Flexures in the Anadarko Basin – Do they indicate faulting or folding?

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Summary

The economic success of the relatively new STACK area of the Anadarko Basin of Oklahoma has justified the acquisition of new 3D seismic data volumes. One of the first tasks in evaluating plays for horizontal drilling is to map the structure and alert the drillers of potential faults that can cause wells to go out of the target formation. Much of the faulting in Oklahoma is basement controlled. The high-quality seismic data illuminate a previously undocumented system of magmatic sills that range from flat to upward climbing to the east. None of these sills or dikes penetrate the sedimentary section, indicating that they occurred before the Cambrian period. These sills do give rise to irregular topography in the basement, which appears in turn to result in measurable differential compaction in the overlying sedimentary formations. In contrast to the sills, many of the basement faults cut through the sedimentary section, indicating that they were either formed or reactivated during late Cambrian to Pennsylvanian time. Although there is significant offset of faults at the top basement and at formations as shallow as the Hunton Limestone, by the time this deformation reaches the target Mississippian age formations, almost all these deeper faults appear as a system of cross-cutting flexures. Given the high quality of the data (especially below the Hunton where one might expect to lose resolution) these flexures indicate either faults whose offsets falls below seismic resolution or a true flexure. Regardless of their actual cause, these flexures are a measure of strain, such that if the rock is sufficiently brittle, they may serve as a proxy for natural fractures.

Structural History

With depths to basement of 30,000-40,000 ft, the south-dipping asymmetric Anadarko Basin along the northern flank of the Wichita Uplift is the deepest Phanerozoic sedimentary basin in North America, shallowing out into the Anadarko Shelf to the north and east (Figure 1). The formation and evolution of Anadarko Basin has strongly influenced the sedimentation rate, erosion, depositional environment, reservoir seal and source rocks from Cambrian through Permian time. Perry (1989) divides the history of the Anadarko basin into four major periods: (1) Precambrian igneous activities leading to crustal consolidation, (2) development of the Southern Oklahoma Aulacogen during Early Cambrian through Middle Cambrian, (3) development of the southern Oklahoma trough during Late Cambrian through Early Mississippian, and (4) initiation of an independent Anadarko Basin during Late Mississippian time.

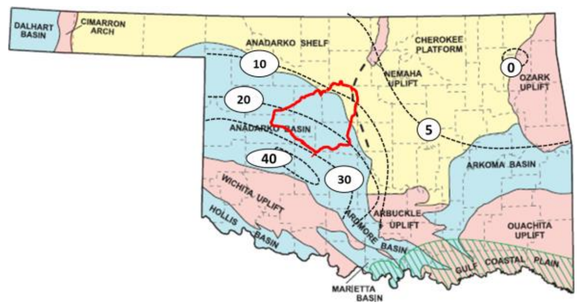

Figure 1. Map showing the location of the basins and structurally significant areas in Oklahoma. The contours shown by the back-dash line indicate the depth of the eroded top of the Precambrian and Cambrian Basement rocks in thousands of feet. The depth of the basement varies from ~1000 ft in the northeast to ~40,000 ft in the deepest part of the Anadarko Basin in the southwest. The red curve outlines the limits of the STACK play. (Figure modified from Johnson, 2008).

Much of the basement of the central Oklahoma was formed during the Middle Proterozoic period (Ham, 1973). Van Schmus et al. (1993) interpreted the basement composition to consist of granitic plutons, metavolcanics, meta-sediments and granitic gneiss. Chopra et al. (2017) showed that basement is highly heterogeneous beneath the STACK area, exhibiting magmatic intrusions and sills that emanate from the Mid-Continent Rift. Burke (1977) inferred rifting in the southern part of the Oklahoma during the Late Paleozoic period. The rifting lead to reactivation of several Late Proterozoic to early Cambrian faults and formation of South Oklahoma Aulacogen. Johnson (2008) reports that a separate episode of igneous activity occurred from the Early Cambrian through the Middle Cambrian periods. This igneous activity lead to the formation of gabbro, rhyolites, granites and basalts in the south-central and southwestern Oklahoma. In 2012 Spyglass Energy drilled the Wha-Zha-Zhi well on a structural high in nearby Osage County and encountered rhyolite, granite and gabbro (Walton, 2012). During the late Cambrian period, earlier Cambrian and Precambrian rocks were eroded for a brief period forming an unconformity. This period of erosion was followed by a long geologic time when sediments were deposited as parts of Oklahoma were alternately flooded by shallow seas and then raised above sea level. Johnson (2008) reported that these marine sediments are about 7,000 ft thick in the southern Anadarko Basin but decreases in thickness towards the north resulting in the 1,000-2,000 ft thick Simpson Group. Up until the last half of the Mississippian, the Anadarko Basin was structurally connected to the Arkoma and Hollis Basins and according to Perry (1989) the southern part of the Basin was possible adjunct to the South Oklahoma Aulacogen. The Anadarko Basin started to form an independent structural basin during Late Mississippian time. The basement continued to have crustal unrest during the Pennsylvanian resulting in the formation of the Wichita Mountains (the southwest margin of the Anadarko Basin), the Arkoma Basin, Ouachita Mountains (southeast Oklahoma) and the Nemaha Uplift and fault zone (Figure 1). This crustal unrest is attributed to both Late Paleozoic Ouachita and Alleghenian Orogenies. This crustal unrest resulted in folding, faulting and reactivation of the previous faults in Anadarko Basin.

3D Seismc Data

The STACK area is covered by some 20 legacy surveys as well as new surveys acquired by TGS and CGG. The resulting "Gigamerge" survey exhibits very little random noise, migration artifacts, or acquisition footprint. In addition to forming a common datum, phase matching, and amplitude balancing the data were subjected to modern surface consistent statics and surface consistent deconvolution. Because of the variation of bin size, number of offsets, and number of azimuths, the data were also 5D interpolated to minimize the differences in offsets, azimuths, and fold, thereby suppressing acquisition footprint. Nevertheless, a modest but valuable improvement in vertical resolution and signal-to-noise ratio can be provided using spectral balancing and edge-preserving structure-oriented filtering. The time-variant spectral balancing is computed using a time-variant amplitude correction to each frequency based on the average power spectrum and 1% of the peak spectral power. Because 5D interpolation suppresses acquisition footprint and interpolates the smoother part of the data structure-oriented filtering had a much more modest impact.

While many of the faults in this area are strike- slip faults, flexures are more prevalent and form a much more persistent pattern in the sedimentary layers (Figure 2a), most of which continue down to the top basement. It is unclear whether these flexures are simple folds, faults smeared by 5D interpolation, faults whose offset falls below the limits of seismic resolution, or folds associated with reactivated basement faults. One of the hypotheses behind the formation of the flexures is paleotopography caused by the sills and other unknown basement features (Figure 2a). Chopra et al. (2018) and Kolawole et al. (2018) have identified diabase sills "stepping up" into the unconformity. Figure 1a shows that these diabase sills do not penetrate the overlying sediments, implying that the sills predate the top of the basement erosional unconformity. Dip magnitude computed on top of the basement shows faults and paleotopography that penetrate into the overlying sediments (Figure 2b).

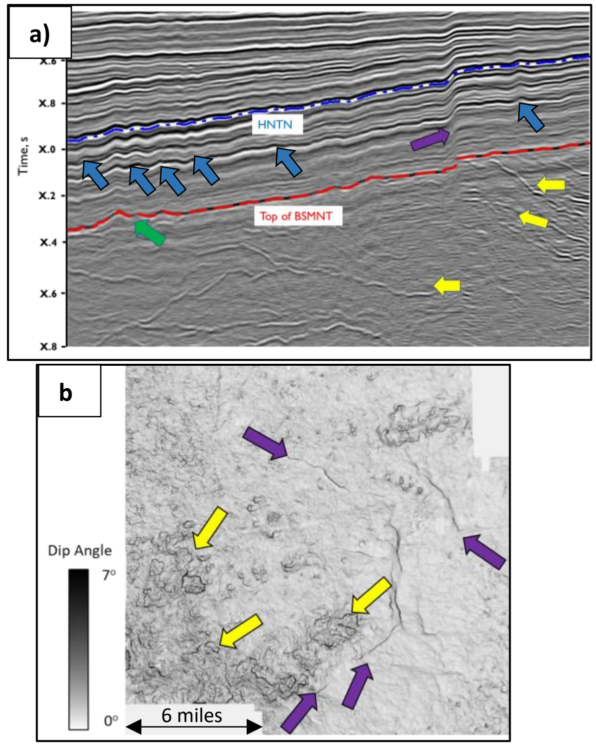

Figure 2. (a) Vertical section through the seismic amplitude volume showing sills (yellow arrows), faults (purple arrow), paleotopography (green arrow) and flexures (blue arrows). The sills and other basement structural features cause paleotopography on the top of the basement, which influences overlying sedimentary layers. Most of the faults cutting the top basement are strike slip faults. In the absence of well control, it is unclear if these flexures are folds or faults whose offset falls below seismic resolution. The top Hunton Limestone (HNTN) forms the base of the STACK play. (b) Dip magnitude computed from the top of the basement time-structure map. Yellow arrows indicate faults that penetrate from basement into overlying sedimentary layers. Purple arrows indicate paleotopography that gives rise to drape and differential compaction in the overlying layers.

Multispectral Coherence

Figure 3a shows a horizon slice along the top Hunton through the coherence volume computed from the (full-bandwidth) seismic data volume. Conventional (broadband) coherence fails to image most of the discontinuities (Figure 3a). This failure is due to structural deformation style; some of the faults are strike slip while others do not have seismically resolvable offset suggesting they may be simple flexures.

Li et al. (2018), Qi et al. (2018) and Marfurt (2017) have shown that "multispectral" coherence can improve fault continuity and suppresses artifacts due to coherent and incoherent noise. The seismic data volume was first spectrally balanced to provide a flat spectrum between 15 to 60 Hz with usable frequencies between 10 to 80 Hz. Because spectral balancing changes the wavelet in the same manner at each time level, broadband coherence computed on the

spectrally balanced data provides a negligible change in the results (Figure 3b). Multispectral coherence computed on the spectrally balanced data in 10-80 Hz bandwidth also provided minimal improvement (Figure 3c).
Partyka et al. (1999), Peyton et al. (1996), Gao (2013), Li and Lu (2014), and Marfurt (2017) show that different spectral components exhibit different geologic details. For this reason, high-frequency spectral voices may better image faults with smaller offset while lower-frequency spectral voices may better image faults with larger offset. In addition, some spectral components may exhibit a larger or smaller signal-to-noise ratio. Experimentation showed that spectral voices ranging between 30 and 55 Hz better delineated smaller as well as larger faults on coherence. Adding higher frequencies resulted in additional noise in the deeper (basement) section without significantly improving the imaging of smaller faults. Adding lower frequencies did not significantly improve the continuity of the larger faults. Using these observations, multispectral coherence on bandpass data provided a significant improvement over the broadband or full-bandwidth multispectral coherence (Figure 3d). The north-south trending El Reno fault can now be tracked across the entire image (blue arrows). The most significant improvement is observed in imaging splay faults associated with east-west trending strike-slip fault in the south (red arrows) and the discontinuity in the center (green arrow) that does not appear in any of the other coherence images.

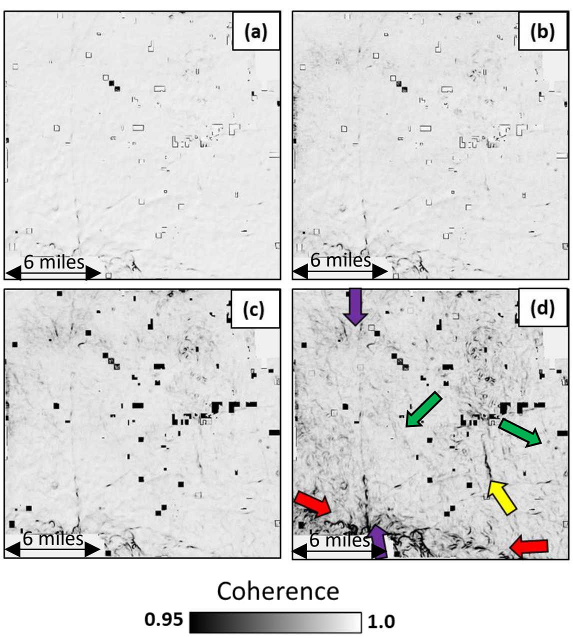

Figure 3. Horizon slices along the top Hunton through (a) broadband coherence volume computed on original seismic data volume, (b) broadband coherence volume computed on spectrally balanced data, (c) multispectral coherence volume computed on spectrally balanced data, and (d) multispectral coherence volume computed on spectrally balanced bandpass data (30-55 Hz). Note that (d) provides better delineation of discontinuities than (c) and (b). Purple arrows indicate the El-Reno fault. Red arrows indicate east west trending faults and associated splays. Green arrows indicate discontinuities that do not appear in any other coherence image.

Mapping Flexures with Aberrancy

Gao (2013) defines aberrancy as a 3rd derivative of a picked surface. In general, normal faults give rise to a positive curvature anomaly on the footwall side and a negative curvature anomaly on the hanging wall side of a normal fault. If there is a significant discontinuity, these two curvature anomalies "bracket" a coherence anomaly that more closely follows the fault trace. Aberrancy measures the lateral change in curvature and also follows the fault trace (Qi and Marfurt, 2018). The magnitude of aberrancy indicates the strength of deformation while the azimuth indicates the direction of the downward facing flexure. Given the observation that deeper faults exhibit little offset at the shallower Mississippian level, aberrancy is the most useful of the geometric attributes in delineating structural deformation.

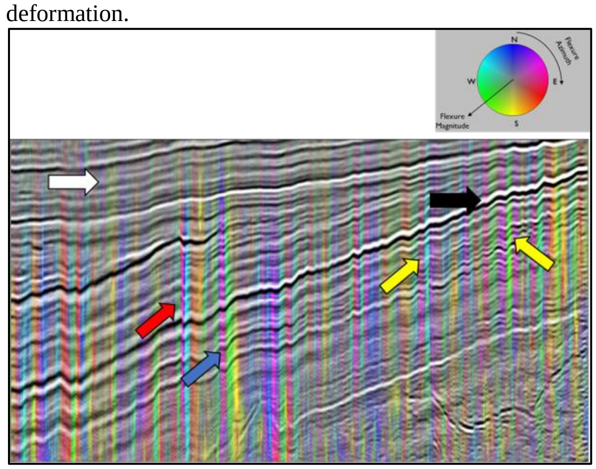

Figure 4. A amplitude cross section corendered with the magnitude and azimuth of aberrancy. Areas of high magnitude aberrancy appear as bright colors (black arrow) while areas of low magnitude aberrancy appear transparent (white arrow). The El-Reno fault (red arrow) appears as a flexure to the east (red) and west (cyan). There is another major fault next to it with flexure oriented northeast-southwest (blue arrow). This is the east-west striking fault (see Figure 3d). Yellow arrows indicate a highly deformed region where most of the flexures are oriented northeast-southwest.

Figure 4 shows the seismic amplitude image corendered with the total aberrancy vector, where the colors provide a means to visually and numerically analyze the different colored anomalies as different fold or faults sets. Nelson (2001) finds that fractures are a function of the amount of strain, the lithology (i.e. brittleness), and layer thickness. Both coherence and aberrancy are direct measures of strain and when combined with estimates of brittleness from P- and S-wave impedance volumes, provide candidate attribute volumes to correlate with both completion and production. When correlated to image logs, aberrancy can yield information on orientation of open or/and closed fractures and diagenetically altered fractures sets.

The amount of deformation in the Mississippian rocks occurs only near the major faults (Figure 5a). The deformation is more ubiquitous in the southeast and northwest within the STACK play (Figure 5b-f) and is no longer confined to the major fault systems. Given the limits of seismic resolution, we do not know if these northwest-southeast and northeast-southwest lineaments are faults or flexures. These deformation trends continue from the top Mississippian to the top of the basement implying that the deformation is basement controlled (see Figure 2a). If the aberrancy anomalies correspond to faults, they may pose drilling hazards. The magnitude and azimuth of aberrancy does not change within the Mississippian (Figure 5b-f), implying that the flexures are conformal. This conformal behavior simplifies any potential correlation between open/closed fractures and aberrancy, where we can hypothesize that the type of fracture assigned to a particular lineament will most probably not change vertically.

Conclusions

The Anadarko Basin has undergone a complex tectonic history with basement faults reactivated by one or more times. The data show a relatively “homogenous” basement cut by a complex system of sills that “step-up” vertically into the top basement unconformity. None of these sills penetrate the sedimentary section. Paleotopography at the top basement gives rise to compaction features at the level of interest. Many of the larger faults exhibit a strike-slip character and show only minimal vertical offset. Due to this reason, full bandwidth coherence fails to image the discontinuities. Since the majority of these discontinuities at the Hunton and above appear to be tuned between 30-55 Hz, multispectral coherence on a band pass data between 30-55 Hz delineates them better than multispectral or conventional coherence computed on the broadband data. While smaller faults exhibit some offset in the deeper section, they appear as flexures within the shallower Mississippian and Pennsylvanian formations. Aberrancy provides a means to map the intensity and orientations of these flexures volumetrically. Although there is significant offset of faults at the top basement and at formations as shallow as the Hunton Limestone, by the time this deformation reaches the Mississippian, almost all these deeper faults appear as a system of cross-cutting flexures. Given the high quality of the data these flexures indicate either faults whose offsets fall below seismic resolution, fault splays where each splay component offsets the reflectors by a small amount, or a true flexure, consistent with extensional fault-propagation fold geometries. Regardless of their actual cause, these flexures are a measure of strain, such that if the rock is sufficiently brittle, they may serve as a proxy for natural fractures. The orientation of the flexures can be used as a hypothesized estimate of the orientation and degree of permeability anisotropy, which can be tested through subsequent history matching.

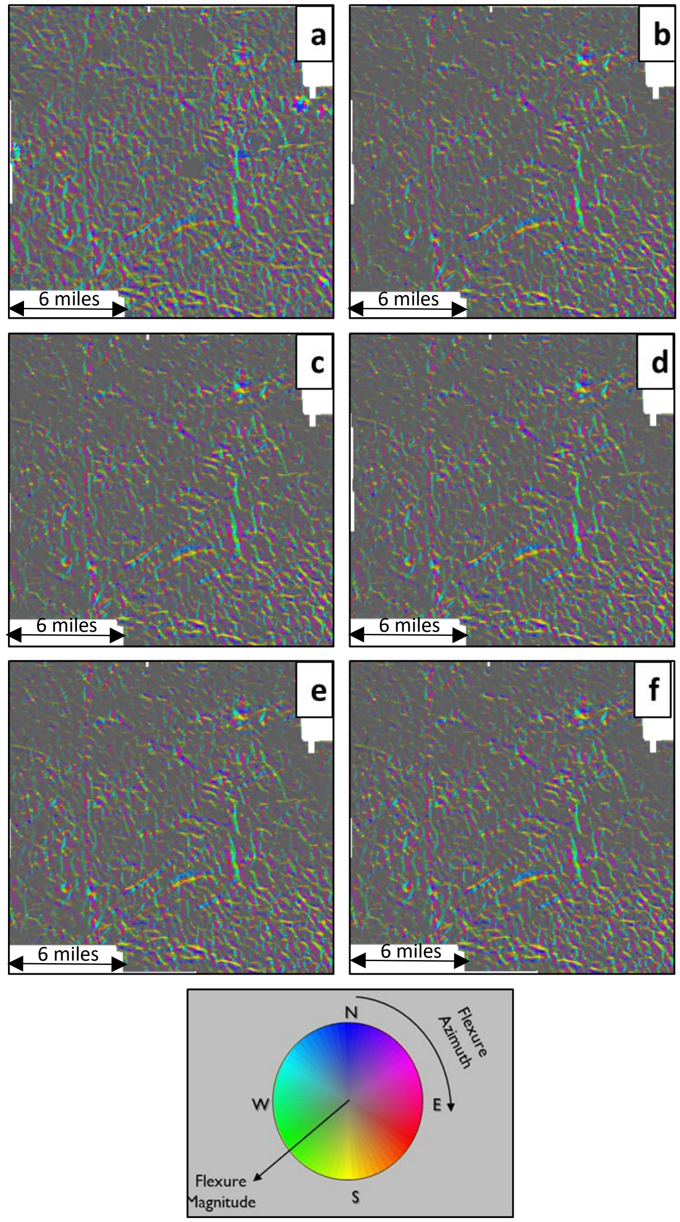

Figure 5. Proportional slices through the magnitude and azimuth of aberrancy (a) along the top of the Mississippian, (b) 20%, (c) 40%, (d) 60%, and (e) 80% between the top and bottom of the Mississippian, and (f) along the base of the Mississippian (top Hunton). There are no significant changes in aberrancy, implying that the flexures are conformal.

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