Seismic characterization of a Mississippi Lime resource play in Osage County, Oklahoma, USA

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Abstract

With the advent of horizontal drilling and hydraulic fracturing in the Midcontinent, USA, fields once thought to be exhausted are now experiencing renewed exploitation. However, traditional Midcontinent seismic analysis techniques no longer provide satisfactory reservoir characterization for these unconventional plays; new seismic analysis methods are needed to properly characterize these radically innovative play concepts. Time processing and filtering is applied to a raw 3D seismic data set from Osage County, Oklahoma, paying careful attention to velocity analysis, residual statics, and coherent noise filtering. The use of a robust prestack structure-oriented filter and spectral whitening greatly enhances the results. After prestack time migrating the data using a Kirchhoff algorithm, new velocities are picked. A final normal moveout correction is applied using the new velocities, followed by a final prestack structure-oriented filter and spectral whitening. Simultaneous prestack inversion uses the reprocessed and time-migrated seismic data as input, along with a well from within the bounds of the survey. With offsets out to 3048 m and a target depth of approximately 880 m, we can invert for density in addition to P- and S-impedance. Prestack inversion attributes are sensitive to lithology and porosity while surface seismic attributes such as coherence and curvature are sensitive to lateral changes in waveform and structure. We use these attributes in conjunction with interpreted horizontal image logs to identify zones of high porosity and high fracture density.

Introduction

Osage County (Figure 1) is home to the Osage Nation and is located in northeastern Oklahoma, sharing a northern border with the Oklahoma-Kansas state line. Osage County has an extensive history of hydrocarbon exploration and production. Recently, interest in the Mississippi Lime play has renewed with the use of horizontal drilling and hydraulic fracturing techniques, making it a "hot" resource play.

The Mississippian Lime of northern Oklahoma and southern Kansas consists of a tight, highly fractured limestone, fractured nonporous chert, and a highly porous (20%–50%) diagenetically altered chert called *tripolite*. The fractured and highly porous Osagean tripolitic chert is the formation of interest with a target depth in our area of 880 m. The tripolite itself is discontinuous and occurs in pockets with varying thickness, making the tripolite a challenge to map. Figure 2 shows a generalized stratigraphic column for our study area in Osage County.

The play concept is to drill horizontal wells perpendicular to the fractures in the limestone and nonporous chert and then increase the number of migration pathways by hydraulically fracturing and/or acidizing the formation to produce from multiple tripolitic chert "sweet spots." Seismic imaging of the Mississippi Lime presents several challenges. First, the target in Osage County is shallow ($t = 530$ ms, $z = 880$ m), giving rise to significant acquisition footprint. Second, the tripolite is a diagenetic product and may not exhibit the same lateral continuity as the unaltered limestones. Third, natural fractures and joints are critical to the orientation of horizontal wells, requiring a surface seismic proxy such as curvature. Finally, optimal placement of horizontal wells requires high vertical resolution and lateral resolution to identify potential geohazards.

Despite production since 1919, relatively little has been published on the Mississippian Lime play. Works by Rogers (1996, 2001), Watney et al. (2001), Farzaneh (2012), Matson (2013), and Snyder et al. (2013) describe the geology of the Mississippi Lime in northern Oklahoma and southern Kansas and the diagenesis and formation of the tripolitic chert. Works by Nissen et al. (2006), Yenugu and Marfurt (2011), White et al. (2012), and White (2013) show the relationship between seismic curvature attributes and fracture trend detection. Angelo (2010), Yenugu et al. (2010, 2011), Matos et al. (2011), and Roy et al. (2012) use gray level co-occurrence matrix (GLCM) seismic texture attributes, self-organizing maps (SOM), and unsupervised 3D seismic

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facies analysis to identify petrofacies within the Mississippi Lime. Finally, work by Dowdell et al. (2012) and Dowdell (2013) show the use of poststack and simultaneous prestack seismic inversion to predict zones of tripolitic chert using petrophysical properties measured on well logs.

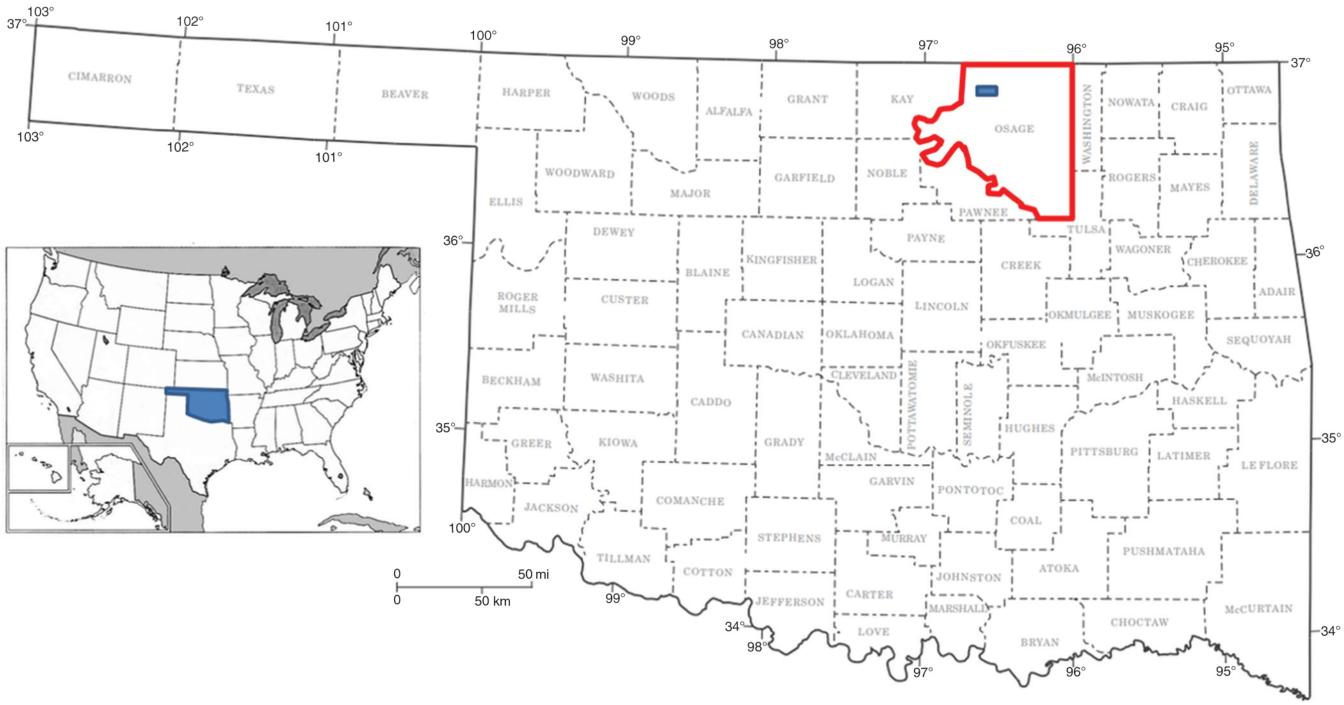
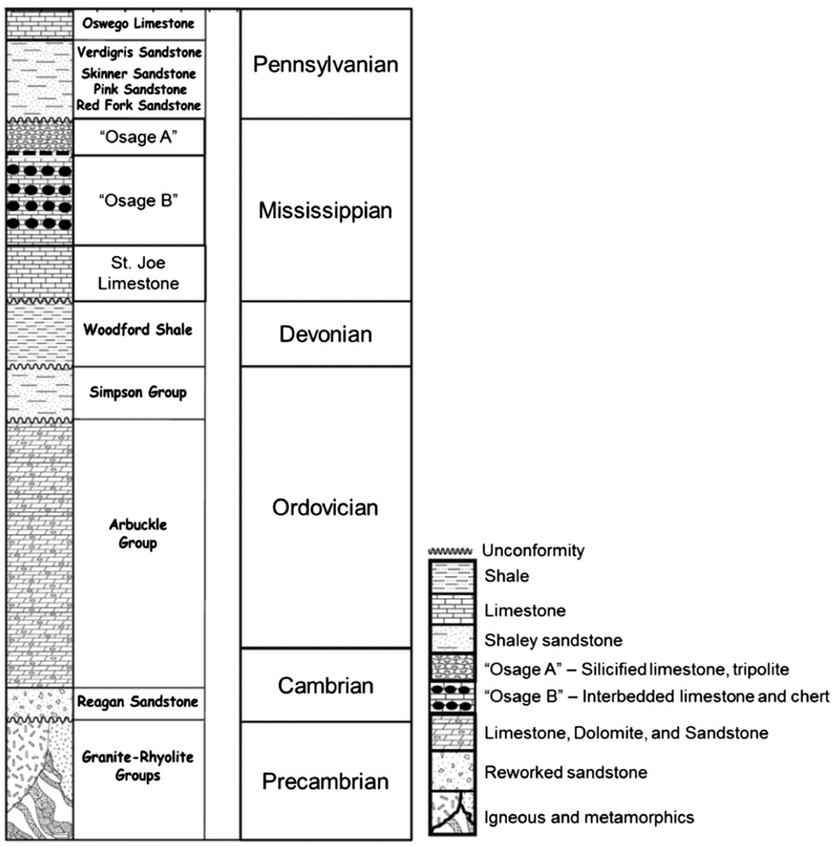


Figure 1. Map showing location of Osage County, Oklahoma, outlined in red. The study area's approximate bounds are denoted by the blue box (modified from OGS OK counties map and University of Texas Libraries PCL map collection).

Figure 2. Generalized stratigraphic column for Osage County. Osage A is a silicified limestone with high diagenetic susceptibility, and is where tripolite most commonly occurs. Osage B contains interbedded tight, fractured limestone and chert and has low diagenetic susceptibility. The St. Joe Limestone is the basal unit of the Mississippian in Osage County and contains no chert (Elebiju et al., 2011; Matson, 2013).



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We hypothesize that prestack impedance inversion of a 3D seismic prestack survey will allow us to successfully map zones of varying lithology. Due to the different petrophysical nature of the tripolite in comparison to the other carbonate and chert facies present in the study area, we believe that pockets of tripolitic chert can be identified using prestack impedance inversion. Additionally, we assert that, when coupled with post stack seismic attributes such as coherence and curvature and with interpreted horizontal borehole image logs, we will be able to map potential tripolitic chert sweet spots consisting of high porosity (low impedance values) and high fracture density.

Methods

Seismic processing

We begin by reprocessing 3D prestack seismic data to improve the spectral content, enhance lateral and vertical resolution, and suppress groundroll and acquisition footprint. Figure 3 shows our processing workflow. The seismic survey was acquired using acquisition parameters commonly used for a Mid-continent USA 3D seismic survey. The CMP bin spacing is 33.5 × 33.5 m, with an average fold of 60 and a maximum fold of 186. The record length is 2 s at a 2 ms sampling interval, with recorded frequencies between 10 and 120 Hz. We retain the contractor's computed refraction and elevation statics, but otherwise the records are in a raw unprocessed state.

We apply surface-consistent spiking deconvolution using a 120 ms operator with 0.1% white noise, limiting the offsets between 152 and 1067 m for calculating the operator, and use five Gauss-Siedel iterations as recommended by Cary and Lorentz (1991). This is followed by air blast attenuation, time-variant spectral whitening, time-variant scaling, and a 10–20–90–120 Hz band-pass filter. These operations reduce the effect of the groundroll, whiten the frequency spectrum, and balance the amplitudes.

We perform velocity analysis, beginning with a single point, which is used to create a brute stack, and calculate the first pass of residual statics. We then pick velocities on an 80 × 80 inline-crossline grid, apply the corresponding NMO correction, calculate new residual statics, and stack for QC. This cycle of velocity analysis, NMO correction, residual statics calculation, and stacking continues using a 40 × 40 grid and finally a 20 × 20 grid, after which the residual statics solution has converged for sources and receivers. Between the final two rounds of velocity analysis, we apply a prestack structure oriented filter to further enhance signal and reduce noise. The filter works as follows: A stack of the NMO corrected input gathers is used to calculate dip using a maximum correlation technique. This dip model is then used to guide the filter planes along modeled constant offset

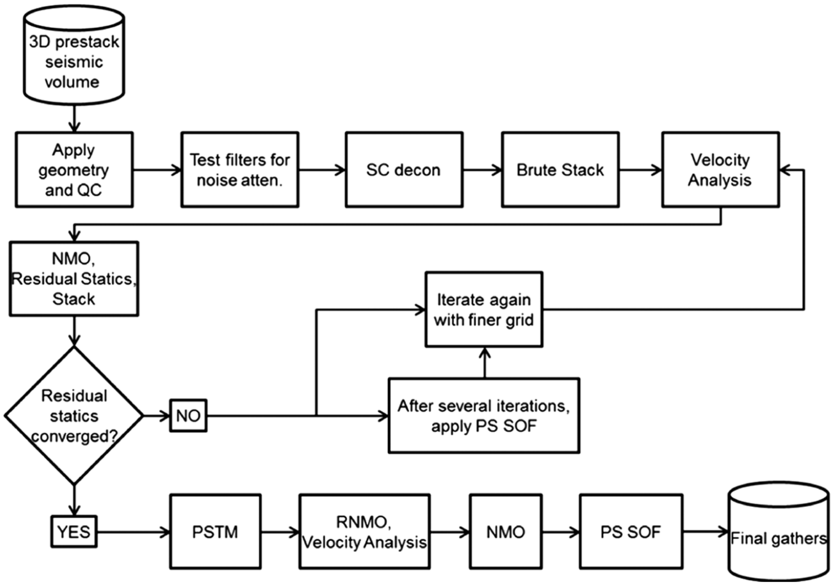


Figure 3. Workflow for reprocessing the 3D prestack seismic data.

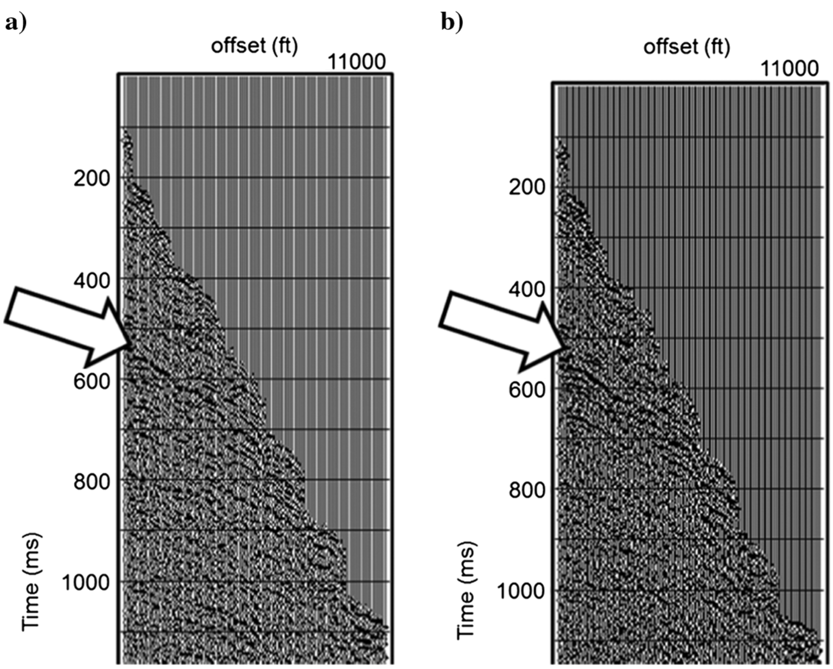


Figure 4. A representative CMP gather (a) after surface-consistent deconvolution, and (b) after applying a prestack structure-oriented filter. White block arrow indicates Mississippian reservoir zone.

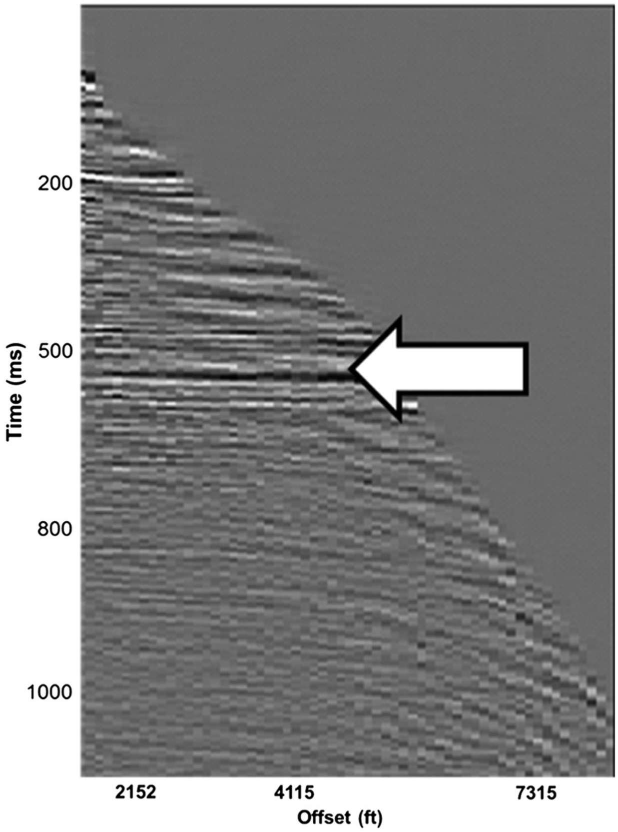


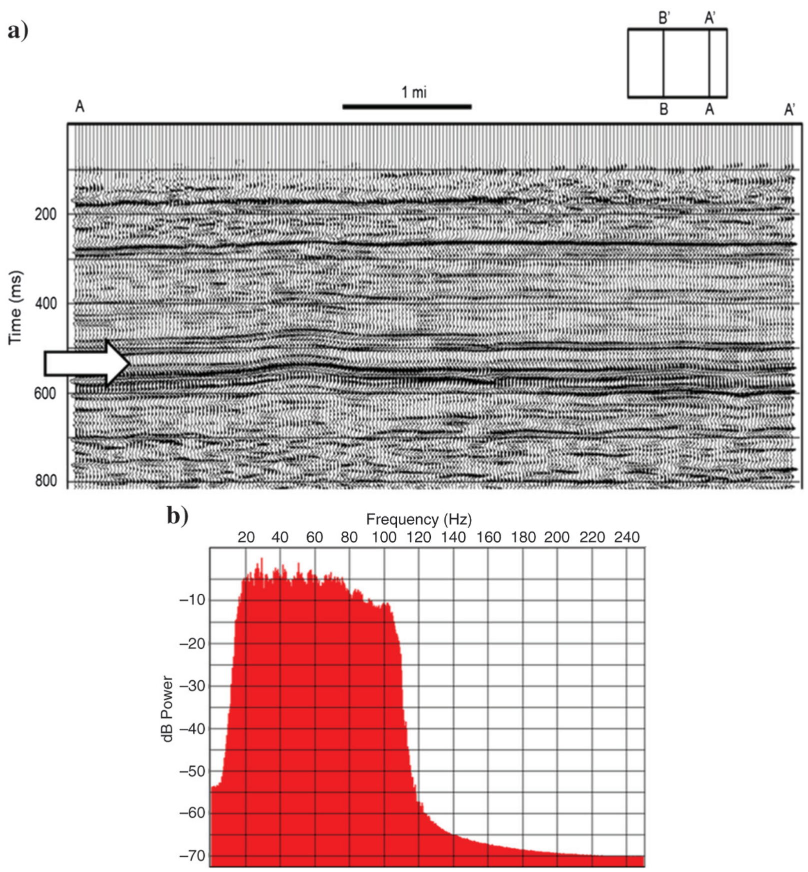
Figure 5. A representative CRP gather after PSTM, residual velocity analysis, NMO correction, a final prestack structure-oriented filter, and spectral whitening.

gathers. The applied filter is a robust statistics filter with edge preserving properties. After filtering the modeled data, the estimated noise model is adaptively subtracted from the original input gathers. Figure 4 shows a representative CMP gather before and after the application of the prestack structure-oriented filter.

Given irregularities in shot and receiver lines and the smooth lateral variation in velocity, we use a Kirchhoff prestack time-migration (PSTM) algorithm. PSTM allows for better imaging of subtle discontinuities in an otherwise mostly flat terrain and improves the seismic data's lateral resolution. A single azimuth bin and 60 offset bins is selected, setting the maximum offset at 3048 m, which will result in incident angles of greater than 45° at our target depth of approximately 880 m. Migration moves the data laterally as well as vertically, and thus usually needs a slightly different velocity. Therefore, we use the migration velocity field to unflatten the migrated gathers by using a reverse NMO algorithm. Velocities are repicked on a 20×20 grid, and a new NMO correction is applied, followed by a final prestack structure-oriented filter and spectral whitening. Figure 5 shows a final common reflection point (CRP) gather.

A significant advantage of reprocessing is access to the previous images and therefore insight into not only the geologic objective but also limitations of the previously used processing workflow (such as acquisition footprint). Figure 6 shows line AA' from the vendor provided stack and its corresponding spectrum. For

Figure 6. Line AA' through (a) the commercially processed seismic data, and (b) the corresponding frequency spectrum. White block arrow indicates Mississippian reservoir zone.



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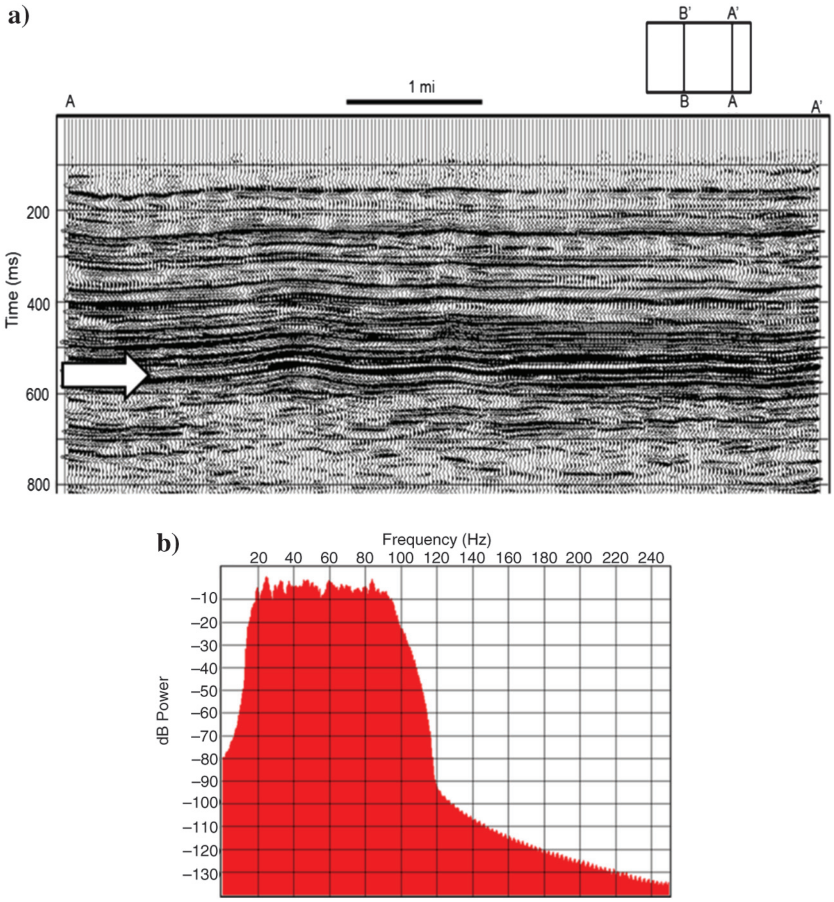

Figure 7. Line AA' through (a) our reprocessed seismic data after PSTM, residual velocity analysis, and applying a nonstretch NMO correction, and (b) the corresponding frequency spectrum. White block arrow indicates Mississippian reservoir zone.

comparison, Figure 7 shows line AA' through the final stack after PSTM, residual velocity analysis, NMO, prestack structure-oriented filtering, and spectral whitening along with its corresponding spectrum. The reflectors in our final stack are more continuous and exhibit higher bandwidth. Additionally, by avoiding f-x deconvolution as applied by the vendor, the sub-700 ms basement structure is better preserved whereas it is masked by "wormy" noise in the vendor's stack. Additionally, the reflectors in the final reprocessed seismic data have not been oversmoothed and higher frequencies are retained better.

Petrophysical analysis

We now turn to well log analysis to examine the petrophysical properties of the various facies encountered in the Mississippi Lime. Snyder et al. (2013) present a characteristic type log for the tripolitic chert versus the tight limestone and tight chert. The tripolitic chert shows low density, low resistivity, and low gamma ray. Matson (2013) defines three unique intervals in the Mississippian section of Osage County near our study area. "Osage A" is encountered at the top of the Mississippian, lying unconformably beneath the Pennsylvanian Cherokee shale. Osage A is characterized as siliceous limestone with high susceptibility for

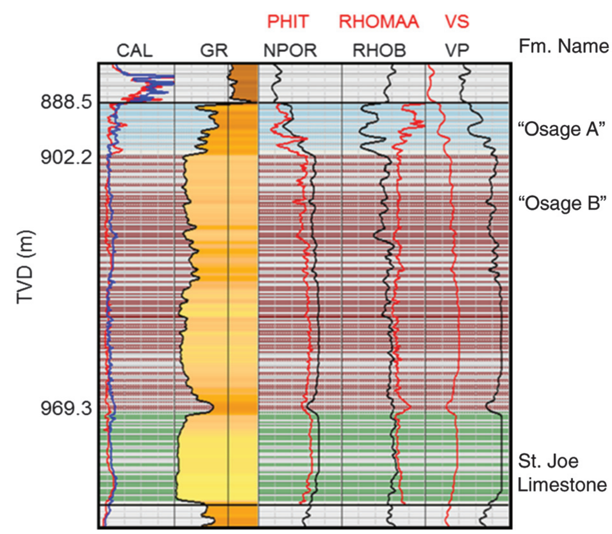

Figure 8. Log response (after editing) through the Mississippian at well B. The caliper track (left) shows significant washout issues at the top of the Mississippian, so log editing was required. The sonic and density log from this well were used for simultaneous prestack inversion.

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diagenetic alteration to tripolitic chert. "Osage B" is below Osage A and contains interbedded tight, highly fractured limestone, and tight nonporous chert and has low potential for diagenetic alteration. The St. Joe limestone (Kinderhookian) lies below Osage B and consists solely of limestone with no chert presence.

Figure 8 shows the log response at "well B" through the Mississippian, which we used for prestack inversion. The top section, in blue, is characteristic of Osage A. The middle section, in brown, is characteristic of Osage B. The lower section, in green, is characteristic of the St. Joe Limestone. The caliper track shows significant washout issues at the top of the Mississippian, as well as several more throughout the section. Therefore, the logs required some editing, which included outlier cleaning and despiking, linear interpolation and splining, and the application of a Gaussian smoother. Bulk density (RHOB) and enhanced thermal neutron porosity (NPOR) are used to calculate total porosity (PHIT), which includes secondary porosity such as fractures, and the density of the apparent matrix (RHOMAA). P- and S-impedance (Z_P and Z_S, respectively), lambda-rho and mu-rho ($\lambda\rho$ and $\mu\rho$, respectively), and V_P/V_S ratio are calculated using the P- and S-wave sonic logs and RHOB log. The volumetric photoelectric factor of the apparent matrix (UMAA) is derived using RHOMAA and the photoelectric factor log, which is sensitive to mineralogy.

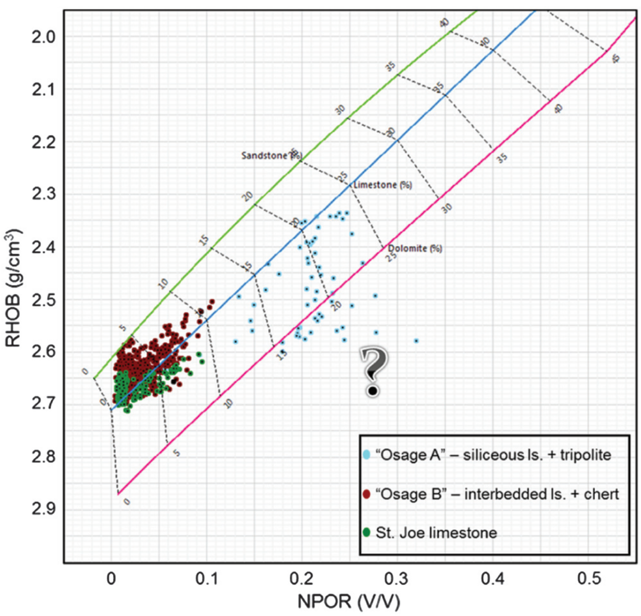

Figure 9. Crossplot of RHOB versus enhanced thermal NPOR through the Mississippian. Osage A, in blue, plots between the limestone and dolomite line, although we expected it to plot closer to the sandstone line due to its highly siliceous content. Osage B, in brown, plots between the limestone and sandstone line, as expected. The St. Joe Limestone, in green, plots mostly on the limestone line, as expected.

Figure 9 shows a crossplot of RHOB versus NPOR through the Mississippian section. The St. Joe Limestone (in green) plots mostly along the limestone line. Osage B (in brown), which consists of interbedded

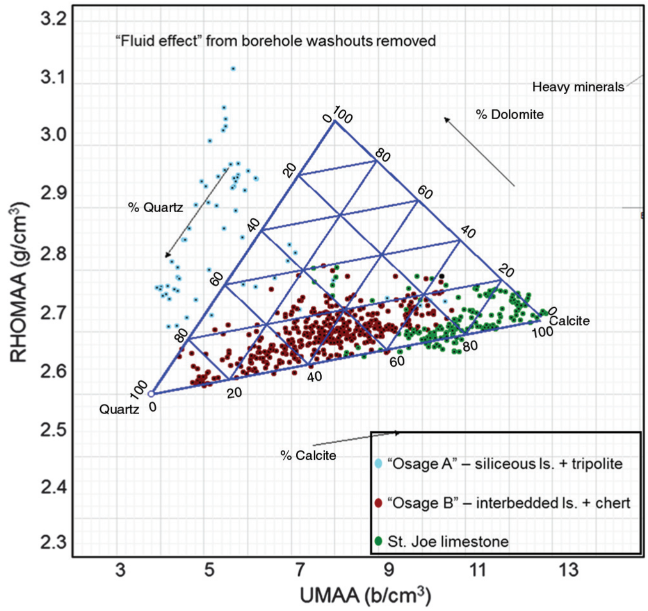

Figure 10. Crossplot of RHOMAA and UMAA. These derived logs contain information about the apparent matrix of the rock. Osage A, in blue, now plots in the quartz-rich zone, as expected. The behavior in the previous figure is likely due to borehole washout problems. Osage B, in brown, plots between quartz and calcite, as expected because it is interbedded limestone and chert. The St. Joe Limestone, in green, plots near the calcite corner, as expected.

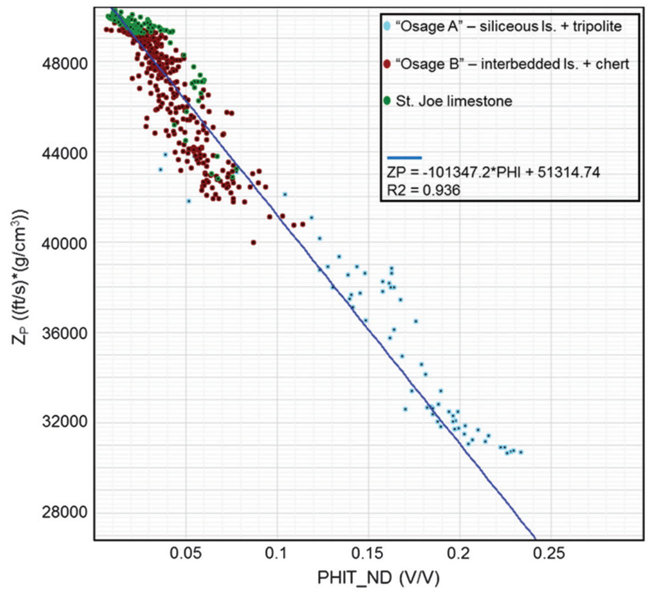

Figure 11. Crossplot of Z_P versus PHIT through the Mississippian. We observe separation of Osage A from Osage B and the St. Joe. Additionally, our hypothesis that impedance decreases with increasing porosity is confirmed.

limestone and chert, plots between the limestone and sandstone lines. Osage A (in blue), which is expected to plot near the sandstone line due to its highly siliceous content, plots between the limestone and dolomite lines. However, it also exhibits the highest porosities and lowest densities of the three intervals in the Mississippian. Figure 10 shows a crossplot of RHOMAA versus UMAA, both of which contain information about the apparent matrix of the rock. The St. Joe (in green) plots near the calcite corner, as expected. Osage B (in brown) plots between the quartz and calcite corners along the bottom edge, which is also expected. Osage A (in blue) now plots well into the quartz region, which confirms that the rock matrix of this section is very silica rich. Therefore, we believe that in the previous figure, Osage A was plotting erroneously due to borehole washout problems.

Figure 11 shows a crossplot of Z_S versus PHIT through the Mississippian, while Figure 12 shows a crossplot of Z_S versus PHIT. In both, we observe a clear separation of Osage A from Osage B and the St. Joe Limestone. Osage A, which contains tripolitic chert, shows the lowest impedance and highest porosities, confirming our belief that as porosity increases, impedance decreases.

Seismic attributes

The prestack, time-migrated data are converted to angle gathers ranging from 0° to 45°. We build low-frequency models for invertingP-impedance (Z_P), S-impedance (Z_S), and density from the seismic data and well logs. The high-angle prestack, time-migrated seismic gathers are then used for simultaneous prestack inversion, generating not only attribute volumes for Z_P and Z_S, but for density (ρ) as well. We then generate Lambda-Rho ($\lambda\rho$), Mu-Rho ($\mu\rho$), and V_P/V_S (Z_P/Z_S) volumes using the Z_P and Z_S volumes (Goodway et al., 1997). Using the picked top of the Mississippian and Arbuckle horizons, we volumetrically crossplot various inversion attributes, using log crossplots as a guide, and extract geobodies corresponding to Osage A, Osage B, and the St. Joe Limestone. Porosity volumes are generated for the Mississippian interval using the linear regressions derived from log crossplots of Z_P and Z_S versus PHIT through the Mississippian. Additionally, surface seismic attributes are generated to aid interpretation of the seismic data, including coherence and curvature. Using these attributes, we are able to better identify the response of tripolitic chert and calibrate the results to well logs.

Results

We show the TWT structure map from the picked Mississippian horizon in Figure 13, with a seismic amplitude inline-crossline chair back. From the crossplots in Figures 11 and 12, we expect pockets of tripolite to occur as low values for Z_P and Z_S, occurring at or near

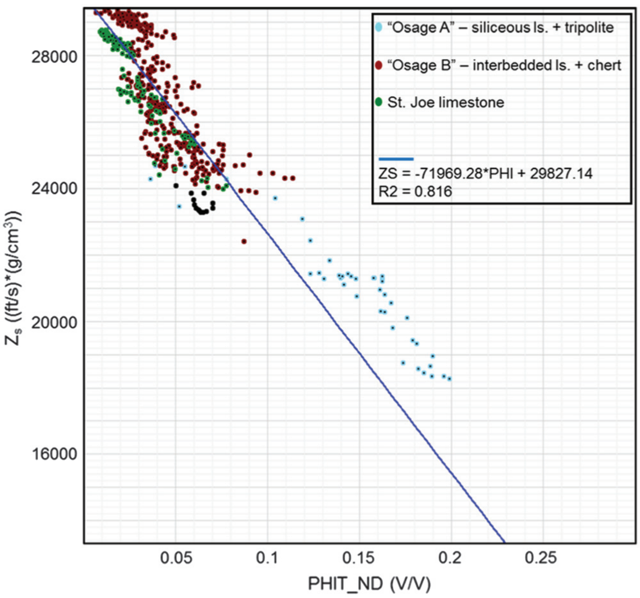

Figure 12. Crossplot of Z_S versus PHIT through the Mississippian. Again, we observe separation of Osage A from Osage B and the St. Joe, with decreasing values of impedance with increasing porosity.

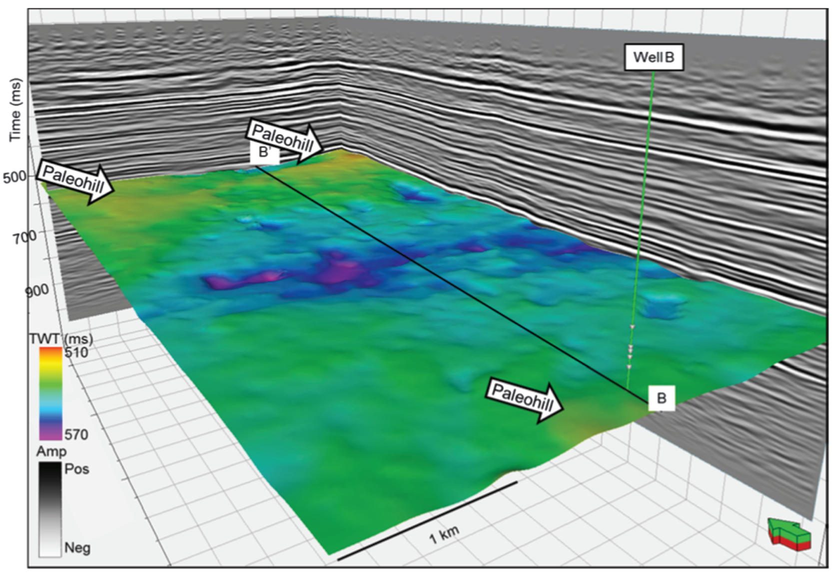

Figure 13. TWT structure map along the top of the picked Mississippian horizon with an inline-crossline seismic amplitude chair back. The location of line BB' is shown. Well B is used in the simultaneous prestack inversion. We observe several paleohills, denoted by white arrows, which are known to correspond with accumulations of tripolitic chert.

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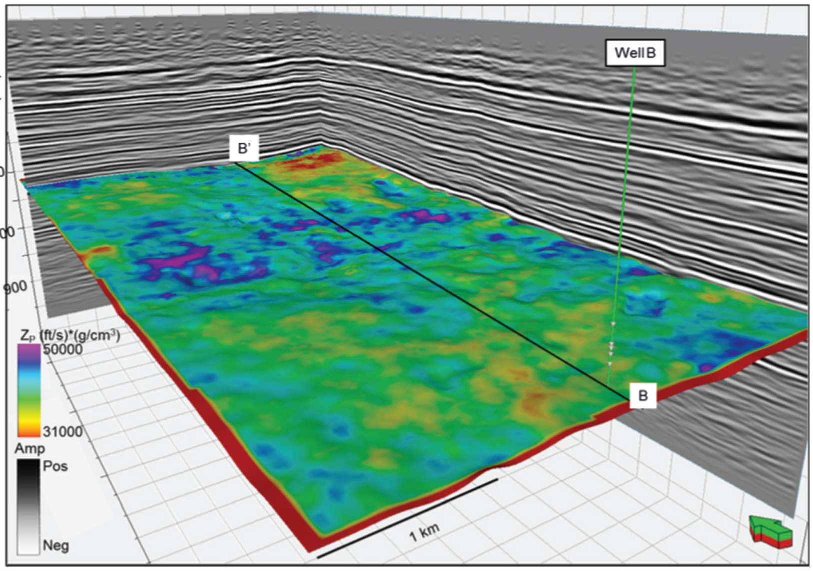

Figure 14. The Z_P along the top of the picked Mississippian horizon with an inline-crossline seismic amplitude chair back. Warm colors denote low impedance values, which we associate with tripolitic chert. The low impedance values also coincide with the location of paleohills observed in the previous figure.

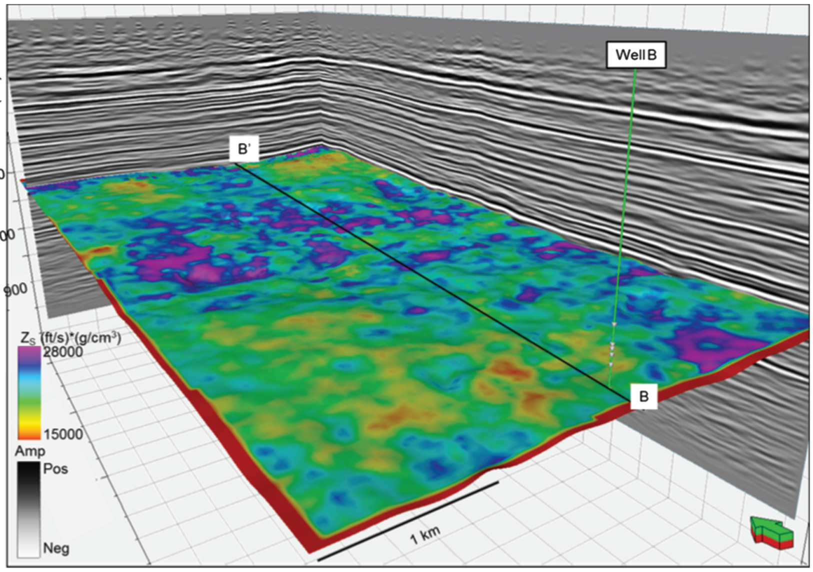

Figure 15. The Z_S along the top of the picked Mississippian horizon with an inline-crossline seismic amplitude chair back. Warm colors denote low impedance values, which we associate with tripolitic chert. We observe similar patterns of low impedance as seen in Z_P.

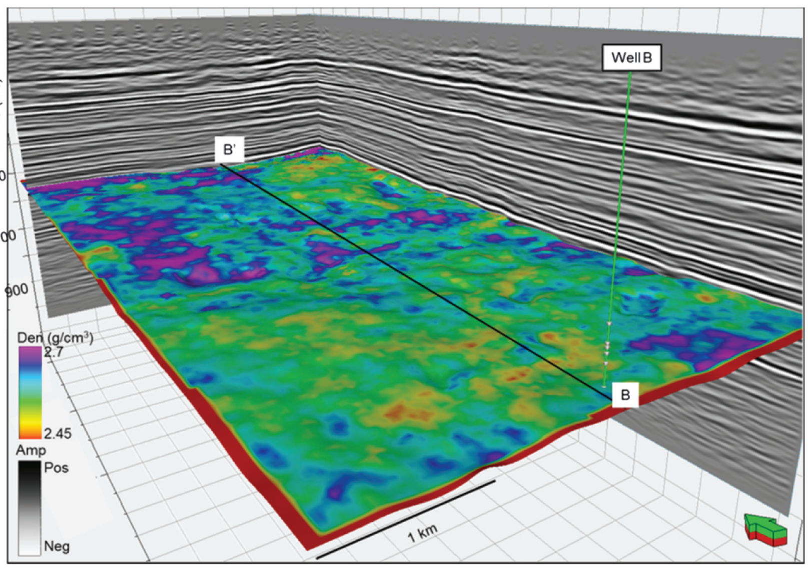

Figure 16. Density along the top of the picked Mississippian horizon with an inline-crossline seismic amplitude chair back. Warm colors denote low density values, which is characteristic of tripolite. On well logs, density is the best discriminator for tripolitic chert.

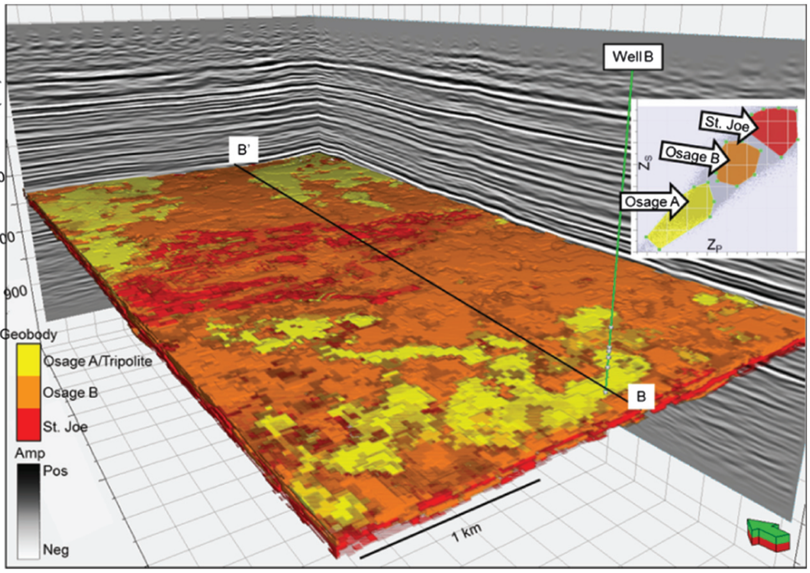

Figure 17. Geobodies corresponding to Osage A (yellow), Osage B (orange), and the St. Joe Limestone (red), extracted by crossplotting the Z_P and Z_S attribute volumes. The geobodies are extracted between the top of the Mississippian and the top of the Arbuckle, representing the entire Mississippian interval.

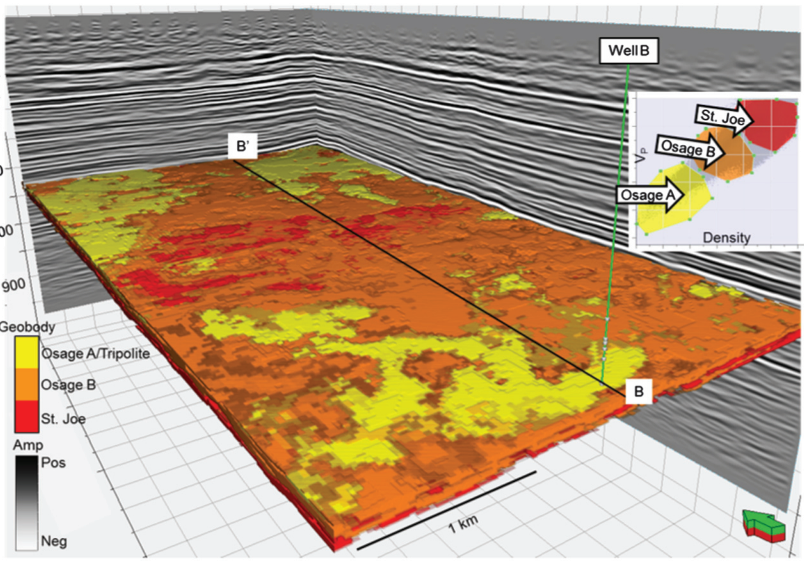

Figure 18. Geobodies corresponding to Osage A (yellow), Osage B (orange), and the St. Joe Limestone (red), extracted by crossplotting the V_P and density attribute volumes. The geobodies are extracted between the top of the Mississippian and the top of the Arbuckle, representing the entire Mississippian interval.

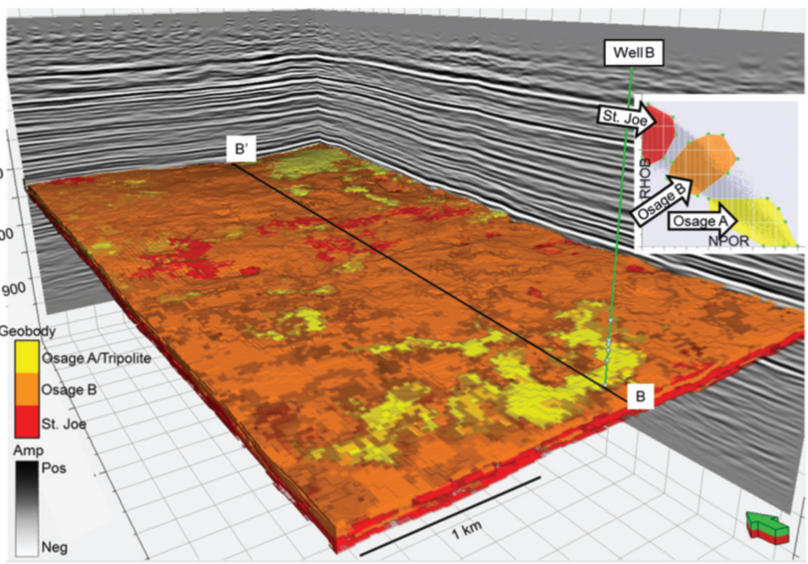

Figure 19. Geobodies corresponding to Osage A (yellow), Osage B (orange), and the St. Joe Limestone (red), extracted by crossplotting the derived PHIT and density attribute volumes. PHIT is derived using the linear regression from crossplotting Z_P and PHIT logs in the Mississippian. The geobodies are extracted between the top of the Mississippian and the top of the Arbuckle, representing the entire Mississippian interval.

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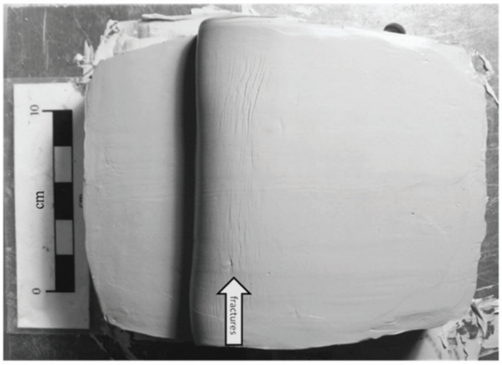
the top of the Mississippian within the Osage A interval. Like Snyder et al. (2013), we find density to be the best discriminating factor to identify tripolite. Figure 14 shows Z_P along the top of the Mississippian, while Figures 15 and 16 show Z_S and density, respectively. Warm colors (red-orange-yellow) correspond to low values for each attribute. All three show similar patterns. Potential accumulations of tripolitic chert correlate with the low values.

Figure 17 shows the extracted geobodies corresponding to Osage A (in yellow), Osage B (in orange), and the St. Joe Limestone (in red) by volumetrically crossplotting Z_P and Z_S through the Mississippian. Figure 18 shows the same geobodies extracted using the V_P and density inversion volumes. Figure 19 shows the geobodies extracted using the density volume and the derived porosity volume.

Both of Rogers' (2001) models for tripolite formation include a stage of SiO_2-rich meteoric water infiltration, resulting in silica replacement of calcite and creation of microporosity. This may help in explaining the observed lateral variability of tripolite within Osage A. Therefore, the extracted tripolite geobodies may also give us insight into the plumbing system in the top of the Mississippian. Understanding fluid flow through the Mississippian and in particular Osage A allows us to improve our prediction of zones for tripolite accumulation.

Experiments by Staples (2011) and White (2013) suggest a relationship between fractures, which form in the presence of strain, and curvature, which is a proxy to strain, shown in Figure 20. A 60-m section from a horizontal borehole image log is shown in Figure 21, both uninterpreted, above, and with interpreted natural fractures, below (White et al., 2012). Figure 22 shows a portion of vertical line BB' with k_1 most positive principal curvature corendered with seismic and the horizontal borehole showing fracture density (White et al., 2012). Curvature, which acts as a proxy to strain, correlates with high fractured density along the horizontal borehole, giving insight into the natural fracture network of Osage A and Osage B. We define tripolitic chert sweet spots as a convergence between low inversion attribute values and intense curvature anomalies, which may indicate an area of high fracture density. Figure 23 shows Z_P corendered with k_1 most-positive principal, and we identify several areas that we think represent tripolitic chert sweet spots.

a)



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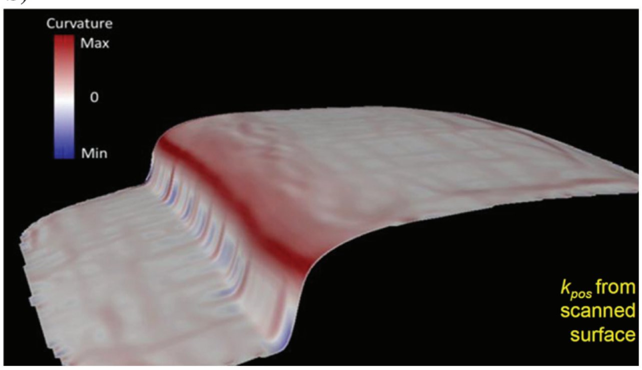

Figure 20. Clay model experiments showing (a) formation of fractures along the hinge of a fold, and (b) associated curvature anomalies detected by laser scanning the surface and calculating curvature (Staples, 2011).

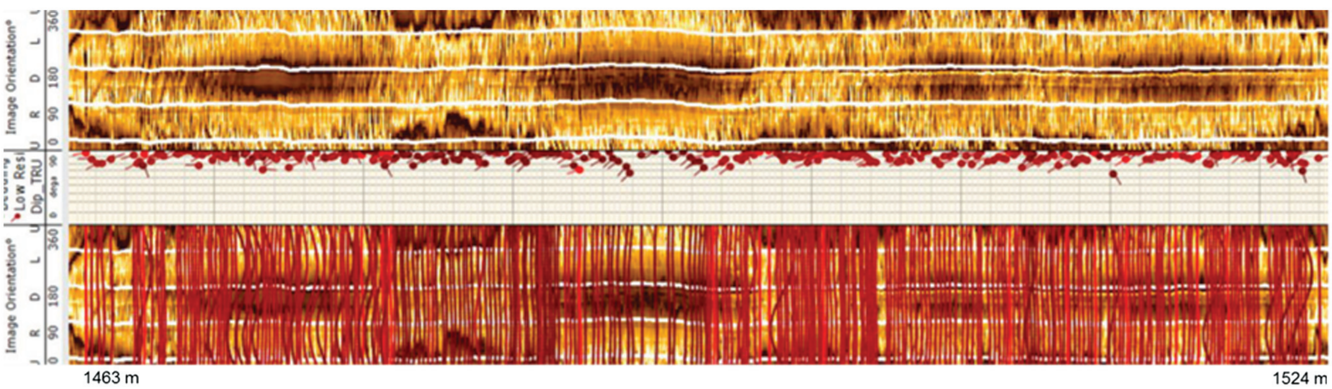

Figure 21. A 60-m section from a horizontal borehole image log from well B. The top shows the uninterpreted log, while the bottom shows the interpreted natural fractures (White et al., 2012).

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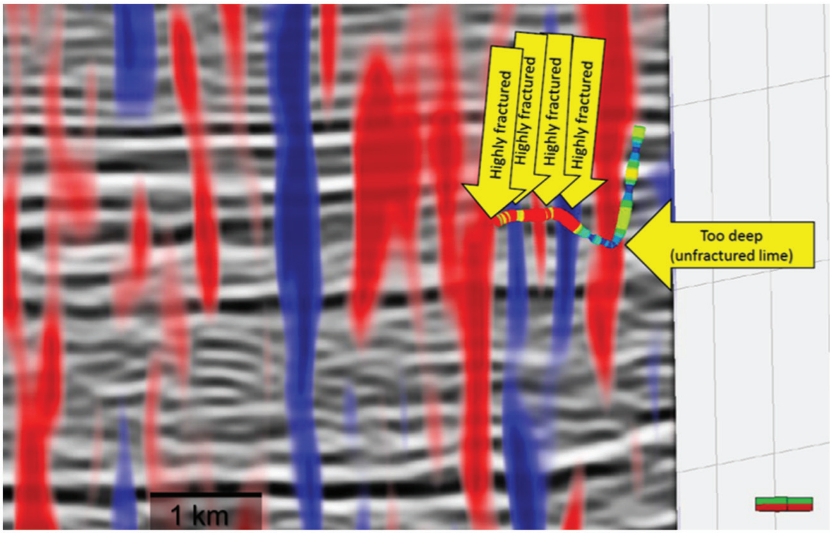

Figure 22. A section of vertical line BB' near well B showing curvature corendered with seismic amplitude. Fracture density calculated from the interpreted image log in the previous figure shows a correlation with curvature anomalies (White et al., 2012).

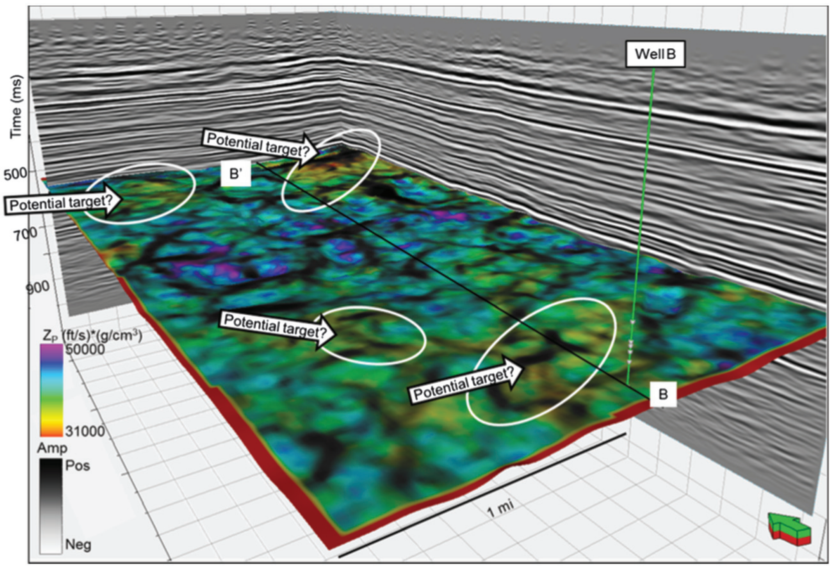

Figure 23. The Z_P along the top of the Mississippian with k_1 most positive curvature corendered in gray scale. We define tripolitic chert sweet spots as the convergence of curvature anomalies, indicative of strain and a proxy for fractures, and low values of impedance, indicative of a rock exhibiting high porosity and low density, which are characteristics of tripolitic chert.

Conclusions

Tripolitic chert is a complex reservoir rock, and its discontinuous lateral distribution makes it challenging to map. Characterized by low density and high porosity, tripolitic chert is very similar to unconsolidated sandstone. Coincidence of tripolite with nonporous chert and tight, highly fractured siliceous limestone adds to reservoir complexity. Tripolite is a weathering, diagenetic product but does not necessarily occur at the top of the Mississippian. For these reasons, using seismic attributes calibrated to well control is extremely beneficial when mapping tripolitic chert.

We have shown that careful reprocessing of 3D prestack seismic data provides high-quality data suitable for long-offset prestack inversion, which is critical when inverting for density. Prestack inversion attributes applied to the long-offset data provide an estimate of not only Z_P and Z_S, but also density, which is the single best discriminator of tripolite. We find that we can use log crossplots to delineate Osage A, Osage B, and the St. Joe Limestone, and that we can additionally use the log crossplots as a guide for volumetrically crossplotting prestack seismic inversion attributes. We see great value in crossplotting the prestack seismic inversion attributes as it facilitates geobody extraction which provides an enhanced 3D spatial awareness for the distribution of Osage A, Osage B, and the St. Joe Limestone in our study area. Combing these results with geometric attributes such as coherence and curvature, and using interpreted horizontal image logs, we believe an ideal target would be to drill horizontally in the thin-bedded limestone and chert perpendicular to folds ("fractures") that fall below the tripolite on the impedance inversion.

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