Calibrating seismic fracture prediction using borehole image logs, application to the Mississippian Limestone

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Summary

The Mississippian Limestone on the shelf margin of the Anadarko Basin in Northern Oklahoma can be a highly productive formation and has had a significant increase in activity during the last 15 years. Well-known tripolitic chert fields have long been exploited on the shelf margin, with areas of the formation with less matrix porosity but significant fracture porosity now being targeted with horizontal drilling. Limestone and cherty limestone can be heavily fractured in this study area. Knowledge of areas with higher fracture intensity can help prioritize wells with increased fracture porosity and permeability.

Most Mississippi Limestone fracture studies have been east of the north-south trending Nemaha Uplift. Our study lies west of the Nemaha Uplift (Figure 1). We hypothesize that fracturing in this area is controlled by lithology, tectonic deformation, and diagenesis. To evaluate these hypotheses we correlate volumetric attributes computed from the surface seismic data to image logs run in six horizontal wells. We find that highly fractured diagenetically altered chert results in anomalously low envelope and low density. We also see a correlation of fractures to isolated coherence and most-negative curvature anomalies, suggesting tectonic fractures in fault damage zones.

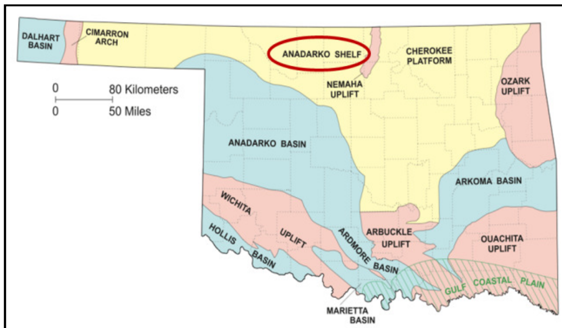

Figure 1. Location map highlighting the general area of the study on the shelf margin of the Anadarko Basin (Northcutt and Campbell, 1995).

Introduction

First produced in 1919, the increase in horizontal drilling in the early 21th century has revitalized the Mississippian Limestone play in southern Kansas and northern Oklahoma. The Mississippian Limestone on the shelf margin is a highly heterogenous formation with a number of lithologiesm with the diagenetically altered highly porous tripolitic chert being the initial target east of the Nemaha Uplift. However, west of the Nemaha Uplift, much of the tripolitic chert was eroded during the uplift and subaeriel exposure during early Pennsylvanian time. With limited coverage of porous tripolitic chert, fracture porosity in the tight cherty lime formations forms the more economic parts of the reservoir after exploitation of limited locations in the tripolitic chert.

Mazzullo, et al. (2011) found that fracturing was dependent on lithology, with an increase of fracturing in chert and cherty limestone. Less fracturing was seen in shale rich limestone. Similarly, Manger (2014) attributes fracturing to diagensis of chertier lithologies, with many fractures associated with shrinkage.

While other studies, such as Young (2010) also attribute fracturing to diagensis, it is important to determine whether fracture development of the Mississippian Limestone on the Anadarko Shelf, west of the Nemaha Uplift is driven more by tectonic deformation or by diagensis. If one or both of these contols are important, the next task is to determine what combination of seismic attributes can be used to highlight fracture intensity throughout the study area. In this paper, a number of seismic attributes are utilized to generate a fracture intensity model with the use of interpreted borehole image logs (Figure 2) and multivariate statistics.

Motivation

Fracturing in the Mississippian Limestone has been investigated with a wide range of studies. However, most of these studies lie east of the Nemaha Uplift (Figure 1). Trumbo (2014) speculated fracturing in the Mississippian based on sporadic production in vertical wells into a reservoir that lacked matrix porosity. Stearns (2015) saw some, but limited correlation between fracturing and curvature. In contrast, he found a strong correlation of fracture intensity with gamma ray values, indicating lithology-driven fracturing. Also east of the Nemaha Uplift, Turnini (2015) found that most positive curvature could be used to identify mounds of tripolitic chert. Holman (2014) conducted a fracture study of the Mississippian east of the Nemaha Uplift using multivariate non-linear regression statistics to create a fracture intensity horizon at the top of the Mississippian. He was able to find a sound correlation of instantaneous amplitude and frequency with fractures. However, his statistics pointed to a correlation with coherence and curvature that indicated a negative correlation of fractures with increased deformation.

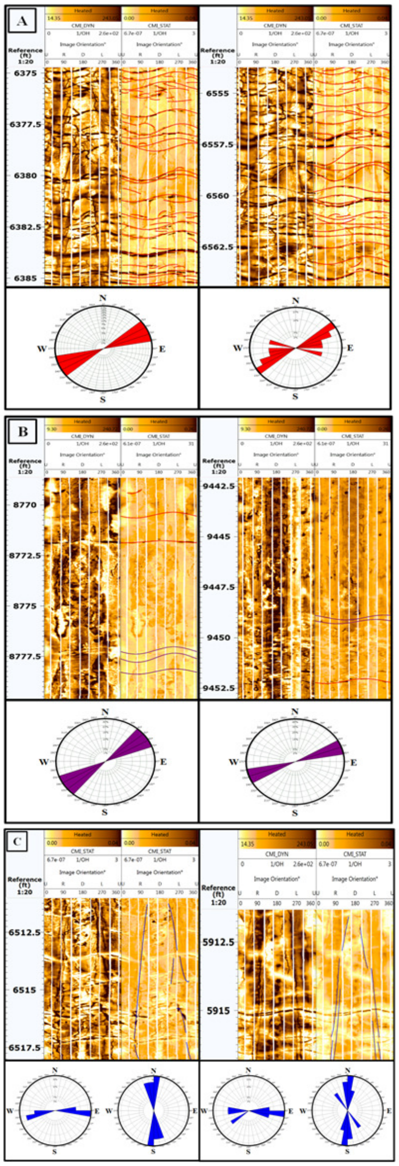

Figure 2. Examples of borehole image logs in the Mississippian Limestone with (a) conductive fractures interpreted in red (b) resistive fractures in purple, and (c) induced fractures in blue. Stereonets of interpreted fracture strike are underneath borehole images in (a) and (b). Dip azimuth of induced fractures is on left and strike on right underneath borehole images in (c).

West of the Nemaha Uplift, Lindzey (2015) conducted a study on the Mississippian Limestone using the same seismic data as this study. Using logs and core tied to the seismic data, she created a 3D lithology, porosity, and water saturation geomodel. The objective of this paper is to investigate which seismic attributes, if any, can best map these fractures, and if successful, determine which parts of reservoir are more intensely fractured than others, potentially prioritizing the order of drilling and completion within a low oil price market.

Geological Background

The Mississippian Limestone was deposited on a sloping shelf margin that dipped southward into the Anadarko Basin from 360 to 320 ma. The study area was covered by a shallow, well oxygenated sea. In this area sponge-spicule mounds were deposited (Rogers et al., 1995). There are two methods of chert replacement in the limestone of the study area. In one setting tripolite is moved downslope with increasing sea level (Rogers et al., 1995). With the Pennsylvanian uplift, subaerial exposure created a second occurance of diagensis and resulted in moldic porosity. This extended period of subaerial exposure and erotion also resulted in the Mississippian-Pennsylvanian unconformity (Montgomery el al., 1998).

The study area lies east of the Cimarron Arch and west of the Nemaha uplift, with present-day east–west stress in the area. Faulting in the study area runs 30º off of maximum horizontal stress, with generally strike-slip faulting that runs east-northeast to west-southwest. Pop-up structures, common in strike-slip environments, are also found in the study area; fractures exhibit the same strike as faulting.

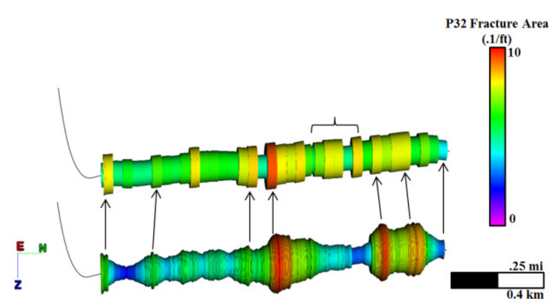

Figure 3. (Top) the predicted fractures and (bottom) the interpreted fractures for the blind well not used in generating the correlations. Arrows illustrate similar fracture intensity increases or decreases in both the modeled fractures and what was interpreted on the borehole image. The bracket highlights an area of inaccurate prediction.

Modeling of fractures is of high importance, because wells targeting areas of high fracturing will have increased permeability.

Fracture Modeling

Five borehole images were interepreted for open, conductive fractures. P32, fracture area logs, were generated as a result of fracture interpertations and a caliper log. A seismic volume covering the five borehole image logs was depth converted. For the depth conversion time horizons, depth formation tops and average velocity models were interpreted for the Missisipian Limestone, an overlying formation and a underlying formation. A number of complex trace, geometric, and inversion volumes were generated for this seismic volume. These seismic attributes, now in depth, were extracted along the laterals of the five wells with borehole image fracture interpreation. The P32 fracture area logs were upscaled to have a resolution similar to seismic resolution. To obtain this, a Backus average was run on the log with a 220 foot window size. Multi-variate non-linear regression statistics was then done on the seismic attributes to obtain which seismic attributes contribute to fracture prediction. A fracture instensity model was generated and compared with a blind well, not utilized in the model generation (Figure 3).

Seismic Calibration to Borehole Image Logs

With the use of multivariate non-linear regression statistics, six attributes were found to contribute to fracture prediction in a way that was geologically sound. The attribute with the highest significance was instantaneous amplitude, or envelope. With decreased amplitude strength, fracture intensity increased. Decreasing density from acoustic impedance also contributed to an increase in fractures (Figure 4). Geometric attributes variance, most negative curvature, and certain dip azimuth angles predicted an increase in fractures as well. Another complex trace attribute, instantaneous frequency, showed that a decrease in frequency correlated to an increase in fractures.

The Fracture Model

The resulting fracture model shows an increase in fracturing near previously mapped faults in the study area. Fracture intensity was elevated in areas of high tripolitic chert content as well (Figure 5). Swaths of high fractures continued laterally in the Mississippian Limestone, most likely in areas that contained a lithology of lower density. Lastly, karsting was seen throughout interpretted borehole image logs, and the resulting fracture model highlighted areas that are known to be highly karsted.

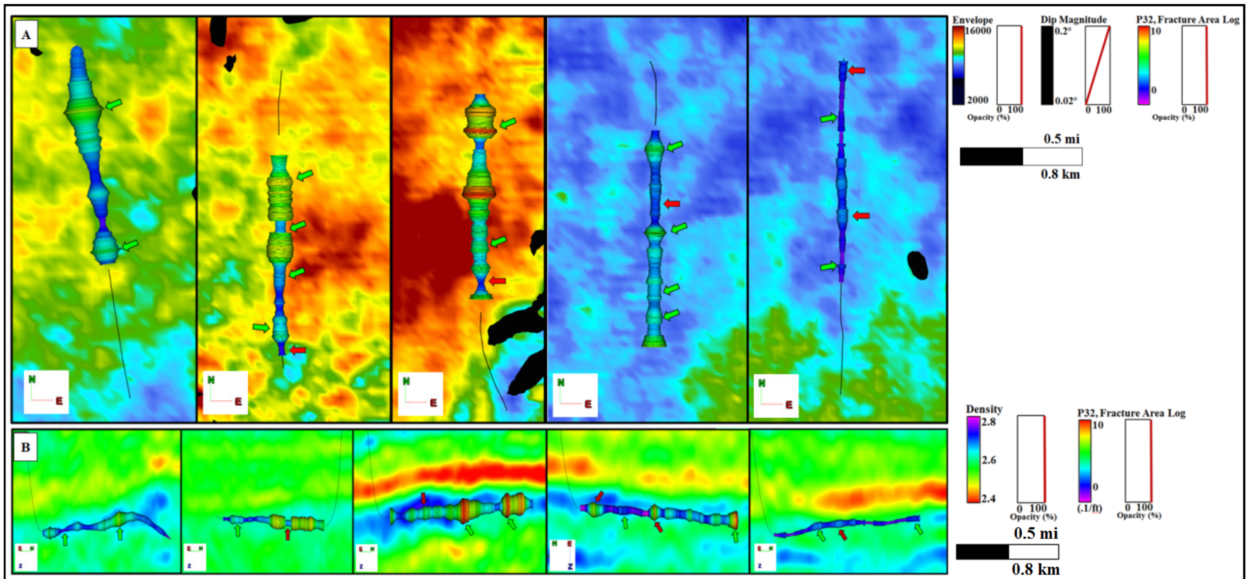

Figure 4. (a) Instantaneous amplitude, or envelope, was the largest contributor to fracture intensity prediction. Interpreted fracture area logs are plotted on envelope, co-rendered with dip magnitude. Green arrows indicate trends where a decrease in amplitude strength correlates with an increase in fracture intensity. Red arrows indicate areas that go against this correlation. (b) The second highest correlation with fractures in the non-linear regression work was a density computed from prestack inversion Here is a look at all five P32 fracture area logs from borehole image interpretation up against the density. In the non-linear regression correlation, fractures increased with decreasing density. Green arrows indicate areas along the laterals that agree with this correlation, and red arrows indicate areas that disagree with this correlation.

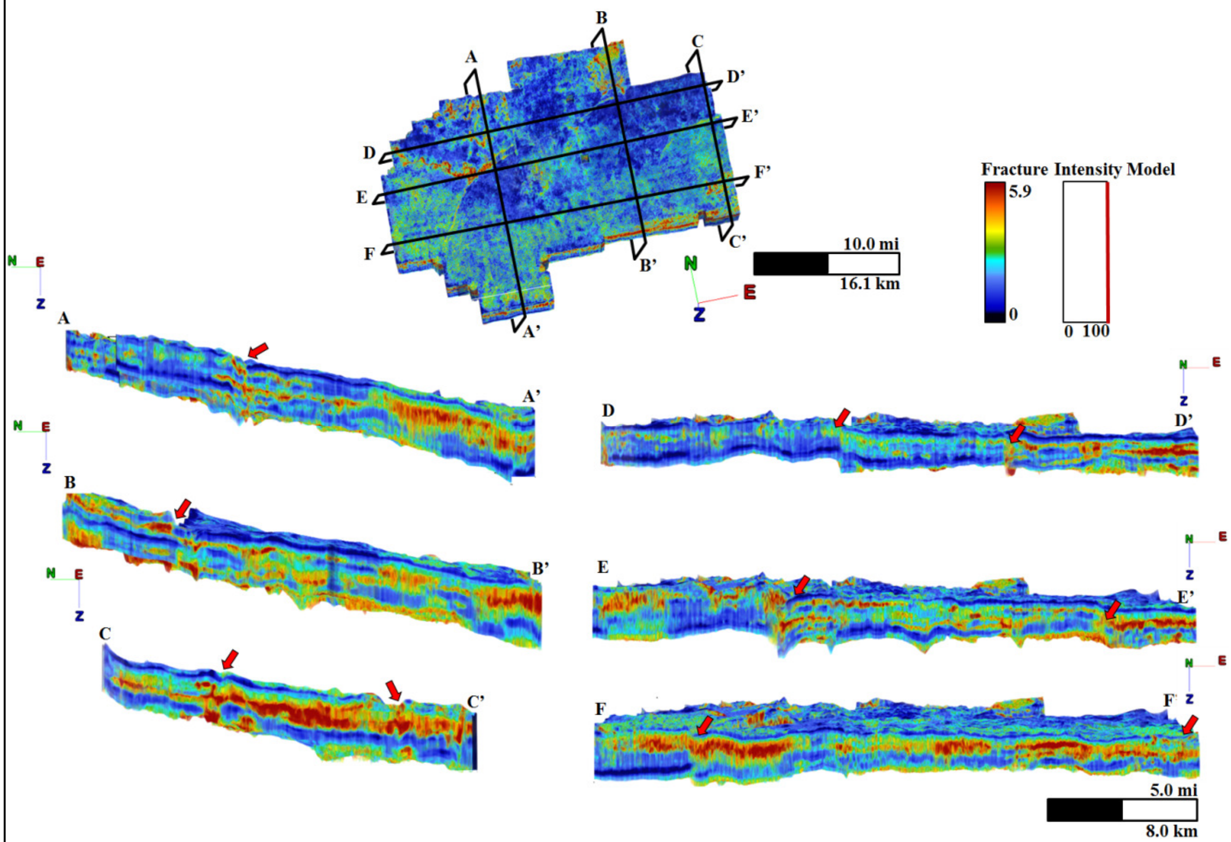

Figure 5. A fracture intensity model through the top of the Mississippian Limestone and cross sections north to south and east to west through the study area. Red arrows indicate interpreted faults where we note prediction of higher fracture intensity. The high fracture intensity swaths run laterally instead of vertically through the section, which is expected considering amplitude and density were the most significant seismic attributes contributing to fracturing. This could be a result of lithology changes throughout this heterogeneous formation contributing to fracturing.

Conclusions

Interpreting borehole image logs reveals high heterogeneity in the Mississippian Limestone with lithologies including chert, cherty limestone, highly fractured limestone, and limestone. Collapse features were also seen in most of the borehole image logs. Modeling fractures with the use of seismic attributes illustrated that fractures are both structurally and diagenetically controlled. Inversion volumes show that diagenetic fracturing resulted in diminished density. Although a relatively flat formation, most negative curvature correlated to zones of higher fracturing and further indicating fracture increase in areas of structural deformation.

Acknowledgements

Thanks to Chesapeake Energy for use of their seismic data volume, well data, and Mississippian Limestone borehole image logs. Borehole image interpretation was done in Schlumberger's TechLog software and fracture modeling was generated using Drilling Info's Transform software.

EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2016 SEG Technical Program Expanded Abstracts have been copyedited 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.

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