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# Workflows for Sweet Spots Identification in Shale Plays Using Seismic Inversion and Well Logs

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## Summary

Worldwide interest in shale plays has rapidly increased in recently years, thanks to the combination of horizontal drilling and hydraulic fracturing. Shale formations act as both the source and the reservoir for the natural gas and usually exhibit anisotropic properties at larger scale. Geological and petropysical studies found that the right combination of thickness, TOC (total organic carbon), maturity, porosity, high gas-in-place and fracability are important for shale plays sweet spots identification. Usually integration of the petrophysical well logs and geological core analysis can easily help to calculate these important elements around the borehole. For example, the Passey equation (Passey, 1990) can be used to estimate TOC, and dipole sonic data can be utilized to optimize the hydraulic fracturing and to measure the formation anisotropic parameters (Horne et al., 2012). Anisotropy plays a key role in the shale gas sweet spots evaluation. Seismic data, especially the wide-azimuth seismic angle gathers, offer valuable information for this shale sweet spots identification. However, special technologies and workflows are required to infer the meaningful properties, such as TOC, anisotropic epsilon and delta parameters, and in-situ stress, from the seismic data and then calibrated with both borehole data and geological understandings. Four major categories will be studied in the paper: 1) petrophysical model for shale gas evaluation; 2) seismic anisotropic inversion to simultaneously estimate the anisotropic epsilon, delta and gamma $(\varepsilon, \delta, \gamma)$ in addition to compressional velocity (Vp), shear velocity (Vs) and density; 3) seismic TOC inversion; 4) geomechanical properties calculation and interpretation.

## Introduction

Shale is regarded as a potential source rock for conventional reservoir and also a potential unconventional reservoir for hydrocarbon. In shale reservoir, shale has low matrix permeability and needs hydraulic fracturing to provide the permeability. Porosity is important for conventional reservoirs, but in unconventional shale plays, shale porosity is not well understood and usually there is no correlation between shale porosity and TOC. Shale gas is comprised of two quite different types of gas: adsorbed gas, the gas adsorbed onto the organic matter and concentrated in the TOC fraction of shale; and free gas, located in the very low porosity within the shale matrix, similar to conventional reservoirs. Using petrophyiscal well logs and geological core analysis, the shale gas properties, such as thickness, TOC, maturity, porosity, gas-in-place and fracability can be evaluated. The right combinations of all these properties are important for shale gas sweet spots evaluation. After properly calibrating with the petrophyiscal results, the seismic data, especially the full-azimuth seismic data, is capable to offer value information to propagate these meaningful shale gas properties from borehole location onto seismic space.

Anisotropy plays a key role in the shale gas evaluation. Failure to account for its presence can lead to errors in the seismic compressional velocity (Vp), shear velocity (Vs) and density inversion, AVO analysis and hydraulic fracture monitoring and optimization. A type of anisotropy often observed in shale is vertical transverse isotropy (VTI) because the layered shale is typically horizontal with vertical symmetry. Another type of anisotropy in shale is horizontal transverse isotropy (HTI) because the shale is preferentially stressed or fractured. The two types of anisotropy can be quantified by estimating the three Thomsen parameters epsilon, delta, and gamma $(\varepsilon, \delta, \gamma)$ (Thomsen, 1986).

Methods for simultaneously estimating Vp, Vs, density and anisotropic epsilon, delta and gamma $(\varepsilon, \delta, \gamma)$ have been presented in this paper. For HTI medium, proper analysis of the azimuthal behavior of the seismic data can determine the fracture strike direction and intensity or maximum horizontal stress direction.

The minimum horizontal stress (closure stress) is one of the key factors for hydraulic facture design, which is the function of compressional velocity and shear velocity of the rock. But in the anisotropic media, the shear velocity will split into fast and slow shear velocity. The closure stress should be properly analyzed based on the fast and slow velocity and maximum horizontal stress direction.

In the paper, I presented special methodologies and workflows to infer the meaningful properties, such as TOC, anisotropic epsilon and delta parameters, and in-situ stress, from the seismic data and then calibrated with both borehole data and geological understandings. The right combination of these meaningful properties enables us to estimate and map the distribution of shale gas sweet spots. When properly analyzed and integrated with borehole and geological data, the seismic data is capable to identify the shale gas sweet spots.

## Petrophysical model for shale gas evaluation

In shale reservoir, shale is regarded as a potential unconventional reservoir for hydrocarbon. The well logging response of the kerogen of shale gas is: high to very high gamma ray; high resistivity; high nuclear porosity, low density, high acoustic transit time and low photoelectric factor (Pef). Shale gas is comprised of two quite different types of gas: 1) adsorbed gas, the gas adsorbed onto the organic matter and concentrated in the TOC fraction of shale; 2) free gas located in the very low porosity within the shale matrix, similar to conventional reservoirs. Figure 1 is our petrophysical model for shale gas evaluation. Based on this model, the well log response equation, for example the density log equation, can be described as:

$$Den_{log} = \sum (1 - \emptyset - V_{cl} - V_{toc}) V_{matrix} + \sum V_{cl} Den_{cl} + V_{toc} Den_{toc} + \emptyset\left(S_w Den_{water} + (1 - S_w) Den_{gas}\right) \quad (1)$$

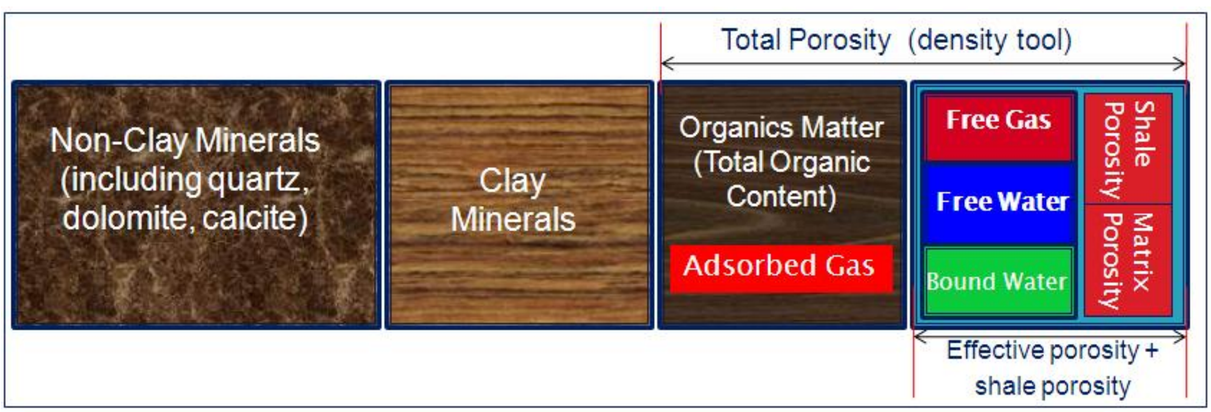


Figure 1: Petrophysical model for shale gas evaluation

The total organic carbon (TOC) is crucial for the shale gas evaluation. Usually the TOC roughly correlates with high gamma ray, low bulk density and high acoustic transit time. Although it is problematic to separate TOC from the total porosity, Passey and its modified procedure (Passey, 1990) can be used to estimate the TOC. The DlogR method based on the cross-plot of true resistivity and acoustic transit time can identify the shale gas formation and then is able to convert the pseudo-sonic separations into TOC through the level of organic maturity parameter (LOM). Usually LOM needs laboratory experiment to measure. The free gas and water are very similar to the ones in the conventional reservoirs, and the conventional petrophysical model can be utilized to calculate these reservoir parameters in shale plays.

## Seismic anisotropic inversion

Anisotropy plays a key role in the shale gas evaluation. Failure to account for its presence can lead to errors in the seismic Vp, Vs and density inversion. A type of anisotropy often observed in shale is vertical transverse isotropy (VTI) because the layered shale is typically horizontal. Another type of anisotropy in shale is horizontal transverse isotropy (HTI) because the shale is preferentially stressed or fractured. When the seismic anisotropic inversion was applied, the first step is to determine the anisotropic type based on the petrophysical and geological data. If the HTI medium was applied, the strike direction or maximum horizontal stress direction should be determined using the AVAZ or VVAZ methods.

The original anisotropic reflection described horizontal transverse isotropy (HTI) is given by Ruger (Ruger, 1997). The Ruger equation can be modified based on isotropic Fatti approximations. The first three parts ($C_1, C_2, C_3$) of the equation (2) are isotropic contributions (Hampson and Russell, 2005) and other three parts ($C_4, C_5, C_6$) are the contributions of the three Thomsen anisotropic parameters respectively. The epsilon, delta, and gamma ($\varepsilon, \delta, \gamma$) are Thomsen anisotropic parameters (Thomsen, 1986).

$$R^{HTI}(\theta,\varphi) = (C_1 R_P + C_2 R_S + C_3 R_D) + C_4\Delta\delta + C_5\Delta\varepsilon + C_6\Delta\gamma \qquad (2)$$

Where: $C_4 = 0.5(cos^2(\varphi-\varphi_0)sin^2(\theta) + cos^2(\varphi-\varphi_0)sin^2(\varphi-\varphi_0)tan^2(\theta)sin^2(\theta))$

$$C_5 = 0.5cos^4(\varphi-\varphi_0)sin^2(\theta)tan^2(\theta)$$

$$C_6 = \frac{4V_s^2}{V_p^2}cos^2(\varphi-\varphi_0)sin^2(\theta)$$

$\theta$ is the incident angle, $\varphi_0$ is the strike direction of fracture, $\varphi$ is the acquisition azimuth of seismic angle gathers.

Like the isotropic analysis (Hampson and Russell, 2005), the HTI anisotropic reflection equation should be convoluted with angle-dependent wavelets and was re-written as:

$$S^{HTI}(\theta,\varphi) = W(\theta)\otimes(C_1R_p + C_2R_s + C_3R_D + C_4\Delta\delta + C_5\Delta\varepsilon + C_6\Delta\gamma)$$

$$= (\widetilde{C_1}(\theta)L_P + \widetilde{C_2}(\theta)\Delta L_S + \widetilde{C_3}(\theta)\Delta L_D) + \widetilde{C_4}(\theta)\Delta\delta + \widetilde{C_5}(\theta)\Delta\varepsilon + \widetilde{C_6}(\theta)\Delta\gamma \qquad (3)$$

Where $L_P$, $L_S$and $L_D$ are the logarithm of the P-impedance, S-impedance and density respectively. The $\Delta L_s$ and $\Delta L_D$ are the abnormal values of the $L_s$ and $L_D$ against their background trends. The background trends can be analyzed through the cross-plot technique of the known boreholes. The three anisotropic variables ($\Delta\gamma, \Delta\varepsilon, \Delta\delta$) are the differences of the Thomsen anisotropic parameters in the two layers. $\widetilde{C_1}, \widetilde{C_2}, \widetilde{C_3}, \widetilde{C_4}, \widetilde{C_5}, \widetilde{C_6}$ are the angle coefficients consisting of wavelets.

For VTI medium, similar anisotropic equations can be derived based on the isotropic and anisotropic contributions respectively.

The Conjugate Gradient method can be used to solve the equation (3) to simultaneously estimate the epsilon, delta, and gamma ($\Delta\gamma, \Delta\varepsilon, \Delta\delta$) in addition to the P-impedance, S-impedance and density ($L_p, \Delta L_s, \Delta L_D$), which can be converted into the Vp, Vs and density (Hampson and Russell, 2005).

## Seismic TOC inversion

We presented the Bayesian-based Support Vector Machine (SVM) method for the seismic petrophysical properties inversion (Liu and Sacchi, 2003, and Liu et al., 2012). The SVM method first described by Vapnik and collaborator in 1995, and now has been widely used in the Artificial Intelligent, especially machine learning community.

In fact, our Bayesian-based SVM method is an integrated approach to incorporate seismic data, geological understandings and well logs to quantitatively characterize seismic petrophysical properties, such as porosity, TOC, hydrocarbon pore volume and even rock mechanical properties, such as Young's Modulus and Poisson's Ratio. It has been proven that the SVM is one of best candidates to build the bridge between seismic data and well logs to construct the reservoir property model.

Given a set of seismic attribute vectors $\{x_{n,}, n = 1, \ldots, N\}$, such as Vp, Vs and density, along with the corresponding petrophysical TOC $\{t_n, n = 1, \ldots, N\}$. The SVM makes the training and prediction of the petrophysical TOC based on a function of the form (Liu et al., 2012):

$$t(x_j) = \sum_{n=1}^{N} \omega_n K(x_j, x_n) + \omega_0 \quad (4)$$

Where $\{\omega_n\, n = 1, \ldots N\}$ are the model weights which can be estimated after SVM training, and $\{K(x_j, x_n)\}$ denotes the kernel functions (Schölkopf, 1999).

## Geomechanical properties calculation and interpretation

The direct way of geomechanical analysis is using dipole sonic log, from which the P-wave velocity and S-wave velocity (fast and slow shear waves) can be extracted. According to the acoustic wave propagation theory, Young's Modulus, Poisson ratio, bulk modulus, shear modulus and lame parameter can be calculated from the Vp, Vs and density respectively, and then the in-situ stress (such as minimum horizontal stress and maximum horizontal stress) and rock strength (such as UCS) can be estimated (Liu et al., 2011).

In shale reservoirs, the anisotropy plays a key role. The VTI medium is often observed in shale because the layered shale is typically horizontal with vertical symmetry, but the cracks and fractures, or even with unequal horizontal stress, can also produce HTI anisotropy.

The minimum horizontal stress (closure stress) is one of the key factors for hydraulic facture design, which is the function of compressional velocity and shear velocity of the rock. But in the anisotropic media, the shear velocity will split into fast and slow shear velocity. The closure stress should be analyzed appropriately based on the fast and slow velocity.

If the crossed-dipole sonic data are available, the Thomsen anisotropic parameters epsilon, delta, and gamma $(\varepsilon, \delta, \gamma)$ can be estimated from the vertical and/or deviated borehole. The discrepancies between the fast and slow shear velocity in vertical and deviated sections can be accounted for the anisotropy presence.

During the seismic anisotropic inversion, the Vp, Vs and density and three anisotropic parameters $(\varepsilon, \delta, \gamma)$ can be simultaneously inferred from the full-azimuth seismic angle gathers. After integration and calibration with borehole information, the meaningful geomechanical properties can be interpreted like the petrophysical properties. Interpretation of these geomechanical properties enables us to better understand the shale formation, such as shale brittleness and shale anisotropy.

## Conclusions

Geological and petropysical studies demonstrated that the shale gas intervals thickness, TOC, porosity, gas-in-place and fracability can be evaluated from traditional well logs and the dipole sonic data. Anisotropy plays a key role in the shale reservoir evaluation. In this paper we presented the workflows to identify shale sweet spots using seismic inversion and well logs. Four major categories have been studied in the paper: 1) petrophysical model for shale gas evaluation; 2) seismic anisotropic inversion to simultaneously estimate the anisotropic epsilon, delta and gamma $(\varepsilon, \delta, \gamma)$ in addition to Vp, Vs and density; 3) seismic TOC inversion; 4) geomechanical properties calculation and interpretation. Seismic anisotropic inversion can be applied to HTI or VTI media to simultaneously estimate anisotropic parameters epsilon, delta, and gamma $(\varepsilon, \delta, \gamma)$ in addition to the Vp, Vs and density. Moreover, seismic TOC can be inferred through incorporating the well logging evaluation and seismic attributes using the Bayesian-based Support Vector Machine (SVM) inversion. Integration of seismic TOC and geomechanical properties and appropriate calibration with borehole information enable us to better understand the shale formation and then identify the potential shale reservoir sweet spots.

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