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Imaging and Characterization of a Shale Reservoir in Onshore Poland Using Full-azimuth Seismic Depth Imaging

M.W. Podolak* (Geofizyka Torun S. A.), H. Kowalski (Geofizyka Torun S. A.), P. Godlewski (Geofizyka Torun S. A.), W. Kobusinski (Geofizyka Torun S.A.), J. Makarewicz (Geofizyka Torun S. A.), A. Nowicka (PGNiG S. A.), Z. Mikolajewski (PGNiG S. A.), D. Chase (Paradigm), R. Dafni (Paradigm), A. Canning (Paradigm) & Z. Koren (Paradigm)

SUMMARY

This paper discusses the application of imaging and characterization in the local angle domain (LAD) in a shale reservoir. The system delivers high-quality images of the reservoir and geomechanical characterization of rocks with the precision needed to steer horizontal drilling, detect sweet spots, locate geobodies resistant to fracturing, or image geobodies of irregular shape. This technique is particularly attractive in Poland, where conventional seismic imaging in complex tectonics has frequently resulted in dry wells. Using this method, and combined with well data, image horizons were accurately tied to well markers, and stress/fracture orientations were highly correlated in the vicinity of the wells.

Introduction

The exploration and development of shale plays in Europe shows that the "statistical drilling" approach, applied in some basins in recent years, cannot be extended to areas where local stress in rocks or fracture distribution varies both laterally and in depth.

This paper discusses the application of a new seismic data imaging method, called *full-azimuth angle domain depth imaging*, which is particularly useful when working with rich-azimuth seismic data. Dedicated software delivers high-quality images of the reservoir and geomechanical characterization of rocks with the precision needed to steer horizontal drilling, detect sweet spots, and locate geobodies resistant to fracturing.

The workflow is based on software specifically developed to meet the challenges of shale gas seismic [Koren and Ravve, 2011, Koren et al., 2013, Canning and Malkin, 2013]. One of the main advantages of this approach is that it works directly in the local angle domain (LAD) instead of the surface offset/azimuth domain. The use of in situ azimuth in LAD, visualized together with dedicated seismic attributes, provides information about the intensity and orientation of geological stress/fracture systems. Geothermal prospecting and seismic imaging of conventional hydrocarbon plays can also profit from this method. This technique is particularly suitable to Poland, where conventional seismic imaging in complex tectonics has frequently resulted in dry wells.

Method

Before undertaking the above-mentioned full-azimuth depth imaging, a series of time domain preprocessing steps were taken: wavelet processing was applied; surface-consistent statics and amplitudes were solved except for spherical divergence which was compensated for in depth imaging; noise and especially multiples were eliminated; diffractions were preserved; and no preprocessing trace interpolation was applied.

The first step in the depth imaging workflow was to estimate and compensate for polar anisotropy (VTI or TTI). This is a prerequisite for estimating azimuthal anisotropy parameters. Estimating the VTI model involves the application of full-azimuth tomography to separate velocity heterogeneities from azimuthal anisotropy. This is important for building a reliable background model of the overburden, and ensures the consistent estimation of azimuthally-dependent phenomena at target. The accuracy of the VTI model was confirmed when new drilling was completed, in which the seismic-to-well ties reached an accuracy of ± 3 m.

The proposed full-azimuth depth imaging workflow offers numerous advantages, including:

- Wavelet stretch compensation in angle domain enables the use of longer offsets.
- Illumination compensation minimizes the impact of complex tectonics on amplitude distribution.
- Full-azimuth tomography can separate heterogeneities from azimuthal anisotropy, allowing proper correction for overburden.
- Effective, azimuthally varying residual moveouts measured along LAD depth gathers are transformed into local (interval) anisotropic velocity parameters.
- Decomposing the seismic wavefield into specular and diffraction components enhances both structure continuity and small-scale discontinuities (faults or cracks).

All of these features provide the ability to see greater detail in the subsurface of unconventional resources, and better analyze the azimuthal anisotropic effects on stress/fracture environments.

Application

A full-azimuth 3D seismic survey was acquired in North Poland, where Silurian and Ordovician gas- and oil-bearing shales are prospective targets. Pre-existing stress and fractures were expected to form an azimuthal anisotropy signature in seismic data. Nominal stacking fold 165, max. offset of 4285 m, CMP bin size 20 x 20 m, and fairly homogeneous azimuth-offset distribution allowed us to assume an

approximately full-azimuth acquisition geometry. Data regularization was applied directly in the local angle domain, optimizing reliability of the azimuthal distribution of the seismic events.

The interpretation of well data (Fig.1) shows moderate intensity of depth-variant azimuthal anisotropy. An azimuthal rose diagram (Fig. 2B) shows a local dominant orientation of azimuthal anisotropy, which agrees with the seismic estimate of the location of the vertical well (also in Fig. 2B).

Many measurements were logged in the wells, the most important of which was obtained using a crossed-dipole sonic tool. Data processing results indicate anisotropy in some parts of the Silurian and Ordovician sections. The general direction of anisotropy confirms the direction estimated from seismic in the most interesting zone. A comparison between WaveSonic results and electrical imager data (XRMI) indicates that anisotropy is predominantly related to the presence of fractures; however, it may also be caused by carbonate or pyrite concretions inside shales.

Figure 1 *Sample of direct images of fractures recorded with XRMI imager (three panels on the left), and with cross-dipole sonic tool (two panels on the right).*

Another issue is the intensity of anisotropy. A detailed analysis of well data suggests that it is depth-variant, and a vertical resolution of 5-6 m is needed to describe the phenomenon. That is below the present seismic resolution estimated from $\lambda/4$ formula. However, the positive correlation between seismic- and well-predicted HTI anisotropy indicates that seismic averaging is acceptable.

To meet the challenges of high precision, conventional seismic imaging was replaced by a new software package dedicated to full-azimuth, angle domain depth imaging – reflection angles and azimuths. Surface azimuth, used in isotropic imaging, was replaced with depth-variant local azimuth. The interval velocity model of the subsurface used in isotropic PreSDM was replaced by a VTI/HTI model. Effective azimuthally-varying residual moveouts measured along the LAD gathers were transformed into local azimuthal anisotropic parameters using a generalized Dix-type method (Koren and Ravve, 2013).

Three vertical wells were available in the reported area. Two of them were logged before the acquisition of 3D seismic data, while the most recent one was made available after the new depth imaging workflow was completed, and was used to verify imaging precision. While the depth of the shallow horizons, i.e. base of Permian and Silurian, were predicted at an accuracy of less than 1 sample (5 m) of depth imaging, the deep horizons (Ordovician and Pre-Cambrian) around the third well were predicted at an accuracy of less than 10 m.

Figure 2 *A – Outline of stratigraphy, symmetry of intervals, and target position in the investigated area. B – Comparison of seismic-derived anisotropy orientation to a rose diagram from well, and from microseismic monitoring of fracturing.*

In addition to the improvement in image quality, the full-azimuth depth imaging system used also provided new options for both unconventional and conventional seismic prospecting. The extraction of two components of the recorded wavefield - reflection and diffraction energies - revealed subtle features related to small-scale, geologic discontinuities (Fig.3).

Figure 3 *Reflection (specular) energy along target seismic horizon (left); Stack of diffraction energy (right).*

Availability of various, independent geophysical measurements of physical properties of the examined geology, creates opportunity for data integration in interpretation process. Integration of borehole information, microseismic fracturing monitoring, surface seismic attributes, and seismic interpretation focused on tectonic system recognition, leads to increased vertical recognition of layers.

Seismic interpretation in the project was based on the workflow presented by A. Daletka and M. Rudzki (2013), applied to seismic data obtained from the CRAM of rich-azimuth prestack depth migration. In this study, the previous methodology was supplemented by performing both acoustic and elastic inversion. Inversion velocities and elastic impedances were extracted in specified intervals, related to particular formations. The differences of velocities and impedances give an information about azimuthal anisotropy of the rock. That workflow was applied in sector-oriented version, and allowed to understand precision of the full-azimuth workflow.

Conclusions

From a seismic perspective: Full-azimuth seismic depth imaging is efficient in unconventional plays, such as shale gas, shale oil, and tight gas, and in geothermal projects. Compared to traditional time-domain, sectored imaging and data analysis, depth imaging in the local angle domain (a natural domain for geologists) provides more reliable attributes for seismic characterization of reservoirs with azimuthal anisotropy.

From a well log perspective: While regional stress may not be relevant to local prospecting, stress orientation predicted from seismic is compatible with an azimuth rose diagram seen in wells, and with information measured from microseismic monitoring during horizontal well fracturing.

From a geological perspective: Analysis of the lithostratigraphic formations of Ordovician and Silurian sections revealed significant anisotropy of their mechanical properties. This can be attributed to their original lithologic differentiation, and the later impact of tectonics, including the present field of stress. Identifying the relationship between core data (e.g. mechanical properties, deformations, pattern of fractures), well logs, and seismic is essential to creating a local geomechanical model. Such a model is necessary for the correct planning and drilling of horizontal wells, as well as for hydraulic fracturing.

***From the perspective of conventional prospecting*:** The search for conventional traps in areas of complex geology can also profit from this method. Bottom-up ray tracing, the precise use of a 360˚ view of irregular surfaces, correction for illumination shadows, non-stretch NMO, and decomposition into reflection and diffraction components offer the potential to derive new images from archived 3D seismic shot over conventional geology, as well as high-resolution imaging of new, dedicated, rich-azimuth seismic data.

Acknowledgements

PGNiG is acknowledged for its contribution to practical application of the imaging, and its permission to publish illustrations of some of the data. We thank Geofizyka Torun for its support of this paper.
We thank Paradigm® for its support in building the workflow and implementing its EarthStudy 360® software.

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