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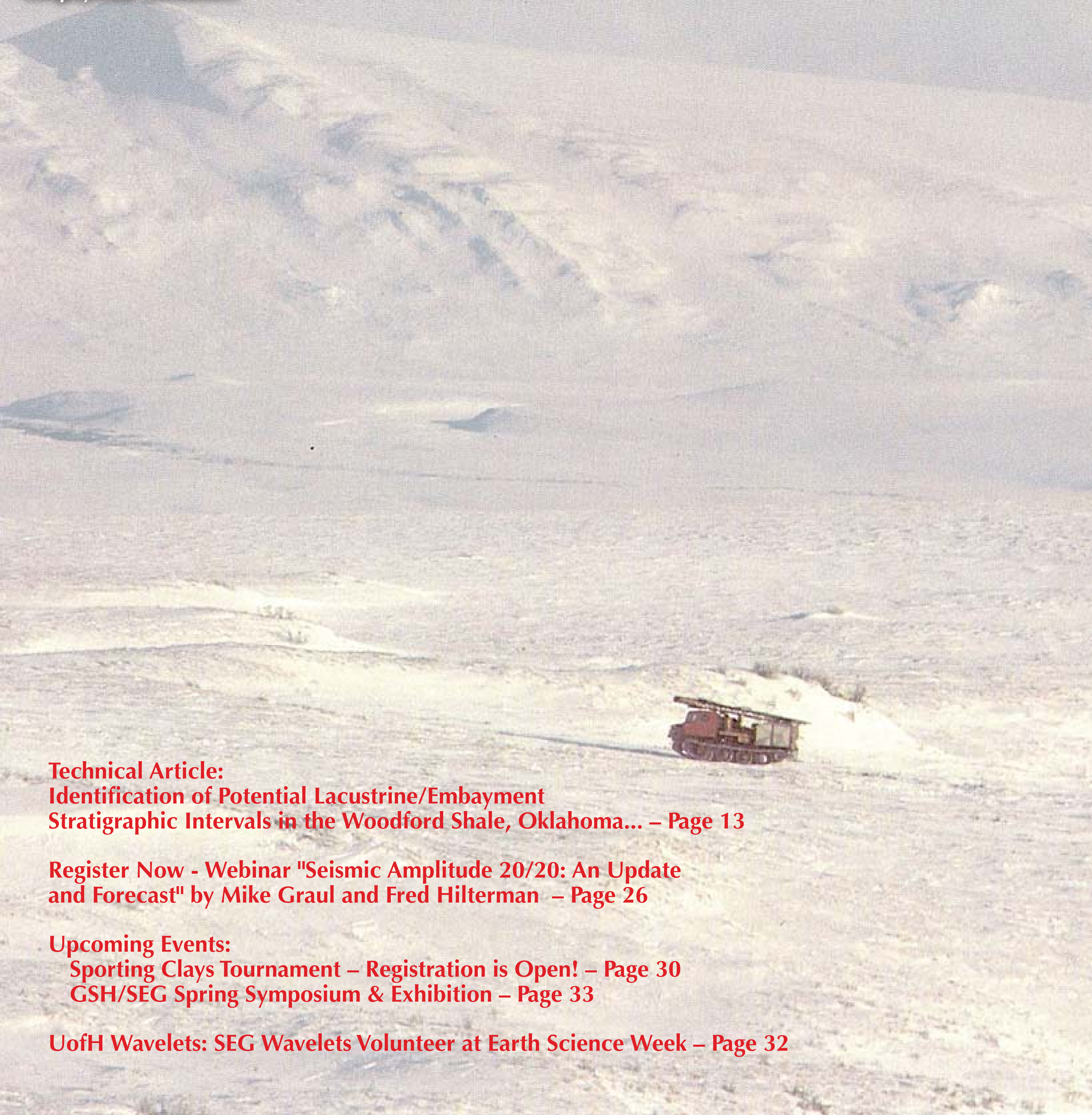

Identification of Potential Lacustrine/Embayment Stratigraphic Intervals in the Woodford Shale, Oklahoma, Using Multi-Attribute 3-D Seismic Displays and a Supervised Probabilistic Neural Network

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Summary

With the latest exploration and development of unconventional shales focused on predominantly marine deposits, the potential of hypersaline, highly restricted marine lacustrine-embayment deposits has not been studied systematically. The primary goal for this study is to resolve whether there are seismic indicators for such rocks within a predominantly marine shale, targeting specifically within the Woodford Shale formation in Oklahoma U.S.A. Several of the North American resource shales have been characterized as marine mega-sequences with the common characteristic of being deposited unconformably above a carbonate formation where paleo sea level fluctuations allowed the development of erosional topography that might lead to restricted hypersaline lacustrine-embayment settings.

The differences in hydrocarbon generation and cracking kinetics result in different thermal maturity windows for marine and saline lacustrine-embayment deposits, where these lacustrine-embayment rocks require higher thermal maturity for oil generation and cracking. Therefore, where high thermal maturity for a rock of a marine depositional environment thermally cracks the oil, in that same maturity yield, the oil might be preserved for a lacustrine-embayment deposit, thus providing previously unidentified exploration and prospectivity targets.

A model based seismic post-stack acoustic impedance inversion and a supervised Probabilistic Neural Network (PNN) analysis was performed to predict the Total Organic Carbon (TOC [weight %]) variation along the Woodford shale in South-Central Oklahoma, U.S.A. The results are tied with the Woodford Shale regional context for the identification of geological variations that potentially allowed the deposition of lacustrine-embayment rock intervals. The neural network confirms that amplitude anomalies and discontinuous reflectors within the Woodford shale window correspond to internal lateral and vertical TOC-bearing facies variation.

The Woodford shale is both thicker and more TOC-rich where the underlying Hunton Group (carbonates) is completely eroded and the topographic relief is high. Seismic analysis at and above the unconformity surface produced by the erosion of the Hunton Group, reveals pod-shaped intervals of high TOC that may have been deposited as a very restricted interval. For this reason, we hypothesize that the structural lows may have been isolated lake/embayment areas represented by locally increased accommodation space and highly restricted Woodford shale organic rich deposits, therefore providing opportunities for more innovative unconventionals exploration targeting.

Introduction

Research over the past few years has focused on the stratigraphy and sedimentology of the Devonian-Lower Mississippian Woodford Shale. The Woodford is not only a good Mid-Continent (U.S.A.) oil and gas producer, but also a good analog for other 'siliceous' unconventional resource shales, particularly if they are underlain by carbonates. The studies have emphasized detailed mapping and stratigraphic characterization of the Woodford (*Figure 1 and Figure 2b*), but have also provided a foundation for extending into relating stratigraphy to geophysical, geochemical and geomechanical characterization.

Shale researchers interpret that the Woodford (and most analog resource shales) is wholly of open marine origin and generally assume it. RockEval Pyrolysis analyses usually indicate Type II kerogen, however, occasionally a Type I kerogen is detected. Other unconventional resource shales show a similar pattern, but these anomalies are often shrugged off as analytical error.

Regional isopach maps of the Woodford Shale and Hunton Group in the Cherokee platform (*Figure 1, Figure 2a and Figure 2b*) and a 3D seismic survey in South East Cherokee Platform, Oklahoma, reveal an unconformity surface on top of underlying carbonate rocks (Hunton Group), with considerable karst topography and ~ >100m of vertical relief (*Figure 5, Figure 6 and Figure 7*.) From this, a geological model claims that during lowstand of sea level, karst topography forms an irregular surface, which can provide discontinuous

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catchment areas for ponding of hypersaline-lacustrine water masses, forming restricted water circulation and establishing conditions for higher deposition and preservation of organic matter (*Figure 2 and Figure 3a.*) The 3D seismic survey is inverted to predict TOC variability that shows discontinuous "pod like" areas of local anomalously high TOC in the deeper paleo-topographic Woodford Shale zones *(Figure 2a.)* This contrasts with common thinking that organic-rich strata are deposit from marine waters in a blanket fashion.

Geological Background

According to Cardott (2009 and 2012) and Jarvie et al (2005 and 2007), the Woodford Shale is a very effective and prolific gas and oil shale reservoir in the world, therefore, there is a specific interest to characterize the possible occurrence of internal lacustrine or highly restricted intervals within this open marine mudstone. This formation is from Upper Devonian-Lower Mississippian age, and its principal lithology has been described as an organic-rich black shale with intercalations of chert, siltstone, sandstone, dolostone, and light-colored shale (Slatt et al., 2011; Molinares, 2013; Turner, 2015.) In addition, laminations of reddish-brown clay, greenish clay and organic matter with scattered siliceous concretions are also present in the formation (Kirkland et al., 1992; Comer, 2007.)

The Woodford Shale unconformably overlies the limestones and dolomites of the Hunton Group (Silurian-Devonian age) and grades conformably into fine-grained silty limestones interbedded with thin layers of dark-gray shales from the Sycamore Formation (*Figure 1*; Perry, 1995 in Portas, 2009; Slatt et al., 2011). Cardott (2012) emphasize that the Woodford Shale has a series of stratigraphic equivalents that extend over central and Eastern United States (e.g. Chatanooga Shale, Arkansas Novaculite, Antrim Shale, Bakken Shale, New Albany Shale, Marcellus Shale) that represent the global marine transgression which occurred during the Late Devonian (*Figure 3*; Sullivan, 1985; Kirkland et al., 1992; Northcutt et al., 2001; Comer, 2005; Slatt et al., 2011; Cardott, 2012.)

Methods: 3D Seismic Multi-Attribute Analysis, Organic Facies (TOC) Identification and Low Frequency Background Model Seismic Inversion.

In order to highlight the presence of potential "lacustrine type" deposits, time thickness interpretation, coherent energy, most-positive and most-negative curvature volumes were computed and interpreted for the Hunton Group horizon which represents the base of the Woodford shale (*Figure 4, Figure 5, Figure 6 and Figure 7.*) Using a coherent energy attribute, negative response features were identified as karsts, and in the study area the Hunton group is almost completely eroded, characterized by low energy values (*Figure 6 and Figure 7.*)

Also, most positive/most negative curvature attribute was a useful tool in identifying karst features. These collapse features (*Figure 5 and Figure 7*) can be recognized as negative values of most-positive curvature (*Figure 5*; Baruch, et al 2009). Also the Hunton Isochrone map shows in the central and north part of the study area a "lake type" topography (*Figure 4 and Figure 7.*)

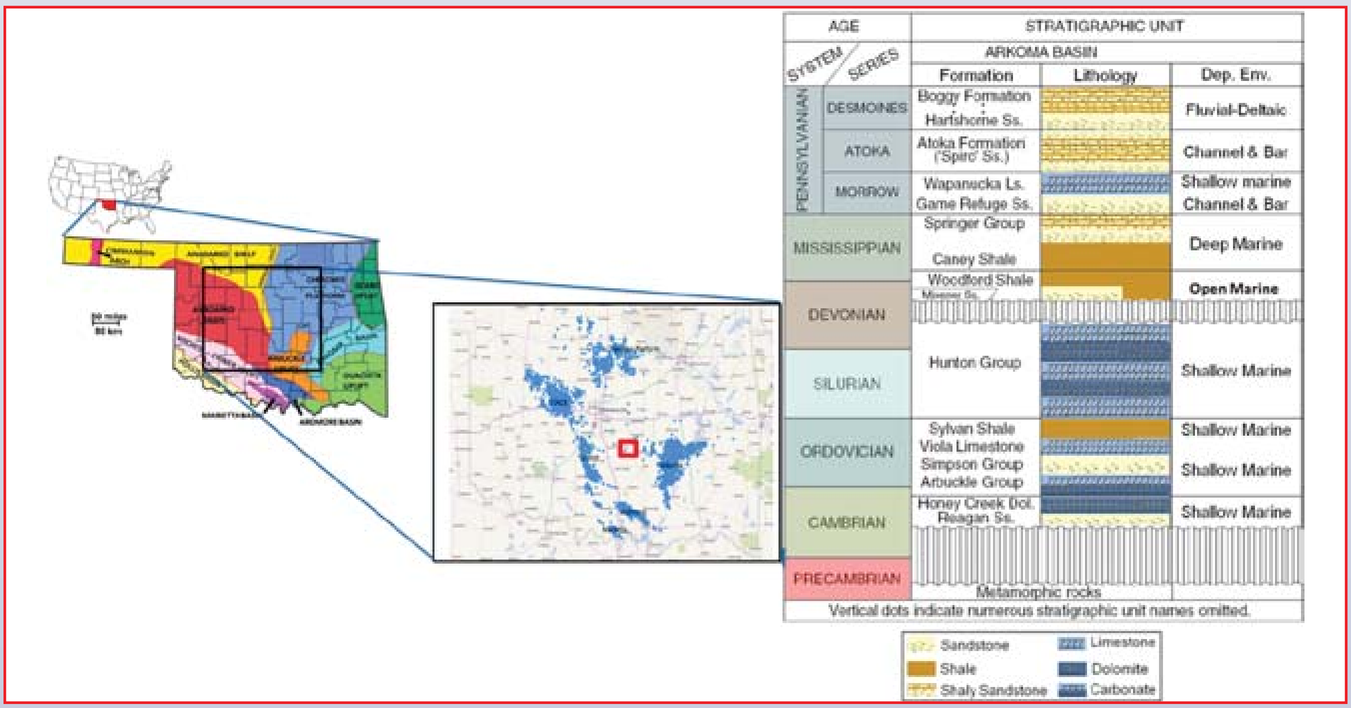

Figure 1. Location Map of the Cherokee Platform (in light blue), and principal geologic provinces in Oklahoma (Northcutt et al., 2001); Image on the right corresponds to the Stratigraphic chart for the Arkoma Basin, southeastern Oklahoma (Perry, 1995 in Portas, 2009.)

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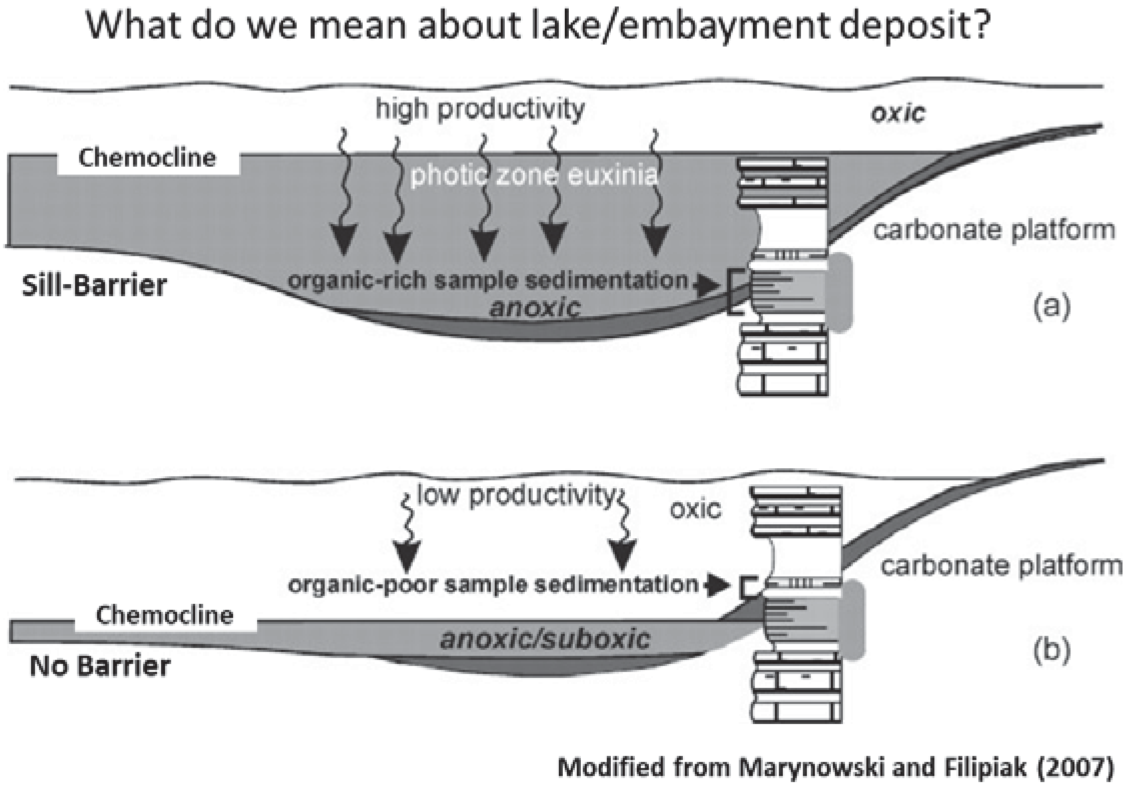

Figure 2a. Schematic illustration of paleo lacustrine/embayment deposit in the Woodford Shale: a) Illustrates silled basin over a carbonate platform, shallow chemocline and more preservation of organic matter; b) Illustrates non-silled basin over a carbonate platform, deeper chemocline and less preservation of organic matter. Modified from Marynowski and Filipiak (2007.)

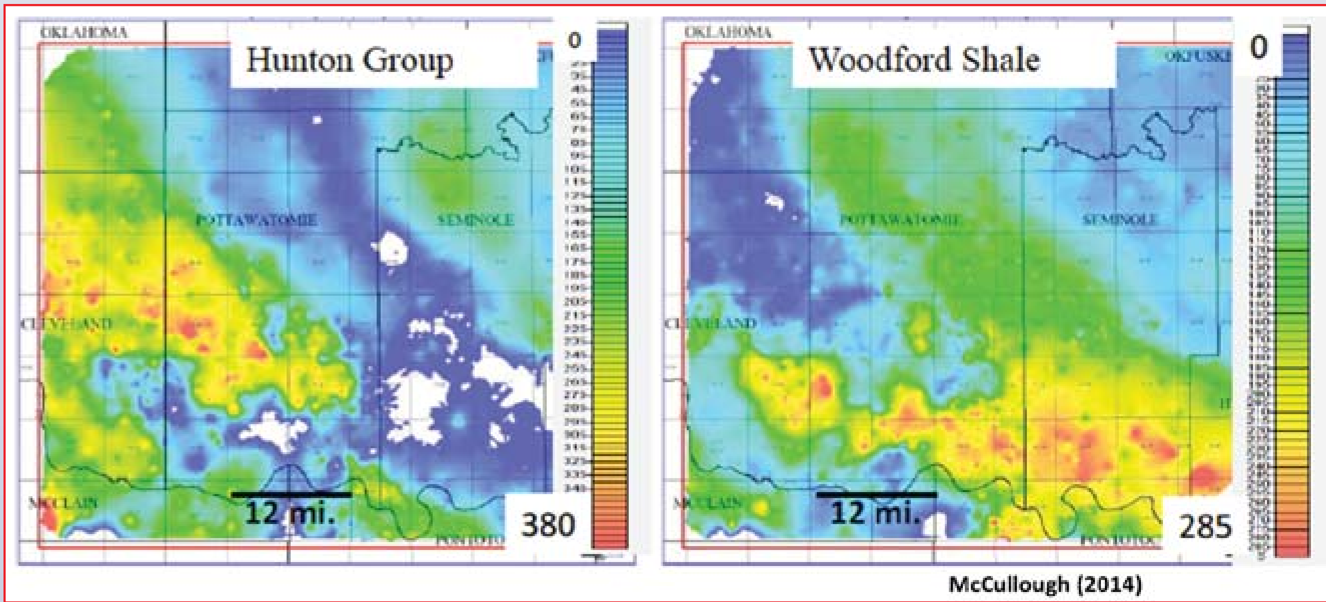

Figure 2b. Regional Isopach maps created from well tops (McCullough, 2014). On the left, the Hunton Group regional thickness map. On the right, the Woodford Shale regional thickness map. The study area is located in the red box of the Southeast Pottawatomie and Pontotoc border, Oklahoma U.S.A. Note the inverse correlation of the formation thickness, where the Hunton is eroded the Woodford shale is thicker, this is attributed to the depositional model of the Woodford shale where karstifications occur to the Hunton exposure leading into more accumulation space for the Woodford depositional fairway.

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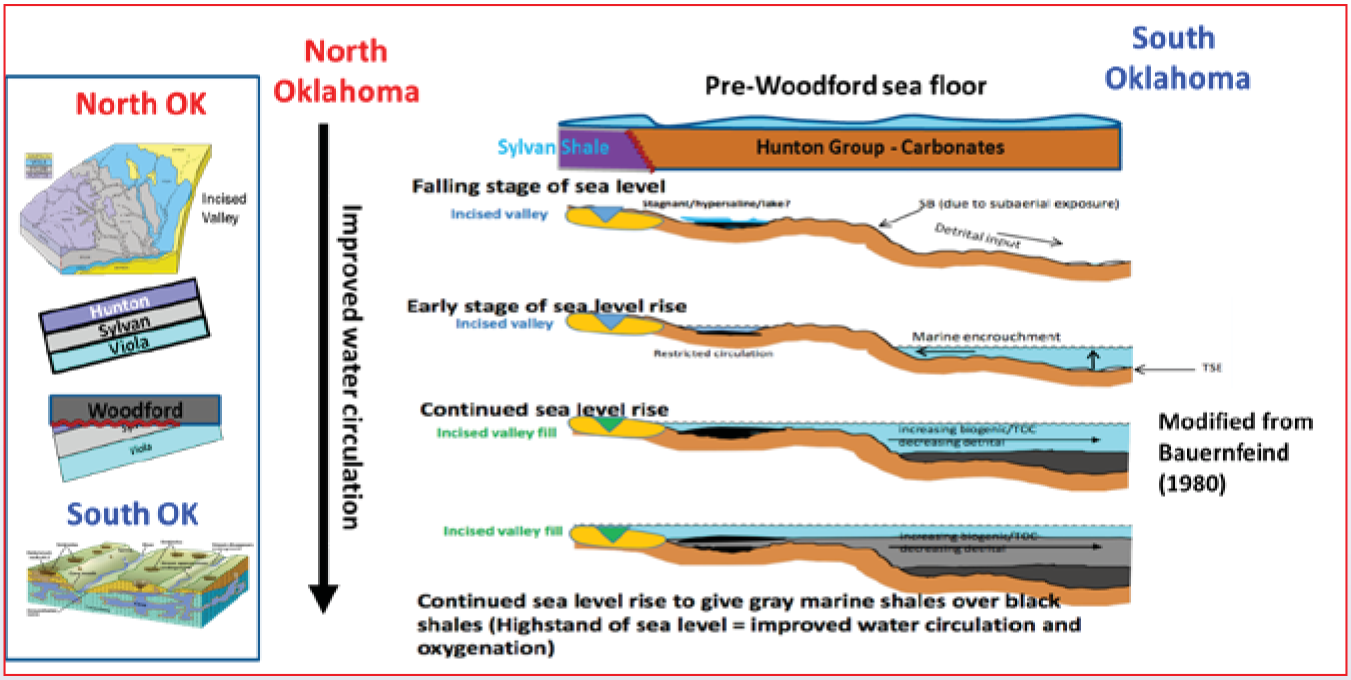

Figure 3a. Depositional model of the Woodford shale through one eustatic sea level cycle: The early stage of falling sea level may result in water mass isolation and restricted water circulation over topographic depressions left by karst/incised valley development on the underlying carbonate (Hunton Group carbonates in the case of the Woodford) surface.

As a proposed strategy for determining the geological and internal organic facies variations, the TOC was calculated in six wells of the study area applying the Passey et al. (1990) methodology, additionally the seismic attributes were extracted and the impedance inversion computed (*Figure 8a and Figure 8b*). The model-based inversion workflow begins with a low frequency background geological model that it is modified until the error has been minimized between the synthetic created by that model and the original seismic data (*Figure 9*.)

Figure 3b shows a representative vertical slice through the seismic time migrated data volume where the zone of interest can be seen. A phase rotation of -7º was applied to the data subsequent to the horizon interpretation in order to represent the base of the Woodford and the top of the Woodford as peak and trough respectively. Horizon interpretation was done by manually picking a grid of 1 inline by 1 crossline. *Figure 3b* shows the time structure map of the top of Woodford. There is a noticeable northwest dip direction and a structural high in the southeast part of the survey. Once the target zone is

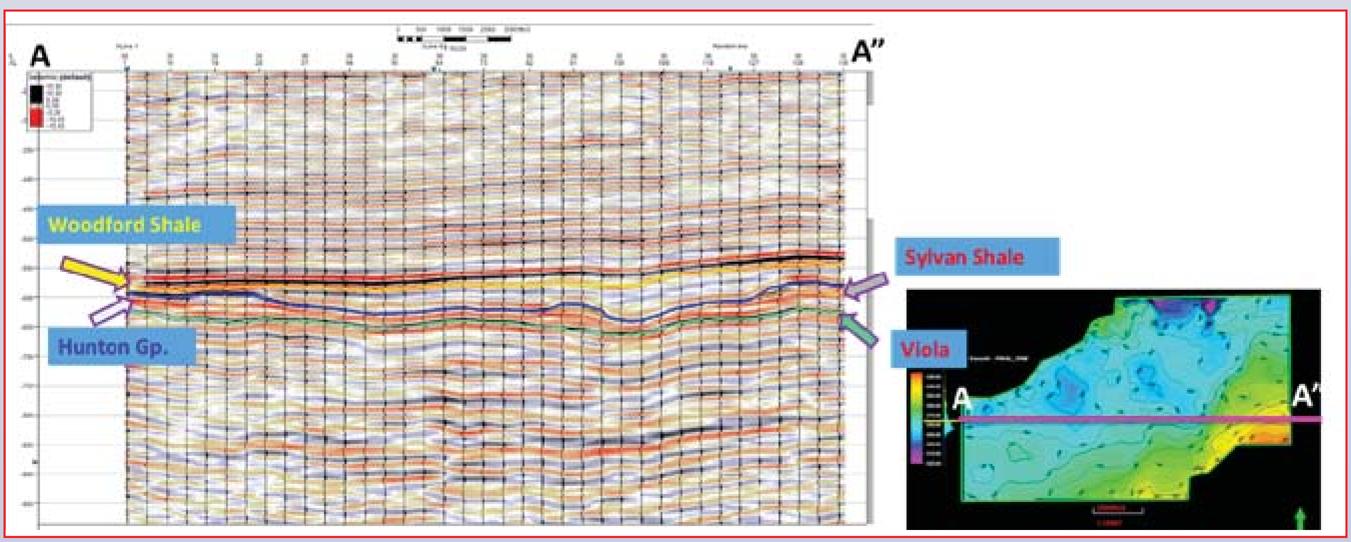

Figure 3b. Vertical seismic section showing the paleo topography of the erosion of the Hunton Group and a "lake-pod" area in the central part of the seismic section.

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mapped and the wells are tied to the seismic data the next step is to perform a post-stack inversion to statistically relate the Zp and Vp to the calculated TOC Passey et al. (1990) method.

The main objective for generating a model-based inversion of the Woodford Shale was to identify vertical and lateral facies changes that may help delineate the "lake type" deposits (*Figure 10*). All six wells were used for the initial model, and the wavelet extracted from the wells was used on the model-based inversion. The inputs for this model (low frequency model) include (a) a geological model created from seismic horizons and (b) Vp and Density logs from all the wells selected for the inversion, which were band passed through a low frequency filter. The Woodford shale has the lowest impedance due to its low velocities and low densities (*Figure 10.*) The initial model revealed a higher vertical resolution and lateral impedance changes within the Woodford shale (*Figure 10.*)

According to Passey et al. (1990) the presence of organic matter and the presence of generated hydrocarbons can have a large response on the resistivity well log *(Figure 8a.)* The technique presented by Passey et al. (1990) uses the overlap of a porosity log, usually the sonic on a deep resistivity curve (*Figure 8a*). Passey et al. (1990) attribute this well-log separation in high organic-rich intervals as the result of the low density/low velocity kerogen, where the resistivity responds to the formation fluid. To calculate TOC using this method, the LOM (Level of Organic Metamorphism, reached by the organic matter in the rock) must be known or estimated. In this case, the previous work by Miceli (2010) and conclusions by Cardott (2012) for the Southeast Cherokee platform acted as valid LOM values in order to calculate the TOC for the wells in the study area. The revised graphic relation of logR vs. derived TOC published by Passey et al. (2010) was used for the calculations. A base line was drawn at the Sylvan shale and a LOM of 8 was applied which is equivalent to a vitrinite reflectance (%Ro) value of 0.56% to honor the published %Ro data of the study area (Cardott, 2012; *Figure 8a and Figure 8b*). For providing an input to the neural network for estimating TOC in three dimensions along the seismic survey, the calculated Passey-methodology TOC is then referred as "actual TOC" (*Figure 8 red curve, and Figure 12 black curve*), and the neural network calculated after estimating the non-linear relationships with the 3D seismic attributes is then named as "modelled TOC" (*Figure 12 and Figure 14 red curve.*)

Results: Post-Stack Seismic Inversion and Supervised Probabilistic Neural Network (PNN) analysis

To predict and distribute TOC along the study area in a confident manner, a supervised probabilistic neural network (PNN) workflow was applied to incorporate the post-stack 3D seismic data in combination of the calculated Acoustic Impedance (Zp) from the seismic inversion with Principal Components Analysis (PCA) of Spectral Decomposition data every 5Hz, and also to include into the calculations the Coherent Energy volumes (directly related to karstification features of the pre-Woodford Strata). Three attributes generated from the seismic interpretation and inversion were used to generate statistical relationship with the calculated TOC log form Passey et al. (1990), these input attributes in the PNN were: Zp, Coherent Energy and Spectral Components, and the PNN operator length was of nine points.

All these three seismic calculated volumes acted as external attributes for the supervised neural network analysis. The input attributes applied in the workflow for

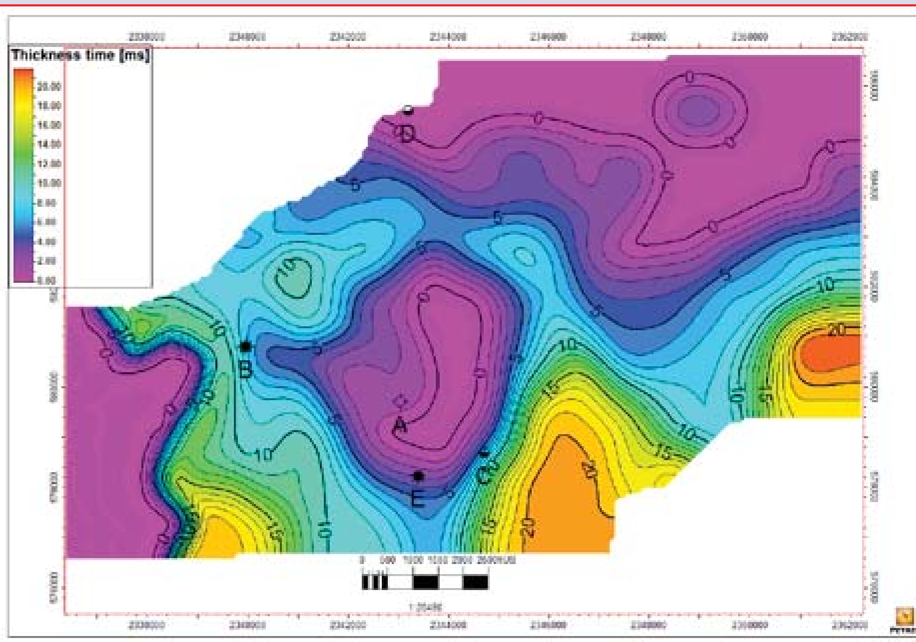

Figure 4. Time thickness map of the Hunton group. Low isochron areas with potential of lake type deposits.

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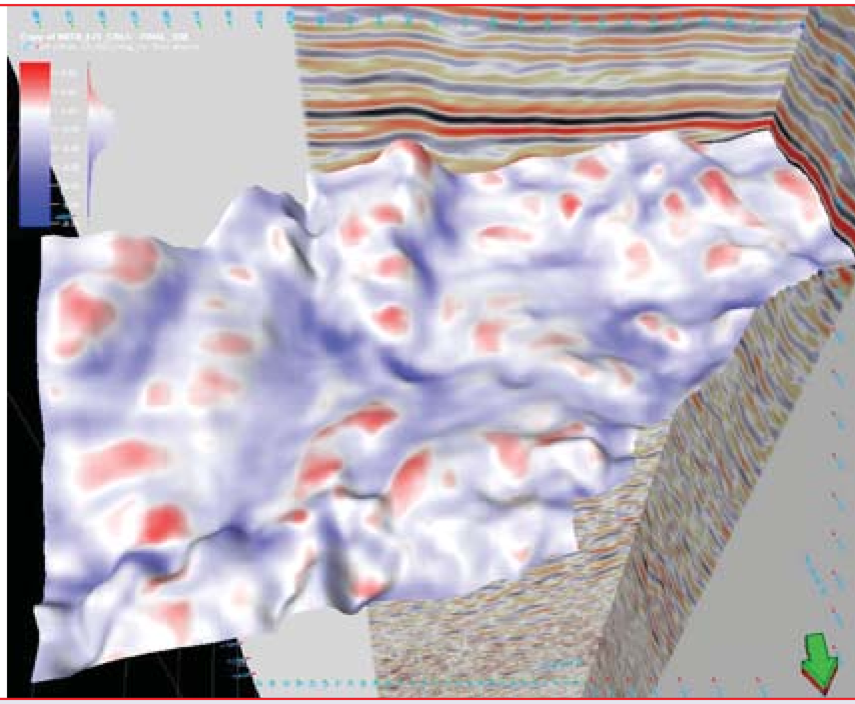

Figure 5. Horizon slice along the top Hunton through the most positive curvature and most negative curvature volume. Most negative curvature (blue areas) associated with major karsting.

properly training the neural network, are shown in the *Figure 12*. During the supervised neural network training (*Figure 12*), the weighting function is adjusted to optimize the prediction of TOC (*Figure 13*) as a directly indicator of organic facies variations, and for avoiding the neural network "overtraining". High TOC zones correlate with the location of karst features of the Hunton and potential restricted hypersaline/lacustrine deposits (*Figure 14 and Figure 16.*)

The analysis window of the supervised PNN, its training and calculations, were limited only to the Woodford shale seismic window (±50 ms from Woodford Shale top and base), and were aimed to be within the stratigraphic zone of

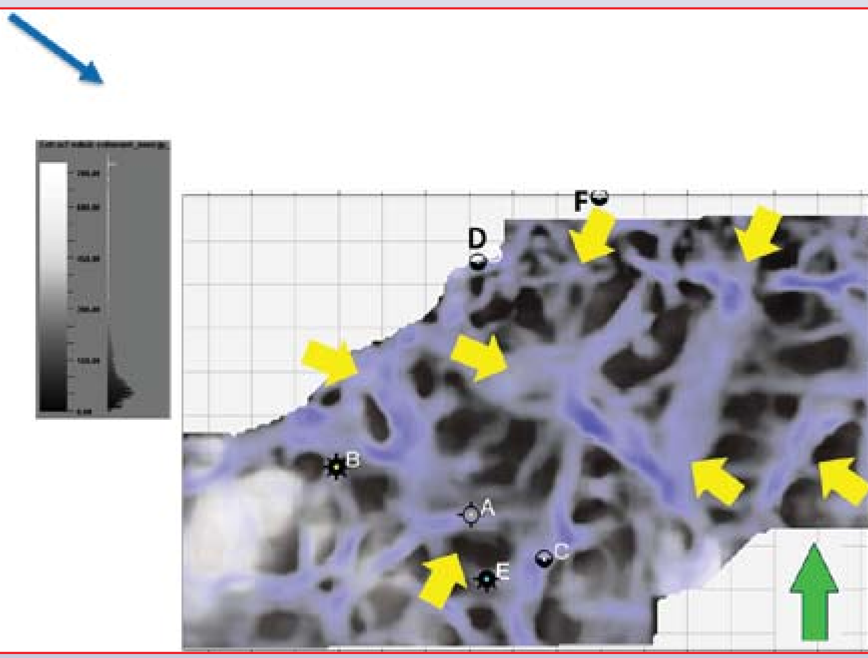

Figure 6. Hunton time-structure co-rendered with coherent energy and most negative curvature (Yellow arrows indicates karst features and possible lake pods, the Hunton Group is eroded (almost gone) in the study area).

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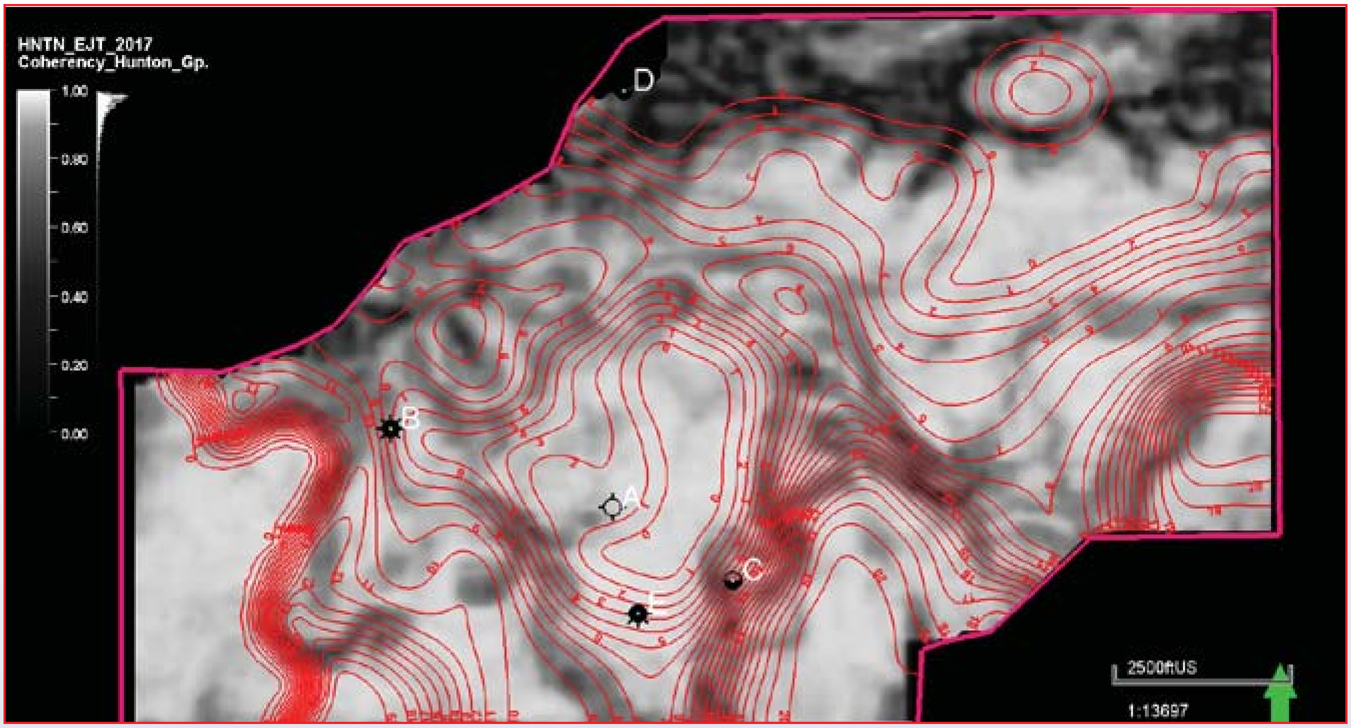

Figure 7. Hunton time-thickness co-rendered with coherent energy (zero and near-zero that correlate with dark coherency features contours indicate karst features and possible lake pods.) Note that the Hunton Group is eroded (almost gone) in the study area.

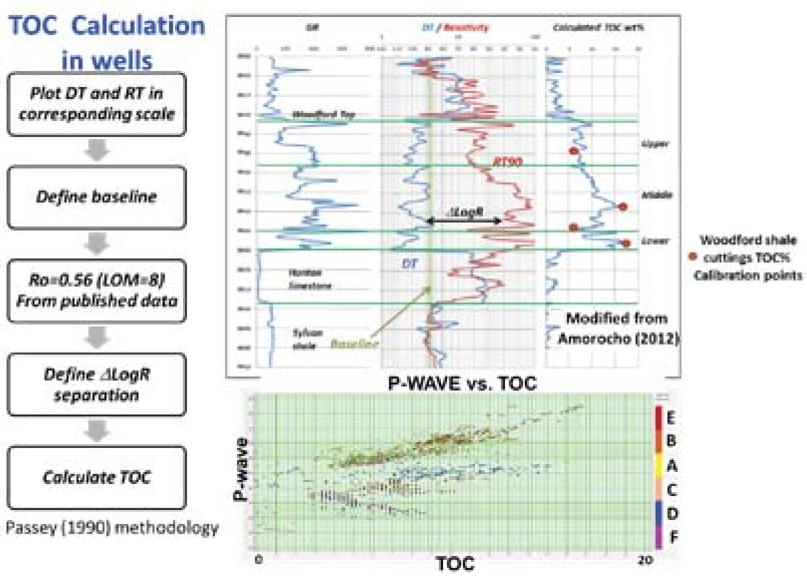

Figure 8a. TOC calculations applying Passey (1990) methodology. TOC from cuttings as calibration points in well D.

interest to obtain a better correlation in the TOC calculations (*Figure 14 and 15.*) *Figure 11* shows a cross plot of calculated TOC from well logs vs. predicted TOC from the probabilistic neural network with the previous multi-attributelist as input (Zp, Coherency and Spectral Components). The neural network performed the non-linear relationship calculation process at every sample location in the seismic volume (Heggland, 2004), and compared in each stratigraphic interval one data sample of the calculated TOC-log in wells with nine data samples of the selected 3D seismic attributes as network inputs (Zp, Coherency and Spectral Components Principal Component Analysis Vector1 [PC1]; *Figure 12.*)

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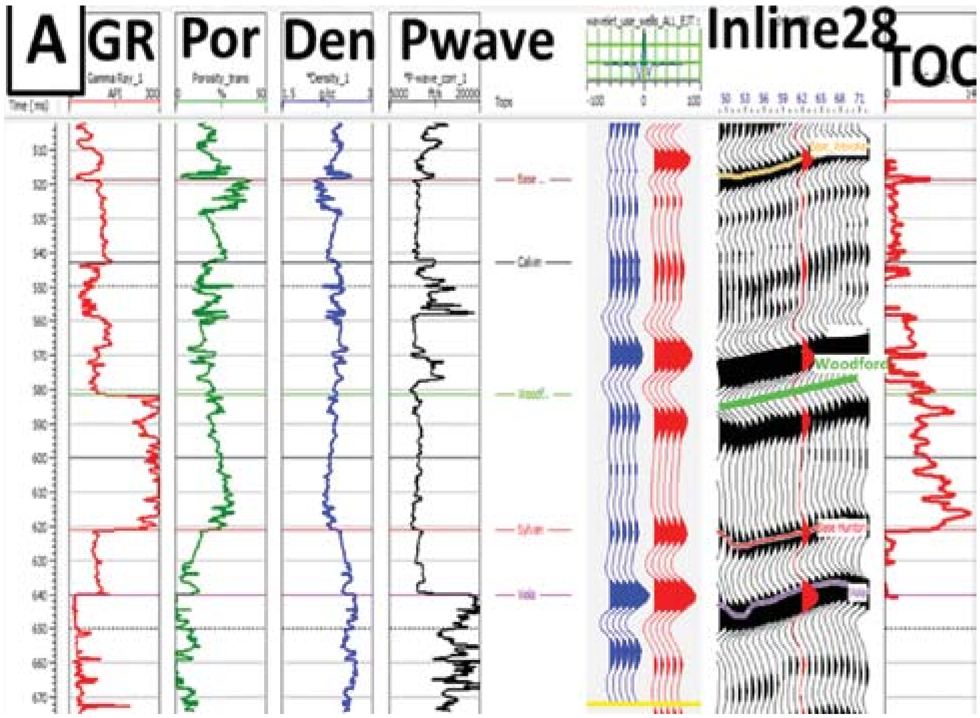

Figure 8b. TOC Calculation and seismic tie for Well A using the Passey et al., (1990) method.

Figure 16 shows the wells used in the PNN as well an as average TOC map for the entire Woodford Formation. Hot colors represent sweet spots with higher TOC values. Notice that higher concentrations of organic richness occur in the central part of the survey, where the Hunton group is eroded and the karstification features lead into the paleo lake pod shape. Also, high TOC is calculated in the Northwest part of the survey.

Conclusions

The Probabilistic Neural Network property extensions confirm that the amplitude anomalies and discontinuous reflectors within the Woodford Shale stratigraphic window correspond to internal lateral and vertical TOC facies variation (*Figure 9, Figure 10, Figure 15, Figure 16 and Figure 17.*) The Woodford shale is thicker and with more TOC where the

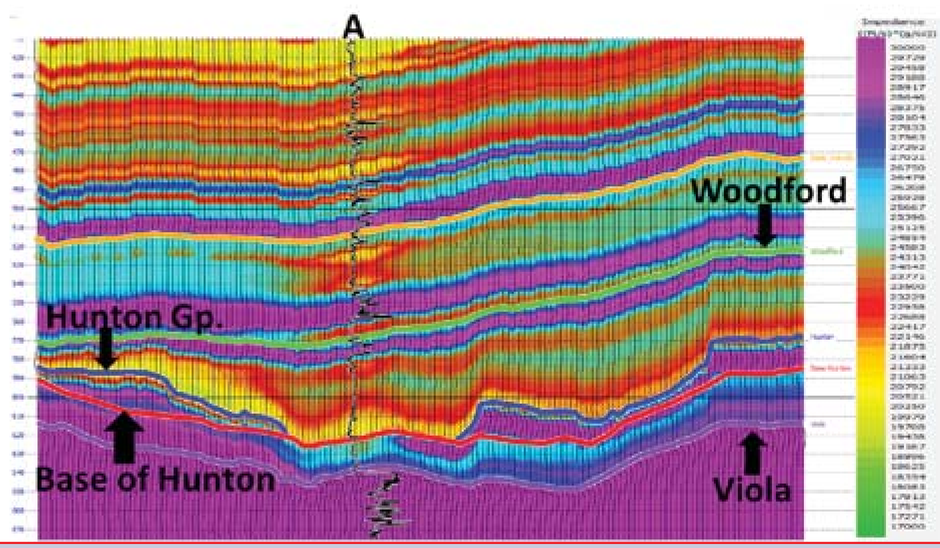

Figure 9. Initial low frequency background model on an in-line passing through well A.

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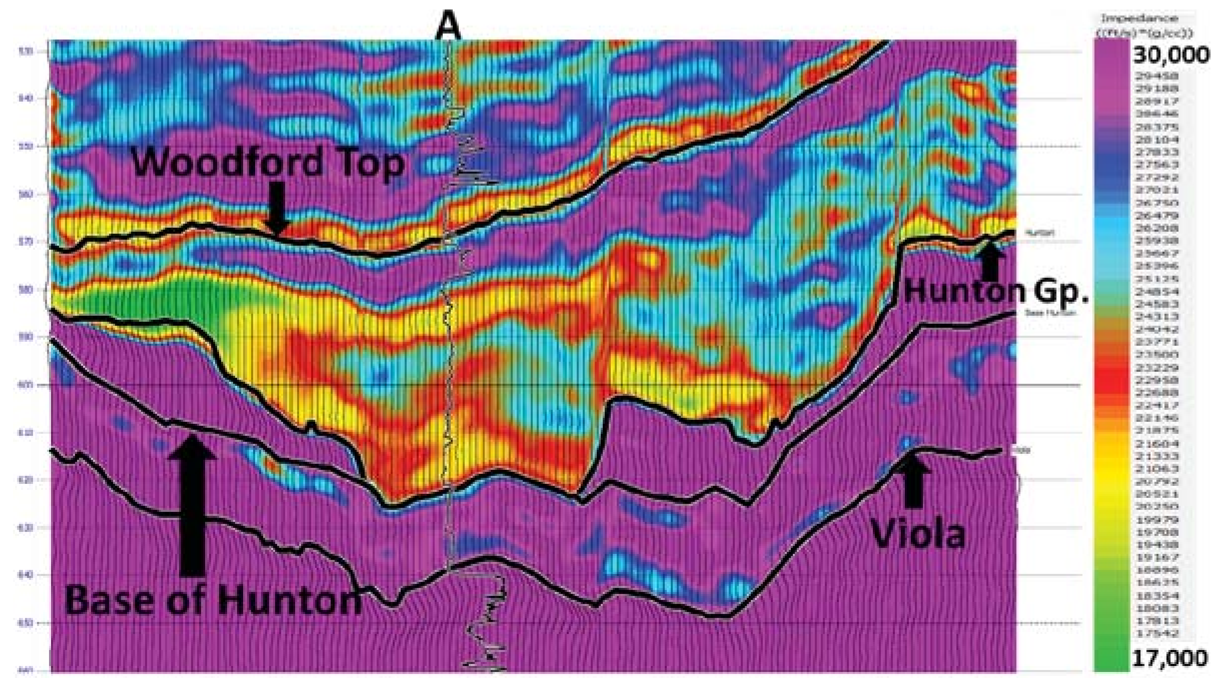

Figure 10. Inversion Zp results in an arbitrary impedance in-line showing well A.

Hunton Group is completely eroded (*Figure 2a and Figure 2b, Figure 4 and Figure 10*) and structural features lead into the identification of lake pods that can be intervals of very restricted Woodford organic rich deposits (*Figure 7, Figure 15 and Figure 17*), thereby providing opportunities for more innovative exploration strategies. As a future analysis, the pre-stack inversion must be done for estimating the elastic properties, and therefore reduce the inversion error, which can provide better TOC estimates.

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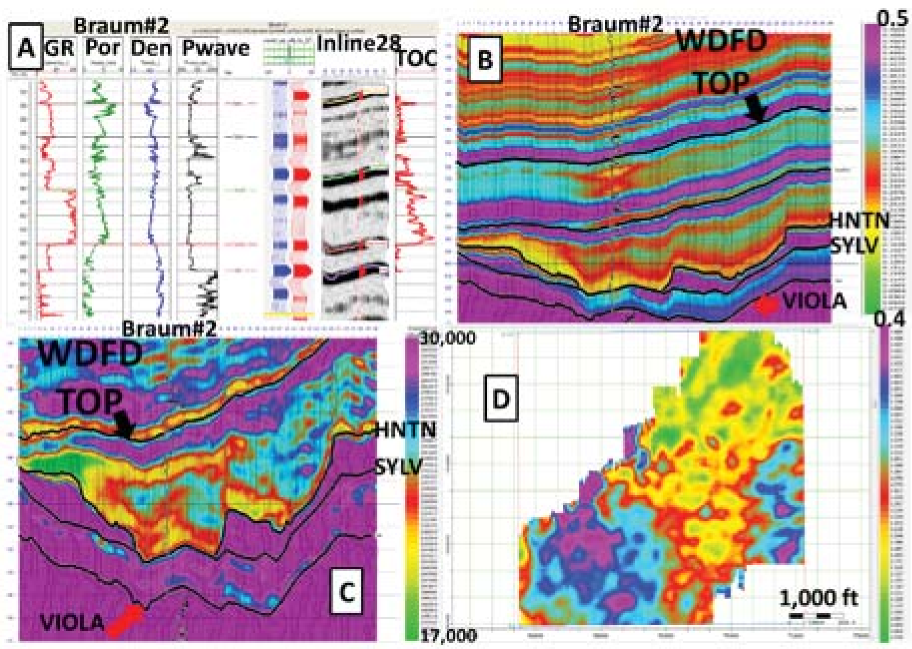

Figure 11. Data-Error slice calculated 2 milli-seconds [ms] below the Woodford shale seismic horizon.

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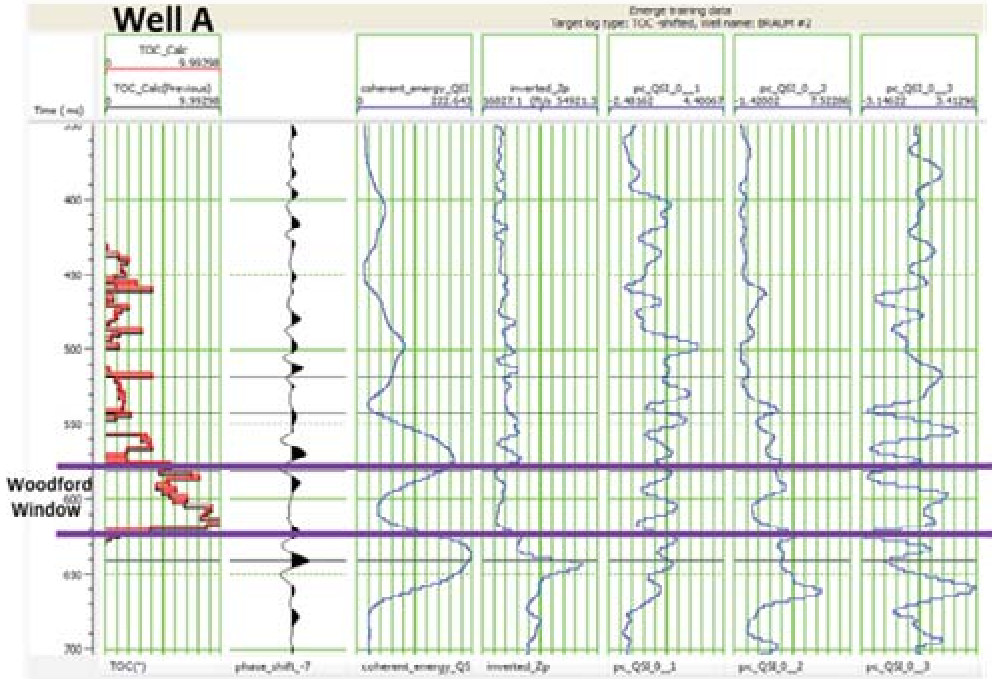

Figure 12. Neural Network Training data in Well A. TOC (red) with extracted seismic data, Coherent Energy and Zp from Seismic Inversion, Spectral Decomposition every 5Hz Principal Components 1, 2 and 3.

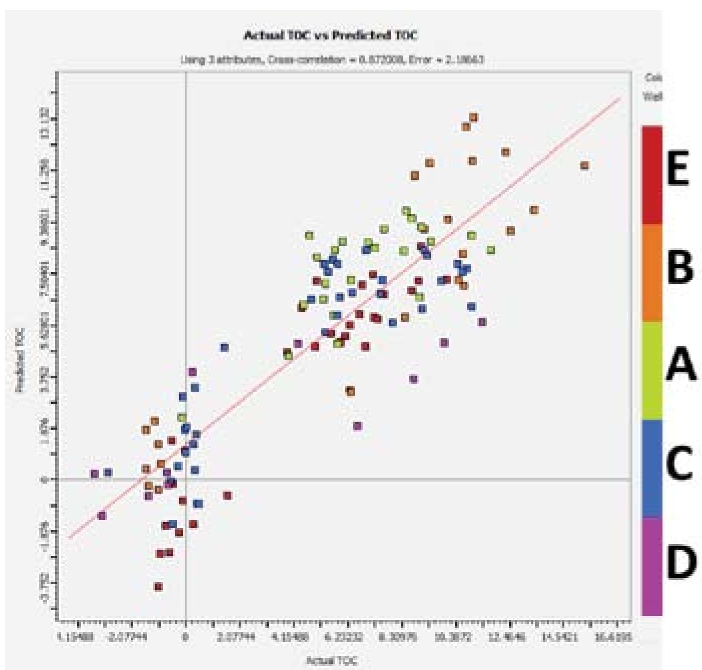

Figure 13. Multi-attribute regression of actual TOC (Passey method calculated) vs. predicted TOC. Three attributes were used in the regression: Zp, Coherent Energy and Spectral PC 2. Negative TOC values correspond to the Hunton Group.

Gerald Wilson (in memoriam) and The Wilson Family, for providing the 3D seismic surveys and the well-log data for this exercise. Special acknowledgements for the kind financial and technical assistance to all the company sponsors of both University of Oklahoma Institute of Reservoir Characterization (IRC) and Attribute Assisted Seismic Processing and Interpretation (AASPI) consortiums. Special thanks to CGG for allowing us to use their Hampson and Russell Emerge package. Special thanks to Schlumberger for providing us the Petrel licenses.

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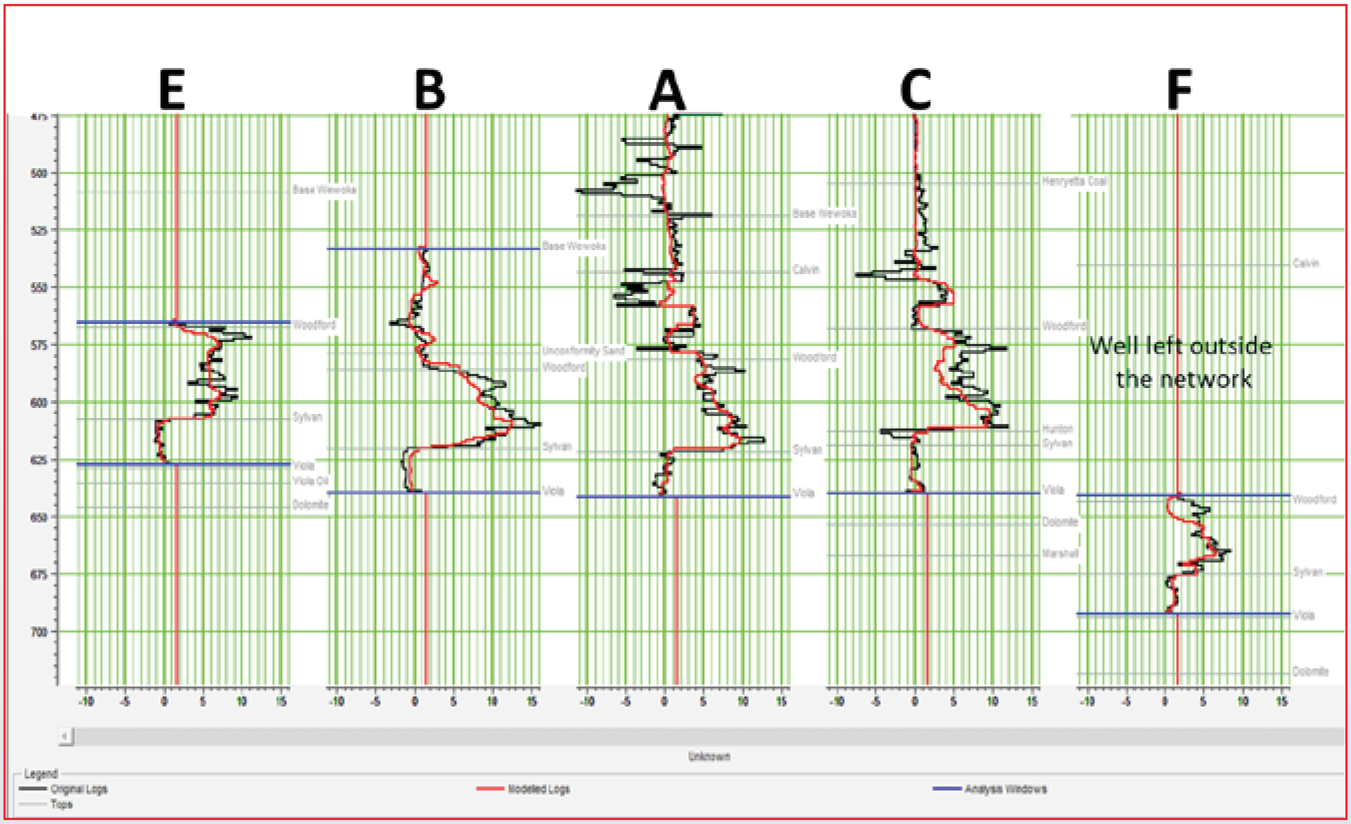

Figure 14. Probabilistic neural network using three attributes. TOC calculated with Passey methodology in black curve, TOC modelled from the supervised neural network in the red curves. Well locations in Figure 6.

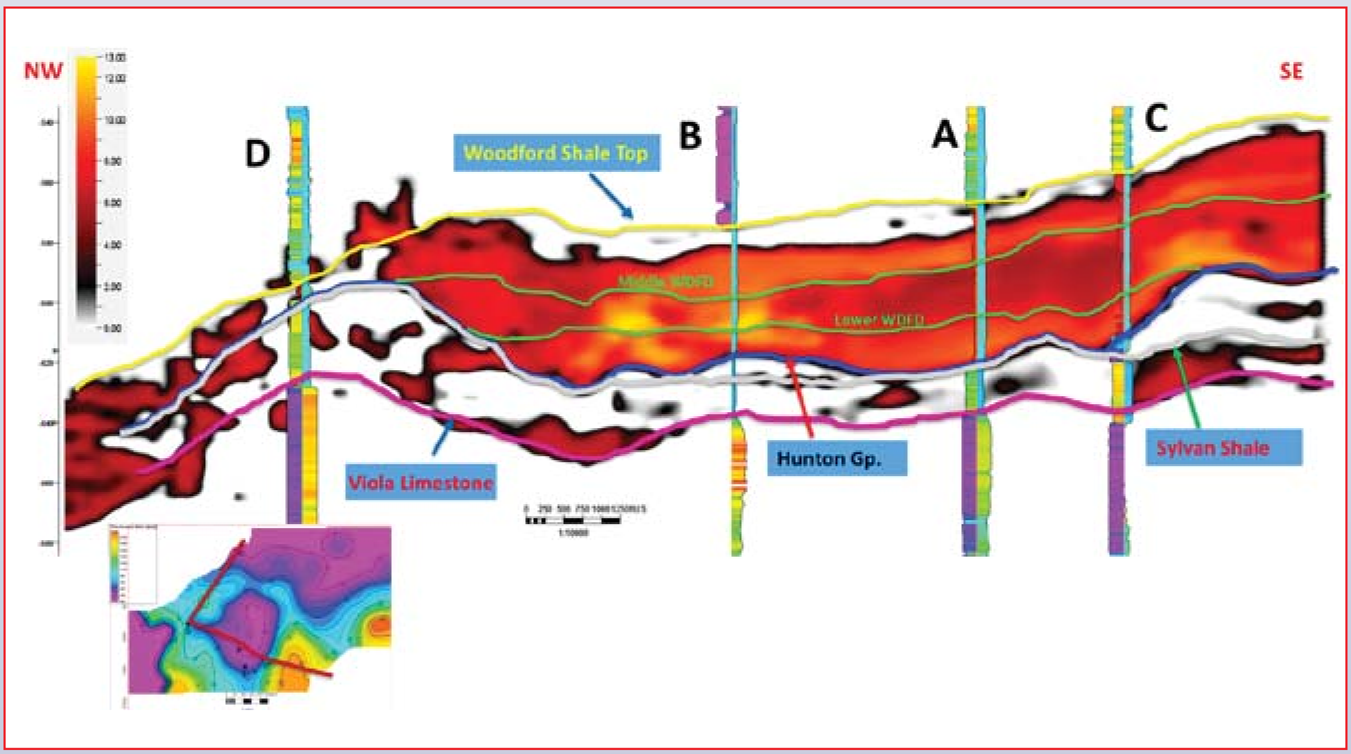

Figure 15. Composite section that correlates all wells in the study area and their TOC calculation for the Woodford shale seismic window. Note the lake-pod shape of the woodford where the well A and C are located.

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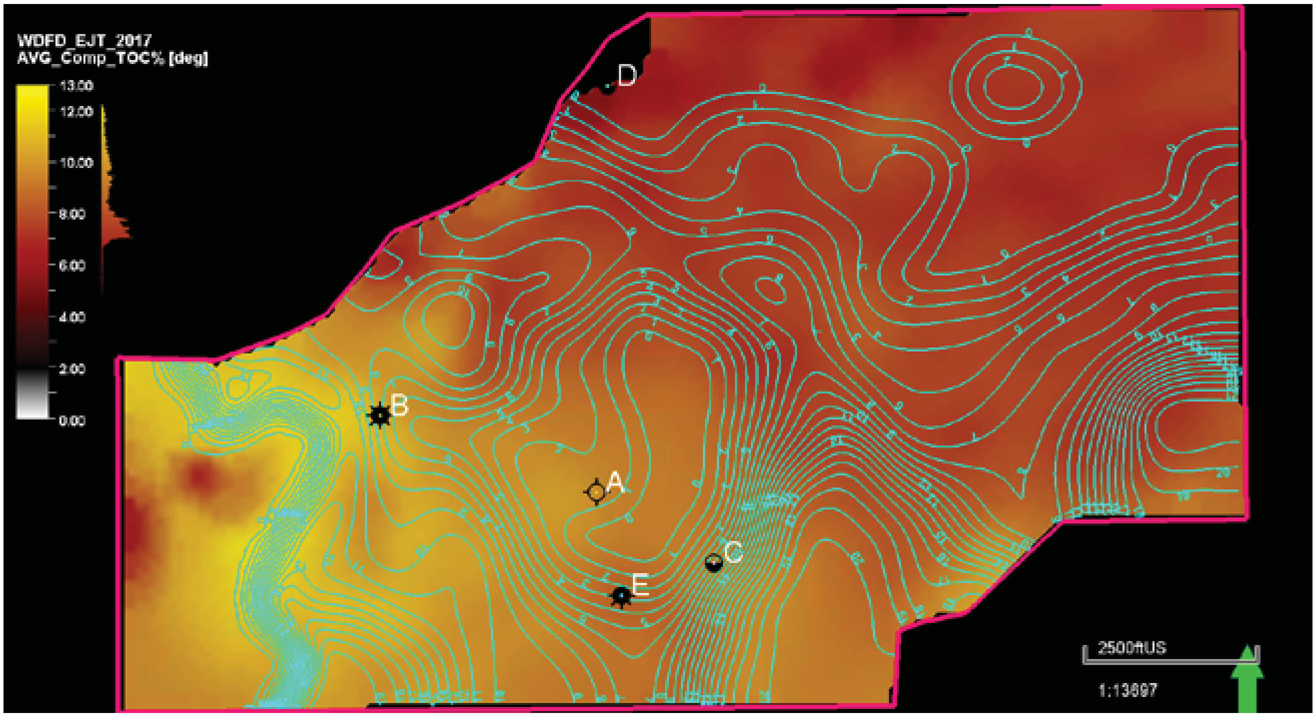

Figure 16. Calculated TOC from the supervised neural network analysis. Average TOC values are extracted for the Woodford shale stratigraphic interval and are shown in the display colors of the map. The contours correspond to the Hunton Group seismic isochrones in milli-seconds [ms].

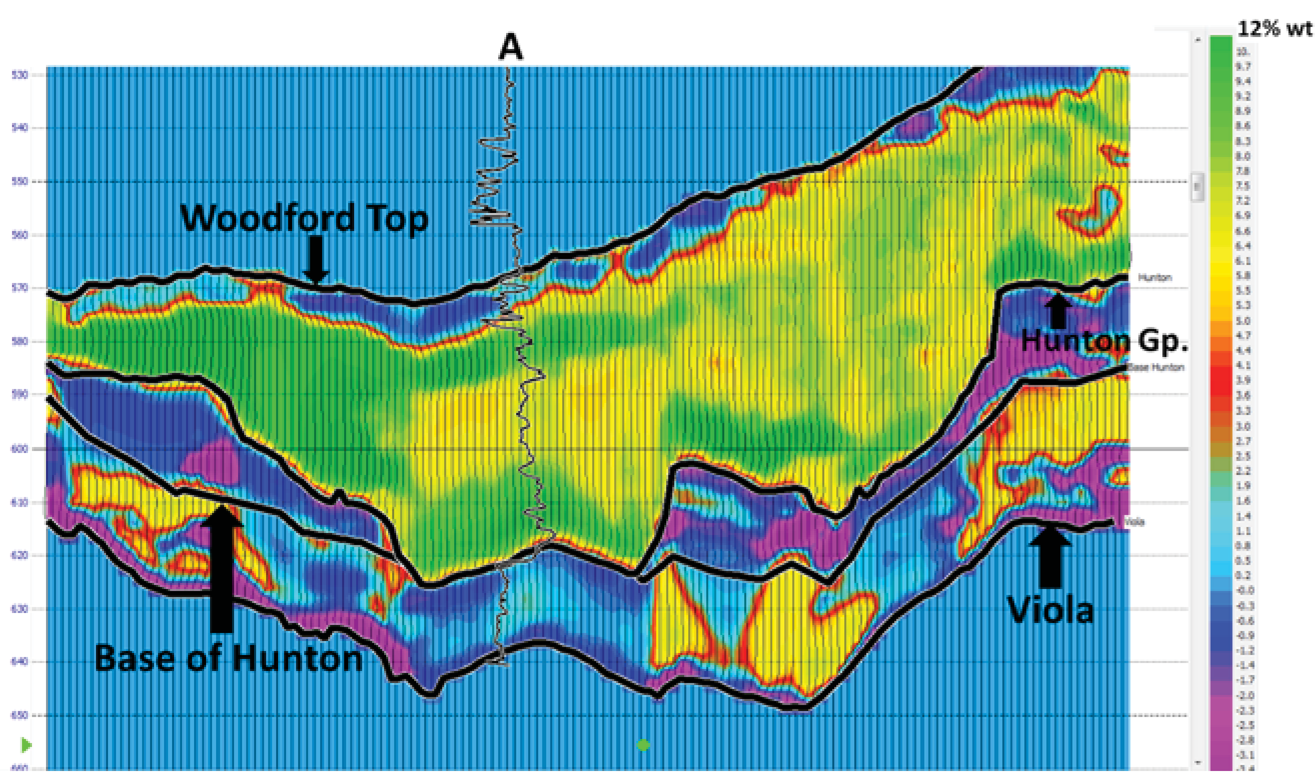

Figure 17. Inline showing the TOC modeling with PNN for the well A. Note the bottom portion that is highly restricted paleo topography has the highest TOC calculated values.

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