Integrated interpretation of seismically derived rock and fracture attributes for shale gas reservoir characterization

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Summary

An integrated study of the well Zhao-104 and surrounding seismic volume within the shale gas reservoir in South China has been conducted with the objective of generating shale formation properties related to fracture orientation and intensity in the area and deriving such reservoir rock properties as data quality allows.

Seismic attribute analysis of anisotropy from elliptical velocity inversion indicates that anisotropy varies horizontally and vertically, and that it is dominantly controlled by stress azimuth, which conforms to the current day stress field as independently determined from borehole break-outs.

For the reservoir, it appears that the modern–day SH (N40E) orientation approximates the conjugate fracture orientation of a wrench-faulted tectonic regime; this map pattern suggests a clockwise net rotation of the stress field from time of deposition to the present-day by 40°. Very large strike-slip faults (cutting the survey) have low anisotropy. Intermediate strike-slip faults cutting the entire shale section may exhibit larger anisotropy. Structural depressions formed by transtension act as TOC-rich sinks and likewise feature large anisotropy vectors. Relative paleo-sea-level change influenced mineral assemblages and elastic properties of systems tracts. Of several interpreted transgressions, only the first transgressive phase is associated with significant TOC-deposition.

Introduction

An integrated study of the well Zhao-104 and surrounding seismic volume within the shale gas reservoir in South China has been conducted with the objective of generating shale formation properties related to fracture orientation and intensity in the area and deriving such reservoir rock properties as data quality allows. Well data, structural seismic information and prestack inversion products were combined in an integrated interpretation.

Measured logging curves were edited and missing curves estimated for entire wellbore for geophysical purposes. Porosity, mineralogy and saturation were also estimated and elastic attributes were examined in crossplot space to find discrimination in properties of interest. Matrix modeling and synthetic seismograms were studied in order to understand likely seismic signatures and AVA behavior.

A set of post-stack volumetric attributes that are indicative of the presence of faults and fractures were derived and fed into an unsupervised neural network to perform fracture facies classification. In addition, seismically resolvable faults and discontinuities were automatically generated from fault sensitive attributes.

Seismic gather conditioning improved seismic data quality prior to prestack inversion by improving signal/noise ratio, removing NMO stretch and aligning reflection events. Velocities from residual moveout (RMO) analysis on individual sectors were used as input to detection of fracture orientation and anisotropy.

Fracture strike and P wave anisotropy were calculated using the RMO updated sector velocity fields in elliptical velocity inversion, while inversion for P and S impedance and derivative attributes produced volumes that relate to rock properties such as brittleness and rigidity that are likely to impact fracturing.

At the end, information from all parts of the project were combined to assess structural characteristics and identify areas of high fracturing and stress direction that are important for the placement of horizontal wells and likely high total organic content (TOC) zones, necessary as a source of hydrocarbons.

Integrated interpretation method

Integrated interpretation uses well log data, structural and seismic products in consideration of the following topics: (1) Current tectonic stresses - Orientation; (2) Rock properties calibration; (3)
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Stratigraphy; (4) Anisotropy; and (5) Geological interpretation.

**Tectonic stress**

The World Stress map project (2009) combines information from earthquakes, borehole breakouts and other sources. Close to the YH1-1 location borehole break-out data suggest a NE-SW orientation of one of the principal stresses (Figure 1), the maximum horizontal stress (SH). This detail of the world stress map features the azimuth of the maximum horizontal stress as depicted from various methods. For the study area, a borehole break-out suggests a NE-SW direction of $S_H$, although the tectonic regime has not been established.

Figure 1: World Stress Map based on the WSM database release 2008; Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences.

**Rock property calibration**

Changing mineral content gives rise to different elastic behaviors observable at the seismic well tie. Rock brittleness is governed by mineralogy: TOC-rich intervals being less brittle and calcite- and quartz-rich sections exhibiting higher brittleness. Elastic attribute values reflecting brittleness facilitate identification of potential hydraulic fracturing carrier beds and TOC-rich patches important as a hydrocarbon source.

In the ERho- Poisson’s ratio crossplot different mineralogies occupy distinct regions in the crossplot (Figure 2). In Figure 3, these lithologies are calibrated to the ERho attribute. The quartz rich shale member would be a good candidate for hydraulic fracturing while the high TOC zone is a source for hydrocarbon.

Figure 2: Mineralogy differentiated in ERho vs Poisson’s ratio crossplot space and projected into log tracks. From left logs are ERho, Poisson’s ratio, volume calcite, volume quartz and volume TOC.

**Interplay of tectonics and stratigraphy**

TOC-rich angular patches are illuminated at low ERho values in attribute extraction map views (Figure 4). TOC-rich patches are truncated by structural lineaments interpreted as wrench-faults and small-scale block rotations. Hence, TOC-rich angular patches are interpreted as structural sinks provided in form of transtensional basin-floor depressions (a suitable geological analog may be TOC-patches in the Horn River Shale, WCSB, Canada).

Figure 3: Calibration of ERho attribute with Zhao-104. Mineralogy track: blue - calcite, yellow - quartz, grey – clay, black – TOC. Calcite rich highest and parasequences are marked by red arrow.
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Seismic stratigraphy

Reflection truncations are diagnostic of the stratigraphic succession of prograding and regressive clastic wedges having formed in response to relative sea-level change and their heterogeneity affects anisotropy.

Figure 4: Coherence and ERho extracted on TS horizon. Map areas featuring low ERho values (dark blue) combining to form angular outlines are interpreted as TOC rich patches accumulated in structural sinks.

Line drawings of truncated seismic reflection events (Figure 5) produce characteristic geometries that conform to stratigraphic termination patterns allowing the definition of chronostratigraphic surfaces and application of sequence stratigraphic principles (Vail et al., 1977). Data from the northwestern corner of the 3-D survey appear to support an interpretation of a stratigraphic succession of prograding and regressive clastic wedges having formed in response to relative sea-level change (e.g., Vail et al., 1977). This stratigraphic heterogeneity contributes to large-scale anisotropy and is expected to influence fract behavior.

Anisotropy

We believe that the sources of anisotropy are a combination of seismic stratigraphy, lithology, fractures, stress and compaction with current stress azimuth being the dominant source of anisotropy. In Figure 6, anisotropy vectors are overlaid on coherence and ERho volumes. Low anisotropy generally matches less faulted zones as well as highly faulted zones (effectively isotropic due to intense deformation). High anisotropy values generally correlate with elevated ERho values; the only major exceptions being parts of possibly annealed fault zones or corridors aligning with the current maximum horizontal stress, $S_H$ (see section on tectonic stresses). The Zhao-4 well penetrates an area characterized by low anisotropy values, around 7%.

In Figure 7 published experimental results in the stress environment $\sigma_1 > \sigma_2 > \sigma_3$ fractures $a$ and $b$ are a conjugate strike slip set. A similar pattern seen in the extraction from the fracture facies volume suggests a conjugate pair formed by a maximum horizontal stress with a north-south orientation in contrast to the probable present day orientation of northeast-southwest. Fault patterns seen at the reservoir level are consistent with a wrench faulting regime in an N-S maximum horizontal stress environment.

We also examined cross-plots of anisotropy versus azimuth for seismic subvolumes at the Zhao-104 and YSH1-1 well locations as well as over the entire shale interval (Figure 8). Most of the anisotropy for the subvolume encasing the Zhao well centers at N40°E. This azimuth corresponds to the probable present-day orientation of the maximum horizontal stress and the paleo-conjugate shear fracture orientation to 160°.
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Figure 6: Anisotropy vectors colored by magnitude are overlaid on coherence, left, and ERho volumes. Low values of anisotropy are generally associated with high coherence while higher values correspond to higher ERho levels.

Figure 7: Left, experimentally formed fractures in Solenhofen Limestone (from Hobbs, Means, and Williams, 1976). σ1 > σ2 > σ3. Faults a and b are conjugate strike slip fracture. A KSOM extraction from the fracture facies volume exhibits a similar pattern (right panel) in map view suggesting that the maximum horizontal stress creating the strike-slip fault blocks was oriented N-S in today’s reference frame.

At the YSH 1-1 well highest anisotropy centers at 160°. This azimuth is approximately equal to N40°E plus 120° - which corresponds to one of the conjugate fracture orientations to N40°E. Most data (intermediate anisotropy) in this subvolume, however, center at ca. 135° which corresponds approximately to the minimum horizontal stress, S0 (S0 = SH + 90°). Most of the high-anisotropy for the entire shale interval centers at 160°, with many secondary peaks. The N40°E (SH) and the 160° (N40°E + 120°) anisotropy orientations are paralleled by low coherence values (jointing and/or paleo-conjugate faults). Most data cluster at N40E (SH).

Figure 8: Anisotropy vs Azimuth colored by voxel density for a, a small volume round the Zhao- 104 well, b, a small volume round the YSH 1-1 location and c, the total shale interval. Peaks in the anisotropy distribution correlate with inferred stress related directions.

Conclusions

Seismic attribute analysis of anisotropy from elliptical velocity inversion indicates that anisotropy varies horizontally and vertically, and that it is dominantly controlled by stress azimuth, which conforms to the current day stress field as independently determined from borehole break-outs. For the reservoir, it appears that the modern-day SH (N40E) orientation approximates the conjugate fracture orientation of a wrench-faulted tectonic regime; this map pattern suggests a clockwise net rotation of the stress field from time of deposition to the present-day by 40°. Very large strike-slip faults (cutting the survey) have low anisotropy. Intermediate strike-slip faults cutting the entire shale section may exhibit larger anisotropy. Structural depressions formed by transtension act as TOC-rich sinks and likewise feature large anisotropy vectors. Relative paleo-sea-level change influenced mineral assemblages and elastic properties of systems tracts. Of several interpreted transgressions, only the first transgressive phase is associated with significant TOC-deposition.
EDITED REFERENCES
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