Brittleness evaluation of resource plays by integrating petrophysics and seismic analysis

Bo Zhang, Shiguang Guo, Fangyu Li, Pan Li and Kurt J. Marfurt, The University of Oklahoma*

Summary

The main considerations for well plan and hydraulic fracturing in the conventional plays include 1) the amount of total organic carbon (TOC) and 2) how much hydrocarbon can be extracted. Brittleness is the direct measurement of a formation about the ability to create avenues for hydrocarbons when suffering to hydraulic fracturing. Usually Brittleness is estimated from 1) laboratory stress-strain measurements 2) rock properties and 3) mineral contents analysis using well logs. However well log based brittleness only shows the properties near the borehole when the amount of wells or log type is limited, resulting a two dimensional result. In this paper, we proposed a workflow to estimate brittleness of shale plays in three dimension at seismic scale by integrating the rock properties from petrophysics and seismic analysis. The workflow begins by brittleness evaluation using well logs at the borehole location. Then we prestack invert the fidelity preserved seismic gather to generate rock property volumes. At last we integrate brittleness estimation from seismic and petrophysics analysis where the petrophysics result serves as the bench mark. We apply our workflow to a survey acquired over Fort Worth Basin, TX, USA where eight wells locate in this survey. The brittleness estimation from seismic analysis shows high correlation to that from petrophysics analysis at the seismic scale.

Introduction

Brittleness and ductileness are used to describe the deformation behaviors when rocks are suffering certain stress. A rock is considered to be ductile if it absorbs a high amount energy before fracturing. Brittle rocks are unable to accommodate significant strain before fracturing, resulting in open microfractures after hydraulic fracturing. In conventional reservoirs brittleness is mainly used to evaluate the drillability in drilling, sawability in rock cutting, and mechanical winning of coal rocks (Jin et al., 2014). Brittleness is one of the main rock parameters in shale reservoirs. It provides key information to evaluate the capability of formation to create an effective avenue network that conducts the hydrocarbons to each borehole. Thus differentiating brittle from ductile rocks has been the key to archive success in shale gas reservoirs.

The methods of evaluating brittleness of rocks are mainly divided into three categories 1) laboratory stress-strain testing, 2) mineral contents, and 3) elastic parameters based methods. The brittleness based laboratory stress-strain testing (Honda and Sanada, 1956; Hucka and Das, 1974; Altindag, 2010) is beyond the scope of this paper and we mainly concentrate on the last two methods. It is widely accepted that brittleness is mainly controlled by quartz content while ductility is related to clay minerals and TOC. Jarvie et al. (2007) proposed a brittleness equation based on the amount of quartz, calcite, and clay minerals where quartz is considered as the brittle mineral while calcite and clay minerals are regarded as ductile minerals. Wang and Gale (2009) improved Jarvie's et al. equation by considering dolomite as one of the brittle minerals and TOC as one of the ductile mineral. The main disadvantage is that determination of mineral content is too expensive and not always available for each well. Furthermore the brittle-ductile behavior of rock is related to but not decided by the content of brittle minerals. Diagenesis and the distribution of mineral may also influence the brittle-ductile behaviors. Rickman et al. (2008) proposed average brittleness equation based on the elastic parameters of Poisson's ratio and Young's modulus. Their equation is under the assumption that more brittle rocks show relative high Young's modulus and low Poisson's ratio while more ductile rocks exhibit low Young's modulus and high Poisson's ratio. Perez Altamar (2013) first compared the brittleness evaluation from mineral content and elastic parameters average and found that there existed conflicts between these two categories. Next he proposed a brittleness evaluation template based on the Lamda-rho ($\lambda\rho$) and Mu-rho ($\mu\rho$) analysis at the well location. At last he estimated the brittleness of shale reservoirs by applying his template to inverted $\lambda\rho$ and $\mu\rho$ from prestack seismic inversion. Jin et al. (2014) first overviewed the most currently used brittleness estimation. Next by considering feldspar, mica, and carbonate minerals (limestone, dolomite, and calcite) as the brittleness contributors, they show a very good correlation between elastic parameters and mineral content based brittleness evaluation. Brittleness estimation based on elastic parameters is more popular in the geomechanics field than that based on mineral content. This is due to the fact that 1) they are easily derived from wire logs and 2) elastic parameters directly describe rocks ability to fail under stress and maintain an open fracture once the rock fractures (Pickman et al., 2008).

The accuracy of elastic parameters derived from seismic inversion mainly depends on whether we can preserve the data fidelity at far offset in the prestack gathers. Stretch and "hockey stick" are two main factors that affect the data fidelity at far offset. We propose a workflow to mitigate these two phenomena at far offset in another submitted SEG expanded abstract. It begins by mitigating the "hockey stick" using automatic nonhyperbolic velocity and followed is a wavelet –based correction to minimize the stretch at far offset. We also compare the inverted elastic parameters of

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formations based on conventional and new processing prestack gathers in another submitted SEG abstract. In this paper we mainly concentrate on the brittleness estimation by integrating petrophysics and seismic analysis.

Preserve the data fidelity at far offset of seismic gathers

The information contained in far offset is critical to generate a stable inverted elastic volume. The most accurate result of simultaneous prestack inversion of P-wave seismic data is P-impedance. In theory, S-impedance estimation becomes reliable with incident angle approaching 30°, while density evaluation become reliable with incident angle approaching 45°. Usually we need to mute the far offset data due to stretch and "hockey stick". We proposed a workflow in Figure 1 in another submitted SEG abstract to mitigate both stretch and "hockey stick". It starts by performing reverse NMO correction on the time migrated gathers. Next we mitigate the "hockey stick" by using automatic nonhyperbolic velocity analysis. At last we minimize the stretch at far offset using a wavelet based strategies named MPNMO (Zhang et al., 2013). In this manner, both stacking power and vertical resolution are improved by aligning the data and avoiding stretch.

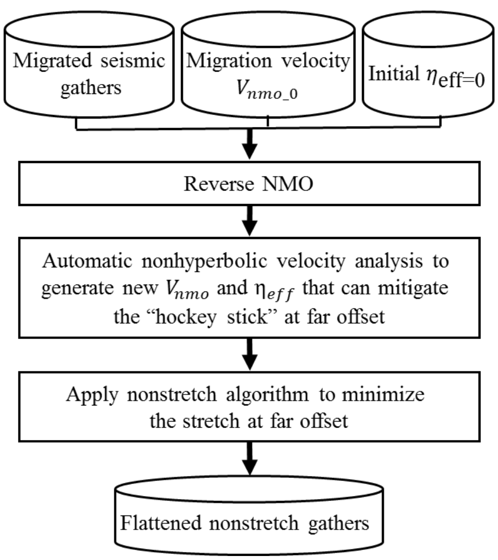

Figure 1: Flowchart showing steps to preserve the data fidelity at far offset. It contains two main steps 1) automatic nonhyperbolic velocity analysis and 2) applying anti-stretch processing on the time migrated gathers

Brittleness evaluation based on elastic parameters

Rickman et al. (2008) proposed a practical brittleness (*BI*) estimation using Young's Modulus and Poisson's Ratio.

$$BI = \frac{E_n + \sigma_n}{2} \tag{1a}$$

where E_n and σ_n are the normalized Young's Modulus and Poisson's Ratio

$$E_n = \frac{E_{max} - E}{E_{max} - E_{min}}, \tag{1b}$$

$$\sigma_n = \frac{\sigma - \sigma_{max}}{\sigma_{max} - \sigma_{min}}, \tag{1c}$$

where E, E_{max}, E_{min} are the instantaneous, maximum, and minimum Young's Modulus; σ, σ_{max}, σ_{min} are the instantaneous, maximum, and minimum Poisson's Ratio.

Application

The Barnett Shale of Fort Worth Basin (FWB), TX, USA is one of the largest unconventional reservoirs in the world. The FWB is a foreland basin and covers approximately 54000 mi^2 (14000 km^2) in north-central Texas (de Silva, 2013). A high quality long offset surface seismic survey has been acquired in 1990s over Wise County which is one of the "cores" of the main production area in the FWB. In our survey, the Barnett Shale formation lies between 1.2s and 1.4s which is the "core" area of the main production area in the FWB. The maximum offset is around 14000 ft while the target Barnett Shale lies at approximately 7000 ft depth.

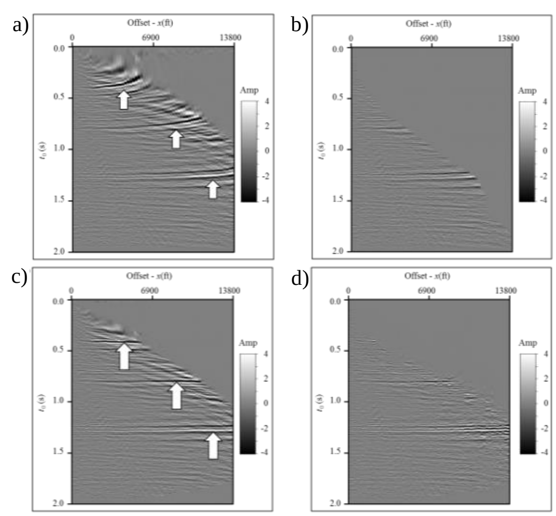

Figure 2: Representative gather showing the proposed processing workflow. Normally, we need to (b) mute the serious stretch appearing at far offset in (a) the time migrated gather. (c) The corrected gather using new RMS velocity and effective anisotropy analysis obtained from automated nonhyperbolic velocity analysis. (d) The anti-stretch processing result applied to (a) using the new RMS velocity and effective anisotropy.

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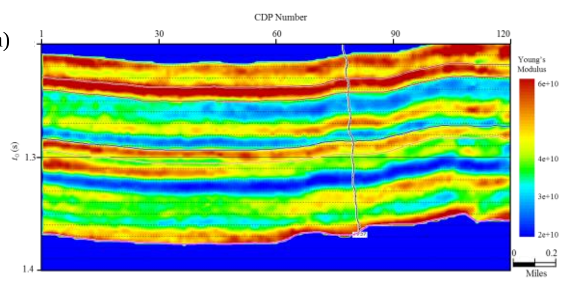
Preserving the fidelity of far offset data is one of the main targets in processing. Figure 2a shows a representative time-migrated CMP gather using two term hyperbolic travel time equation. Note the “hockey stick” and stretch indicated by the white arrows at far offsets. The “hockey stick” blurs the reflection events while the stretch lowers the resolution in the stacked volume. Usually, seriously stretched data are muted out (Figure 2b) based on a user-defined muting criterion. In this example we allow wavelets to stretch no more than 130%. However muting the far offset data neglects the critical information contained in the far offset. Figure 2d shows the flattened nonstretch gather. Note that MPNMO minimizes the stretch that occurs at the far offset when compared to the original time-migrated gathers.

We have eight wells located in our seismic survey. All the wells have P-wave sonic and density logs. S-wave sonic logs are available for three of them. By using a nonlinear regression, we derive S-wave sonic logs for other wells using P-wave sonic. First six interpreted horizons and eight wells are used to build the background P-impedance, S-impedance and density models. Next we apply simultaneous prestack inversion to the conditioned gathers (Figure 2d) to obtain elastic parameters at seismic scale. Figures 3a and 3b show the inverted Young’s Modulus and Poisson’s Ratio. Figure 4 shows the predicted brittleness using equation 1a. We use the elastic parameters derived from well logs as the bench mark to evaluate the results (Figure 5) inverted from seismic gather. The left, middle, and right tracks in Figure 5a show the comparison of P-, S-impedance, and density panels. The left, middle, and right tracks in Figure 5b show the comparison of Young’s Modulus, Poisson’s Ratio and predicted brittleness panels. The blue curves are the original logs. The black curves are low passed filtered results from original logs. The red curves are the results inverted from seismic gathers. Note that the inverted results from seismic lose the details when compared to that of well log, but they bear an excellent low frequency trend matching at the seismic scale.

a)



b)

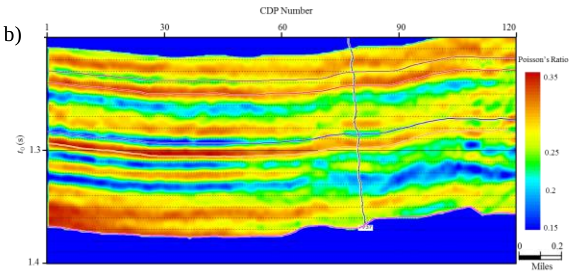


Figure 3: Inverted (a) Young’s Modulus and (b) Poisson’s Ratio from prestack seismic gathers.

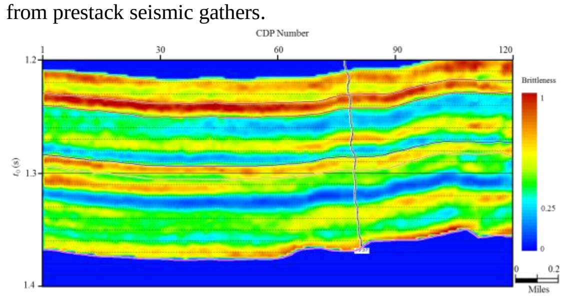
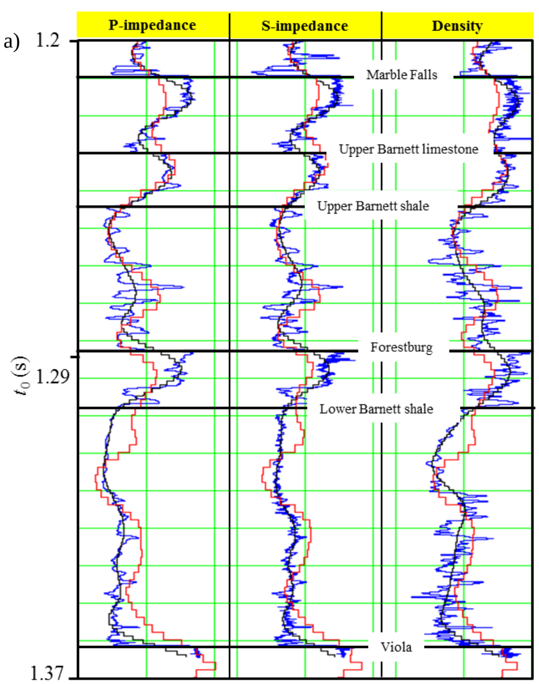


Figure 4: Predicted Brittleness by employing equation 1 and using inverted elastic parameters shown in Figure 3.

a)



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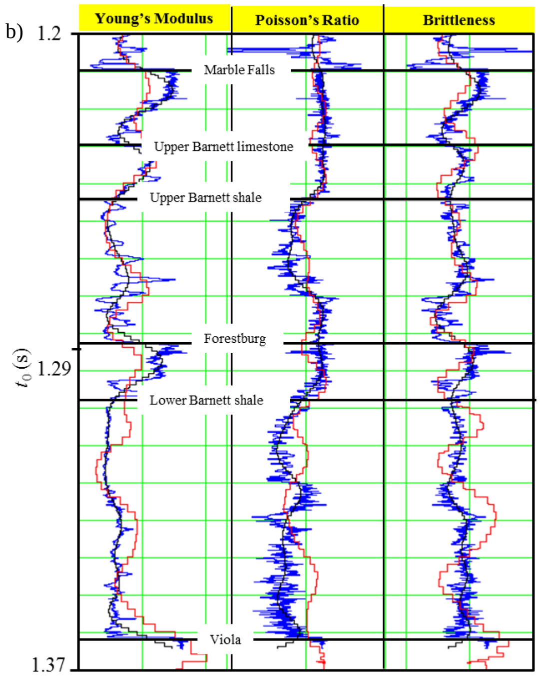

Figure 5: Quality control the inverted results with original well logs. (a) The original and inverted P-, S- impedance and density logs. (b) The derived and inverted elastic parameters. The blue, black, and red curves are the original logs, low pass filtered logs and inverted results, respectively.

Conclusions

By mitigating the "hockey stick" and minimizing the stretch, more far offset data are available for the subsequent prestack inversion resulting in reliable rock parameters estimation from seismic. Then the inverted elastic parameters can are used for brittleness evaluation for the shale reservoirs. Although the results from seismic inversion lose details compared to those of well logs, they exhibit a good correlation at the seismic scale.

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