Improving knowledge about earth subsurface based on anisotropic depth imaging. Case of land, full azimuth seismic survey for unconventional hydrocarbons exploration in Poland.

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Summary

An innovative, practical workflow for estimation of azimuthal anisotropy parameters is presented. The workflow is based on state-of-the-art applications which are able to deliver true information about subsurface azimuths and successfully use them – e.g. a series of 3D full azimuth modules: RMOs (resisdual moveouts) picking, anisotropic tomography, pre-stack depth migration, and QC. Such approach enables to overcome many limitations, inaccuracies and shortcuts related to workflows based on time-domain imaging, processing data in sectors, and analyses in post-stack domain. The main product of full azimuth PreSDM (pre-stack depth migration) – 3D continuous full azimuth angle domain reflection gathers (CRP) are among the other benefits, source of information about azimuthal anisotropy. Parameters of azimuthal anisotropy are calculated from both kinematic and dynamic attributes of the events in CRP gathers.

Products of the workflow comprise diffraction and specular stacks obtained from the second product of the full azimuth PreSDM – 3D directional gathers. The illumination gathers, the third product of migration are used to correct relative amplitudes for irregular number of ray hits which reach CRPs. Effectiveness of the full azimuth applications in model building procedure in comparison with standard ones is demonstrated.

Presented are differences between results of PreSTM (pre- stack time migration) and PreSDM, in quality of imaging and lateral positioning events in case of simple geology. It is shown that taking into account anisotropy, improves seismic imaging, well ties, AVO/AVA analysis, and delivers information about seismic anisotropy, which, for geologists and drilling engineers, is an indicator of stress and fracture directions.

Keywords: Anisotropy, depth imaging, full azimuth, fractures, heterogeneity, illumination, stress, tomography, unconventional.

Introduction

Shale plays are important source of unconventional hydrocarbons. Seismic data play a substantial role in unconventional prospects, and in particular in identification of sweet spots. Traditionally, they are used to interpret structural horizons, delineate seismic scale discontinuities, and to extract many valuable attributes.

But seismic data can also be used for horizontal well planning in shale plays, and to support procedure of hydraulic fracturing. In these procedures, understanding of the stress and its orientation is critical.

Nowadays state-of-the-art methods of seismic data processing make it possible to extract from seismic data many pieces of information not used so far – e.g. azimuthal anisotropy and diffraction image. It is connected with the possibility to identify structures much smaller than the seismic wavelength, based on theories of effective medium and seismic waves scattering.

Seismic azimuthal anisotropy can be an indicator of directions of stress and fractures. Directions of fractures strike as well as maximum and minimum stress can be determined in the case of P-waves, based on phenomena of azimuthal variation of kinematic (travel time, NMO velocity) and dynamic (amplitude) attributes of the events in full azimuth CRP gathers. In case of S-waves in anisotropic medium the phenomena of wave splitting is an additional source of information.

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The range of information about in-situ stress and fractures obtained from analysis of full azimuth CRPs is an information which corresponds with range of seismic survey. Other methods, like core analysis, results of microimager and dipole sonic, deliver very local information.

At this time, most of workflows for analysis of azimuthal anisotropy are based on imaging seismic data in sectors in time domain (3D PreSTM), and sometimes scan only stacked data for parameters of azimuthal anisotropy. Such approaches have much more limitations and assumptions than imaging data in depth domain (3D PreSDM), where pre-stack data are analyzed in full range of angles and azimuths. All limitations, assumptions and shortcuts in algorithms and workflows influence resolution, quality and reliability of results.

Reliable analysis of stress and fracture directions must be based on seismic data with neither distorted nor falsified information about amplitudes and RMOs. Obtaining such data is possible only based on accurate anisotropic velocity model. Time imaging in most of the cases is not able to deliver such a model.

With conventional seismic techniques (migration, tomography), information from different azimuths belonging to the same image point is averaged – so the information about azimuths is lost. Processing and imaging data in sectors selected arbitrarily is a kind of shortcut – the integrity and resolution of the result is compromised. Assumption that surface azimuth is the same as subsurface is not necessarily true.

Analysis of pre-stack data in full range of azimuths (AVAaz, RMOaz) can deliver more reliable data then analysis of seismic attributes calculated on sectored stacked data.

The experience shows that presented method is superior to arbitrary sectoring and time imaging. Depth imaging delivers 3D CRPs in continuous spectrum of true subsurface azimuths and reflection angles. Then other applications (e.g. 3D full azimuth anisotropic tomography, 3D RMO picking, RMOaz inversion, AVAaz inversion) use these data to update anisotropic velocity model and for azimuthal anisotropy analysis. Analysis of azimuthal anisotropy is performed based on both kinematic and dynamic attributes.

Theory

The theory of propagation elastic waves in elastic, anisotropic media was formulated in 19th century. At the turn of 20th century this theory was introduced to seismology by the creator of the first geophysics chair in Europe (Krakow, Poland) Maurice P. Rudzki. The concept that fractures and stress lead to seismic anisotropy, which in turn can be a source of information about them was formulated in the late seventies of 20th century (Helbig K., Thomsen L., 2005). From that time, the theory became mature and was confirmed by many numerical and laboratory studies as well as many seismic projects (Liu E., Martinez A., 2013).

The concept of the presented workflow was widely described by Z. Koren and I. Ravve (Koren Z., Ravve I., 2011, Ravve I., Koren Z., 2011).

All work, has been carried out with Paradigm's EarthStudy 360 system and GT in-house solutions.

Geological setting

The area of study is located in Europe, the Baltic Basin, in the Northern part of Poland – Fig.1. The geological structure of the region is not very complex with two main structural levels: Old Paleozoic (Cambrian to Silurian sediments) and Permian- Mesozoic. Mentioned stages are separated by Variscan hiatus (Devonian and Carbon). Old Paleozoic and basement formations are of interest for shale exploration.

Data acquisition

The location of the 3D seismic survey was chosen after careful examination of the results of previous 2D surveys and also based on the first vertical exploration well. The well, ended up in Cambrian deposits, drilled 1843.5 m of Silurian and 63 m of Ordovician strata, brought a significant amount of core, geochemical, petrophysical and geophysical data, which confirmed the presence of unconventional gas. The 3D seismic survey generally followed "full-azimuth" geometry, having the following parameters: source area 33 sq km, orthogonal layout, receiver interval 40 m, receiver line interval 200 m, source point interval 40 m, source line interval 280 m, symmetrical split spread, active channels per line 154, live channels 4620, patch length 6120 m, patch width 5800 m, maximum offset 4285 m, bin size 20x20 m and nominal fold 165 (Daletka A., Rudzki M., 2013).

Fig.1: Location of 3D seismic survey acquired for the purpose of unconventional gas exploration.

Methodology

Building correct, anisotropic model of the medium is a fundamental task, which enables at next stages to define reliable parameters of azimuthal anisotropy. Presented depth imaging workflow consists of 3 stages to depict differences in the final results obtained with standard and advanced (continuous full azimuth angle domain) applications.

The first and second stages were accomplished with standard applications, which do not retain and do not use azimuthal information. In the first one the isotropic model, and in the second one, anisotropic VTI (vertical transverse isotropy) models were build. In the third stage the most advanced, full azimuth applications were used to build final anisotropic VTI model and perform final, full azimuth angle domain PreSDM. Comparison of the final results from second and third stages enabled to assess effectiveness of the full azimuth applications.

The preconditioned gathers from time domain processing, and horizons interpreted on results of PreSTM, were used to build initial isotropic depth model – Fig.2.

The procedure of velocity model update was carried out iteratively through PreSDM, RMOs (residual moveouts) determination along horizons and global tomography. Because of the problem with NMO stretching on high velocity gradient boundary, evident from the offset domain PreSDM output, the layer stripping approach to update Tp2-Z3 interval was necessary (1st and 2nd stages). The problem of NMO stretching was reduced with angle domain PreSDM,

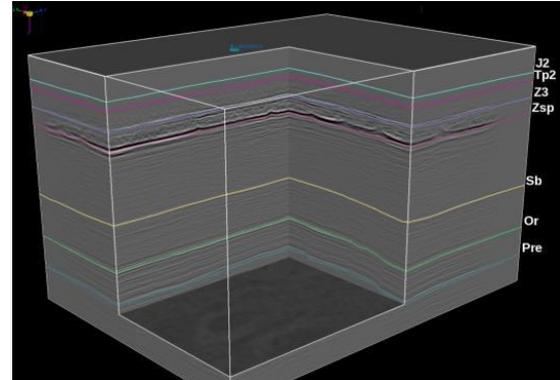and then tomography approach was possible (3rd stage) – Fig.3.

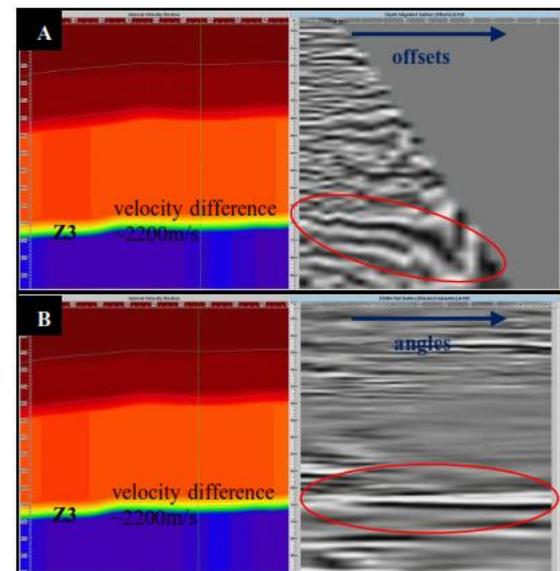Fig.2: Seismic horizons used for initial depth model building.

Fig.3: Comparison of signal stretching by A) 3D Kirchhoff offset domain PreSDM and B) 3D CRAM - common reflection angle domain pre-stack depth migration.

The isotropic model building procedure requests only one parameter to be provided – interval velocity model, which flattens events in CRP gathers in the near and middle offset range – Fig.4. The final results of isotropic PreSDM exposed effects related to occurrence of VTI anisotropy (which at this stage was not taken into account) – hockey sticks in CRP gathers, and substantial misties of seismic horizons with well tops – Fig.5.
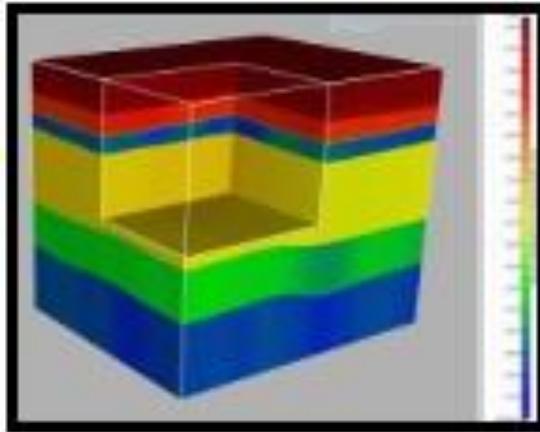
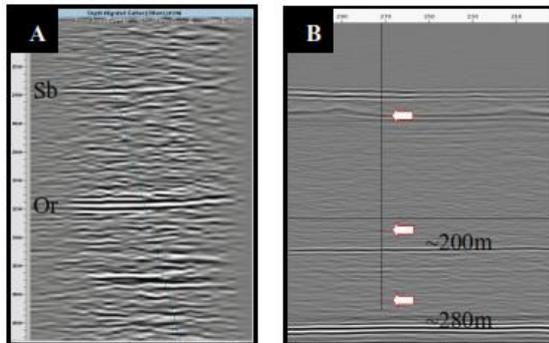Fig.4: Parameter of isotropic model – instantaneous velocity.

Fig.5: Results of final (stage 1) isotropic Kirchhoff PreSDM. A)CRP gather, B) stack.
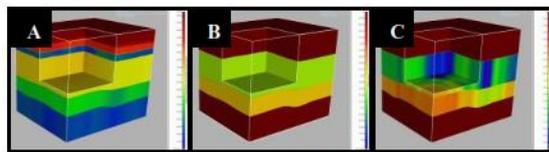

Fig.6: Parameters of VTI anisotropic model: A) compressional velocity, B) interval delta, C) interval epsilon
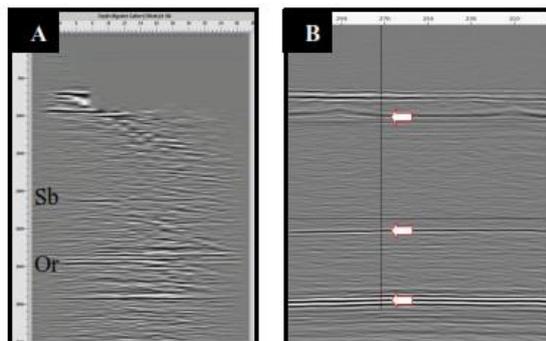

Fig.7: Results of final (stage 2) VTI anisotropic Kirchhoff PreSDM. A) CRP gather, B) stack.

To eliminate those problems of seismic image, which influence incorrect vertical and lateral positioning of seismic features, as well as deterioration of the seismic events focusing, the anisotropic VTI model was built. The building of such a model for P-waves consisted in determination of 3 parameters instead of 1 for isotropic model – compressional, vertical instantaneous velocity, interval delta and interval epsilon – Fig.6.

Based on final VTI anisotropic model, the final Kirchhoff 3D PreSDM was run. The procedure of building final VTI model using standard depth imaging tools, which do not take azimuths into account, was finished (stage 2). The events in CRP gathers were flat in full range of azimuths and seismic horizons were tied to well tops – Fig.7.

In the third stage, based on final VTI model from the second stage, advanced full azimuth angle domain 3D PreSDM was run.

The applied full azimuth pre-stack depth migration delivers 3D continuous azimuth reflection angle gathers as the primary output, 3D continuous azimuth directional angle gathers as secondary output and gathers with information about illumination of CRPs.
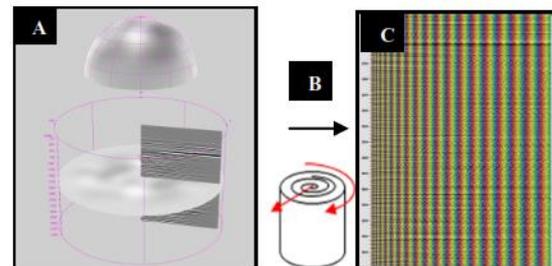

Fig.8: A) 3D cylindrical spiral CRP gather – reflections as a function of depth azimuth and reflection angle. Presented are traces for given azimuth, and for all angles, B) the idea how 3D CRP gather is unwrapped into 2D plane, C) unwrapped "spiral" gather – 2000 traces. Color presents periodical change of azimuths.

Reflection gathers are used to build anisotropic model. They enable to pick RMOs in full range of azimuths and reflection angles.

As amplitude relations are reconstructed, the reflection gathers can be utilized for investigation of azimuthal anisotropy.

Directional gathers are used to calculate dip, azimuth, and continuity volumes, and to construct structural images with enhanced continuity of reflections, and on the other hand, to produce diffraction images.

Illumination gathers contain information about number of ray hits which reach particular pieces of CRPs. They are

used to improve amplitude relations when irregular illumination occurs.

3D full azimuth anisotropic tomography utilizes RMOs picked in full range azimuths and reflection angles to get high resolution model of anisotropic medium.

Full azimuth angle CRP gathers resulting from the anisotropic migration, reveal oscillations of events with azimuth – Fig.8. Such oscillations can be caused by azimuthal anisotropy as well as by heterogeneities of medium, which were not included in anisotropic model.

The attempt of updating VTI anisotropic model based on advanced full azimuth tools was done. Possibilities of the advanced applications to work in full range of azimuths and reflection angles were utilized to improve reliability of the VTI model. Picked RMOs were used by 3D full azimuth global anisotropic tomography, whose effectiveness is much better than standard application. Despite of relatively small changes in VTI model, the image of oscillations in resulting CRP gathers changed substantially – Fig.9. The heterogeneities of the model not seen by standard tools were included to improve VTI anisotropic model. This change had fundamental impact on reliable determination of azimuthal anisotropy.
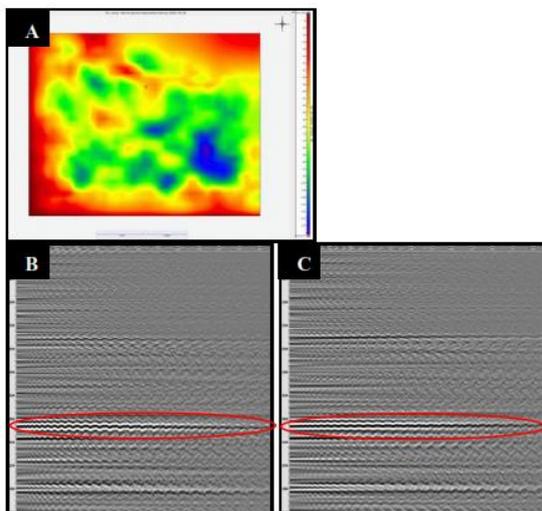

Fig. 9: A) example map of the velocity difference for Sb horizon before and after full azimuth anisotropic tomography, B) "spiral gather" before and C) after full azimuth anisotropic tomography.

Based on full azimuth reflection angle CRP gathers, effective parameters of azimuthal anisotropy were determined. Both kinematic and dynamic attributes of events were analyzed . Analysis of kinematic attribute was based on investigation of variation of RMOs with

azimuth (RMOaz) and dynamic attribute – variation of amplitudes with angles and azimuth (AVAaz). The parameters of azimuthal anisotropy determined using different attributes, show high correlation – Fig.10. Each method have pros and cons. Used together they give better understanding of lateral distribution of stresses and fractures.
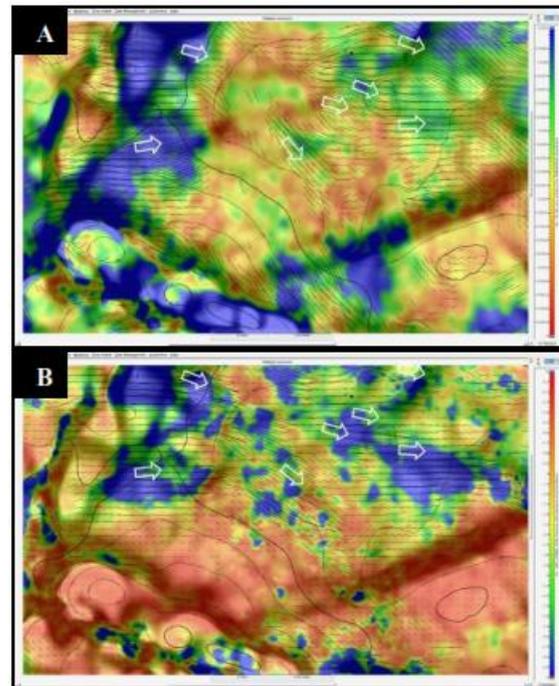

Fig.10: Maps of effective parameters of azimuthal anisotropy for Or horizon. A) based on RMOs, B) based on amplitudes. Intensity is shown in colors (blue – higher intensity) and length of black dashes. Azimuth of fractures strike (direction of max. stress) is shown as orientation of dashes. White arrows are drown on the maps in the places of higher intensity (the same places) to compare azimuths.
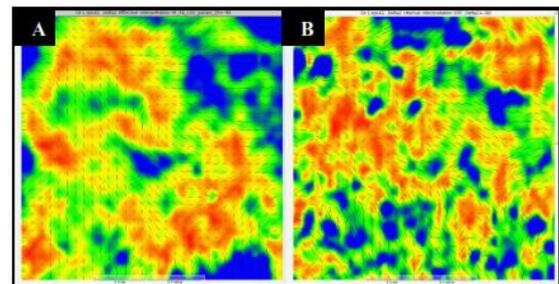

Fig.11: Maps of parameters of azimuthal anisotropy for Or horizon calculated based on kinematic attribute. A) effective parameters, B) interval parameters. Intensity is shown in colors (blue – higher intensity) and length of black dashes. Azimuth of fractures strike (direction of max. stress) is shown as orientation of dashes.

The overburden of the target layer with orthorhombic anisotropy consists of isotropic and orthorhombic anisotropy layers. Removal of influence of overburden on target for parameters estimated from kinematic attributes was performed. The layer, orthorhombic parameters - intensity and azimuth - of azimuthal anisotropy were calculated – Fig.11. This procedure was done using algorithms described by Zvi Koren (Koren Z., et al., 2013) . The directional gathers were used to get diffraction and specular images. The first one is an indication of fractures which cause diffractions, the second enhances continuities of horizons –Fig.12 and Fig.13.

The information about ray hits was used to correct relative amplitudes connected with irregular illumination of the objects. The CRP gathers after this correction are more reliable for AVA/AVAaz analysis – Fig.14.

Despite of relatively simple geology, the differences in lateral positioning of the events as well as focusing of the events on stacked sections between results of 3D PreSTM and 3D PreSDM were observed – Fig.15.

The analysis of illumination of target horizon for explanation of poorer image of horizon was done. The analysis revealed that poor image is connected with poor illumination. Based on analysis of different acquisition geometries it is possible to minimize undesirable imaging effects – Fig. 16.
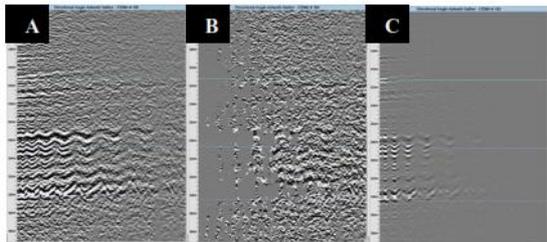

Fig.12: Directional "spiral" gathers filtering. A) original directional CRP gather, B) directional gather filtered to enhance diffractions - diffraction gather, C) directional gather filtered to enhance specularity – specular gather.
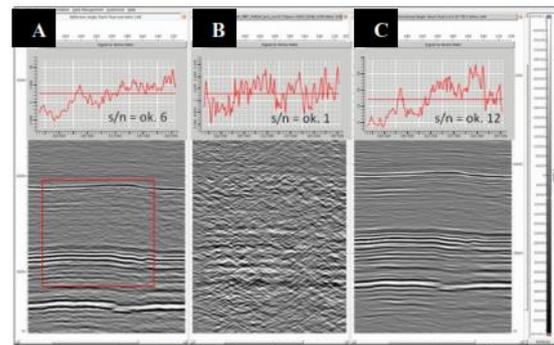

Fig.13: A) original directional stack, B) diffraction stack, C) specular stack. The s/n (signal to noise) ratio is shown for each stack.
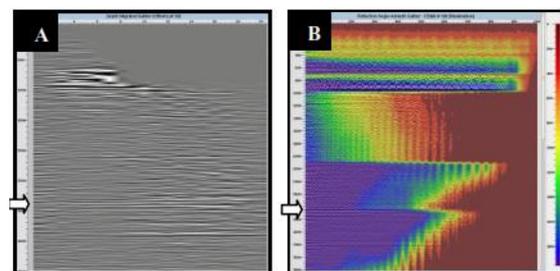

Fig. 14: Relative amplitudes restoration/preservation. A) Kirchhoff PreSDM CRP gather, B) full azimuth angle domain migration CRP gather (colors show illumination of the gather).
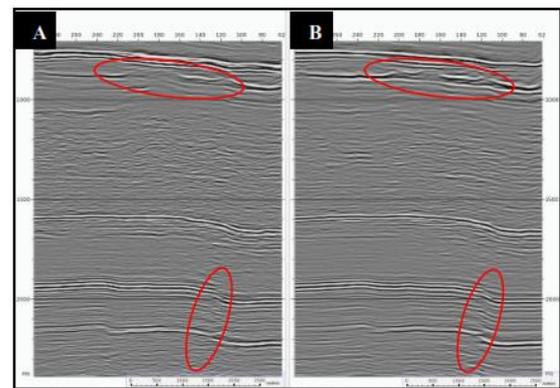

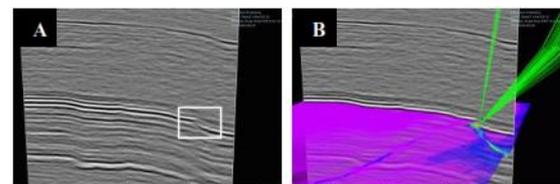Fig.15: Results of A) PreSTM and B) PreSDM.

Fig.16: Analysis of target illumination. A) the place of poorer illumination, B) map of illumination (weak – red, yellow, blue, strong – purple) and rays connected with actual geometry.

Conclusions

In this work, a novel approach to determination of azimuthal anisotropy parameters based on seismic data, is described. A key component of this workflow is working in angle, depth domain on pre-stack gathers in full range of azimuths. Parameters of azimuthal anisotropy are calculated from both kinematic and dynamic attributes of seismic events in CRPs. It assures reliability and confidence in the final results. Knowledge about fractures can be supported by diffraction image.

Additionally, this workflow gives possibility to create specular images for supporting interpretation and possibility to analyze illumination of the horizons for optimal acquisition.
Parameters of azimuthal anisotropy, obtained from seismic data with the presented novel method, are consistent with results obtained using other methods (core analysis, microimager, and dipole sonic). The results are also consistent with results of microseismic monitoring.

It was shown that the described method was successfully applied to shale plays and fracture reservoirs. But the method enables to fully exploit wide azimuth data and build high resolution anisotropic velocity models in every geology. It is advised to use it in areas of illumination ambiguities and complex wave phenomena.

Acknowledgments

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