Improving Pressure Sensitivity Analysis of Brazilian Pre-Salt Carbonates

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Abstract

The understanding of how pressure changes affect elastic properties of reservoir rocks is valuable information in time-lapse seismic studies. Nevertheless, it is not an easy task to accurately predict the elastic behavior of heterogeneous reservoirs rocks. In this paper we present an approach based on porosity which can be a powerful tool for improving velocity and elastic moduli predictions on carbonate reservoirs undergoing production. Moreover, besides reducing uncertainties, the proposed method allows to incorporate them in order to create different scenarios.

A large set of dry samples ultrasonic velocity measurements of Brazilian pre-salt carbonates was analyzed. Among other interesting conclusions we observed that high porosity samples tend to present greater changes in elastic properties due to pressure variation. On the other hand, low porosity samples show larger uncertainties ranges. Because of that, considering optimists and pessimists scenarios, which mean large and small elastic properties variation, respectively, we can found different behaviors. So for an optimist scenario a carbonate reservoir low porosity regions can be more detectable in terms of 4D signal – considering only pressure effect – than average scenarios of higher porosity regions.

Introduction

Recently large amounts of oil and gas accumulated in pre-salt carbonate rocks were discovered at ultra-deepwater southeast Brazilian coast. The production of hydrocarbons from this reservoir implies a variety of challenges (Estrella, 2011). Nowadays, reservoir seismic monitoring is a recognized tool for improving hydrocarbon field development strategy. The use of time-lapse (4D) seismic aims to identify changes in rock elastic properties derived from production. The most important effects which cause detectable variations on elastic properties of reservoir carbonate are expected to be: rock-fluid interaction, saturation and pressure changes. It is still not guaranteed the feasibility of 4D seismic projects for these pre-salt targets. One of the main reasons is the predominance of low compressible carbonate reservoirs. Calvert (2005) suggests that the chances of success of a 4D seismic project with low detectability can be improved increasing the repeatability of seismic acquisitions. The understanding of how the elastic properties changes as a function of saturation/pressure variations and rock-fluid interactions have a meaningful importance since feasibility studies until the interpretation stage.

Based on Biot's theory, several authors (e.g. Todd and Simmons, 1972 and Christensen and Wang, 1985) demonstrated experimentally that velocities and hence elastic moduli of porous rocks are function of effective pressure. The effective pressure is defined in Equation 1:

$$P_{eff} = P_o - \alpha P_p \quad (1)$$

Where P_{eff}, P_o *and* P_p represent the effective, overburden and pore pressures, respectively. The parameter α is the Biot's coefficient.

In practice, it is common to adopt a single empiric relation between elastic properties and effective pressure (called pressure law) to represent the average elastic behavior of reservoir rocks. However, the pre-salt reservoirs consist of complex and heterogeneous carbonates. Consequently, core samples present a wide range of velocities which are not well predicted using a single relationship. This work is focused on improving the modelling of pressure changes effects on elastic properties of strongly heterogeneous rocks, using Brazilian pre-salt carbonates as an example.

The dataset consists in laboratory measurements of ultrasonic P and S velocities in 277 dry core samples confined at different effective pressures. These pre-salt carbonate samples belong to 13 wells from 5 different fields. The effective pressure range in which the samples were submitted is from 500psi to a maximum of 7400psi. The original effective pressure of these reservoirs is around 4000psi.

Method

Lumley (2003), MacBeth (2004) and Mavko (2004) propose different equations for modelling the elastic moduli and seismic velocities behavior of dry samples with effective pressure variation. Vasquez et al. (2005) compare these equations using Brazilian rock samples and suggests that despite Lumley's proposed equations are more indicated to unconsolidated rocks, they bring up good results also for consolidate rock. In this paper we discuss results based on Lumley (2003) proposal (Equation 2):

$$Y_{DRY} = a + b\ln\left(P_{eff}\right) \quad (2)$$

Where Y_{DRY} represents elastic parameters of dry rock $(VP_{DRY}, VS_{DRY}, K_{DRY}$ or $\mu_{DRY})$ and P_{eff} the effective pressure. a and b are empirical coefficients.

Coefficient a preserves some relation with the rock stiffness, while coefficient b indicates how rock elastic properties are sensible to pressure changes.

As mentioned in several papers (Dvorkin et al., 1996; Han and Morgan, 1986) porosity has an important role on elastic moduli and velocities estimation. It is well known (e. g. Eberli et al. 2003) there are other factors, such as pore type and amount/type of cementation controlling the elastic behavior of carbonate rocks. We classify the dataset by effective porosity considering it has a first order effect. The adopted approach in this paper could be extended to include these other effects whenever more detailed data is available.

One important objective of this study is to improve the prediction of seismic velocities – pressure relations taken into account samples porosity. Figure 1 shows the crossplots of elastic properties and effective pressure and their fitted curves by porosity classes. As expected, high porosity samples are normally associated to low velocities and elastic moduli. Notice that still remains a significant spread of the data due to other factors mentioned above.

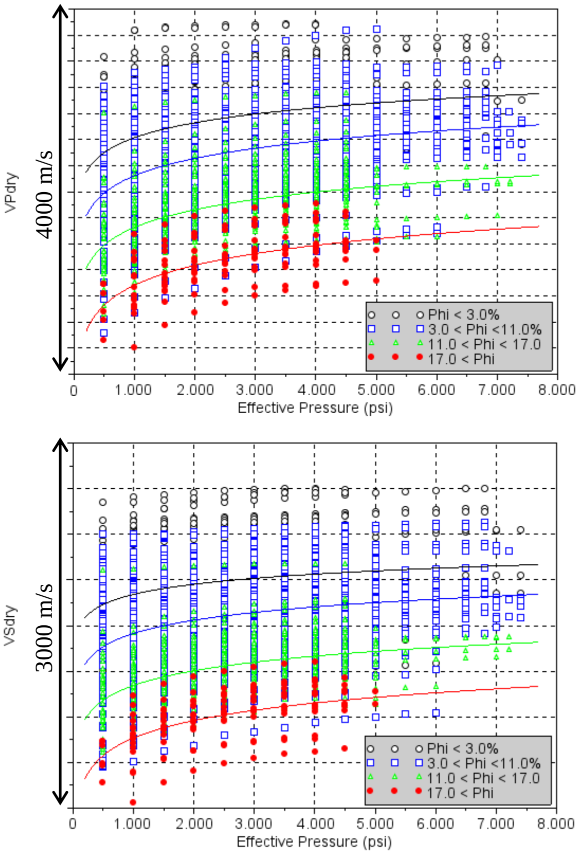

Figure 1 *– Laboratory ultrasonic velocities versus effective pressure colored by porosity and respectively fitted curves.*

We also compute the empirical relations between elastic properties and effective pressure for each sample and record their coefficients. Figure 2 shows an example of these relations for one particularly pre-salt field.

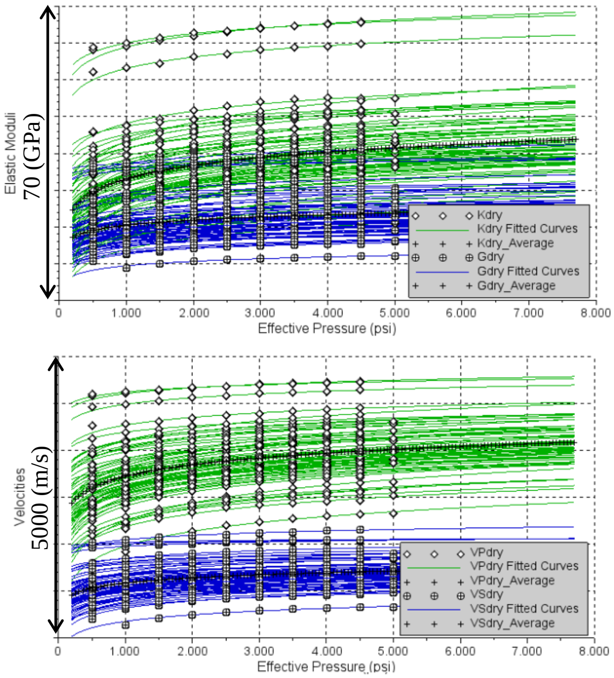

Figure 2 *– Crossplots of elastic moduli (Kdry and Gdry) and velocities (compressional and shear) versus effective pressure and their fitted curves (green and blue) computed for each sample of a given field. Black curves represent the average curve calculated for all samples of the field.*

Another important aim of this study is to capture uncertainties and incorporate them to possible scenarios. For that, we compute a pair of coefficients for each one of the 277 samples using Equation 2. We observe a strong negative linear correlation between these coefficients indicating that soft rocks (small a) tend to be more sensitive (high b) in terms of pressure changes. Fitting a straight line for each porosity interval we can verify that they are nearly parallels, especially for P velocity data.

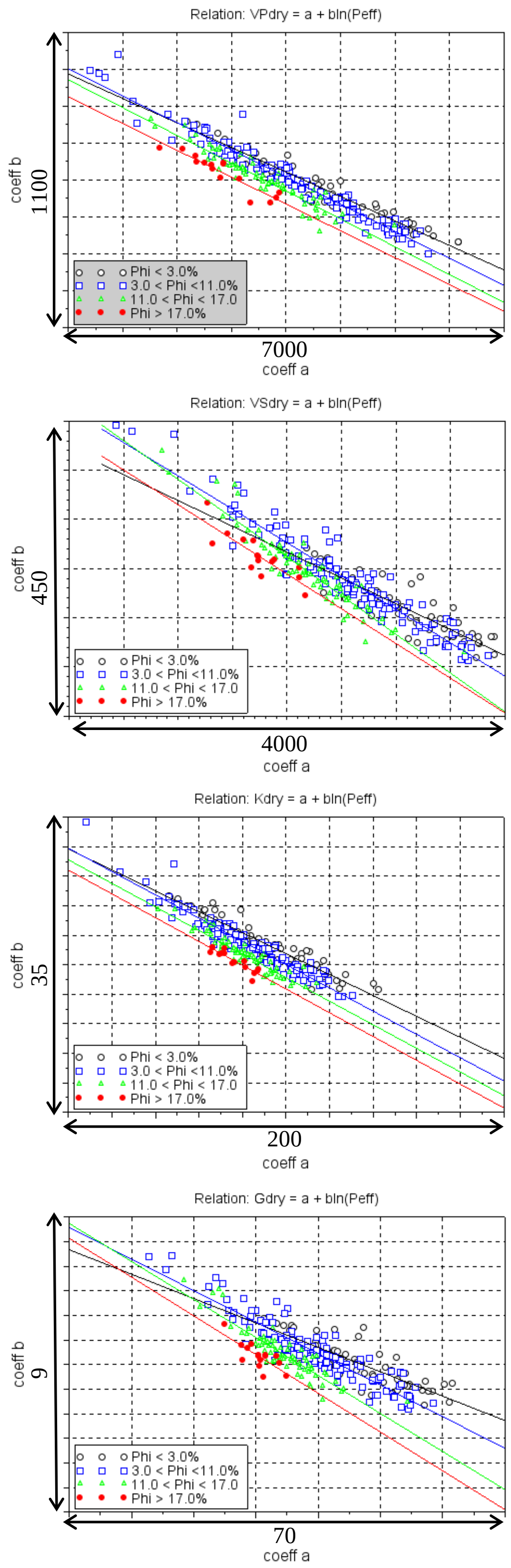

Figure 3 *– Crossplots of a and b coefficients computed for each sample and colored by porosity classes.*

Results

We aim to reduce uncertainties associated to elastic properties prediction of the pre-salt heterogeneous carbonates calculating for several porosity classes the dependence of velocities and effective pressure. The results of the proposed approach are evaluated based on the mean absolute percentage error (MAPE), expressed in Equation 3, between measured and predicted velocities derived from 2 methods: (i) a single and average relation considering all range of porosities and (ii) several relations considering porosity intervals.

$$MAPE = \frac{100}{n}\sum_{s=1}^{n}\left|\frac{M_s - C_s}{M_s}\right| \qquad (3)$$

Where n represents the number of samples and elastic parameters of dry rock, M_s *and* C_s the measured and calculated properties, respectively.

The results are shown in Table 1. We can attest, at least for the available dataset, that using an average velocity - pressure relation to represent a pre-salt carbonate field is less accurate than to compute the same relations using porosity intervals. Moreover, the prediction of both P and S velocities using porosity classes presents lower errors than the average velocity-pressure in approximately 67% of cases. The results are even better if we consider only porosities above 11.0%, which represents the most interesting classes economically. At these conditions the methodology using porosity classes provide better P and S velocities estimations in 90% and 93% of cases, respectively.

	MAPE (%)				Standard Deviation			
	VPdry	VSdry	Kdry	Gdry	VPdry	VSdry	Kdry	Gdry
Average Relation	8,9	8,6	24,8	22,6	6,8	6,6	23,8	20,0
Porosity Classes Relations	6,8	6,9	16,2	13,4	5,2	5,3	13,2	11,3

Table 1 *– MAPE (%) of velocities and elastic moduli estimations by both average and porosity classes relations computed between elastic properties and velocity pressure and their standard deviations.*

Considering the observed spread on velocities-pressure crossplots it is necessary to define uncertainties scenarios associated to the obtained pressure laws. First, we calculate 10 and 90 percentiles of a coefficient distribution for each porosity interval. Then we combine the resulting values and the computed relation between a and b coefficients to create pessimists (P90) and optimists (P10) scenarios (Figure 4). We also compute a relation considering P50 cases which proved to be very close to the fitted curves.

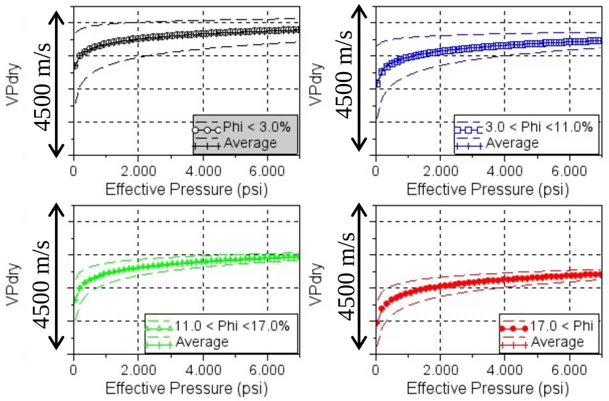

***Figure 4** – An example of the fitted curves computed for relations between P velocity for each porosity class and their range of uncertainty using P10, P50 and P90 of α coefficient distribution.*

Analyzing the fitted pressure laws for each porosity interval, we are able to conclude that lower porosities present lower responses to pressure changes (Figure 5). However, this affirmative is not always truth due to the fact that the uncertainty is higher in low porosities. Therefore, in some cases, in an optimist scenario (P10), low porosities can exhibit a greater potential of 4D seismic detectability in terms of pressure change. The uncertainties also tend to become higher at low effective pressure (Figure 6). It can be seen in Figure 7 the predicted changes in seismic velocities of dry rock samples at pessimist, probably and optimist scenarios. For that was considered the effective pressure ranging from 4000psi to 5000psi. Figure 8 shows the predicted changes in compressional velocity by fitted pressure law and uncertainties curves for each porosity class. In this example was considered an original effective pressure of 4000psi.

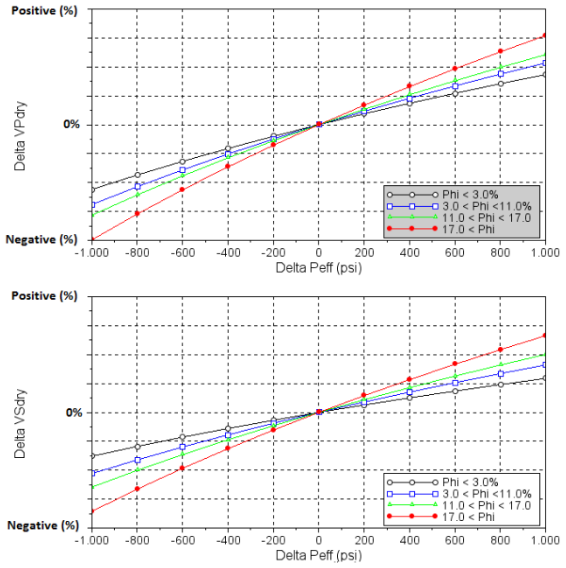

***Figure 5** – Predicted velocity changes for a reasonable range of effective pressure classified by porosity. Were considered 4000psi as the original in-situ effective pressure.*

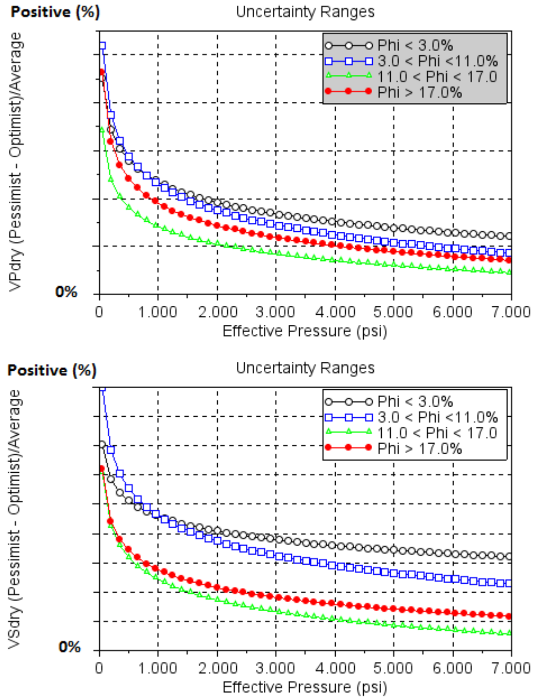

***Figure 6** – Uncertainty range of velocities with respect to mean curve calculated for each porosity class. Uncertainty decreases as the effective pressure increase; low porosities are related to higher uncertainties.*

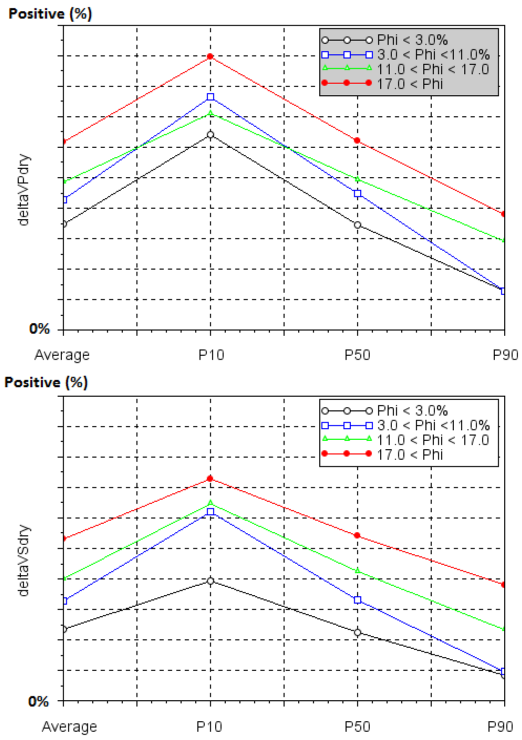

***Figure 7** – Predicted percentage variation on P and S velocities for each porosity class in pressure change scenario from 4000psi to 5000psi. Integer number at the horizontal axis represents the relations computed for each porosity class and the relations obtained by P10, P50 and P90 of α coefficient distribution.*

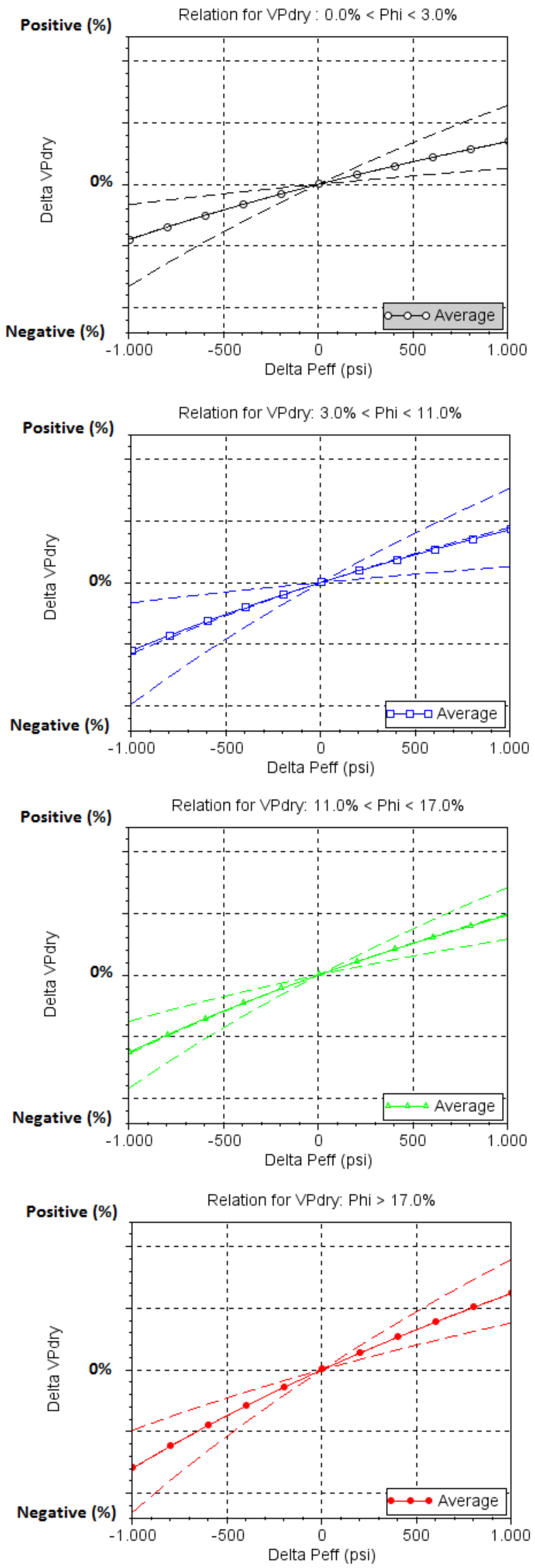

***Figure 8** – These graphics show an example of predicted velocity changes for all range of effective pressure separated by porosity classes. Were considered 4000psi as the original in-situ effective pressure.*

Conclusions

In order to correctly predict and interpret time-lapse seismic (4D), it is important to understand elastic parameters dependence on pressure. Usually this dependence, important for petroelastic modelling, is based on an average curve computed from several velocity – pressure ultrasonic laboratory measurements on samples extracted from the reservoir under study.

In this paper we analyze 277 core measurements from a complex and heterogeneous pre-salt carbonate reservoir and we find a large dispersion of elastic response to pressure. It is well known that many factors cause this dispersion in carbonates and, among them, porosity has a first order effect (Eberli et al. 2003). Very often porosity volumes derived from seismic inversion are available and are potentially useful - whenever impedance and porosity correlation is confirmed from well logs.

We propose a methodology that, instead of using an average law to predict the elastic behavior of dry rocks as functions of pressure, uses various laws based on porosity intervals. We obtain a and b coefficients for a logarithmic elastic parameter – pressure relation (Lumley, 2003) for each pre-defined porosity interval. This approach can be easily incorporated to the conventional workflow and better represents the spatial variability of the carbonate elastic behavior over the field.

The adequacy of this approach is verified through mean absolute percentage error (MAPE) between measured and predicted velocities derived from: (i) a single and average relation and (ii) several relations considering porosity intervals. The results show a decrease of approximately 22% in mean error in velocities estimations using porosity classes method instead of an average law. Were observed that proposed methodology returns better P and S velocities estimations in 67% of cases. But considering only porosities above 11% P and S velocities estimations were better predicted by porosity classes relations in 90% and 93% of cases, respectively. It shows that the proposed methodology improves the elastic response prediction for reservoir pressure change, specially, at the main economic interest areas of the fields.

More complex analysis of elastic behavior considering mineralogy, pore type, facies can also be made but it requires more time, investments and not always it will be easy to introduce this information in 3D/4D modelling. However, considering just the porosity we can verify that samples with very high porosity tend to present much more pressure sensitivity – around twice - than very low porosity samples.

Besides improving velocity – pressure relationship prediction, we capture uncertainties and incorporate them to create possible scenarios. This was done computing a pair of coefficients for each one of the 277 samples and getting P10 and P90 percentage of a coefficient distribution. We conclude that the coefficients a and b from fitted logarithmic curves computed for each rock sample have a good linear correlation. Coefficient a is an indicative of rock stiffness and preserves an inverse correlation with coefficient b which controls the curvature of logarithmic function. In addition, the relation between these coefficients tends to differ as a function of porosity. Most of the linear fits made for each porosity class are apparently parallels. These fits can be used to define uncertainty ranges associated to the previously computed pressure laws.

We observe that large uncertainties are associated to low effective pressure and, manly, low porosities, given that effective pressures below 1500psi are not expected. This implies that the proposed method predicts P and S velocities with much more accuracy for high porosities.

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