

Elastic Velocity Models of A Stratigraphically Complex Carbonate Reservoir, Midland Basin, West Texas, USA

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Abstract

Crosswell seismic survey having resolution ten-times the resolution of surface seismic data was conducted in a section of midland basin across two existing wells. The aim of the study was to reveal the full geometry and the internal features of the carbonate reservoir. Surface seismic survey previously conducted in the area has insufficient resolution to reveal the geometry and internal features of the reservoir. The crosswell data were processed for P and S waves travel-time. A finite frequency based optimized velocity inversion method (OVIM) was applied to image the velocity structure of the carbonate reservoir after validating OVIM using synthetic geological model of 'Rainbow' Field. Results of the synthetic study gave high resolution complex velocity model showing horizontal beds and a vertical fracture that are similar to the true model. The P and S velocity tomograms inverted for the carbonate reservoir show consistent structures that correlate with the logs from the two wells in the area. The velocity tomograms identified the reservoir interval as a low velocity structure adjacent to and overlain by high velocity tight siliciclastic units. The reservoir was delineated as a ~70 m thick stratigraphic trap. The observations in the inverted velocity image were supported by the velocity log from well B. Interpretation of the velocity tomograms shows that the main pay zone is about 32 m thick extending laterally from well B to the mid-point between wells B and A.

Keyword: Surface Seismic Survey; Crosswell Seismic Data; Seismic Velocity Tomography; Carbonate Reservoirs; Midland Basin.

Introduction

Three-dimensional (3D)-surface seismic data acquired in the Midland Basin of west Texas, United States revealed a carbonate reservoir in the Wolfcamp Formation. The reservoir section was identified by subtle amplitude and travel-time anomalies. Because surface seismic data has characteristic long wavelength due to low frequency, the shortest wavelength in the 3D data (~60 m) could not illuminate the internal architecture of the ~70m thick reservoir (Langan *et al.*, 1997). To understand the stratigraphic-structural relationship of the reservoir and its adjacent units and to plan oil production, high resolution crosswell seismic survey (having frequencies ten-times greater than those of the surface seismic data) was conducted between two wells, namely wells A and B, present in the area. The two wells are separated by a distance of about 640 ft (194 m).

Using the seismic data acquired across the two wells, this study applies the techniques of seismic velocity tomography to construct P-wave and S-wave velocity images of the rock volume between the two wells. Crosswell velocity tomography has been used to provide high resolution structural and stratigraphic features of hydrocarbon reservoirs around the world (Harris *et al.*, 1995; Lee *et al.*, 1995; Lazaratos *et al.*, 1995; Langan *et al.*, 1997; Lazaratos and Marion, 1997; Zhu and Harris, 2015; Raji *et al.*, 2016) and the results

have been found to be consistent with well logs and core measurements, thereby providing useful information for reservoir characterization and oil production. Harris *et al.* (1995) used high resolution velocity tomography to provide the missing low frequency bandwidth that illuminates dipping beds beneath unconformity in San Andres Formation, McElroy Field. In addition to its higher resolution than surface seismic images, crosswell velocity image has higher volumetric coverage than the well logs and core measurements (Rector *et al.*, 1995; Langan *et al.*, 1997; and Pereira and Jone, 2010). Crosswell data can provide the missing information at unique scales between surface seismic data and well logs/core data.

Seismic velocity tomography is the process of building an image of velocity distribution of a section of the earth using travel-time or amplitude information in the seismic data (Bishop *et al.*, 1985). It is an inversion process and the inverted velocity model is commonly known as velocity tomogram, velocity image, or velocity map. Crosswell velocity tomography is reliable for studying lithology heterogeneities in stratigraphically complex areas where the desired geological information extends beyond the wells. Velocity signatures can be adapted for reservoir quality: high velocity often correlates to low porosity and low saturation, while low velocity is often correlated to high porosity and high saturation. Velocity perturbations

primarily associated with large-scale heterogeneities can be related to porosity and permeability (Mathisen *et al.*, 1995; Harris *et al.*, 1995). If the appropriate transformation is known from petrophysics (Nolen-Hoeksema *et al.*, 1995), velocity variation can be used to estimate reservoir quality. Crosswell acquisition allows placement of sources and receivers near the target layers, its velocity image offers superior stratigraphic image of the subsurface than the velocity image from surface seismic survey due to attenuation or Q-absorption (Raji and Rietbrock, 2013; Raji *et al.*, 2014).

Velocity modeling of rocks is commonly done by two methods: (i) waveform tomography and (ii) travel-time tomography. In waveform tomography, amplitude or phase (dynamic) information is used to construct the velocity image of the area or lithology under study. In travel-time tomography, the arrival time or depth (kinematic) information is used to build the velocity image of the area or lithology of interest. The method applied in this study uses travel-time data, ray tracing technique, crosswell transmission time (Bishop *et al.*, 1985; Pratt *et al.*, 1996) and some geological constraints (Hardy, 2003; Clap *et al.*, 2004) to build P-wave and S-wave velocity models of a producing reservoir. Because the data is from the U.S. distance and velocity are given in ft and ft/s respectively. Where necessary, the SI unit equivalence is provided. The aim of the study is to reveal

the structural-stratigraphic features around the reservoirs, and to delineate the lateral and vertical extent of the reservoir unit. The inability of the 3D data, previously acquired in the area, to resolve the reservoir interval necessitated the acquisition of crosswell seismic data and the application of crosswell tomography.

Geology of the Study Area

The study area is within the Midland Basin Section of the Permian Basin— West Texas, U.S.A. The Permian Basin extends from west Texas to the Southeast New Mexico. The two sub-basins of the Permian Basin are Midland and Delaware Basins (Fig. 1a). The Permian Basin of west Texas has about 54 reservoirs and it is the largest onshore oil-producing region in the United States, accounting for about 18% of the U.S. crude oil, and 23% of the U. S. National Oil Reserve (Dutton *et al.*, 2005). Oil production in the Midland Basin is primarily from the Permian Shale Reservoirs— The Wolfcamp Formation (Ward *et al.*, 1986; Harris and walker, 1988). Wolfcamp formation is present in the Midland and Delaware Basins (Fig. 1a) and is of Permian age, but those of the Delaware Basin are known to be younger. Wolfcamp Formation of the Midland Basin is generally a two-lithology based system of shale and limestone (Ball, 1995). Porosity and pressure around the

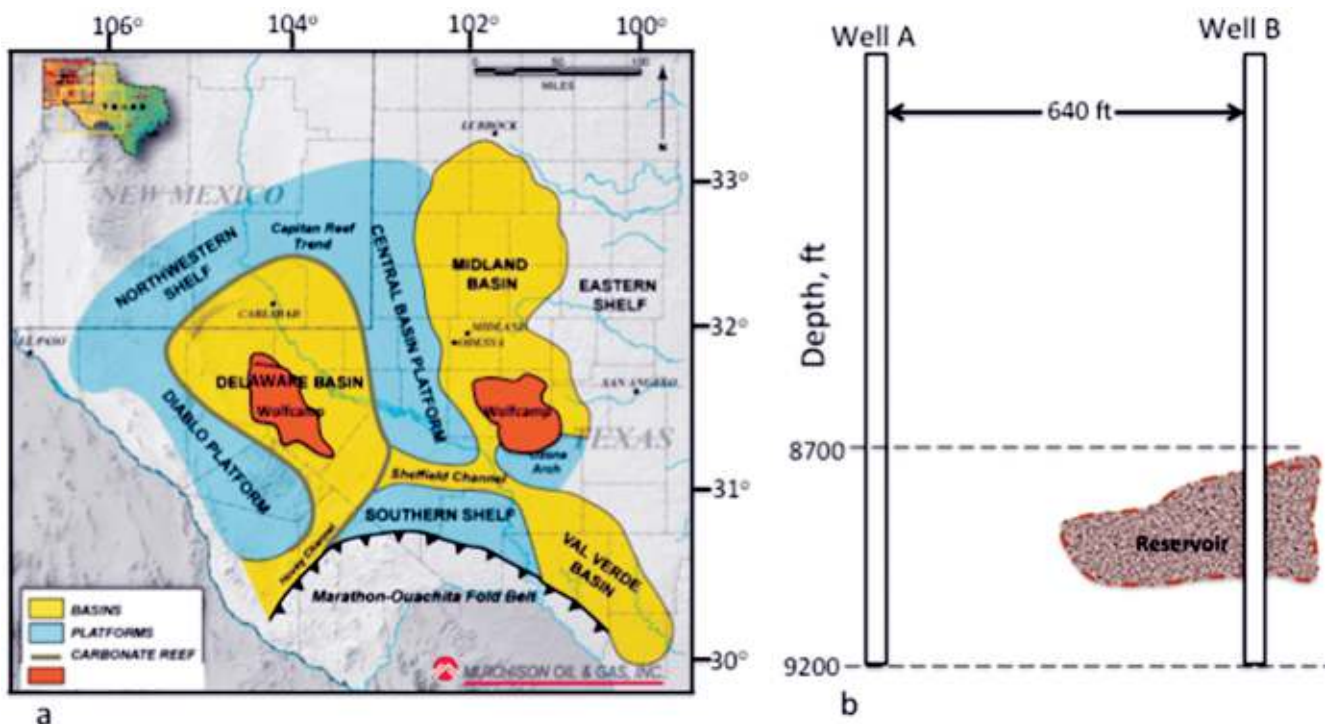


Fig. 1: (a) The Permian Basin of West Texas U.S. (Google) (b) Schematic image of the crosswell and the carbonate reservoir under study.

reservoir range from 4 – 12% and 0.60-0.70 PSI, respectively. Permeability is very low but enhanced by the abundant natural fractures. The reservoirs are composed of highly cyclic shallow-water carbonate facies that are variably overprinted by diagenesis that took place at and below the cycle tops during sea-level fall events. Although reservoirs developed in Wolfcamp platform carbonates are commonly referred to as reefs because of their geometries, recent studies have illustrated that many of the reservoirs are composed of cyclic deposits of interbedded skeletal and ooid-bearing grainstones and organic-rich wackestones and packstones (Tyler and Banta, 1989; Ball, 1995). Wolfcamp Shale of Midland Basin is a part of “Wolfberry” play that encompasses Mississippian, Pennsylvanian, and Lower Permian reservoirs (Dutton *et al.*, 2004). Continuous oil and gas is dispersed throughout a geologic formation rather than existing as discrete localized occurrences, such as those in conventional accumulations.

Methodology

Data Acquisition

High resolution crosswell survey was conducted by Chevron in early 1990s. Crosswell seismic data was acquired across two wells (here known as well A and well B) in the area using 201 piezoelectric cylinder sources and 203 hydrophone receivers deployed in well A and well B respectively at depth level of 8200 - 9200 ft (~2500 – 2800 m). Well B penetrated the shale reservoir at about 8700 ft (~2637 m) while well A missed the reservoir (Fig. 1b). The two wells are separated by 640 ft (~194 m). The source and receivers are uniformly spaced by 5 ft (1.5 m). The acquisition resulted in over 40,000 seismic traces of length 200 milliseconds, each with sample interval of 0.25 ms. Wireline logs show that the carbonate has higher reservoir quality and lower velocity compared to the units adjacent and above it, but the 3D surface seismic data has insufficient resolution to reveal the internal features of the reservoir. The inability of the 3D data to resolve the reservoir interval necessitated the acquisition of crosswell seismic data. The frequency bandwidth of the crosswell data ranges from 250Hz to 2000Hz. The data was correlated and edited in the field (Langna *et al.*, 1997). The quality of the crosswell data is generally good allowing clear observation of the different seismic arrivals.

Velocity Imaging process

The velocity structure of the carbonate reservoir and its

surrounding was constructed using travel-time tomography. Travel-time tomography is a seismic inversion technique where the velocity along the ray path is inverted from travel-time data (Lazaratos *et al.*, 1995). The mathematical relationship between the travel-time, t and velocity, v can be described as:

$$t = \int_R S(x, z) dl \dots\dots\dots (I)$$

Where slowness S is the inverse of velocity, v ; and dl is the distance along ray path. R is the path along which integration is performed, x and z are the coordinates of S . If a geological model is discretized into matrix cells, the discrete representation of equation 1 can be written as shown in equation 2, where G_{ij} is the path length for i -th ray in j -th cell with slowness S_j ; where $i = 1, 2, 3, \dots, m$ and, $j = 1, 2, 3, \dots, n$.

$$t_i = \sum_m G_{ij} S_j \dots\dots\dots (II)$$

In reality, the mathematical description of velocity tomography is ill-posed. Quite the contrary, the relationship between measured data and the inherent geological model is non-linear. Several attempts to correct or circumvent the drawbacks in the mathematical formulation for seismic tomography in order to improve the quality of inverted velocity image are well published in the literature. Some examples of the relevant literature include Tikhonov and Arsenin (1977); Van de Made *et al.* (1984); Bishop *et al.* (1985); Sword (1986); Guiziou *et al.* (1990); Zelt and Barton (1998); Nocedal and Wright (1999); Bube and Langan (2008); Zhu and Harris (2015); Raji *et al.* (2016). To reduce inversion artifacts and improve the geological uniqueness of the inverted velocity structure of the area under study, the inversion technique is regularized (Tikhonov and Arsenin, 1977) using additional constraints (β) where β is defined as:

$$\beta(w) = \phi_d(w) + \lambda \phi_m(w) \dots\dots\dots (III)$$

where ϕ_d is the difference between the observed and predicted data, ϕ_m is a parameter that enforces the priori of the true shape and structure of the geological model; λ is the regularization parameter that checks the goodness of fit of the inverted data to the field data. ϕ_d and ϕ_m are defined (Tikhonov and Arsenin, 1977; Zhu and Harris, 2015) as:

$$\phi_d(w) = \frac{1}{2} \| Gw - t^{obs} \|_2^2 \dots\dots\dots (IV)$$

$$\phi_m(w) = \frac{1}{2} \| Ww \|_2^2$$

Gw is the predicted data, w is the data vector, and t^{obs} is the observed data. The term W may be chosen as the first and second order spatial derivative. The purpose of equation (3) was to introduce additional constraints that will enhance the uniqueness of the inversion result. ϕ_m is chosen based on the shape and structure – flatness or curvature of the true geological model (Raji *et al.*, 2016). The mathematical procedure is implemented as a finite difference algorithm written in C++ and operated in MATLAB environment.

At first, the appropriateness of the optimized velocity inversion method was tested with synthetic data of the Rainbow Field. The synthetic geological model consists of low velocity horizontal geological units of varying thicknesses and a vertical fault bounding a high velocity mound. The choice of this model was informed by its stratigraphic-structural complexity, especially at depth 300–400 m (Fig. 2a). Sharp lateral and vertical contrast in velocity has been a source of challenge for some velocity imaging algorithms, and it will be a good test for the optimized inversion method discussed above. The travel-time map (Fig. 2b) was computed by Eikonal solver using the fast marching method (Sethian & Popovici, 1999). The inversion is set up for 10 iterations. The results are presented and discussed in the next session. Subsequently, OVIM was applied to image the carbonate reservoir of Wolfcamp Formation. The

picked travel-times are shown on the field seismograms in Figs. 3a and 3b. The maps of the picked travel-time for the full survey are plotted against the source and receiver depths in Figs. 3c and 3d. The starting/initial velocity models for the forward modeling is a constant (1D) velocity computed from the respective logs; velocity logs were computed from sonic logs and the starting models were computed as the mathematical means of the respective velocity logs. The computation mesh consisted of 133 by 208 cells. Each cell was 5 by 5 ft (1.5 by 1.5 m); the source wavelet was a 200Hz Ricker wavelet.

Results and Discussion

For the synthetic test, the inverted velocity tomogram using the optimized inversion method (Fig. 2d) matches the true velocity model (Fig. 2a) and show higher vertical and lateral resolution than the velocity tomogram inverted by the conventional tomography method (Fig. 2c). Figure 2d presents focused image along the faultline unlike in Figure 2c where the fracture image is blurred. Overall, the inverted velocity tomogram matches the true geological models. The result of the synthetic test confirms the appropriateness of OVIM for imaging velocity of complex geological structures.

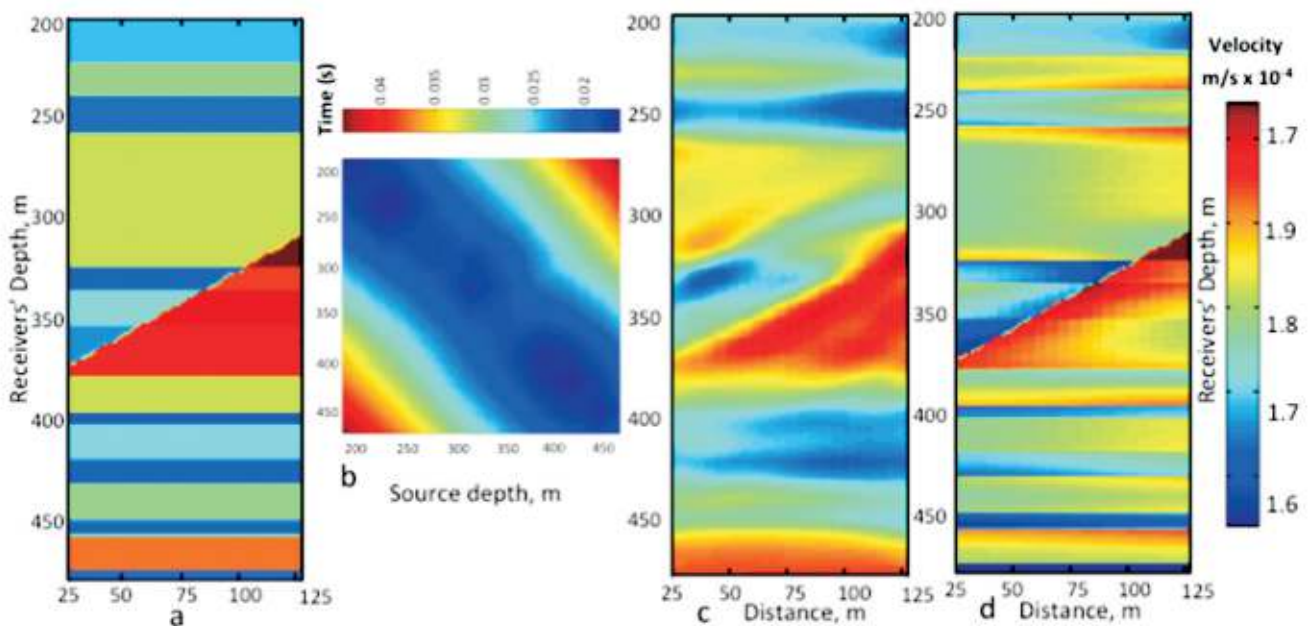


Fig. 2: Velocity tomograms and travel-time map.

- (a) True velocity model of 'rainbow' field,
- (b) travel-time data computed by Eikonal solver,
- (c) inverted velocity model of rainbow field using conventional tomography method, and
- (d) inverted velocity model of rainbow field using OVIM.

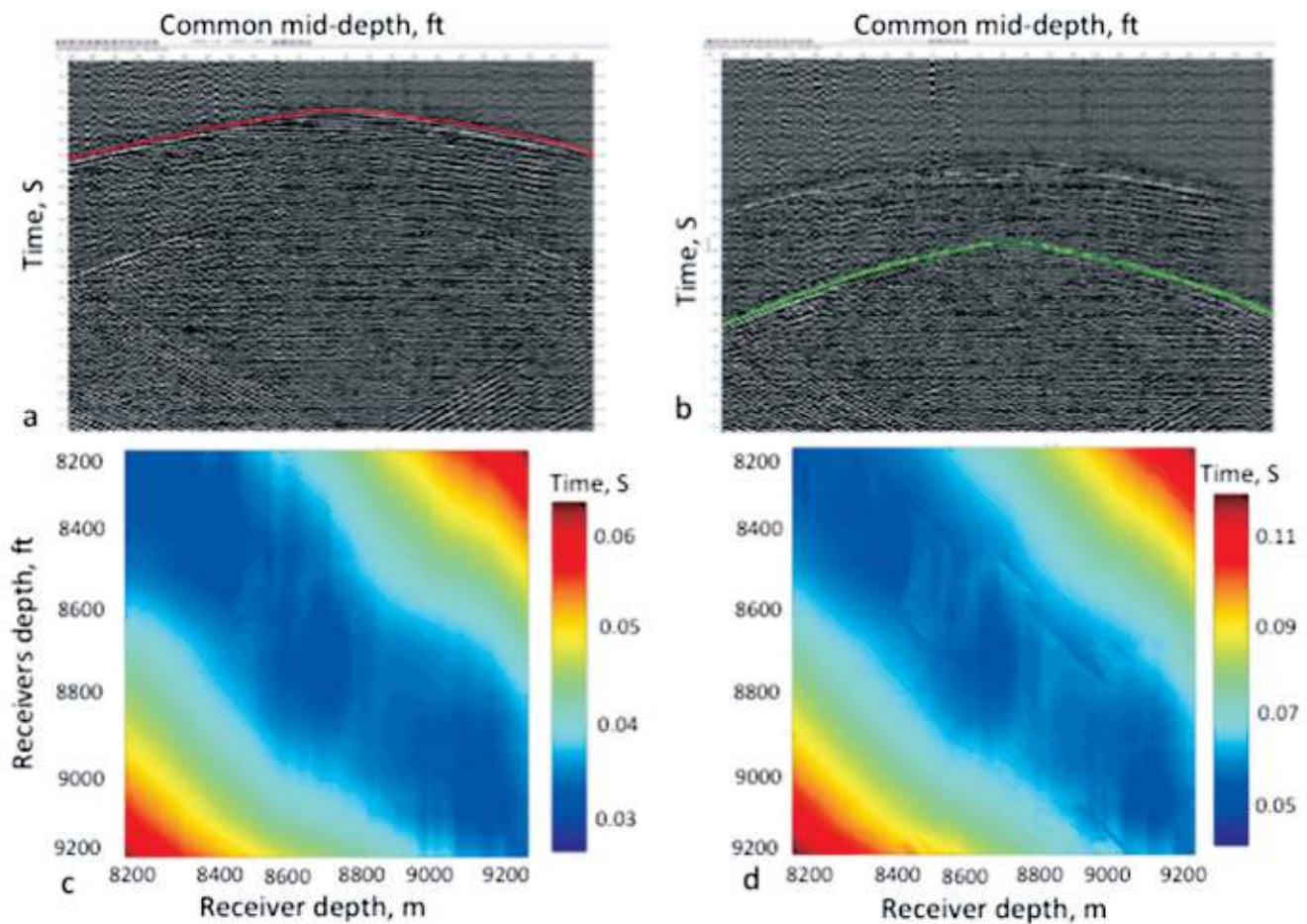


Fig. 3: Sample seismogram and travel-time maps. (a) Common mid-depth # 107 with P-wave time picks shown in red, (b) Common mid-depth # 107 with S-wave time picks shown in green, (c) P-wave travel-time map for the full survey, and (d) S-wave travel-time map for the full survey.

For the Wolfcamp reservoir case, the inverted P-wave and S-wave velocity tomograms (Figs. 4a & 4b) show striking similarities, with minor misfits, revealing detail stratigraphic geometry of the reservoir and its neighboring lithological units. These details were not achievable in surface seismic data due to insufficient resolution (Langanet et al., 1997). The inverted P-velocity tomogram is plotted with the velocity logs from wells A and B in Fig. 5a. The tomogram shows consistencies with the velocity logs, and is able to illuminate the regions between the two wells – which is not visible to the well logs. The velocity values in the logs range from 12,000 to 22,000 ft/s (or 3656 to 6706 m/s) while the velocity value in the P-velocity tomogram range from 14,250 to 22,270 ft/s (4343 to 6788 m/s). The velocity logs from well B show low velocity at depth level 8700–8925 ft similar to what was revealed by the P-velocity tomogram (Fig 4a & 5a). The left side of P-velocity tomogram shows high velocity structures at depths intervals corresponding to 8200–8250 ft; 8420–8500 ft; 8600–8650 ft; 8670–8710 ft; and 9020–9120 ft.

These high velocity features are also present in the velocity log from well B at similar depths. On the left hand side of the velocity tomogram, a low velocity structure is located at depth level 9125–9175 ft. This low velocity structure is also seen in well A velocity log at similar depth.

The tomogram provides salient information on the reservoir geometry, which is important for reservoir characterization and well economics. Velocity signatures in the tomogram are classified into three: the low (14,000–17,000 ft/s); the high (20,000–22,000 ft/s); and the background velocity structure (> 17,000 < 20,000 ft/s). Velocity is interpreted for porosity and saturation: hydrocarbon reservoirs typically exhibit lower velocity, have higher porosity and saturation than the neighbouring lithological units. This is corroborated by the result shown in Fig. 5a from depth 8600 to 9100 ft. The low velocity structures between depth levels 8700 ft and 8900 ft in the tomogram is interpreted as the carbonate reservoir. Using well logs and geological

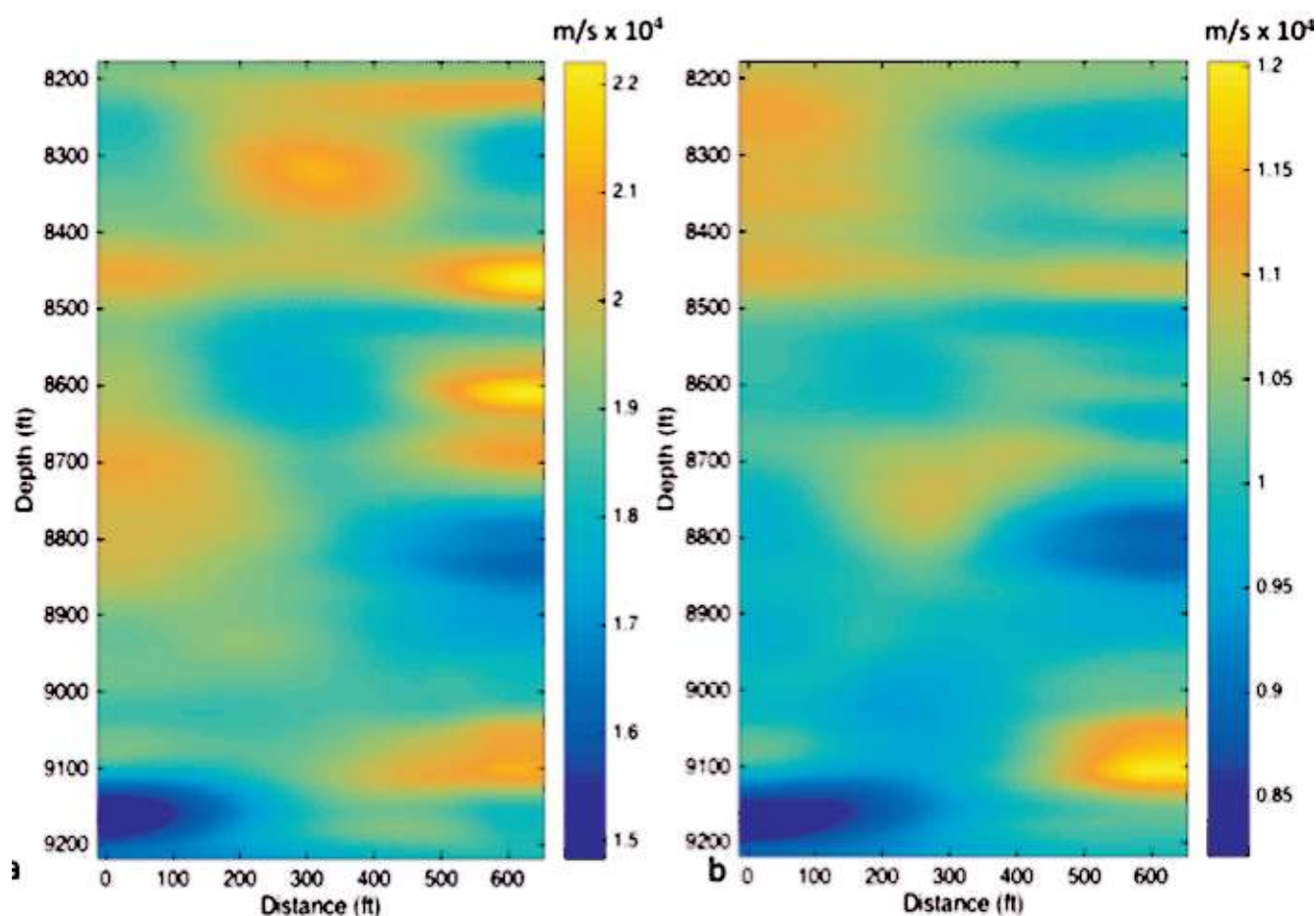


Fig. 4: Velocity Tomograms (or velocity structures) inverted for the carbonate reservoir and its surrounding.
(a) P-wave velocity structure, (b) S-wave velocity structure

information available in the literature (Broadhead, 1993; Dutton *et al.*, 2005), velocity based stratigraphic interpretation is attempted (Fig. 5b).

Interpretation of the velocity image (Fig. 5a) shows that the main pay zone is ~ 32 m (105 ft) thick. The reservoir zone shows velocity variation (deep blue top and light blue base) that is indicative of facie. Adjacent to the reservoir is a high velocity zone corresponding to siliciclastic units. These high velocity units often indicate low porosity. At the top of the reservoir units is another high velocity siliciclastic rock that serves as the cap rock. High velocity structures are prominent at shallower section of the velocity tomogram- extending from well B to A in some places. The velocity image and well A velocity logs show the presence of low velocity structure at depth levels 9100 – 9200 ft. This structure does not show amplitude anomalies in surface seismic data. Its interpretation would require additional set of data.

Conclusion

High resolution crosswell velocity tomogram of a section of Midland Basin was built using optimized velocity inversion method. The method utilizes an objective function that consists of two parts: a part that reduces the misfit between the observed and inverted data; and a part that incorporates the geological priori. The velocity structures inverted for the synthetic 'Rainbow' Field and midland basin reservoir show high resolution velocity images and plausible geological features that was validated by true geological model. The producing Wolfcamp carbonate reservoir is defined on P- and S-velocity tomograms as a low velocity structure surrounded by high velocity lithological units. The reservoir has a gross thickness of about 70 m and a pay zone of 32 m thick. The reservoir is located between depth interval 8700 – 8900 ft (2637 m and 2727 m) corresponding to the carbonate reservoir already identified by surface seismic data and confirmed by well logs. This low velocity region is absent in well A at

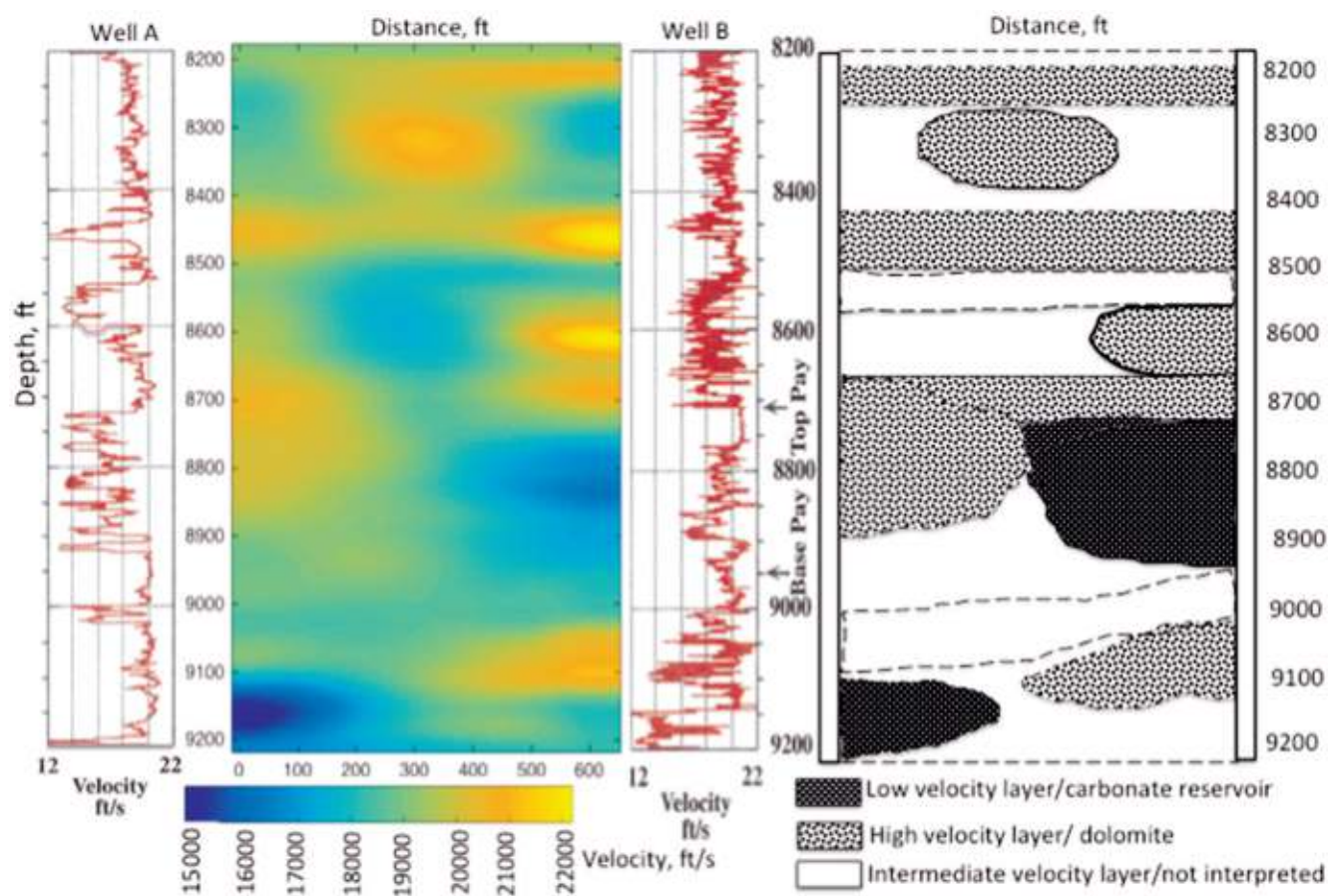


Fig. 5: (a) P-velocity tomogram plotted against velocity logs. (b) a schematic image of the stratigraphy based on velocity structure.

similar depth interval. The reservoir interval shows velocity variation indicating the presence of geological facies. The inverted velocity image is consistent with velocity logs from the two wells. The velocity tomogram shows the stratigraphic units surrounding the reservoir and the internal stratification around the reservoir. The velocity tomogram is able to illuminate areas that are not visible to well logs and therefore present a unique scale between the surface seismic data and well logs. The study demonstrates one of the many potentials of crosswell velocity tomogram to address reservoir delineation and characterisation problem.

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