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Time-lapse AVA Analysis for Evaluating Pressure and Saturation Sensitivity in Water-Alternating-Gas (WAG) Injection Wells

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Introduction

Amplitude Variation with Angle (AVA) analyzes how seismic amplitudes change with incidence angle to reveal subsurface rock properties and fluid content. This technique is especially useful for characterizing hydrocarbon reservoirs, where understanding fluid dynamics is crucial. Alternatively, Time-lapse Amplitude Versus Angle (Time-lapse AVA) analysis may facilitate distinguishing between changes in fluid saturation and pore pressure. This study applies time-lapse AVA modeling to Water-Alternating-Gas (WAG) wells in Brazil's Tupi field. The Tupi field is a pre-salt carbonate reservoir where WAG injection is used to improve oil recovery. Historical injection data indicate that before the baseline survey, WAG1 injected gas and WAG2 injected water. Between the baseline and Monitor-1 surveys, both wells switched WAG cycles: WAG1 shifted to water injection, and WAG2 to gas injection. Our method uses only the time-lapse AVA intercept-gradient technique to assess pressure and saturation effects. This study demonstrates that the intercept-gradient AVA method has the potential to differentiate pressure-driven responses (WAG1) from combined fluid-pressure effects (WAG2) in carbonate reservoirs.

Methodology

We generated synthetic AVA responses using a Petro-Elastic Model (PEM) that combines static reservoir properties (lithology, porosity, mineralogy) with dynamic changes (saturation, pressure) to calculate elastic properties (Vp, Vs, ρ). For Tupi field, we used a specialized PEM approach addressing carbonate-specific challenges. Seismic responses were modeled using the Zoeppritz equations to generate amplitude variations across different incidence angles. For WAG1 and WAG2 wells, we created synthetic seismic data using real angle-dependent wavelets, modeling various pressure/saturation scenarios during WAG injection. Analysis used the intercept-gradient method (R_0, G) based on Shuey's approximation ($R(\theta) \approx R_0 + G \sin^2\theta$) where R_0 (intercept) and G (gradient) help identify fluid and pressure changes. By analyzing differences between R_0 and G values across time-lapse surveys, we identified distinct patterns correlating with saturation changes (water/gas substitution) and pressure variations. It should be noted that 4D AVA heavily relies on high-quality data and amplitude-preserving processing as a function of angle, often requiring data pre-conditioning to mitigate amplitude biases. This approach provided diagnostics for reservoir monitoring that can complementing the 4D interpretation from full-stack time-lapse data.

Results and Conclusions

For WAG1, amplitude increased between the baseline and monitor survey in both scenarios, but the water-to-water case with pressure reduction better matched time-lapse AVA observations, indicating pressure changes dominated the seismic response. In WAG2, amplitude decreases aligned most closely with water-to-gas substitution plus pressure reduction. The normalized amplitude analysis and two-term curve fitting evaluated these dynamic changes, demonstrating time-lapse AVA's ability to distinguish between pressure and saturation effects in carbonate reservoirs. The time-lapse AVA intercept-gradient method revealed distinct reservoir responses in the Tupi pilot field. For WAG1, pressure-driven changes from AVA complemented fluid-related signals observed in full-stack seismic data. For WAG2, the method indicated combined fluid substitution and pressure effects, showing alignment with prior full-stack data interpretations. These findings highlight the potential of the AVA analysis utility for monitoring WAG injection in complex carbonate systems. Future applications could expand to more wells and incorporate advanced rock physics models for enhanced predictive capability in similar carbonate reservoirs.