

Resolving subtle structural relief with ultra-dense 3D seismic for the hydrogen storage at Devine site

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SUMMARY

Ultra-dense, compact 3D seismic data are interpreted to characterize the spatial distribution of target formation properties. Among the structure, thickness, and dip of the Olmos sandstone at the Devine test site, it is the structure that benefits the most from seismic data. The well log data indicate the presence of fine-scale structural features within the target, but sparse, discrete measurements are insufficient to reconstruct the structural variability of the target across the area. In contrast, dense and continuous seismic images of the subsurface enable mapping of the subtle low-relief (2-10 ft) features, which are important for constraining the geometry of the reservoir model for buoyancy-drive hydrogen migration. These results demonstrate that the imaging-interpretation seismic workflow can reliably resolve subtle low-relief structures despite the uncertainty in the velocity model used for pre-stack depth migration of land data. The presented interpretation illustrates practices for reservoir characterization of ultra-dense, compact 3D surveys with a lateral extent comparable to the target depth.

INTRODUCTION

Structural trapping is one of the primary mechanisms enabling aquifer storage of injected hydrogen, given its high buoyancy and mobility (Bonabi et al., 2025). The high sensitivity of the spatial extent of an updip tongue of the hydrogen plume just beneath the caprock to the geological dip of the storage reservoir was illustrated by modeling the buoyancy-driven migration of the hydrogen injected into an aquifer (Bakulin et al., 2025). Studies on hydrogen migration during injection and production cycles indicate that the grid size of the reservoir model is a key parameter that influences reservoir simulation results Alhotan et al. (2023). Thus, a detailed structural analysis of the target formation is needed to construct an accurate model of the reservoir geometry and to simulate the spatial and temporal evolution of the hydrogen plume.

The geological dip of the target formation, along with its thickness, geometry, and relief, can be obtained from well log data. Although well logs are not always suitable for characterizing the local geological settings of storage sites, as reservoir continuity and heterogeneity cannot be fully captured by well log data alone (Pawar et al., 2006). Therefore, the methods that continuously sample the subsurface are needed.

Continuous measurements of reservoir properties and geometry can be obtained from 3D seismic data. For geologic storage sites, compact 3D seismic surveys with lateral extents comparable to the target depth can be used. For example, for the carbon sequestration field test in the West Pearl Queen reservoir, New Mexico (Pawar et al., 2006), 3D seismic sur-

veys covering an area of $1,6 \times 1,6$ km around the injector and monitoring wells were used for time-lapse imaging of the target reservoir 12-m-thick at about 1,4 km depth. Another example is the Aquistore storage site located in Saskatchewan, Canada (White et al., 2015), where a sparse, permanent array of buried geophones was installed over an area of approximately 3×3 km to monitor the injection of CO₂ into a 200-m-thick reservoir at approximately 3,2 km depth. Interpreting such compact surveys can be difficult, as seismic data illuminate only a small area of the subsurface. Consequently, establishing interpretation practices for such compact seismic data is important for gaining a full understanding of imaged structures needed for an accurate model of the reservoir geometry.

We present the results of the structural interpretation of 3D surface seismic data acquired over the Devine site, Texas, for the reservoir characterization of the geologic hydrogen storage complex (Bakulin et al., 2025). The survey covers an area of about 650×650 m and targets the 17m-thick sandstone at about 500 m depth. The sensitivity analysis carried out using the imaging-interpretation workflow confirms the ability of seismic data to image low-relief features (Figure 1). These structural features are being considered for determining the placement of the injector well.

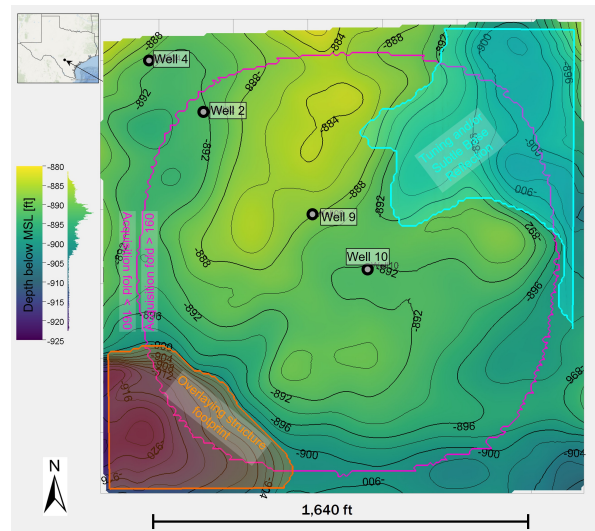


Figure 1: The structure map of Olmos, interpreted from 3D pre-stack depth-migrated data acquired at the Devine site, Medina County, Texas. The wells with log data are placed diagonally from the NW corner to the center of the site. The structure near the edges of the site is less constrained than that in the center due to the low acquisition fold. The orange and blue polygons outline the areas where the structure should be interpreted with caution. The low-relief (2-10 ft) structure and the saddle in the SW-to-NE direction across the site are identified as key structural features of the Olmos sandstone.

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RESERVOIR CHARACTERIZATION

Geological Settings

The study focuses on the Upper Cretaceous sandstone unit of the Olmos Formation, deposited in the eastern half of the Maverick Basin, South Texas (Tyler and Ambrose, 1985). A recent analysis of core data from the Big Foot field, located near the study area, indicates that the Olmos deposits are open-marine sand (Ambrose, 2025). The regional assessment of the Olmos sandstone estimates its geological dip to be less than 2 degrees in the NS direction and suggests a uniform sand distribution.

Well Log Data

At the Devine site, Medina County, the Olmos sandstone is 58 ft thick and at about 1,550 ft depth (Figure 2). Given log data from 4 wells strategically placed on the diagonal across the site (Figure 1), a saddle of at least 4 ft was identified for the structure of Olmos. This saddle suggests that small-scale patterns and structural features may occur in the study area.

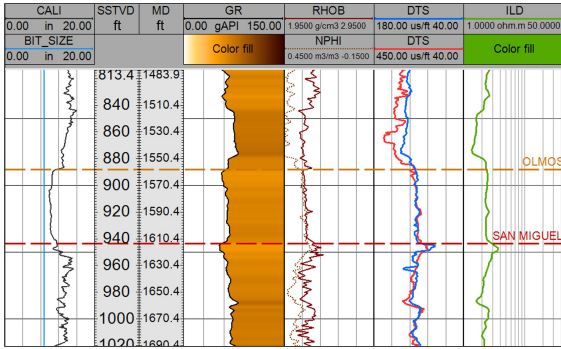


Figure 2: The log curves from well 9 for the target interval. The subsea true vertical depth (SSTVD) is used to label the depth axis in depth-migrated seismic data.

3D Depth-Migrated Seismic Data

The ultra-dense layout of sources (30.0×7.5 m) and receivers (7.5×7.5 m) deployed for acquiring surface seismic data yields an ultra-dense inline and crossline spacing of 3.75 m (12.3 ft) in the 3D seismic cube. Equipped with a 12.3 ft bin spacing, the subsurface between wells 9 and 10, spaced at about 330 ft, is sampled with about 27 points (Figure 1). The source frequency ranged from 2 to 110 Hz, sufficient to illuminate the subsurface with wavelengths of 250 ft or less, given the velocities from the log.

The acquired seismic data were processed using a standard time-domain processing workflow. The imaging was performed using a Kirchhoff pre-stack depth-migration algorithm with an aperture of about 330 ft, which was determined to be optimal for this survey configuration (Titova et al., 2026).

The depth-migrated data were interpreted in a subsurface interpretation software using a seismic-to-well tie for well 9 (Figure 3). The geological markers from other wells were overlain to verify the vertical geometry of the depth volume and assess the quality of depth-imaging of the subsurface strata. Overall, the formation tops of the shallow (Escondido) and deep (Austin) formations are close to their respective horizons.

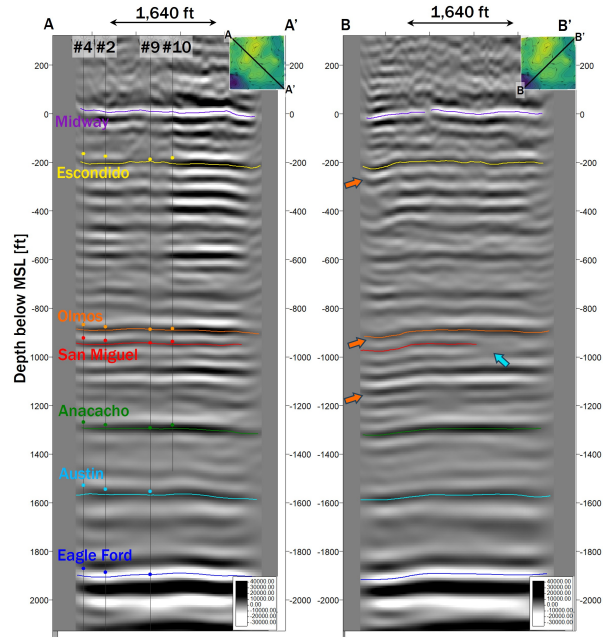


Figure 3: The interpreted seismic sections from the pre-stack depth-migrated volume in (a) NW-SE and (b) SW-NE directions. The geological markers for four wells are overlain as circles in panel (a). In panel (b), the orange arrows point to several horizons at different depths that exhibit a similar structural variation. The blue arrow points to the location where the San Miguel reflection is poorly observed. These observations were incorporated into the structure map of Olmos as blue and orange polygons.

The visual inspection of the depth cross-sections suggested that across the central portion of the survey, the Olmos and San Miguel are observed as two separate reflectors. To support this observation quantitatively, the depth-migrated data were transformed into the Fourier domain. Similarly to the frequency spectrum, which is commonly evaluated for the time-migrated data, the wavenumber spectrum of the depth-migrated data was calculated (Figure 4). The depth window for computing the spectrum was 160 ft long and was centered on the target horizon, Olmos. The dominant wavelength in the vertical direction of the seismic volume was estimated as 66 ft. Even if the wavelength of about 125 ft is considered, two reflectors 31 ft apart are resolved.

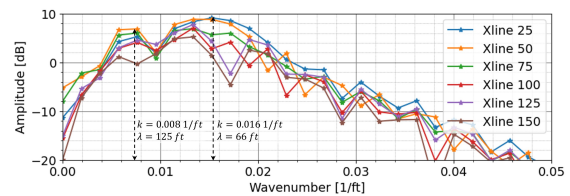


Figure 4: The wavenumber spectrum showing the wavelength composition of the depth-migrated seismic data along the vertical direction. The spectrum attains its maximum at about 0.016 ft^{-1} with the second peak at about 0.008 ft^{-1} . For both wavelengths of 66 ft and 125 ft, the Olmos thickness of about 60 ft is above the resolution limit of $\lambda/4$.

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The interpreted Olmos horizon is shown as a depth-structure map in Figure 1. The main structural features of Olmos are low-relief (1 ft to 5 ft) closures and the saddle in the SW-to-NE direction across the site. The dip of Olmos was calculated by as the steepest angle between the 3D surface and the horizontal plane. For structural closures in the center and toward the north-west, the dip does not exceed half a degree.

The isopach of Olmos in Figure 5 was derived by taking the difference between the depth-structure maps of Olmos and San Miguel. For the central part of the study area, the isopach is almost uniform and, on average, attains 58 ft. This value is comparable to the dominant wavelength in the vertical direction, and, thus, in this area, tuning is not considered a major factor affecting the structure of the target.

In the north-east direction, the isopach is thinning, and the thickness of Olmos decreases from 60 ft to about 20 ft. The tuning effects should be taken into account when interpreting the depth structure map shown in Figure 1. For instance, the structural high observed in the middle-right portion of the map can be rendered as a structural closure. However, given that the north side of this closure passes through a tuning area, the actual geometry of this structural feature may differ from the closure and, in general, can be difficult to constrain.

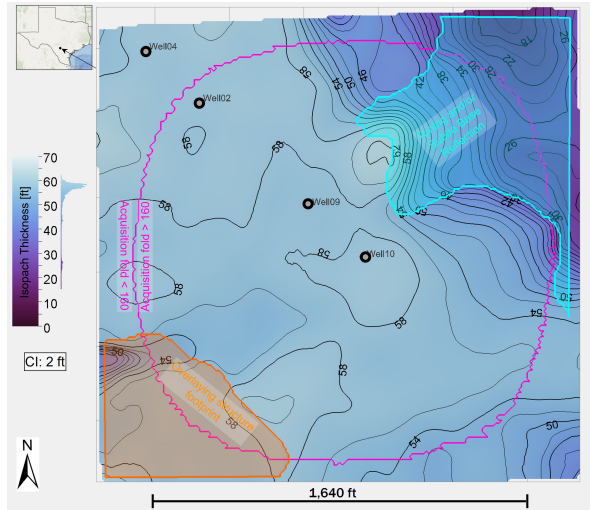


Figure 5: The isopach map of the Olmos sandstone as derived from the depth-migrated data in Figure 3. For the central part of the site, the calculated Olmos thickness is about 58 ft, consistent with the thickness estimated from the well log data. In the north-east section of the site, the thickness decreases.

Sensitivity Analysis of Seismic Structure

The robustness of the structural characteristics of Olmos, such as geometry, thickness, and dip, derived from seismic data was assessed using the imaging-interpretation workflow shown in Figure 6. It comprises standard steps such as depth migration and horizon tracking, and its main purpose is a sensitivity analysis of the depth structure to the velocity models used for depth migration. Thus, one of the inputs that varies is the velocity model used for seismic migration of processed pre-stack gathers, and other parameters and steps are fixed.

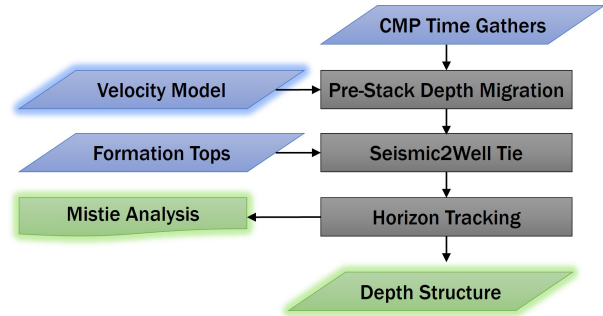


Figure 6: The workflow devised to analyze the sensitivity of the depth structure to velocity models used for depth imaging of seismic data. For each model version, the processed CMP gathers were migrated, and the results were interpreted to obtain a realization of the structure map and the misties.

The first velocity model was built using a 1D velocity function derived from zero-offset VSP data at well 9. This model is a reasonable choice for a study area with horizontally-layered strata. For the second velocity model, this 1D velocity function was propagated along the horizons picked from the volume migrated with the first velocity model. The depth volume migrated with the second velocity model is shown in Figure 3, and it was considered the primary volume for seismic interpretation.

The third velocity model was derived by applying the velocity scalars to the second velocity model to minimize depth misties between the geological markers and the seismic horizons. The depth volume migrated with the third velocity is further referred to as the depth-calibrated volume.

The results of implementing the imaging-interpretation workflow are shown in Figure 7. The horizons interpreted from the depth volumes migrated with the first, second, and third models are overlain on the NW-SE seismic section from the depth volume migrated with the second velocity model. The realizations of the Olmos structure are displayed on the right. The structure map for the second velocity model is the one shown in Figure 1. The amplitude of low-relief features remains in the range of 2 to 10 ft, independent of the velocity model used for migration. As a result, the dip angle of the Olmos horizon is also consistent across different realizations of the velocity model. The structural highs are observed at similar locations, and appear to be separated by a saddle in the SW-to-NE direction across the site.

The misties for the first and second depth-migrated volumes are smaller for wells closer to the center of the survey area than for those near the edges. This behaviour is anticipated because the acquisition fold decreases with increasing distance from the center, making the data less reliable at the edges. For the depth-calibrated volume, the structure in the NW section was uplifted. This uplift may not be entirely justified since the acquisition fold at well 4 is only 20 and a small depth mistie at this location might not be admissible. The mistie at well 9 became larger than in the first and second velocity models; however, a saddle of 2 ft is achieved in the central area of the seismic section.

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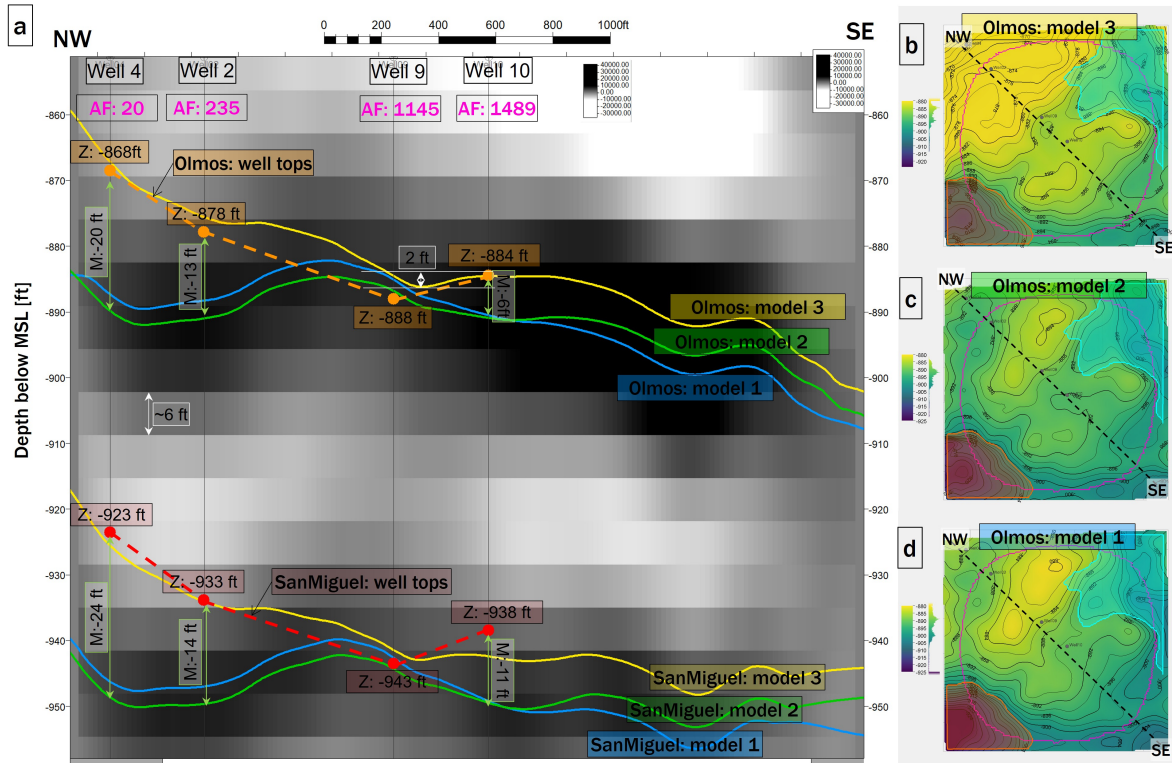


Figure 7: Enclosed portion of seismic section from the depth volume migrated with the second velocity model showing the interpreted horizons and depth misties. The latter are labeled as *M*. For each well, the acquisition fold and the depth of the formation tops are labeled as *AF* and *Z*, respectively. The realizations of the structure of Olmos are shown on the right in panels (b), (c), and (d). Despite their small vertical amplitudes (2-10 ft), the low-relief structures persist across different realizations of the velocity model, though the vertical amplitudes vary slightly. For the depth-calibrated volume, a saddle of about 2 ft is more pronounced in the Olmos structure than in the first and second versions of the Olmos structure. The presence of a saddle of at least 4 ft between wells 2 and 10 in the Olmos structure is indicated by the well data.

Interpretation of Subtle Relief

The subtle low-relief structural features have been mapped using the 3D seismic and well log data. The depositional settings of Olmos, described as a constructive, but wave-dominated delta, imply that the target sand unit of the Olmos Formation is not expected to exhibit substantial structural variations. The subtle low-relief may also result from modifications in sand distribution patterns that occurred during the erosion of the up-dip Olmos Formation. The spatial extent of subtle structural closures should be interpreted with caution, given the limited size of the seismic survey.

CONCLUSIONS

The properties of the Olmos sandstone at the Devine site were studied using the 3D seismic and well log data. Among the geometrical characteristics of the target formation - such as thickness, geological dip, and structure - it is the structure that benefits the most from seismic data.

The seismic isopach map of the Olmos sandstone provides thickness values consistent with well-log measurements and suggests a uniform thickness distribution, as anticipated for wave-reworked delta sequences. The geologic dip of the Olmos sandstone, estimated from seismic data, is less than 1 de-

gree, which does not contradict the regional assessment of the target formation. As for the structure of the Olmos sandstone, the well log data indicate the presence of fine-scale patterns in the study area. However, only four well log points are insufficient to constrain the structural variability of the target over the area. The analysis of the spatially continuous, densely sampled (12.3 ft) seismic images of the subsurface enables mapping of fine-scale structural variability. In particular, subtle low-relief features with vertical amplitudes of 2-10 ft were resolved in the depth-structure map of Olmos using the seismic workflow.

The resolved, subtle relief structures of the target formation are needed to build an aquifer model with fine vertical grids and avoid hydrogen gravity override effects in the reservoir simulation. The reservoir characterization of the Olmos sandstone at the Devine test site illustrates practices for imaging and interpreting ultra-dense, compact surveys with a lateral extent comparable to the target depth.

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