Ultra-dense nodal 3D seismic for high-resolution characterization the Devine injection field laboratory

Andrey Bakulin, Bureau of Economic Geology, University of Texas at Austin, Allan Chatenay, Explor, Sujith Swaminadhan, Roy Burnstad, Mark Shuster, Bureau of Economic Geology, University of Texas at Austin*

Summary

The increasing use of the subsurface for oil and gas production, gas storage, and wastewater injection necessitates the development of best practices that are reproducible, accountable, and address environmental concerns. At the Devine Test Site, we advance subsurface monitoring to the next level by preparing for a hydrogen injection test at ~1,600 ft through the acquisition of ultra-dense nodal 3D and 2D seismic surveys with a 7.5 × 7.5 m receiver grid, supplemented by dense 2D and 3D VSP acquisitions. We present details of the acquisition, initial data assessment, and early brute-stack results, which confirm the achievement of our objective—high-resolution imaging of a shallow, weak reflector. Despite the seemingly straightforward nature of shallow targets in gas storage and wastewater injection, our results highlight significant wavefield complexity, necessitating dense spatial sampling and advanced processing. In addition to providing high-resolution characterization of the overburden, which is essential for assessing potential leakage risks, the well-sampled 3D seismic and VSP characterization surveys will serve as the foundation for designing optimized sparse monitoring strategies. These datasets will serve as prior models and constraints for sparse 4D time-lapse monitoring, reducing uncertainty in detecting hydrogen plume migration.

Devine Test Site: Overview and Future Directions

The Devine Test Site, operated by the Bureau of Economic Geology at UT Austin (Hardage, 1999, 2004; Devine Test Site, BEG UT Austin), is a premier geophysical research facility and a state-of-the-art geophysical field laboratory where surface-based seismic and potential-field experiments are conducted in conjunction with downhole and crosswell experiments. The site was donated by *bp* and has since been the focus of extensive research efforts. Over the years, significant investments have been made in infrastructure, geologic characterization datasets (Hosseini and Nicot, 2016), and seismic and VSP experimental programs (Hardage, 2004, 2013). The site features five deep boreholes extending to 3,000 ft, as well as shallow (100–200 ft) steel-cased holes for borehole-based seismic energy sources and other instrumentation. Additionally, the facility includes several shallow (330-ft) fiberglass-cased wells, permanently instrumented with distributed acoustic and temperature sensing (DAS/DTS) fiber optics and electrical resistivity tomography (ERT) arrays (Devine Test Site, BEG UT Austin).

The upcoming hydrogen injection test represents the next phase of development at the site, supported by a major new investment in seismic characterization and permanently instrumented wells. The target formation, the Olmos Sandstone, lies at a relatively shallow depth of ~1,600 ft, where hydrogen remains in a gaseous phase, unlike CO_2 storage, which requires greater depths for supercritical conditions. The Olmos is a high-porosity (~30%), moderate-permeability (~100 mD) sandstone, lacking a structural trap, meaning hydrogen containment will rely on capillary trapping and small dip-driven migration.

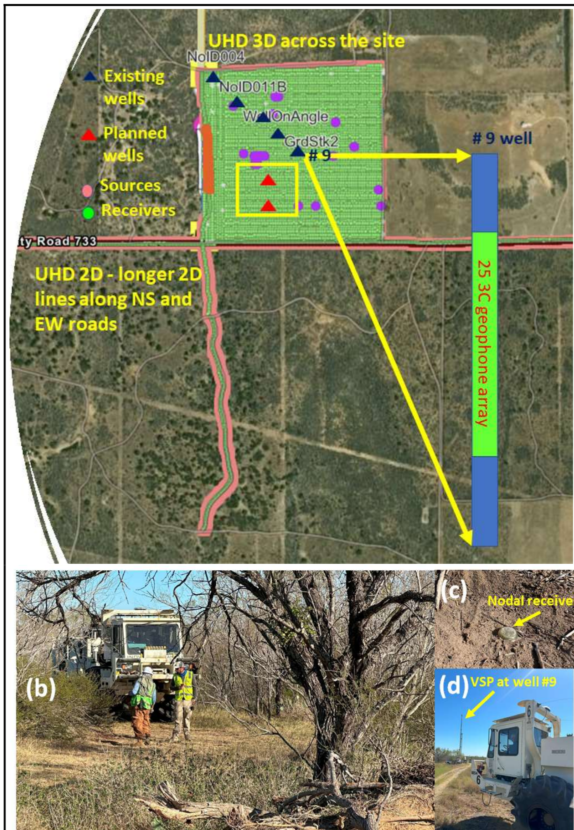

Figure 1: Schematic of the Devine Test Site with existing and planned wells (a), illustrating the acquisition geometry of the ultra-high-density (UHD) 3D+2D seismic survey and the 3D VSP survey, which share the same source carpet. (b–d) Field photos from acquisition: (b) High-density vibroseis operation navigating along tree-lined paths, (c) nodal receiver top protruding from the ground, and (d) crane deployed at Well #9, simultaneously acquiring 3D VSP data.

From a seismic characterization and monitoring perspective, the Olmos Sandstone presents significant challenges as a relatively weak reflector, often obscured by near-surface arrivals, making fluid migration tracking difficult and necessitating novel imaging solutions.

Given the limitations of traditional survey designs, we implemented an ultra-dense nodal 3D seismic survey and a complementary 3D VSP program. These datasets serve as both a high-resolution baseline and a testbed for optimizing future monitoring designs. The characterization phase aims to de-risk injection operations, ensuring that the two planned instrumented wells—equipped with fiber-optic sensors and Electrical Resistivity Tomography (ERT) arrays—are optimally placed for effective hydrogen migration monitoring.

Ultra-dense nodal seismic combined with 3D VSP

The ultra-high-density (UHD) 3D seismic, combined with a 3D VSP survey at the Devine Test Site, was designed to achieve high-resolution imaging of the target formation and optimize monitoring strategies for hydrogen injection. This effort follows a data-driven approach, where repeatability is predicted based on the signal-to-noise ratio from characterization surveys of any kind, as outlined by Bakulin et al., 2024. The survey follows best practices for shallow subsurface characterization, similar to previous studies of CCS sites with comparable depth constraints and limited spatial extent (Ourabah and Chatenay, 2022).

Table 1 summarizes the key acquisition parameters for the 3D seismic, 2D seismic, and 3D VSP datasets, which together form a comprehensive baseline for characterization and monitoring. The UHD 3D survey covered 650m × 650m, utilizing a dense 7.5m × 7.5m receiver grid with 6,994 live nodal sensors and a source grid of 1,714 vibroseis points (VPs) spaced 30m × 7.5m. A simultaneous 3D VSP survey was conducted in Well #9 using a 25-level, 3C clamped geophone array to complement surface seismic imaging.

Parameter	3D Seismic	2D Seismic (EW/NS)	3D VSP
Survey Area	650m × 650m	4,077m (EW), 1,642m (NS)	Well #9
Receiver Spacing	7.5m × 7.5m	2.5m	15.24m (vertical)
Number of Receivers	6,994	1,315 (EW), 544 (NS)	25 3C levels
Source Spacing	30m × 7.5m	5m	Shared with 3D
Number of Sources	1,714	666 (EW), 268 (NS)	Shared with 3D
Sweep Parameters	2–110 Hz, 24s sweep	2–110 Hz, 24s	2–110 Hz, 24s

Table 1: Acquisition parameters.

A standardized seismic acquisition setup was implemented for both the 3D and 2D surveys. The survey utilized AHV-IV PLS-364 vibroseis units (67,600 lbs gross vehicle weight, 60,000 lbs maximum hold-down weight, 275 kN peak force) as the seismic source (Figure 2b,c). Each source point was activated with a single 24-second linear sweep from 2 Hz to 110 Hz, incorporating a 300 ms Blackman taper at the start and a 750 ms taper at the end, operating at 60% of peak force. Recording was conducted using single 1C Stryde nodal receivers, with one node deployed at each receiver point.

The 2D seismic survey, designed for high-resolution vertical and lateral imaging, included an east-west (EW) line of 4,077m and a north-south (NS) line of 1,642m, with 5m shot spacing and 2.5m receiver spacing. The 3D VSP dataset, recorded in Well #9, will be analyzed separately to assess its potential for 4D monitoring. As we show below, this high-density acquisition was crucial for characterizing the relatively weak Olmos reflector, which is often obscured by near-surface arrivals.

Justification for ultra-dense design and nodal technology

In CCS applications, CO_2 must be stored below 800–1,200m to reach its supercritical state, behaving as a dense fluid. In contrast, hydrogen remains in a gaseous phase at all practical geological storage depths, removing the need for deep reservoirs. However, shallow imaging is still crucial for detecting potential leakage pathways, requiring enhanced vertical resolution. Given the challenges of hydrogen injection monitoring, where subtle subsurface migration must be precisely tracked, the Olmos Sandstone's weak reflectivity and overlying near-surface complexity demand an ultra-dense seismic acquisition strategy. This ensures high spatial resolution and signal fidelity, allowing for accurate reservoir characterization and long-term monitoring.

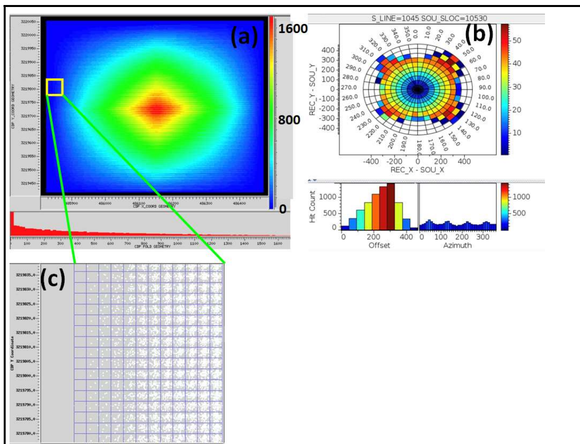

Figure 2: Fold map (a) as well as offset-azimuth distrubtion for representative shot gather in the middle of the survey (b) and graphical midpoint distribution (c) at the survey's edge.

With a trace density of 29 million/km² (75 million/sq mile), this survey significantly surpasses legacy surveys, despite covering a compact ~0.42 km² area. Figure 2 shows an average fold of approximately 800 for a nominal bin size of 3.75m × 3.75m, comparable to modern high-trace-density 3D surveys for deep targets (Lewis et al., 2021). As expected for a fixed "All-Live" receiver patch, fold increases toward the center of the site. A representative midpoint distribution at the survey's edge is shown in Figure 2c. The most frequent offsets are around 300 m, with longer offsets extending up to 500 m (Figure 2b), approximately equal to the target depth, indicating that the available site area is sufficient for imaging.

A key distinction of this survey is its much denser trace spacing, allowing similar fold coverage to be achieved at significantly shorter offsets (Figure 2b). This demonstrates how the principles of high-resolution 3D imaging, typically applied for deep targets, can be successfully adapted for shallower targets. Despite the smaller recording patch and shallower target depth, both trace density and fold are comparable to modern high-trace-density 3D surveys for deep targets (Lewis et al., 2021), ensuring high-quality imaging of the relatively weak Olmos reflector.

Nodal technology enables cost-effective, high-density seismic acquisition, allowing small teams to efficiently manage subsurface risks while maintaining flexibility in positioning and deployment. This approach ensures consistent imaging quality, provides a robust assessment of 4D monitoring potential, and informs the design of future time-lapse programs. By integrating UHD 3D, dense 2D lines, and 3D VSP, the project establishes a comprehensive seismic baseline for injection monitoring at Devine.

Preliminary assessment of the shot gathers confirms strong signal quality. The following sections provide an initial evaluation of the 2D and 3D datasets.

Data assessment – 2D acquisition

While processing is ongoing, an initial assessment of the dense 2D dataset confirms the effectiveness of the acquisition design. Figure 3a shows a shot gather, capturing all near-surface energy. However, the shallow reflector of interest remains within the ground-roll noise cone and is not directly visible, while energy outside the cone is still obstructed by near-surface multiples and other elastic energy (Figure 3b). This underscores the need for dense acquisition to enhance signal quality and resolve key subsurface features. Additionally, the 2D lines were recorded simultaneously as a cross-spread, allowing further evaluation of 3D filtering on an even denser 2.5m receiver geometry. Processing outcomes will be shared in future publications.

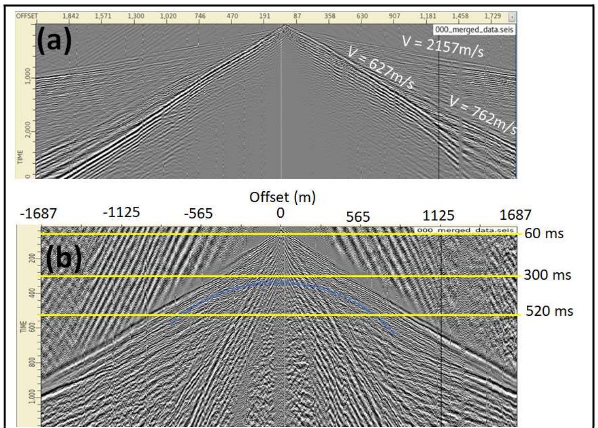

Figure 3: Shot gather from the dense 2D north-south (NS) line (a) and a zoomed-in view of the shallow section after AGC, highlighting the approximate positions of the weak target reflectors (b). Yellow lines indicate the time positions used for the time slices shown in Figure 5 from the 3D data.

Data assessment – 3D acquisition

The 3D dataset benefits from three acquisition directions sampled at 7.5 m and one at 30 m, ensuring dense spatial coverage. Figures 4a and 5 illustrate the 3D data across different domains, demonstrating the advantages of ultra-dense sampling. Figure 4a shows a densely sampled shot gather along one of the receiver lines with 7.5 m spacing.
Figure 5 presents time slices from a raw shot gather, fully sampled on the 7.5 × 7.5 m receiver grid. While not as densely sampled as the 2D dataset, the 3D data captures nearly all wavefield components, including slow near-surface arrivals. Figure 5 illustrates the evolution of the wavefield over time:

- 60 ms (Figure 5a): Refractions and ground roll are closely packed, forming an indistinguishable wavefront.
- 300 ms (Figure 5b): Refractions weaken, and ground roll begins to separate, revealing scattering effects.
- 520 ms (Figure 5c): Ground roll expands, fully occupying the inner noise cone. Several secondary scatterers (yellow arrows) become visible, while many weaker scatterers densely populate the noise cone but remain unresolved individually.

A similar pattern appears in vertical cross-sections of both the 3D dataset (Figure 4a) and the 2D dataset (Figure 3b). These observations highlight the power of ultra-dense acquisition in imaging near-surface complexity and optimizing data quality for seismic monitoring.

Noise attenuation and initial imaging

Figure 4b demonstrates the effect of applying a 3D FK filter to common-shot gathers with 7.5 × 7.5 m receiver spacing, effectively suppressing energy within the noise cone and enhancing shallow reflectors. Figure 4c highlights the removed energy, confirming the filter's effectiveness in improving signal clarity. Though these results are from raw gathers without statics corrections, they already show promising improvements.

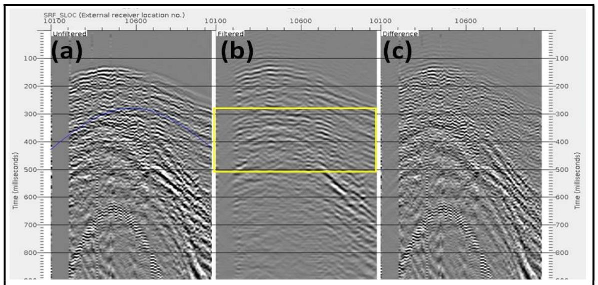

Figure 4: Receiver line from a 3D common-shot gather at different processing stages: (a) raw data, (b) after 3D FK filtering, and (c) difference between (a) and (b), highlighting the removed noise.

Figure 6 presents presents a brute stack of the 3D dataset after applying only 3D FK filtering, approximate 1D NMO correction, gap deconvolution and elevation statics. Post-stack processing is trace balance. The image, taken from one of the N–S lines, clearly reveals a weak reflector of interest below 400 ms, along with several even shallower reflectors. This result validates our acquisition design for this challenging task: achieving high-resolution imaging of weak, shallow reflectors that were previously completely obscured, as confirmed by Figure 3b.

Discussion and conclusions

The Devine Test Site is evolving into a fully instrumented field laboratory for injection monitoring, with preparations underway for a hydrogen injection test. As part of this effort, we successfully completed an ultra-dense 3D seismic survey with 7.5 × 7.5 m receiver spacing and high trace density, ensuring exceptional wavefield sampling. Early imaging confirms that the Olmos Sandstone, despite being a weak reflector heavily affected by near-surface distortions, is successfully imaged. These results validate our acquisition design, demonstrating that ultra-dense seismic is effective for resolving weak, shallow reflectors critical to hydrogen storage applications.

A detailed assessment of the ultra-dense 3D and super-dense 2D datasets reveals significant wavefield complexity. Even in a seemingly simple geological setting, dense sampling exposes substantial near-surface distortions that must be accounted for in characterization and monitoring. These challenges highlight the necessity of dense acquisition to fully unravel underlying imaging challenges in characterization and set the stage for detecting subtle 4D signals, which are essential for gas storage and injection monitoring.

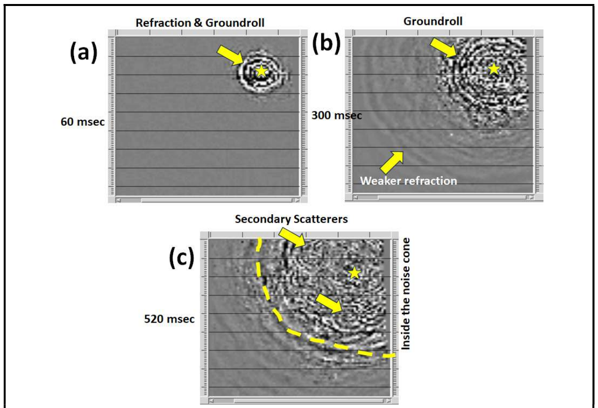

Figure 5: Time slices from the full receiver carpet for a single shot at the NW corner at different time positions—(a) 60 ms, (b) 300 ms, and (c) 520 ms—illustrating wavefield evolution in the raw data.

The next phase will focus on finalizing 3D and 2D surface seismic processing, followed by 3D VSP analysis. These datasets will form the foundation for designing optimized sparse monitoring strategies, where time-lapse 4D inversion of sparse datasets will be constrained by well-sampled 3D seismic and VSP. Moving forward, this work will establish a structured, replicable monitoring approach driven by data, calibrated to the expected 4D signal under specific geological conditions.

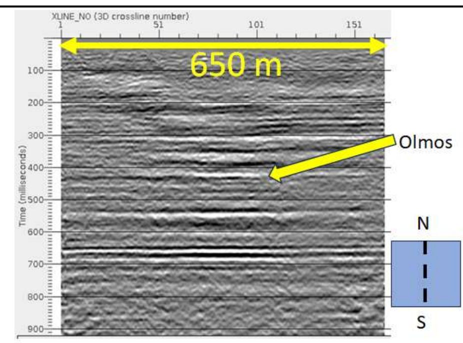

Figure 6: Brute stack along one of the N–S lines from the 3D dataset, revealing the reflector of interest along with several other shallow reflectors.

Acknowledgements

We thank Explor for acquiring the 3D seismic data and Borehole Seismic for VSP acquisition, as well as for their close cooperation.