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A Machine-Aided Seismic Signal Analysis Workflow for Subsurface Faults and Facies Visualization and Interpretation, South Central Anadarko Basin, Oklahoma

Wade Martin
West Virginia University, wpm0005@mix.wvu.edu

Recommended Citation

Martin, Wade, "A Machine-Aided Seismic Signal Analysis Workflow for Subsurface Faults and Facies Visualization and Interpretation, South Central Anadarko Basin, Oklahoma" (2019). *Graduate Theses, Dissertations, and Problem Reports*. 3900.
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A Machine-Aided Seismic Signal Analysis Workflow for Subsurface Faults and Facies Visualization and Interpretation, South Central Anadarko Basin, Oklahoma

Wade Martin

Thesis submitted to
to the Eberly College of Arts and Sciences
at West Virginia University

in partial fulfillment of the requirements for the degree of

Master of Science in
Geology

Dengliang Gao, Ph.D., Chair
Tim Carr, Ph.D.
Jamie Rich, Ph.D.

Department of Geology and Geography

Morgantown, West Virginia
2019

Keywords: Seismic texture, geophysics, Anadarko basin, seismic attribute

ABSTRACT

A Machine-Aided Seismic Signal Analysis Workflow for Subsurface Faults and Facies Visualization and Interpretation, South Central Anadarko Basin, Oklahoma

Wade Martin

Seismic attribute analysis enhances the understanding of subsurface geology and has continually gained traction in the oil and gas industry since the 1970's. Many seismic attributes are available for petroleum geoscientists. This research intends to provide insight to an analytical attribute workflow for rock property estimation in the Anadarko basin of Oklahoma that is prolific in oil and gas exploration, with a particular focus on seismic texture. 3-D volumes processed for seismic texture facies and structure enhance geophysical investigation and interpretation of amplitude data. This study will contribute valuable insight to reservoir studies and the potential for texture attribute well calibration across exploration. Seismic responses are directly related only to the velocity and density of the rocks and fluids present in the subsurface. An analytical attribute workflow will provide insight to depositional facies, structural geology, and small-scale features that are otherwise unclear from reflection seismology alone. The Pennsylvanian sandstones, the Mississippian and Devonian carbonates, and early Mississippian Woodford Shale are three proven petroleum targets that can be further evaluated within the Mountaineer 3D seismic data set. Application of an analytical attribute workflow with an emphasis on seismic texture attributes provides an insight to the subsurface basin structures and depositional facies, which are fundamental for successful exploration for and effective development of conventional and unconventional energy resources in the basin.

ACKNOWLEDGMENTS

I would like to thank Dr. Dengliang Gao for advising this research and providing seismic attribute datasets from his Bright-Spot Technology Consortium that made this research possible through a joint industry agreement. I would also like to thank Dr. Jamie Rich for his mentorship during my time at the University of Oklahoma, and for making this research possible with the academic release of the Mountaineer 3D data set through Devon Energy. Dr. Tim Carr served on my committee and provided intellectual support and guidance throughout my time here at West Virginia University that I am grateful for.

A special thanks goes out to the community here at the Department of Geology and Geography for the opportunity to complete this research. During my time as a graduate teaching assistant I learned many lessons that will continue to affect my life once I have graduated.

I could not have succeeded without the help and care of my closest friends who have seen me through this process. From camping together to editing my work, I will always appreciate the time we have spent together.

In addition to everyone mentioned above, it would be a disservice to those closest to me if I did not mention their patience and support of the time I have spent here at West Virginia University. My family has continued to care and look after me while I move far from home, and I am forever grateful for the bond we will share as I follow in my parent’s geology footsteps – I stand on the shoulders of giants.

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1. INTRODUCTION

1.1 Objectives and Approach

The primary objective of this research is to investigate and compare seismic texture attributes to conventional attributes within a 3D seismic data set. This will be accomplished by exploring the relationship between amplitude data, conventional seismic attributes and seismic texture volumes through an analytical seismic attribute workflow. Analysis of the seismic data will provide insight to geologic properties related to facies and structure. An investigation of seismic texture will increase the understanding of this relatively new seismic attribute and its usefulness for subsurface reservoir characterization, prediction and structural modeling.

This study of seismic texture coupled with an analytical attribute workflow presents a new visual analysis of the Anadarko basin in Oklahoma. While a texture attribute study can provide the opportunity for qualitative and quantitative analysis, this study relied on qualitative assessments of the subsurface. Facies texture volumes enhance depositional patterns and structure texture volumes illuminate deformation patterns that can be challenging to see in amplitude data alone.

1.2 Data Set

Devon Energy provided a ~75 mi^2 seismic data set to West Virginia University. The Mountaineer 3D seismic data is found in Caddo County Oklahoma, south-central Anadarko basin (Figure 1). Outside of relative county information, the specific location of any data analyzed will be sanitized per Devon Energy’s request. In addition to the Mountaineer 3D, Devon Energy provided WVU a suite of wells and images of previous seismic interpretations. The seismic data set has a sample rate of 2ms with a total record length of 6 seconds, and the inline and crossline spacing is 82.5 ft. A total of 16 wells were loaded into the Petrel project, along with their associated well logs. These wells are primarily located in the upper sections of the seismic data and contain gamma ray, sonic, caliper, resistivity, density and porosity logs.

2. BACKGROUND GEOLOGY

2.1 Tectonic History, Stratigraphy, and Structure

The Anadarko basin of Oklahoma and Texas is the deepest basin on the North American Craton, and one of the deepest on Earth. The geographic location of this study is in Caddo County, Oklahoma, which is in the southern portion of the Anadarko basin (Figure 1).

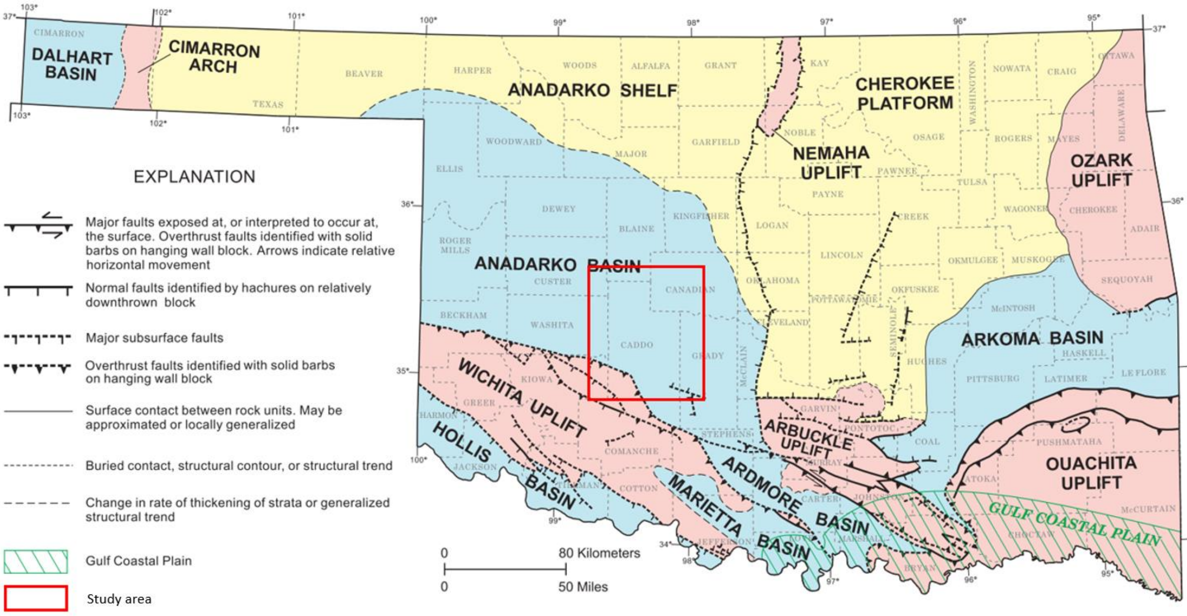


Figure 1: Map view of the Anadarko Basin and geologic features of the region. Red square highlighting Caddo County. Modified from Johnson (2008).

The Anadarko basin is bounded to the south by the Wichita mountains, to the east by the Nemaha uplift, and to the west-south-west by the Amarillo uplift and the Cimarron arch (Figure 1). Development of this asymmetrical basin can be characterized by four major geologic episodes (Figures 2 & 3) that led to the deposition of nearly 40,000 feet of sediment in the deepest parts of the Anadarko basin (Johnson, 1989).

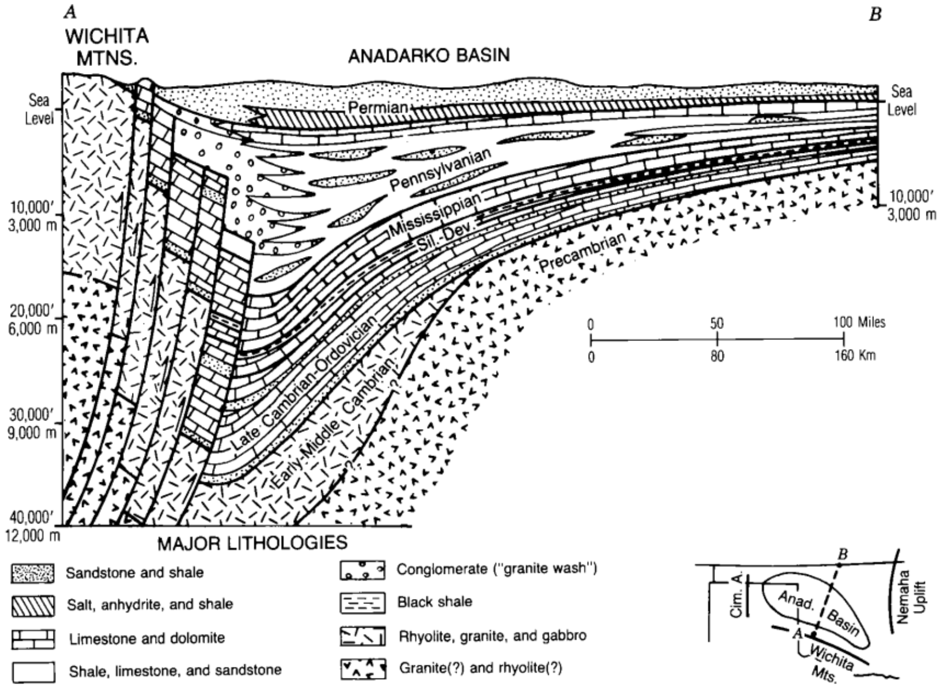


Figure 2: Generalized north-south structural cross section through the Anadarko basin, location shown in map (Johnson, 1989).

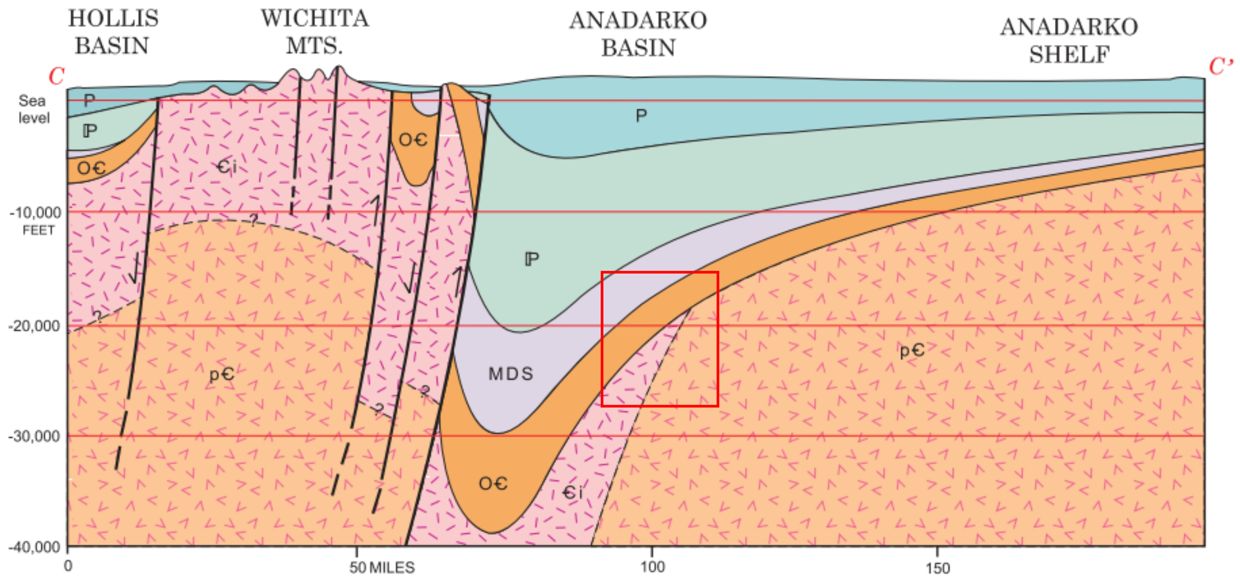


Figure 1: Generalized cross section showing major units and faults from Johnson (2008). Ages are marked by letters. Important: Ci, Cambrian igneous and metamorphic rocks; OC, Ordovician and Cambrian sedimentary rocks; MDS, Miss., Devonian & Silurian; IP, Pennsylvanian; P, Permian.

During late Precambrian, rifting began and created the oldest igneous rocks known in Oklahoma (Johnson, 2008). These rocks include Cambrian intrusions, composed of gabbro and basalt from 535±30 Ma, and granites and rhyolites, from 525±25 Ma (Feinstein, 1981). These igneous rocks formed along a west-northwest trend through southern Oklahoma and into the panhandle of Texas, and acted as the basement in conjunction with the Precambrian igneous rocks (Figures 2 & 3). This magmatic package marks the last time there was igneous activity in Oklahoma and cooling of intruded magma and extruded lava controlled basin subsidence.

After the closure of the rift arm, late Cambrian through Mississippian sediments were deposited. These sediments form the southern Oklahoma aulacogen into the southern Oklahoma trough. During the late Cambrian to Ordovician, southern Oklahoma was dominated by intermittent shallow and deep seas depositing sandstone, limestone, and shale. These lithologies combine to a total of 9,500 ft in the deeper parts of the trough (Johnson, 2008). The 9,500 ft of sediment thins northward from the southern Oklahoma trough to less than 1,500 ft thick on the Anadarko Shelf (Figure 3). Carbonate deposits were overlain by late Devonian shale, totaling roughly 1,000 ft of sediment during the Silurian and Devonian periods.

The latest Mississippian through Pennsylvanian were tectonically active periods and an unconformity marks the base of the section. The sediments deposited are predominately marine shale; however, beds of limestone, conglomerate, shale, and sandstone are found throughout. This section thins northward from 15,000 ft in the southern Oklahoma trough to the 2,000 ft (Figure 3) on the Anadarko Shelf (Johnson, 2008). Orogenies and uplifts, specifically the Wichita mountains, occurred throughout deposition of Pennsylvanian sediments, and largely controlled the facies distribution and axes of sedimentation (Figure 4).

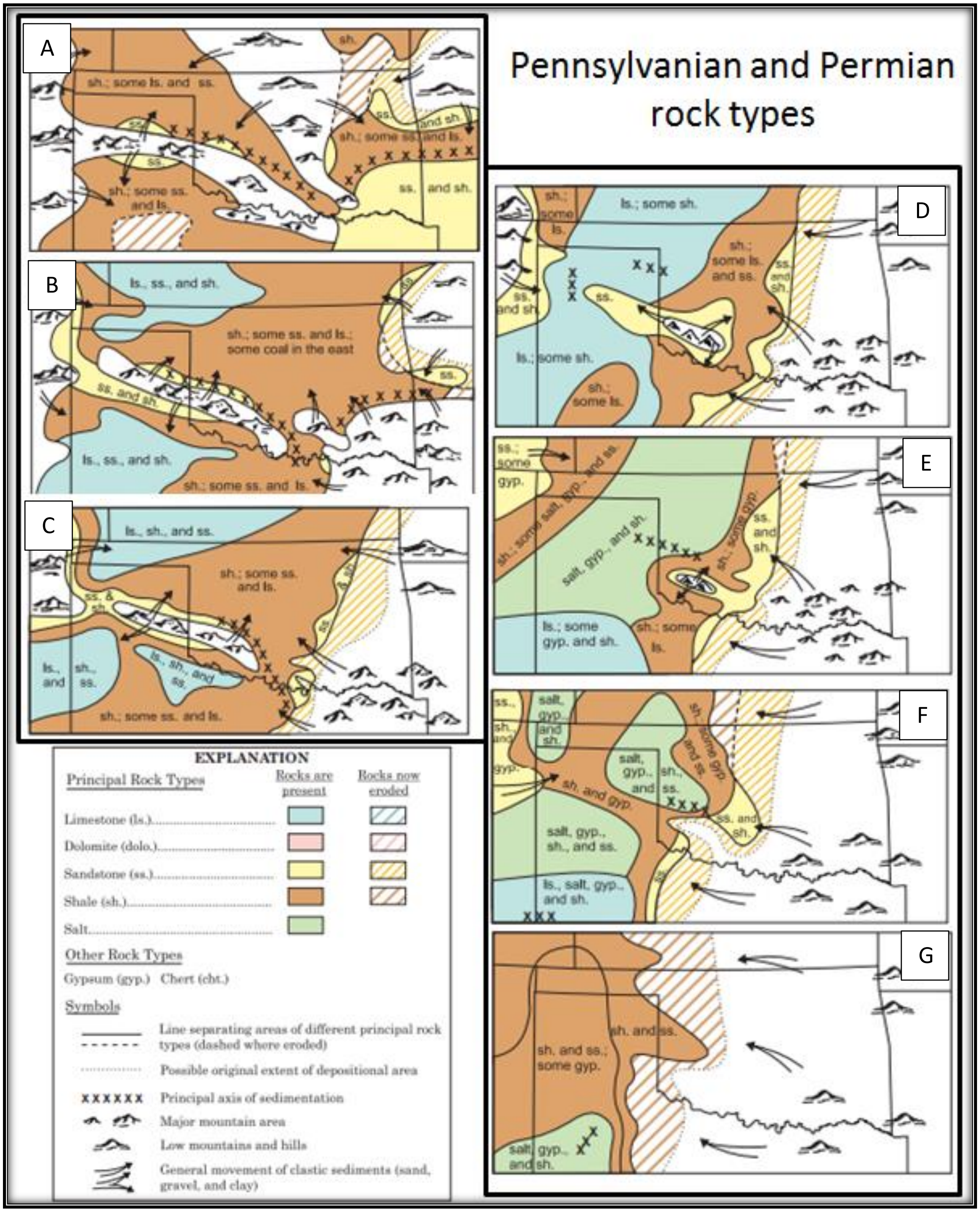


Figure 4: Generalized Pennsylvanian rock deposits shown on left from youngest to oldest (A through C). Permian deposits shown on the right from youngest to oldest (D through G). During the Wichita Orogeny (A-B) there was ~15,000feet of uplift. Modifiend from Johnson (2008).

The Anadarko basin has been in an epeirogenic episode since the Permian, and the majority of Cenozoic and Mesozoic sediments have been eroded (Johnson, 1989). The entire Permian sequence totals 6,000 ft in thickness in the deep Anadarko basin and 1,000 ft on the shelf. This sequence is comprised of alluvial sediments, shallow marine sediments, and evaporites that were deposited in the early to middle Permian. By the late Permian, the Anadarko basin was dominated by red sandstone, shale, and salt (Johnson, 2008).

Four major geologic episodes in Oklahoma are represented by roughly 40,000 feet in the deepest portions of the Anadarko basin (Figure 5). These sediments, buried and lithified during the Mississippian, Devonian, Silurian and Pennsylvanian, provide opportunities for oil and gas exploration and exploitation.

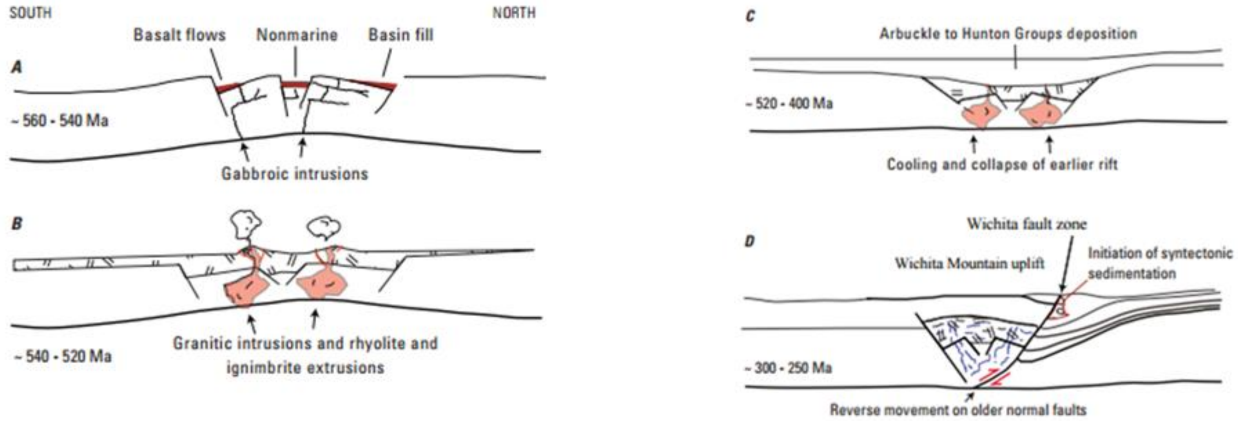
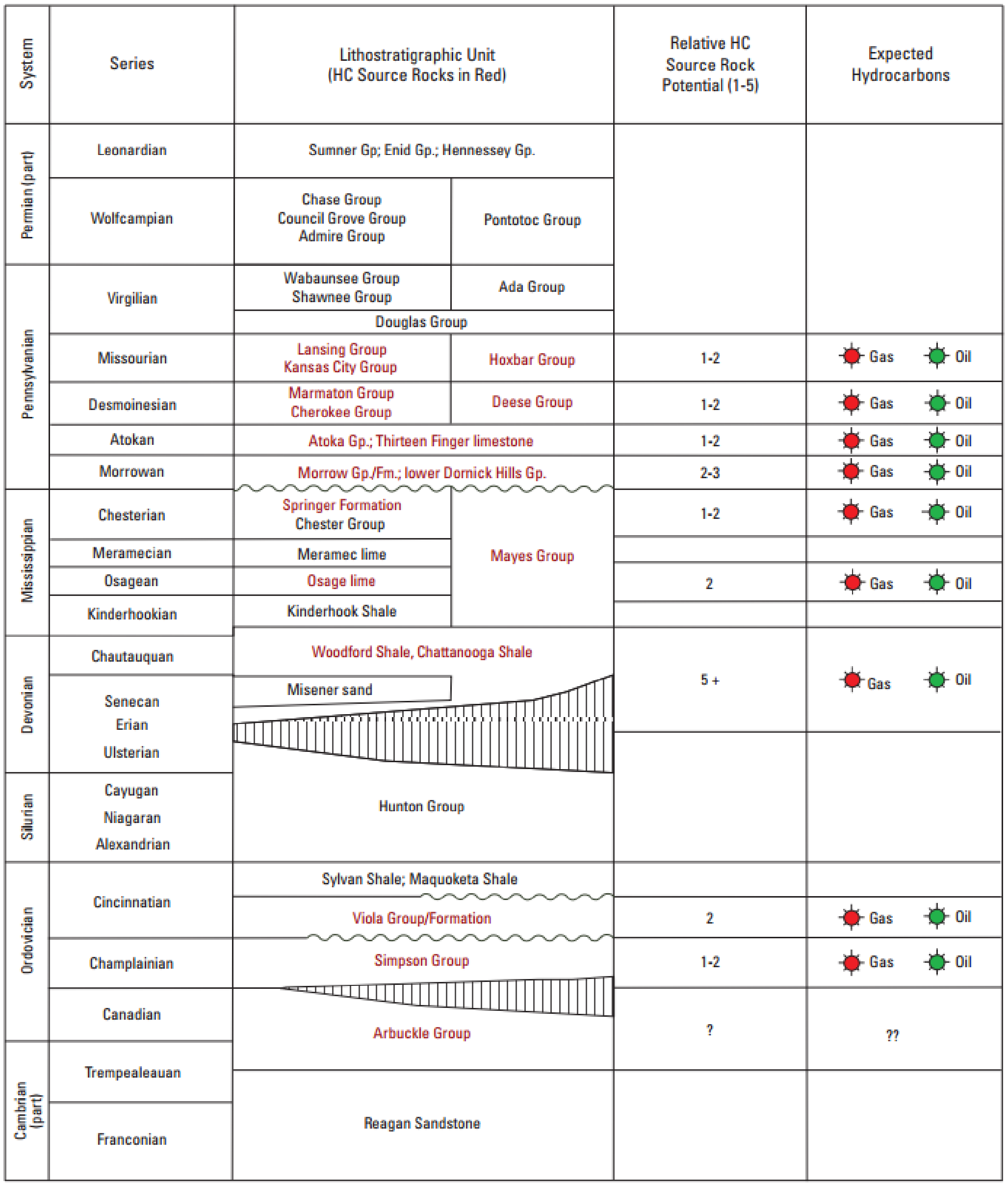


Figure 5: South to North generalized cross sections showing stages of tectonic activity that affected the Anadarko basin. A and B represent the formation of the southern Oklahoma Aulacogen, while C and D represent the sedimentation seen in the Anadarko basin. Modified from Higley (2014).

2.2 Petroleum System

The Anadarko basin has large potential for hydrocarbon exploration and exploitation due to the size, depth and geologic history of the basin. This basin contains more than 150 fields and is highly productive for oil and natural gas (Lee, 2002). With fifteen known source rocks containing both gas and oil, it is important to characterize and understand the petroleum systems.

The subsurface geology of the Anadarko basin has been extensively researched by academia and private companies. This project will rely on proven petroleum systems from Cambrian to Permian strata (Figure 6). The major horizontal drilling targets are found in the Devonian, Mississippian and Pennsylvanian strata, and especially the late Devonian to earliest Mississippian Woodford Shale.



System	Series	Lithostratigraphic Unit (HC Source Rocks in Red)		Relative HC Source Rock Potential (1-5)	Expected Hydrocarbons
Permian (part)	Leonardian	Sumner Gp; Enid Gp.; Hennessey Gp.			
	Wolfcampian	Chase Group Council Grove Group Admire Group	Pontotoc Group		
Pennsylvanian	Virgilian	Wabaunsee Group Shawnee Group	Ada Group		
		Douglas Group			
	Missourian	Lansing Group Kansas City Group	Hoxbar Group	1-2	Gas Oil
	Desmoinesian	Marmaton Group Cherokee Group	Deese Group	1-2	Gas Oil
	Atokan	Atoka Gp.; Thirteen Finger limestone		1-2	Gas Oil
	Morrowan	Morrow Gp./Fm.; lower Dornick Hills Gp.		2-3	Gas Oil
Mississippian	Chesterian	Springer Formation Chester Group	Mayes Group	1-2	Gas Oil
	Meramecian	Meramec lime			
	Osagean	Osage lime		2	Gas Oil
	Kinderhookian	Kinderhook Shale			
Devonian	Chautauquan	Woodford Shale, Chattanooga Shale		5 +	Gas Oil
	Senecan Erian Ulsterian	Misener sand			
Silurian	Cayugan Niagaran Alexandrian	Hunton Group			
Ordovician	Cincinnatian	Sylvan Shale; Maquoketa Shale			
		Viola Group/Formation		2	Gas Oil
	Champlainian	Simpson Group		1-2	Gas Oil
	Canadian	Arbuckle Group		?	??
Cambrian (part)	Trempealeauan	Reagan Sandstone			
	Franconian				

Figure 2: Generalized stratigraphic column of the Anadarko basin with source rocks in red (Higley, 2014).

3. SEISMIC ATTRIBUTES

3.1 Seismic Attributes

A seismic attribute is a measurement derived from seismic data. A useful seismic attribute is directly related to a geologic feature and helps define reservoir properties of interest (Chopra, 2008). Seismic attributes aid in interpretation and analysis for determining many of the important factors needed to optimally produce oil and natural gas. A seismic amplitude texture refers to a characteristic pattern defined by the magnitude and variation of neighboring amplitude samples at a given location in an image space (Gao, 2011).

3.2 Attribute Background

Using amplitude volumes for seismic interpretation has been standard industry practice for many years. Amplitude provides the interpreter with general structure and stratigraphy data by showing changes in impedance in three dimensions.

Variance is a geometrical attribute that compares neighboring waveforms or traces. This is the opposite of the well-known coherency attribute. Variance measures lateral variations between neighboring seismic traces by representing the trace-to-trace variability of a particular sample interval (Chopra and Marfurt, 2007). A variance volume provides a medium to delineate edges of strata and faults by visualizing differences in traces. Low variance is the result of little change from trace to trace while high variance is produced by variations within the stratigraphy.

The curvature attribute is geometric and is a measure of deformation along a plane. Curvature measures a seismic horizon for deformations by fitting mathematical quadratic surfaces to a selected seismic horizon (Chopra and Marfurt, 2007). The curvature attribute characterizes the reflector shape independently from bulk rotations and translations of seismic reflections (Chopra, 2007). Curvature enhances the understanding of the structural geology and geometry by delineating folds and flexures. Additionally, curvature has the potential to highlight fracture networks associated with flexures (Hart et al., 2002).

The structure texture attribute enhances low-frequency waveform character resolution and visibility through a waveform model regression (WMR) algorithm with constant phase (Figure 7) that produces high-frequency reflection events (Gao, 2018). The structure texture attribute greatly enhances and illuminates the number of horizons to interpret structural relationships. On the contrary, the seismic texture facies attribute uses a different WMR algorithm with an adaptive phase waveform (Figure 8) that discriminates waveform features in a small window. The facies attribute volume illuminates depositional variations.

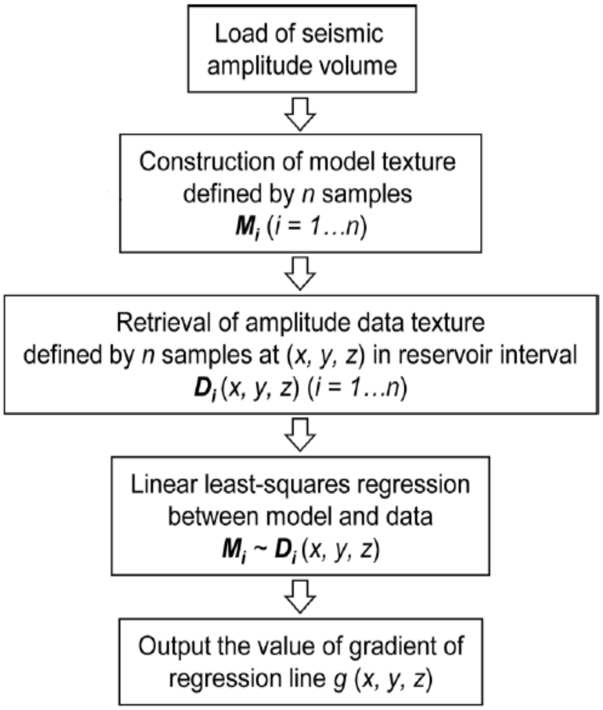


Figure 7: Flowchart for process of converting amplitude volume to seismic structure enhanced volume using waveform model regression (WMR) algorithm. This process is carried out at each location in space at a defined interval size.

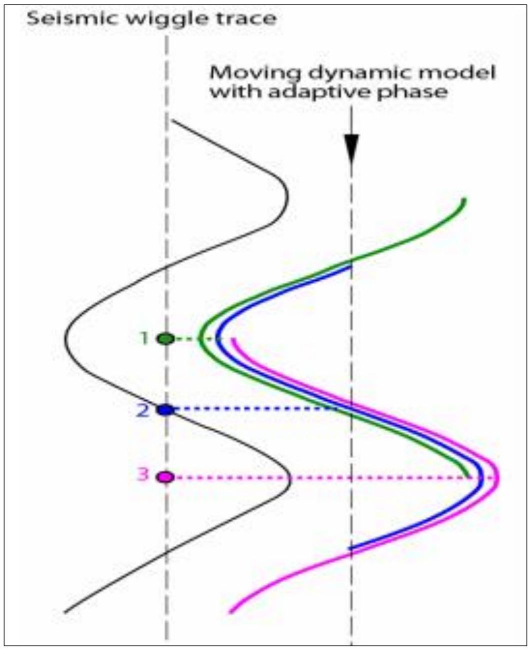


Figure 8: Schematic representation of WMR process along a seismic wiggle trace using a dynamic model with adaptive phase for seismic facies analysis (Gao, 2004, 2006).

3.3 Attribute Comparison

Understanding the general structure and its magnitude can be done with amplitude, curvature, and variance. Curvature and variance attributes are referred to as geometric because they enhance the visibility of geometrical characteristics in seismic data. Attributes like amplitude and frequency are related to mechanical properties and are referred to as physical attributes. Seismic texture is capable of fulfilling both roles as a physical and geometrical attribute depending on the algorithm used (Gao, 2001, 2004). The model texture can be updated through trial and error if the resulting volume does not display enhanced resolution or clarity of geologic features. When coupled with a standard attribute workflow, the two different types of texture volumes provide ample opportunity to enhance exploration through the geometric and physical relationships improved by seismic texture.

4. PREVIOUS WORK

4.1 Seismic Texture

Texture analysis has been employed in seismic interpretation since the 1980’s, when it was used as a method of classification by picking zones of common signal character (Love and Simaan, 1984). Texture is an underutilized attribute compared to many attributes utilized in industry today and only recently have seismic texture techniques been used to enhance 3D volumes. Since the 2000s, seismic texture has proven useful in enhancing interpretation capabilities for facies discrimination when compared to amplitude data (Chopra, 2005; Gao, 2004, 2006). Texture is very useful in extracting quantitative information through statistical measures. Seismic texture refers to lateral and vertical changes in amplitude and waveforms at a given location within a seismic volume (Gao, 2004, 2006). In 3D seismic, texture refers to a characteristic pattern defined by the magnitude and variation of neighboring amplitude samples at a given location within a small zone in 3D space (Gao, 2011).

Historically speaking, texture is an underutilized attribute compared to many attributes used in industry today. Since the 2000’s seismic texture has proven useful in enhancing interpretation capabilities for facies discrimination when compared to amplitude data (Chopra, 2005; Gao, 2004, 2006). In 2011, Gao investigated GLCM vs WMR methods for texture and showed their benefits to well calibration efforts. Multiple texture model sizes can be run through WMR and their results have differing geologic implications. A constant phase texture model is best at identifying the structural fabrics, a model with an adaptive phase is useful for visualizing seismic facies, and a texture model with variable amplitude, frequency, and size is instrumental in calibrating seismic to reservoir properties (Gao, 2011).

4.2 Study Area

It should be noted in-depth reservoir studies have been conducted by Devon Energy geoscientists, but these were not made available for use or publication in this study. Raw seismic data was processed by Devon Energy and WVU received the post-stack seismic volumes. The depth of the Woodford shale is estimated by the top of the underlying Hunton Limestone. Devon Energy also provided WVU with horizon cross-section calibrated to wells showing the Hunton, Chester and Oswego Limestones (Figure 9). These three horizons were then picked across the survey area and provide insight to the adjacent stratigraphy of these lithostratigraphic units.

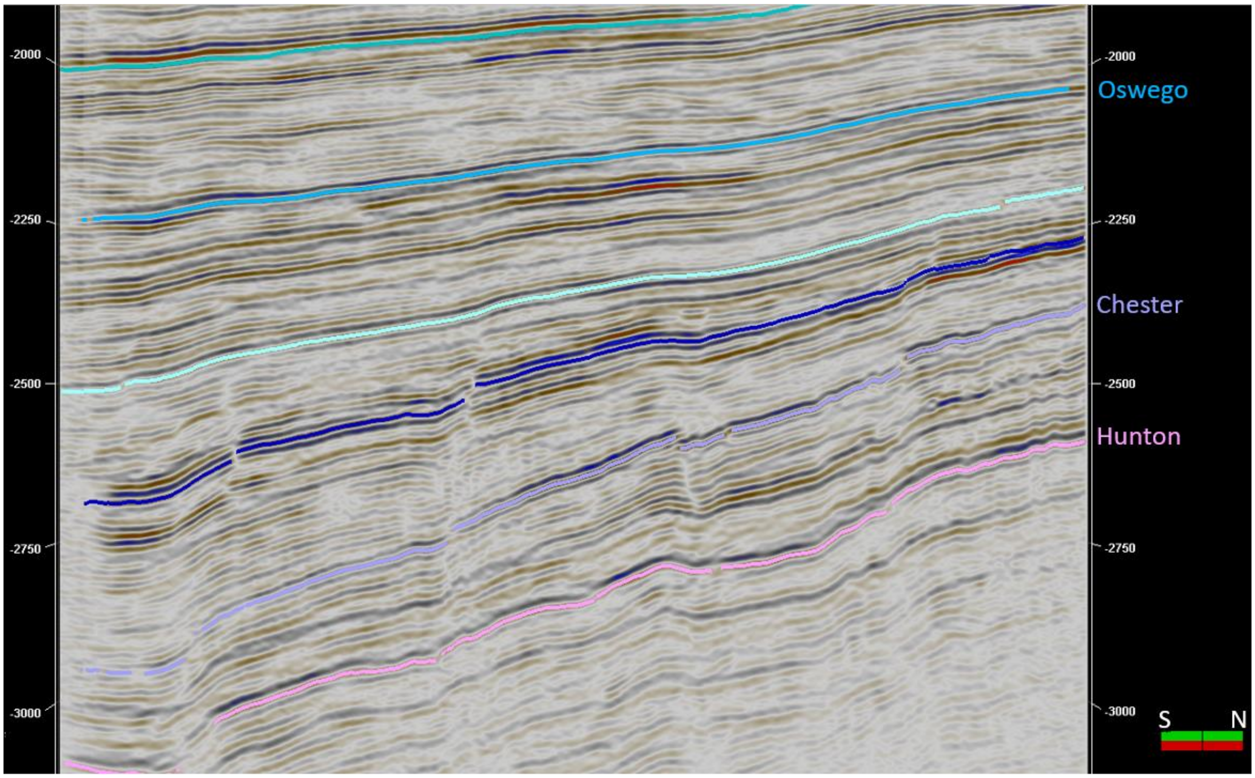


Figure 9: Inline from PSTM Mountaineer 3D data. View from the east with a vertical exaggeration of 10. Picked stratigraphic horizons Oswego, Chester and Hunton are colored and labeled accordingly.

4.3 Analog Basins

The Arkoma basin of Oklahoma is relatively similar age to the Anadarko basin, containing many of the same stratigraphic units, most importantly including the Woodford Shale. Volumetric seismic attributes have been used to successfully map and characterize structural deformation (Guo et al., 2010). This study utilized coherence, curvature, and production data to interpret curvature anomalies and naturally fractured areas that enhanced production.

Offshore Angola data from a Gao study in 2008 showed very promising results with regard to WMR facies volumes. Lateral variations could be delineated across the survey in a deep offshore marine environment with channel sands. The Anadarko basin contains similar depositional environments.

The Appalachian front across the eastern United States provides an analog for the structural evolution of the Wichita mountains in Oklahoma. The foreland basin created during the Silurian through the Pennsylvanian in northeastern United States has a style similar to that seen in the Anadarko basin – though the Anadarko rotated 90° counterclockwise to the Appalachian front. While the Wichita mountains are an extension of the Appalachian front, the stratigraphy varies significantly, and, most importantly, does not contain the massive Salina salt, which acts as a detachment for large-scale normal faulting (Gao, 2018).

5. DATA AND METHODOLOGY

5.1 Attribute Workflow

Seismic attributes aid in interpretation and analysis for determining many of the important factors needed to optimally produce oil and natural gas. This research utilizes attributes that are known to be directly related to geologic features and rely on those assumptions to help understand and characterize subsurface geology. Initial interpretations and exploration relied on amplitude, minimum and maximum curvatures, and variance. These attributes provide insight to the structure and facies throughout the seismic data set, and help isolate areas of interest for comparison to texture volumes.

5.2 Synthetic Seismic Modeling

A suite of wells provided by Devon Energy allows for the forward modeling of a synthetic seismogram. A synthetic seismogram is generated by convolving the reflectivity, calculated from acoustic and density logs, with a wavelet similar to the input seismic data. The synthetic seismogram is not guaranteed to match with the original seismic data because of data collection differences, and particularly results in differences in the absence of check shots and a partial sonic log (Ewing, 2001). The well data lacked check shots and had an incomplete sonic log, but a time-depth relationship was still created in order to successfully create a synthetic seismogram (Figure 10). An accurate well-tie could be established in this data set with the combination of a correct vertical shift, well tops and known shallow seismic horizons for future work.

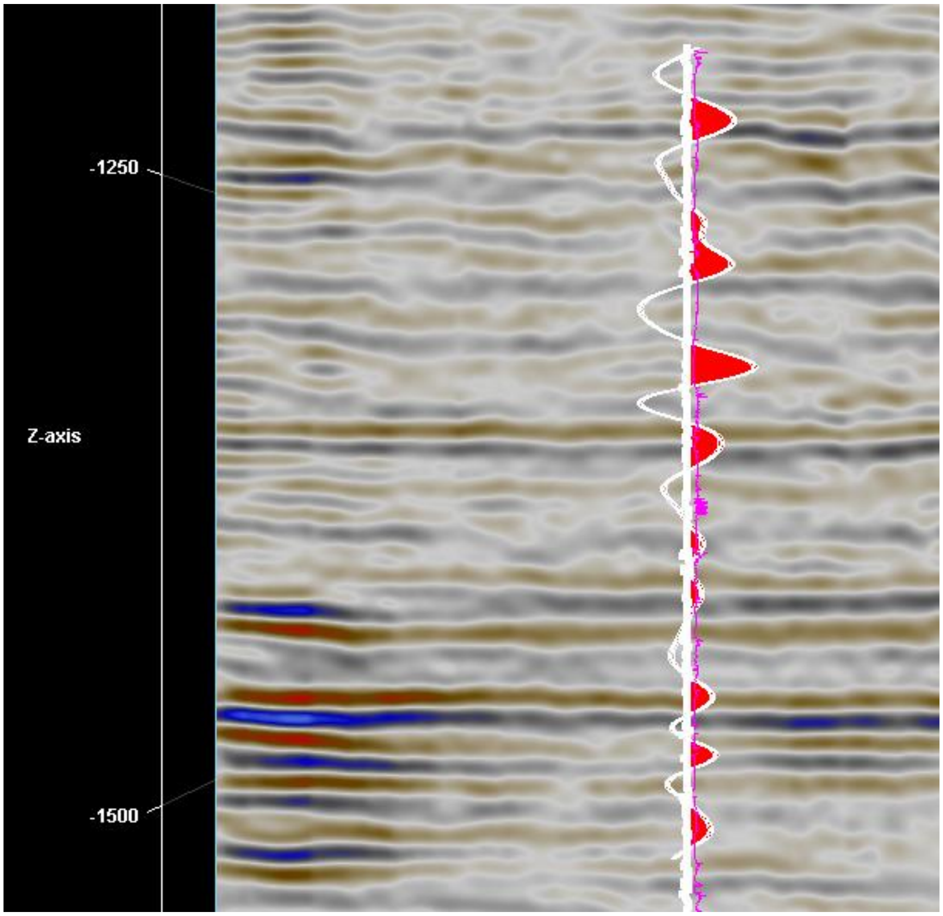


Figure 10: A synthetic seismogram created with a Ricker wavelet overlaid on PSTM amplitude data.

5.3 Waveform Texture Analysis Methodology

WMR-based texture attributes were used to produce facies and structure volumes to investigate geologic implications within the Mountaineer 3D. Using a post-stack seismic volume, Gao's waveform method creates a tool for seismic visualization that is more useful than amplitude or coherency volumes. While coherency highlights discontinuities alone, texture highlights discontinuities as well as how adjacent traces differ (Gao, 2011).

Waveform texture attributes are computed by using each original amplitude trace waveform and lateral location within the Mountaineer 3D. A model waveform is computed from each original trace and is compared to adjacent traces through a linear least-squares regression

(Figure 11). Following the regression a correlation coefficient is calculated and results in the new attribute value. This process is computed throughout the Mountaineer 3D volume and is outlined previously in Figure 7. While there is some variation between waveform texture attributes, the basic steps stay the same. Waveform texture attributes are the product of comparing an input data to a model data then analyzing the regression between the two. As a result, the final output provides a relationship between the original post-stack seismic and the model waveform.

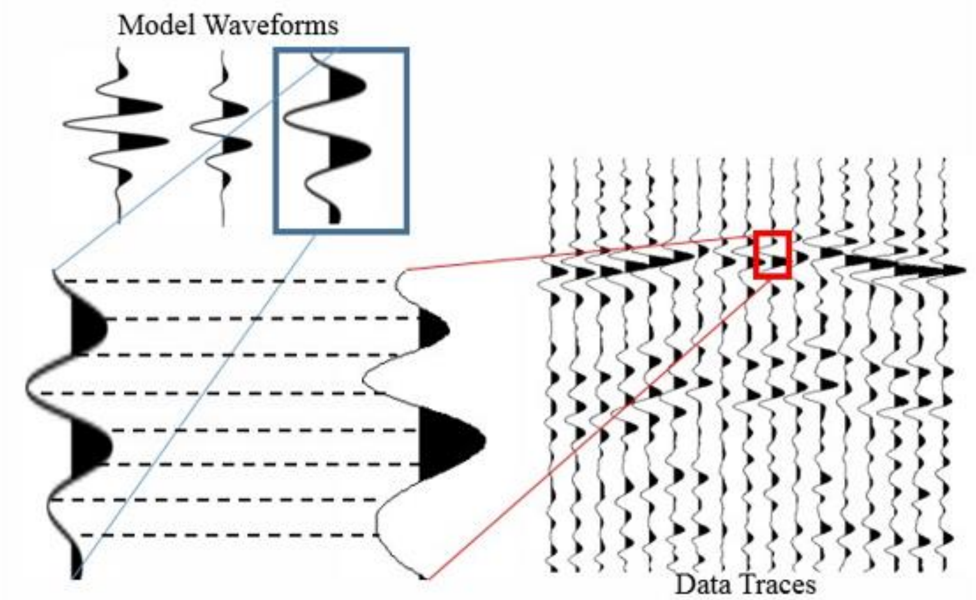


Figure 11: Schematic representation of WMR using model waveforms and to real data traces. Each pair of samples (connected by dotted lines) are used in linear least squared regression and the slope of the line of best fit is the output used for texture attributes (Geiger, 2016).

5.4 Structure Volume

Multiple structure volumes were created using varying frequency and window sizes through WMR in order to better visualize structure. This research utilizes two structure volumes using 7 and 15 sample window sizes and 71Hz and 33Hz frequencies, respectively. Figures 12, 13 and 14 show the differences in varying frequency and window size compared to PSTM amplitude data.

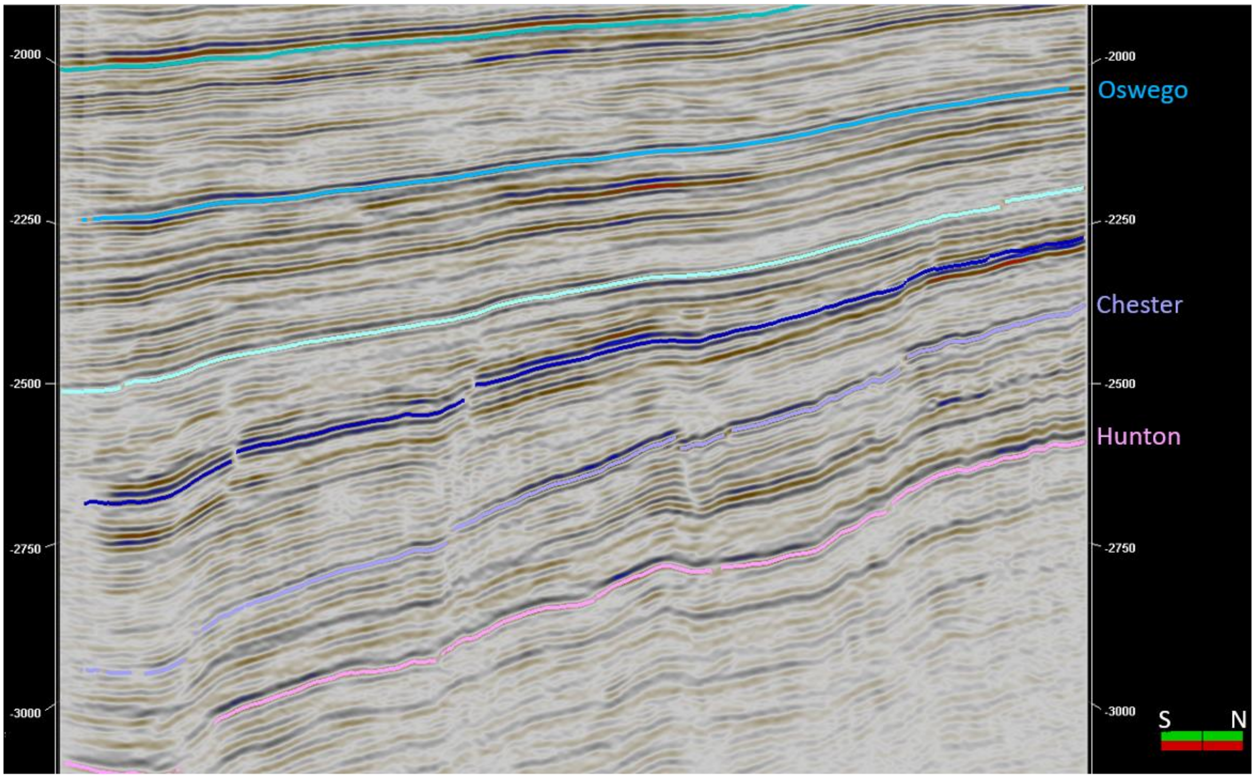


Figure 12: Inline from PSTM data view from the east with a vertical exaggeration of 10. Picked stratigraphic horizons are colored and known units are labeled.

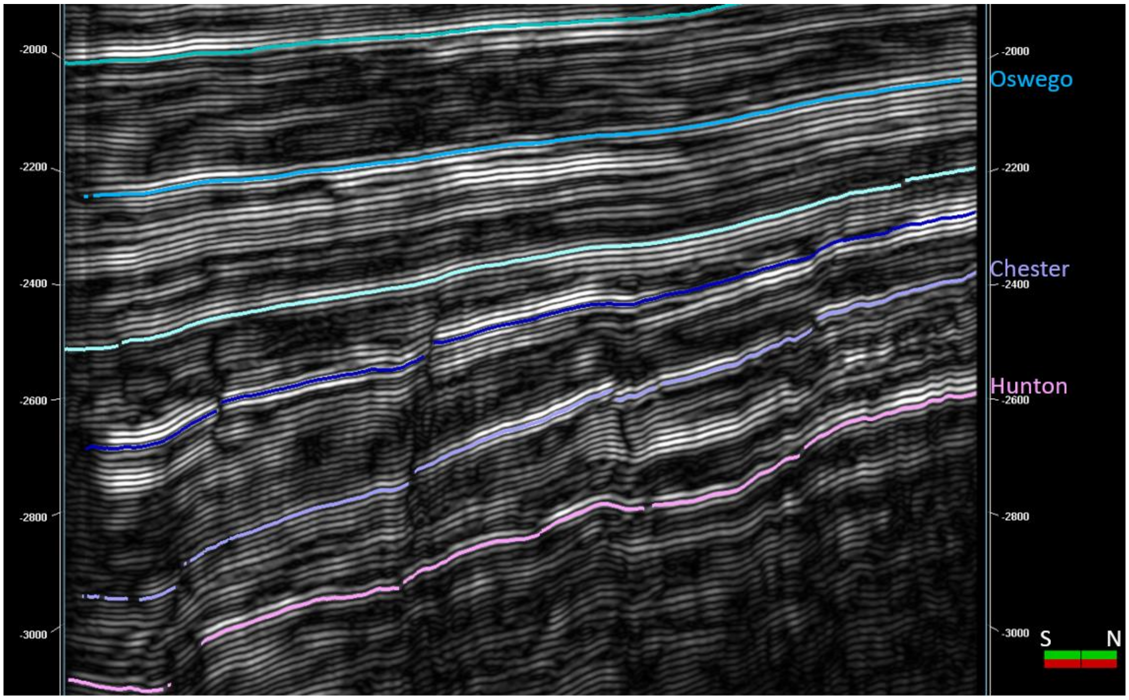


Figure 13: Inline from seismic structure data volume with a frequency filter of 15. View is from the east with a vertical exaggeration of 10. Picked stratigraphic horizons are colored and known units are labeled.

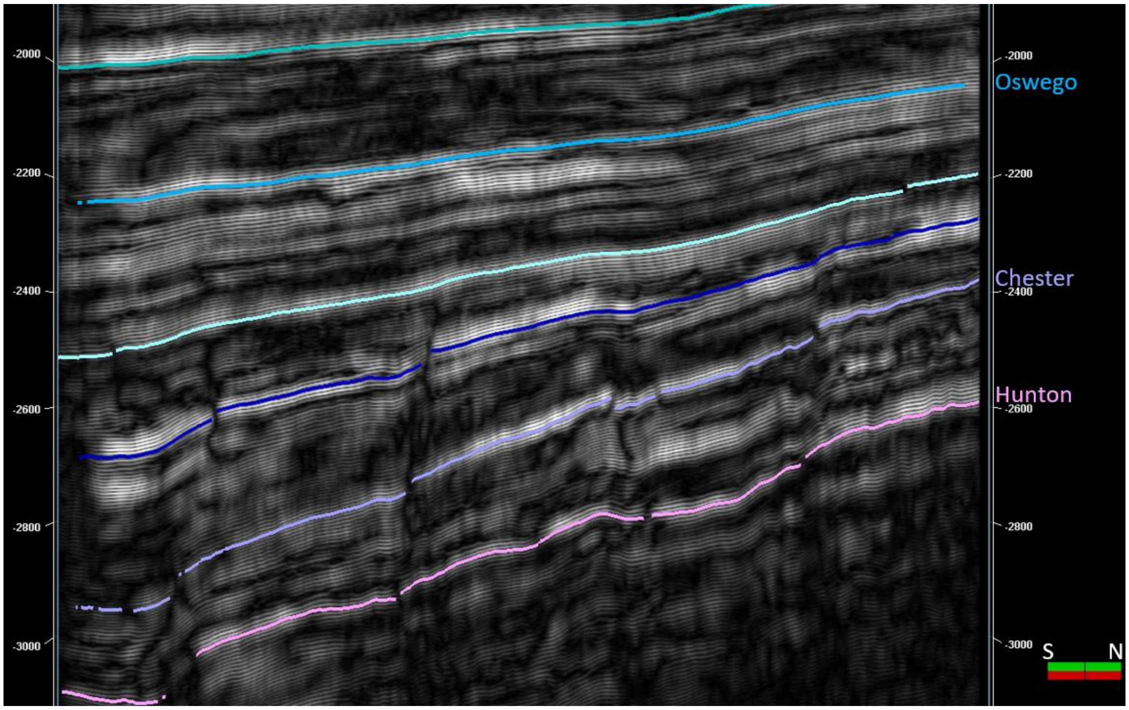


Figure 14: Inline from seismic structure data volume with a frequency filter of 7. View is from the east with a vertical exaggeration of 10. Picked stratigraphic horizons are colored and known units are labeled.

The visual result is seen immediately when comparing a structure volume to the original input amplitude data. In conventional amplitude data, reflection events and their discontinuities are limited in many cases because of weak reflection energy, low dominant frequency and poor signal-to-noise ratio (Gao, 2011). The two structure volumes allow for greater detection of structural deformation when interpreting on in-lines, cross-lines and time-slices within a seismic volume. Seismic structure volumes rely on a constant phase wavelet to enhance the structural geometry. High-angle faulting, semi-parallel to strike, is apparent beneath the Oswego. These are generally normal faults, stepping down into the deeper part of the basin from the northeast to southwest, and can be seen on in-lines and cross-lines. Additionally, oblique faults in the deeper section can be seen on time-slices and surfaces.

5.5 Facies Volume

3D seismic facies analysis through WMR isolates distinct seismic features in 3D space, and utilizes a variable phase to differentiate waveform characters (Gao, 2011). An instantaneous phase model restrains structural interference and highlights facies changes. This difference allows isolation of more complex facies that are not clearly visible within amplitude data alone. Multiple seismic facies volumes were computed with different scales. This is computationally achieved by instantaneously changing the phase of the model until a maximum regression gradient is found between the model and the data, and is repeated sample to sample (Gao, 2011). This research utilizes two scales of waveform windows. Variations in seismic facies are seen when comparing facies volumes to the amplitude volume, and are of greatest significance near channel deposits. A smaller scale is able to distinguish smaller features, and larger scales distinguish broader, large-scale features. The upper section of the Mountaineer 3D data has multiple channels and is visually enhanced through seismic facies volumes.

6. RESULTS

6.1 Preliminary Seismic Analysis

The Anadarko basin subsided throughout the Paleozoic Era as the result of cooling of precedent igneous activity followed by the formation of the Wichita uplift (Johnson, 1989). Post-stack amplitude data in Figure 15 shows the general southwest dipping trend of the Anadarko basin seen throughout the Mountaineer 3D.

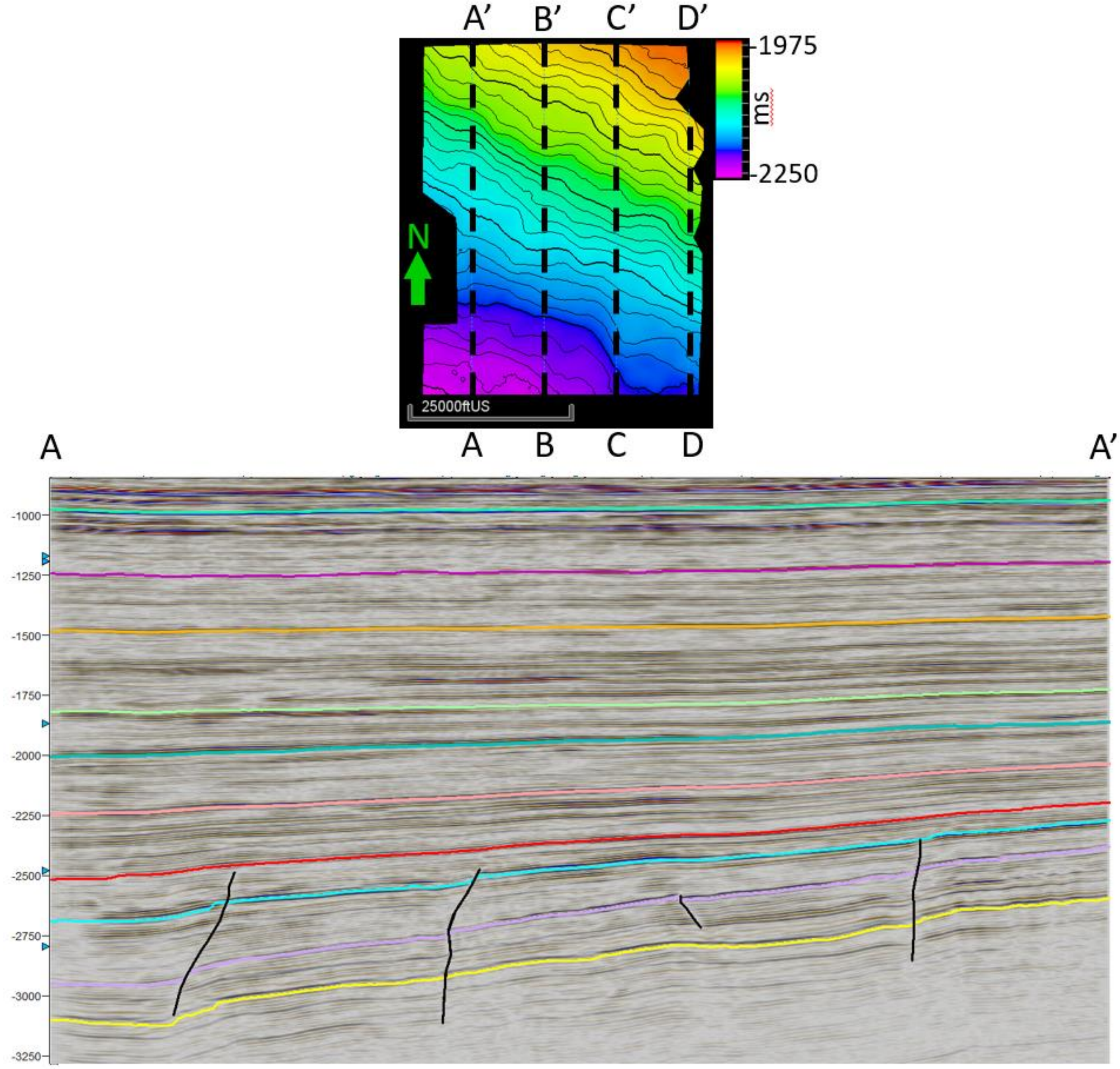


Figure 15: Cross-section from A-A’ shown on a surface map of the Oswego. Stratigraphic horizons are colored lines and faults are black lines.

Eleven generally continuous and major stratigraphic boundaries were mapped throughout the data to investigate variations in deposition and structure style. The dip and structural deformation increase with depth within the seismic data. The most drastic change can be noted above and below the Oswego surface, where deeper stratigraphic units are structurally complicated and have much larger variations in depth compared to shallower stratigraphic units (Figure 16). This trend is representative of the known structural geology of the Anadarko basin. To the Southwest is the Wichita mountains, the hinterland, and the Mountaineer 3D is located in the foreland, which explains the wedge formations seen in the bottom portion of the data. Below the Oswego there are four picked horizons, two of which are the Chester and Hunton limestone unit, and above are six unknown horizons. The upper horizons have extremely similar structure trends and provide the basis for the facies analysis, particularly in regards to sedimentary features. The lower units provide the foundation for investigation into enhanced structure deformation.

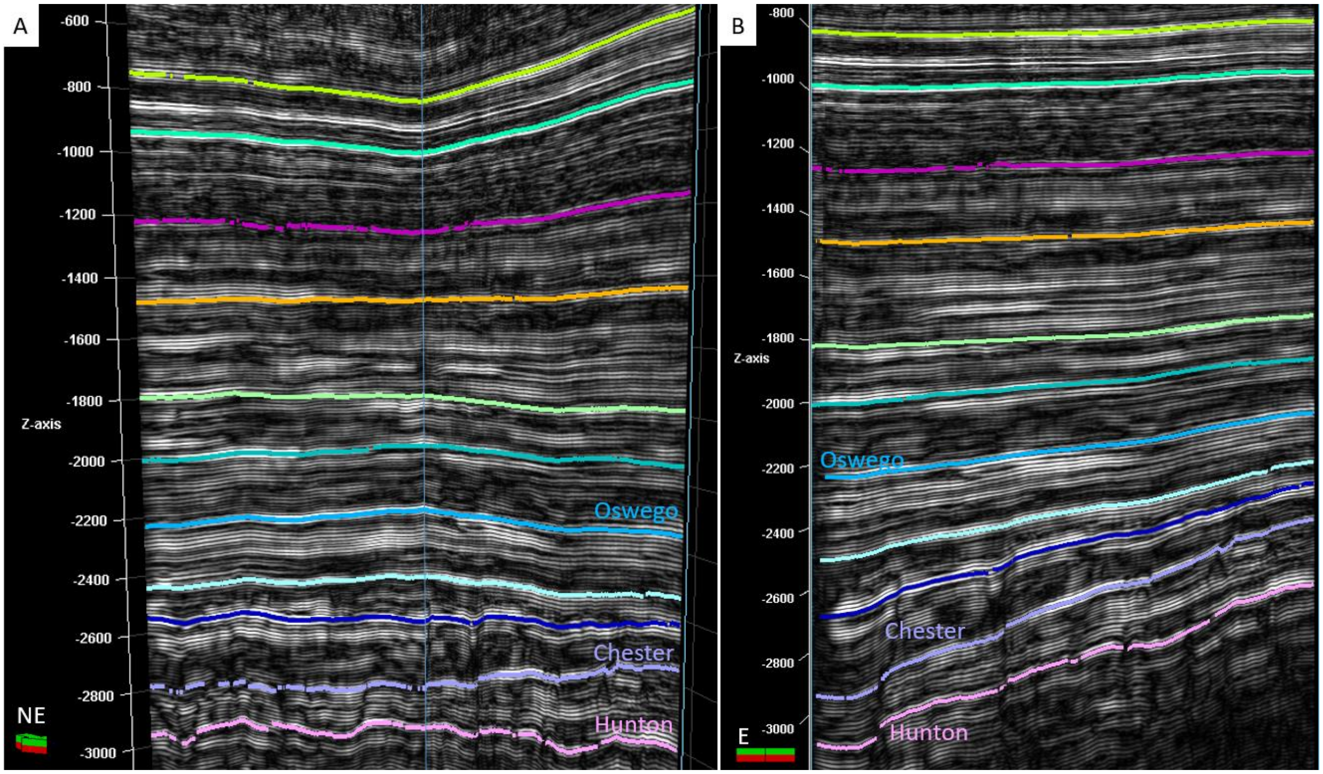


Figure 16: Image A shows both inline and crossline views of texture structure data from the northeast, and image B shows a crossline viewed from the East and meet along the vertical blue line. Stratigraphic horizons are colored lines, with the Oswego, Chester and Hunton horizons are color coded to the respective horizon's color. The two images provide clear insight to the structural differences from top to bottom.

6.2 Seismic Structure Analysis

The structure of the Anadarko basin within the Mountaineer 3D is categorically different above and below the Oswego horizon. Above the Oswego horizon the stratigraphy is generally free of structural faulting or fracturing when compared to the stratigraphy below the Oswego.

The upper horizons dip decreases from roughly 6.5 degrees until the beds are nearly horizontal at -1000ms (Figure 16). The Hunton and Chester limestone units, as well as two unknown horizons, have been picked beneath the Oswego and show substantial deformation. The Silurian Hunton limestone and Mississippian Chester limestone were heavily fractured and faulted during the formation of the Wichita mountains. The primary structural development of the Anadarko basin during this orogeny can be interpreted as an oblique compressional system, as well as influence from transpressional forces (Ball et al., 1991).

Figure 17 visualizes the general structure seen across the Mountaineer 3D below the Oswego and shows important kinematics. The bulk of major faults impact only the deepest strata (Hunton and above), propagate up through horizon 2 occasionally and rarely intersect horizon 1. In addition, the Oswego remains unfaulted. The faults picked in red are predominately hinterland-vergent normal faults, where the southern strata drop in relation to the adjacent northern counterparts. This detachment is most likely driven by gravitational pull from the southwest during rapid subsidence caused by the thrusting of Wichita mountains. There are graben-like features found throughout and an example is shown in Figure 17, C-C'.

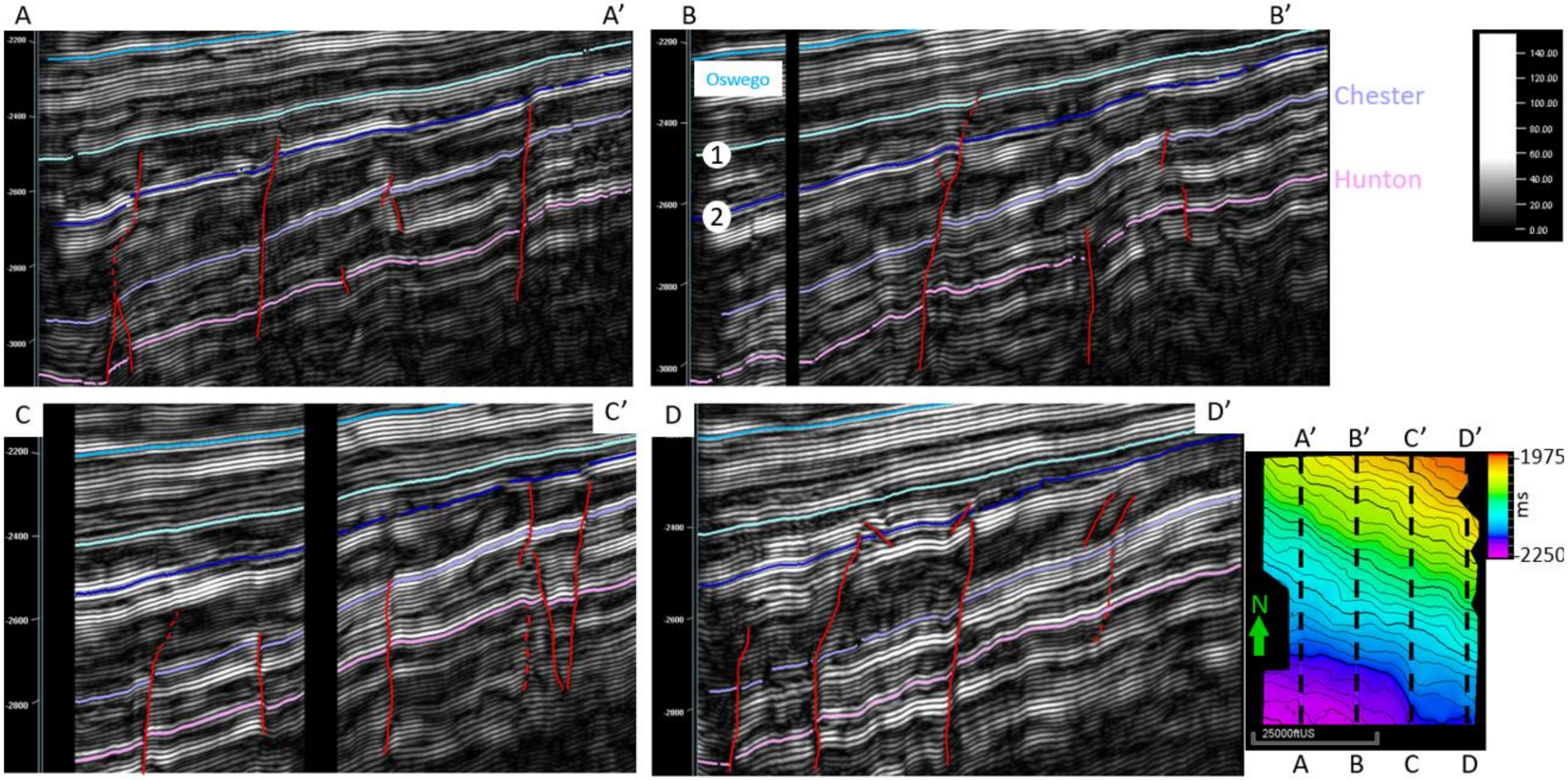


Figure 17: Cross-sections from seismic texture (15) with faults and surfaces picked. Oswego, Chester and Hunton are labeled, and two others horizons are number. The locations of each cross-section are shown on the map of the Oswego time surface.

The southern flank along the Chester and Hunton horizons is bounded by a folded, reverse-like feature, implying external forces are at play in addition to simple gravitational pull. Additionally, structures oblique to strike can be found across the horizons below the Oswego horizon, particularly near the Chester horizon. More often than not the oblique structures are found en echelon and could be representative of transpressional forces causing shearing during parts of the Wichita orogeny (Figure 18). The Chester horizon in Figure 18A contains a swath of oblique fault features in the large circle to the North, and to the South a primary East-trending normal fault is offset by multiple oblique faults. Coherence highlights this discontinuous nature of these faults, while structure texture provides insight to the deformation of the strata as a whole. In Figure 18 C and D the higher frequency structure time-slice provides greater detail of potential faulting than what can be seen in the other figures. This provides the opportunity to expand on fault and fracture analysis near the Chester Limestone.

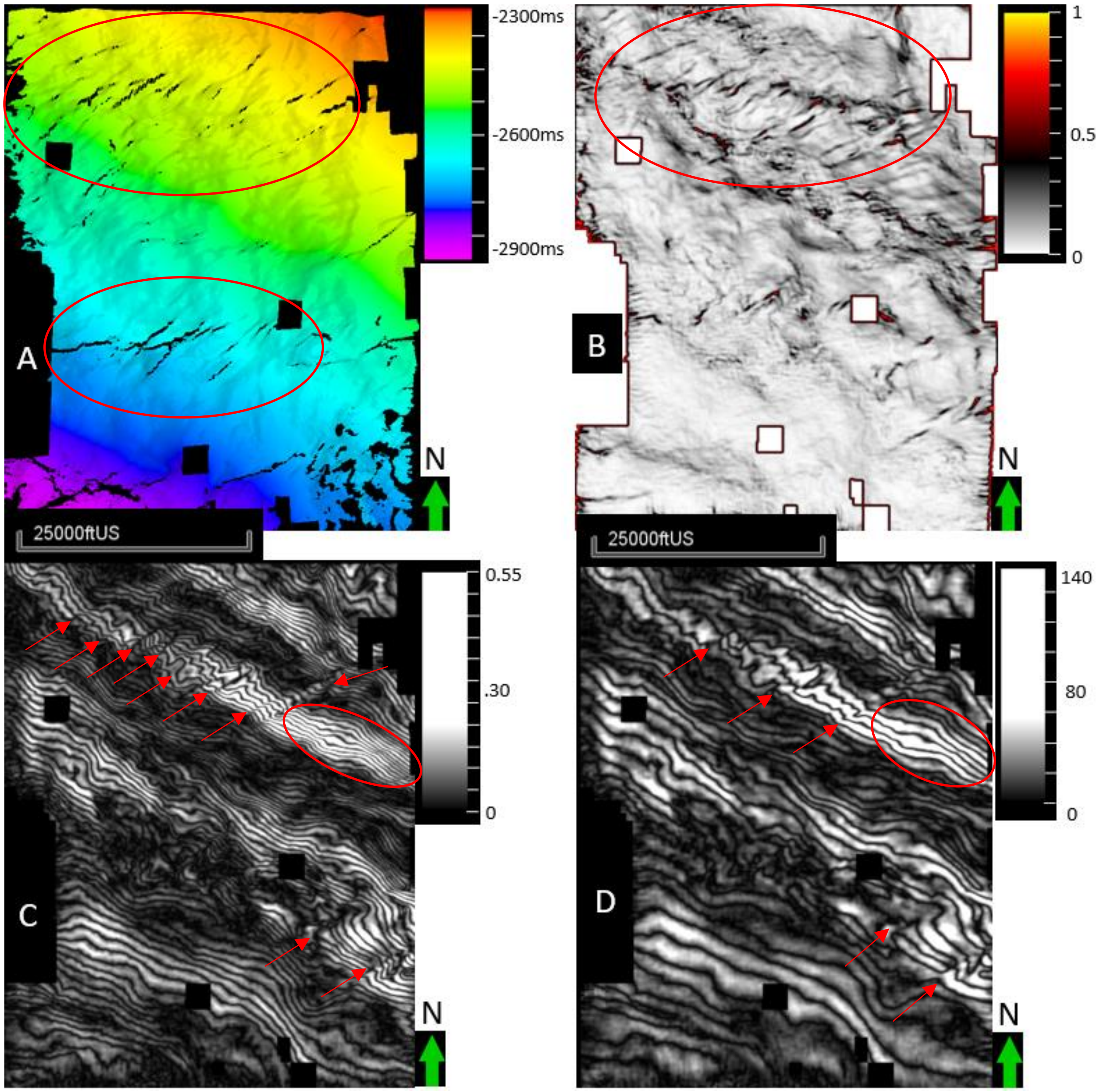


Figure 18: Four seismic interpretations of and around the Chester limestone. (A) TWT Chester horizon dipping from the NE to SW 600ms. The larger northern circle highlights oblique, en echelon faulting, and the smaller circle highlights large-scale normal faulting with oblique faults en echelon. (B) Variance time-slice at -2416ms overlaid by the same large circle from (A) highlighting variance in continuity of strata. (C) and (D) are texture structure time slices at -2416ms. Arrows point to en echelon style deformation. (C) is the high frequency (71Hz) volume while (D) is the low frequency (33Hz) structure volume.

6.3 Seismic Facies Analysis

In the shallower section of the post-stack seismic amplitude data set there is strong evidence for the presence of river channels. Features commonly found in amplitude data that relate to meandering rivers are found throughout, and were investigated further with additional attributes. While RMS amplitude and curvature provide an outline for the presence of these southwestern traveling rivers, seismic texture facies illuminate and distinguish more features. Figure 19 shows a river channel in seismic horizon 3 and surface 3.

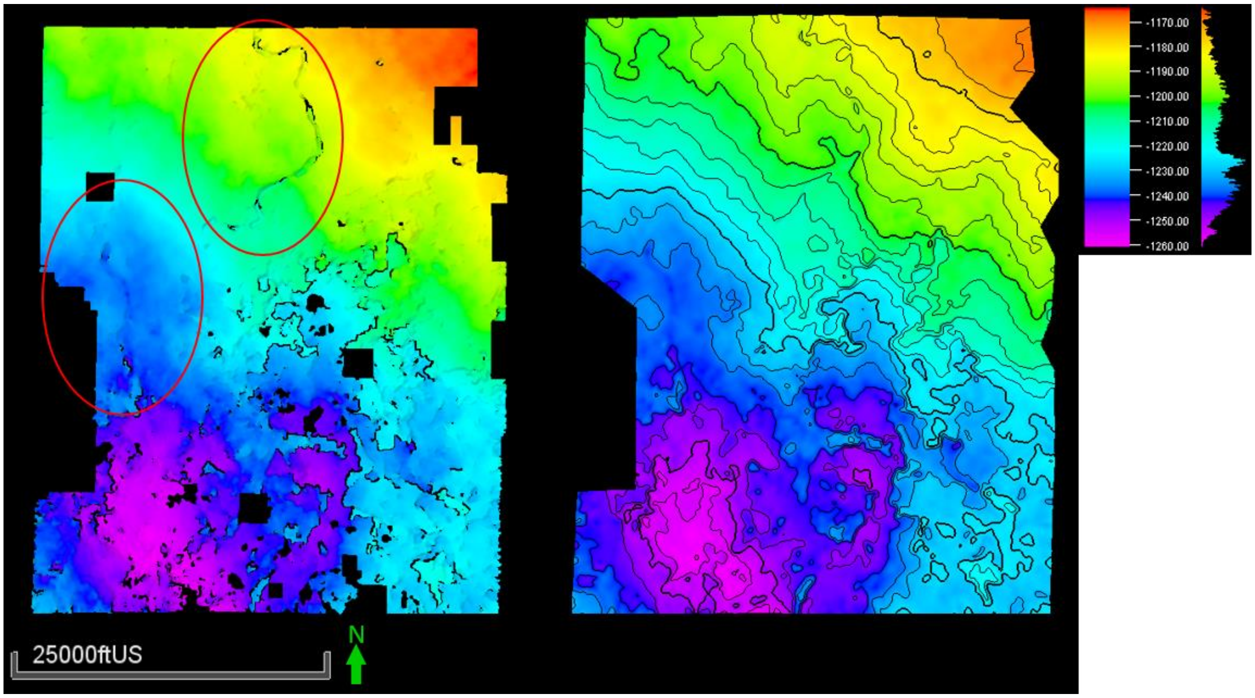


Figure 19: Horizon 3 and Surface 3, respectively, showing the presence of a river channel highlighted by the red circles.

While the creation of the surface from the horizon smooths the visual presence of the river channel, the contour “V” pattern persists where the river channel is found on horizon 3. The quality of this surface diminishes to the South because alluviation can create a disrupted, discontinuous seismic response making consistent amplitudes picks challenging. The amplitude data shows the presence of the river channel, and can be enhanced by comparing the result to texture facies volumes (Figure 20).

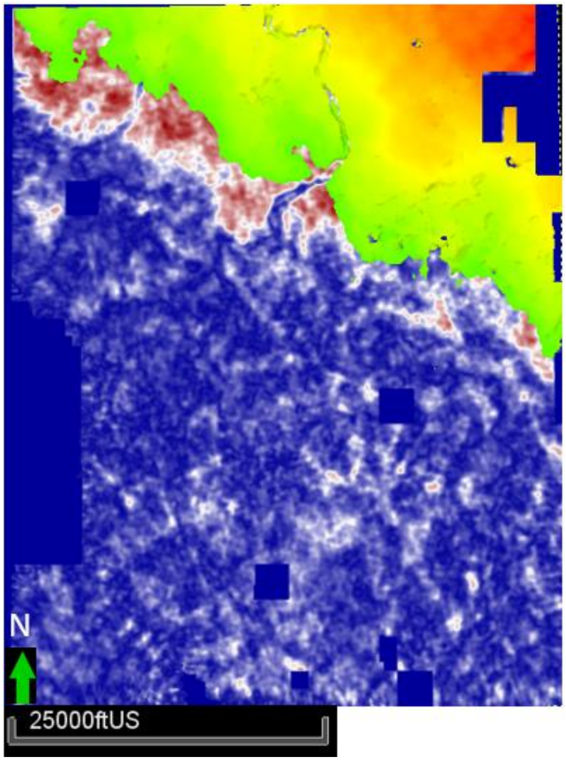


Figure 20: Horizon 3 overlaid on a seismic facies timeslice from -1200ms showing a river channel migrate southwest.

The comparison of the river channel system seen near horizon 3 is stark in seismic time-slices. Figures 21-24 highlight the quality of texture volume attributes to distinguish river channel deposition as compared to amplitude alone. Horizon 3 spans roughly 100ms of vertical section, and these four time-slices cover the majority of this depth. Comparing amplitude to the facies data the apparent difference is the visibility of the river channel. The river meanders from the northeast to the southwest over the entire seismic horizon with multiple point bars, cut bank and potential splay deposits that cannot be confidently mapped and characterized in amplitude time-slices alone. The differences in the facies volumes should be noted in their ability to distinguish facies patterns near and outside of the river channels. Of particular interest is the presence of river channels in facies 7 than cannot be seen in the lower frequency facies 11

(Figures 22 & 23). Facies volumes output data directly related to the input waveform (soft data) and can be interpreted to distinguish varying facies during deposition (Gao, 2011).

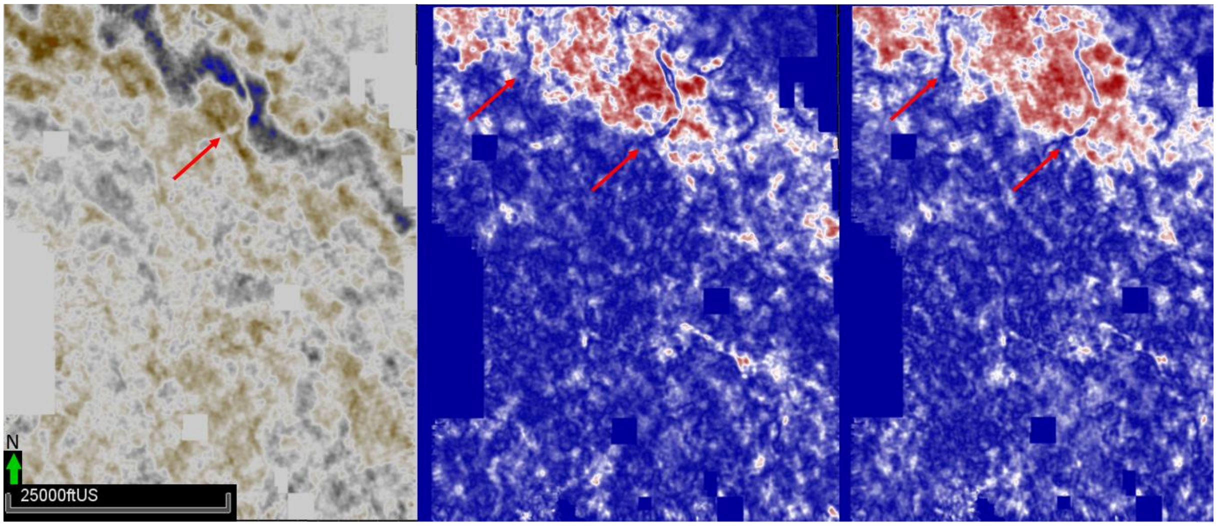


Figure 21: Three timeslices taken from PTSM, Facies 7 and Facies 11 data, respectively. The timeslices are located at -1192. River channel can be clearly seen on the Facies data set.

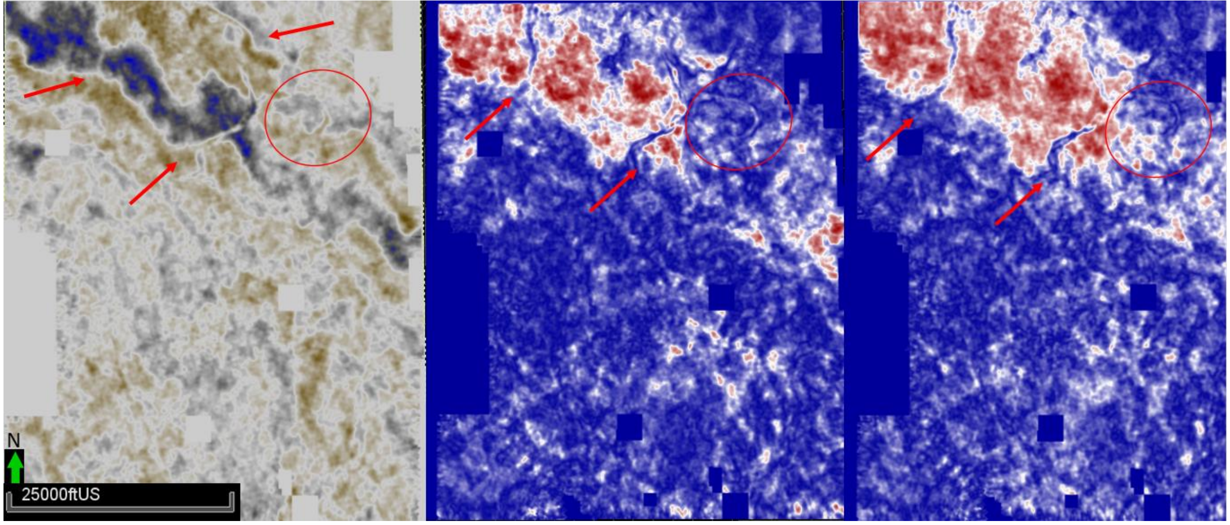


Figure 22: Three timeslices taken from PTSM, Facies 7 and Facies 11 data, respectively. The timeslices are located at -1200. River channel can be clearly seen on the Facies data set.

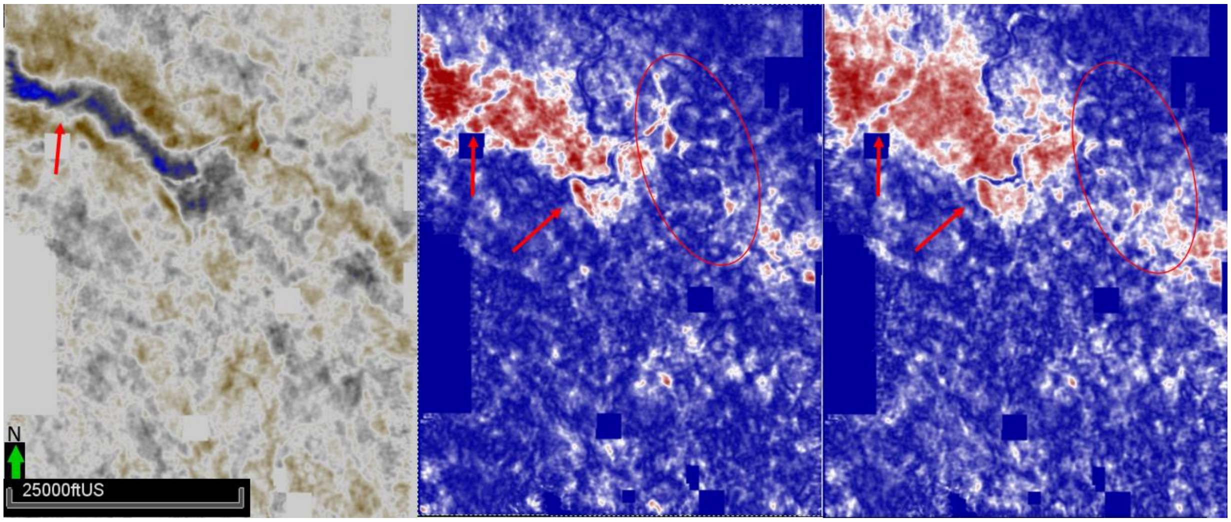


Figure 23: Three timeslices taken from PTSM, Facies 7 and Facies 11 data, respectively. The timeslices are located at -1210. River channel can be clearly seen on the Facies data set.

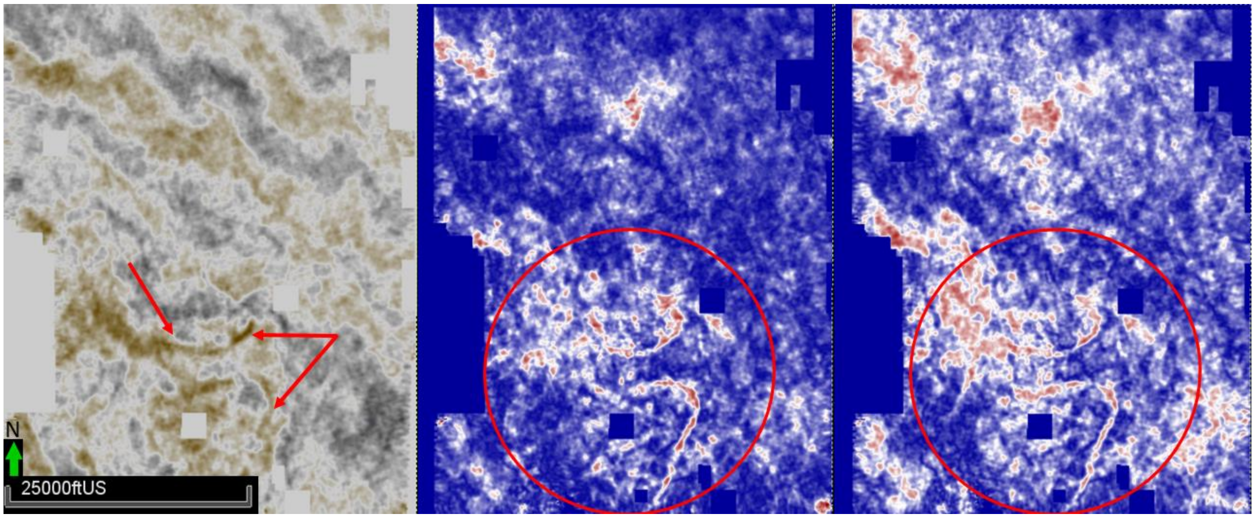


Figure 24: Three timeslices taken from PTSM, Facies 7 and Facies 11 data, respectively. The timeslices are located at -1250. River channel can be clearly seen on the Facies data set.

Surface attributes show additional detail and follow the horizon's general dip instead of horizontally slicing through with a constant time-slice. Figures 25 and 26 are surface attributes extracted onto horizon 3, and illuminate the river channel in one image. Minimum and maximum curvature map the lateral movement and extent of the river channel, while ignoring insightful data outside the river banks useful in delineating different depositions. The curvature attributes are useful for initial interpretation, but offer little more than amplitude and are inferior to texture attribute analysis. Figure 26 shows three surface attributes – facies 7, facies 11, and PSTM amplitude, respectively – and their ability to better distinguish lateral facies variations compared to curvature. The input amplitude surface is capable of showing the presence of a river channel, while the facies surfaces provide greater detail and variation.

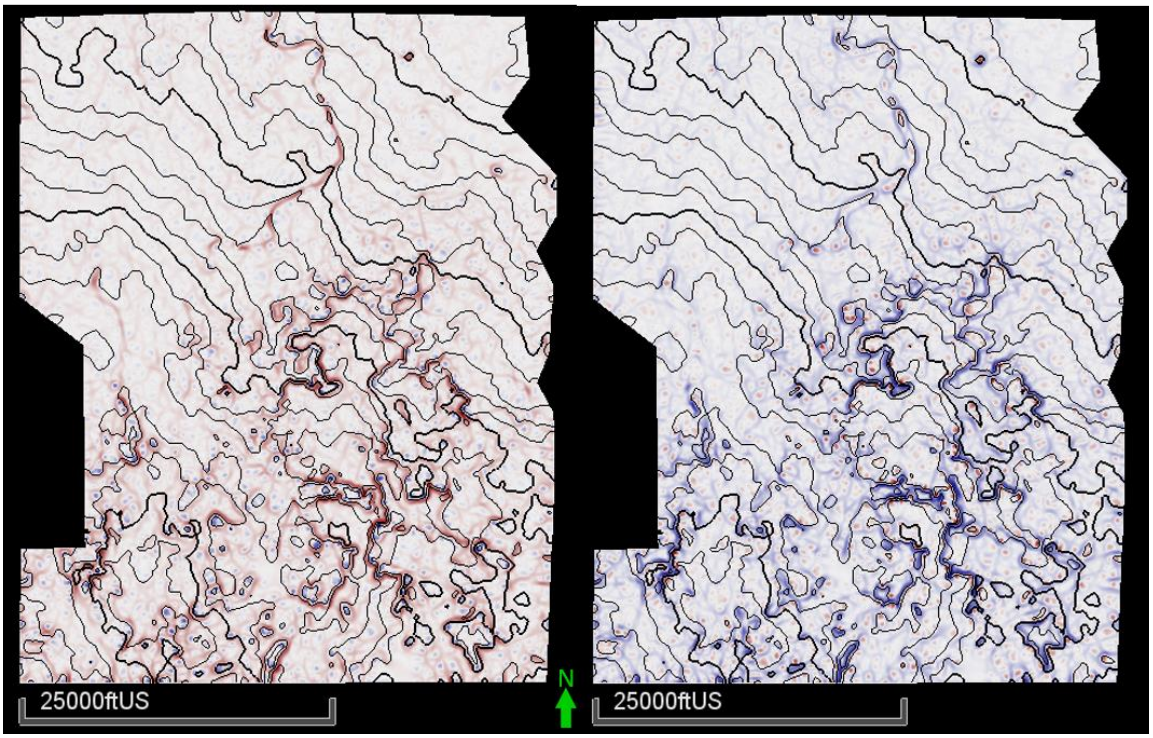


Figure 25: Minimum and maximum curvature of Surface 3.

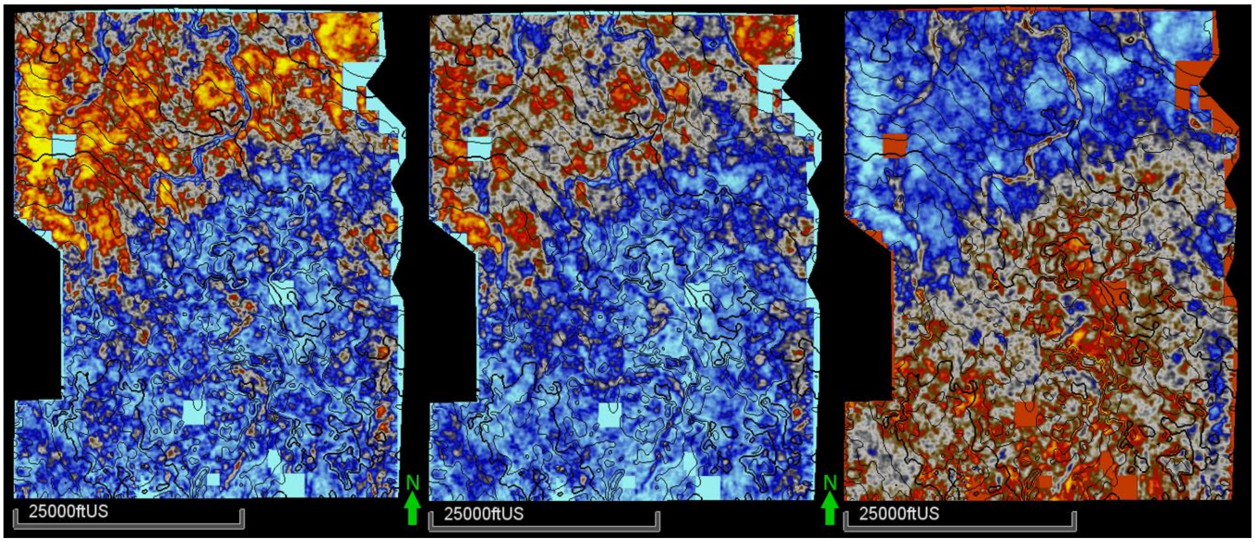


Figure 26: Three surface attributes extracted on Surface 3: Facies 7, Facies 11 and PSTM Amplitude, respectively.

7. FUTURE WORK

Well log data can be used to determine the accuracy of estimations made within the facies volumes. Different responses within a facies volume should represent different rock types – shale, sandstone, etc. Geiger’s 2016 work showed promise in comparing gamma ray responses to varying facies texture, and directly relates to rock property estimation. The Pennsylvanian sandstone, the Mississippian and Devonian carbonate, and early Mississippian Woodford Shale are three proven petroleum targets that can be further evaluated within the Mountaineer 3D seismic data set with accurate well ties. Once able to determine where certain geologic zones are located, texture analysis would aid better characterization of fractures, faults and facies near the reservoir.

Gao’s 2008 work in offshore Angola and 2018 work in the Appalachian basin shows great potential for further exploration of seismic texture analysis within the Mountaineer 3D. Incorporating additional well information, such as detail logs and production data, could enhance the understanding of structure control on the reservoir and establish greater insight to lateral variation within the petroleum targets of the Anadarko basin. The foundational understanding of structure established in this study can be used to better understand structural controls within conventional and unconventional reservoirs. Geomechanical properties in general, brittleness in particular, are controlled by fracture orientation and could be better characterized through the high frequency seismic texture analysis.

8. CONCLUSIONS

The application of an analytical attribute workflow with an emphasis on waveform texture attributes provides an insight to subsurface basin structures and depositional facies, which are fundamental for successful exploration for and effective development of conventional and unconventional energy resources in the Anadarko basin. While many seismic attributes are available for petroleum geoscientists, seismic texture is a developing concept and methodology that has been underutilized in the oil and gas industry. This research should provide motivation for applying seismic texture analysis in 3-D seismic volumes for subsurface structure and facies characterization, leading to enhanced geophysical interpretation of 3D seismic amplitude data. The Anadarko basin of Oklahoma is prolific in oil and gas exploration. This study has contributed insight to the potential for texture attribute to well calibration. The suite of well logs provides the opportunity to continue this research for in-depth structure and facies calibration. An analytical attribute workflow provided insight to depositional facies, structural geology, and small-scale features that are otherwise unclear from reflection seismology alone. Characterization of channel flow and deposits were enhanced with seismic texture facies, and oblique structures were visualized more clearly through seismic texture structure volumes. Gao’s waveform texture attributes were used to produce facies and structure volumes to investigate geologic implications within the Mountaineer 3D. Using a post-stack seismic volume, the waveform texture analysis provides a tool for seismic visualization that is more useful than amplitude or coherency volumes and provides interpreters with more detail for subsurface structure and facies characterization in the basin.

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