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TIME-LAPSE CRITICAL REFLECTION: DOES IT REALLY WORK IN SEISMIC MONITORING OF LOW POROSITY AND HIGH EFFECTIVE STRESS CONDITIONS?

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ABSTRACT. We present an evaluation of the time lapse critical reflection method from the point of view of sensitivity and uncertainty analysis. The purpose of this analysis is to establish the link between changes in the p-wave velocity in the reservoir, due to fluid substitution, and the critical distance (X_C), a dynamic parameter. Two static parameters of the overburden are considered in the analysis: its thickness and its effective or equivalent P-wave velocity. Stochastic uncertainty analysis by means of Monte Carlo simulations was carried out to determine the sensitivity of X_C to velocity contrast between that of the reservoir and the corresponding one to the overburden (incident medium). Results show that the effect of the velocity values in each medium, overburden and reservoir (reflecting medium), on estimates of X_C depends on the velocity contrast between the two media. It turns out that the greater the velocity difference between the two media, the greater the effects associated with the reservoir P-wave velocity. On the other hand, the dependence of X_C on overburden velocity (Vrms of the incident medium) is just the opposite. From the inversion viewpoint, predicting changes of the reservoir P-wave velocity from changes in critical distance is strongly dependent of the uncertainty in the initial estimate of the reservoir P-wave velocity, followed by degree of importance by the uncertainty in the overburden velocity. Other sources of uncertainty in this analysis turned out to be negligible. Geomechanical effects have not been accounted for in this analysis.

Keywords: critical reflection, time-lapse seismic, reservoir monitoring, sensitivity analysis.

RESUMO. Apresentamos uma avaliação do método da reflexão crítica *time-lapse* do ponto de vista da análise de sensibilidade e de incertezas. O propósito desta análise é estabelecer um vínculo entre variações da velocidade ondulatória compressional (P) num reservatório, devido à substituição de fluidos, e a distância crítica (X_C), um parâmetro dinâmico. Dois parâmetros estáticos da sobrecarga (*overburden*) são considerados na análise: sua espessura e sua velocidade ondulatória efetiva (ou P equivalente). Análise estocásticas de incertezas, usando simulações através do método de Monte Carlo, foram realizadas para determinar a sensibilidade de X_C relativamente ao contraste de velocidade entre o reservatório e sua correspondente sobrecarga. Resultados mostram que o efeito do valor da velocidade em cada meio, reservatório e sua sobrecarga, na estimativa de X_C depende do contraste de velocidade entre os dois meios. Eles revelam que quanto maior for a diferença de velocidade entre os dois meios, maiores serão os efeitos associados com a velocidade P no reservatório. Por outro lado, a dependência com relação à velocidade (Vrms do meio incidente) é, exatamente, oposta. Do ponto de vista da inversão, a previsão das variações da velocidade P no reservatório através de variações da distância crítica, é fortemente dependente de incertezas na estimativa inicial da velocidade P no reservatório, seguido, pelo seu grau de importância, pela velocidade associada ao meio incidente. Outras fontes de incertezas revelaram-se desprezíveis nesta análise. Efeitos geomecânicos não foram aqui considerados.

Palavras-chave: reflexão crítica, sísmica *time-lapse*, monitoramento de reservatório, análise de sensibilidade.

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INTRODUCTION

Landro et al. (2004) proposed an intriguing idea to indirectly determine subtle changes in the P-wave velocity in a reservoir by using variations of the critical distance, X_C, associated with the critical reflection, due to fluid substitution, e.g. oil by water during production events. This idea is attractive because X_C turns out to be very sensitivity to modest variations of the reservoir P-wave velocity. The existence of a critical angle in seismic refraction leading to critical reflection is only possible for reflecting medium (reservoir) that offers a positive contrast in velocity with respect to the incident medium, i.e. the reservoir exhibits higher wave velocity than the overburden. Under this condition, a critical reflection can be registered at its corresponding critical distance, as shown in Figure 1.

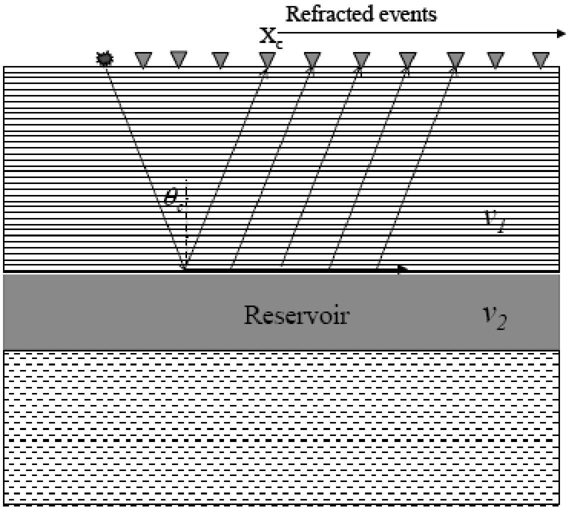

Figure 1 – Refracted rays.

Considerable effort has been dedicated for a number of years to find out under what circumstances $4D$ seismic would provide useful information on reservoir dynamics. There is a general consensus among practitioners and researchers that $4D$ seismic monitoring is particularly effective in high-porosity sandstone reservoirs. This condition is usually encountered in poorly consolidated or unconsolidated reservoirs with a low degree of diagenesis or under conditions of low effective stress.

Reservoirs subject to high effective stresses, due to low rock compliance, would exhibit very small changes in the propagation velocity, even if reservoir pressure were severely altered by production events or fluid injection. Highly accurate techniques would be required to detect the expected subtle changes in the propagation velocity in this type of reservoir setting. This might not even be possible in practice.

In the case of non-clastic reservoirs, production-induced changes in density or velocity are also generally small, requiring the development of new techniques to enable the record of such small changes (Landro et al., 2004).

All of the aforementioned ideas have been confirmed in conventional seismic monitoring studies for the passed 2 years. Experience shows that in an overwhelming majority of the successful field cases, $4D$ seismic monitoring was carried out in high-porosity sandstone reservoirs (Landro et al., 1999; Koster et al., 2000).

Critical reflection based methods can be offered as an alternative to detecting effectively subtle changes in the propagation velocity due to fluid substitution or production events, hardly attainable by conventional techniques, once the hurdles are overcome and the appropriate conditions for its applicability have been identified. One important aspect of this seismic refraction technique is to establish a clear understanding of how sensitive X_C is to small variations (perturbations) of depth and velocity contrast $\Delta V (\Delta V = V_2 - V_1)$, so that variations of the propagation velocity in the reservoir can be quantitatively determined from changes in X_C. The latter heads in the direction of inverse analysis, so rather than looking at how X_C depends on changes in the reservoir properties, we would like to use changes in X_C to estimate reservoir properties, which would be one of the purpose of any time lapse seismic technique. To accomplish this task, it is necessary to see how sensitive ΔV_2 is to changes in X_C, reservoir depth, Z, and the effective overlaying or incident medium velocity, usually taken as the value of V_{RMS}.

METHOD

A minimum condition for critical reflection is a positive velocity contrast between the incident (overburden) and the refracted (reservoir) media, Snell law allows us to calculate X_C as a function of V_1, V_2, and Z. As previously stated, V_1 is approximated by replacing it by the root mean square velocity value, V_{RMS}. Snell law yields:

$$X_C = \frac{2Z}{\sqrt{\frac{V_2^2}{V_{RMS}^2} - 1}} \qquad (1)$$

For instance, if a reservoir (reflecting medium), initially saturated with oil, suffers a velocity change due to fluid substitution (total oil replacement by water), Eq. (1) can be rewritten as:

$$X_C' = \frac{2Z}{\sqrt{\frac{(V^2+\Delta V_2)^2}{V_{RMS}^2}} - 1} \qquad (2)$$

where ΔV_2 represents a variation in P-wave velocity due to fluid substitution, as indicated previously.

Landro et al. (2004) went further and subtracted Eq. (2) from Eq. (1), and then carried on with a series expansion to first order in $\Delta V_2 / V_{RMS}$ to yield:

$$\Delta X_C = X_C - X_C' \approx -2 \frac{V_2 \cdot \Delta V_2}{V_{RMS}^2} \frac{Z}{\left(\frac{V_2^2}{V_{RMS}^2} - 1 \right)^{3/2}} \quad (3)$$

Sensitivity and uncertainty analysis

In functional terms, and direct sense, X_C can be represented as:

$$X_C = f\big(V_2, V_{RMS}, Z\big). \quad (4)$$

In this context, perturbation in V_{RMS} and Z are associated with estimation errors (but disregarding geomechanical effects), and perturbations in $V_2(\Delta V_2)$, linked to fluid substitution events in the reservoir. A stochastic analysis of uncertainty propagation was completed by means of Monte Carlo simulations. This way, the variance of X_C was obtained in the direct formulation of the problem. Perturbations of input parameters were modeled as Gaussian probability density functions (PDFs). The particular choice of perturbation models was not considered too relevant, because the interest here was focused on the relative impact of the different uncertainty (sensitivity) sources. Gaussian PDFs are naturally centered, with well-defined variance values. Figure 2 shows the relative contributions of perturbations in the input parameters to the variance of the critical distance as a function of the contrast between the overburden and the reservoir velocities. V_2 and V_{RMS} clearly contribute dominantly to the variances, with increasing contributions from V_2 and decreasing contributions from V_{RMS}, with minor contributions coming from perturbations in Z. Analytical perturbation analysis results via tornado diagrams (not shown) yielded a similar trend as those found through Monte Carlo analysis.

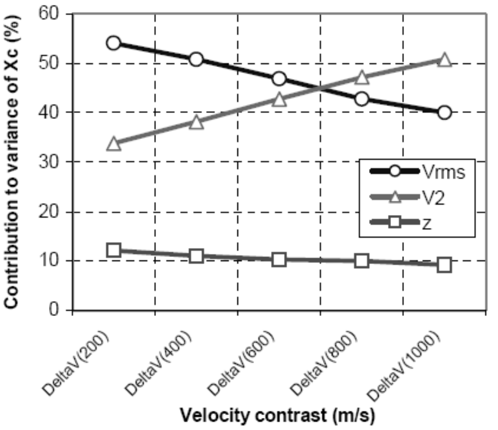

Figure 2 – Variance components of X_C as a function of the velocity contrast.

Other simulations were carried out to evaluate the effect of depth (Z). Figure 3 shows the increasing variance of X_C as a function of depth. This variance is larger for lower velocity contrast, $(V_2 - V_1)$.

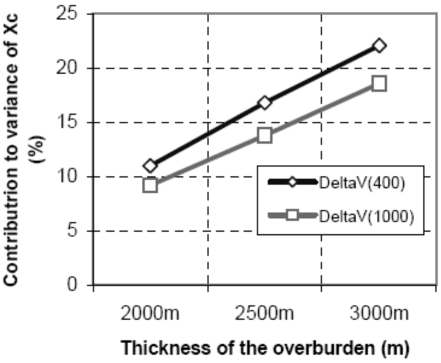

Figure 3 – Variance components of X_C as a function of thickness of the overburden.

In terms of inverse analysis, the objective is the indirect quantification of the P-wave velocity in the reservoir, due to fluid substitution or changes in pressure. ΔV_2 can be calculated by rearranging Eq. (3), as follows:

$$\Delta V_2 = -\frac{\Delta X_C \cdot V_{RMS}^2}{2Z \cdot V_2} \left(\frac{V_2^2}{V_{RMS}^2} \right)^{3/2} \quad (5)$$

Monte Carlo simulations with total of 100,000 realizations were carried out. Each of the input parameters was considered as independent (parameters can be considered dependents) and was represented with a Gaussian PDF. The error was calculated as twice the standard deviation $(\varepsilon = 2)$. Figure 4 shows that ΔV_2 is more sensitivity to uncertainties in V_2 (for instance, P-wave velocity in the reservoir prior to fluid substitution), followed by a significant contribution originated in uncertainties of V_{RMS}. ΔV_2 is relatively insensitive to errors in the remaining two parameters. Sensitivity results using examples from Landro et al. (2004), corresponding to a model with $Z = 2000$ m, $V_2 = 2500$ m/s, $V_{RMS} = 1800$ m/s, and $\Delta X_C = 85$ m; are shown in Figure 5.

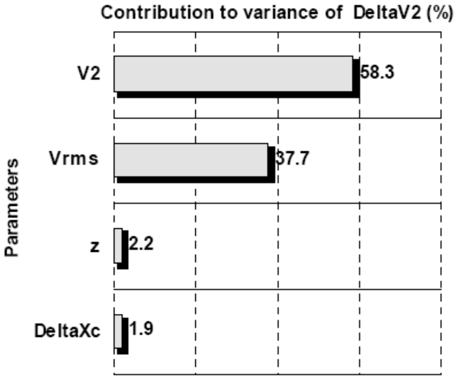

Figure 4 – Sensitivity of ΔV_2 to uncertainty in the input parameters.

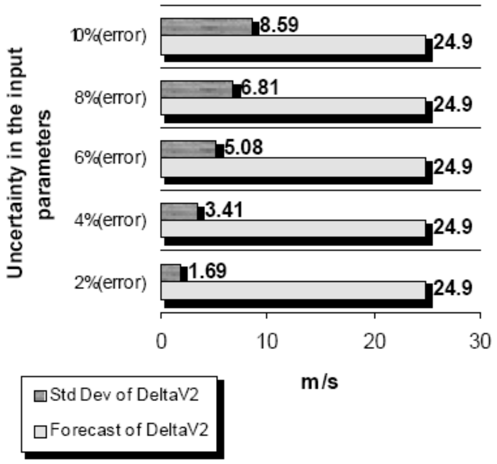

Figure 5 – ΔV_2 uncertainties induced by uncertainties in the input parameters.

CONCLUSIONS

The results presented here show that there is a strong link between the critical distance and velocity values of both the reservoir and the overburden. This link is a strong function of the velocity contrast. X_C grows with increasing values of the velocity difference, but the dependence on V_{RMS} or velocity in the overburden diminishes with increasing velocity contrast instead. On the other hand, the sensitivity with respect to uncertainties in depth is a function of the overburden thickness, generally increasing in sensitivity with depth.

In terms of inverse analysis, results show a strong dependence of the reservoir velocity variations due, for instance, to fluid substitution with respect to the estimation of the initial velocity. Although not negligible, there is a less significant influence of overburden P-wave velocity. Therefore, even if we assume an undisturbed overburden (neglecting geomechanical effects), changes in the P-wave velocity of the reservoir estimated by methods of critical reflection can contain significant associated uncertainty, due to uncertainties in the estimate of V_{RMS}. Geomechanical effects can compromise even more the estimate of ΔV_2. Finally, uncertainties sources from Z and ΔX_C can be neglected.

To summarize the concluding remarks, it can be stated that the method analyzed in this article can be effective if a significant contrast in elastic properties between the incident medium and the reflector exists; this turns out to be an ideal condition in carbonates. On the other hand, the greater the contrast in elastic properties, the lower the influence of errors associated to incident medium velocity (Vrms).

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