3D seismic in the western Powder River Basin, Wyoming.

The integrated model is focused on the upper Cretaceous (Turronian) Wall Creek member of the Frontier Formation which varies in thickness from <10m to 60m across this area, and contains a complex assembly of lithofacies, ranging from fine-grained mudstones to coarse grained sandstones, with the latter forming the legacy conventional reservoir facies. A total of twelve distinct core facies and three sub-facies were identified based on grain size, physical and biogenic sedimentary features, ichnology, and petrology.

Propagation of the core facies at wireline log resolution across a geographically significant and well resolved area was accomplished by employing a principle component analysis technique utilizing standard wireline log suites. The initial twelve core facies were upscaled to nine uniquely identified log (electro) facies based upon their statistical occurrence within each individual log facies.

Log facies were subsequently upscaled again into six seismic facies based upon elastic parameters. Favorable elastic and geomechanical properties distinctly correlate to net pay facies derived by wireline logs which in turn correlate to coarser-grained sandstone facies. A simultaneous, geostatistical, prestack seismic inversion was conducted on a 3D seismic volume and probability volumes of encountering each seismic facies in addition to a most likely seismic facies volume were analyzed.

The fully integrated results from core to log to seismic facies along with 3D seismic inversion-derived reservoir parameters calibrated to well control offer an added geologic comprehension of the stratigraphic architecture and reservoir distribution in the Wall Creek member as well as highlighting areas of better reservoir development potential thereby demonstrating the significant value of this integrated approach.

Introduction

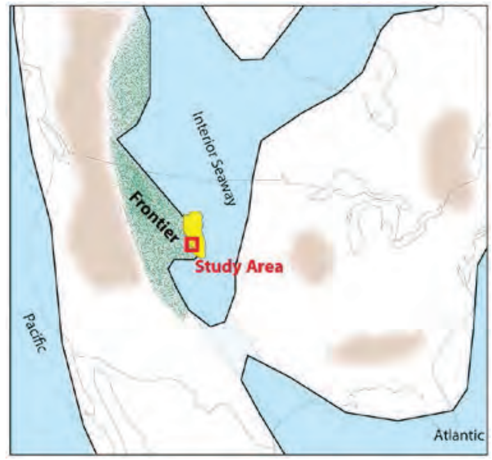

Figure 1: Paleogeographic map of North America during the time of the Frontier Sandstone deposition; blue areas are marine basins; terrestrial areas are highlighted in white, brown (highlands), and green (major delta systems); the study area (red box) is located in Wyoming along the western flank of the Powder River Basin (yellow); map modified from Bhattacharya and Willis, 2001).

The upper Cretaceous Frontier Formation in the Powder River Basin in Wyoming is a well-known, prolific hydrocarbon reservoir. Exploration efforts in the late 70's and early 80's focused primarily on the coarse grained conventional sands within the Wall Creek member of the Frontier Formation. These vertical wells were prolific producers, many of which are still on line today. Over the last decade, advances in horizontal drilling and hydraulic fracturing technology have opened a new era allowing access to the tighter, unconventional facies within the Frontier Formation. However, significant challenges are faced in identifying and characterizing both the vertical and lateral heterogeneity in this play due to the complexity of the depositional environment. In order to tackle this challenge an integrated geologic, petrologic, petrophysical and geophysical study was conducted based upon the analysis of thirteen sediment cores, over 800 wireline log suites and 440 square miles of 3D seismic in the western Powder River Basin. The primary focus of this study was the Wall Creek member of the formation which varies in thickness from < 10m to 60m in the study area and contains a complex assembly of core facies ranging from fine-grained mudstones to coarse grained sandstones. The study identified a total of twelve distinct core facies upscaled to 9 distinct log facies which were further upscaled and propagated through six distinct seismic facies across a geographically significant and well resolved area accomplished through geostatistical inversion of the 3D seismic data. The resultant mapping of the seismic facies distributions offer an added geologic comprehension of the stratigraphic architecture and reservoir distribution in the Wall Creek member. These results provide a new framework of facies heterogeneity observed in the Wall Creek Member of the Frontier Formation in the western Powder River Basin and allow for optimization of current reservoir development plans.

Methodology

Core facies methodology

The interpretation of facies and application of facies models has been a powerful tool for classifying and explaining ancient sediments. The sedimentary strata observed in the thirteen cores included in this study are best described by 12 distinct facies, mainly based on their mineralogic and petrographic characteristics, as well as physical and biogenic sedimentary features. A wide variety of cross-stratified and rippled sandstones, bioturbated sandstones and siltstones, and mud rip-up clasts and mud drapes are indicative of a number of sedimentary processes and depositional environments, ranging from offshore to mouthbars. Similarly, ichnofacies assemblages range from a diverse and robust infaunal community implying substantial reworking of those facies in a normal marine offshore transition zone environment, to a trace fossil suite recording environmental stresses closely associated with nearshore (tidally influenced) deltaic settings.

In general, the 12 distinct facies can be categorized into two facies associations based on the broad depositional environment in which they occur, namely a wave dominated marine facies association (core facies 1-6; Figure 2), and a tidally influenced facies association (core facies 7-11; Figure 3). In addition to a wealth of sedimentary structures associated with wave and storm deposition, most of the facies included in the marine facies association exhibit abundant and variable bioturbation (Figure 2). Traces recognized belong primarily to the *Cruziana* ichnofacies, but in some intervals traces of the *Skolithos* or *Nereites* ichnofacies are dominant. In contrast, the facies associated with the tidal facies association are commonly less textural mature, and contain sedimentary structures indicative of tidal influence. These include herringbone cross stratification (core facies 8; Figure 3), heterolithic strata with abundant rip-up clasts (core facies 10; Figure 3), and double mud drapes (core facies 8 and 9). The traces in this facies association have a low variability and are indicative of a stressed environment.

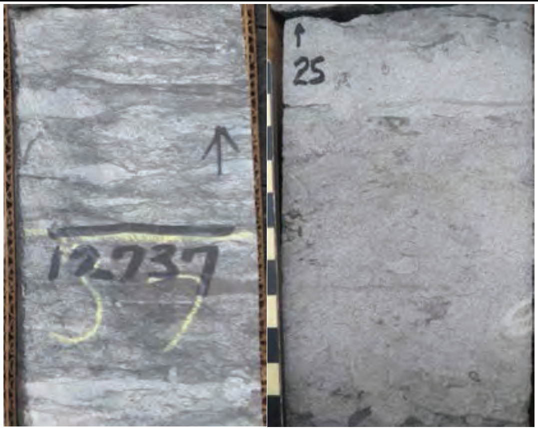

Figure 2: Core examples of common facies associated with the marine facies association; the left image exhibits an example of the bioturbated, sandy mudstone (core facies 2, left), and the photo to the right displays an example of the bioturbated sandstone facies (core facies 5, right).

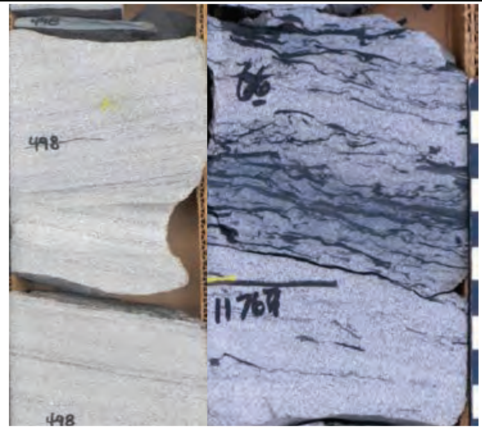

Figure 3: Core example of crossbedded sandstone (core facies 8, left), and heterolithic sandstone with abundant rip-up clasts (core facies 10, right), both very common in the tidally influenced facies association.

Core facies 7 exhibits the best reservoir quality throughout the study area. Detrital grains in this facies are largely composed of monocrystalline and polycrystalline quartz grains, and chert, with subordinate rock fragments (mainly volcanic and sedimentary clasts, some metamorphic), feldspar, and detrital mica flakes; this facies is generally poorly sorted (<50µm to >500µm) and grains of all lithologies are angular to sub-rounded (Figures 4, 5). Cementation and effective porosity in core facies 7 are variable. Figure 4 shows a well compacted example core facies 7 with abundant convex-concave and pressure solution contacts between grains. Quartz overgrowth is common in particular on monocrystalline quartz grains and calcite and dolomite cement effectively fills the remaining intergranular porosity. Porosity is restricted to minor dissolution pores. In stark contrast, Figure 5 shows an example of core facies 7 that contains an abundance of intergranular porosity with only minor cement. Cement is usually restricted to minor quartz overgrowth and minor carbonate cement.

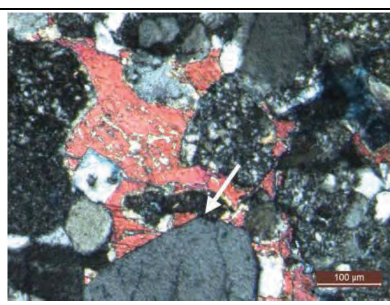

Figure 4: Cross polarized light photomicrograph of well cemented core facies 7. Abundant calcite cement (stained red) is effectively destroying almost all porosity; the majority of detrital grains are quartz and chert and minor sedimentary lithic grains; quartz overgrowth is common on monocrystalline quartz grains and is evident by the presence of euhedral quartz crystal boundaries (white arrow).

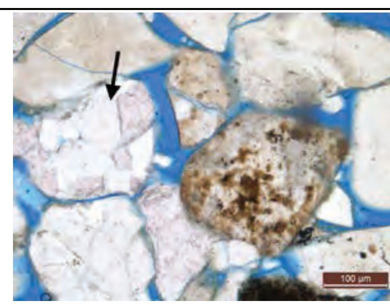

Figure 5: Plane polarized light photomicrograph of core facies 7 with abundant porosity (blue). Most pores are intergranular pores; detrital grains are mainly quartz, chert, lithic fragments and feldspar. Most of the lithic fragments are of volcanic and sedimentary (black arrow) origin.

Petrophysical facies methodology

The effective integration of core data with log data on a regional scale requires a methodology for interpreting vertical heterogeneity at both the core and log scale. The identification of log scale heterogeneity was accomplished by employing the Heterogeneous Rock Analysis (HRA) module in Techlog.

HRA uses n-dimensional principle component analysis to rotate the input data (logs) into uncorrelated axes. Once the rotation is complete, a K-means clustering algorithm is used to create the HRA log (electro) facies (Doveton, 1994). While the software itself is very robust, the input logs require significant attention in order to achieve meaningful results. The initial challenge is to define a curve set pervasive enough throughout the area of interest to create a regionally robust model. For this particular study, the GR, RHOB, NPHI and Deep Resistivity logs from standard triple combo log suites were selected for developing the log facies model. The next challenge faced was the overall quality of the logs being input into the model. The majority of the logs were acquired in the early 70's through the late 80's by a series of logging vendors. In order to accurately reflect changes in rock and fluid properties rather than artifacts associated with varying environment corrections (or lack thereof) or the digitization process, a regional normalization technique (Bornemann, 1981) was used on both the GR and NPHI curves. A regional map based normalization technique was required in order to account for geologic variability across the large area encompassed by the study. Upon completion of the normalization step, a series of "Tier 1" wells were identified based upon log quality, the presence of core over the interval of interest and regional coverage within the study area. The Tier 1 wells were then used to define the seed log facies model for the region (Figure 6).

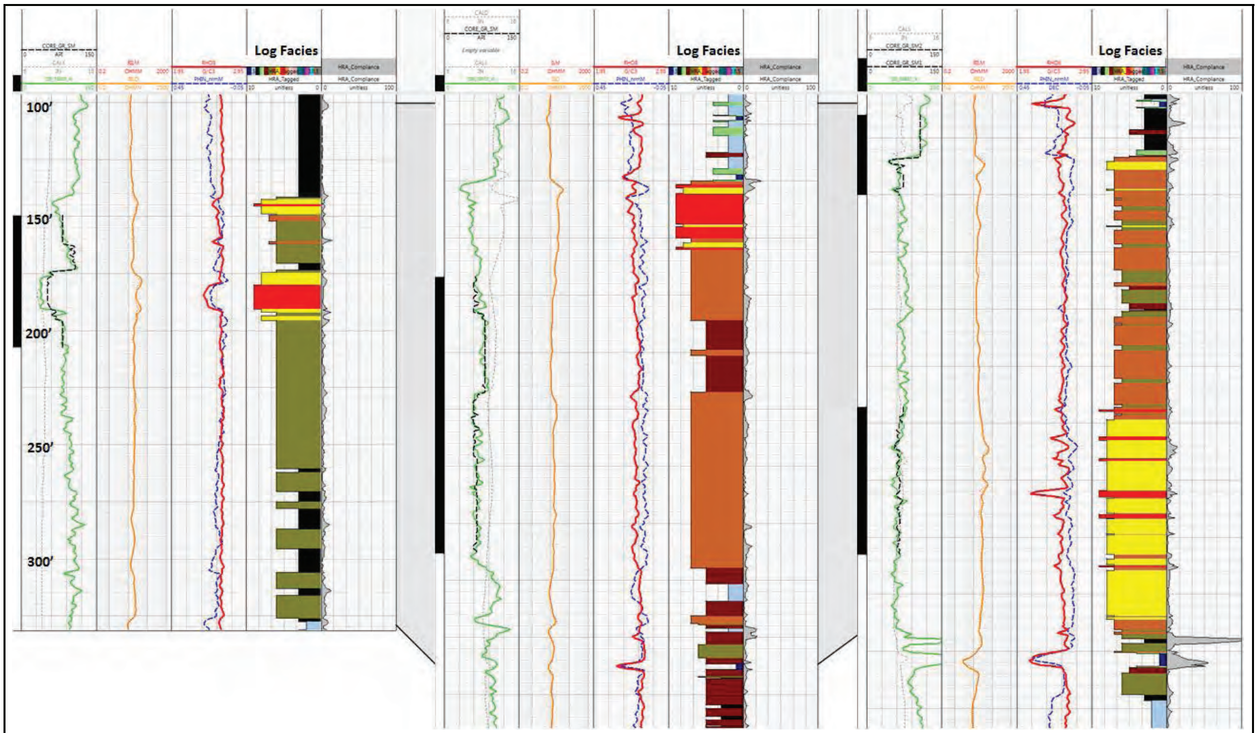

Figure 6: Three Tier 1 HRA model wells illustrating the vertical heterogeneity identified at log scale as well as the stratigraphic representation of cored intervals (black bar) for integration.

The HRA process which captured the log scale heterogeneity in the initial seed wells was then extrapolated to the remainder of the wells within the entire region of interest using the HRA tagging module within Techlog. The initial model was then extrapolated to over 400 wireline log suites across the region of interest. Isopach maps of each log facies were created in order to quality control the extrapolation process. Areas exhibiting bull's-eyes or that did not fit the regional trends were investigated further and were typically identified as the result of poor log quality driven by hole rugosity.

Following the quality control steps outlined above, the cores were shifted to log depth. This in itself posed many challenges as there were no core gamma logs available and therefore an initial rudimentary shift was applied based upon matching core total porosity with calculated total porosity from the density log. In order to effectively integrate the core facies, a higher level of precision was required for depth shifting. Using the initial shift as a guide, the digital core facies were each individually filtered for their average log gamma values which were subsequently applied back to the core facies to generate a synthetic core GR. In a last step a two foot Gaussian smoothing filter was applied to the synthetic GR which allowed for a more dynamic core to log shift to be applied (Figure 7).

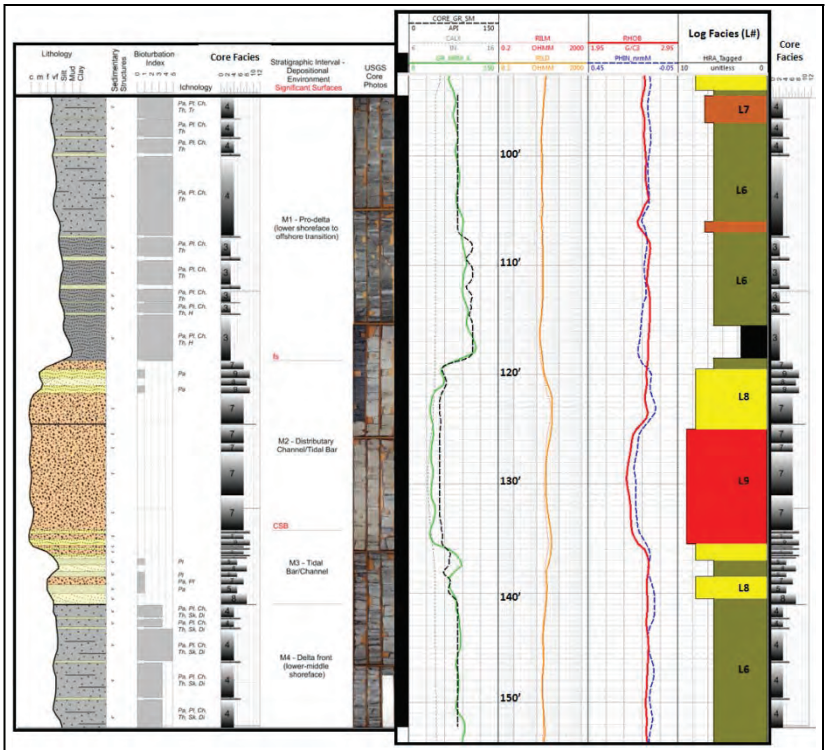

Figure 7: Detailed core description from one of the "Tier 1" HRA model wells (left), triple combo log suite from the same well with the synthetic core gamma ray shown as well as the core facies juxtaposed next to the log facies.

One of the challenging aspects of core to log integration is dealing with the inherent smoothing effects of the basic log suites. Discrete transition zones in the core between separate core facies exhibiting appreciable differences in their properties often manifest themselves as more gradual transitions over one to two feet within the logs. Even when employing the more rigorous core to log shift using the synthetic core gamma ray, this issue is still present and ultimately leads to broader distributions of core facies at the log scale. Based upon this, and the common presence of thin beds in the formation, often below the log scale resolution, when upscaling from core to log the dominant characteristics, typically represented by 1-2 core facies and associated with a particular depositional environment are used to define each log facies in terms of lithotype and its representation in the overall stratigraphic framework (Figure 8).

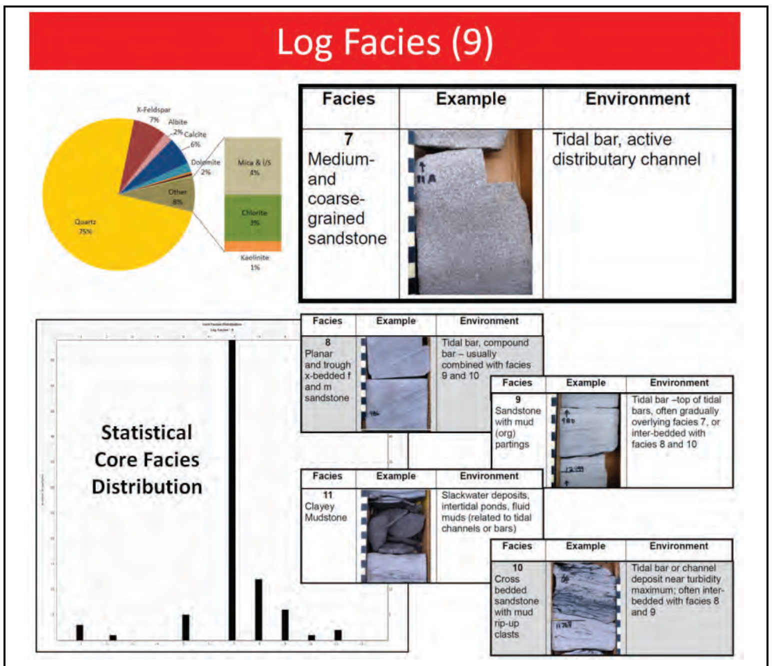

Figure 8: The statistical distribution of core facies for log facies 9. Core facies 7 represents the dominant characteristics for this particular log facies.

Seismic facies methodology

For the last step in the upscaling workflow, the log facies are cross plotted by seismic parameters to determine if individual facies can be discriminated. Seismic parameters typically employed for facies discrimination include compressional /acoustic impedance, shear /elastic impedance, VpVs ratio, Poisson's ratio, Young's modulus, lambda rho, or mu rho.

If log facies plotted at log resolution cannot be discriminated by seismic parameters, then log facies will be indistinguishable from each other with seismic data. If log facies can be discriminated, then the facies are upscaled to seismic resolution to determine if they are still distinct. The upscaled seismic facies that link core data and petrophysical data provide the foundation to map the heterogeneous nature of the unconventional reservoir. Figures 10-12 create the foundation for linking core, log, and seismic parameters into an integrated geologic model to be utilized in a seismic inversion to predict reservoir properties laterally across the area of interest. The log data in Figures 10-12 discriminate seven seismic facies at log resolution, but merge into six seismic facies after upscaling.

A cross plot was generated illustrating Poisson's ratio versus acoustic impedance for 20 wells that penetrate the Wall Creek formation (Figure 9). Seven distinct seismic facies were identified, S1 to S7, before upscaling. Each seismic facies has an associated log facies, L2 through L9 and, each log facies has a dominant core facies, C2 through C9. The best reservoir quality is associated with seismic facies S7, log facies L9, and core facies C7 which is composed of medium and coarse grained sand (Figures 5, 8, red ellipse in Figure 9). As grain size and porosity decrease, the acoustic impedance increases since the bulk density and velocity of the rock increases. Therefore, the S7/L9/C7 facies shift to seismic facies S6, log facies L8, and core facies C8-9 which is composed of fine to medium sand and sand with mud partings (Figure 3, yellow ellipse in Figure 9). As the core facies increase in bioturbation or shale laminations from a muddy sandstone (seismic facies S4, log facies L6-7, and core facies C4-5-9, olive ellipse in Figure 9) to a bioturbated sandy mudstone (seismic facies S1, log facies L4, core facies C3, green ellipse in Figure 9, acoustic impedance decreases and Poisson's ratio increases.

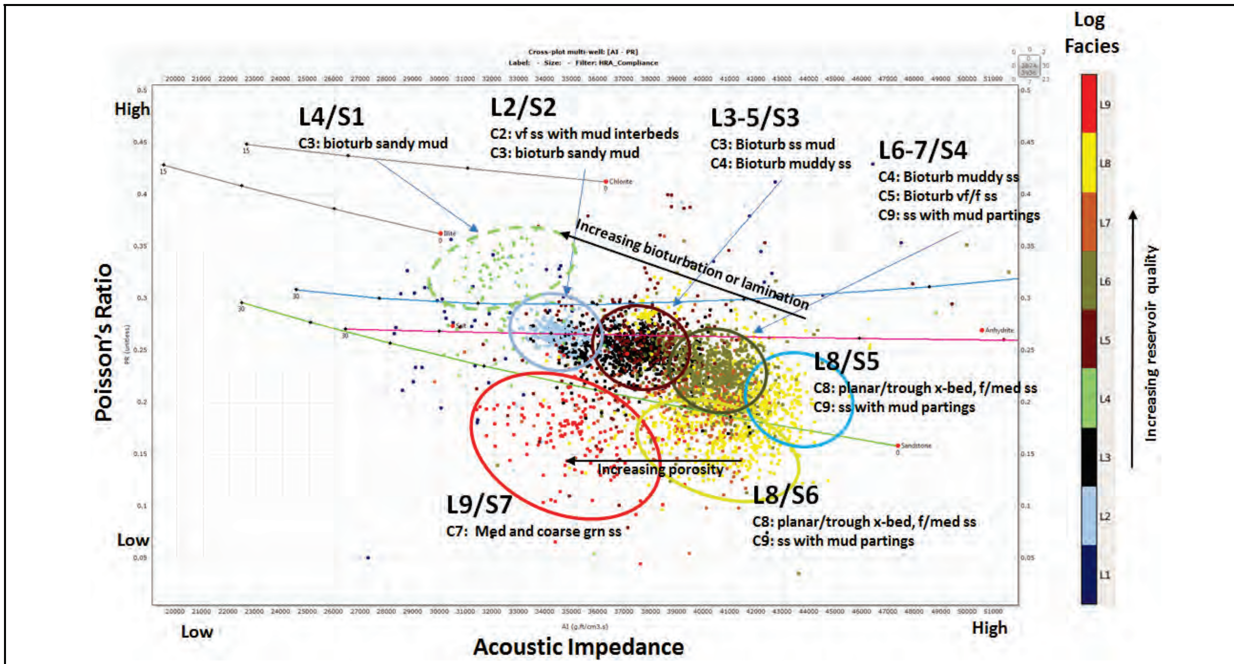

Figure 9: Poisson's ratio versus acoustic impedance cross plot demonstrating relationships between core, log, and seismic facies (listed as C, L, and S, respectively, with a number suffix). Core and seismic facies reservoir quality increases as numbers increment.

A geomechanical crossplot was generated illustrating Young's modulus versus Poisson's ratio (Figure 10). As porosity decreases, Young's modulus increases since bulk density and velocity increases; the red ellipse in Figure 10 shifts to the yellow ellipse, which represents seismic facies S6, log facies L8, and core facies C8-9. For samples with a higher clay content, the seismic facies S4, log facies L6-7, and core facies C4-5-9 (olive ellipse in Figure 10) decrease in Young's modulus and increase in Poisson's ratio toward seismic facies S1, log facies L4, and core facies C3 (green ellipse in Figure 10) due to increased bioturbation and shale laminations. Rocks with higher Young's modulus and lower Poisson's ratio tend to stimulate easier during hydraulic fracture treatment due to higher potential for brittle behavior of the rocks.

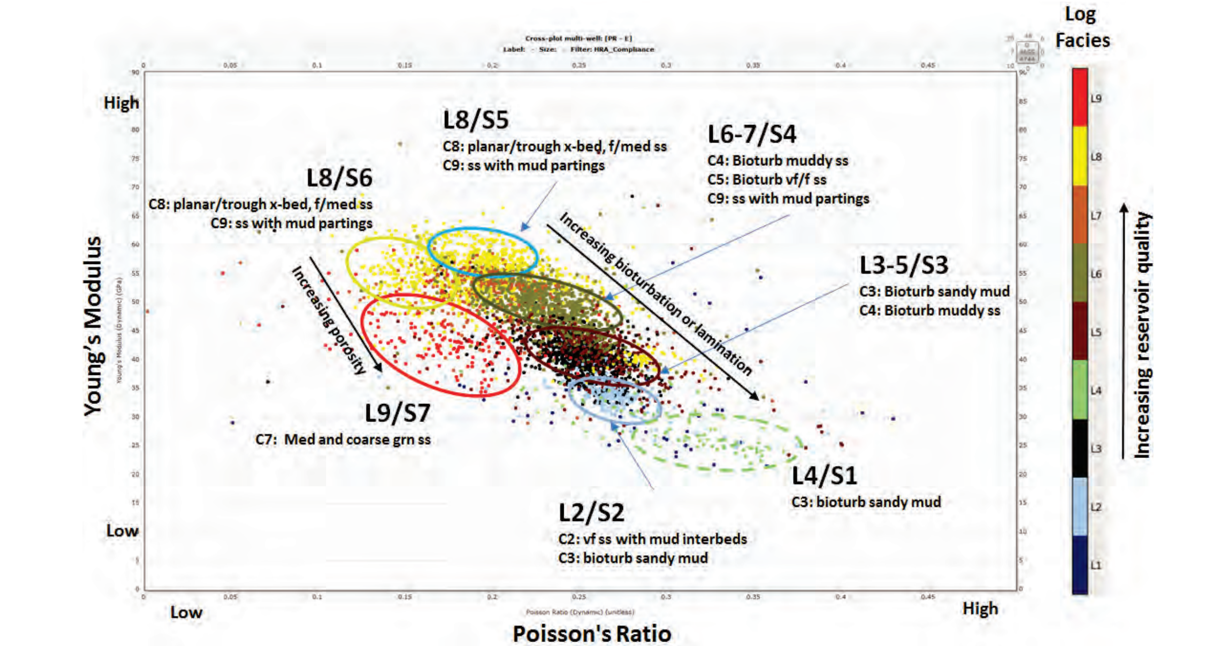

Figure 10: Geomechanical crossplot ofYoung's modulus versus Poisson's ratio cross plot demonstrating relationships between core, log, and seismic facies (listed as C, L, and S, respectively, with a number suffix). Core and seismic facies reservoir quality increases as numbers increment.

A final crossplot (Figure 11) was generated illustrating mu rho versus lambda rho with mu and lambda defined as rigidity and incompressibility, respectively (Goodway et al, 2010). The best reservoir quality is associated with seismic facies S7, log facies L9, and core facies C7 (red ellipse in Figure 11). As porosity decreases, mu rho and lambda rho increase and the red ellipse shifts to the yellow ellipse. For facies with higher clay content, the seismic facies S4, log facies L6-7, and core facies C4-5-9 (olive ellipse in Figure 11), decrease in lambda rho and mu rho toward seismic facies S2, log facies L2, and core facies C2-3 (light blue ellipse in Figure 11) due to more bioturbation and shale laminations.

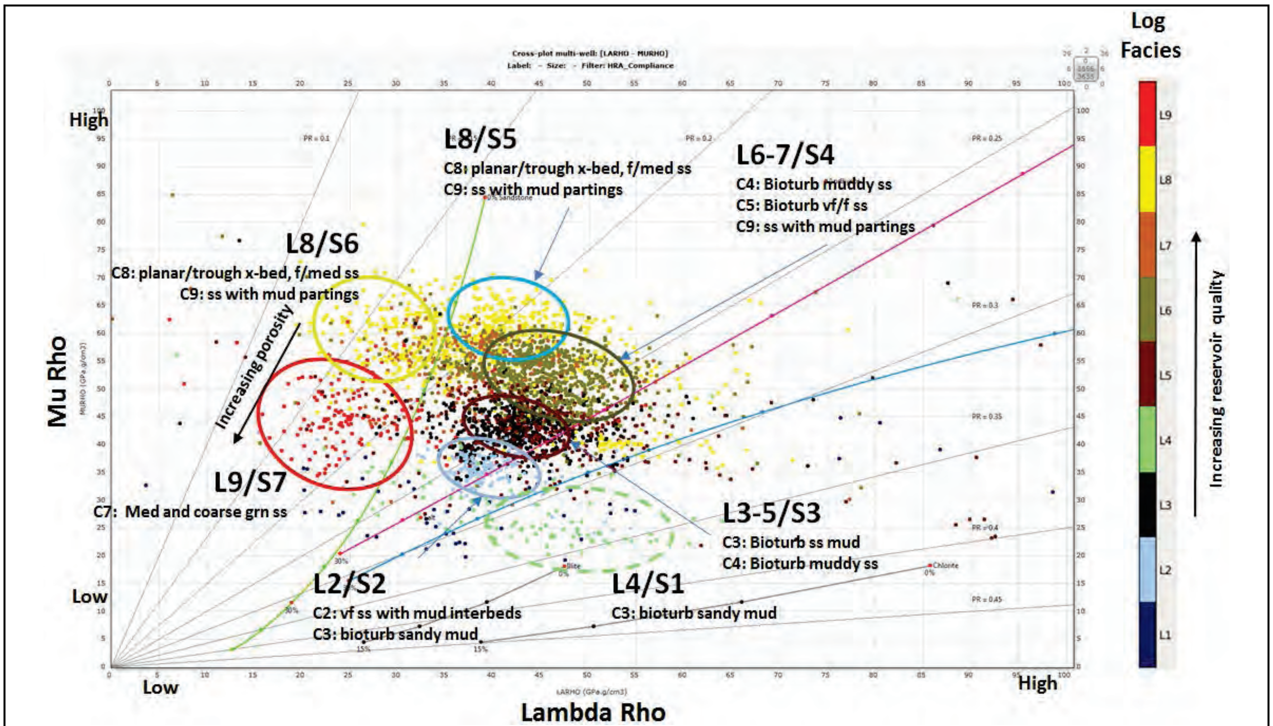

Figure 11: Mu-rho versus Lambda-rho ratio cross plot demonstrating relationships between core, log, and seismic facies (listed as C, L, and S, respectively, with a number suffix). Core and seismic facies reservoir quality increases as numbers increment.

The seven seismic facies at log resolution in Figures 9-11 merge into six seismic facies after upscaling to seismic resolution. These figures provide the foundation to link core, wireline, and seismic data and transform 3D seismic data into reservoir rock property volumes through geostatistical inversion (Wang et al, 2015). Figure 12 displays a strata-slice and cross-section through the most probable seismic lithofacies volume. This figure highlights the heterogeneous nature of the reservoir and stratigraphic architecture. Better reservoir quality is associated with seismic facies S6 and S7, orange and yellow colors, respectively. The vertical and lateral variability of the reservoir changes between well control, as observed in the cross-section and strata-slice, and provides a method to highgrade potential drilling locations.

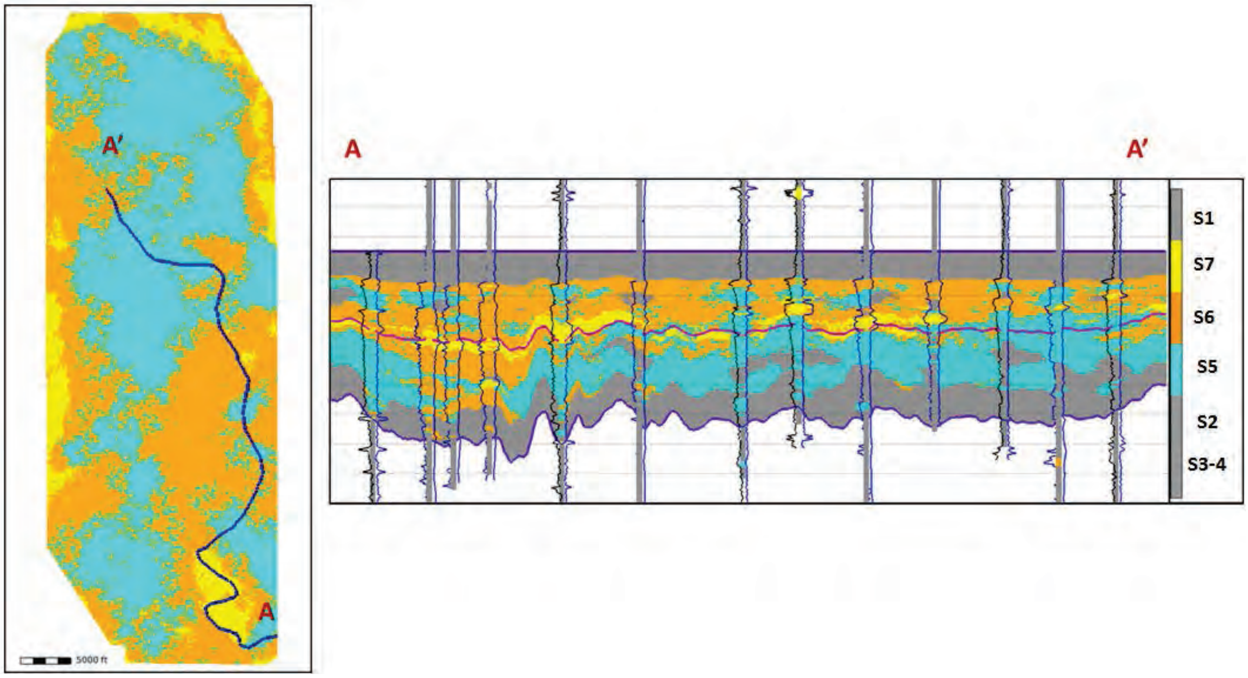

Figure 12: Strata-slice and cross-sectional view of the seismic lithofacies dervied from the geostatistical inversion. The best reservoir quality is associated with seismic facies S6 and S7. The map view strata-slice is highlighted as a purple line in the cross-section. The cross-section and strata-slice define the hetergenous nature of the reservoir and provides a method to highgrade potential drilling locations.

Conclusions

The integration of geologic information on a variety of scales provides a powerful tool for added comprehension of regional heterogeneity in complex depositional systems. The thoughtful and iterative upscaling process from decimeter scale observations, as provided by detailed core facies description, to log facies on a meter scale, and to a seismic facies on tens of meter scale, provides a means for predicting the complex stratigraphic architecture at a high lateral and vertical resolution across the region of interest, away from the known control points. In the Powder River basin this methodology provides the tools necessary to de-risk delineation and development well locations and assist in full field development planning. This tool can be used to evaluate changes in material properties and reservoir quality, thereby allowing for optimization of lateral placement and completion parameters as the stratigraphy varies along a given lateral length (Figure 13).

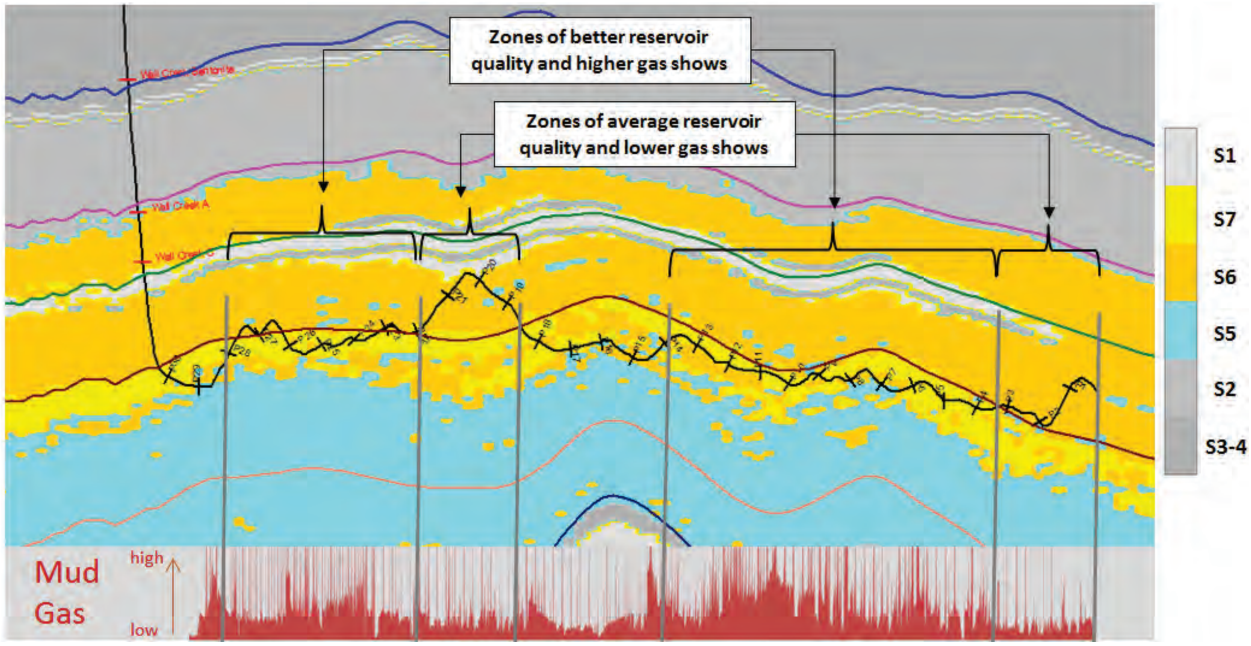

Figure 13: Cross-sectional view of the seismic lithofacies derived from the geostatistical inversion along a horizontal wellpath. The well was planned to target sesimic facies 7. Mudgas along the horizontal generally increased while penetrating seismic facies 7 (best reservoir quality) and decreased while in seismic facies of less reservoir quaility, adding validity to the seismic facies model.

Acknowledgements

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References

Bhattacharya, J.P., Willis, B.J., 2001, Lowstand deltas in the Frontier Formation, Powder River basin, Wyoming: Implications for sequence stratigraphic models. AAPG Bulletin, V.85, NO.2 (February 2001), PP. 261-294

Bornemann, E.; Doveton, J. H. 1981, Log Normalization By Trend Surface Analysis. Society of Petrophysicists and Well-Log Analysts.

Doveton J.H. 1994, Geologic Log Analysis Using Computer Methods. AAPG Computer Applications in Geology No. 2. American Association Of Petroleum Geologists (May 10, 1994). ISBN, 0891817018

Goodway, B., M. Perez, J. Varsek, and C. Abaco, 2010, Seismic petrophysics and isotropic-anisotropic AVO methods for unconventional gas exploration: The Leading Edge, **29**, 1500-1508.

Wang, H., H. Titchmarsh, K. Chesser, J. Zawila, S. Fluckiger, G. Hughes, P. Kerr, A. Hennes, and M. Hofmann, 2015, Maximizing recoverable reserves in tight reservoir using geostatistical inversion from 3D seismic: a Powder River Basin case study, Unconventional Resources Technology Conference.