V_p-V_s ratio sensitivity to pressure, fluid, and lithology changes in tight gas sandstones

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Summary

Low V_p/V_s anomalies can assist in prospect identification in tight gas sandstone reservoirs, because they are related to good quality rocks (sandstones with low clay content), presence of gas, and overpressure conditions. In such rocks, gas saturation lowers V_p/V_s and the effect is larger if the gas is overpressured. On the other hand, with water saturation, V_p/V_s increases and the effect is enhanced with decreasing differential pressure. Furthermore, tight gas sandstones typically have a V_p/V_s lower than that in shales.

Introduction

Recent United States and world resource assessments (e.g., U.S. Geological Survey and National Petroleum Council) indicate that most of the future gas resources in the U.S. will be in unconventional reservoirs such as tight gas sandstones. Masters (1979) describes them as low porosity (7-15%) and low permeability (0.15 to 1mD) reservoirs with moderate water saturations (34-45%) located in the deeper portions of their respective basins.

Today, tight gas sandstone reservoirs are a vast resource, especially in the Rocky Mountain basins of the Western United States. Due to their complexity and our poor understanding of these unconventional petroleum systems, new technologies are necessary to successfully exploit them. Some of the geological challenges present in tight gas sandstone reservoirs are: high reservoir heterogeneity, very low porosity and permeability, possible presence of natural fractures, uncertainty in gas/water contact and high possibility of overpressures.

Methods for prediction of overpressured zones from elastic measurements in unconsolidated sands have been reported by several researchers (e.g., Prasad, 2002; Zimmer et al., 2002). However, very little work has been done in tight gas sandstones. Most of the empirical correlations between ultrasonic velocity and porosity, clay content and effective pressures in shaley sandstones (Eberhart-Phillips et al., 1989) are valid for medium to high permeability rocks. These correlations fail in tight gas sandstones (Tutuncu et al., 1994). Experimental studies of tight gas sandstones will allow us to better understand the correlations between their seismic and reservoir properties.

In this work, we have collected ultrasonic data on tight gas sandstone cores. We also analyzed cross-dipole sonic log data to understand the relations between elastic properties (e.g., V_p/V_s, P- and S-impedance) and petrophysical properties (e.g., porosity, lithology). We show the effects of pressure, lithology and pore fluids on V_p/V_s. Finally, we quantify V_p/V_s variations due to changes in reservoir properties of tight gas sandstones with the potential to apply this information to interpret V_p/V_s extracted from AVO analysis or multicomponent reflection data.

The following results from our analysis of core and log data from Rulison Field, Colorado, can be used to interpret seismic data in tight gas sandstones.

1. V_p/V_s variation due to pore fluid changes (100% gas to 100% brine) is approximately 8%. This change is less at partially saturated conditions and is enhanced by overpressure conditions.
2. V_p/V_s variation due to lithology changes (clean sandstone to shaley sandstone) is approximately 12%.
3. V_p/V_s variation for typical tight sandstone due to pore pressure increases (hydrostatic to overpressure) is approximately 6%. V_p/V_s variation due to pore pressure decreases (primary depletion) is less than 0.5% in unfractured tight sandstone cores.

Field Description

Reservoir geology and production history

Rulison Field is located in the Piceance Basin, Colorado. Gas production is primarily from the Late Cretaceous Williams Fork Formation. Gas is trapped in a 1700-2400 ft interval of stacked, very low porosity and permeability (Figure 1), and commonly overpressured discontinuous fluvial sandstones with high irreducible water saturations (40-65%). A thin shale interval in the upper part of the Williams Fork Formation is a strong seismic reflector that possibly acts as a seal to build overpressures in the basin (Cumella and Ostby, 2003).

Although gas production in the Williams Fork Formation began in the 1960s, commercial production started in the mid-1980s, primarily through the use of hydraulic-fracturing technology. According to Williams Oil Co., the Williams Fork Formation contains up to 135 billion cubic feet of gas in place per section. However, since sands are lenticular and discontinuous, the drainage area is limited. Within the field, dry holes are rare, but uneconomic wells can occur, due to insufficient permeability in areas of little natural fracturing. The discontinuous nature and very low permeability of these sandstones require a well spacing of 20-acres or less to adequately drain the reservoir (Cumella and Ostby, 2003).

Figure 2 shows the pore pressure gradients measured from well tests in the U.S. DOE's Multiwell Experiment (MWX) site at Rulison field (Spencer, 1989). Down to 5200 ft the pore pressure gradient is 0.433 psi/ft, leading to a pore pressure of approximately 2250 psi. In the zone of interest

V_p-V_s ratio sensitivity to pressure, lithology and fluids

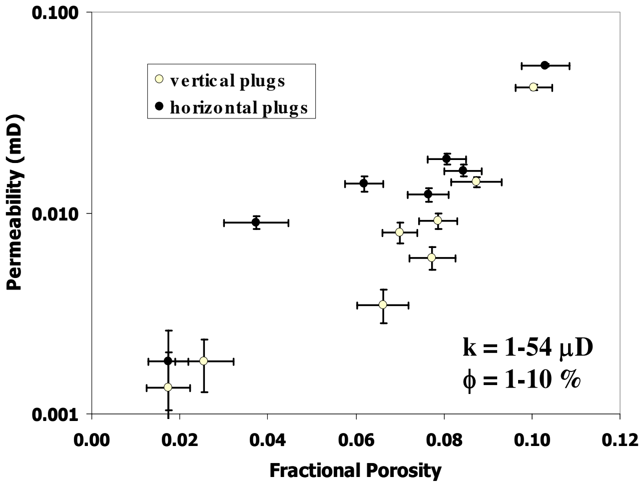

Figure 1: Klinkenberg corrected nitrogen permeability vs. fractional porosity measured in vertical and horizontal core plugs from Rulison Field, Colorado.

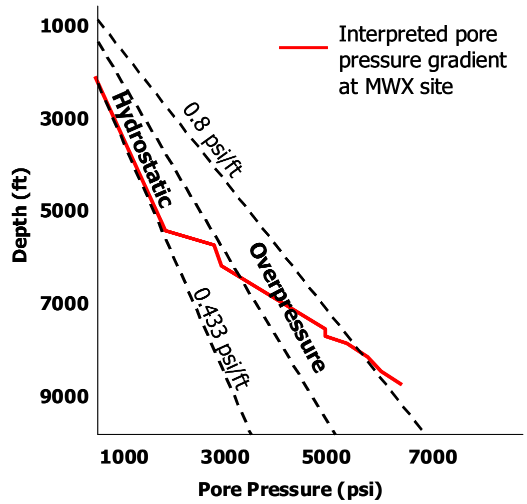

Figure 2: Pore pressure gradient measurements as function of depth at the U.S. DOE's Multiwell Experiment (MWX) site, Piceance Basin (modified from Spencer, 1989).

(5000-6500 ft) the pore pressure gradient increases with depth up to 0.68 psi/ft at 6500 ft, leading to a pore pressure of 4420 psi at a depth of 6500 ft. In general, pore pressure increases with depth to progressively larger overpressure gradients. Pore pressure decreases during primary depletion. However, due to high reservoir heterogeneity, production wells drain only small areas leading to overpressured zones in undrained areas.

Core and log data

Two cross-dipole sonic logs were acquired in the field during the last two years. Core samples were obtained from the U.S. DOE's Multiwell Experiment site (MWX) located in the Rulison field in the east-central portion of the Piceance Basin. Core samples were chosen from areas of interest (depth range from 5000 to 6500 ft).

Methodology

In this study, we show an integrated methodology to understand V_p/V_s sensitivity to pore pressure, fluid and lithology effects in tight gas sandstones. The results could be applied to interpret seismic data in terms of pore pressure, pore fluid and lithology. For example, calibrating the laboratory V_p/V_s variations due to pore pressure changes can help interpret time lapse seismic for monitoring purposes.

Laboratory measurements

We measured Klinkenberg-corrected nitrogen permeability at 500 psi for 15 samples (7 horizontal plugs and 8 vertical plugs). Porosities were measured at room conditions (Figure 1).

The pulse-transmission experimental setup for dry measurements consisted of a digital oscilloscope and a pulse generator. Piezo-ceramic transducers were used to generate P- and S-waves. Hydrostatic confining pressure was applied to the sample in a pressure vessel. Travel time was measured after digitizing each trace (time resolution 0.2 μs). Instrumental errors are less than 2% for velocity measurements.

P- and S-wave velocities were measured in dry tight sandstones at differential pressure between 100 to 6000 psi. Velocities at in-situ saturation conditions were calculated from the dry-rock velocity using Gassmann's fluid substitution equations (Gassmann, 1951). Due to the large compressibility of gas, the in-situ velocity in a gas-saturated rock is very close to that in an air-filled rock at the same differential pressure. Using the measured ultrasonic data, we calculated velocities at in-situ conditions, and we analyzed the V_p/V_s behavior under different pressure conditions.

Log measurements

This phase includes: (1) quality control of the logs, (2) derivation of elastic properties (V_p, V_s, V_p/V_s, P- and S-wave impedance) of the formations from P- and S-wave travel time and density information, (3) calculation of water saturation from resistivity logs and, (4) identification of relations between elastic and petrophysical properties.

Overpressure and fluid effects on velocities

Analysis of ultrasonic P- and S-wave velocities in dry tight sandstones shows that V_p/V_s ratio at low differential pressures (overpressure conditions) decreases rapidly with pressure (Figure 3). For pressures greater than 2500 psi, V_p/V_s does not change much with pressure. The ultrasonic

V_p-V_s ratio sensitivity to pressure, lithology and fluids

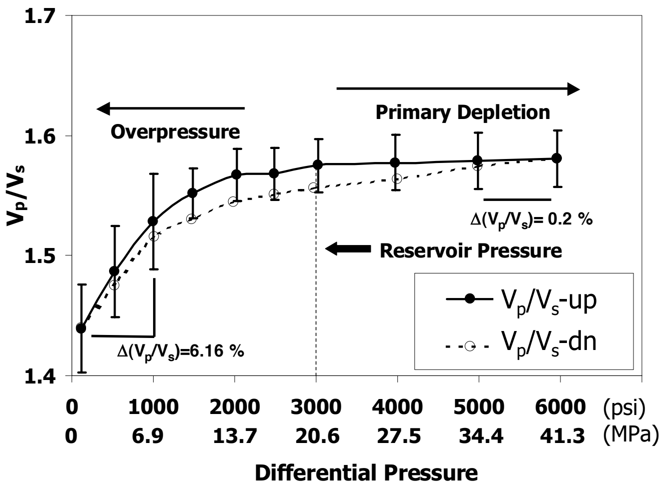

Figure 3. V_p/V_s versus differential pressure in a dry tight sandstone (ϕ=10% and k=42 μD, depth=5719 ft). Filled symbols are velocities measured while increasing confining pressure. Open symbols are velocities measured while decreasing confining pressure.

data show that V_p/V_s ratio can be used as an indicator of overpressure zones in tight gas sandstones (Figure 3).

V_p/V_s sensitivity to different fluids under differential pressure changes is shown in Figure 4. Rulison gas bulk modulus was calculated considering a mixture (Batzle and Wang, 1992) of 85% methane, 10% nitrogen, and 5% ethane. Due to the large compressibility of gas, the in-situ velocity in a gas-saturated rock is very close to that in an air-filled rock (dry measurements) at the same differential pressure (Figure 4). Thus, measured velocity versus pressure data combined with fluid substitution can be used to predict velocity changes during the production process. This information can be used for time-lapse seismic data interpretation. Figure 4 shows that in water-saturated sandstones, V_p/V_s increases with increasing pore pressure (differential pressure decreases) and that an opposite trend exists for gas-saturated sandstones.

Lithology and fluid effects on velocities

P- and S- impedance and V_p/V_s from two dipole sonic logs acquired in the field were used to analyze their correlations with lithology and pore fluids.

P-wave velocity alone is not a good indicator of lithology because of the overlap in V_p for various types of rocks. Additional information provided by V_s reduces the ambiguity. Figure 5 shows different regions identified in the V_p/V_s versus P-impedance crossplot. We can observe that it is possible to discriminate lithologies from V_p/V_s measurements. However, P-impedance alone is highly affected by fluid effects and there is ambiguity in lithology separation. Combining both P- and S-wave information

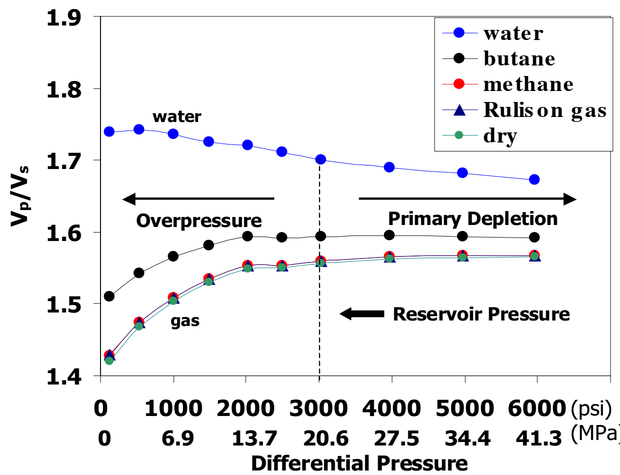

Figure 4. V_p/V_s versus differential pressure for a saturated sample (tight gas sandstone, ϕ=10 %, k=42 μD, depth= 5719 ft). Fluid substitution using Gassmann's equation was done for 100% water saturation (salinity 25000 ppm), butane, methane and a mixture of gases (85% methane, 10% nitrogen and 5 % ethane.) which represents Rulison Field gas.

we can separate fluid effects and lithology as shown in Figure 5. Low V_p/V_s values are directly related to sandstones with low clay content. Generally, there is a small increase in V_p/V_s for sandstones with more clay or shaliness. Shales themselves have significantly higher V_p/V_s than sandstones. Figure 5 shows a decrease in V_p/V_s and P-impedance for gas-saturated sandstones and an increase of V_p/V_s and P-impedance for water-saturated sandstones.

S-wave impedance is less affected by fluid effects, therefore a crossplot of V_p/V_s versus S-wave impedance color-coded by gamma ray measurements shows a better lithology discrimination (Figure 6). Tight sandstones will typically have a V_p/V_s lower than 1.7, while shales will have V_p/V_s higher than 1.7. Thus, we expect a decrease in V_p/V_s from shales to reservoir sandstones. Typically, the presence of gas-saturated sandstones lowers the V_p/V_s even further (V_p/V_s of 1.6 or lower) and overpressure conditions can lower V_p/V_s even more (<1.5).

Discussion - Quantifying V_p/V_s variations

From Figure 4, we estimate V_p/V_s variation for a typical tight sandstone due to pore fluid changes (100% gas to 100% brine) is approximately 8%. This change is less at partially saturated conditions and is enhanced by overpressure conditions. Similarly, from Figure 6, we estimate the V_p/V_s variation due to lithology changes (clean to shaley sandstone) is approximately 12%. V_p/V_s variation for a typical tight sandstone due to pore pressure increases (hydrostatic to overpressure) is approximately 6%. V_p/V_s

V_p-V_s ratio sensitivity to pressure, lithology and fluids

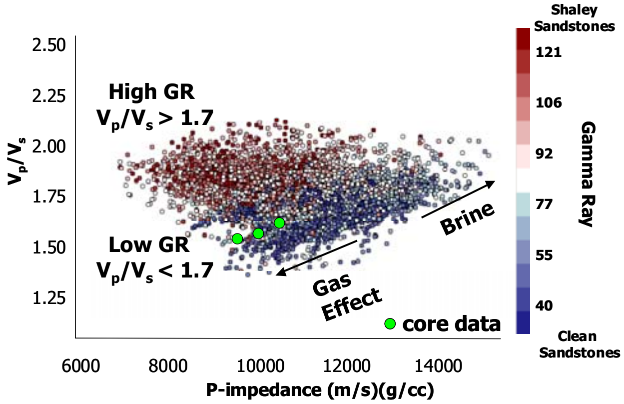

Figure 5. V_p/V_s versus P-wave impedance calculated from two dipole sonic logs in Rulison Field tight sands and shales. Blue symbols are for low gamma ray values. Red symbols are for high gamma ray values. The gas and brine effects are shown with the arrows. Gas saturated sandstone core data are integrated in the chart (green symbols).

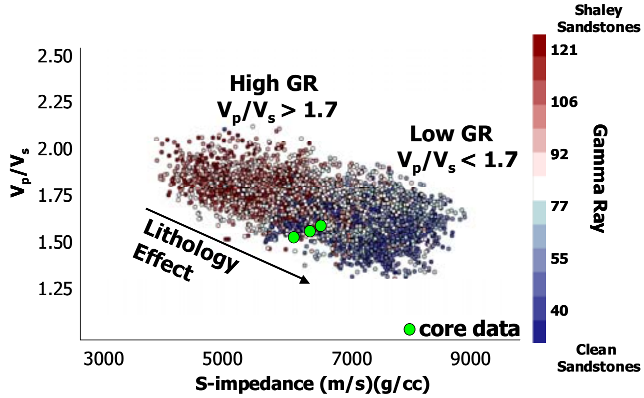

Figure 6. V_p/V_s versus S-wave impedance calculated from two dipole sonic logs in Rulison Field tight sands and shales. Blue symbols are for low gamma ray values. Red symbols are for high gamma ray values. Core data are integrated in the chart (green symbols). The arrow shows the trend of a V_p/V_s decrease and S-impedance increase due to the presence of clean sandstones.

variation due to pore pressure decreases (primary depletion) is less than 0.5% in unfractured tight sandstone cores.

The results show that lithology has a significant influence on V_p/V_s. Fluid effects on V_p/V_s are significant but less than lithology effects. V_p/V_s changes due to primary depletion (pore pressure decreases) are difficult to observe in tight gas sandtones. However, V_p/V_s is more sensitive to pore pressure increases and could be used as an overpressure indicator.

The possibility of detecting pressure, lithology and fluid effects by analyzing V_p/V_s extracted from AVO analysis or multicomponent reflection data, will depend on the accuracy of the velocities obtained from seismic. Discrimination between the different effects from seismic is difficult. However, at Rulison field, low V_p/V_s anomalies can be interpreted as a prospect indicator, since we are looking for gas-saturated sandstones preferably at overpressure conditions (undrained areas) and we have shown that in this case, fluid, lithology and pressure conditions, all contribute to lower V_p/V_s.

Conclusions

Low V_p/V_s (<1.5) is related to good quality rocks (sandstones with low clay content) and gas overpressure conditions in tight gas sandstones. V_p/V_s changes due to lithology, pressure and fluid effects are quantified using core and log data. The results could be used to identify prospect areas at Rulison Field and could be applied as well in other tight gas sandstone reservoirs.

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EDITED REFERENCES

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Vp-Vs ratio sensitivity to pressure, fluid, and lithology changes in tight gas sandstones

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