An integrated, multi-disciplinary approach utilizing stratigraphy, petrophysics, and geophysics to predict reservoir properties of tight unconventional sandstones in the Powder River Basin, Wyoming, USA

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Summary

Numerous unconventional resources have become economically viable with the development of horizontal drilling and multi-stage hydraulic fracturing. Unconventional reservoirs have variable degrees of heterogeneity and identification of good and poor reservoir properties is essential for efficient development to define the economic limits of a resource play. An integrated, multi-disciplinary approach of correlating core facies to petrophysical wireline facies to seismic facies for tight unconventional sandstones is presented in this paper along with the results of a simultaneous, geostatistical seismic inversion. Seismic facies and reservoir rock properties, which are calibrated to wireline logs and core data, are mapped from 3D seismic inversion volumes. The maps provide a detailed understanding of the characteristics of the reservoirs, namely their spatial distribution, geometry, and internal architecture. This methodology demonstrates the tremendous value of incorporating stratigraphic, petrophysical, and geophysical data into a quantitative, integrated reservoir model.
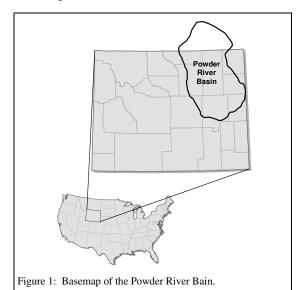
Introduction

The Powder River Basin, located in northeastern Wyoming and southeastern Montana, USA (Figure 1) has produced conventional oil and gas since the 1890's with the discovery of the Shannon and Salt Creek fields north of Casper (Roberts, 2015). Recent advances in horizontal drilling and multi-stage hydraulic fracturing renewed interest in the basin to test the economic viability of tight sandstone and carbonate resource plays. Since 2009, oil production in the Powder River Basin has increased 200% due to horizontal drilling mainly targeting the Turner/Wall Creek, Parkman, Niobrara, Sussex, and Shannon formations (US EIA, 2014).

Methodology

Seismic inversion is a tool to predict reservoir facies and properties away from calibrated well control. This technique has been successful in delineating the lateral extent and distribution of reservoir rock properties of conventional reservoirs. The same methodology is being applied to unconventional resource plays successfully as long as properly calibrated well control is available and seismic facies can be discriminated by acoustic and elastic parameters (Metzner and Smith, 2013; Goodway et al, 2012; Sena 2011).

This project follows a two-step process of integrating stratigraphy, petrophyiscs, and geophysics data into a subsurface reservoir model which then utilizes the model in a simultaneous, geostatistical 3D seismic inversion. The first step involved the discrimination of twelve distinct lithofacies from core upscaled to nine distinct electrofacies discernable with wireline logs. These facies are correlated to acoustic/elastic parameters and upscaled to generate seismic facies (Fluckiger et al, 2015). The second step transforms 3D seismic data into reservoir rock property volumes by a geostatistical seismic inversion. Each of the core, log, and seismic facies were correlated to each other in an integrated model.

Figure 1: Basemap of the Powder River Bain.

Core Facies:
The study includes approximately 20 cores from the Shannon Sandstone and the Frontier Formation in the western Powder River Basin. The cores were described on a decimeter scale to capture the fine-scale variability in these siliciclastic dominated systems. Core facies were discriminated using grain size, physical and biogenic

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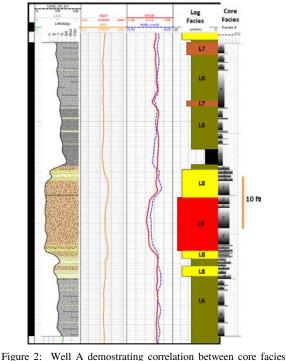

Figure 2: Well A demostrating correlation between core facies and log facies for the Wall Creek formation.

sedimentary features, ichnology, and results from petrographic analysis. The coarsest core facies recognized in the sample suite are coarse grained, cross bedded sandstones (core facies C7; Figure 2), that were the target for historic hydrocarbon development in the Frontier formation. Other reservoir facies include fine to medium grained trough cross bedded sandstones (core facies C8) and fine grained sandstones with abundant mudstone drapes (core facies C9). Although stacking of facies is variable between the different formations as well as different cores in the basin, the core facies are best categorized into a tidally influenced facies association (facies C7-C11), and a wave or storm dominated marine facies association (facies C1-C6).

Log Facies:
Principle component analysis combined with K-means clustering was utilized to define nine electrofacies from a standard wireline log suite composed of resistivity, density, gamma ray, and neutron from 19 regionally dispersed wells. This log facies model defined for the initial wells was then applied to an additional 400+ wells across the entire region of interest. The nine log facies were then characterized by upscaling the twelve distinct core facies based upon the statistical occurrence within each of the log facies. Each log facies is composed of 1-2 primary core facies and 2-4 secondary core facies. Well A demonstrates

the core to log facies relationships for the Wall Creek member of the Frontier formation (Figure 2). Increased grain size and improved reservoir properties defined by core facies C7 agree with better reservoir properties identified by wireline logs facies L9. These relationships are valid independent of the reservoir quality; core facies C3-4 tend to correlate with log facies L6.

Seismic Facies:
Seismic facies are distinguished based on acoustic and elastic parameters. Figure 3 exhibits an example of the relationship between log facies and seismic facies for a well in the Shannon sandstone. Log facies L2-3, L6, and L8 correlate to seismic facies S3, S4, and S5, respectively.
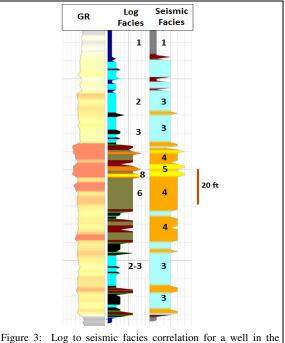

Figure 3: Log to seismic facies correlation for a well in the Shannon sandstone.

Figures 4a and 4b display cross plots of Poisson's ratio versus acoustic impedance (Figure 4a) and Young's modulus versus Poisson's ratio (Figure 4b) for 20 wells that penetrate the Wall Creek formation. The color-coding on the cross plots represents the log facies. The ellipses represent the distribution of each respective seismic facies before upscaling. Where the ellipses overlap, uncertainty increases in discriminating individual facies. The cross plots in Figure 4 form the foundation for linking core facies to petrophysical facies to seismic facies and for mapping the reservoir heterogeneity in the 3D seismic inversion volumes.

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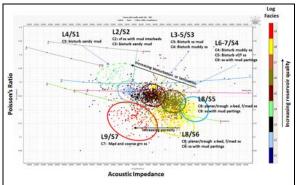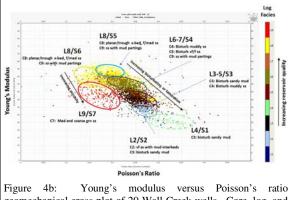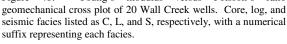

Figure 4a: Poisson's ratio versus acoustic impedance cross plot for 20 Wall Creek wells. Core, log, and seismic facies listed as C, L, and S, respectively, with a numerical suffix representing each facies.

Figure 4b: Young's modulus versus Poisson's ratio geomechanical cross plot of 20 Wall Creek wells. Core, log, and seismic facies listed as C, L, and S, respectively, with a numerical suffix representing each facies.

Seismic Inversion:

A simultaneous, geostatistical seismic inversion was performed on a 60 square mile 3D seismic data volume. This provided improved resolution of geological detail and discrimination of tight sandstone unconventional resource plays (Wang et al, 2015). The 3D geostatistical inversion follows a three step process to synergistically and quantitatively honor all input data. First, discrimination of facies based on acoustic/elastic parameters and creation of statistics such as probability distribution functions (PDF's), variograms, etc. Second, iterative calibration of the 3D seismic to well control where the wells are systematically fed to the seismically constrained geomodel. Third, geostatistically inverting the entire 3D survey to generate a seismic constrained geomodel comprising multiple lithology, elastic property and reservoir rock property volumes.

The first phase of the geostatistical inversion involves petrophysical analysis and rock physics modeling of the

wirline log data from key wells. Core calibrated wireline facies are discriminated into lithotypes according to their relationship with the acoustic and elastic responses of the logs as seen in Figure 4a. These logs are upscaled to seismic resolution to confirm that the facies are still discriminated into distinct lithotypes.

The second phase of the seismic inversion involves calibration of the seismic data to well control and seismic data conditioning. The phase of the seismic data was calculated across 4 angle stacks from key wells. A layer-based deterministic inversion was computed to reinterpret seismic horizons once wavelet and tuning effects were removed.

The third phase of the project involved the simultaneous, geostatistical inversion of the 3D seismic dataset. The stochastic process produced multiple realizations of lithology, elastic properties, and reservoir rock properties, all of which are equa-probable. Summary volumes of stacked realizations were also produced: P impedance, effective porosity, VpVs ratio, etc. A volume of the most probable lithotype along with probability volumes of encountering each lithotype were created. Based upon the lithotype discrimination observed in the first phase, each seismic facies identified in the cross plot is characterized in the 3D volume. Therefore, the overall subsurface stratigraphic geometry and architecture defining the lateral and vertical variability of the lithofacies is identified and accurately mapped away from known well control. Lithology and reservoir rock properties derived from core and log data are honored and quantitatively integrated with each seismic facies and distributed throughout the 3D dataset to identify reservoir quality.

Results

The generation of a 3D seismically constrained stochastic subsurface geomodel produced via geostatistical inversion enabled the accurate prediction of lithofacies and reservoir rock properties away from known control points provided by the well and core data. Maps and 3D geo-body captures identified areas of interest and provide an improved understanding of the subsurface. The integrated subsurface model is used to optimize well penetrations to efficiently develop the unconventional play and maximize recoverable reserves.

Figure 5 displays a map and cross-sectional view of the seismic facies from the 3D seismic data set. Reservoir quality increases from seismic facies S1 to S5 with the pay reservoir as the S4 and S5 facies, orange and yellow color. The cross-section and map display the heterogeneous nature of the tight sandstone. Reservoir quality improves

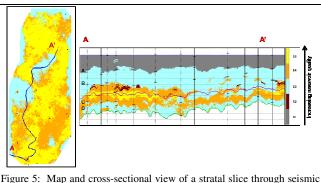and thickens on the left side of the cross-section compared to the right side.

Each seismic lithofacies has a porosity probability distribution function (PDF) derived from wireline logs and core data. The porosity PDF is applied to each seismic lithofacies voxel in the 3D volume. Therefore, the porosity height (Phi-H) can be calculated over the 3D volume, well, or drilling spacing unit. Figure 6 displays the seismic-derived Phi-H map utilized to calculate original oil in place (OOIP). Areas of high and low OOIP demonstrate the heterogeneous nature of the tight sandstone reservoir. This data is used to high grade potential drilling locations and is calibrated directly to petrophysical and core properties.
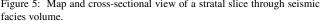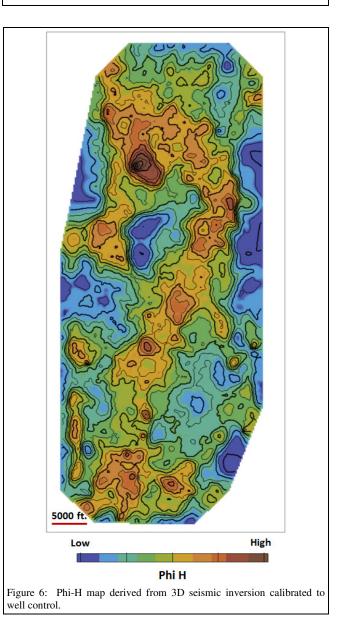
Conclusions

The subsurface geomodel presented here synergistically integrated geoscience data in a quantitative manner from multiple disciplines. The study successfully identified thin bed inter-well lithofacies and reservoir rock properties which accurately correlated the stratigraphy of the unconventional reservoirs to the wireline log properties to the seismic properties. These correlations build the foundation of a simultaneous, geostatistical inversion to understand the reservoir heterogeneity and distribution of facies extending away from known well control. This integrated and synergistic approach creates significant value and reduces play risk by linking and honoring multiple geoscience data types. The approach presented here provides a predictive understanding of the complex nature of unconventional tight sandstone resources and enables high grading of areas for efficient development.

Acknowledgements

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Figure 5: Map and cross-sectional view of a stratal slice through seismic facies volume.

Figure 6: Phi-H map derived from 3D seismic inversion calibrated to well control.

EDITED REFERENCES
Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2015 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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