Integration geoConvention 2013 geoscience engineering partnership

Recent advances in the characterization of unconventional reservoirs with wide-azimuth seismic data

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Summary

Wide-azimuth long-offset seismic data allow azimuthal anisotropy and direction resulting from the presence of natural fractures and anisotropic in-situ stress to be estimated. This can be done by measuring how seismic velocities and amplitudes vary as a function of the acquisition azimuth. Rock intrinsic properties like anisotropy, azimuth of fast and slow directions, fracture density and total porosity, as well as constraints on the in-situ principal stress components, can be inferred and used to help with well design, placement and completion strategies.

Recent advances in seismic azimuthal analysis of media with orthotropic symmetry are illustrated using high resolution pre-stack seismic inversion on an unconventional play in the Williston basin in North America. The algorithm, which is valid for orthotropic symmetry, was first tested on synthetic data, and then applied to real wide-azimuth 3D data. Results indicate that azimuthal variation of amplitude analysis (AVAz) for orthotropic media using wide-azimuth seismic, can be used to estimate anisotropy, azimuth and constrain principal in-situ stresses.

In addition, the middle Bakken member can be fully resolved seismically through the application of a suitable, high fidelity inversion algorithm to the azimuthal seismic data. This allows the characterization of the middle Bakken member in 3D in terms of thickness and lithology, as well as elastic and rock strength parameters. With the implementation of a suitable rock physics model, the inversion results can be used to estimate high resolution fracture density and total porosity 3D volumes and to provide information on the in-situ principal components of the stress tensor.

Introduction

Surface seismic plays a vital role in the characterization of unconventional reservoirs. Many operators worldwide are embarking on full field evaluation projects that involve acquisition and processing or re-processing of seismic data. Properly processed, imaged, and well calibrated surface seismic can be used for the early delineation of 'sweet spots', for the prioritization of drilling operations and for providing valuable information on the elastic and rock mechanics properties of unconventional reservoirs as well as anisotropy and in-situ principal stress components.

Narrow azimuth seismic 2D and 3D surveys are widely available over large unconventional exploration areas and are certainly suitable for initial screening and prospect ranking. Through construction of appropriate rock physics models and calibration to available well control, this narrow azimuth data can be used to estimate lithology, porosity and organic material content, fracture and faults and, with some simplifications and further calibration, elastic and rock strength properties and pore pressure.

It is with wide-azimuth and long-offset seismic data that azimuthal anisotropy (and direction) can be estimated. This can be done through measuring how seismic velocities and amplitudes vary as a function of the acquisition azimuth. Rock intrinsic properties like anisotropy, azimuth of fast and slow directions, fracture density and total porosity, as well as information on the in-situ principal stress components, can be inferred and used to help with well design, placement and completion strategies. This work illustrates recent advances in seismic azimuthal analysis of media with orthotropic symmetry and high resolution pre-stack seismic inversion on an unconventional play in the Williston basin in North America.

The widely used HTI formulation was expanded to accommodate orthotropic symmetry for fractured shale, a more realistic model for unconventional plays. The algorithm was first tested on synthetic data and then applied to real wide-azimuth 3D data. Results indicate that azimuthal variation of amplitude analysis (AVAz) for orthotropic media using wide-azimuth seismic, can deliver stable results that can be utilized to estimate anisotropy, azimuth and constrain in-situ stresses.

As the inversion method here uses the full bandwidth , the middle Bakken member can be fully resolved seismically through the application of a suitable, high fidelity inversion algorithm to the azimuthal seismic data. This allows the characterization of the middle Bakken member in 3D in terms of thickness and lithology, as well as elastic and rock strength parameters. With the implementation of a suitable rock physics model, the inversion results could be further used to estimate high resolution fracture density and total porosity 3D volumes and to provide information on the in-situ principal components of the stress tensor.

Workflow and application to real data

The Bakken shale play consists of three members: an upper and a lower member, generally described as organic rich marine shale, considered to be the source rock for the Bakken, and a middle member, a silty dolomitic sandstone of variable thickness (up to 80') and mineralogy. Horizontal drilling activity has been very high recently in the Williston basin, targeting the low porosity, low permeability middle member of the Bakken shale play.

Reservoir thickness, facies variation, natural fracture network, horizontal lateral length and azimuth, and in-situ principal stress components, are some of the key reservoir quality and completion quality drivers that can be addressed by wide-azimuth, full offset 3D seismic data.

The wide-azimuth 3D seismic survey targeted a Bakken shale play in North Dakota, U.S. The wide-azimuth seismic volume was processed through an anisotropic depth migration workflow that took into account overburden heterogeneities, transverse isotropy and azimuthal anisotropy (Johnson and Dorsey, 2010). Well data for one vertical well was used, including a complete log suite, a check-shot and petrophysical analysis. The target middle Bakken member at this well location is at 10,000' depth and its thickness is approximately 60'.

Azimuthal velocity anisotropy analysis (VVAz) was performed on the densely sampled 3D data. With seismic data properly sampled in offset and azimuth, travel time perturbations relative to a reference NMO (Normal Moveout), can be computed, and an elliptical fitting routine can define velocity in the fast and slow directions and the azimuth of the fast direction at arbitrary time intervals (Johnson and Miller, 2012).

The AVAz workflow proposed by Bachrach (2009) was further extended using the Psencik and Martins (2001) reflectivity approximation for orthotropic media. This approximation is more accurate than the conventional Rüger method developed for transversely isotropic media (Rüger, 1998) and more realistic for the characterization of unconventional plays. Using the measured amplitude as a function of azimuth and polar angle of incidence, the new orthotropic formulation can be written as a system of linear equations. Due to the wide-azimuth acquisition geometry, there are many more measurements than unknowns resulting in an over-determined system of equations that can be solved using singular value decomposition. Inversion of synthetic data has shown acceptable stability of the inversion engine for the current 3D acquisition geometry. The orthotropic AVAz workflow was then applied to the wide-azimuth 3D seismic data volume.

The general inversion process used to transform P-impedance (here defined as associated with P wave propagation along vertical direction), S-impedance or Poisson's ratio equivalent (here defined as associated with vertical Vp to Vs ratio) and Anisotropy reflectivity volumes into their absolute layer properties begins with a wavelet shaping process that is performed to correct the data to zero phase and stabilize any residual variation in the minimum phase component of the seismic wavelet. The wavelet is then iteratively removed from each seismic trace to generate the reflectivity series that, when integrated, represents relative layer properties of P-impedance, Poisson's Ratio and Anisotropic parameters. This process is a trace-by-trace process which can accommodate seismic velocity information (derived from moveout) or any other prior model, together with the reflectivity volumes to derive integrated seismic inversion volumes which delivers maximum resolution within the limit imposed by the wavelet bandwidth and the signal-to-noise ratio. The low frequency information is derived by integrating seismic velocity and well log data to derive a single answer that honors both seismic moveout and reflection strength.

A modified Hashin-Shtrikman (Gal et al., 1998) model, accounting for critical porosity and clay percentage variation, was derived from all available data and was used to correlate mineralogy and porosity for the background transversely isotropic elastic properties of the system, for the shaley dolomitic sandstone middle Bakken member. Azimuthal anisotropy was introduced within the model using the Schoenberg and Sayers (1995) compliance model and the fracture compliance was applied to predict fracture density using the model of Liu et al. (2000).

Lithology classification and joint stochastic inversion for prediction of reservoir properties, with associated probabilities, was carried out from the wide-azimuth inversion results. The method is based on a complete Bayesian approach that integrates different measurements at different scales. It uses Bayesian classification techniques (Bachrach, 2006; Sengupta and Bachrach, 2007) for generating the probability density functions associated with different lithologies. The advantage of this approach, compared to other classical inversion methods, is to ensure consistency between properties, here porosity, volume of clay and fracture density, by running a joint estimation of all properties together using a consistent rock physics model. The stochastic simulation and Bayesian estimation theory address the multi-scale effect between the log domain and the seismic domain and to capture associated uncertainties. Differentiating between the various lithology units is an essential prerequisite for computing rock-mechanical properties, as different relationships between dynamic and static elastic moduli apply in different lithofacies (Bachrach, 2006).

Dynamic elastic and rock mechanical properties, like Young's modulus, unconfined compressive strength, tensile strength and pore-pressure, were derived from the AVAz inversion results using engineering, correlation-based relations. These properties can be used to estimate brittleness and rock failure criteria as well as other drilling parameters.

Reservoir properties and mechanical rock properties were combined to estimate the in-situ principal components of the stress tensor, following the Schoenberg and Sayers (1995) model. The ability of the AVAz method to estimate in 3D the stress tensor components can effectively impact horizontal well placement and provide valuable input to hydraulic stimulation design.

Conclusions

Naturally occurring fractures in hydrocarbon reservoirs can increase the porosity and permeability of the reservoir, and knowledge of the orientation and density of fractures is necessary for optimizing production. Using wide-azimuth long-offset data from an unconventional play in the Williston basin in North America it was shown that azimuthal variation of amplitude analysis (AVAz) for orthotropic media using wide-azimuth seismic, can deliver stable results that can be used to estimate anisotropy, azimuth and to constrain in-situ stresses. In addition, the middle Bakken member can be fully resolved seismically through the application of a suitable, high fidelity inversion algorithm to the azimuthal seismic data. This allows the characterization of the middle Bakken member in 3D in terms of thickness and lithology, as well as elastic and rock strength parameters. With the implementation of a suitable rock physics model, the inversion results can be used to estimate high resolution fracture density and total porosity 3D volumes and the in-situ principal components of the stress tensor.

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