Post-Stack Multi-Azimuth Stratigraphic Inversion Applied to Unconventional Reservoir Characterization: A Case Study in the Fort Worth Basin*

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Summary

Stratigraphic inversion is currently used by oil companies to improve resolution and, as a consequence, the quality of the seismic images at the target level. As the new marine or terrestrial seismic acquisitions allow recording a good azimuthal coverage, it is now possible to perform independent azimuthal inversion to provide azimuthal optimal parameters. Furthermore, the quantitative analysis of azimuthal parameters variations could help to enhance fracturing information, leading to better understanding and interpretation of the seismic data. The goal of our study is to provide an efficient multi-azimuths inversion workflow able to characterize an unconventional reservoir in terms of anisotropy, probably due to fracturing. In a first attempt, we have worked from a seismic survey recorded over a part of the well-known Barnett Shale and considering only full and azimuthal post-stack seismic data. After performing a series of independent azimuthal isotropic inversion, a quantification study of anisotropy reveals some interesting geological trends not visible with the same study from seismic amplitude.

Introduction

Stratigraphic inversion is an efficient tool for providing integrated information for reservoir characterization, in particular when azimuthal anisotropy is taken into account (Angerer et al., 2004; Ribeiro et al., 2008). Based on logs and seismic data, it derives impedance cubes which can be implemented in reservoir engineering. The aim of our study is to apply a robust three-step methodology, considering azimuthal post-stack seismic data, in order to characterize the anisotropy of a special kind of "a gas-shale reservoir", the Barnett Shale.

The Barnett Shale is a geological formation located in Texas and made of sedimentary rocks of Mississippian ages (323-354 Ma). Shales accumulated in an early foreland basin bordered by the Ouachita thrust belt in the east and the Bend structural arch in the west. The Barnett formation is underlain and overlain by limestones, the Ellenburger (Ordovician) below and the Marble Falls (Pennsylvanian) above (Plummer and Moore, 1922). The Barnett Shale is generally divided into two units, the Upper and the Lower Barnett, separated by the Forestburg

Limestone. However, in our study area, the Forestburg Limestone is absent and the Barnett is continuous without distinction between Lower and Upper Barnett.

Data and Method

The Barnett Shale lies at a depth of around 1200 m in our study area, with a thickness of about 35m in wells located in the vicinity of the seismic area (Well 1 in the northwestern part of the survey and Well 2 in the eastern part). The top of Barnett is clearly defined on the log data by the contrast in gamma ray features existing between the Marble Falls, the Barnett Shale and the Ellenburger Formation lying beneath them (Figure 1).

Two 3D surveys were acquired in 2005 and 2006 in the Fort Worth Basin. The combined dataset is some 88.88 square miles (Figure 1). The right and left parts of Figure 1 illustrate the comparison between acoustic impedances (Ip) derived from density and acoustic sonic logs, converted in two-way time, with the migrated seismic traces extracted at well locations. The lithologies are also shown, based on gamma ray data. Two strong reflectivities are visible on extracted seismic trace: the top of the Marble Falls at around 600ms (called H600) and the base of the Barnett Shale at around 680ms (called H680). In this part of the basin, the Barnett Shale has a thickness of only about 20ms (seismic sampled with 2ms). The seismic data have been sorted and partially stacked according to six azimuthal sectors: 0-30°, 30-60°, 60-90°, 90-120°, 120-150° and 150-180°.

The inversion workflow is divided into three main steps. An exhaustive description of the workflow is presented in Delépine et al. (2010). The first one consists in calibrating the seismic at reservoir level to the well log data (Lucet et al., 2000). The main challenge is to find for each azimuthal stack, a common optimal wavelet satisfying the correlation between surface seismic and synthetic traces computed at each well. These synthetics are obtained by convolution of the acoustic reflectivity logs, converted in two-way time domain, by the estimated wavelet. The second step corresponds to an acoustic a priori model building; it is a mono-parameter representation because only post-stack data are available. This step also requires interpreted horizons derived from the full stack of seismic data and associated with major geological units. In the target area we have identified two main horizons: the top of the Marble Falls (H600) and the base of Barnett Shale (H680) used to define sedimentary mode of deposition inside the main geological units. The third step consists in performing independent model-based isotropic post-stack inversions for each azimuth, using the same a priori model previously described. All three steps are part of a workflow we call multi-azimuthal post-stack inversion in the following. This workflow provides us as many acoustic impedances cubes as azimuth sectors, i.e. six in our case study.

A further step is to quantify the 3D azimuthal variations of acoustic impedances; to achieve this goal we use an explicit ellipse-fitting algorithm which initial equations are derived from Dey and Ray (1999). In fact, inputs could be any kind of parameters, like original seismic amplitudes, attributes, like coherency, curvature and more interestingly inverted acoustic impedances. For a given bin of the inverted target area, the fitting uses 12 values (6 azimuthal values on 0-180° and their projections on 180-360°) in a spherical coordinate system to compute the best ellipse. We can apply the ellipse fitting for all bins of the 3D target in a sequential process to produce two outputs attributes: the ratio between the larger and the smaller semiaxis and the tilt of the ellipse. The ratio corresponds to the deviation according to the isotropic case in which the ellipse would be a circle and it is called anisotropic ratio in the following sections.

Results

We firstly proceeded to a classical and robust full post-stack inversion to provide an acoustic impedance cube of reference. However, we did not use the full stack provided. Indeed, some processing phases have modified the original seismic amplitudes, probably for specific reasons. To get around the problem, we performed a new full stack seismic data by stacking all the azimuthal partial stacks on which we are sure that relative amplitudes have been preserved. This new full post-stack seismic allows us to get over the missing amplitude preservation and can be quantitatively compared to partial azimuthal seismic stacks. The upper image in Figure 2 presents acoustic impedances obtained with the full post-stack inversion extracted at horizon H680 (base Barnett). Each of the two wells is denoted by a little black cross, Well 1 in the northwestern part and Well 2 in the eastern part. We can observe that impedances are quite similar in all the area (around 15000 g/cm^3.km/s), except in the western part, where they are much lower (above 10000 g/cm^3.km/s) due to edge effects like seismic image defocusing enhanced by the presence of a major fault precisely known in this area. The fault alignment is north-south according to the main extension direction of the basin. Except around the vicinity of Well 1, there is no significant variation of impedances apparently in the Barnett Shale. The full post-stack inversion provides us a first sight on the evolution of acoustic impedances in the Barnett field.

Then we performed independent inversion using azimuthal post-stack seismic. We use the same a priori model built from interpreted horizons on the full post-stack seismic. A step further consists in applying a kind of residual NMO corrections, based on semblance algorithm, to perfectly align seismic events from each azimuthal post-stack to the full post-stack seismic considered as a reference base time. This step has improved amplitude continuity in the neighboring of the Davis Lake well (not displayed in the text). Middle and lower images of Figure 2 present the acoustic impedances obtained at H680 for azimuth 3 (60-90°) and azimuth 6 (150- 180°). The westernmost part of the field is still characterized by very low impedance values due again to edge effects. Moreover, in the vicinity of Davis Lake well, we observe an interesting azimuthal acoustic impedance variation. Some lineaments are highlighted by this method: a north-south trend is visible in particular on azimuth 6. Globally, the inverted impedances from azimuth 3 are smaller than those from azimuth 6, may be linked with irregularity in survey fold. Nevertheless, we did a further interpretation quantifying azimuthal impedance variations, taking into account all the six acoustic impedances cubes and using the previously cited ellipse-fitting algorithm.

Figures 3 and 4 present the anisotropic ratios obtained from seismic amplitudes (upper images) and the inverted impedances (lower images) extracted from horizons: H600 at the top of Marble Falls in Figure 3 and H680 at the base of Barnett Shale in Figure 4. The high values obtained on the edges of the survey are not significant and due to migration smiles. One has to keep in mind, outside the survey inversion results is the a priori model; consequently, ratio is equal to 1. The comparison between anisotropic ratio from seismic amplitudes and inverted impedances shows how integrated inversion workflow brings new kind of information on reservoir structuring. Indeed, the fitting performed on seismic amplitude presents very noisy result; some trends are revealed, presenting high anisotropic ratio, incompatible with natural anisotropy ratio due to fracturing (generally comprised between 0 and 10 %; i.e. a ratio between 1 and 1.1). On the contrary, results of anisotropy ratio obtained from impedances seem to be in the good scale and may be interpreted as anisotropy due to cracks. Furthermore, some kinds of lineaments are also visible with anisotropic ratios from impedances and are consistent with what is observed in Figure 2.

Figures 3 and 4 also bring significant results for the characterization of hydrocarbon reservoirs. Indeed, the anisotropic ratio obtained from impedances are globally higher on the horizon H600 than on horizon H680. A possible explanation is that horizon H600 corresponds to the top of a carbonate layer, the Marble Falls, which is expected to be more fractured than the underlying Barnett Shale. Inversion results show this trend and, more particularly, some lineaments seem to disappear between the carbonates and the shale. At this stage of the study, open questions remain: do the prospective faults responsible for a vertical variation of anisotropy really disappear in the shale? Do they still exist in the shale, but they are more difficult to be seen by seismic because impedance contrast is smoother? We are more confident with the second hypothesis based on other studies (Burhannudinnur and Morley, 1997; Morley and Burhannudinnur, 1997). Consequently, even if a fault induces an offsetting of strata in the shale, it should be possible for wave propagation not to be affected, and nothing would appear on the seismic signal recorded at the surface.

Conclusions

In this study, we present a multi-azimuths inversion workflow which enables us to extract azimuthal anisotropy information from post-stack seismic data only, and it is probably linked with some geological trend. Anisotropic ratios and ellipse tilts could be seen as complementary information with seismic attributes.

For the unconventional plays, these preliminary results are encouraging to generalize the multi-azimuths post-stack inversion workflow to multi-azimuths pre-stack data allowing recovery of elastic *P*- and *S*-wave impedances. The ellipse fitting on inverted impedances seem to be a good tool to find a better way to predict where sweet spots are located.

We have to go further by investigating the potential link between our anisotropic spots and the chasing sweet spots which are keys to optimize reservoir production.

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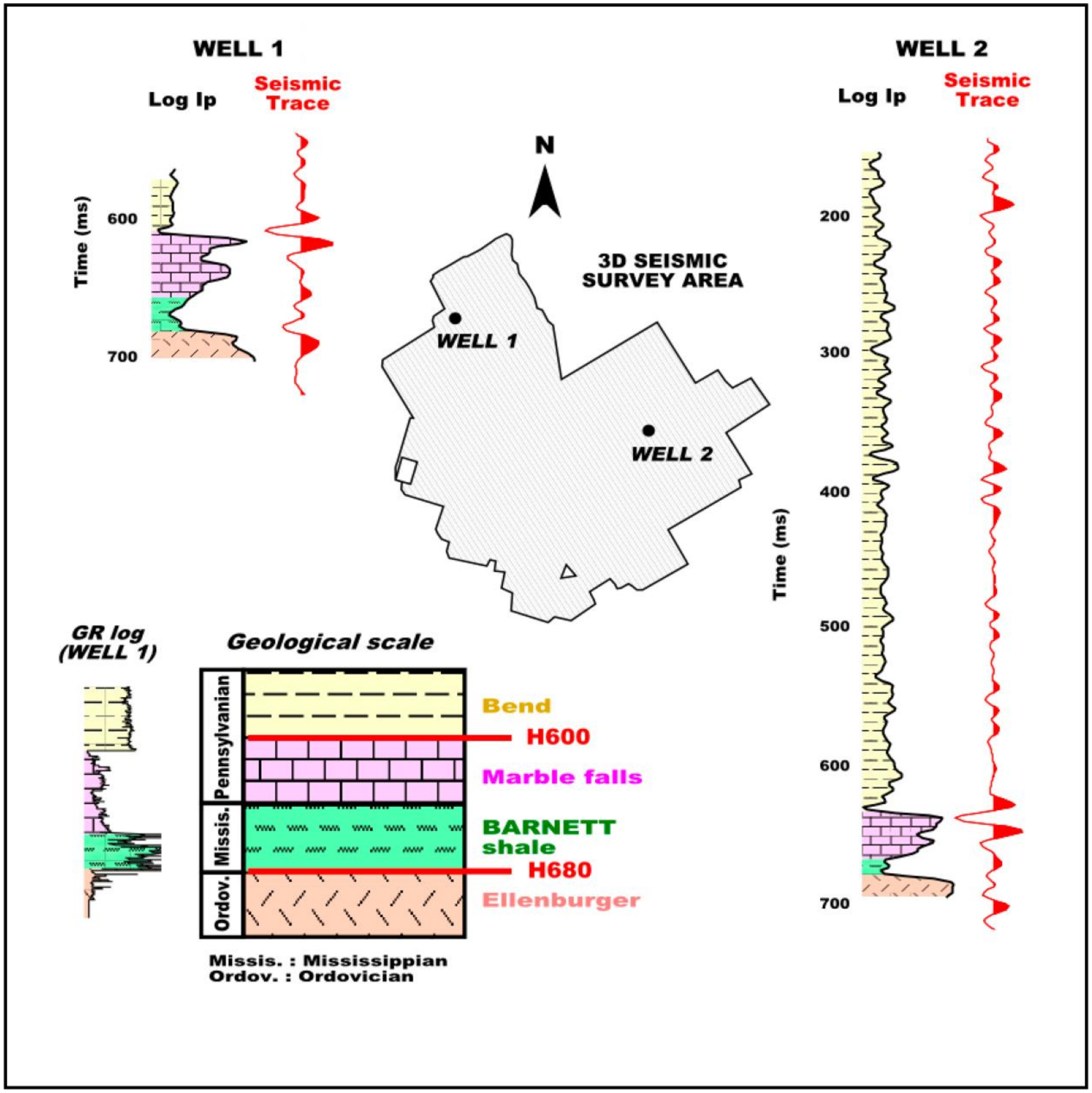

Figure 1. Seismic and well data.

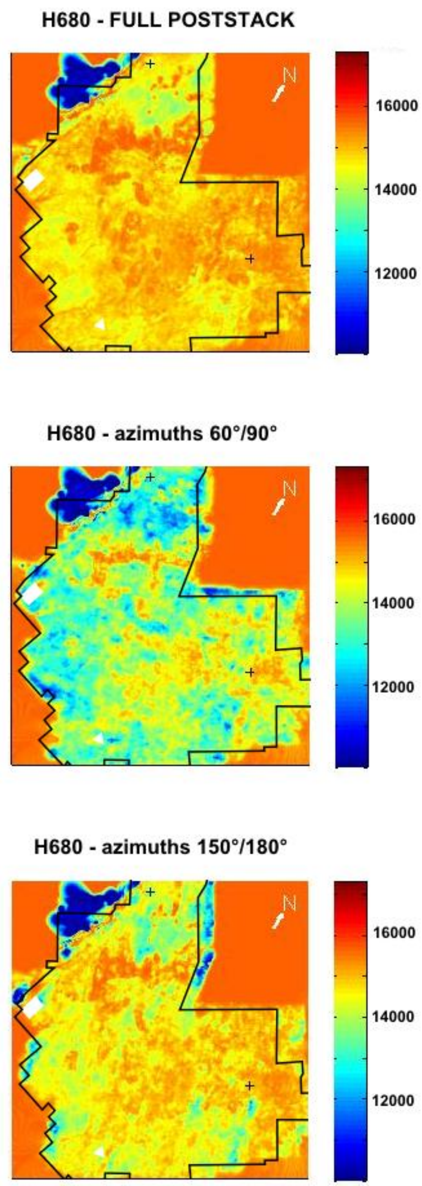

Figure 2. Horizon extracted acoustic impedances from full post-stack inversion (upper) and two azimuthal post-stack inversions (middle and lower) showing significant variations.

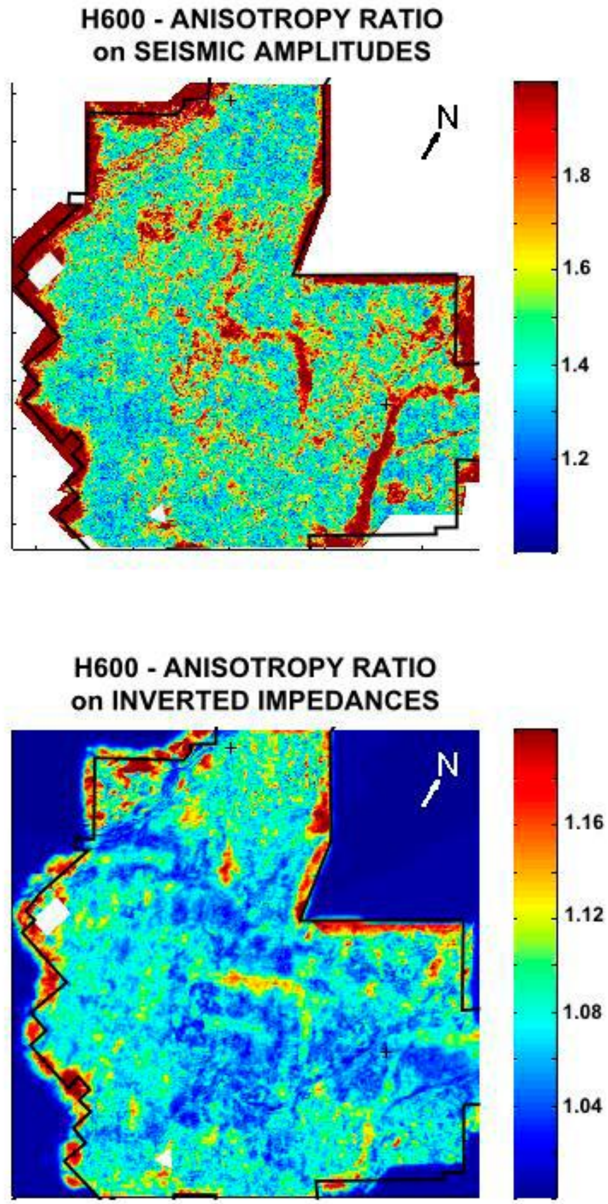

Figure 3. Comparison of anisotropic ratio obtained from seismic amplitudes and from inverted acoustic impedances extracted on horizon H600 (top carbonates).

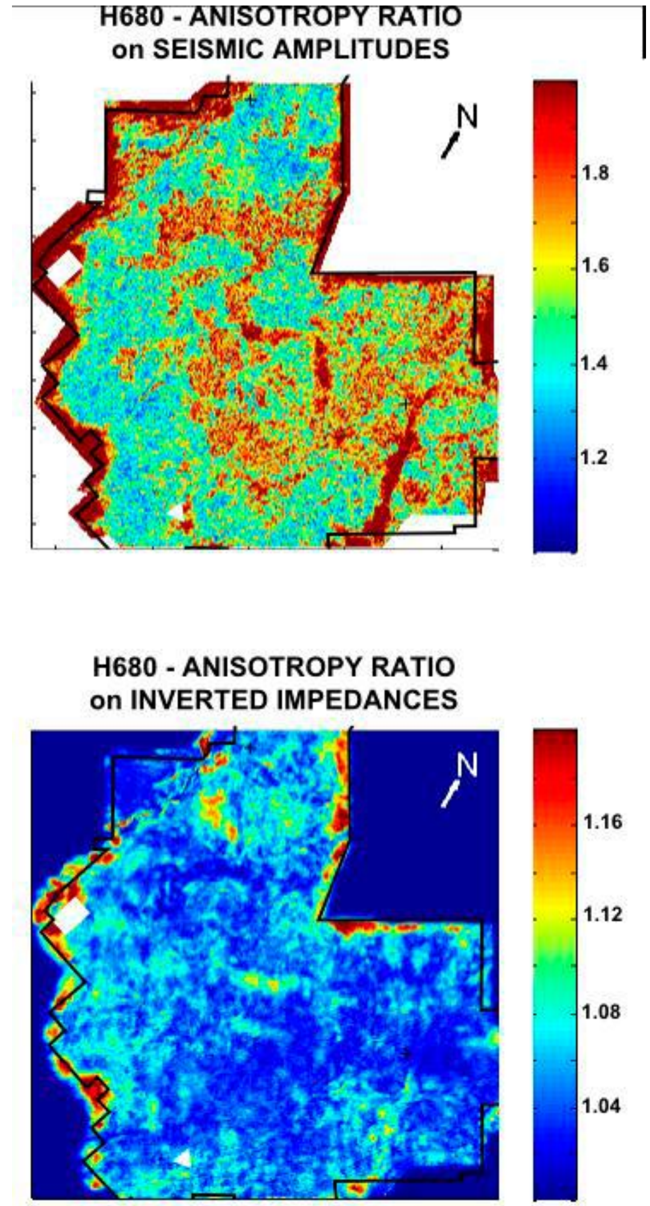

Figure 4. Comparison of anisotropic ratio obtained from seismic amplitudes and from inverted acoustic impedances extracted on horizon H680 (base Barnett).