

# Elastic Impedance analysis in Fruitland coals, San Juan Basin

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## Summary

We evaluate the use of Elastic Impedance Coefficient (EC) to discriminate methane from CO<sub>2</sub> in coalbeds, and apply this methodology to a dataset of the Fruitland Formation coals, in the North of the San Juan Basin, U.S. We complete a fluid simulation having as a target a 15.25 m (50 ft) coalbed at a depth of 914.4 m (3000 ft) over an area of 31.4 km<sup>2</sup>. We perform the production forecast for primary production and enhanced coalbed methane by CO<sub>2</sub> injection for 24 wells, from 1999 until 2031. Using these results, we perform a Gassmann fluid substitution and estimate the variation in V<sub>p</sub>, V<sub>s</sub> and density due to the changes of fluid saturations in the pore space. Three cases are evaluated in this paper: primary production, after two years of CO<sub>2</sub> injection, and one year after shutting the injector wells. As a result, we observe that the most representative changes are associated with V<sub>p</sub> which presents a decrease of 55-65 m/s after shutting the injector wells. Finally, we estimate the EC values associated to the coalbed. We observe that it tends to increase around CO<sub>2</sub> injection areas and that it is not possible to discriminate CO<sub>2</sub> from methane. The magnitudes of the changes of EC are small and it is difficult to predict whether the changes will be appreciated in seismic data.

## Introduction

The coalbed methane industry has been growing and important advances in exploration, production and the development of technology have been achieved (Jenkins et al., 2008). Thanks to these advances, coalbed methane has become an important source of natural gas, and studies that aim to determine the physical properties of coals and monitor coalbed methane primary and enhance production are increasingly important.

In this project we attempt to discriminate coals saturated with methane from coals saturated with CO<sub>2</sub> by estimating the Elastic Impedance Coefficient. We also evaluate the possibility of monitoring the movement of the CO<sub>2</sub> flood by using this attributes.

This paper begins with a brief introduction to the concept Elastic Impedance Coefficient and its use for lithology and fluid discrimination. Then, we describe the methodology applied during the development of this project, including the fluid simulation, estimation of the fluid properties, and the Gassmann fluid substitution (Gassmann, 1951). Finally we present the results of the Gassmann fluid substitution (Gassmann, 1951) and the estimation of the Elastic Impedance Coefficient for three production stages: primary production, after two years of enhanced production by CO<sub>2</sub> injection, and one year after stopping injection.

## Theoretical development

The Elastic Impedance derivation is based on the Aki and Richards (1980) linearization for the Zoeppritz equation (Whitcombe, 2002).

EI is a function that relates the compressional wave velocity ( $V_p$ ), the shear wave velocity ( $V_s$ ), and the density, as shown in equation 1:

$$EI = V_p^{(1+\tan^2\theta)} V_s^{(-8K\sin^2\theta)} \rho^{(1-4K\sin^2\theta)} \quad (1)$$

where  $\theta$  is the incidence angle (Connolly, 1999), and  $K$  is defined as a constant over the section of interest and is estimated as the mean value of  $(V_s/V_p)^2$ .

Cao et al. (2008) introduce the concept of the Elastic Impedance Coefficient (EC) as relationship proportional to the AI and inversely proportional to EI as shown in equation 2. The EC establishes a combination of the AI and the EI to create a stronger attribute for lithology, and fluid discrimination; and gas saturation estimation. Cao et al. (2008), provides some examples in which the EC produce better results for lithology discrimination and the detection of the presence of gas than the AI and the EI by themselves (Cao et al., 2008).

$$EC = \frac{AI}{EI} \quad (2)$$

## Methodology

For the development of this study we use well log and production data that from the coalbeds of the Fruitland Formation, in particular the Coal Fairway from the North part of the San Juan Basin. The Coal Fairway is an over-pressured area that presents thicker coalbeds in the Fruitland Formation (Jenkins et al., 2008), with higher coal rank, lower ash content, better developed cleat systems (Magill et al., 2010) and higher permeability in the range of 20-100 mD (Jenkins et al., 2008).

Geological data and production data from the Fruitland coals are used here to develop a proxy model of the Fruitland Coal Fairway in the San Juan Basin. Initially, we build a vertical single well model, include dynamic flow data, and use well log data from this well to perform the history match. This single well model allows us to evaluate and verify the relative permeability and relative adsorption data.

We build the field model based on the single well model previously mentioned. The reservoir model has a grid dimension of 175x175x1, with producing wells on 320-acre spacing. For this project, we model a single coalbed layer with a thickness of 15.24 m (50 ft), at a depth of 914.4 m (3000 ft), and over an extension of 31.4 km<sup>2</sup>.

Using the reservoir model, we perform the production forecast of primary depletion for 24 wells in the area of study, which started in 1999 and extends until 2031. This model is also used to forecast enhanced coalbed methane production by CO<sub>2</sub> injection. In this case, we include 4 CO<sub>2</sub> injection wells to the model. We assume that the injection starts in July 2003, shut in October 2010, and the forecast continuous until 2031.

The  $V_p$ ,  $V_s$  and density values to perform the fluid substitution come from well log data available for different fields in the San Juan Basin. We estimate the fluid properties with the equations presented by Batzel and Wang (1992) and perform a Gassmann fluid substitution (Gassmann, 1951). The applicability of the Gassmann equation (Gassmann, 1951) is based on assumptions about the structure and pore space of the rock. We use the Gassmann equation (Gassmann, 1951) in coals based on the fact that the matrix porosity present low permeability and that the macroporosity system (cleats) is the one that controls the fluid flow. For this study, we assume that the fluid substitution is performed taking into account only effective porosity.

Finally, using equation 2, we calculate the EC for the three production stages that we were studying: primary production corresponding to model of 2002; enhanced coalbed methane production in 2005 and one year after shutting the injector wells in 2011.

## Results

The fluid simulation provides us with prediction data for methane, CO<sub>2</sub> and water saturation, pressure, and CO<sub>2</sub> and methane concentration from 2002 until 2031. In this paper we present three models: primary production (2002 model), 2 years after CO<sub>2</sub> injection (2005 model), and 1 year after shutting the injection wells (2011 model). For the primary production case, 2002 model, there is a high saturation of methane over the complete area of study, more specifically around 80% of methane saturation. For the 2005 model, after 2 years of injection of CO<sub>2</sub> into the coalbed, there is a decrease in the methane saturation around the injector wells. In the zones surrounding the injectors well it is possible to identify the footprint of the CO<sub>2</sub> injection with a radial distribution. In these zones, there is a reduction of the methane saturation from 80% to less than 15%. One year after finishing the CO<sub>2</sub> injection (2011 model), the area affected by the CO<sub>2</sub> injection has expanded through the years and in these zones the methane saturation is close to 10%. The distributions of the CO<sub>2</sub> flood around the injector wells do not present a radial distribution anymore and they move to the South where lower pressures are dominant.

Figure 1 presents the changes in Vp, for the three models, which are the results of the Gassmann fluid substitution. Figure 1a presents a decrease in Vp, from the initial value of 2450 m/s to a range of 2390-2395 m/s when replacing brine by methane in the pore space. In the velocity map presented in Figure 1a, Vp tends to slowly increase from SW to NE. In figure 1b, after CO<sub>2</sub> injection, we observed that in the area around the injector wells there is an area of lower velocity associated with the increase of CO<sub>2</sub> saturation in that zone of coalbed. After shutting injector wells, the CO<sub>2</sub> flood seems to be moving to the South, where the area presents the lower pressures, and this is also evident in the velocity map in Figure 1c. In this case, we observed a decrease in Vp over the complete area of study that can be associated to depletion. The lowest velocities are in the South of the area of study and this can be related to a decrease in the methane saturation and lower pressures in this zone (Figure 1c).

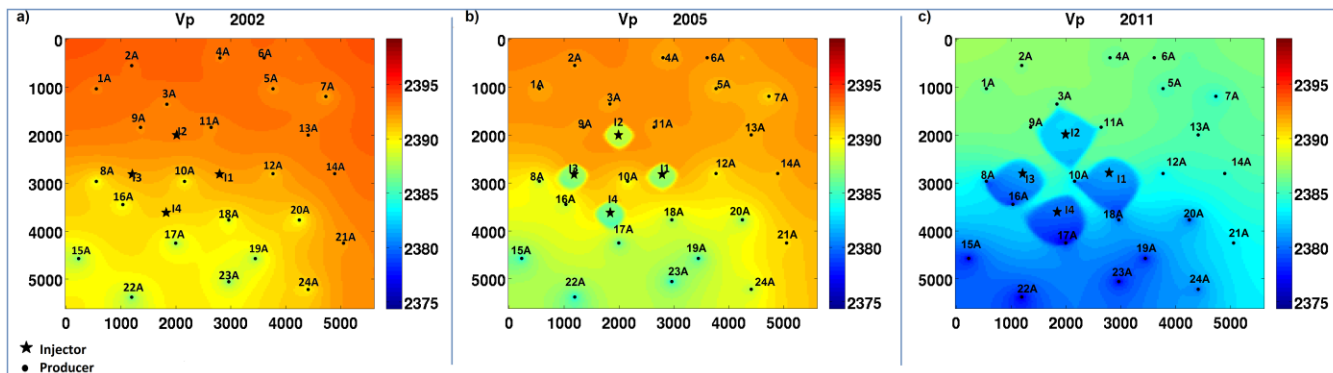


Figure 1: Compressional wave velocity Vp. a) Primary production (2002); b) Enhanced coalbed methane by CO<sub>2</sub> injection (2005), after two years of CO<sub>2</sub> injection; and c) one year after shutting the injector wells (2011).

We use EC to attempt to discriminate methane from CO<sub>2</sub> in a coalbed. Figure 2 presents EC for the area of study along the three productions stages. Figure 2a show an increase of the EC from South to North and along the area of study we can appreciate peaks of high EC. These peaks of high EC are associated to the location of the 24 wells in the area of study and it can be consequence of the decrease of the compressional wave velocity in that area and reduction of pressure due to depletion. The wells located in the northern area, where the highest pressures are present, produce a stronger response.

Figure 2b shows EC response two years after starting CO<sub>2</sub> injection. In Figure 2b we can still observe the higher EC response in the vicinity of the well locations and that the EC tends to increase from South to North. In this case, it is also possible to observe the path of the flood of CO<sub>2</sub> that has been injected. In the area inside the red circle, there are four zones of high EC that corresponds to the vicinities of the injector wells and the areas of higher CO<sub>2</sub> saturation in that period of time (2005). The changes in EC that we observe in the area of study allow us to monitor the movement of the CO<sub>2</sub> that has been injected, through the coalbed. However this attribute did not provide a good discrimination between the

coalbed saturated with CO<sub>2</sub> and the coalbed saturated with methane. In Figure 2b, we can observe that the EC values associated with the coalbed saturated with mostly CO<sub>2</sub> are also associated to some zones mostly saturated with methane.

Figure 2c show the EC response one year after stopping CO<sub>2</sub> injection. In Figure 2c, we observe that the most representative anomalies are associated with the zones with higher CO<sub>2</sub> saturation. In this case we appreciate the displacement of the CO<sub>2</sub> flood after injection showing as a high EC response in Figure 2c (red circle).

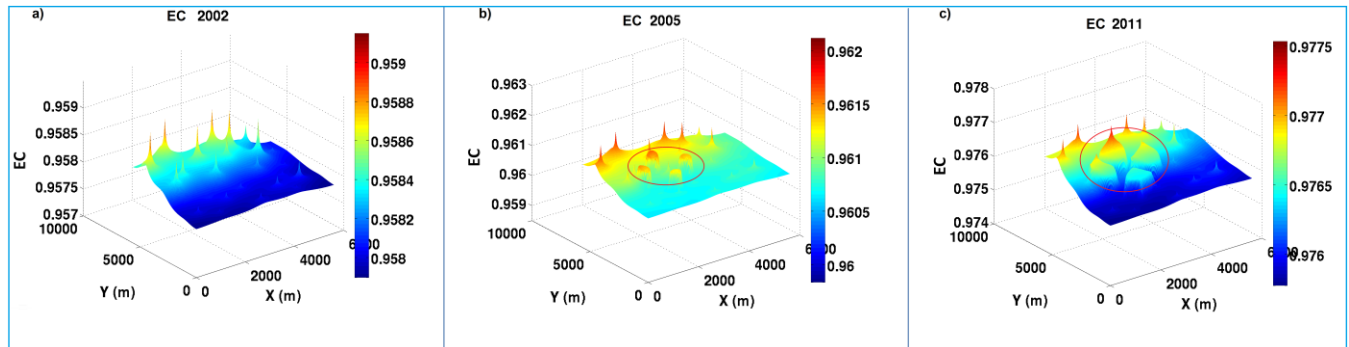


Figure 2: Elastic Impedance Coefficient (EC). a) Primary production (2002); b) Enhanced coalbed methane by CO<sub>2</sub> injection (2005), after two years of CO<sub>2</sub> injection; and c) one year after shutting the injector wells (2011).

## Conclusions

The fluid simulation gives us important information about the distribution of CO<sub>2</sub>, methane and brine in the area of study as well as of the saturation of each of them. The fluid simulation provides the data required to perform the fluid substitution and estimate changes in V<sub>p</sub>, V<sub>s</sub> and density, associated with coalbed methane primary production and enhanced coalbed methane by CO<sub>2</sub> injection.

The changes in V<sub>p</sub> obtained from the Gassmann fluid substitution, after replacing brine by methane, is a decrease of ~55 m/s by 2005 (primary production), and ~65 m/s by 2011, following CO<sub>2</sub> injection. The movement of the CO<sub>2</sub> flood is observed in the velocity maps and is associated with a decrease in V<sub>p</sub>.

Elastic Impedance Coefficient (EC) is used as a tool to attempt the discrimination of CO<sub>2</sub> and methane saturated coalbeds as well as for monitoring the CO<sub>2</sub> injected flood. In this case EC is not able to completely differentiate the presence of CO<sub>2</sub> from methane, but it was possible to monitor the movement of the CO<sub>2</sub> flood during and after injection. The changes in EC are small and it is difficult to determine if these changes are going to be evident in seismic.

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## References

- Batzle, M., and Wang, Z., 1992, Seismic properties of pore fluids: *Geophysics* **57**, 1396-1408.
- Cao, H., Yang, Z., and Li, Y., 2008, Elastic Impedance Coefficient (EC) for Lithology Discrimination and Gas Detection. SEG Las Vegas Annual Meeting, SGA001526.
- Connolly, P., 1999, Elastic Impedance: The Leading Edge **18**, 438-452.
- Gassmann, F., 1951, Über die elastizität poröser medien: *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zurich* **96**, 1-23. Paper translation at <http://sepwww.stanford.edu/sep/berryman/PS/gassmann.pdf>.
- Jenkins, C., DeGolyer, MacNaughton, and Boyer, C., 2008, Coalbed and Shale Gas Reservoirs: *Journal of Petroleum Technology* **60**, 92-99.
- Magill, D., Ramurthy, M., Jordan, J., and Nguyen, P., 2010, Controlling Coal-Fines Production in Massively Cavitated Openhole Coalbed-Methane Wells: SPE Asia Pacific Oil and Gas Conference and Exhibition, SPE 134031-MS.
- Whitcombe, D., 2002, Elastic Impedance normalization: *Geophysics* **67**, 60-62.