Relation between seismic curvatures and fractures identified from image logs - application to the Mississippian reservoirs of Oklahoma, USA

Malleswar (Moe) Yenugu and Kurt J Marfurt, University of Oklahoma, USA

Summary

Tensile fractures are often associated with structural heterogeneities such as geological anticlines and domes, which can influence the charge, seal and production rates of hydrocarbon reservoirs. Here we correlated high dense fractured zones measured from image logs with curvature attributes generated from post-stack seismic data.

Introduction

A large portion of the world's proven oil and gas reserves have been found in reservoir rocks that are naturally fractured. Fractures in reservoirs create both problems and opportunities for exploration and production. Fracture identification and characterization is very important as they impact the porosity and permeability. Fractures can provide both storage and pathways for oil production and connection to adjacent acquifers. Fracture prediction in subsurface reservoirs is critical for exploration through exploitation of hydrocarbons. Fractures are defined as discontinuities that occur in rocks due to brittle/semi brittle deformation.

Surface seismic data can aid in the prediction of fracture orientation and intensity. The main targets of the study area are the Mississippian limestone and tripolitic chert reservoirs. The success of the wells depends on the number and orientation of open fractures that are encountered by the horizontal wells.

Fracture formation in normal faulting

Figure 1 shows an outcrop image of Reeds spring formation, one of the primary targets in the Mississippian chert plays in the Mid-Continent of USA. The Reeds spring (and sometimes the overlying Burlington-Keokuk formation) consists of thin (20cm) alternating layers of chert and tight limestone. This brittle formation is almost highly fractured. In this example, there are two main orthogonal sets of fractures that can be seen on all four sides of the quarry. The chert diagenetically alters to tripolite (white on a fresh face, buff color on outcrop) that serves as an excellent reservoir rock. In this face, 50% of the rock is tripolite.

Stress is defined as the force per unit area acting on a plane. Any stress state at a point in a solid body can be described completely by the orientations and magnitudes of the three principal stresses. For a normal faulting regime, the principal stresses are defined: σ1 (vertical direction) > σ2 (maximum in horizontal direction) >σ3 (minimum in horizontal direction). Joints and styolites are the common fracture types seen on outcrops and in the subsurface for normal fault setting.

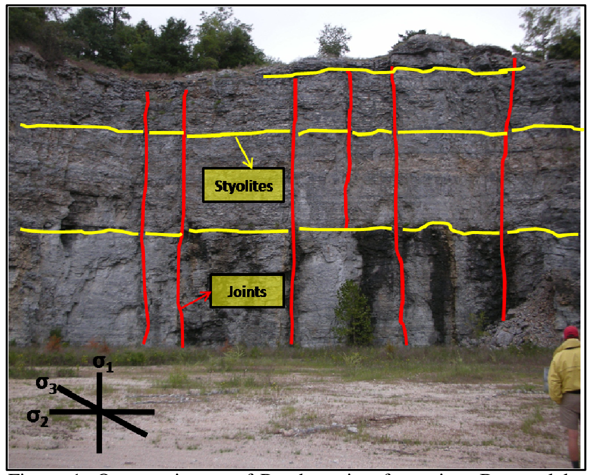

Figure 1: Outcrop image of Reeds spring formation, Beaver lake dam, Arkansas.

Seismic characterization of fractures

Fractures can be characterized from pre-stack, post-stack and VSP (Vertical Seismic Profiling) data. Pre-stack seismic methods such as AVAz (Amplitude Variation with Azimuth) and VVAz (Velocity Variation with Azimuth) (Hunt el al., 2010) have been useful in characterizing the azimuthal anisotropy caused by near vertical fractures using P-wave acquisition and processing. Shear wave splitting also useful in measuring the anisotropy caused by fractures. From post-stack seismic data, geometric attributes such as coherence and curvature are useful in understanding the structural deformation of the rocks. Lisle (1994) and Hennings et al. (2000) have calibrated the fractures measured from outcrops with curvature attributes.

We computed volumetric curvature and coherence attributes from the post stack seismic data. Figures 2a and b show horizon slices extracted within the Mississippian target zone through the most positive principal curvature and coherence volumes. Coherence is sensitive to the vertical displacement between traces indicative of faults and curvature measures the relative folding of the rocks (Chopra and Marfurt, 2007). Figure 2c is a co-rendered image of both positive curvature and coherence slices. The folding identified from curvature and faulting identified from coherence has been highlighted with arrows in the

Relation between seismic curvatures and fractures identified from image logs – application to the Mississippian reservoirs of Oklahoma, USA

Figure 2c. The faulting is mainly on the limbs of a fold. Nelson (2001) has observed that major fracturing will occur on the hinge zones of a fold for limestones.

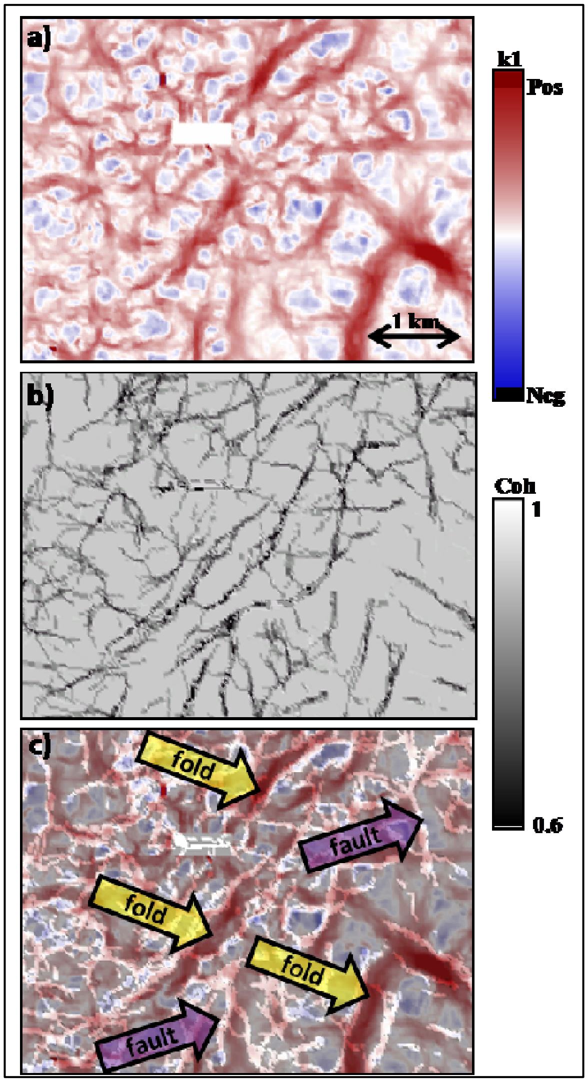

Figure 2: (a) Horizon slices through the Mississippian through most positive principal curvature (b) coherence and (c) co-rendered image of coherence and curvature volumes.

We calculated two types of curvature from the seismic data. We computed 2[nd] derivatives of the reflector time on depth (1[st] derivatives of structural dip components) which we denoted as structural curvature (Figure 2a). We also compute 2[nd] derivatives of amplitude (1[st] derivatives of amplitude gradients), along dip which we denote as amplitude curvature. Figures 3a and b show the horizon slices of positive and negative amplitude curvatures measured from seismic data.

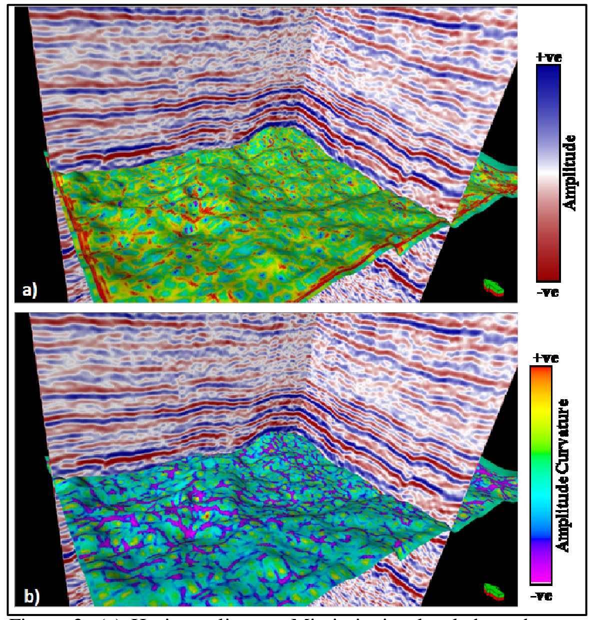

Figure 3: (a) Horizon slices at Mississippian level through most positive and (b) most negative amplitude curvature volumes

Relation between curvatures and local stress

Curvature attributes measure the structural shape of the seismic data (Chopra and Marfurt, 2010). Anticlinal features, especially hinge zones, show clearly on most positive curvature maps. Nelson (2001) describes how zones of greatest curvature relate to the zones of greatest strain in the rock. The relation between curvature and strain allows us to use curvature measures from 3D seismic to infer fractures. Although curvature measures relative bending and structural deformation and possible fractures at the time of deformation, we need to estimate the present day stress field from borehole breakouts, image logs and azimuthal anisotropy measurements.

From the borehole breakouts, the present day local stress is estimated along the N70E direction such that the fractures aligned in this direction will be open and the fractures aligned the perpendicular will be closed. Figure 4 shows the most positive principal curvature horizon slice with the fracture hypothesized on the hinge zones. The fractures aligning the present day stress should be open (indicated by black arrows) and the fractures aligned perpendicular to the present day stress should be closed (shown by green

Relation between seismic curvatures and fractures identified from image logs – application to the Mississippian reservoirs of Oklahoma, USA

arrows). A horizontal well which passes through multiple open fracture zones will yield maximum production.

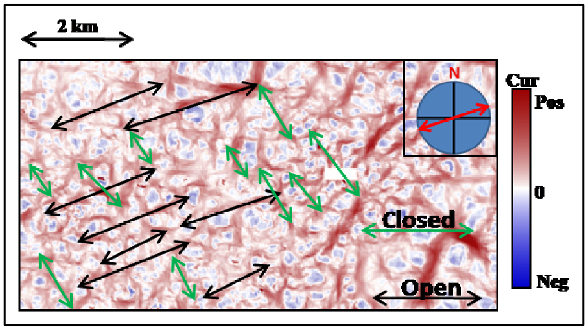

Figure 4: Horizon slice through most positive principal curvature volume within the target zone. Identification of open and closed fracture prone zones inferred from present day stress information. The direction of the present day stress measured from borehole breakouts is shown in red (inset).

Relation between curvatures and fracture density

All geometric attributes such as curvatures generally predict higher fracture intensity in the crest-forelimb region of the fold, which we can correlate and to be consistent with mapped fracture intensity on outcrops (Zahm and Hennings, 2009). The image log is a high-resolution borehole tool that can image the fractures in the wellbore at the centimeter and millimeter scale. The image log tool provides its electrical image from micro-resistivity measurements. Hunt et al. (2010) have calibrated the fracture density from image logs with AVAz and curvature attributes.

Figure 5a shows the horizontal well drilled within the Mississippian section. The advantage of drilling horizontal wells is that we will get the fracture density due to HTI.
Figure 5b shows the zoomed view of the horizontal well along the most positive principal curvature slice with the intensity of fractures identified from the image log. The high density fracture zones (> 10 fractures per 10 feet) have been highlighted with red color and low density fracture zones (< 10 fractures per 10 feet) have been highlighted by black color along the well path.

The high fracture zone lies on the hinge zone of a fold measured from curvature. The low density fractured zone fall on the synclinal part of the folded rock. We thus interpret the hinge zones of the folded rock to be more highly fractured than the other parts of the fold.

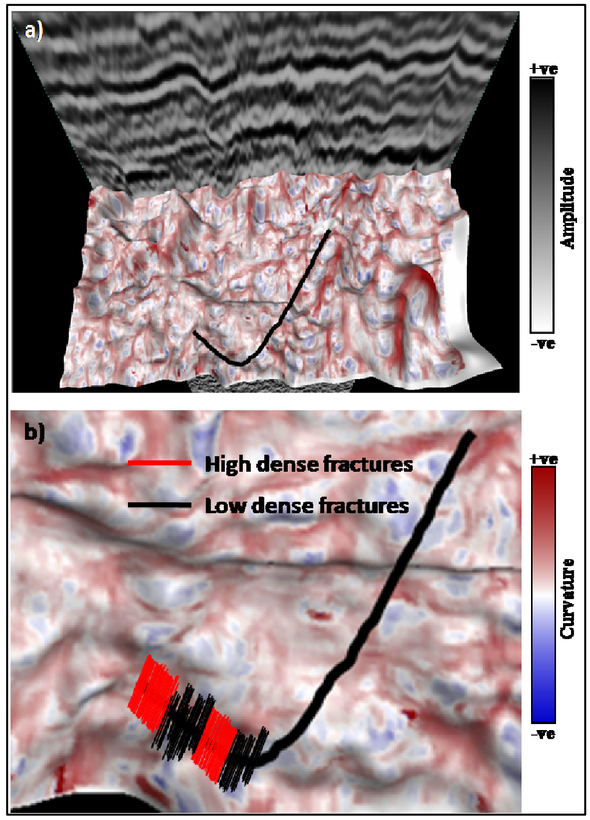

Figure 5: (a) The location of the horizontal well along the most positive principal curvature slice (b) Zoomed view of the horizontal well location with fracture density demarcated along the well path.

Conclusions

Fractures play an important role in hydrocarbon production. Seismic characterization of fractures is very important for drilling wells. The local stress identified from image logs or borehole breakouts can be utilized to identify the open or closed fracture zones from curvature attributes. The curvature attributes will be helpful to identify the high fractured zones measured from image logs.

Acknowledgments

Thanks to Spyglass Energy Group for the use of data. Thanks to sponsors of AASPI research consortium at OU. Thanks also to Schlumberger for Petrel academic licenses.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2011 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Chopra, S., and K. J. Marfurt, 2007, Volumetric curvature attributes adding value to 3D seismic data interpretation: The Leading Edge, **26**, 856–867, doi:10.1190/1.2756864.

———, 2010, Integration of coherence and volumetric curvature images: The Leading Edge, **29**, 1092–1107, doi:10.1190/1.3485770.

Hennings, P. H., O. E. Jon, and T. B. Laird, 2000, Combining outcrop data and three-dimensional structural models to characterize fractured reservoirs: An example for Wyoming: AAPG Bulletin, **84**, 830–849.

Hunt, L., R. Scott, B. Tyson, H. Scott, D. Jon, and C. Satinder, 2010, Quantitative estimate of fracture density variations in the Nordegg with azimuthal AVO and curvature: A case study: The Leading Edge, **29**, 1122–1137, doi:10.1190/1.3485773.

Lisle, R. J., 1994, Detection of zones of abnormal strains in structures using Gaussian curvature analysis: AAPG Bulletin, **78**, 1811–1819.

Nelson, R., 2001, Geologic analysis of naturally fractured reservoirs: Elsevier

Zahm, C. K., and P. H. Hennings, 2009, Complex fracture development related to stratigraphic architecture: Challenges for structural deformation prediction, Tensleep sandstone at the Alcova anticline, Wyoming: AAPG Bulletin, **93**, no. 11, 1427–1446, doi:10.1306/08040909110.