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Understanding the Spatial Geological Heterogeneity of the Delaware Basin from Pre-Stack Seismic Inversion.

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Abstract

We describe a case study to extract meaningful geological information from a modern high-fold seismic dataset in the north-east Delaware basin. The target of the study is the heterogeneous geology of the Bone Spring and Wolfcamp Formations. A database of well data was used to understand the variation in elastic properties in terms of geological changes that include: mineralogy, organic content and the likely onset of over-pressure. The geology was represented by a set of 5 elastic facies: carbonates, calcareous mudstones, siliciclastics, organic-rich and clay-rich shales. The well data were also used to calibrate seismic amplitudes prior to performing a Bayesian pre-stack inversion to solve for estimates of facies and impedances. The results are shown to provide insights into the regional stratigraphic deposition and evolution of the formations, including mapping of discontinuous carbonate and high TOC intervals. The property volumes are the starting point for future predictive geological, formation-pressure and stress models for informing optimal resource exploitation within the study area.

Introduction

The geology of the Delaware Basin is heterogeneous in both lateral and vertical directions. Understanding the geological complexity is critical for optimizing exploitation strategies in both the Bone Spring and Wolfcamp Formations. Seismic data provide valuable spatial information between and away from well locations, however, the process of extracting the geological information from the seismic amplitudes is non-trivial. In this paper, we describe a state-of-the-art pre-stack seismic inversion study in the north-east Delaware Basin, with the objective of obtaining reliable estimates of the geology across the 380 square mile study area, Figure 1.

The workflow applied in the study was built on an understanding of the rock properties from a regional database of 14 wells. The seismic data were acquired in 2017 using point source-receiver technology and a maximum fold of 396. A Bayesian pre-stack seismic inversion approach was used that simultaneously solves for both facies and impedances, without the requirement of a conventional low frequency model (Kemper & Gunning, 2014). This approach is particularly advantageous when dealing with the laterally discontinuous geology of the Bone Spring and Wolfcamp Formations as the creation of a low frequency model by well log interpolation, as used in conventional seismic inversion tools, would result in an inversion product where laterally discontinuous geology is either smoothed or suppressed.

Methods

A database of 14 wells was constructed for the study as shown in Figure 1b. The selection of wells was based on the availability of logs, in particular P- and S- sonic data. Formation well tops were provided by experts in the Permian Basin stratigraphy at the Bureau of Economic Geology at the University of Texas, Austin - Texas. This stratigraphic model is the basis of the terminology used in this paper.

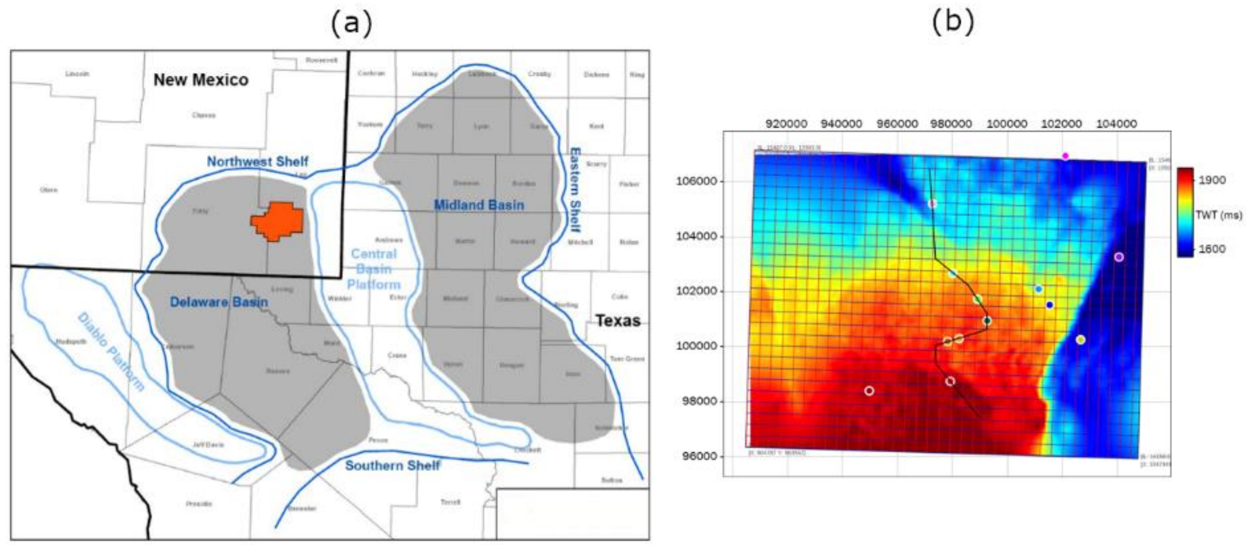


Figure 1. The location of the study area. (a) The seismic survey outline is shown by the red filled polygon. (b) Well locations within the seismic survey area shown by the colored dots. The background color is the time structure map of the top Strawn Formation. The black line is the location of the arbitrary line shown in Figure 10.

A deterministic petrophysical model was applied to calculate volumes of clay, silicates, carbonate and kerogen, calibrated to regional core data. An important aspect of the petrophysical interpretation for unconventional mudrocks is the requirement to calculate the volume of organic material in the rock, expressed by the total organic content (TOC). In this study the TOC was calculated using a blend of two methods. TOC was initially estimated using the Passey method (Passey et al. 1990). The second method used to calculate TOC was from bulk density using the Alfred & Vernik (2012) approach. This approach calculates the TOC from the bulk density log using physical principles and the assumption that the fluid phases are discreet to the inorganic and organic (kerogen related) porosity. Both methods used to calculate TOC require knowledge of certain physical properties of each phase of the rock and fluids, which can be estimated from core measurements. Within the study area, the Bone Spring Formation is observed to be at a depth that correlates with vitrinite reflectance values of approximately 0.85% (Pawlewicz et al., 2005), which places the formation in the oil maturation window. In contrast, the deeper intervals of the Wolfcamp Formation are observed to correlate with vitrinite reflectance values of approximately 1.10%, which are associated with the transition into the early gas condensate generation window.

The relationships between the measured elastic properties and mineralogy, depth and spatial variability were then analyzed and understood in terms of regional geological mechanisms such as kerogen maturity and over-pressure. A series of cross-plots of the sonic velocity as a function of depth are shown in Figure 2. Within the Bone Spring Formation, a change in the range of velocity values occurs at the base of the First Bone Spring Carbonate. The lower velocities observed in the Avalon and First Bone Spring Carbonate intervals are observed to be associated with higher organic content. The three main mineral components are shown to be associated with the high, intermediate and low velocity end-members. Little lateral or depth dependent variation is observed in the end-member velocity trends. In contrast, the velocity trends for the Wolfcamp Formation exhibit a velocity reversal with depth. A component of the velocity reversal is likely to be related to the development of over-pressure. However, a mineralogical effect is also observed as the lower Wolfcamp intervals become more clay-rich and have a higher organic content.

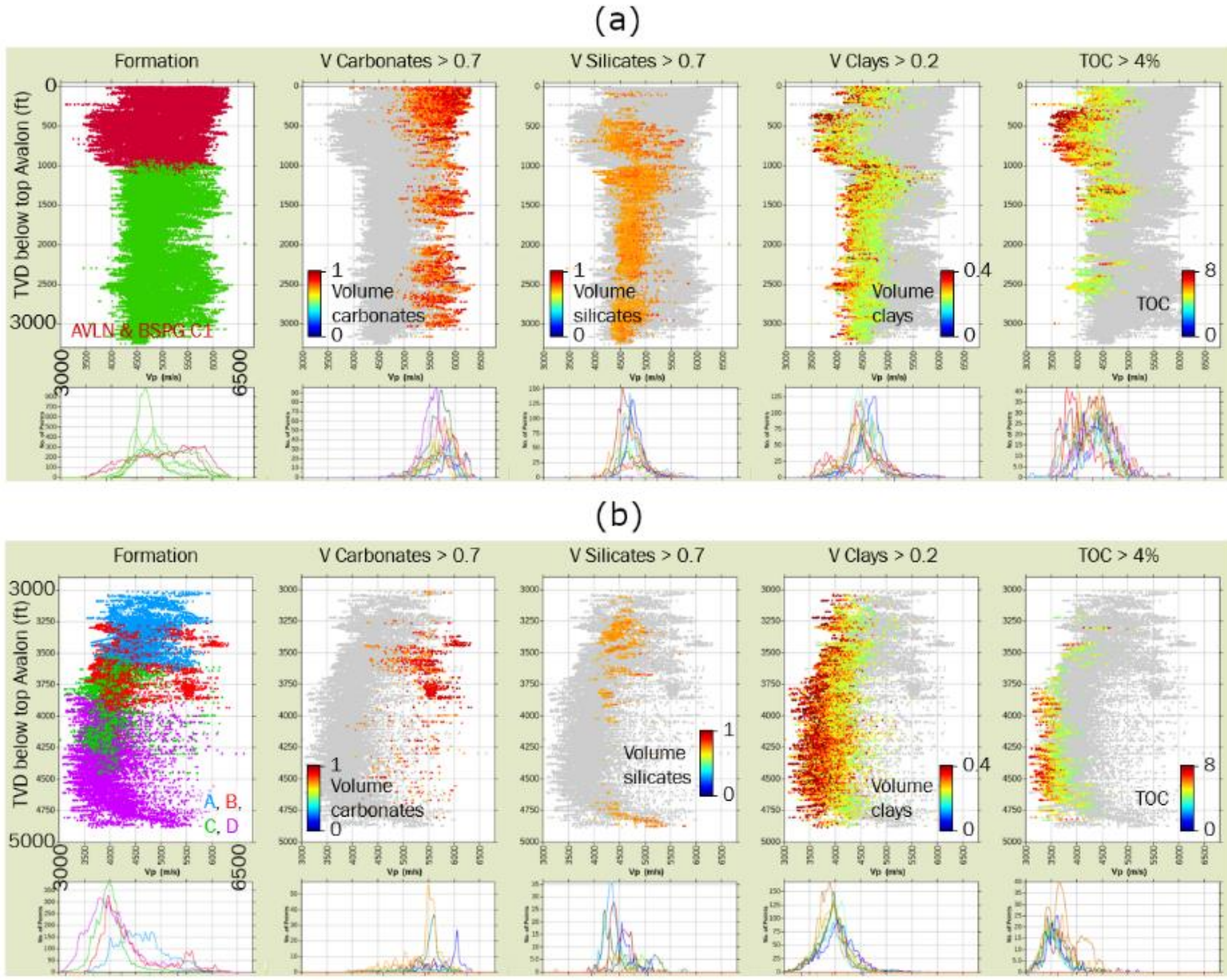


Figure 2. Sonic velocity (Vp, m/s) as a function of true vertical depth below the top Avalon for: (a) the Bone Spring Formation and (b) the Wolfcamp Formation. The five plots show the same data colored, left-to-right, by: interval, volume of carbonates, volume of siliciclastics, volume of clays and TOC. The Bone Spring Carbonate Formation is sub-divided into an upper interval (red) that includes the Avalon and First Bone Spring Carbonate. These intervals have a different range of Vp compared to the lower Bone Spring intervals (red). The Wolfcamp Formation is sub-divided into the A, B, C and D intervals.

A five-fold facies classification was devised to cluster the data in terms of elastic properties. The facies definition was performed using cut-offs from the petrophysical logs (Table 1). A database of elastic property trends of Vp-depth, Vp-density and Vp-Vs was then compiled for each facies. This database included a number of sub-formation zones to describe the observed variability in the elastic properties. An example of how the facies cluster in an elastic property cross-plot is shown in Figure 3. The facies definition and associated trends were used to condition the logs and predict intervals of missing data.

Table 1. Details of the facies definition used in the study. Some facies are only considered present in one of the formations.

Facies Name	Formation(s)	Cut-off Definition
Carbonate	Bone Spring & Wolfcamp	Volume carbonates > 0.6
Calcareous mudstone	Bone Spring	0.3 < Volume carbonates < 0.6
Siliciclastics	Bone Spring & Wolfcamp	Volume carbonates < 0.3 & TOC < 0.1
Organic-rich	Bone Spring	Volume carbonates < 0.3 & TOC > 0.1
Clay-rich	Wolfcamp	Volume carbonates < 0.4 & Volume silicates < 0.6

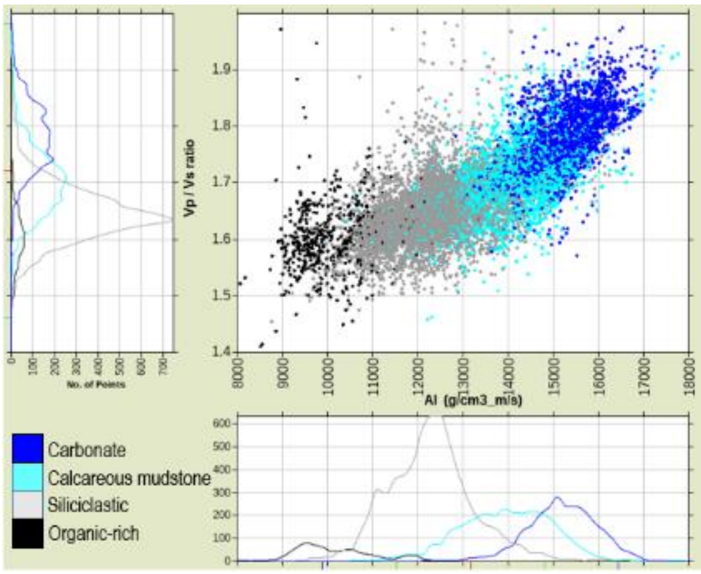


Figure 3. Cross-plot of Vp/Vs ratio as a function of acoustic impedance, colored by the facies model for the Bone Spring Formation. The histograms show the degree of overlap in properties. The spread is reduced when considering the sub-formation zones.

The facies definition and associated database of elastic properties became the calibration for the Bayesian pre-stack seismic inversion. A 16ft mode and Backus average filter were applied to up-scale the facies and elastic logs respectively to a 2ms TWT sample resolution, which is the maximum expected resolution of the inversion approach. An example of the up-scaled facies log is shown in Figure 4.

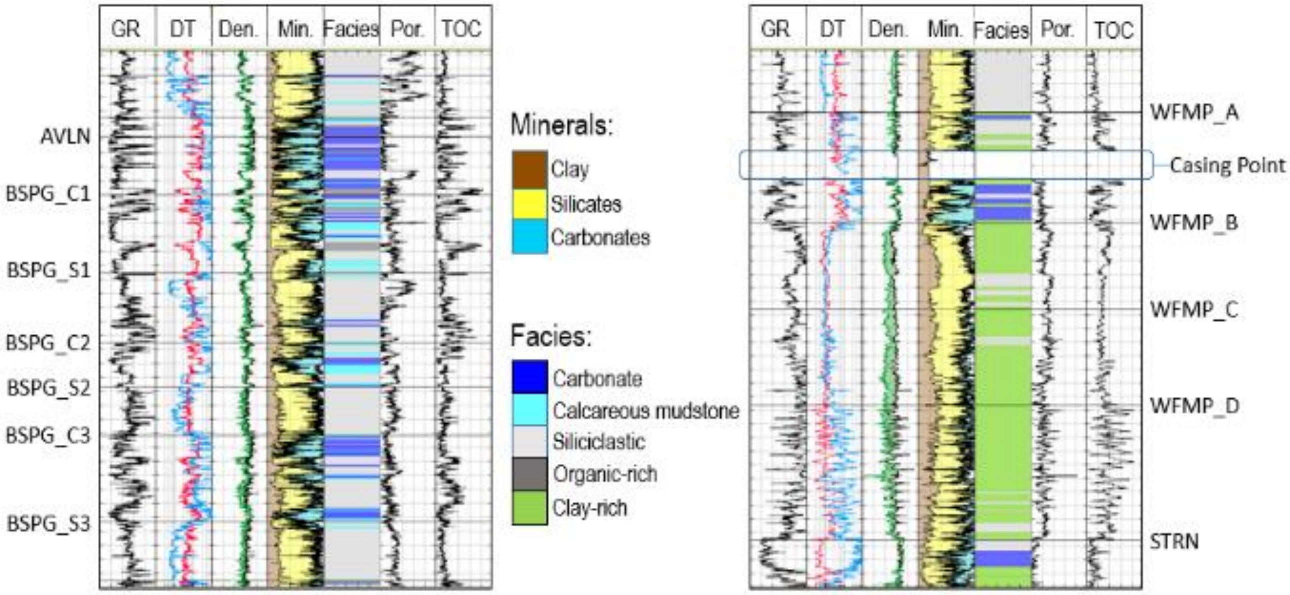


Figure 4. Elastic logs, including the seismic facies, for an example well. The upper Bone Spring Formation section is shown to the left and the lower Wolfcamp Formation section is shown to the right.

Seismic well ties and estimates of the seismic wavelet were performed using the least squares matching technique (White, 1980). Good ties were observed with cross-correlation values greater than 80% for the full stack seismic volume over a time window of more than 500ms; an example is shown in Figure 5. The well ties and estimated wavelets became the basis to assess and calibrate the seismic amplitudes prior to inversion. The estimated wavelets were observed to have relatively stable frequency bandwidth and phase between well locations. However, the wavelets showed a significant variation in amplitude, Figure 6. In order to understand this variation further, a series of RMS maps were generated from the seismic data at multiple intervals throughout the overburden and target levels. These RMS maps show a similar pattern that begins to diminish with increasing depth, evidence that there is a strong imprint of shallow subsurface features that begin to be undershot at depth. The peak amplitude of the estimated wavelets exhibit a strong correlation with the patterns observed in the RMS amplitude maps.

The spatial amplitude patterns observed in the RMS maps were interpreted to be related to: (i) a channel of low velocity Cenozoic sedimentary fill to the SE, (ii) the interaction between the Capitan Reef complex and the juxtaposing Castile Formation and (iii) an area of low fold due to surface infrastructure associated with the waste injection pilot plant to the SW. The Capitan Reef complex is a carbonate reef that formed in the mid-Permian. A portion of the reef runs through the shallow subsurface of the survey area from NW to SE. At the reef margins, water from the carbonate has interacted with the salt from the juxtaposing Castile Formation. Seismic lines through the area show a complex package of events at the reef margins, below which the seismic amplitudes are significantly reduced (Figure 7). A review of the seismic gathers in these areas demonstrates that the effect is primarily a seismic transmission issue Figure 8.

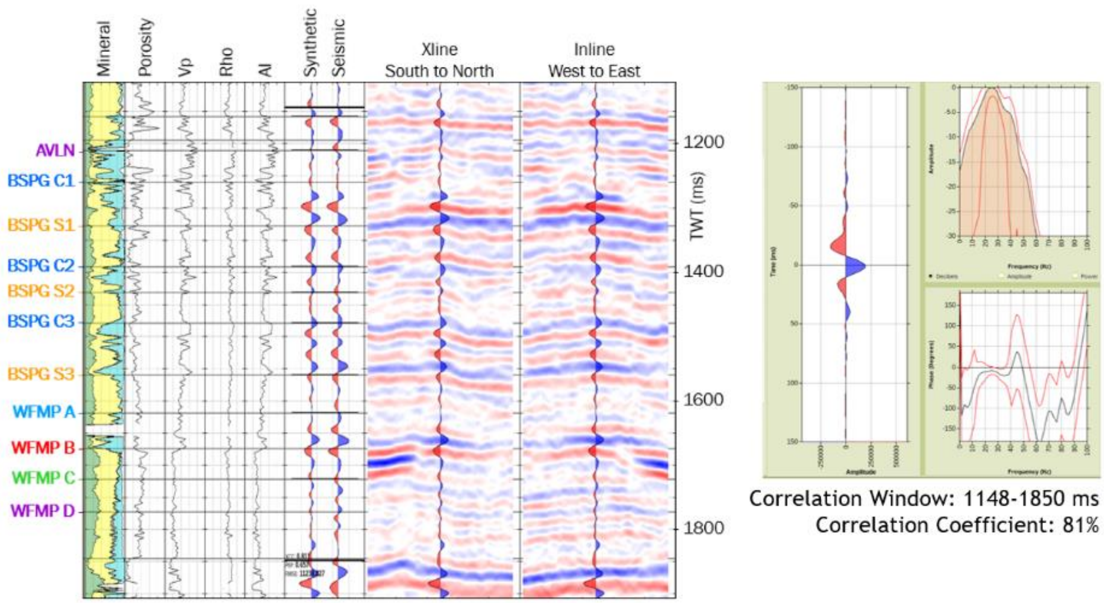


Figure 5. Example well-to-seismic tie and estimated wavelet.

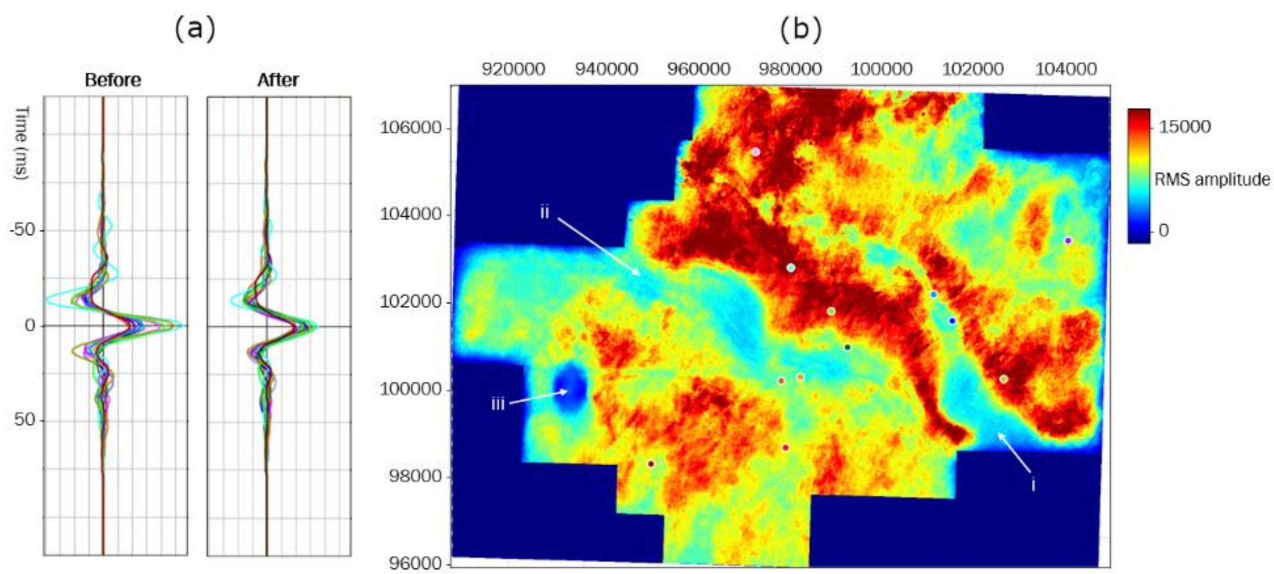
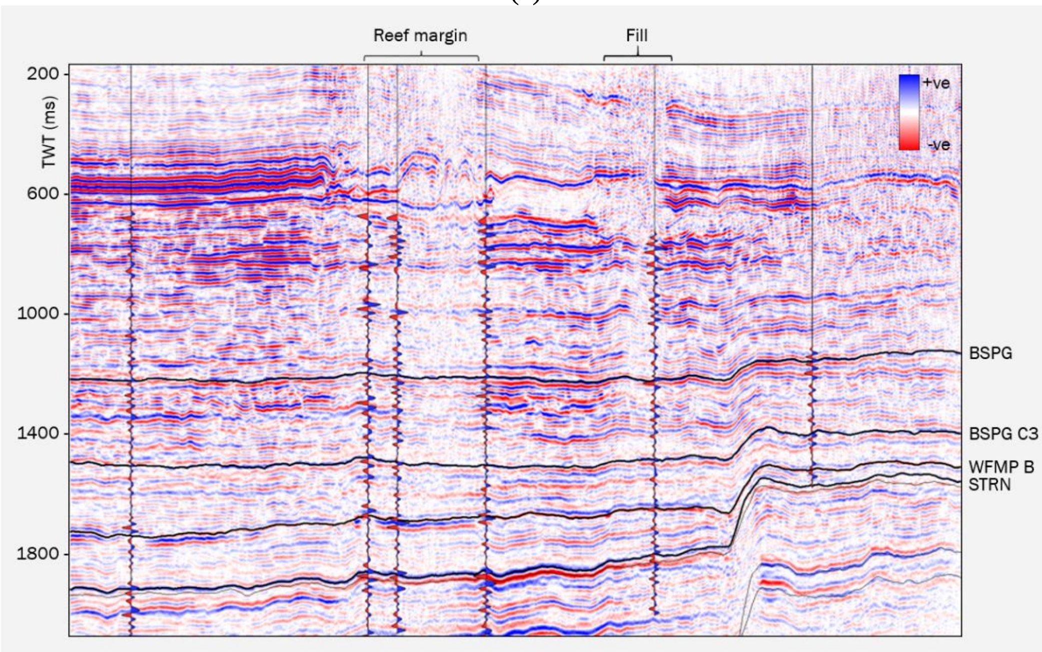


Figure 6. (a) Estimated seismic wavelets before and after the spatial amplitude correction. The variation in amplitude scaling is significantly reduced after correction. (b) RMS amplitude map calculated from the Lamar to Strawn Formation. Three anomalous low amplitude areas are labelled (i)-(iii) and are described in the text.

A spatial amplitude correction was applied to the seismic data to minimize these overburden imprints. The correction was based on RMS maps at various intervals. The results were validated through the re-estimation of seismic wavelets post correction, which show much more consistent amplitudes. RMS maps generated post correction exhibit a significantly reduced imprint from the overburden features and reveal amplitude patterns that can be associated with the geological variations within the formations. The spatial amplitude correction procedure was applied to each of a set of five partial angle stacks and validated using estimates of the seismic wavelets at the correct reflectivity angle range. The results of this process was a seismic dataset ready for pre-stack inversion.

(a)



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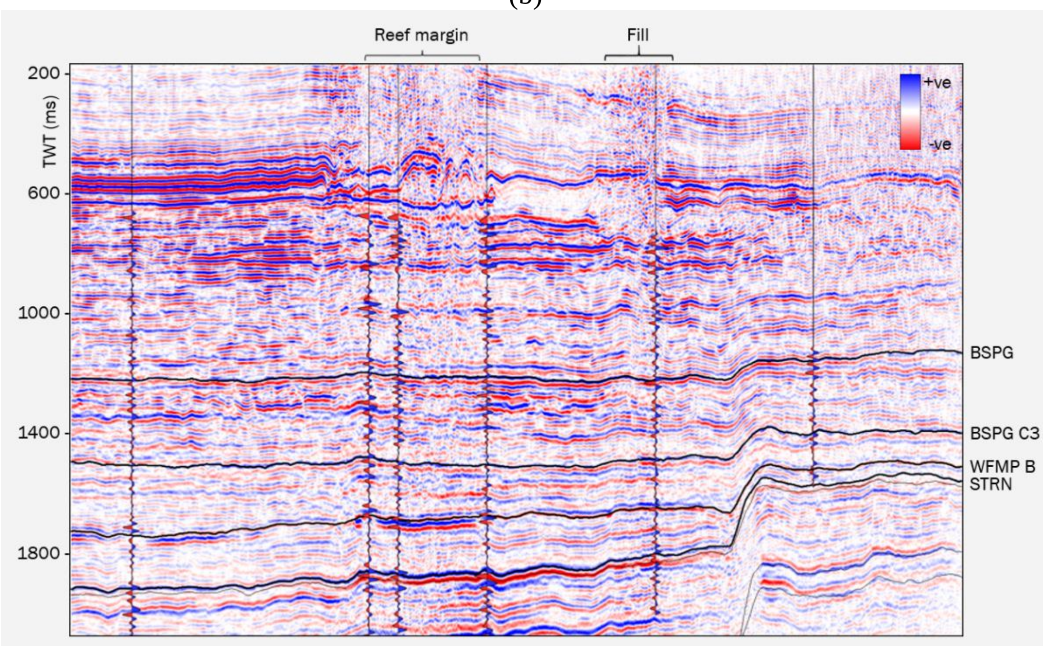
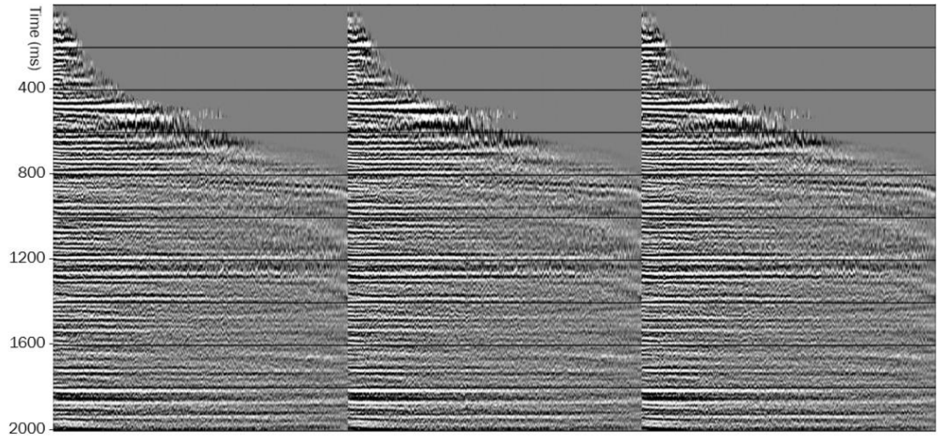


Figure 7. Seismic section before (a) and after (b) spatial correction. The margin of the Capitan Reef and Cenezoic Fill are labeled and can be observed in the upper 600ms of the section. The spatial correction balances the amplitudes beneath these features.

(a)



(b)

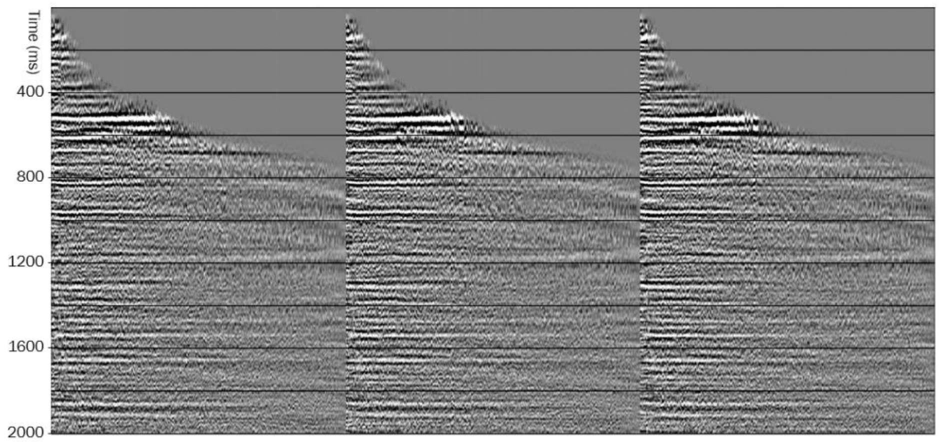


Figure 8. Seismic offset gathers from: (a) an area of strong amplitude response and (b) an area of low amplitude beneath the reef margin. Coherent, flat events are observed in both images but the seismic amplitudes are significantly reduced beneath the reef margin.

Results

An example of the seismic inversion results at a calibration well is shown in Figure 9. Good correlations between the up-scaled elastic properties measured in the well and inverted properties from the seismic are observed for Vp, AI and Vp/Vs ratio.

The seismic, predicted facies and acoustic impedance are also shown on an arbitrary line in Figure 10. The lateral continuity of the carbonate bodies is controlled by the seismic reflectivity alone as unlike conventional model-based inversion approaches, no lateral interpolation of well log data is used. This makes the approach ideally suited for mapping the discontinuous geology of the Bone Spring and Wolfcamp Formations. A series of thick channelized carbonates, which are potential debris flows, are observed within the upper Wolfcamp and can be mapped spatially using the inversion results. An example is shown in Figure 11. The probable source direction of this example can be interpreted from the north-east and a strong bounding fault is observed on the south-east side.

The occurrence of carbonate units is higher in the Bone Spring Formation but individual flow packages can again be identified and mapped. An example of mapping a carbonate unit in the First Bone Spring Sandstone interval is shown in Figure 12. A potential channelized debris flow can again be interpreted that fans to the south. The presence and location of these carbonate intervals will have a significant effect on drilling and the rock's response to fracture stimulation. Therefore the spatial mapping of the carbonate intervals away from well control is important for informing well design and completion strategies. Areas of increased development of organic-rich facies within the Avalon and First Bone Spring Carbonate can also be mapped using the facies prediction volume. Further subdivision of the facies is also expected to be possible based on the spread of elastic impedance properties.

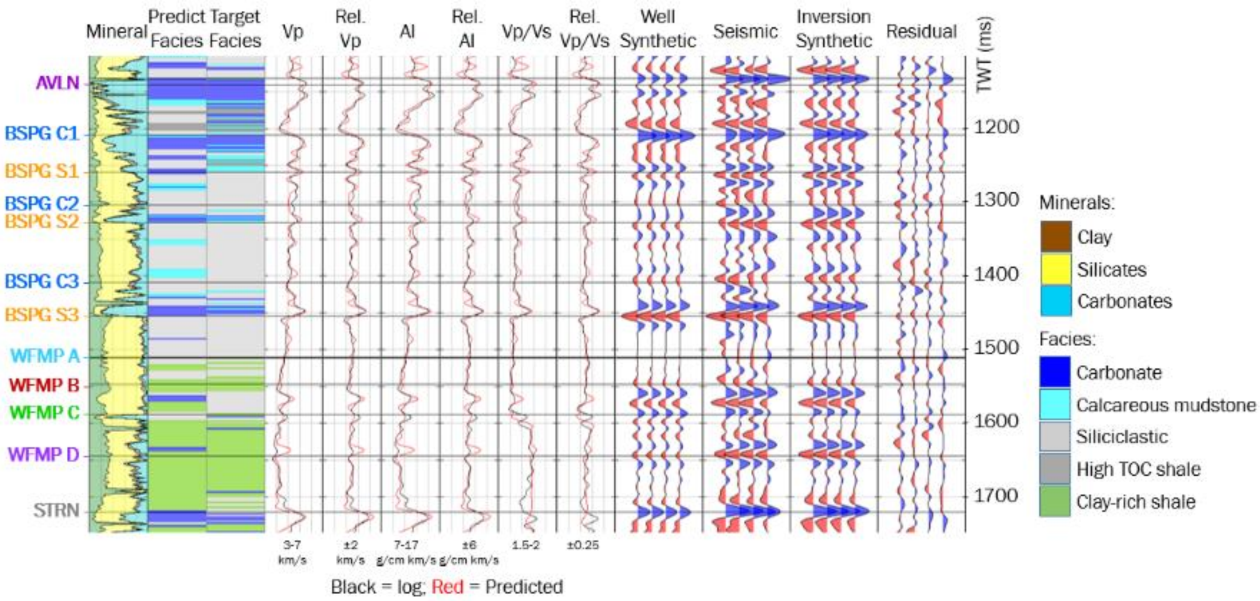


Figure 9. Comparison of inversion results to the up-scaled log data. The relative (Rel.) elastic logs were computed by applying a low-cut filter to the properties.

Conclusions

A geologically calibrated pre-stack seismic inversion study was performed in the north-east Delaware Basin to image the vertical and lateral geological heterogeneities in the Bone Spring and Wolfcamp Formations. The calibration to well and core data is essential. The Bayesian seismic inversion approach applied made use of a regional well database to understand the variations in elastic properties in terms of geological changes including: mineralogy, organic content and the likely onset of over-pressure. High organic content was associated with the Avalon and First Bone Spring Carbonate and lower Wolfcamp Formations. The definition of elastic facies was an important step in calibrating the seismic inversion but also for communicating the detectability of geology from seismic data.

The results of the study are a set of 3D volume estimates of the geology, represented by facies and elastic impedance properties. These estimates of the geology provide insights into the regional stratigraphic deposition and evolution of the Bone Spring and Wolfcamp Formations, including mapping of discontinuous carbonate and high TOC intervals. The property volumes are also the starting point for future predictive geological, formation-pressure and stress models for informing optimal resource exploitation within the study area

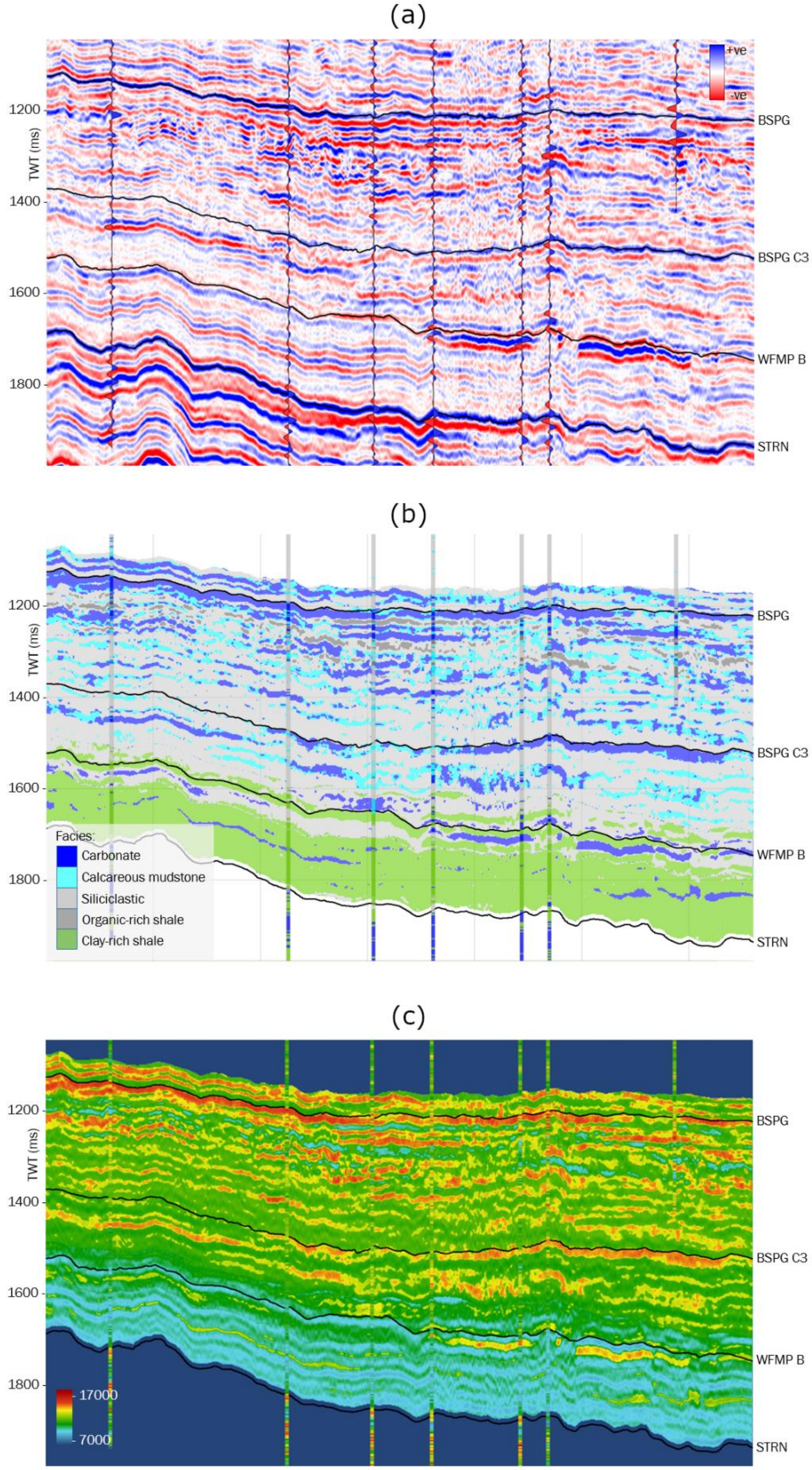


Figure 10. (a) Seismic full stack and synthetic traces, (b) facies prediction and (c) acoustic impedance along an arbitrary line. The location of the line is shown in Figure 1. Up-scaled facies and impedance logs are shown at the well locations. AI units in m/s . g/cm^3.

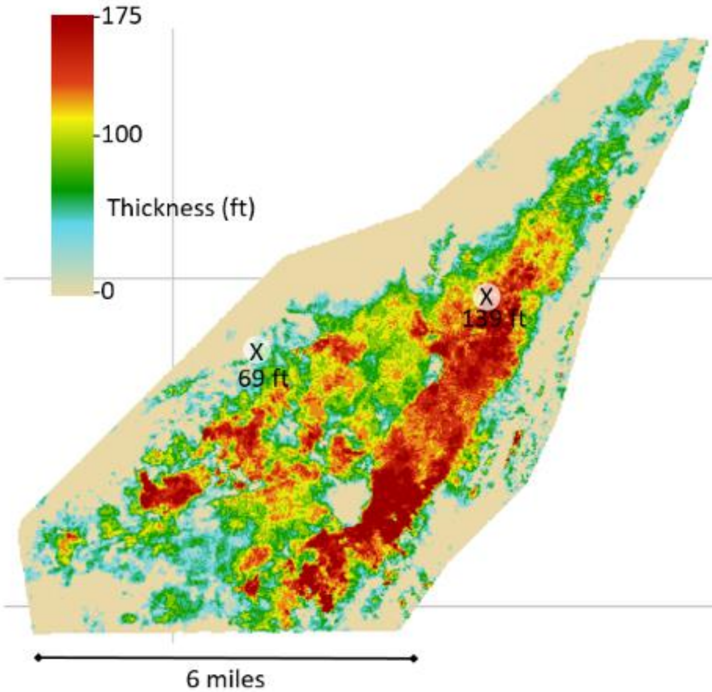


Figure 11. Thickness of a carbonate unit in the upper Wolfcamp Formation, mapped using the inversion results. The thickness of the carbonate interval, as encountered by two wells is shown for comparison.

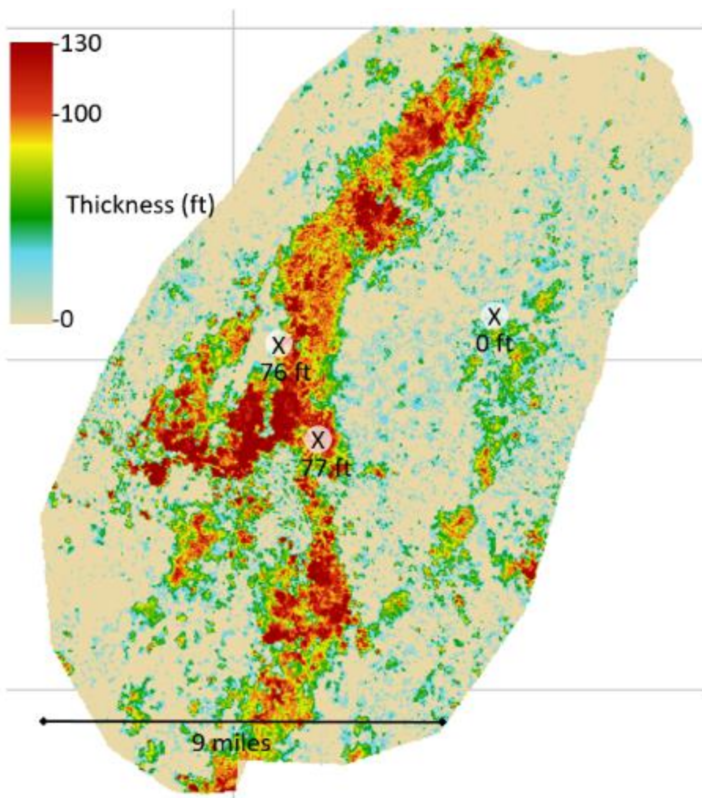


Figure 12. Thickness of a carbonate unit in the First Bone Spring Sandstone interval, mapped using the inversion results. The thickness of the carbonate interval, as encountered by three wells is shown for comparison.

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