Seismic attribute driven integrated characterization of the Woodford Shale in west-central Oklahoma

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**ABSTRACT**

The organic-rich, silty Woodford Shale in west-central Oklahoma is a prolific resource play producing gas and liquid hydrocarbons. We calibrated seismic attributes and prestack inversion using well logs and core information within a seismic geomorphologic framework to define the overall basin architecture, major stratigraphic changes, and related variations in lithologies. Core measurements of elastic moduli and total organic content (TOC) indicated that the Woodford Shale can be broken into three elastic petrotypes important to well completion and hydrocarbon enrichment. Upscaling these measurements facilitates regional mapping of petrotypes from prestack seismic inversion of surface data. Seismic attributes highlight rugged topography of the basin floor of the Paleo Woodford Sea, which controls the lateral and vertical distribution of different lithofacies containing variable quantity of TOC as well as quartz, which controls brittleness. Depressions on the basin floor contain TOC-lean cherty lithofacies alternating with TOC-rich lithofacies, resulting in brittle-ductile rock couples. In contrast, basin floor highs are characterized by overall TOC-rich ductile lithofacies. Seismic attributes illuminate complex post-Woodford tectonic deformation. The Woodford Shale is known to be naturally fractured on outcrop. Image log analysis in other shale plays showed a good correlation between such tectonic features and natural fractures. These features need to be correlated with well trajectories and production data to determine which hypothesized “fracture sets,” if any, improve well performance.

**Introduction**

The Late Devonian Woodford Shale was deposited in an epeiric sea covering a wide area of the southern midcontinent. Regionally, the Woodford Shale play is divided into three parts: the Woodford, the Cana-Woodford of the midwest, and the Barnett Woodford of the southwest, with estimated technically recoverable resource of 22.21, 5.72, and 32.15 trillion cubic feet, respectively (Energy Information Administration, 2011). The current study focuses on the Woodford Shale of the midwest (Figure 1) where the shale is reported to produce dry gas, condensate, and oil and has an average thickness of 60 m (200 ft). Core analyses discussed by Gupta (2012) indicate that the Woodford Shale is characterized by lithological heterogeneity and nonuniform fracture distributions within the study area. Our goal is to integrate core analysis results with the seismic data to identify areas with high total organic content (TOC) in conjunction with more brittle lithology that favors natural fractures.

Several authors have used seismic attributes to illuminate geomorphologic features such as collapse chimneys and fracture zones within resource shales. Sullivan et al. (2006) use a set of seismic attributes to highlight collapsed chimneys associated with the karsting followed by the collapse of the underlying Limestone. Marfurt (2010) presented a set of volumetric seismic attributes to quantitatively highlight different shapes of seismic reflector. Chopra and Marfurt (2010) discussed seismic attributes useful for highlighting fracture zones. Guo et al. (2010) used seismic attributes to illuminate zones of faults and fractures within the Woodford Shale in the Arkoma Basin. Portas-Arroyal (2009) presented a multiscale study highlighting fractures within the Woodford Shale and directly correlates potential fracture zones identified from seismic attributes with the fracture zones identified on the outcrop. Schuelke (2011) used a set of attributes to map drilling geohazards and showed how curvature volumes can be used to link natural fractures in shales to hydraulic fracture performance.

In this paper, we present a workflow for the regional characterization of the Woodford Shale. We start with the mapping of regional geomorphologic features. Next,
we show a comparison between petrophysical properties extracted through simultaneous prestack seismic inversion, well logs, and core measurements. This workflow provides the calibration necessary to map the regional distribution of different elastic petrotypes within the Woodford Shale in the study area. Finally, we use seismic attributes to map areas that have been highly deformed and are thus more likely to exhibit natural fractures. We conclude with a summary of reservoir potential and data needed for improved implementation of the workflow discussed in this paper.

Figure 1. Thickness map showing the distribution of the Woodford Shale in Oklahoma. The star shows the study area. Map modified from Comer (2008).

Figure 2. Approximate boundary of the Oklahoma basin and other major features in the early and middle Paleozoic time. Figure modified from Johnson (1988).

Figure 3. (a) Stratigraphy and (b) type logs for the Woodford Shale. The informal members are defined on the basis of palynomorph, geochemistry, and log signatures. Figures are modified from Cardott (2008). (c) Well logs from well 1 in the study area.

Geologic setting
Depositional environment and stratigraphic framework
The late-Devonian/early-Mississippian Woodford Shale was deposited in an epeiric sea covering the huge
Oklahoma basin extending over most parts of the southern Midcontinent (Figure 2) with the Anadarko basin being one of the protobasins of this ancestral Oklahoma basin. The Anadarko basin was formed as the Oklahoma basin was broken into a series of sharp uplifts and major basins during a post-Woodford, Pennsylvanian orogenic episode. The present day geographic boundary of the Anadarko basin is defined by the Wichita and Amarillo uplifts on the south, the Nemha uplift on the east, and the Cimarron arch on the west. The northern end extends across much of western Kansas, part of which is denoted as the Hugoton embayment. The Woodford Shale was deposited as the sea progressed from south-southeast to northwest during a global sealevel rise. A widespread regional unconformity (period of nondeposition and erosion) defines the base of the Woodford Shale that in most places rests on the Silurian Hunton Limestone. Paleogeographic reconstruction indicates that during late Devonian time, North America (Laurentia) moved north, which placed the southern midcontinent near 15° to 20° south latitude. Such latitudes are associated with frequent ocean upwelling and a temperate climate, both of which aided the high biologic production and resulting TOC enrichment seen in the Woodford Shale. Figure 3 shows the generalized stratigraphy of southern Oklahoma and type log for the Woodford Shale in the study area.

Pre-Woodford basin geomorphology shows irregular remnant topography that formed the basin floor of the Woodford Sea, which in turn controlled the distribution of different lithologies, key to mapping the resource potential in the study area. Time-structure maps (Figure 4) of the Woodford Shale and the underlying Hunton Limestone show an overall flat topography with structural dips of less than 2°. Such time-structure maps reveal that the paleo shoreline was located toward the northeast while the basin depocenter was located toward the southwest. The time-thickness map of the Woodford Shale (Figure 5) shows little correlation between the top and base time-structure maps shown in Figure 4. Vertical slice through the 3D seismic amplitude volumes (Figure 6) shows many faults.

**Figure 4.** Time structure map of the (a) base of the Woodford Shale/top of the Hunton limestone and (b) top of the Woodford Shale. Vertical slice along line AA’ is shown later in Figure 6.

**Figure 5.** Time thickness map of the Hunton Limestone, which ignores any erosion along the top Woodford, approximates the paleo seafloor topography. Thicker areas of the Woodford Shale correspond to thinner areas of Hunton Limestone. Vertical slice along line BB’ is shown later in Figure 7. Circles indicate seven wells used for the impedance inversion of the prestack seismic data discussed later. Well 1 is a cored well.

**Figure 6.** Vertical slice along AA’ through the seismic amplitude volume showing the Woodford Shale and the underlying Hunton limestone. Faults cutting through these two horizons are marked with red lines. The location of AA’ is shown in Figure 4b.
extending through the Woodford interval indicating that significant tectonic activity affected the study area. Most faults stop below the Oswego Limestone horizon indicating that tectonic activity occurred during Pennsylvanian time, consistent with Johnson’s (2008) observation that the Pennsylvanian was a time of crustal unrest when orogeny and basin subsidence affected Oklahoma.

We have flattened the seismic volume along the top of the Woodford prior to attribute calculation to remove most of the rugged topography on the Hunton Limestone resulting from postdepositional tectonic deformation. Figure 7 shows vertical slice through the areas least affected by the tectonic activity to illuminate the original basin geomorphology at the time of Woodford deposition. Ideally, a detailed structural restoration is needed to fully reconstruct the basin geometry of the Woodford Sea. However, given the overall dip of 2° the flattened volume provides sufficient insight into the depositional processes at a regional scale. Figure 8 shows a suite of volumetric seismic attributes computed from this flattened volume to illuminate paleotopographic anomalies. High coherent seismic energy (Figure 8b) and high $\mu$ values (Figure 8e)

Figure 7. (a) Vertical slice along BB’ through the seismic amplitude volume showing the Woodford Shale and the underlying Hunton limestone. (b) Seismic amplitude volume flattened along the top of the Woodford showing the Woodford Shale and the underlying Hunton limestone.

Figure 8. Horizon slices through the attributes calculated from a seismic volume flattened along the top of the Woodford Shale such that the top of the Hunton Limestone reflects the geomorphologic features of the basin floor during Woodford deposition. The following figures show attribute expressions of a horizon slice taken along the basal Woodford. (a) Horizon slice through the corendered most positive ($k_1$) and most negative ($k_2$) principal curvature attribute volumes. (b) Horizon slice through the coherent seismic energy attribute volume. (c) Color bars used in (a, b, d, and e). (d) Horizon slice through the corendered most positive ($k_1$) and most negative ($k_2$) principal curvatures and coherent seismic energy attribute volumes. The coherent seismic energy attribute volume is rendered transparent (~50%) in this figure. (e) Horizon slice through the $\mu$ values obtained from impedance inversion. Note the areas with high $\mu$ values match with higher values for the coherent seismic energy shown in (b).
calculated from the impedance inversion of the prestack 3D surface seismic volume correspond to the remnant Hunton Limestone, present as topographic highs in the Woodford Sea. Stratal slices through the corendered high curvature values and coherent seismic energy (Figure 8d) show strong negative curvature values in juxtaposition with areas with high seismic energy. Such correlations suggest that these paleo lows are filled with higher impedance quartz-rich Woodford sediments compared to clay enriched Woodford sediments.

This rugged Hunton palaeotopography formed the rugged basin floor topography of the Woodford Sea. The Woodford Shale was deposited as the sea progressively transgressed onto the unconformity surface with depressions on the seafloor inundated earlier compared to topographically higher areas. Figure 9 was chosen over an area with no visible faults or folds and is thus unaffected by the post-Woodford tectonic deformation thereby preserving the original basin floor topography. Although the top Woodford is also an unconformity, it is not deeply eroded (Johnson, 2008). For this reason, the time thickness map in Figure 5 and horizon slice in Figure 9 are good approximations to the paleo water bottom. A relatively thick accumulation of the Woodford Shale exists in topographically low areas of the basin while thinner Woodford interval exists in topographically high areas. Moreover, basin floor lows are likely areas for storm current/turbidity current related flows which give rise to the brittle cherty lithofacies identified in the subsurface cores (Gupta, 2012). Thus, the overall organic-rich shale in the depressions often contains intervening brittle cherty lithofacies, which are absent in topographically higher areas. Such intervening cherty layers are critical for initiating hydraulic fractures and producing hydrocarbons from impermeable shale reservoirs.

Core analyses indicate three petrotypes within the Woodford Shale, based on subtle changes in petrophysical properties (Gupta, 2012). These petrotypes are only loosely connected to elastic parameters detected by seismic data. Lithologic heterogeneity results in laterally highly variable impedance contrasts posing challenges for high-precision hori-

![Figure 9](image9.png)

**Figure 9.** (a) 3D display of a horizon slice through most positive and most negative principal curvatures along the base of the Woodford Shale and a vertical slice through seismic amplitude. Curvature computed and image capture from seismic volume flattened along the top of Woodford. (b) Schematic diagram drawn from the curvature expression of the horizon in (a) showing the rugged seabed topography of the Woodford Sea as defined by the unconformity surface on the top of the Hunton Limestone. Line BB’ is shown in Figure 5.

![Figure 10](image10.png)

**Figure 10.** Stratal slices generated by co-rendering coherent energy with in-line energy gradient. Figures from bottom to top represent (a) top of the Hunton unconformity, (b) the lower Woodford, (c and d) the middle Woodford and (e) near the top of the Woodford Formation. Notice the subtle high seismic-energy nature (represented by cyan color) in the top-most stratal slice. White circle indicates location of the cored well.
zon picking. Our analyses show that volumetric seismic attributes help to map subtle but important stratigraphic components, especially when calibrated with well logs and core measurements to facilitate the construction of the depositional history. To this end, we examined 20 Woodford stratal slices through corendered coherent seismic energy and in-line energy gradient volumes to track stratigraphic changes in the study area. Five of these slices are shown in Figure 10. Low-seismic-energy areas (magenta- and blue-colored) in Figure 10a represent the initial shale deposition on top of the high-seismic-energy Hunton Limestone. Structural lows on the seafloor inundated earlier are affected by storm and turbidity currents as well as debris flows resulting in thin intervals of quartz rich silty deposits rather than homogeneous clay-rich suspension fallout. Areas marked with orange ellipses in Figure 10a and 10b indicate that shale deposition didn’t start until the beginning of the Middle Woodford deposition (Figure 10c). The high-seismic-energy areas contained by white polygons in Figure 10d and 10e are areas with possible silica enrichment within the Woodford Shale, which are otherwise characterized by low seismic energy (Figure 10a–10c). Such an increase in silica in the Upper Woodford is in accordance with the cherty Upper Woodford intervals reported in the literature (Gupta, 2012).

**Analysis**

**Prediction of elastic rock types from seismic inversion**

Core measurements of elastic moduli and TOC indicate that the Woodford Shale can be grouped into three elastic petrotypes containing high, intermediate, and low TOC on a Young’s modulus versus Poisson’s ratio crossplot (Figure 11a). Comparison between elastic moduli calculated from ultrasonic core measurements and well logs from well 1 (Gupta, 2012) helped to map these three petrotypes to the well log scale (Figure 11b) and ultimately to the seismic scale (Figure 11c).

We performed simultaneous angle dependent inversion (Hampson et al., 2005) of the prestack structure-oriented filtered seismic gathers to estimate elastic properties from the seismic data. Fatti et al.’s (1994) modification of Aki and Richard’s (1980) approximation of the Zoeppritz equations provide the basis for this inversion technique. The inversion was achieved through five steps: (1) selecting wells located across the seismic survey, (2) generating angle gathers from the offsets, (3) extracting representative wavelets for each angle to generate synthetic seismic that ties at the wells, (4) modeling low-frequency components of the P- and S-impedances from well logs and picked seismic horizons, and (5) ultimately inverting the seismic data. Locations of the wells used to build the background model and tie the seismic inversion are shown in Figure 5.

Crossplots of Young’s modulus $E$ and Poisson’s ratio $\nu$ from impedance inversion of prestack 3D surface seismic data are shown in Figure 11c. Note, the higher $E$ values calculated from ultrasonic measurements made on horizontal core plugs compared to values calculated from well logs from vertical wells can be attributed to the transverse isotropic nature of the shales.

Core measurements on well 1 (Figure 5) indicate that TOC-rich rocks are ductile and TOC-lean rocks are brittle. The TOC-lean rocks typically occur as cherty lithofacies within the Woodford Shale (Gupta, 2012). Further core analysis of well 1 highlights intervals containing alternating TOC-rich ductile rocks and TOC-lean brittle rocks (Gupta, 2012), which are identified as ideal intervals for placing horizontal wells within the Woodford Shale.

Figure 12 shows maps of the three elastic petrotypes within the study area. The middle Woodford member contains high amounts of petrotype 2 with intermediate TOC. Such characteristics of the middle Woodford match the geologic history and good reservoir performance of the middle Woodford member (Gupta, 2012).
The middle Woodford member is likely to contain the highest amount of brittle-ductile rock couplets (Gupta, 2012) for most of the study area and hence, generate an average response for the petrotypes with intermediate TOC. It is possible to correlate the elastic petrotypes with the petrotypes identified using mineralogy in the petrophysical analyses (Gupta, 2012) by incorporating additional well-log information. Such additional information will ultimately lead to integrated 3D reservoir descriptions and 3D geomechanical properties to better illuminate the sweet spots within the Woodford Shale.

**Tectonic deformation and natural fracture distribution**

Natural fractures play a critical role in the evaluation of tight, low-permeable resource shales. Open fractures often improve the host rock's permeability, while mineral-filled fractures often provide weak areas in rocks that are more amenable to hydraulic fracturing. Natural fractures can also affect reservoir performance in a negative way. For example, large natural fractures in the Barnett Shale may connect to the underlying Ellenburger aquifer (Schuelke, 2011). Structural deformation seen on seismic data (Figures 6 and 9), the tectonic history derived from outcrop studies (Portas-Arroyal, 2009) along with detailed core descriptions indicate that major, multistage tectonic activity affected the Woodford Shale resulting in highly deformed areas and a heterogeneous distribution of natural fractures in the study area. Volumetric seismic attributes highlight areas with fault offsets, folds, and flexures and areas with rotated fault blocks. Such attributes are direct measures of strain, which is one of the key components in mapping natural fractures (Nelson, 2001).

Figure 13 highlights faults and the irregular unconformity surface at the base of the Woodford Shale (which is also the top of the underlying Hunton Limestone) in a horizon slice through Sobel filter similarity, an edge-detecting attribute. Detailed structural analysis of the north–south-trending fault on Figure 13 indicates that it is a strike-slip fault. Collapse features in the Hunton Limestone highlighted by the Sobel filter similarity (Figure 13) form low areas (Figure 9) on the Woodford Sea characterized by high curvature values (Figure 8) and suggest not only increased natural fractures but also locally thicker Woodford Shale accumulation.

Murray (1968) correlated natural fractures and improved production from the Bakken formation of North Dakota with curvature obtained from well tops and 2D seismic data. In this study, we have used the most positive and most negative principal curvatures to highlight potential areas for a higher number of natural fractures. Guo et al. (2010) correlated natural fractures and the curvature attribute in the Woodford Shale of the Arkoma Basin.

Multiattribute analyses through corendering of geometrically independent and interpretationally complementary attributes highlight potential areas with natural fractures. Corendered Sobel filter similarity and most positive and most negative principal curvatures...
highlight potential areas of greater natural fracture density (Figure 14).

Amplitude curvature (Figure 15) highlights lateral changes in reflectivity and is independent from structural curvature. Amplitude curvature often highlights joints in carbonates and large cleats in coals. Such lineaments are due to either local stress release or diagenetic alteration of a zone sufficiently large to be seen by surface seismic data.

The strike of the most negative principal curvature $\psi_{k_2}$ modulated by the magnitude of the most negative principal curvature $k_2$ (Al-Dossary and Marfurt, 2006) shows the progressive change in lineament strike from northeast–southwest to northwest–southeast across the survey within the Woodford Shale interval (Figure 16). Such changes in strike indicate nonplanar fault planes and subsequent twisting of the Woodford Shale. The reflector rotation with respect to reflector normal attribute volume (Marfurt and Rich, 2010) further shows such...
“twisting” and maps the relative movements of the fault blocks with respect to each other (Figure 17).

Guo et al. (2010) used the shape index modulated by the curvedness attribute volume to illuminate the surface irregularity of the Woodford Shale in the Arkoma Basin. They show that anticlinal areas of a reflector (ridges and domes) are most likely areas for the microseismic events and most likely follow a higher number of natural fractures in those areas (Figure 18). Thompson (2010) showed the opposite phenomenon in

Figure 16. Horizon slice through the strike of the most negative principal curvature $\psi_{k2}$ (plotted against hue) modulated by the magnitude of the most negative principal curvature $k_2$: (a) 10 ms above the Hunton top and (b) near the Woodford top using (c) a 2D color bar and making the low curvature values transparent. (d) Cartoon illustrating a valley trending northwest–southeast colored cyan (top), a valley trending north–south colored blue (middle), and a valley trending northeast–southwest colored magenta (bottom). Note the change in the orientation (indicated by white arrows) of the lineaments in the Woodford compared to the Hunton, indicated by white arrows.

Figure 17. Reflector rotation about the average reflector normal. The horst and graben blocks show considerable contrast and can be interpreted as separate units. (a) Horizon slice at $t = 10$ ms above the top of the Hunton Limestone and (b) horizon slice near the top of the Woodford Shale. Ellipse and arrows in (a and b) indicate progressive changes in the fault block rotation from the base to the top of the Woodford Shale. (c) Chair display of a time slice through reflector rotation about the average reflector normal and vertical profiles through seismic amplitude. Yellow ellipses show the same fault seen on the vertical slice through the seismic amplitude volume and on the time slice. Yellow arrows indicate several fault branches connected to a parent fault block.
Figure 18. (a and b) Corendered horizon slice through the shape index modulated by curvedness and microseismic events. (b) Microseismic events are visible when the dome and ridges are rendered transparent indicating favorable areas for artificial fracturing in those areas and are also possible areas for higher number of natural fractures. Modified from Guo et al. (2010). Microseismic data courtesy of Pablo LLC. Seismic data courtesy of CGG-Veritas.

Figure 19. Chair display of shape index modulated by curvedness corendered with seismic amplitude. Red (dome) and blue (bowl) indicate irregularities associated with the unconformity surface. The base of the Woodford is shown as a horizontal display. Note the correlation of the reflector shape attribute with the structure seen on the vertical slices through the seismic amplitude.
her work on the Barnett Shale where microseismic events were concentrated in bowl-shaped structures. We use the same attributes to quantitatively highlight the shapes of seismic reflectors and highlight ridges and domes as potential areas for higher number of natural fractures. We show a corendered image of shape index modulated by curvedness and seismic amplitude delineating the similarity between reflector shape and the calculated shapes of reflectors in Figure 19. Bowl-shape collapse features are possibly associated with the collapse of Hunton Limestone appear blue (blue arrow) and areas of thicker accumulation of the Woodford Shale.

Conclusions

Seismic data provide the most promising means to extend core and well log measurements to map 3D distributions of reservoir quality. Seismic geomorphology provides a means to define the depositional environment. Prestack seismic inversion, calibrated to core and logs, provides estimates of petrotypes at a regional scale. Geometric attributes indicate areas more prone to natural fractures.

Due to the competitive acreage positions at the time of this work, we do not have access to the dense well control common to shale resource plays. Horizontal image logs can provide direct correlations between impedances, curvature, and natural fractures. The seismic data used in this study are from a megamerge with 70% of our study area covered by lowfold narrow azimuth 1994–1996 surveys that cannot be used to estimate azimuthal or vertical transverse anisotropy. The hundreds of triple combo well logs can provide the statistical control for high-resolution neural network estimation of petrotypes. Microseismic measurements provide direct evidence of brittle versus ductile behavior. Our hope is that as these data are released for publication, others can build on our preliminary analysis.

Acknowledgments

Our thanks go to CGG-Veritas for the license to the megamerge survey and to Cimarex for the well data used in this study and for permission to publish these results. Thanks to Cimarex for financial support of the first author through the OU Rock Physics Shale Consortium. Interpretation was performed using licenses for use in education and research of SLB’s Petrel and Techlog and CGG-Veritas/Hampson Russell’s Strata software package. Most of the attributes were generated using software developed as part of the OU Attribute-Assisted Seismic Processing and Inversion consortium.

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