Time-lapse V_P/V_S analysis for pressure mapping, Rulison Field, Colorado

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Summary

Time-lapse V_P/V_S volumes have been estimated in order to enhance the dynamic characterization of the tight-gas sandstone reservoirs in Rulison Field, Western Colorado. Based on compressional (PP) as well as fast- (S11) and slow (S22) shear datasets from 4D-9C surveys, the V_P/V_S volumes were generated after cross-equalization, post-stack inversion and multi-component registration. Previous work has shown the feasibility of using V_P/V_S as a characterization tool for lithology and pressure was established through cross-dipole sonic logs analysis and ultrasonic core lab measurements. In this paper we show that by combining V_P/V_S and rock physics data it was possible to predict reservoir pressure wherever the sandstones are over-pressurized. Since the absolute magnitude of time-lapse amplitude anomalies is not enough to determine the actual pressure regime on partially depleted intervals, a classification scheme for time-lapse V_P/V_S anomalies is proposed in order to judge whether an anomaly corresponds to a still-over-pressurized interval or a depleted interval. Our methodology can help on well placing and completion in order to optimize the development of this unconventional but significant gas accumulation.

Introduction

The Reservoir Characterization Project (RCP) at Colorado School of Mines acquired three time-lapse dedicated 3D-9C surveys in 2003, 2004 and 2006 in order to improve the dynamic characterization of tight-gas sandstones in Rulison Field, Western Colorado. Most of the gas in this field is produced from Late Cretaceous fluvial sandstones and coals from the Williams Fork Formation (Figure 1), characterized by very low porosity (<12%) and permeability (0.1 µd-2 µd). Low porosities and permeabilities, in addition to low lateral continuity of sand bodies, make difficult the development of this reservoir. Hydraulic fracturing during well completions is usually needed in order to improve sands connectivity by interconnecting natural and induced fracture sets.

The low impedance contrasts and high lateral discontinuity of sand bodies require the use of enhanced seismic tools to image the reservoir in terms of lithology, fluids, fractures, and pressure. Previous work on lab measurements and well logs (Rojas, 2008) showed that the ratio of compressional and shear wave velocity or V_P/V_S may help on reservoir characterization in this field since low values of this attribute correlate to low GR values (cleanest sands), low water saturation, and high reservoir pressure (low effective pressure) (Figure 2). Since the reservoir is not undergoing any significant fluid saturation change because is being produced by primary depletion, lithology and effective pressure are the only reservoir variables controlling V_P/V_S.

For an appropriate estimation of the pressure it is necessary to obtain high-resolution V_P/V_S volumes (Guliyev and Davis, 2007), from pure PP and SS wave-modes. Using V_P/V_S in a time-lapse basis has the advantage of decoupling the influence on V_P/V_S of effective pressure and lithology.

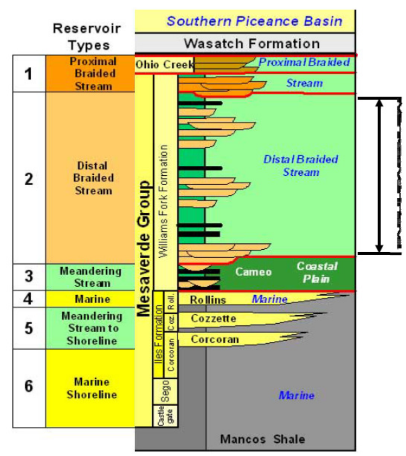

Figure 1: Generalized stratigraphic column at Rulison Field

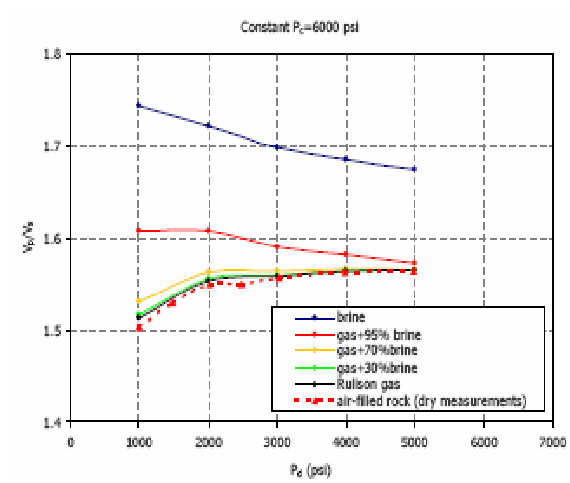

Figure 2: V_P/V_S vs effective stress at different pore fluid saturations (from Rojas, 2005)

Estimation of time-lapse V_P/V_S volumes

The V_P/V_S volumes were obtained following these steps:

- Cross-equalization: This is a series of processes applied to the same wave-mode surveys of different vintages in order to reduce the time-lapse differences not-related to the reservoir development. This procedure operates in time, amplitude, and frequency.
- Post-stack inversion: This process is applied to each cross-equalized volume in an iterative way (model-based). For each wave mode used, the same low frequency initial model (based on the two interpreted horizons UMVS and Cameo, and the RU-7 well log data) and same wavelet were used in order to avoid introducing time-lapse changes on impedance volumes related to different inversion parameters. The quality control of the inversion is performed by comparing, on the control well location, how close the estimated impedances are with respect to the low-pass filtered impedance logs.
- Multi-component registration: The vertical scaling of pure shear data in order to match events in PP data.
- Calculation of V_P/V_S: Since $Z_P/Z_S = (V_P*\rho)/(V_S*\rho)$, then V_P/V_S volumes are estimated by simply dividing the registered impedance volumes for each mode (fast and slow) and vintage (2003, 2004 and 2006) (Figure 3).

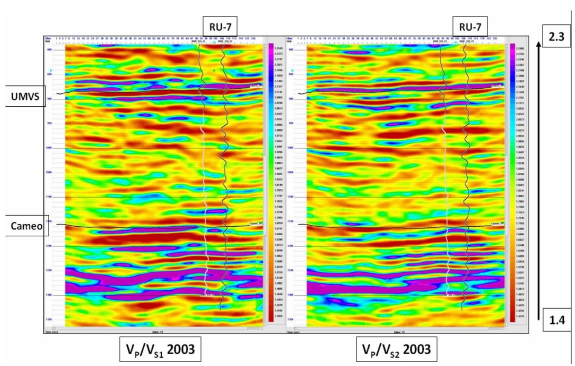

Figure 3: Fast (left) and slow (right) V_P/V_S volumes 2003.

V_P/V_S for lithology discrimination

Based on well-log data and petrophysical analysis, the impedance space or Z_P-Z_S cross-plot contains lines of equal V_P/V_S value. The points on this space can be color coded using a particular flag or reservoir quality indicator log like shale volume (Figure 4). It can be noticed that the points are distributed in a clear background linear trend but there is a cluster corresponding to clean sands located in an anomaly in this space. From these observations it might be concluded that V_P/V_S alone cannot discriminate lithology, so V_P/V_S values on V_P/V_S volumes corresponding to sands can be highlighted on seismic (Figure 5) by applying a filter designed on the Z_P-Z_S space from well-log data. This may help constraining the static characterization from the reservoir based on V_P/V_S, Z_P and Z_S seismic data.

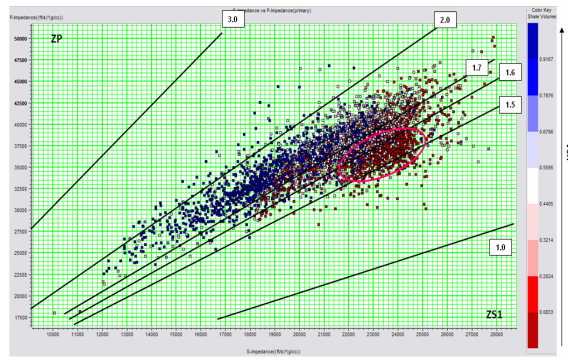

Figure 4: Z_P (y-axis) versus Z_{S1} (x-axis) color-coded by shale volume. The lines represent iso-V_P/V_{S1} contours.

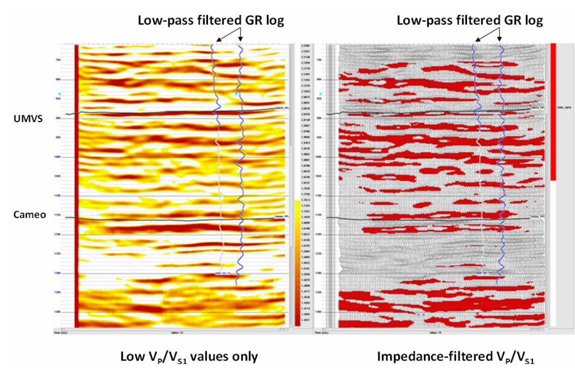

Figure 5: Low V_P/V_{S1} values only (left) and impedance filtered V_P/V_{S1} (right), with low-pass filtered GR logs overlaid.

Reservoir pressure prediction

The prediction of reservoir pressure based on seismic data follows the effective pressure concepts which are valid on low-porosity clastics (Hoffmann et al, 2006), allowing to obtain the reservoir pressure (P_P) whether the litho-static pressure (P_C), Biot's constant (n) and vertical effective stress (P_E) are known. The litho-static pressure can be obtained though integration of the density logs. Biot's constant is 0.7 based on the 3D geomechanical model performed in Rulison Field (Wikel, 2008) and the effective pressure can be obtained from V_P/V_S volumes by using a mapping function obtained from the ultrasonic lab measurements. Since the slow-shear attributes are more sensitive to pressure changes (Wikel et al, 2007) on this fractured media, the slow V_P/V_S for the 2006 vintage was used in order to predict reservoir pressure (Figure 6) using the expression:

$$P_P = \frac{P_C - P_E}{n}$$

We compared this prediction with the mini-frac test acquired on well RU-4 that year. It is observed that there is no correlation among predicted and actual reservoir pressure values at this well location because the sandstones tested are depleted. V_P/V_S is not sensitive to pressure when the interval is depleted (Figure 7).

However, comparison of high-pressure intervals in 6 other measured locations with the corresponding predicted pressure values show a high correlation (Figure 8) which is also supported by the rock physics measurements (Figure 7), indicating that V_P/V_S is able to predict reservoir pressure with confidence when the pressure in the reservoir interval is high enough.

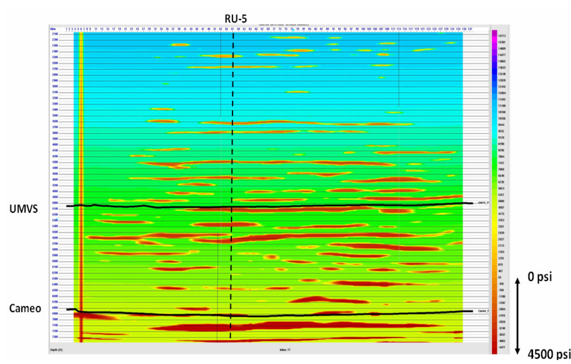

Figure 6: 2006 predicted reservoir pressure from slow V_P/V_S.

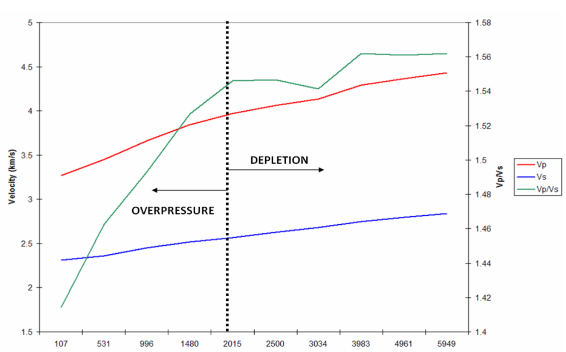

Figure 7: V_P/V_S versus effective pressure from lab measurements.

Time-lapse anomalies classification scheme

Considering the higher pressure drops on the 2003-2006 lapse compared to the 2003-2004 lapse, the time-lapse anomalies seen on V_P/V_S are clearly imaged in most cases, and related to producing wells (Figure 9). It is observed that some of the anomalies related to producing wells do not have a radial pattern, which indicates either complex hydraulic fracturing pattern or drainage interference with nearby producing wells.

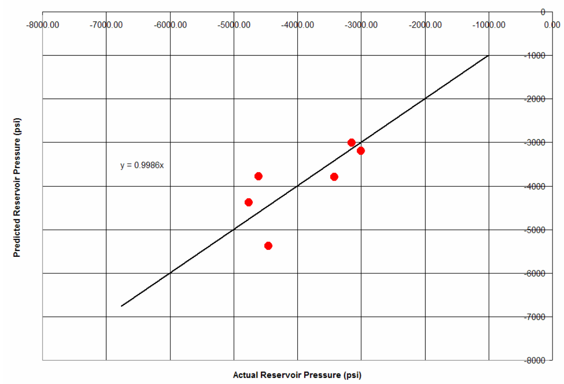

Figure 8: Predicted (y-axis) versus actual (x-axis) reservoir pressure for high-pressure intervals in different locations.

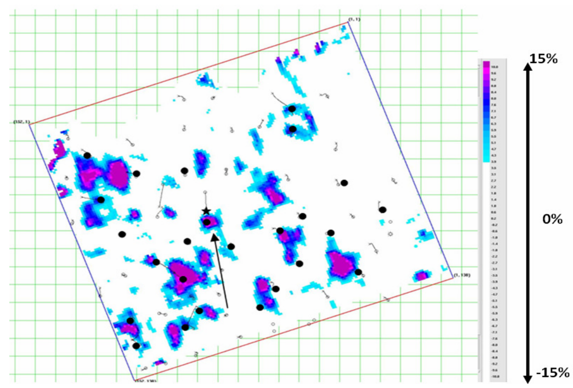

Figure 9: Slow relative V_P/V_S 2003-2006 difference @6500 ft.

The magnitude of time-lapse anomalies is not enough to determine the level of depletion of the corresponding reservoir interval. Based on rock physics lab measurements and making analogies to AVO cross-plotting and anomalies classification, a time-lapse classification scheme can be used to estimated the level of depletion of a sandstone based on cross-plotting of the baseline and monitor volumes of V_P/V_S (Figure 10) and how anomalies are classified in the space. In case of primary depletion, type I anomalies corresponds to intervals not depleted enough to abandon the over-pressure regime, and type II anomalies corresponds to those intervals depleted and not over-pressurized. Highlighting these anomalies using such classification scheme (figure 11) allows discriminate bypassed zones (type I) from those depleted (type II), depending of course on how well the cross-plotting discrimination is performed and the rock physics knowledge about the relations between V_P/V_S and effective pressure.

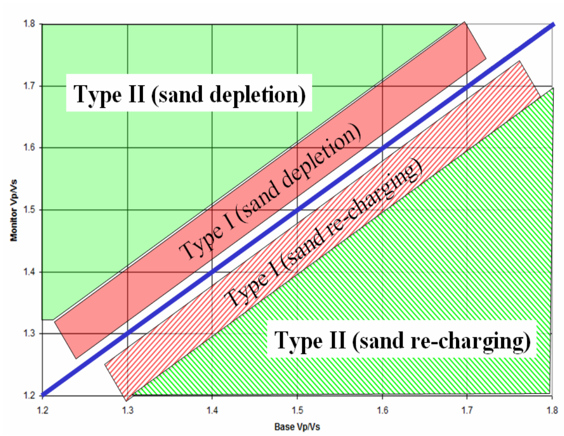

Figure 10: Classification scheme for time-lapse anomalies in tight-gas sandstones. Monitor (y-axis) and baseline V_P/V_S (x-axis).

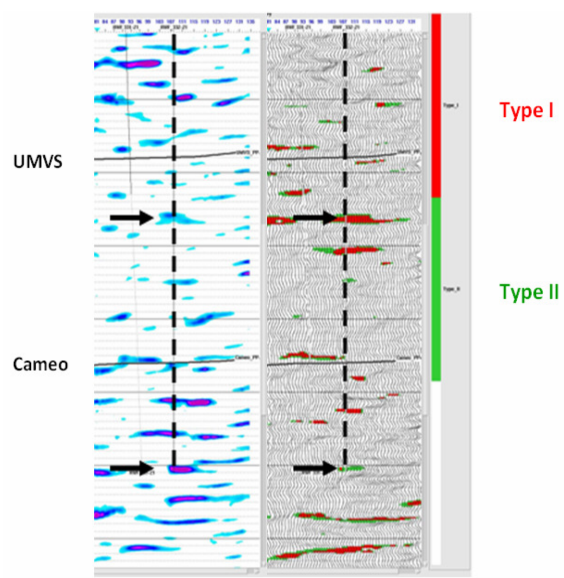

Figure 11: Vertical section showing 2003-2006 relative time-lapse positive anomalies (left) and classification of anomalies (right).

Conclusions and future work

V_P/V_S has shown to be a powerful tool for reservoir characterization, especially imaging time-lapse anomalies and predicting absolute high reservoir pressure intervals. The classification scheme for time-lapse anomalies proposed in this work can help to identify both bypassed and depleted zones. This technique can be improved through enhanced cross-plotting and multi-attribute analysis techniques. V_P/V_S and impedances can also be used to estimate sand distributions, which combined with the V_P/V_S time-lapse classification scheme, can help constraining the reservoir simulation process and well placing/completion.

Acknowledgements

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EDITED REFERENCES

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