Developing a strategy for CO2 EOR in an unconventional reservoir using 3D seismic attribute workflows and FMI logs: Teapot Dome, Wyoming

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Summary

In this study we develop a composite 3D seismic attribute to identify areas of high open-fracture intensity. The composite attribute consists of a combination of 3D seismic discontinuities and directional curvature. NE trending seismic discontinuities are predominant across Teapot Dome and often have visible offset. A major NE trending fault bounds the oil reservoir to the north and movement along this fault is interpreted to be right-lateral transpressional. Uplift of the southern block along this fault produces the trapping culmination. Open reservoir fractures observed in 5 FMI wells along the structure are dominated by a northwest hinge-oblique set with ~N76°W trend. This trend is close to the orientation of S_{Hmax} (N74°W) inferred from induced fractures observed in the FMI wells. 3D seismic curvature computed in the direction orthogonal to the dominant open fracture trend is extracted from the seismic. High curvature orthogonal to the dominant hinge-oblique fracture trend may enhance their aperture. The oblique open set trend also coincides roughly with the the direction of S_{Hmax}. Discontinuity and directional curvature were upscaled into the reservoir grid and combined to form a composite fracture driver. The driver reveals the potential for reservoir compartmentalization and areas where fracture intensity is likely to be highest. Distribution of predicted high intensity areas is consistent with the distribution of oil production in the field. We recommend that enhanced oil recovery operations employ lateral wells oriented in the ~N20°E direction through areas of predicted high fracture intensity and approximately normal to the S_{Hmax} trend.

Seismic Interpretation

Teapot Dome developed primarily as a forced fold in response to basement uplift and partly in response to compression resulting in a west-southwest verging fold developed over a steeply east-northeast dipping basement thrust. Poststack processing was used to enhance the 3D migrated stack data (Figure 3). The absolute value of the

Introduction

Teapot Dome is a doubly plunging Laramide-age basement cored uplift (Figure 1) located along the SW margin of the Powder River Basin in northeastern Wyoming. Oil production from the Tensleep is concentrated in a fault-bounded culmination in the southern part of the field (figures 1 and 2). The Tensleep has produced approximately 1.5 million barrels of oil or 30% of the estimated 5 million STBO originally in-place. Production from the Tensleep is water driven with an oil cut of approximately 1%. Matrix porosity in the Tensleep is ~10% with permeability of ~30mD (Friedmann et al., 2004). Production is largely controlled by fracture permeability. The major structures associated with the productive area are resolvable in 3D seismic over the field. A potential strategy for CO2 enhanced recovery of remaining oil reserves at Teapot Dome is proposed in this paper.

Figure 1: Two-way time structure on the top of the Tensleep with locations of FMI logged wells. Rose diagrams of Tensleep open fractures are presented on a well-by-well basis at left and, in-total, within the map view.

Figure 2: Depth converted view of the top of the Tensleep B Sandstone, Teapot Dome, Wyoming. Enhanced seismic profile cuts through the producing culmination. Production (log 10 year cumulative) is draped over the Tensleep structure. Colored dots locate well penetrations.
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Figure 3: A) 3D migrated stack data (TWT); B) display of enhanced seismic data (TWT).

derivative of seismic amplitude (Figure 3B) helped increase resolution and enhance reflection discontinuities. The derivative transforms peaks and troughs into zero crossings. Peak and trough amplitudes generally stand out well above the background noise. The absolute value flips negative derivatives to positive and the result is a series of positive amplitude cycles separated by sharp, zero-derivative transition lines. This series of processes increases high frequency content and enhances structural details, discontinuities and stratigraphic features. The process is time variant and phase adaptive (see Wilson et al., 2009 and 2012a).

Natural Fracture Characteristics

Cooper (2000) mapped fractures exposed in the Mesaverde Parkman Sandstone Member exposed at the surface along the flanks of Teapot Dome. His observations revealed the presence of 3 systematic joint sets consisting of hinge-parallel, hinge-perpendicular and hinge-oblique sets. The hinge-parallel and hinge-perpendicular extension joints were interpreted to have developed coevally in response to basement uplift. The third, NW hinge-oblique set was interpreted to predate folding based on fracture termination relationships.

Schwartz (2006) analyzed FMI log interpretations from the dome and found that open fracture sets were dominated by the NW hinge-oblique set along the axis of Teapot Dome. The hinge-parallel set was less distinct and present mainly near the producing area. Smith (2008) developed a reservoir fracture model that incorporated 11 fracture sets distributed through Tensleep Sandstone A, Dolomite B and Sandstone B intervals. The sets incorporated in Smith’s (2008) model were based on open fracture orientations observed in these intervals and consisted largely of NW hinge-oblique, hinge-parallel and hinge-perpendicular sets. Smith (2008) used Ant Tracking (Pedersen et al., 2002) to control the distribution of fracture intensity in her model. Ouenes et al. (2010) employed a continuous fracture modeling approach that used lithology, structure, proximity to faults and other geologic factors to control the location and intensity of fracturing. Model fracture trends throughout the field were estimated using a neural network approach.

Fracture image logs (FMI) revealed considerable variability in open fracture orientation on a well-by-well and interval-by-interval basis; however, the number of observations in these subdivisions is quite low and this makes significant trends difficult to differentiate. Here, we consider the image log data well-by-well and in its entirety. This increases the number of observations and gives us a more representative sample. Trends observed in individual wells reveal notable consistency (Figure 1). In particular, we note that the WNW trending (hinge-oblique) fractures are the most prevalent throughout the area (Figure 1). This set of fractures corresponds to Cooper’s (2000) early-formed (pre-Laramide) NW hinge-oblique set. Although Cooper reported that the strike-parallel set was the most abundant in surface exposure, FMI log observations suggest the northwest hinge-oblique set is the most abundant reservoir fracture set (Figure 1). S_{Hmax} inferred from the orientations of drilling induced fractures for all wells is N75.5°W with well-to-well variations between N73°W to N78°W. The S_{Hmax} trend coincides closely with the N76°W dominant hinge-oblique open fracture set in the reservoir.

Fracture intensity varies considerably, but generally ranges between 0.1 to 0.3 fractures per vertical foot along the wellbore (Schwartz, 2006). Image log derived apertures were observed to vary from about 0.004 mm to 0.12 mm. Apertures are log-normally distributed with the majority of apertures falling between 0.003 and 0.1 mm. Schwartz inferred minimum fracture lengths of between 2 and 7 feet using an approach developed by Ozakaya (2003). Smith (2008) and Schwartz (2006) assumed fracture heights equal to bed thickness and Smith (2008) defined fracture-lengths using a power-law distribution. Analysis of seismic scale discontinuity lengths suggests that at field scale they follow a power-law distribution with powers between -2 and -2.6.

3D seismic analysis

Seismic data were converted to depth using velocities estimated from sonic, synthetic seismic well ties and formation top depths. Discontinuities (Figure 4) were extracted from the 3D seismic using the pre-processing workflow noted above. Discontinuities are interpreted to represent small flexures, small faults and/or fracture zones. In general fracture intensity increases near faults, along flexure axes and within fracture zones. Extracted discontinuities are generally centered on alignments of individual traces associated with subtle signal incoherence. In this study, they occur across zones with widths of approximately 220 feet (twice the trace spacing). Areas of seismic discontinuity are interpreted to be potential areas of
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increased fracture intensity. However, this may not always be the case. Faults such as the S1 fault are interpreted to result from transpressional shear and are likely to be impermeable zones. These discontinuities may help seal the reservoir (as is the case for the S1 fault) or create reservoir compartmentalization. These NE trending discontinuities (e.g. Figure 4) are also oriented about 70° relative to $S_{\text{Hor}}$, so that NE trending open fractures are likely unless propped open through partial mineralization. The distribution of production within the culmination (figures 4 and 5) suggests that local permeability barriers may be present that partially obstruct and divert reservoir flow. So that tensile stresses are maintained in much of the strata overlying the forcing member. Assumptions about stress distribution are complicated by the occurrence of late-stage right-lateral shear along the length of the dome. The combination of discontinuities and maximum directional curvature shown in a volume probe (Figure 6) reveals discontinuities in white with maximum directional curvature in reds (positive) and blues (negative). Cross-strike discontinuities cutting through the producing culmination are referenced by arrows (figures 5 and 6).

Curvature has been used to identify areas of abnormal strain for many years (e.g. Lisle, 1992; Chopra and Marfurt, 2012). Volume curvature can be calculated using various inline and crossline ranges and vertical window sizes to view curvature at different scales. Maximum volume curvature at the scale of the seismic discontinuities (Figure 4) did not reveal coherent structural grain. Maximum volume curvature at intermediate scale (~440 feet and greater) in the direction orthogonal to the N75°W dominant open fracture set was extracted since the component of curvature in this direction may enhance fracture aperture and reservoir permeability along that trend. Teapot Dome developed largely in response to upward compression resulting from minor slip along a basement upthrust. The neutral surface is generally much deeper in the forced fold (e.g. Cosgrave and Ameen, 2000).
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Composite fracture driver

The discontinuity and curvature volumes were first upsampled into a model grid. The relationship of discontinuities to the open fracture distribution is complicated by the many NE trending discontinuities interpreted to be low permeability zones. These zones generally represent higher scored discontinuities. High Ant Track values were negated to minimize fracture intensity along these NE trending zones. Maximum positive curvature in the direction orthogonal to the oblique fracture trend was added and the resultant was shifted to the positive. Resultant values in the grid (Figure 7) can be scaled into a suitable intensity range for future use in the discrete fracture network generation process.

![Composite driver upscaled into the model grid. Zero intensity cells have been filtered out to highlight potential reservoir compartments. Orange colors represent intermediate fracture intensity with blue colors defining intermediate to high intensity. The producing area in the culmination is outlined in black.](Image)

Figure 7: Composite driver upscaled into the model grid. Zero intensity cells have been filtered out to highlight potential reservoir compartments. Orange colors represent intermediate fracture intensity with blue colors defining intermediate to high intensity. The producing area in the culmination is outlined in black.

Conclusions

Teapot Dome is a relatively simple forced fold of Laramide age located near the southwest margin of the Powder River Basin in northeastern Wyoming. Open fractures generally fall into one of three sets, including: 1) the dominant N76°W hinge-oblique set, 2) NNW hinge-parallel set and 3) NE hinge-oblique set.

Wilson et al. (2012b) combines seismic discontinuities and maximum curvature to control fracture intensity distribution. The driver developed in this study differs from that developed earlier by Wilson et al. (2012b) in two important respects: 1) the new driver addresses the possibility that the higher-score discontinuities may represent low permeability zones that could compartmentalize the reservoir; 2) use of maximum directional curvature orthogonal to the more prevalent N76°W hinge-oblique open fracture set in the reservoir focuses specifically on the curvature component that could enhance apertures of fractures with this trend. This trend also coincides with orientation of $S_{\text{Hmax}}$ inferred from induced fractures observed in the fracture image logs.

The results of this analysis suggest the following strategy for combined CO₂ storage and enhanced oil recovery at Teapot Dome. We recommend that NE-SW oriented CO₂ injection laterals be drilled in the up-dip direction, roughly normal to $S_{\text{Hmax}}$. Injection laterals should be placed just up-dip of the NE trending tight zones that may represent compartment boundaries. The producing laterals would be drilled down-dip to the NE along the upper side of interpreted compartments. This arrangement will enhance up-dip CO₂ flow through the dominant open fracture set in the reservoir and optimize opportunities to produce swept oil along up-dip compartment edges.

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