Quantitative interpretation using facies-based inversion applied to the Ordovician Red River U4 dolomite interval, Williston Basin

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SUMMARY

Quantifying anomalies detected on seismic-generated attributes is critical to evaluate carbonate reservoir heterogeneities prior to planning and designing CO_2 enhanced oil recovery operations. In this study, facies-based pre-stack inversion method is applied to a 3D compressional wave seismic survey to characterize the Ordovician Red River U4 dolomitic reservoir. The facies-based inversion technique is able to delineate reservoir and non-reservoir facies and quantify porosity from inverted elastic volumes and the developed rock physics model.

INTRODUCTION

The target reservoir is unit 4 of the Red River Formation at approximately 9,000 feet below the surface. The field is located in the Williston Basin and will undergo carbon dioxide (CO_2) enhanced oil recovery operations (EOR) in the near future. The objective of this reservoir characterization study includes understanding the heterogeneity within the reservoir and its potential influence on the CO_2 flood. Available data consist of a 2014 3D compressional wave seismic survey and borehole measurements from 17 wells existing within, or in close proximity to, the study area (Figure 1). Figure 2 shows interpreted events across the seismic survey.

The Red River reservoirs are typically subdivided into A, B, C and D units (from youngest to oldest). They represent a period of 6 million years of cyclic depositional packages that grade from highly burrowed, open marine limestones through laminated dolomite mudstone into bedded anhydrites (Longman and Haidl, 1996). Red River U4 (RRU4) petrophysical unit is the study reservoir interval and corresponds to the dolomitic B zone in literature.

In this paper, reservoir heterogeneity is characterized from the inverted elastic volumes using a facies-based pre-stack inversion method applied to the seismic dataset. At the request of the operator, the field's name and location are omitted for confidentiality. Seismic surface extractions are limited to the field unit and edge effects are present where field unit reaches seismic survey limit. This study is the first published application of the facies-based inversion method on a deep and thin carbonate reservoir.

DATA PREPARATION

The data preparation step includes conditioning well data, synthetic shear logs, wavelet extraction, seismic gathers pre-processing, and seismic to well tie. The seismic processing step

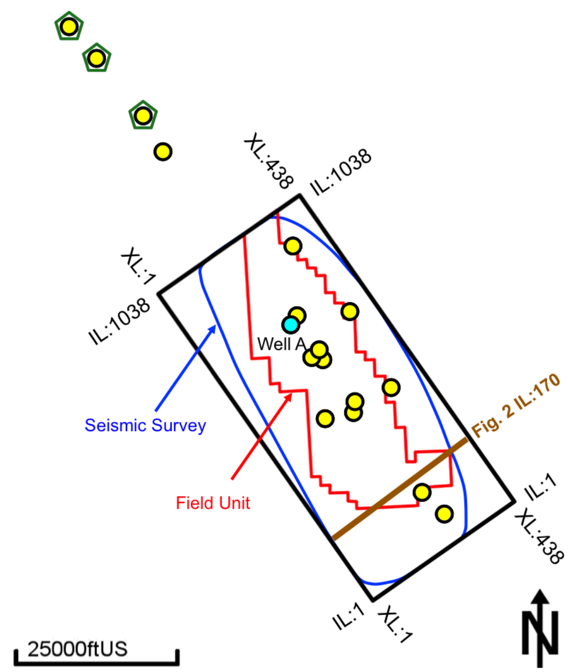

Figure 1: Available dataset include 44 mi^2 seismic dataset (blue polygon) and 17 wells (dots). Green pentagon corresponds to wells with dipole sonic. The field unit outline (red) defines all subsequent seismic extractions and well extraction in Figure 3 is from well A in cyan color.

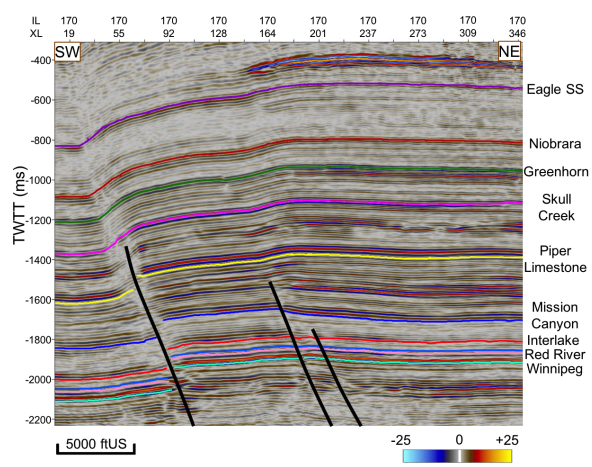

Figure 2: IL170 seismic interpretation.

10.1190/segam2018-2987218.1

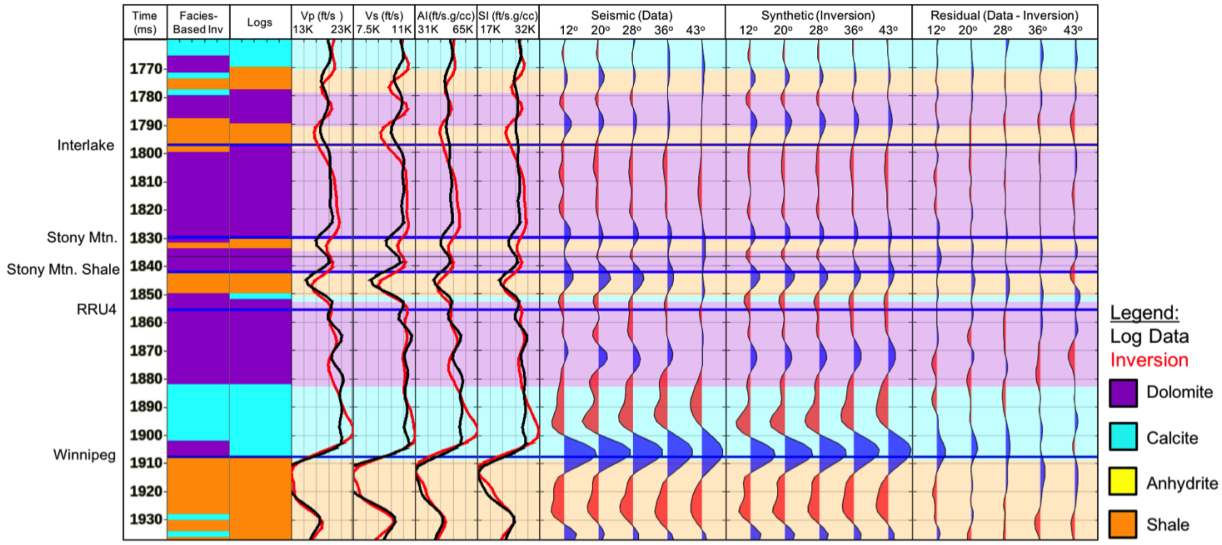

Figure 3: Well A facies-based inversion elastic properties results. Log data in black, and inversion results in red. Track 1 displays output facies results from inversion while track 2 shows well log facies (data). Refer to Figure 1 for well location.

includes additional multiple suppression using the radon transform, wavelet deconvolution, band pass filtering, and time-variant trim statics. Then, five angle stacks are extracted between 8^o and 46^o centered at 12^o, 20^o, 28^o, 36^o and 43^o, respectively. Seismic to well tie average cross-correlation is 76% (range 70% to 83%). In addition, rock composition logs are used to classify facies based on the dominant mineral content. The four litho-facies are shale (high GR), anhydrite (present mainly above the Mission Canyon), calcite (non-reservoir tight rock), and dolomite (reservoir porous rock).

FACIES-BASED INVERSION

Facies-based inversion is grounded on a Bayesian seismic inversion approach to analyze the distribution of reservoir bodies through a range of facies-based sensitivities to simultaneously invert for facies and elastic properties (Zabihi Naeini and Exley, 2017). Unlike conventional impedance inversion techniques, a depth trend is derived for each facies to generate the equivalent low frequency model. The per facies depth-trended rock physics models are constructed by fitting a compaction curve to the elastic log data (Vp, Vs, density) belonging to that facies with an assessment of uncertainty. The low frequency model (LFM) is constructed from multiple LFMs for each expected facies.

The inversion derives models of impedances (from the seismic) given facies, and then facies (from the impedances) at each iteration of the optimization loop. According to Kemper and Gunning (2014), an iterative method is applied where the code first inverts the seismic for facies (given a simple impedance model), then given these facies the code inverts the seismic for impedances, then given these new impedances the code inverts the seismic for a new facies volume and so forth, until convergence. This optimization is a form of Expectation-Maximization. In the Expectation step the code inverts the seismic for facies given the impedances, and in the Maximization step the code inverts the seismic for impedances given the facies. The final LFM is not a static input as in standard model-based inversion but is the seismically-driven output of the new inversion system, which incorporates known facies and rock physics. The outputs of the facies-based inversion are the most-likely elastic properties (acoustic impedance (AI), shear impedance (SI), velocity ratio (Vp/Vs), and density) and facies volumes.

Figure 3 shows the facies-based inversion result at Well A. The facies profile (track 1) is an output of the inversion and correlates to the original facies classification (track 2). Thin shale layers are identified from the inversion. Inverted elastic impedances are comparable to the input logs, and low residual synthetic seismic is obtained. Furthermore, elastic properties are identified throughout the inversion window with no edge effect (LFM approaching to zero at inversion window) as observed in the Winnipeg Formation.

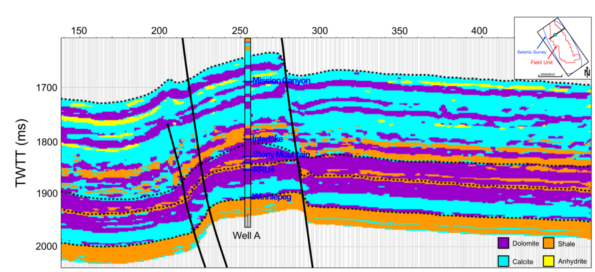

Figure 4: Lateral inverted facies variation across IL760 and Well A.

Figure 4 displays the inline facies across Well A. Individual Red River intervals cannot be resolved at the seismic frequency;

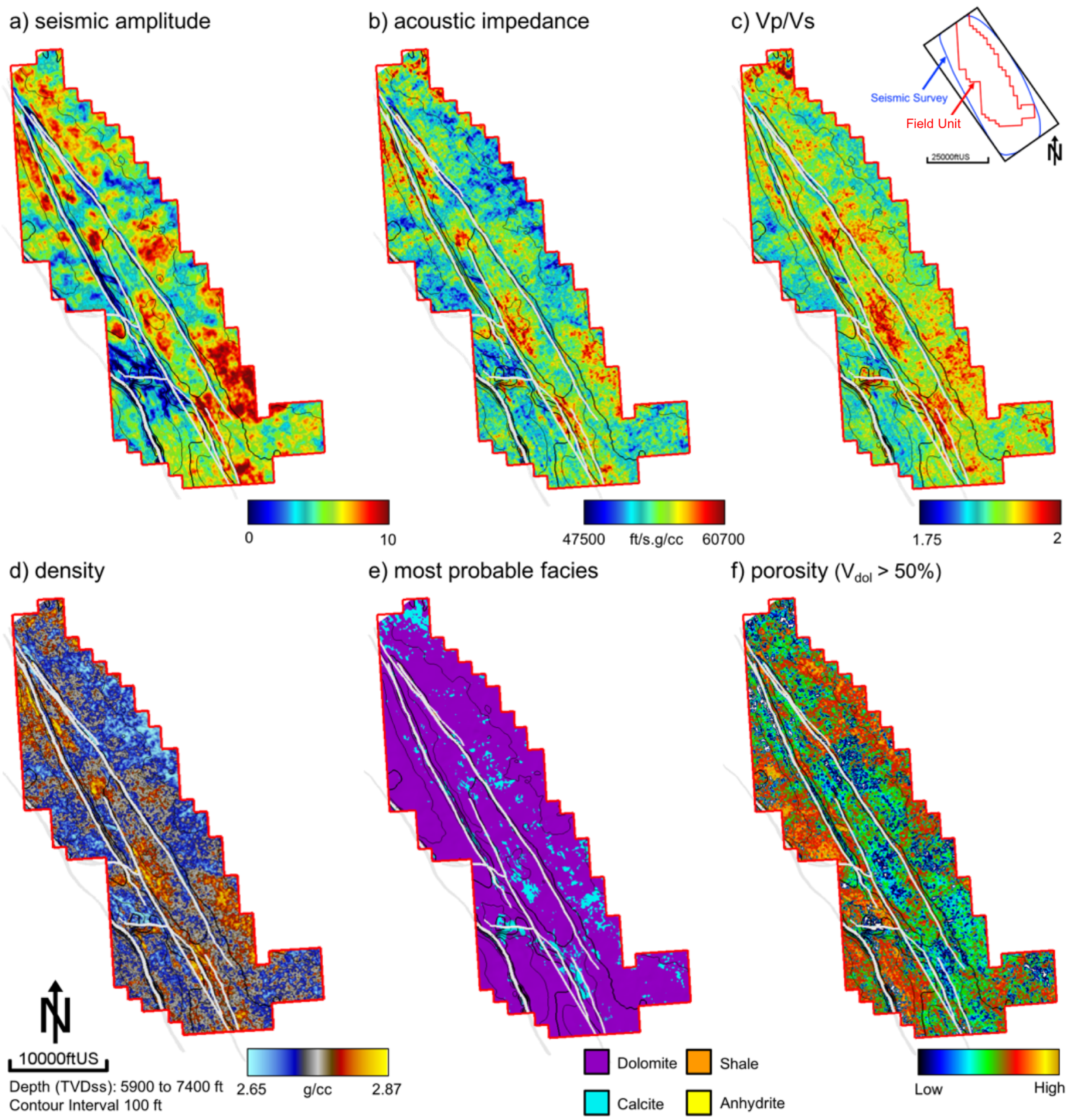

Figure 5: Facies-based inversion elastic volumes and quantitative interpretation extractions at RRU4 horizon.

consequently, the upper Red River Formation is mainly dolomitic with few calcite intervals and the lower Red River Formation is mainly calcite. We are able to identify continuous anhydrite layers (Mission canyon - shallow section) and continuous shale intervals above the Interlake and within the Stony Mountain and Winnipeg Formations.

Figure 5a-c shows the extraction of seismic amplitude, inverted acoustic impedance, and inverted Vp/Vs velocity ratio at RRU4 surface for the facies-based inversion. Anomalies are consistent between seismic amplitude, acoustic impedance, and Vp/Vs maps. In general, high seismic amplitude corresponds to high AI and Vp/Vs. Density determination indicates the presence of porous dolomite in RRU4 (Figure 5d). Dolomite in pure mineral phase is 2.87 g/cc and calcite in mineral phase is 2.71 g/cc. Adding porosity will cause density to drop.

SEISMIC DERIVED FACIES AND POROSITY

Quantifying anomalies detected on the acoustic impedance and velocity ratio maps is vital to understand the reservoir spatial heterogeneities. The most probable facies volume is a by-product of the facies-based inversion. Figure 5e illustrates that RRU4 interval is mainly classified as reservoir rock (dolomite facies).

Porosity is the main driver for compressional and shear variations in the reservoir rock. Figure 6 plots velocity ratio (Vp/Vs) versus acoustic impedance trends of constant mineralogy for a dolomite / calcite mix at various porosity based on a developed rock physics model (El Khoury et al., 2017).

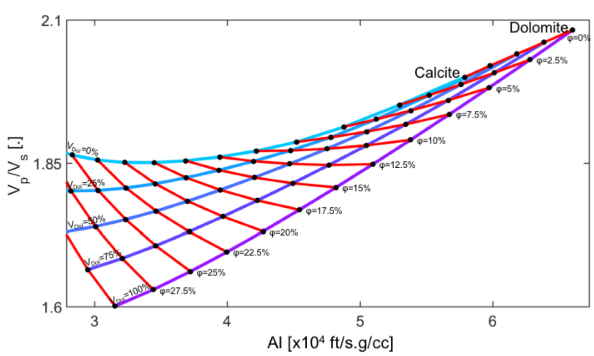

Figure 6: Red River Formation rock physics model with constant mineralogy and porosity trends.

Porosity at RRU4 is evaluated given the inverted acoustic impedance and Vp/Vs (Figure 5b-c) in conjunction with the Red River RPM model (Figure 6). Figure 5f shows the porosity distribution at RRU4 given 50% or more dolomite volume (expected reservoir facies). Figure 7 compare seismic derived porosity to well data from 9 different wells. From the porosity log, the mean and standard deviation porosity is extracted within the RRU4 interval and plotted on the horizontal axis. The porosity from the seismic inversions is extracted at the corresponding well location and plotted on the vertical axis with a constant 2.5 p.u. standard deviation based on the RPM bin size. The facies-based inversion is able to predict porosity values proximal to the data from logs.

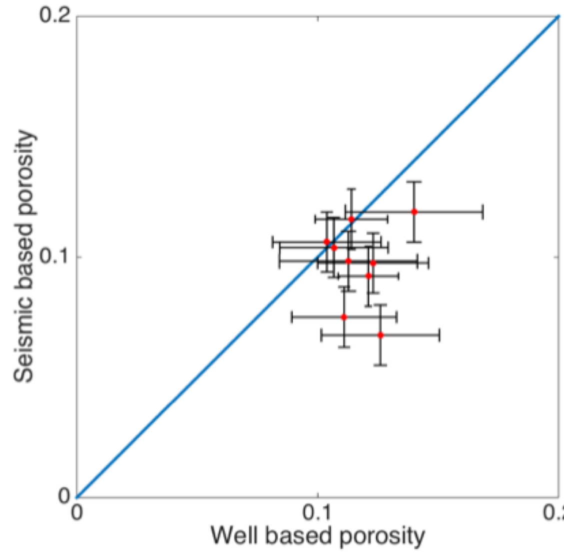

Figure 7: RRU4 seismic derived porosity versus porosity from well data. Red dots represent 9 wells within field unit. Porosity value at each well correspond to the mean log value (red dot) for RRU4 interval and uncertainty bar (horizontal) is the standard deviation. Seismic derived porosity is extracted at corresponding well location with 2.5 p.u. uncertainty bar width (vertical). Blue line represents the 1:1 line.

CONCLUSIONS

The facies-based inversion is a robust technique that incorporates prior facies knowledge into the inversion process to concurrently invert for elastic and litho-facies volumes. The latter method is independent of traditional low frequency related issues and takes advantage of facies-based depth trends from the rock physics model. In this study, the facies-based inversion technique is able to retrieve accurate facies and porosity values at RRU4 by adding information gained from well logs and core description during the inversion process.

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank Denbury Onshore for providing the field dataset to the Reservoir Characterization Project (RCP) at Colorado School of Mines to conduct this study. Thanks to Ikon Science for the special permission to provide Ji-Fi license to RCP consortium. Finally, this work would not have been possible without RCP industry sponsors.

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