PS Modeling Discrete Fracture Networks in the Tensleep Sandstone: Teapot Dome, Wyoming*

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Abstract

The Tensleep Sandstone at Teapot Dome, Wyoming is a tight, naturally fractured oil-producing reservoir. In this case study, we develop a model of the discrete fracture network in this unconventional reservoir. The observational foundations used to develop the reservoir fracture network include FMI log interpretations, fracture characterization at the surface above the reservoir and examination of Tensleep field analogs. Analysis incorporates 3D seismic interpretation and post-stack processing of a 3D depth-converted seismic volume. 3D seismic enhancement workflows include Ant Tracking on a dip-deviation volume integrated with 3D volume curvature. Ant Track discontinuities are interpreted to represent possible reservoir scale faults and fracture zones. Volume curvature is used to identify areas of increased flexure that are likely to be more intensely fractured. Ant Track discontinuity and volume curvature are combined to produce a single fracture intensity driver that is upscaled into the gridded reservoir model. Areas bounding faults and areas of relatively high bed curvature often correspond to areas of increased fracture intensity. Fracture sets included in the reservoir model are based primarily on FMI log observations. FMI log observations are consistent with fracture data collected from Tensleep exposures along the culmination of the Alcova anticline and on the northeast flank of Granite Mountain anticline. The FMI logs from Teapot Dome reveal three prominent open fracture sets: hinge-oblique, hinge-parallel and hinge-perpendicular sets that are present in the approximate ratio of 4 to 2 to 1, respectively. Teapot Dome is a Laramide structure that developed partly as a forced fold in response to basement uplift and partly through compression resulting in a west-southwest verging fold developed over a steeply dipping east-northeast dipping thrust fault. Open fractures penetrated by the wellbore are about twice as numerous as healed fracture penetrations. The discrete fracture network developed in this process is used to define fracture porosity and permeability distributions throughout the field scale model. The results define pore volume (potential capacity) variations throughout the reservoir and yield insights into potential EOR and CO_2 sequestration strategies. The variability of porosity and permeability distribution predicted from the model compare favorably with the variations of oil production localized in the Teapot Dome structural culmination.

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West Virginia University DEPARTMENT OF GEOLOGY AND GEOGRAPHY

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ABSTRACT

The Tensleep Sandstone at Teapot Dome, WY is a tight, naturally fractured oil producing reservoir. In this case study, we develop a model of the discrete fracture network in this unconventional reservoir.

The observational foundations used to develop the reservoir fracture network include FMI log interpretations, fracture characterization at the surface above the reservoir and examination of Tensleep field analogs. Analysis incorporates 3D seismic interpretation and post-stack processing of a 3D depth-converted seismic volume. 3D seismic enhancement workflows include Ant Tracking on a dip-deviation volume integrated with 3D volume curvature. Ant Track discontinuities are interpreted to represent possible reservoir scale faults and fracture zones. Volume curvature is used to identify areas of increased flexure that are likely to be more intensely fractured. Ant Track discontinuity and volume curvature are combined to produce a single fracture intensity driver that is upscaled into the gridded reservoir model. Areas bounding faults and areas of relatively high bed curvature often correspond to areas of increased fracture intensity.

Fracture sets included in the reservoir model are based primarily on FMI log observations. FMI log observations are consistent with fracture data collected from Tensleep exposures along the culmination of the Alcova anticline and also on the NE flank of Granite Mountain anticline. The FMI logs from Teapot Dome reveal three prominent open fracture sets: hinge-oblique, hinge-parallel and hinge-perpendicular sets that are present in the approximate ratio of 4 to 2 to 1, respectively. Teapot Dome is a Laramide structure that developed partly as a forced fold in response to basement uplift and partly through compression resulting in a west-southwest verging fold developed over a steeply dipping east-northeast dipping thrust fault. Open fractures penetrated by the wellbore are about twice as numerous as healed fracture penetrations. The discrete fracture network developed in this process is used to define fracture porosity and permeability distributions throughout the field scale model.

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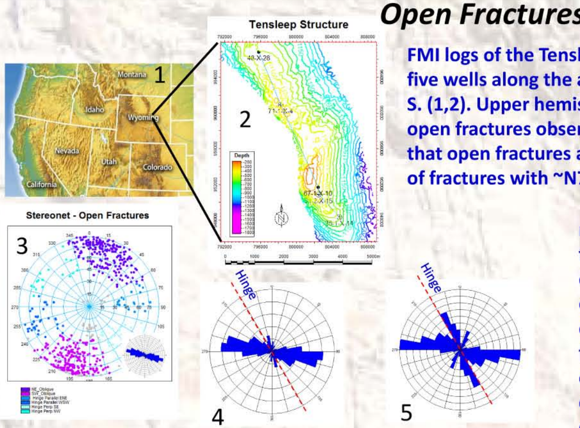
Open Fractures Observed in FMI Logs



FMI open fractures all wells: mean N72ºW, N=559

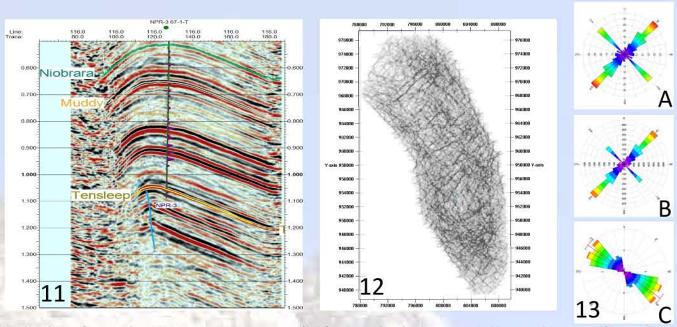
Tensleep open fractures all wells. N=219

Tensleep open fractures (n=52) from well closest to the culmination (67-1X-10)

FMI logs of the Tensleep Sandstone are available from five wells along the axis of Teapot Dome, Wyoming, U. S. (1,2). Upper hemisphere projections of poles to open fractures observed in these 5 wells (3) reveal that open fractures are dominated by a diffuse cluster of fractures with ~N72ºW orientation.

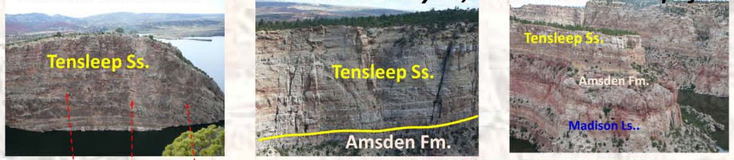
Open fracture rose diagrams reveal pervasive NW hinge oblique fractures extending through the entire section (3). The NW hinge oblique set is also the dominant set observed in the Tensleep (4). Open fractures observed in the FMI log closest to the producing culmination (5) fall into 3 sets: the dominant NW hinge-oblique set, and interpreted hinge-parallel and NE hinge-oblique-sets.

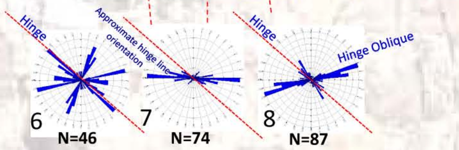
Seismic Scale Fracture Zones and Faults

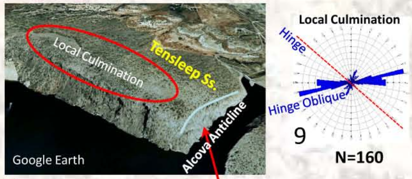


A dip line from the 3D seismic survey (11) reveals that Teapot Dome is a northwest vergent anticline, very similar in appearance to the exposed Alcova Anticline analog (10). Data were preprocessed (see Footnote 1) and then run through the Ant Track workflow to extract discontinuities associated with minor faults and fracture zones (12). Ant track orientations are dominated by hinge-parallel and hinge-perpendicular sets (13 A & B). Filters incorporated in the Ant Track workflow reveal the hinge-oblique set (13C).

Field Analogs



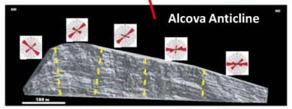




Alcova Area: Exposed Analog of Tensleep Ss. Fracture Systems

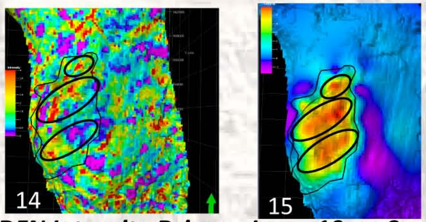
Fracture orientation data were collected over numerous exposures of the Tensleep Ss. on the Alcova anticline and the northeast flank of Granite Mountain in the Sweetwater Uplift. Field measurements reveal fracture systems quite similar to those inferred from FMI observations in the subsurface at Teapot Dome. Measurements across Alcova Anticline show some variability in fracture orientation (6, 7 and 8). The ENE hinge-oblique set is pervasive. NNE hinge-oblique and hinge-parallel sets are less abundant. Fracture observations out along the fold axis and across a local culmination (9) also reveal a dominant ENE hinge oblique set with secondary NNE hinge-oblique to hinge-perpendicular set.

10



Gilbertson (2006) LIDAR derived fracture orientations (10)

Building the Discrete Fracture Network - DFN

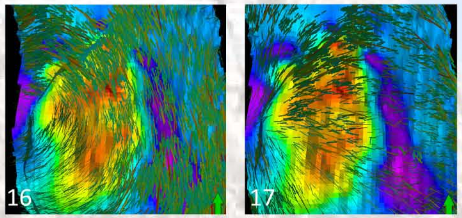


DFN Intensity Driver

Log_{10} 10 yr. Cum

Ant Track discontinuity and volume curvature are combined to produce the fracture intensity drivers (14). Drivers are used to control discrete fracture intensity and upscale fracture network properties into the reservoir model. Intensity driver (14) is compared to log_{10} 10 yr cumulative production (15).

The model DFN incorporated three sets: the early formed hinge oblique set (see Cooper, 2000), the hinge-parallel set (16) (modeled as concentric fractures) and the hinge- perpendicular set (17) (modeled as radial fractures). See Footnote 2.



Hinge Parallel (concentric)

Hinge Perpendicular (radial)

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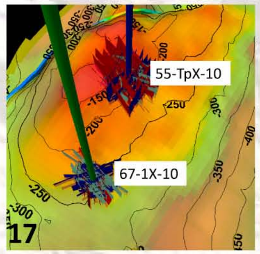
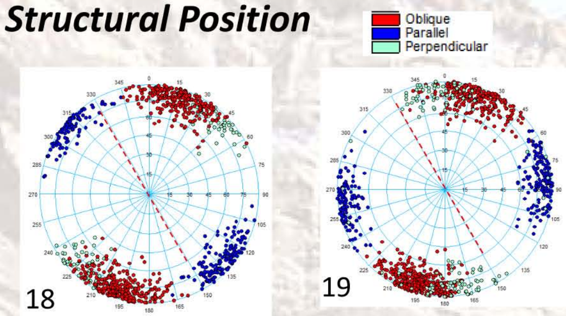
Fracture Patterns and Structural Position

Fractures in the vicinity of the 67-1X-10 and 55-TpX-10 wells include all three sets (17). Due to local structure, the hinge –parallel set in well 67-1X-10 appears to be NE hinge-oblique, and the hinge-perpendicular set overlaps some with the early formed NW hinge-oblique set (18). Orientations shift near the crest (19).



17

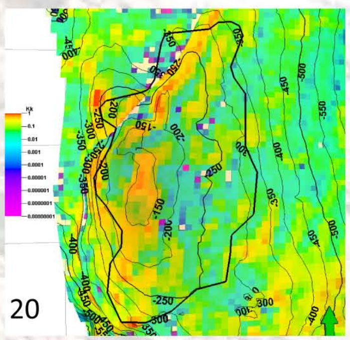


18 67-1X-10

19 55-TpX-10

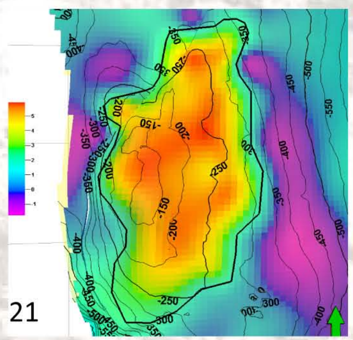
Early-formed hinge-oblique fractures maintain a consistent orientation in the model regardless of position on the dome, but hinge-parallel fractures in the 55-TpX-10 well (blue dots) are rotated into a NE hinge-oblique position in well 67-1X-10.

Reservoir Properties Upscaled Fracture Network



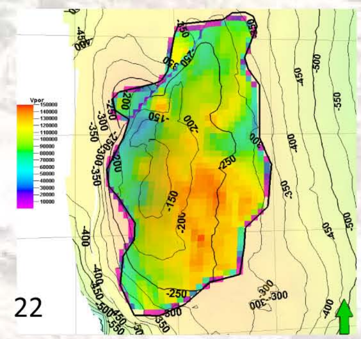
20

Fracture Permeability (vertical)



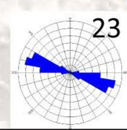
21

log $_{10}$ 10 yr cumulative production



22

Pore Volume



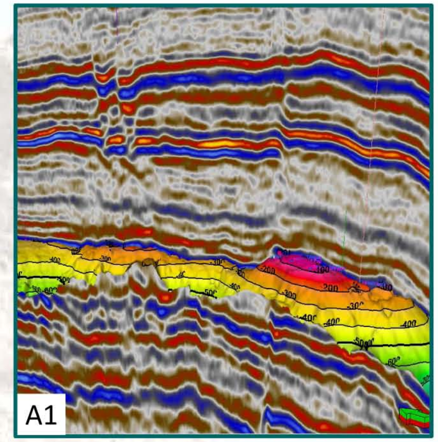
23

Drilling induced fracture orientations (σ_{hMax}) ~N74°W (23) (see Footnote 3).

CONCLUSIONS

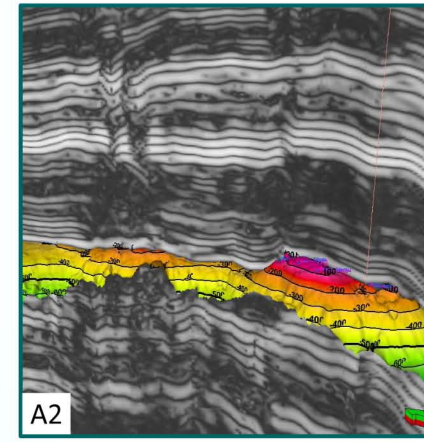
The workflow introduced here provides robust estimates of the Teapot Dome DFN and its flow parameters. The DFN is constrained by observations at well log, outcrop, seismic and production scales. CO_2 EOR can benefit from strategic placement of wells in predicted high permeability zones (20) near high producing areas (21). EOR and high volume CO_2 storage could be facilitated through down dip injection in thicker, higher pore volume areas (22). Frac'ing of horizontal wells with laterals oriented N15-17°E (normal to σ_{hMax} of ~N74°W) would enhance fracture permeability along the most pervasive hinge-oblique fracture trend.

Footnote 1: Extracting structural details through post-stack processing



A1

Depth Converted Amplitude Display



A2

Discontinuity Enhanced Display

Migrated stack data (A1) have limited resolution. Poststack processing and seismic interpretation were focused on the enhancement and extraction of seismic features that might be associated with fracture zones and faults. The absolute value of the derivative of seismic amplitude (A2) helped increase resolution and enhance discontinuities that might be associated with potential faults and fracture zones. 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. The series of processes increases high frequency content and enhances structural details and discontinuities. The process is time variant and phase adaptive (see Wilson et al. ,2009 &2012).

Footnote 2: Discrete Fracture Network: Tensleep Reservoir

Fracture observations at the surface in the Cretaceous Mesaverde Formation (Cooper, 2000) suggest that hinge-parallel and hinge perpendicular fractures maintain constant trend across the southeastern plunging nose of the Dome. We do not dispute Cooper's model, however, the FMI log observations in the Tensleep Formation suggest increased variability of open fracture orientations on the plunging nose southeast of the culmination . The DFN's developed in this study use concentric and radial fractures that might develop in response to forced folding. Some of these differences in fracture trend may be explained by differences in sample distribution and increased structural complexity at the depth of the Tensleep Sandstone.

Footnote 3: Drilling induced fracture orientations

Drilling induced fractures observed in the 5 FMI wells at Teapot Dome are consistent in trend along the length of the dome., varying by approximately 5° from about N73°W to N78°W.

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Acknowledgements

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