Sensitivity Analysis in Various Inversion Schemes for evaluating Saturation and Pressure changes in the Context of 4D seismic studies

Fredy A. V. Artola, Vladimir Alvarado and Sergio Fontoura, PUC-Rio

Abstract

Here, a sensitivity analysis on saturation (ΔS) and pressure (ΔP) variations due to uncertainties in the input parameters of several inversion schemes is presented. In this sense, input parameters can be classified with respect to how their uncertainties impact the value of estimated inverted parameters, all of which depend on reservoir thickness, or stage of production, and the particular inversion scheme considered. In this sense, the possibility of diminishing uncertainties in the predicted values of ΔS and ΔP is tied to the feasibility for discrimination of the critical input parameters, as sources of uncertainty for the inverted indicators (ΔS and ΔP). This way, it would be possible to concentrate efforts in obtaining reliably the important inputs for inversion.

Introduction

Undoubtedly, 4D seismic is currently one of the most paradigmatic themes in the Exploration and Production business. The reason for this comes from the fact that 4D seismic allows us to "see" remotely the complex dynamics that take place in a reservoir, due to production operations. The integration of well-established disciplines and techniques such as conventional 2D or 3D seismic survey and multicomponent seismology, Rock Physics, Petrophysics and Reservoir Engineering increases confidence in such visualization possibility.

At the beginnings of 4D Seismic, efforts focused predominantly on gathering qualitative information on the reservoir dynamics. It was this way that clues about displacement fronts in mature reservoirs could be identified by using successive seismic acquisitions in the form of pockets of undrained areas.

The work developed by Landro (2001) and Landro et al. (2003) opened new directions in regards to make possible a quantitative analysis in the context of time-lapse seismic. These authors discuss a feasibility path for discriminating between effects caused by changes in saturation from those originated from pressure changes, reflected in the time-lapse image by integrating Rock Physics information with data obtained by two distinct seismic surveys, the conventional 3D one on one hand, and the multicomponent survey (OBS).

In general, the equations that allow us to estimate pressure and saturation changes use information on travel time, amplitude, AVO gradient and some linearized Rock Physics parameters. The method by Landro et al. has driven further studies, with consequent improvements to the method. Meadows (2001) suggested two modifications to Landro's approach. In his first modification, he inverted the rock physics time-lapse variations from the seismic impedances instead of using the intercept and the AVO gradient. In his second modification he presented the changes in P-wave velocity as a quadratic function of water saturation time-lapse changes. Recently, Angelov et al. (2004) suggested a new approach to fit the relation between effective stress variations and changes in seismic impedance.

Regardless of the method used, the determination of ΔS and ΔP is subject to different sources of uncertainties from the input parameters. It may be that some of these uncertainty sources or uncertain parameters turn out critical for the result of the inversion.

Landro (2002) carried out a deterministic quantitative analysis of the time-lapse seismic response in the presence of uncertainties. Here, we present an alternative approach based on a probabilistic analysis on the impact of uncertainties in the inversion result of time-lapse seismic data. In this approach, each parameter is represented with a probability density function (PDF) that is intended to represent uncertainty of its values (whether measurement errors or other sources). Likewise, the estimated ΔS and ΔP are obtained by Monte Carlo simulations, so that in turn ΔS and ΔP are depicted as PDF's (Figure 1). This way, it can be determined how each of the input parameters contribute to the variance of the predicted ΔS and ΔP and hence determine their degree of importance in a given inversion scheme.

Probabilistic Approach

In general, ΔS and ΔP can be estimated from data of seismic origin $d_i^{(seis)}$, given by ΔT_{PP} (PP-mode travel time difference), ΔT_{PS} (PS or converted-mode travel time difference), ΔR_0 (vertical reflectivity variation) and ΔG (AVO gradient variation). In addition, Rock Physics data $d_i^{(Rock-Phys)}$ used for this purpose is usually represented by κ_{vp}, κ_{ρ}, l_{vp} and l_{vs}, which are empirical regression coefficients associated to the P-wave obtained from (saturation/relative variation) curve in Vp, density from (saturation/relative variation) curve in density, and those associated to (stress/relative variations) curves in Vp and Vs, respectively. In functional form, the estimated values can be written as:

$$\Delta S, \Delta P = f\left(d_i^{\ (seis)}, d_i^{\ (rock-phys)}\right) \quad (1)$$

Due to the uncertainty associated to each of input parameters, they are represented as PDF's, or more precisely:

$$d_i^{\ (seis)}, d_i^{\ (rock-phys)} = \underbrace{\boxed{PDF's}}_{\text{State of knowledge}} \qquad (2)$$

Since the interest here is to establish a probabilistic approach to examine the results in light of several inversion schemes, the PDF's for all input parameters consists of a triangular symmetrical distribution, whose minimum and maximum values or range equates the variance or dispersion of the uncertainty source for each parameter.

Inversion Schemes

Two known possibilities exist for determining ΔS through inversion within the framework of time-lapse seismic. The first approximation uses P-wave travel-time data, while the second utilizes both amplitude and travel time of the compressional wave. On the other hand, other approximations proceed to carry out simultaneous inversion of ΔP and ΔS based upon either travel-time data from PP-wave surveys alone or from amplitude and travel-time data in multicomponent surveys (PP and PS mode).

Landro (2001) shows that the uncertainties associated with ΔP and ΔS due to uncertainties in the input parameters diminish as more seismic information is incorporated into the inversion process. Therefore, the uncertainty associated with ΔP and ΔS is lower when travel-time and amplitude data are used in successive multicomponent surveys as compared with inversion schemes using conventional survey data.

Here, we evaluate the sensitivity of the ΔP and ΔS uncertainties associated to input parameters in the inversion schemes described previously. In general, each parameter is considered as a random variable with a mean value μ and a standard deviation σ, where the relative error is equated to 2σ, that is the range of the triangular distribution.

Results

ΔS estimation from ΔT_P, ΔR_0, κ_ρ and κ_{Vp}

To evaluate sensitivity in this inversion scheme the input parameters, ΔT_P, ΔR_0, κ_ρ and κ_{Vp}, are represented by PDF's. Various reservoir thicknesses were considered (in their time scales as travel times).

Figure 2 shows that the contribution to uncertainty from ΔR_0 is small in thin reservoirs (less than 10% in 10ms reservoir thickness), but grows rapidly as the thickness gets larger, even resulting predominant for reservoirs thicker than 60 ms.

The contribution to variance of κ_{Vp} , which is the empirical regression coefficient, is predominant for thin reservoirs (between 10 to 20 ms) contributing over 70% of the total variance of ΔS. However, this contribution decreases quickly, being of little significance for thickness values greater than 50 ms.

On the other hand, ΔT becomes a significant source of uncertainty in thin reservoirs (20% contribution for 10ms in thickness), but turns out to be less significant for reservoirs thicker than 50 ms, leading to contribution to variance less than 10%.

Finally, κ_ρ is not a critical parameter. Its contribution is negligible in thin reservoirs, only contributing with 10% to the total variance of ΔS for thick reservoirs.

ΔS-ΔP estimation from I_p, ΔG, ΔR_0, κ_ρ and κ_{Vp}

In this method, the sensitivity of ΔP and ΔS to uncertainties in the input parameters depends on the magnitude of changes in pressure and saturation that occur in the reservoir. For instance, if a change of –0.8 MPa in pressure takes place, the associated uncertainty contributions for this value of ΔP during inversion is qualitatively and quantitative different from a case where a variation in pressure is –5 Mpa, for the same reservoir. Much in the same way occurs for changes in saturation, since input parameters contribution both qualitatively and quantitatively differently for slightly different variations of saturation (e.g. 0.48 vs. 0.50). Hence, the degree of the required certainty in the input parameters will strongly depend on what is happening in particular situations in terms of pressure and saturation, so that there is not a unique recipe (see Figures 3a and 3b). On the other hand, it is noticed that uncertainties associated with κ_ρ and I_p contribute negligibly to the total variance of ΔS. However, the situation is different for ΔP, whose variance turns out to be very sensitive to I_p uncertainties.

ΔS-ΔP estimation from I_{vp}, ΔG, ΔR_0, κ_ρ and κ_{Vp}, κ_{Vs}, ΔT_{PS}, ΔT_{PP}

In this more complex scenario of inversion the number of input data is the greatest. The new information derives from the empirical regression coefficient associated to the S-wave and from the travel time of the converted mode, Tps, obtained in the multicomponent seismic survey. In this case, there is a tendency to redistribute the degree of importance of contributions to the total variance of ΔS. This is reflected by the fact that none of the input parameters contribute with more than 40% (see Figures 4a and 4b). The most significant contributing sources to variance are the uncertainties associated to ΔG, ΔR_0, κ_{Vp}, ΔT_{PS}, and ΔT_{PP}. The remaining parameters do not exhibit an appreciable contribution. The general trend, however, is to balance or dilute contributions to the variance of ΔS. A different situation relates to ΔP in the inversion process, since I_{vp} contributes dramatically to variance. Now, given that the determination of I_{vp} is a strong function of the rock's compliance, the estimation of ΔP can not be reliable, because the compliance under reservoir conditions can differ significantly from those typically obtained in Rock Physics tests, that is from core experimental conditions.

Conclusions

The results in this study show the importance of knowing the sensitivity of ΔP and ΔS for some inversion protocols, considering actual reservoir conditions as well as the thickness of the targeted formation for time-lapse seismic. It is clear that approaches as the one elaborated here pave the way to determining possible reduction in uncertainties in the estimated values of ΔP and ΔS by helping to identify critical contributing factors (input parameters) in the context of time-lapse seismic inversion.

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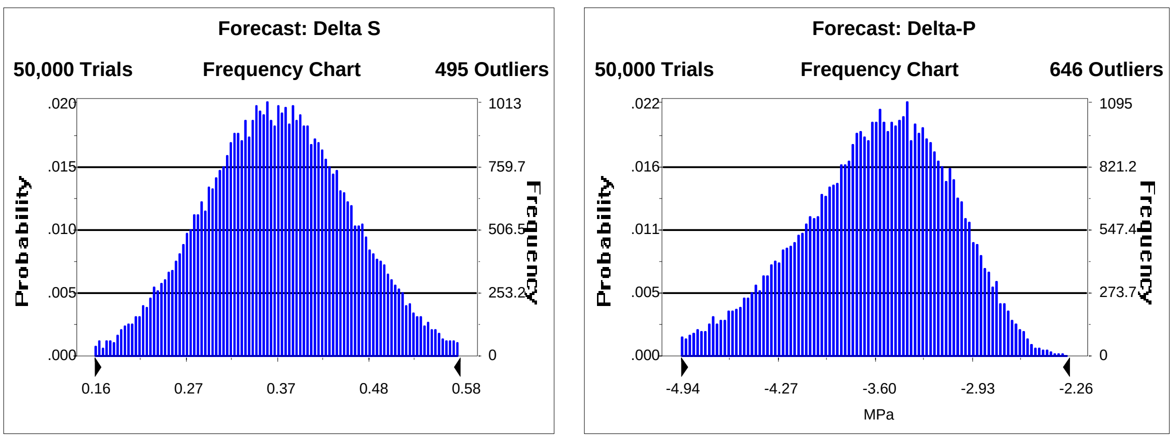

Figure 1. Monte Carlo results for ΔS e ΔP represented by normalized histograms.

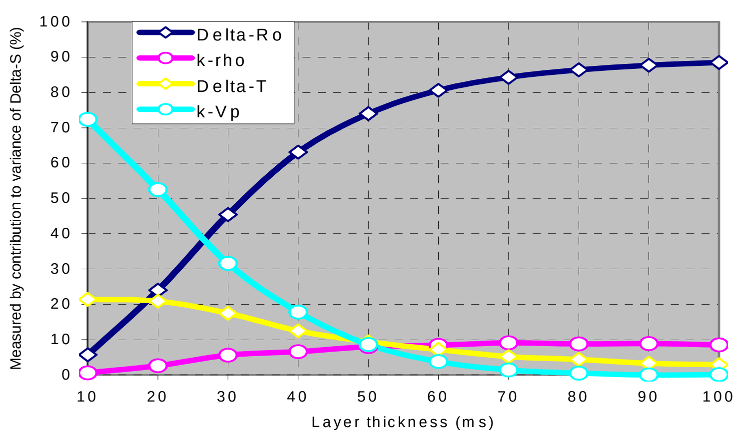

Figure 2. Sensitivity of ΔS to input parameters as function of reservoir thickness.

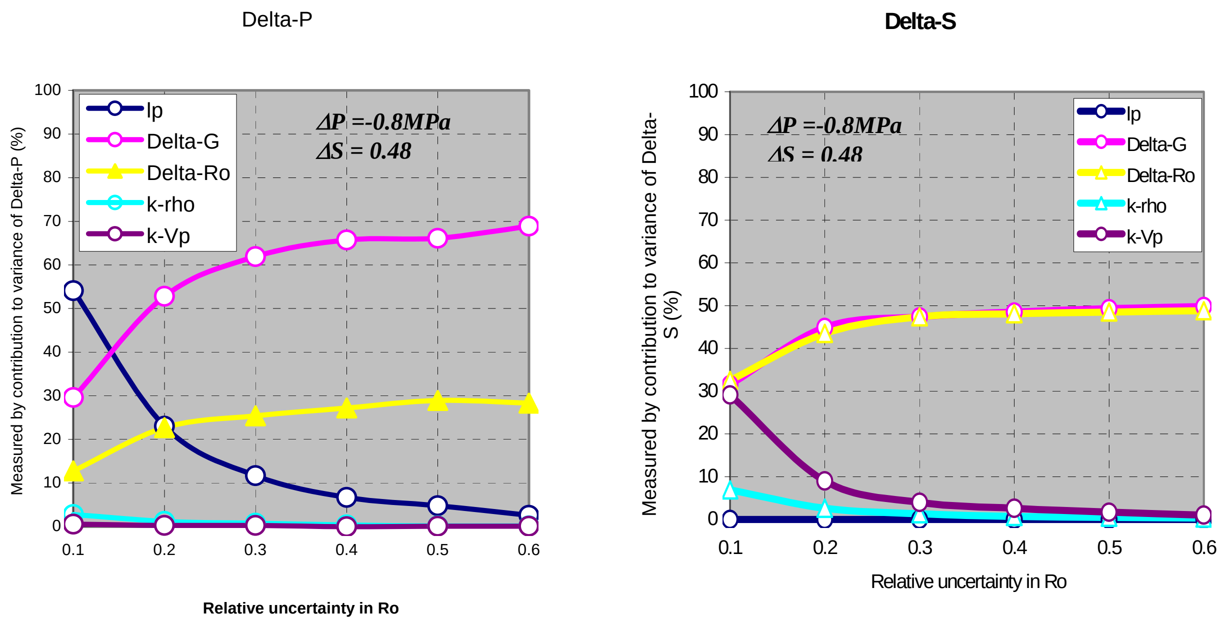

Figure 3. Sensitivity of ΔP and ΔS to uncertainties in input paramerters for reservoir conditions represented by *ΔP = -0.8 MPa* e *ΔS = 0.48.*

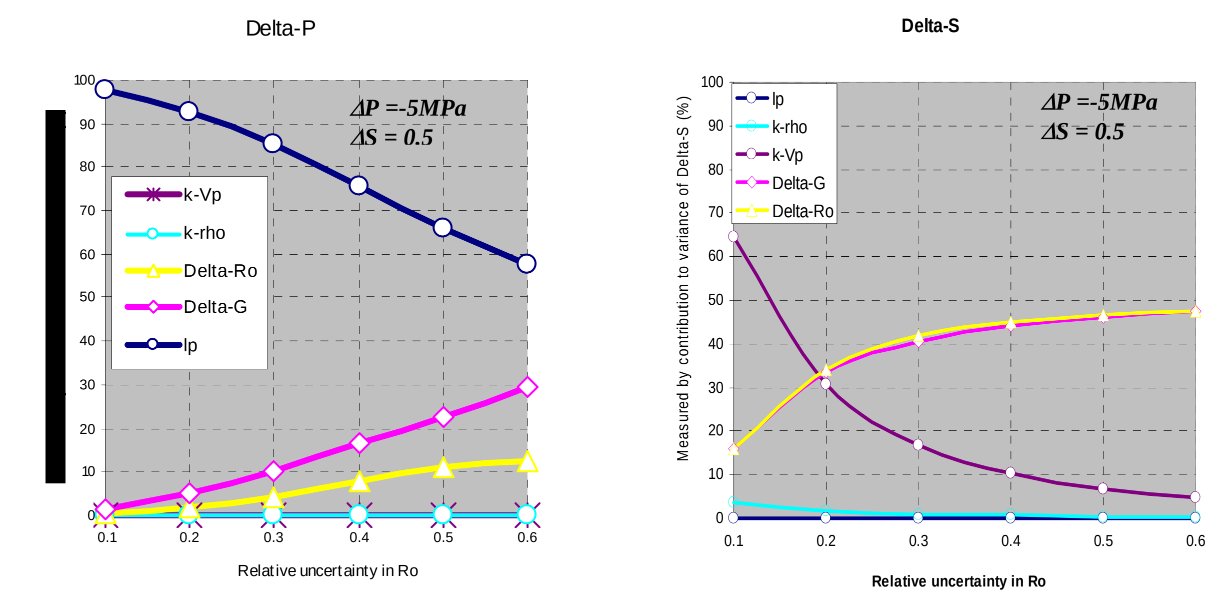

Figure 4. Sensitivity of ΔP and ΔS to uncertainties in the input parameters (conditions *ΔP =-5 MPa* e *ΔS = 0.5*)

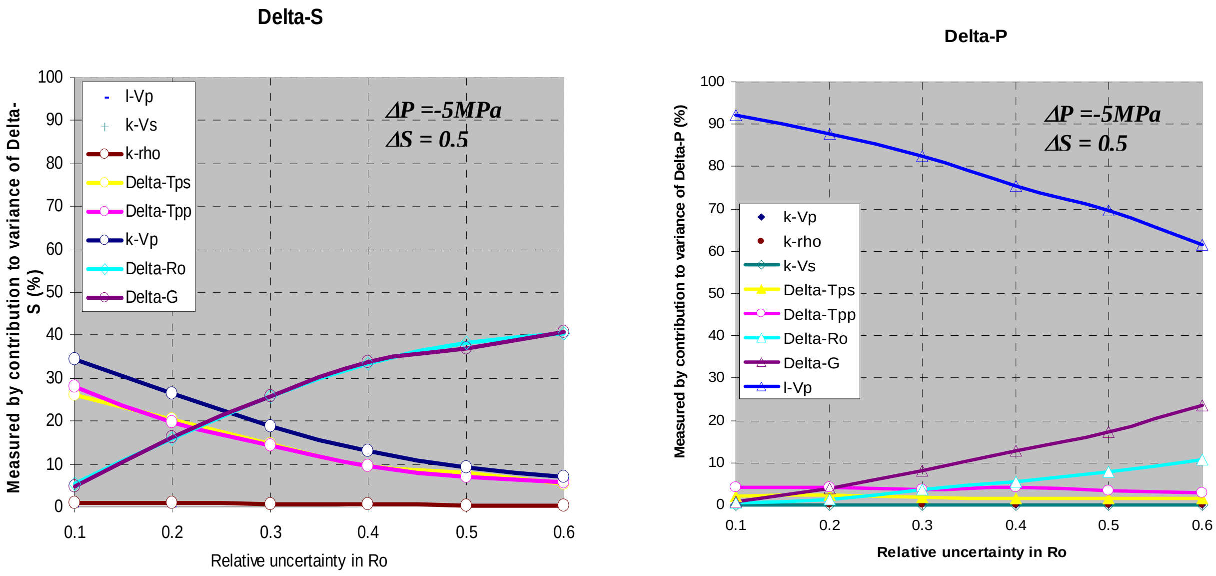

Figure 5. Sensitivity of ΔP and ΔS to uncertainties in an inversion scheme using shear wave data (*ΔP =-5 MPa* e *ΔS = 0.5*)