# Elastic imaging and its benefits — Permian Basin example

David Langton[1*], Alex Biholar[1], Kenton Shaw[1], Steve Adams[1], Mike Bradshaw[2], Jeff Codd[2], Xiaoling Tan[2], Allon Bartana[2] and David Kessler[2] present the long-anticipated move of using elastic anisotropic reverse time migration as the leading prestack depth migration algorithm.

## Introduction

Seismic imaging has been continuously advancing since the early days of computer revolution in the 1970s. Practical imaging during this time was carried out only in two dimensions using simplified wave equations on poststack data. Subsequently, in the early 1980s algorithm improvements in wave equation migration after the introduction of one-way phase shift methods and two-way reverse time migration occurred. Concurrently, improvements in ray-based Kirchhoff migration emerged after the introduction of eikonal and wavefront reconstruction solvers for calculation of travel times. In the late 1980s, 3D prestack Kirchhoff migration began to be used.

By the early 1990s, 3D wave equation poststack migration began to be used and was followed shortly by implementation of wave equation prestack migration. After the turn of the century, 3D prestack reverse time migration became practical, and a few years later VTI, TTI, and orthorhombic rheology were introduced into the imaging.

Today, despite the improvement in imaging technology and computer capacity, seismic imaging suffers from a serious drawback in that it is based on the acoustic assumption. This assumption considers the earth as a fluid which supports only P-waves. This has been justified since pure P-wave propagation, in an acoustic medium, and an elastic medium produce the same travel times. However, even for marine acquisition, where only P-waves are recorded, some of the reflection events propagate as S-waves in part of the propagation path. These events supply important information about the subsurface structure as in many cases they can propagate in areas where P-waves cannot. Furthermore, shear waves are very important for resolving subsurface parameters. This includes the estimation of S velocity directly from the seismic data as well as more accurate definition of anisotropic parameters. In addition, anisotropy is only accounted for approximately with acoustic imaging, creating artefacts from slowly propagating quasi shear waves.

Using modern computer hardware, the full elastic wave equation as the basis for prestack depth migration (PSDM) is possible and economic. This is done without any approximations, enabling the use of both P- and S-waves in imaging (i.e. the full wavefield). In this work, we present the long-anticipated move to use the elastic anisotropic reverse time migration as the leading prestack depth migration algorithm. This is demonstrated using a data set recorded in the Permian basin of West Texas and southeast New Mexico in the US. As demonstrated in the examples shown here, use of the full wavefield leads to increased resolution of the depth migrated data, enabling more detailed and accurate interpretation of subsurface formations.

## The Permian Basin – geology, oil and gas production and seismic processing challenges

### *Permian Basin – introduction*

The Permian basin of West Texas and southeast New Mexico is among the most prolific basins globally and has produced more than 33.4 BBL and 118 Tcf since hydrocarbons were discovered in 1921 (EIA 2019). The EIA estimates that proven reserves within the Permian Basin exceed 8 BBL oil and 27 Tcf of natural gas making it one of the most significant oil-producing basins in the world. The Permian Basin covers an area of 220,000 km$^2$, and the Delaware Basin, which is the westernmost sub-basin of the Permian Basin, is approximately 26,000 km$^2$ (DOE, 2019). Hydrocarbon exploration within the basin has targeted multiple intervals within the Ordovician through Permian sediments ranging in depths as shallow as 70 m to as deep as 7.6 km (Adiletta et al., 2019). Modern unconventional exploration and development efforts have mostly targeted the Permian-aged formations: Wolfcamp, Bone Spring, and Leonard/Avalon (Figure 1).

### *Stratigraphy*

Sediments within the Permian section of the Delaware basin are sourced from the northwest shelf, central basin platform, and western basin margin with local perturbations to the regional trend occurring due to the relative position of the basin to the bounding paleo-highs (Figure 2). Sediment sourcing within this study area is dominantly from the north-northwest.

The early and middle Permian sediments of the Wolfcamp, Bone Spring, and Avalon Formations are mostly deposited by sediment gravity flows that formed deep-water fan systems with

[1] Devon Energy | [2] SeismicCity Inc
[*] Corresponding author, E-mail: David.Langton@dvn.vom
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| System | Period | Series | Formation |
|---|---|---|---|
| Permian | Ochoan | Dewey Lake | |
| | | Rustler | |
| | | Salado | |
| | | Castille | |
| | Guadalupian | Delaware Mountain Group | Bell Canyon |
| | | | Cherry Canyon |
| | | | Brushy Canyon |
| | Leonardian | Avalon/Leonard | |
| | | 1st Bone Spring | |
| | | 2nd Bone Spring | |
| | | 3rd Bone Spring | |
| | Wolfcampian | Wolfcamp | |
| Pennsylvanian | Pennsylvanian | Pennsylvanian | Cisco |
| | | | Canyon |
| | | | Strawn |
| | | | Atoka |
| | | | Morrow |

**Figure 1** Stratigraphic Column of the Delaware Basin's Pennsylvanian through Permian Sediments.

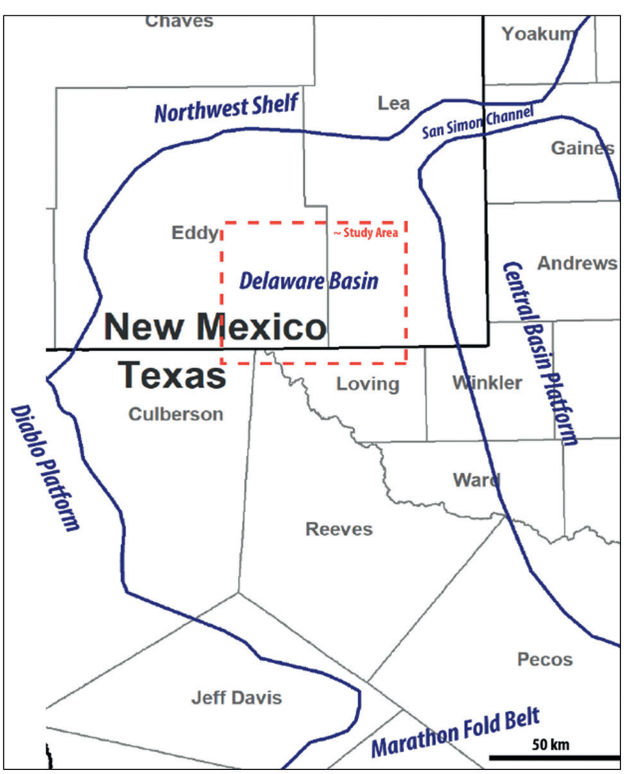


**Figure 2** Simplified map of major tectonic features defining the lateral limits of the Delaware Basin of southeast New Mexico and West Texas. The approximate study area is located within the red rectangular area.

complex interfingering relationships and lateral facies changes where fan lobes intermix. Subsequent remobilization of sediments in mass transport complexes locally complicates mapping efforts. The Avalon Formation is overlain by the Brushy, Bell and Cherry Canyon Formations of the Delaware Mountain Group, the latter two being contemporaneous with the deposition of the late Permian, Guadalupian Capitan Reef Formation. Deposition of the Capitan Reef was followed by the restriction of the basin to the global ocean during the Ochoan, that along with arid conditions and limited riverine input, resulted in increased salinity and the gradual evaporation of the cratonic sea (Forney, 1975; Ross and Ross, 1987). This period of evaporation deposited >1700 m of evaporites within the Castile, Salado, Rustler, and Dewey Lake Formations (Lucas, 2006a, 2006b). Subsequent dissolution of these sediments due to exposures to atmospheric water from near the time of deposition in the Permian to present day have resulted in an extensively karsted terrain in the shallow sub-surface (Bachman, 1984). The Permian section is locally capped by Mesozoic sediments and Quaternary alluvium.

### *Stratigraphic complications for imaging*

Permian sediments within the Delaware Basin have traditionally been difficult to coherently and consistently image by 3D seismic data. The imaging problems are a function of complexities both within the reservoir intervals that interpreters are tasked with characterizing as well as the overburden that juxtaposes high-velocity (6000 m/s) evaporites adjacent to low-velocity (3000 m/s) collapsed zones associated with karsting of the Ochoan formations within the near-surface. Historical imaging efforts struggle particularly below these 'collapse-zones' (Figure 3). These imaging issues propagate throughout the interpretation workflow and limit the types of geophysical analysis that interpreters can employ. Wells are difficult to synthetically tie to the seismic data, horizons are difficult to definitively track, and wavelets extracted for use in inversion have greater uncertainty leading to less accurate rock property prediction.

The deep-water gravity flows that dominate the sedimentation within the reservoir intervals of the Permian strata form thin beds in their most distal positions where current exploration and development efforts are centered. Seismic frequency content is limited in the data with nominal frequencies of 30 Hz within the zones of interest and high-velocity rocks (>4250 m/s). This combination of high-velocity rocks, low-frequency seismic data, and thin beds means what the geologic interpreters are most interested in is often below tuning thickness. Furthermore, post-depositional faulting of the Permian intervals, if present, is difficult to detect on historical datasets.

### *Processing objectives and challenges*

PSDM processing is done to produce the seismic data used in interpretation. The objectives of PSDM processing are multifold: to provide accurate, high-resolution vertical and lateral placement of reflectors with effects of overburden artefacts removed while preserving amplitudes and phase.

Improvements in vertical seismic resolution are necessary to resolve thin-bedded intervals, and improvements in lateral resolution are necessary to accurately delineate stratigraphic

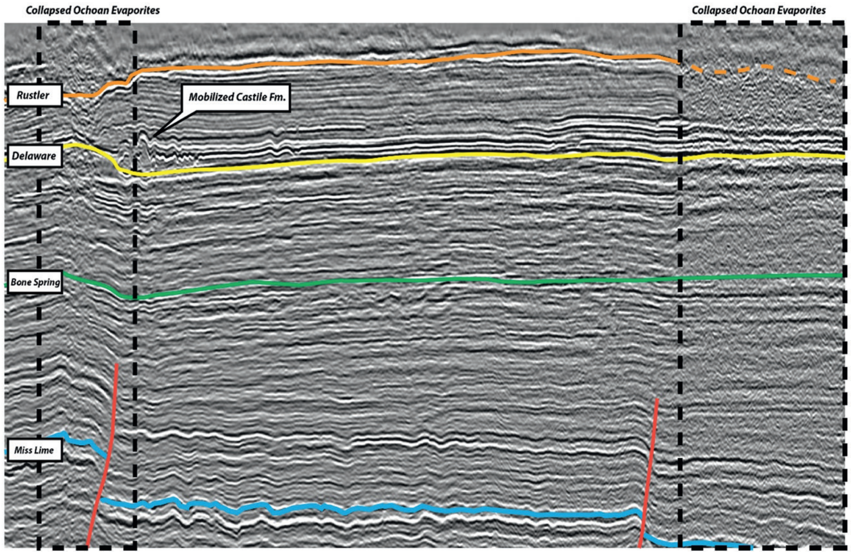


**Figure 3** Generalized cross section along an arbitrary seismic line that illustrates the near-surface, karsted, evaporite section complexities and their effects on deeper strata. The dashed rectangular regions define areas where surface and/or near-surface karsting have occurred. The coherence of the seismic data is significantly reduced beneath the collapsed Ochoan evaporites which masks changes in stratigraphy or subtle structures at the reservoir intervals between the Bone Spring and Mississippi Limestone.

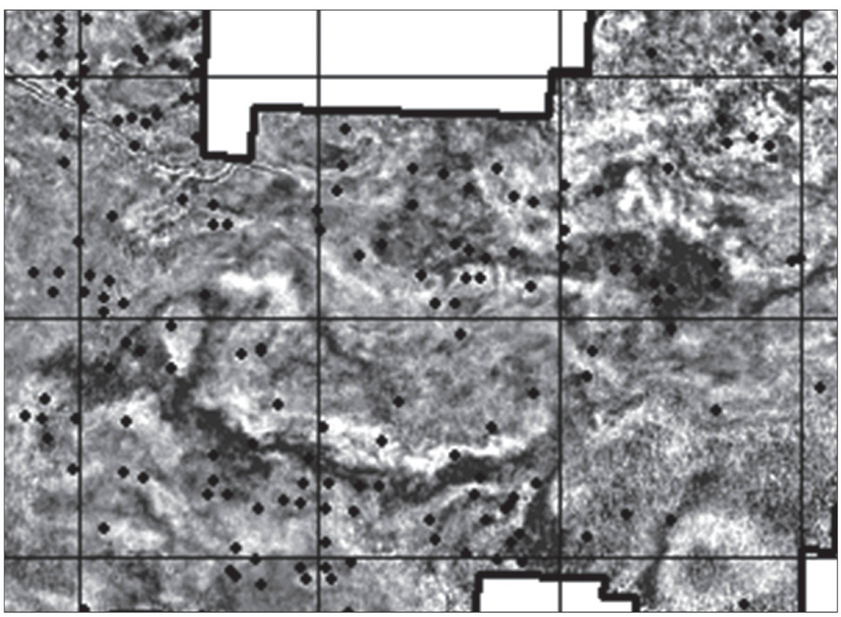

**Figure 4** Depth slice showing part of the project area. The survey size is more than 3400km$^2$. The bin size used in the processing is 25 m x 25 m. The total depth imaging depth is 9150 m.

changes and fault systems. A high level of certainty for the vertical placement of events in the PSDM is imperative as modern horizontal wells average ~3000 m in length and are geosteered with input from the seismic data in intervals that are often less than 20-m thick. Inaccurate placement of reflectors can lead to wells being drilled out of zone resulting in costly side-tracks or poor performance when brought on production.

Artefacts inherited from the shallow overburden need to be effectively removed. Finally, the seismic data needs to be processed to preserve relative amplitudes and phase as migrated gathers resulting from processing work are subsequently utilized in a prestack inversion workflow.

## Modern model building and depth imaging — Permian Basin

Wide azimuth seismic data covering part of Devon Energy's operational area was used as input in a recent model-building and depth-imaging project. This was done using modern anisotropic and depth imaging workflow and tools aimed at achieving both superior imaging as well as accurate time-to-depth conversion of the seismic data. Today, both seismic data and well data are used for construction of the anisotropic model. The input seismic data for the project consisted of pre-processed and interpolated gathers. The project was divided into two parts, a larger eastern part and a smaller western part. Each part was processed separately and towards the end of the project the two models were merged. The final PSDM was done using both surveys merged into a single dataset (Figure 4).

Model building work started with the construction of an initial velocity model. The accuracy of the initial model is very important as it enables more accurate convergence of the final model. The initial model included the following parameterization: from datum to surface a replacement velocity of 3650 m/s was used. From the surface to the Rustler Formation a velocity model derived from the PSTM velocities was used. Between the Rustler and Delaware Formations a velocity model was constructed from sonic well logs. For the section between the Delaware and Mississippian Lime Formations a gradient function was derived

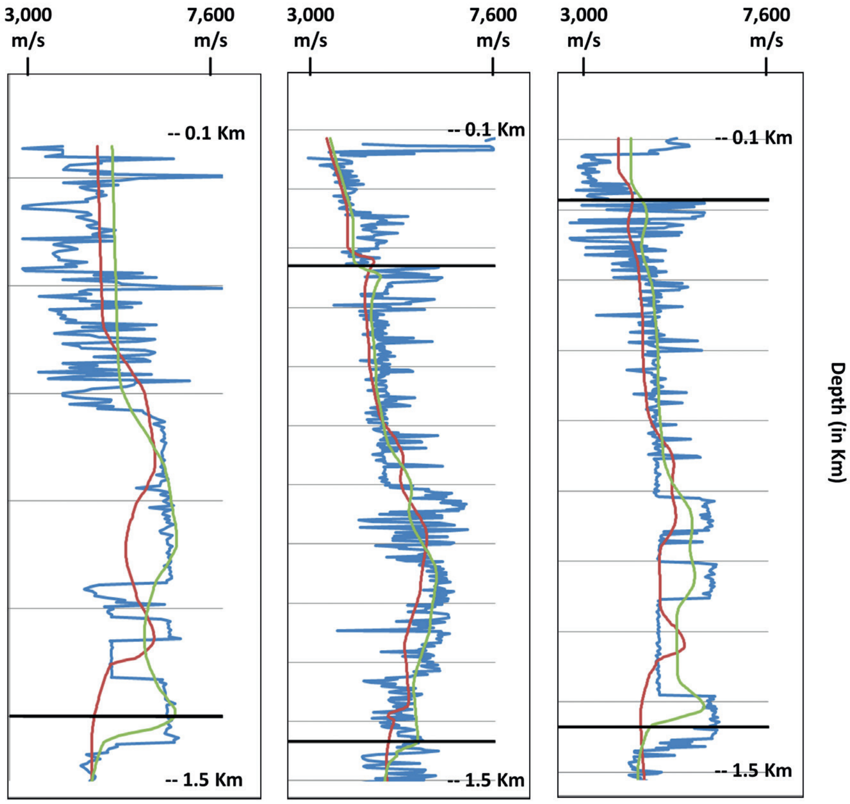


**Figure 5** A total of 345 wells were used to assist in the construction of the anisotropic model. Well data sonic logs were used for both construction of the initial model as well as constraint of the velocity updated using reflection tomography. Red and green curves show convergence of the velocity model.

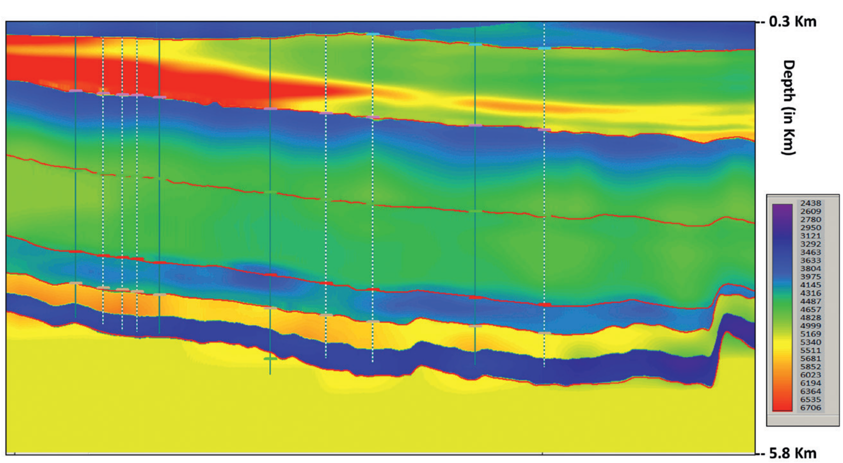


**Figure 6** Velocity model. The shallow section includes both salt as well as fill zones.

from deep sonic well logs, and finally from the Mississippian Lime to total depth a constant velocity of 4100 m/s was used. The initial model was updated using iterations of full volume PSDM by a tomographic update of the model. The velocity updates were constrained using the available well data (Figure 5). Having a stable velocity field, the anisotropic fields were added and updated using reflection tomography. Using the anisotropic field, the velocity field was updated again. Construction of the deeper section velocity model was guided by several key markers. Updates of the layered model were done using a tomographic update to achieve optimal stack as well as to best match well data. Optimization of the anisotropic field at each layer is done by both gather moveout-based tomographic inversion as well as mis-tie tomographic update. Mis-tie tomographic inversion works using depth differences between two horizons, one picked from well formation tops and the other picked from the PSDM data. To achieve the best solution, key horizons are reinterpreted using the PSDM volume. The anisotropic parts of the model (delta and epsilon) were updated simultaneously to incorporate the interpretation updates, model adjustment and velocity field optimization resulting from mis-tie tomographic update. This work involved repeated updates of the layer geometries to make sure the velocity correctly ties the data.

Having an anisotropic model that produced a satisfactory image we examined the guidelines for model building workflow. The objective of the model building process is to achieve the four following tasks: (1) to develop a PSDM velocity model that correlates closely with sonic log velocities, (2) to develop a PSDM velocity model that results in optimal tie of seismic data to well data, (3) to produce optimal PSDM imaging, and (4) to produce flat image gathers. In construction of the anisotropic model we found that the only way to achieve the above four goals (in the stated order) is to incorporate negative values to the anisotropic delta field in the shallow section. Review of published material about the anisotropic field confirmed that in certain geological settings, negative delta is a documented property (Wang et al., 2018). This methodology was therefore incorporated in the anisotropic model. Figures 6, 7, and 8 show the velocity, delta and epsilon models constructed in model building of the presented dataset.

Completing the model building, the final full volume PSDM run was executed (Figure 9). The algorithm used for the final PSDM run is an anisotropic Kirchhoff summation algorithm based on the wavefront reconstruction method for calculation of travel times. With use of a small depth sample interval (4.5 m), the output PSDM volume consists of high-fidelity details and matches all provided well formation tops.

## The move to Full Elastic Depth Imaging

### *Elastic Reverse Time Migration PSDM*

Until recently, most seismic data processing has been carried out under the acoustic assumption. Accordingly, the layers of earth are considered as fluids without resistance to shear tractions. Although obviously this description does not represent the rheology of the earth properly, it correctly predicts the arrival time of the primary P-waves and gives an estimate of the amplitude decay due to geometrical spreading. Consequently, despite the wrong physics, seismic data processing to date has been very successful.

A rheological model which better matches the response of the earth is an anisotropic elastic solid. The model correctly predicts the generation of shear waves in addition to the P waves. Operating under the elastic assumption enables the extraction of more useful information from the seismic data. The shear arrivals which seldom have been used contain additional information about the subsurface material properties. Imaging can be carried out using pure shear arrivals of converted waves in addition to the currently used P-wave images.

Although the advantage of Full Elastic Data Processing is obvious, there are challenges in its implementation. Elastic Reverse Time Migration (ERTM) is based on a numerical solution of the equation of dynamic elasticity. For land datasets, the solution scheme needs to include the treatment of the free surface boundary condition on the earth's surface. There are also practical issues in implementing elastic solution schemes. A large number of spatial variables are required. For a realistic computation these variables do not necessarily fit within a single compute node memory and the problem needs to be split by domain decomposition. However, using optimized numerical schemes these algorithmic and optimization challenges are solved, enabling the move to full elastic imaging.

Elastic migration improves imaging and the determination of the subsurface material parameters. In this migration two types of waves are present, namely P-waves and S-waves which usually travel in different paths. As the subsurface is illuminated by both waves, in areas of poor illumination by one type of wave, there is

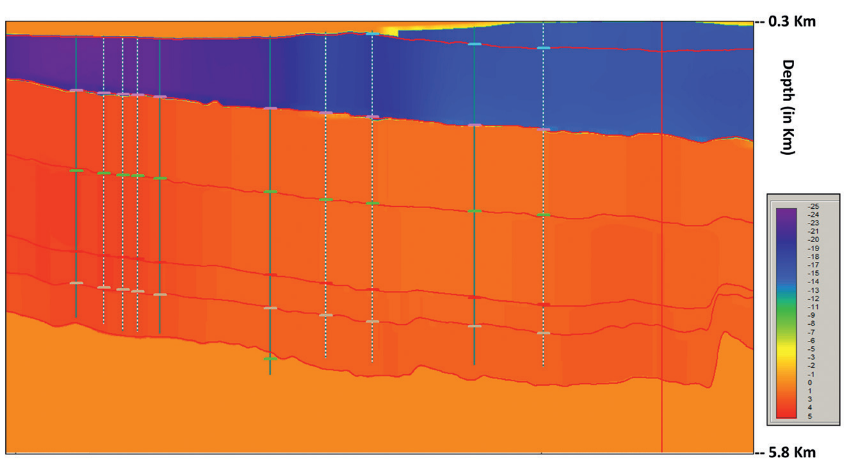


**Figure 7** Delta model. The delta model consists of values of about 3%. Delta values in the shallow section are in the order of -20%.

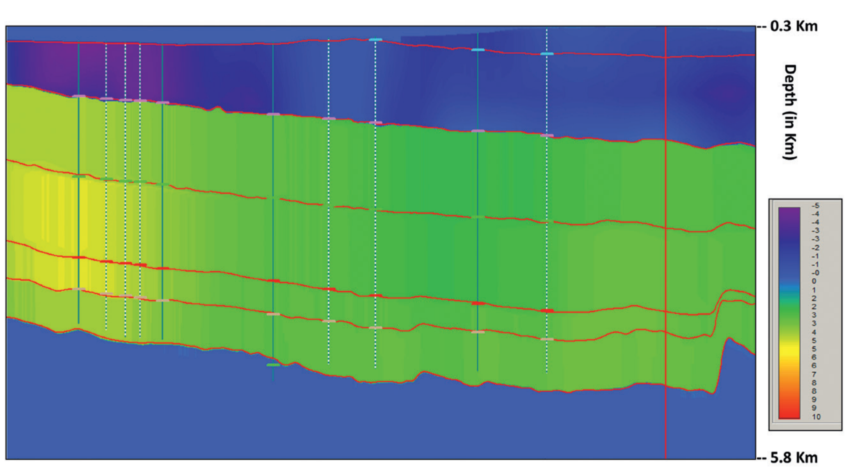


**Figure 8** Epsilon model. The epsilon model consists of values of about 5%. Epsilon values in the shallow section are around 0%.

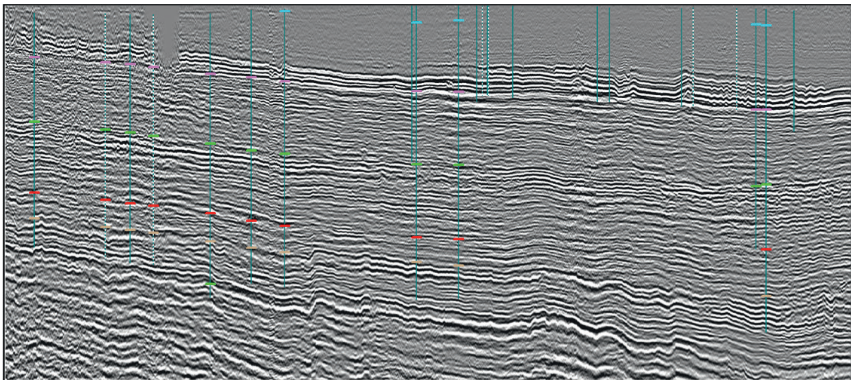

**Figure 9** Final anisotropic Kirchhoff summation PSDM. Depth sampling is 4.5 m. A total of seven full-volume PSDM runs were done for the construction of the layer-based anisotropic model and final PSDM imaging.

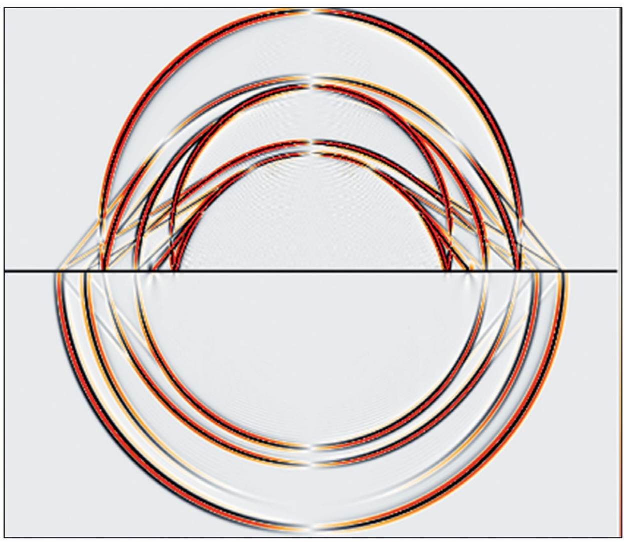

**Figure 10** Transmitted and reflected wave fronts crossing a material interface.

a chance of good illumination by the other type. In addition, shear waves travel with a velocity which is different from the P-wave velocity and thus its determination helps to resolve the subsurface material properties. Shear waves in general are more sensitive to anisotropy and a combined use of P- waves and S-waves enables tighter resolution of the anisotropic parameters.

When a propagating P-wave encounters a material interface, it creates four new waves, namely reflected and transmitted P-waves and reflected and transmitted converted S-waves (Figure 10). Similarly, a propagating S-wave will create transmitted and reflected S-waves and reflected and transmitted converted P-waves. The degree of conversion depends on the interface. An interface across which the velocity changes abruptly will create a high degree of conversion. Conversely an interface across which the velocity change is spread over an area will create less converted waves.

Elastic RTM (ERTM) migration is based on the same principle as acoustic RTM (ARTM) migration except that three displacement components are propagated instead of the single component pressure field. Unlike conventional ARTM there are more options to create migrated images such as correlations between modelled and back propagated displacement components. A more practical alternative is to extract from the displacement components P-wave and S-wave amplitudes and create the images PP, PS, SS, and SP respectively (Duan and Sava, 2010).

The advantages of elastic imaging in a marine salt environment were demonstrated in Jing et al. (2017). This can be extended to many other geological settings, both using marine data and land data. Mode conversions take place at interfaces that consist of changes in material properties. Shear waves are normally slower than the pressure waves and will appear on migrated PSDM gathers as events that were propagating in much slower velocity. We commonly identify these 'slow events' as multiples. However, these events can be converted waves that were propagated at slower S velocity. Therefore, use of elastic PSDM enables us to correctly migrate both the faster propagating P-waves as well as the slower propagating S-waves. Use of both the P and S waves will result in a more detailed image as well as increased resolution of the migrated PSDM data.

### *Elastic RTM PSDM of Permian Basin dataset*

ERTM PSDM was added to the depth imaging project of the Permian basin dataset described above. Analysis of image gathers resulting from application of acoustic PSDM showed that although most of the events are flat, additional events travelling in lower velocity are present in the data. These events could be either inner bed multiples or alternatively converted waves created at layer boundaries. Application of ERTM PSDM was carried out based on a correlation of P wave events both from the shot field and the downward continued field. A constant Vs/Vp ratio of 0.6 was used for the ERTM. The resulting ERTM PSDM image (shown in Figure 11) reveals many more details of the subsurface geology than the image resulting from Kirchhoff summation PSDM (Figure 12).

### *Optimization of the shear-wave velocity model*

The ERTM stack displayed in Figure 11 was imaged using a constant ratio between P-wave and S-wave velocities. This provides an adequate approximation at the reservoir for a first pass imaging, but optimal imaging of both P-waves and S-waves requires a more detailed shear-wave velocity model. To achieve this, several data sources are utilized, and these include shear sonic logs, inverted Vp/Vs data, VSP data and move-out characteristics from the pre-stack PSDM gathers themselves. Unfortunately, sonic logs and inverted Vp/Vs data is generally limited to the reservoir interval and little information outside of the seismic data is available to aid in the characterization of the shallow S-wave velocities (Figure 13).VSP data can fill in some of the shallow velocity information if a good down-going shear-wave is present due to a shallow conversion or if a shear-wave surface source was utilized. The move to full Elastic imaging enables us to use the seismic migrated data to define the Vp/Vs ratio in the entire section and with this directly link imaging results to evaluation of rock properties normally done as part of inversion processing. Moreover, the recorded components of a multi-component survey (Figure 14) can be directly inputted to ERTM PSDM enabling the use of all recorded components in depth imaging. Using Elastic imaging, we can create the data needed for velocity and anisotropy estimation of both the P-waves and S-waves to improve the model-building workflow and PSDM imaging.

## Summary

The US Permian basin presents both opportunities and challenges and is one of the most prolific basins in the world with significant oil and gas production and reserves. Establishing successful and long-term production is dependent on a coherent understanding of the subsurface and geophysical interpretations added to the geologic model are not simple as the seismic data used for structural and stratigraphic interpretation is very difficult to work with. The main reason is an exceptionally complex shallow geological setting. We address these difficulties by incorporating the most advanced seismic processing tools

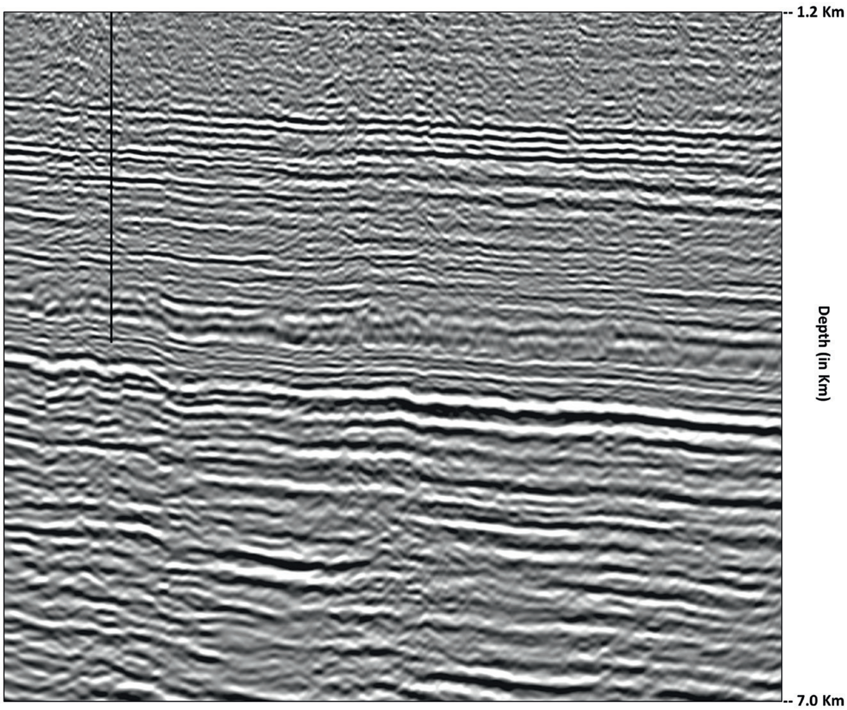


**Figure 11** ERTM PSDM. The maximum frequency for the Elastic PSDM was 45 Hz.

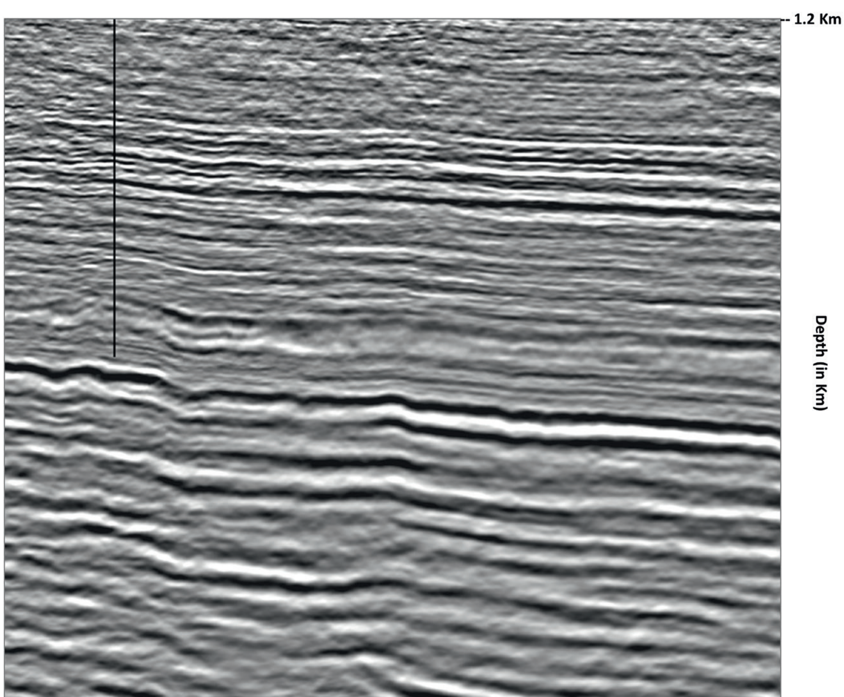


**Figure 12** Kirchhoff summation Acoustic PSDM.

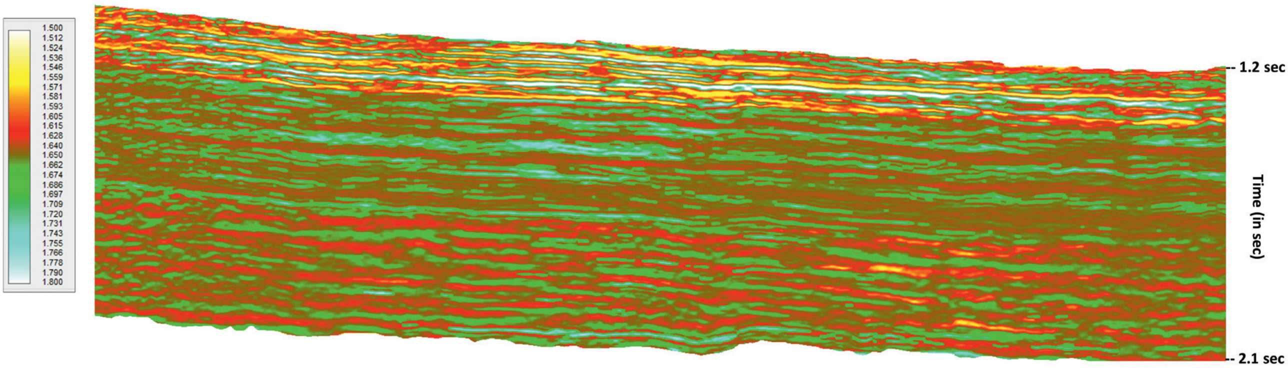


**Figure 13** Vp/Vs ratio field generated at the reservoir level.

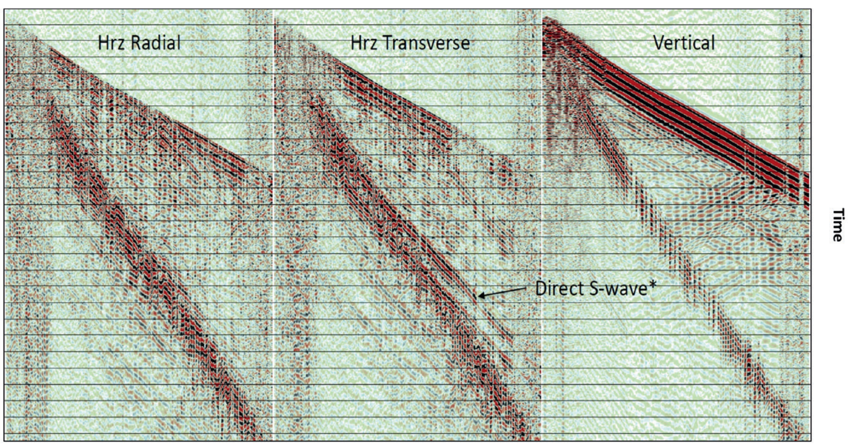


**Figure 14** Multi-component data. Radial, transverse and vertical recorded wave fields. We can identify direct down-going shear energy generated from a shallow conversion point. ERTM PSDM is capable of imaging both the P waves as well as the S waves.

and workflows, with depth imaging as the leading processing technology. This involves construction of detailed, layer based, anisotropic models that will result with both optimal imaging as well as correct time to depth conversion. However**,** the combination of high-velocity rocks, low-frequency seismic data, and thin beds means that the resolution needed is often below tuning thickness. More than that, faulting that is present in the basin is difficult to detect.

A solution to these imaging and interpretation difficulties can be achieved by use of the total wavefield, meaning both P-waves and S-waves, in seismic pre-processing and depth imaging. This can be done by use of the full Elastic wave equation as the basis to PSDM. Improvements in computer hardware and development of new numerical algorithms enable the use of Elastic RTM (ERTM) PSDM as the basis to depth imaging. In the work presented here, we demonstrated the application of full Elastic imaging to a dataset recorded in the Permian basin. Use of shear waves together with pressure waves resulted in much greater resolution of the PSDM volume, enabling better and more accurate interpretation and mapping of the key geological markers. Additionally, the ERTM PSDM volume revealed faulting that is key for optimization of the drilling paths.

The work presented here demonstrates only the beginning of full Elastic imaging. Generating new types of imaging products such as S-waves PSDM volumes will enable us to more accurately construct the S velocity models needed for ERTM and this will result in more accurate imaging. Construction of S velocity models alongside with P velocity models is linking imaging work to inversion work and will enable the improvement of computation of rock properties. In the past few years Acoustic RTM PSDM became the leading PSDM algorithm used in the industry. With the advantages of full Elastic imaging we expect the use of Elastic RTM PSDM to become the new standard of depth imaging technology.

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