Brittleness, porosity, and total organic carbon estimation from elastic attributes in Eagle Ford shale through the application of the multi-attribute rotation scheme

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Summary

This paper presents a workflow to estimate brittleness, porosity, and total organic carbon from elastic attributes. The estimation is carried out through the application of the multi-attribute rotation scheme. This method is a hybrid rock-physics/statistical approach that uses a global search algorithm to estimate a customized transform for each geologic setting in order to predict petrophysical properties from elastic attributes. After the application of this technique, customized transforms were derived for the analyzed geological setting, to estimate porosity, brittleness, total organic carbon and litho facies logs from elastic attributes. The final goal of this workflow is to apply these transforms over seismically-derived attributes to generate volumes of these petrophysical properties that can be used for reservoir characterization and production optimization.

Introduction

Three of the most important reservoir properties to characterize in unconventional reservoirs are the brittleness, porosity, and total organic carbon volume (TOC) of the rock. This information together with the fracture, thickness, and stress information constitute the basic information to find and characterize the so called “sweet spots”, which are the best volume of rock in terms of favorable petrophysical properties to maximize the hydrocarbon production of the wells drilled in the area. These rock properties can be estimated at well location using a set of petrophysical logs, (such as gamma ray, resistivity, density, etc) calibrated with core information, however the extrapolation of these properties away from well location is a common and difficult challenge that affront geoscientists and reservoir engineers in order to spatially characterize unconventional reservoirs. Surface seismic measurements play a fundamental role in this task. From a 3D pre-stack seismic inversion, it is possible to estimate volumes of P-wave impedances (Ip) and S-wave impedances (Is), which are linked to these key petrophysical properties, and will constitute the means to extrapolate the well information into a tridimensional context by transforming these volumes of elastic attributes into volumes of these key petrophysical properties. This paper presents a methodology to transform Ip and Is attributes, and their derivative attributes, into petrophysical properties through the application of the multi-attribute rotation scheme (MARS) (Alvarez et al., 2015). The final goal of this workflow is to apply the resultant transform over seismically derived elastic attributes to predict the spatial distribution of petrophysical reservoir properties and locate the sweet spots for optimal hydrocarbon production.

MARS: Theory & Method

MARS uses a numerical solution, based on a global search algorithm, to estimate a transform to predict petrophysical properties from elastic attributes. The transform is computed from well-log-derived elastic attributes and petrophysical properties, and is posteriorly applied to seismically derived elastic attributes to predict the spatial distribution of petrophysical reservoir properties. MARS estimates a new attribute τ in the direction of maximum change of a target property in an n-dimensional Euclidean space formed by an n number of attributes. The method sequentially searches for the maximum correlation between the target property and all the possible attributes that can be estimated via an axis rotation of the basis that forms the aforementioned space. Figure 1 shows a sketch illustrating the methodology.

![Figure 1. Sketch of a cross-plot of two attributes colour coded by a target property. Dashed grey lines represent new attributes estimated via axis rotation, and the blue line represents the attribute that shows the maximum correlation coefficient with the target property.](image-url)

Multiple elastic attributes such as Ip, Is, P-to-S velocity ratio (Vp/Vs), the product of density and Lamé’s parameters (λρ and μρ) (Goodway et al., 1997), Poisson’s ratio (PR), the product of density by bulk modulus (Kp), the product of density and dynamic Young’s modulus (Ep), Poisson dampening factor (PDF) (Mazumdar, 2007), etc. can be used in the MARS assessment. Because different attribute combinations produce different results, this methodology uses an exhaustive evaluation of all possible n-dimensional spaces (formed by n attributes) and angles to find an attribute that represents the global maximum correlation with the target petrophysical property.
Brittleness, porosity, and TOC estimation from petrophysical analysis

Log and core data are used to calibrate the petrophysical model in the wellbore. A statistical approach was implemented to calculate each mineral fraction for the facies observed in the well. This rock matrix solver assumes an independent TOC calculation input. Core derived and Passey’s methodology TOC estimations indicated good correlation to each other. In this study, TOC content is derived from P-wave velocity and deep resistivity Passey’s relationship. The average organic content in the Lower Eagle Ford section is about 6% v/v, with total porosities ranging between 8-12%. Once the rock and fluid models are defined, the following steps are included in preparation for the multi-attribute analysis:

Step 1: Geophysical Well-Log Analysis (GWLA) and Rock Physics Diagnostics (RPD) – This is required to build a good and consistent well-log data set for the rock physics modeling. This step also includes the lithology based brittleness index calculation (BI), and brittle constituents (A) are assumed to be only quartz and calcite. Equation 1 indicates the mineral derived expression used for this, while Figure 2 shows the final in situ logs (red curves) and litho-fluid facies estimated within the zone of interest.

\[ BI = A / (V_{Calcite} + V_{Quartz} + V_{Clay}) \]  

Step 2: Once the petrophysical model is known, the reservoir is analysed in multiple attribute crossplot domains to understand the overall trend in porosity, BI and mineral composition changes from the lower sediments of the Austin Chalk to the Buda limestone. Litho-facies are selected using petrophysical properties cutoffs (see Table 2). In general, the litho-facies are very distinctive in this wellbore. The immediately overlaying chalk is clearly distinguishable from the Eagle Ford pay. High BI and low impedances (Ip, Is) are generally associated with highly gas saturated sediments within the Lower Eagle ford.

Brittleness, porosity, and TOC estimation from elastic attributes using MARS

Figure 2 shows the well-log data used as an input for the MARS application. These data consist of fundamental elastic attributes (Ip and Is) and target petrophysical properties, such as brittleness, porosity, and TOC logs. Since the final goal of MARS is to predict petrophysical properties using seismically derived elastic attributes, the first step applied consists of filtering the input logs to seismic resolution (black logs in Figure 2). In this way, all the transforms that are estimated from the MARS analysis can be directly applied to seismically derived elastic attributes. The MARS algorithm was run three times, using for each case the target properties brittleness, porosity, and TOC. For each run, MARS evaluated all 2D combinations of the 64 elastic attributes shown in Table 1, resulting in the assessment of 2016 independent bi-dimensional attribute domains. The purpose of applying a mathematical operation (such as square root, power, inverse, logarithm, etc.) to attributes is to be able to model physical phenomena that exhibit nonlinear behavior. This is a mathematical strategy used to linearize potential nonlinear relationships between the elastic attributes and the petrophysical properties, with the goal of improving the correlation between the attribute and the target petrophysical property.

Figure 2. From left to right: Lithologic track, Ip, Is, volume of clay, volume of calcite, total porosity, Sw, volume of TOC, and brittleness. Red curves show the original logs, while black curves show versions upscaled to seismic resolution.
Table 1. Evaluated Attributes. Each number represents a single attribute, which is obtained after applying the mathematical operation shown in the leftmost column to the attribute shown in the uppermost row, e.g., the number 21 represents the attribute $1/\lambda_p$

For the brittleness estimation, Figure 3a shows a matrix of the absolute value of the correlation coefficient between the brittleness log and the attribute $\tau$, for each evaluated crossplot space. In this figure, the row and column indexes represent the attributes specified in Table 1. Note that this is a symmetric matrix, and the color map has been set to highlight the highest correlation coefficient values; i.e., all the values in the matrix less than 0.969 are shown in blue. As a result of this analysis, it was found that in the $(\lambda/\mu)^2$ versus $\lambda_p$ attribute space (identified with the index 33 and 18, respectively), and at an angle of $\theta_i$ equal to $-39^\circ$, the attribute $\tau$ has the global maximum correlation to brittleness curve (see Figure 3c). This indicates that a linear projection in this attribute space at that specific angle yields the optimal seismic inversion attribute with the highest sensitivity to the brittleness variations. Once the optimal parameters to estimate brittleness from elastic attributes have been found these were then applied to the elastic log data to test the validity of the transform.

Figure 3. a) Matrix showing the absolute value of the correlation coefficient between the brittleness log and the attribute $\tau$, for each evaluated cross-plot spaces. Note that color map has been set to highlight the highest correlation coefficient values. b) Attribute space where the highest correlations with the brittleness log were found. c) Crossplot between $\theta$ versus the correlation coefficients between the brittleness log and the set of attributes estimated via axis rotation for the optimal attributes space.

Figure 4. Comparison between the actual and predicted porosity, brittleness, and TOC logs, at seismic resolution, in the optimal crossplot space obtained from the MARS analysis. Gray arrows, orthogonal to the blue lines, indicate the maximum direction of change of target petrophysical property in its corresponding optimal attribute space estimated from the MARS assessment.
Figures 4 and 5 show a comparison of the actual and predicted brittleness, porosity, and TOC logs in their respective optimal attribute space determined from the MARS assessment, and in the spatial domain respectively. Note that a very good correlation between the actual and predicted reservoir property was found in all the cases demonstrating the feasibility of spatially characterizing these key petrophysical properties in an unconventional reservoir from seismically-derived volumes of Ip and Is.

**Litho-facies estimation from elastic attributes**

Finally, the porosity, brittleness, and TOC logs were combined into a single discrete litho-facies log that aimed to characterize the reservoir in terms of the best petrophysical properties for reservoir production and stimulation. Table 2 shows the criteria used for the computation of litho-facies log. As a final test, the litho-facies log was estimated from the actual and MARS-predicted porosity, brittleness, and TOC logs. The results are shown in Figure 5, where it can be seen that a good correlation between litho-facies log was reached, which implies that is possible to estimate a 3D litho-facies volume to locate and characterize the “sweet spots” in the target formations.

<table>
<thead>
<tr>
<th>Litho facies</th>
<th>Britteness</th>
<th>Vtoc</th>
<th>Phit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittle &amp; Rich</td>
<td>≥0.45</td>
<td>≥0.07</td>
<td>≥0.06</td>
</tr>
<tr>
<td>Brittle &amp; Poor</td>
<td>≥0.45</td>
<td>&lt;0.07</td>
<td>&lt;0.06</td>
</tr>
<tr>
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<td>≥0.06</td>
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<tr>
<td>Ductile &amp; Poor</td>
<td>&lt;0.45</td>
<td>&lt;0.07</td>
<td>&lt;0.06</td>
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Table 2. Criteria used to compute a litho-facies log from the porosity, brittleness, and TOC logs

**Conclusions**

For the case studies shown, customized transforms were derived for the analyzed geological setting, to estimate porosity, brittleness, TOC and litho facies logs from elastic attributes. The final goal of this workflow is to apply these transforms over seismically-derived attributes to generate volumes of petrophysical properties, which can be used in exploration and production settings for reservoir characterization and production optimization, and as secondary variables in geostatistical workflows for static model generation and reserve estimation.

![Figure 5. Comparison of the upscaled actual and predicted porosity, brittleness, TOC and litho facies logs. Notice the good match between the elastic and petrophysical derived logs, what imply that is possible to estimate a litho facies volume after apply the well-log derived transform to 3D seismically derived elastic attributes.](image-url)
EDITED REFERENCES
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REFERENCES
