Shallow Water GoM Data Rejuvenation for CCS Prospecting

R. Collings[1], G. Suarez[1], J. Kinkead[1], T. Tang[1], B. Sellers[1], I. Marino[1], M. Pila[1]

[1] PGS

Summary

The development of carbon capture and storage (CCS) relies heavily on high-resolution seismic images to characterize both the geological framework of the storage site and its overburden. In this study we show, that by applying the latest imaging technology, we can produce results suitable for characterizing and derisking a site, within the shallow water region of the Gulf of Mexico.

Analysis of the field data unveiled geometry issues, amplitude variations, as well as strong contamination from various types of noise. To prepare the data for imaging, we deployed a comprehensive wavelet processing workflow.

To obtain a high-resolution velocity model, a seismic inversion workflow was implemented. To achieve the resolution required, a Least-Squares Kirchhoff migration was run. However, as the water depth varies from 3-15 m, the near-offset seismic coverage from primary reflections was insufficient to estimate shallow reflectivity. Instead, imaging with multiples was used.

The legacy Kirchhoff volume is of limited bandwidth and does not image any shallow reflectivity. Imaging with multiples reveals a network of channels, as well as shallow faults that reach the water bottom, which are critical for characterizing the geologic framework of the storage complex and assessing the risk correctly.

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Introduction

Carbon capture and storage (CCS) is gaining increasing traction in the shallow waters of the Gulf of Mexico (GoM) (Zaremsky et al., 2023). Critical to CCS development are high-resolution broadband seismic images used to characterize the geologic framework in and around the target storage complex (Reiser et al., 2022). High-resolution seismic data allows detailed mapping of the faulting framework and characterization of the capacity and containment, a critical part of the risk analysis within the larger CCS value chain. The environmental regulations and the shallow water environment bring both prohibitive costs and complexities for acquiring new seismic data, specific for CCS needs. However, there is an abundance of legacy ocean bottom cable (OBC) data available for reprocessing. In this study we show how applying cutting-edge imaging technologies to these vintage datasets can help unlocking additional information, providing results suitable for characterizing the capacity and containment of a carbon storage site.

Field Data

The data available in the study area came from a single component hydrophone OBC survey, acquired between 1994-1997 in Texas State waters with a depth of 9-50 feet. The seismic data was acquired in four overlapping tiers, with each tier representing a different phase of acquisition. Each tier was made up of multiple swaths, with a single swath comprised of five source lines, 110 feet apart, with two receiver lines, 1650 feet apart. Each receiver line contained between 100-198 hydrophones 330 feet apart, with the survey design providing maximum offsets from 20,000 to 40,000 feet. The multiple phases and long duration of the acquisition saw several different source vessels being used, along with numerous recording systems each with different configurations and a low-end recording system response of around 8 Hz with an 18 dB/octave slope, severely limiting the low frequency content of the data.

Analysis of the field data unveiled navigation errors, significant amplitude variations within swaths and across tiers, and both strong and variable contamination from various types of noise commonly observed in transition zone environments. In addition to the familiar low-frequency, coherent and dispersive ground roll, a pronounced presence of continuous mud roll noise was observed up to 20 Hz.

Pre-Processing

Prior to commencing any signal processing, the errors in the positioning of the data had to be identified and resolved. This is typically achieved by comparing the recorded first-break arrival times with those predicted by the location information in the trace headers, and any discrepancies are used to derive new positions. The variable data quality and shallow water depths made this challenging. First-break energy could not always be clearly identified, so only large errors (> 25 m) were corrected.

The pre-processing comprised three main phases:

Comprehensive wavelet processing – various denoising techniques, statics correction, surface consistent deconvolution, surface consistent amplitude compensation, and source and receiver deghosting.

Demultiple – a pragmatic, iterative approach was used to suppress the shorter and longer period multiples separately. The very short period sea-bed reverberations are removed from the data by considering them as ghosts embedded within the source wavelet. Longer period multiples model and subtracted using a combination of wavefield propagation and convolutional surface-related multiple elimination techniques (SRME).

Regularization – the sparsity of sources was addressed through regularization techniques to increase their density. Two approaches were used: 1) Fourier ALFT approach to prepare the data for Kirchhoff depth imaging; and 2) Tau-P based matching pursuit method to increase the trace density within a receiver gather for wave equation imaging.

Velocity Model Building and Imaging

Velocity model building used a novel seismic inversion workflow that inverts simultaneously for both velocity and reflectivity. The workflow utilizes a vector reflectivity parameterization of the wave equation (Whitmore et al., 2021) with an efficient scale separation of the FWI gradient based on inverse scattering theory (Whitmore and Crawley, 2012; Ramos-Martinez et al., 2016). This approach enables velocity and earth reflectivity to be estimated iteratively within a common inversion framework (Yang et al., 2021) to provide an accurate and high-resolution velocity model and seismic image.

As the observed data lacked usable signal below 8 Hz, FWI commenced at 8 Hz and utilized the whole wavefield, with the diving waves driving the shallow updates and the reflections driving the deeper updates.

Standard inputs for a FWI workflow are: 1) minimally processed field (observed) data; 2) a starting velocity model; 3) a source wavelet; and 4) an initial estimate of reflectivity. For this study, the observed data had the corrected positioning and statics corrections applied, with basic denoise. The starting velocity model came from a previous processing of the data: VTI anisotropic velocity model, with 3% delta and 4.5% epsilon. Limited information was available about the sources used during the acquisition, so the source wavelet was estimated from the recorded data.

The shallow water depth over the survey area (3 to 15 m) and the poor near-offset coverage limits the ability of primary reflections to provide a reliable image of the shallow subsurface. Therefore, the initial estimate of the reflectivity was derived using a technique that creates an image from the recorded multiples (Lu et al, 2015). The approach, also known as separated wavefield imaging (SWIM), extends the near surface illumination and recovers reflectivity information for imaging the shallow subsurface. In the context of this OBC dataset, SWIM uses each shot as a “virtual” receiver, expanding the surface coverage of the seismic experiment to the shot patch and enhancing the subsurface illumination. This results in a survey that has a spatial sampling richer in offsets and azimuths. The improved spatial sampling greatly enhances the angular diversity of the data at every image point which results in the imaging of reflectivity, including the water bottom, in shallow water environments.

SWIM was a powerful tool for this study, providing the initial reflectivity estimate and serving as an important QC for the velocity model building, in addition to being a part of the final image.

To obtain the resolution required to characterize the CCS storage site, a least-squares Kirchhoff pre stack depth migration (LSK) was run and combined with the image from the multiples. Conventional depth migration produces a representation of the earth reflectivity, but the image resolution is constrained by several factors: the acquisition parameters (source and acquisition geometry); the earth properties (velocity, illumination, and attenuation); and the migration algorithm. When the overburden is complex and the acquisition provides variable or insufficient source and receiver coverage at the surface, both the illumination and wavenumber content of the migrated images can be sub-optimal. By posing the imaging step as a least squares problem, the illumination and resolution can be improved. Least Squares Migration (LSM) produces improved images of the sub-surface by estimating and correcting for distortions to the wavefield caused by these limitations. For this study, an image-domain LSK solution was used to explicitly solve for the earth reflectivity using Point Spread Functions (PSFs).

Results and Discussion

Figure 1 compares results from the legacy and new processing. The example line from the legacy processing shown in Figure 1a illustrates the limited bandwidth of the original Kirchhoff processing, and clearly shows the absence of reflectivity down to 150 m below the seafloor. Features such as faults and channels, which could act as potential leakage pathways or seals for injected CO2 plumes, cannot be identified; assessment of the CO2 storage complex could be challenging using this data. The increased resolution, data quality and accurate velocity in the new volume (Figure 1b) significantly reduces those challenges, providing greater confidence when characterizing the site's potential.

The extent of the bandwidth improvements is quantified by the amplitude spectra shown in Figure 1c. Targeted denoise techniques, proper wavelet conditioning and attenuation of both seabed and longer period multiple energies have enhanced the character of the signal during pre-processing, while the least-squares Kirchhoff Migration has corrected for illumination and blurring distortions at the level of the storage complex. This improved bandwidth is important for extracting key attributes such as lithology, porosity, and thickness.

The importance of the image created by the multiple reflections and FWI derived velocity model are clearly illustrated by the depth slices extracted at 25 m (Figure 2). A network of channels and shallow faults are visible, critical for characterizing the geologic framework around the potential storage complex. Pipelines present at the time of acquisition can also be seen. Figure 3 shows a slightly deeper depth slice at 50 m. Channels and faulting seen on the image correlates with features on the FWI derived velocity model due to their velocity contrast to the background sediments.

Conclusion

We have shown how use of the complete wavefield – primary and multiple reflections, refractions, diving waves – incorporated into the latest technology, allow vintage shallow water OBC data to provide information that has the potential for characterizing the capacity and containment of a carbon storage site.

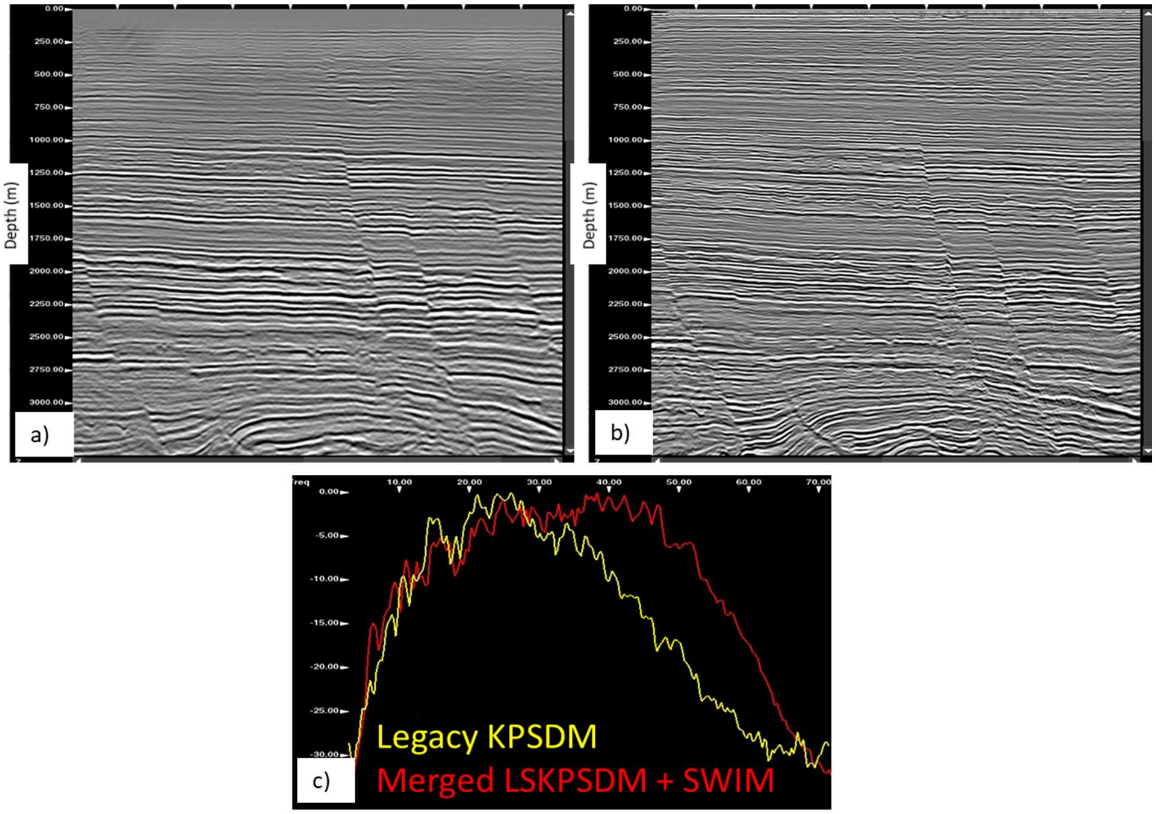

Figure 1 *Comparison of the legacy Kirchoff volume (a) to the new LS-Kirchoff merged with the multiple imaging (b) with the corresponding frequency spectra (c). Imaging with multiples results in high resolution imaging of the water bottom and shallow reflectivity.*

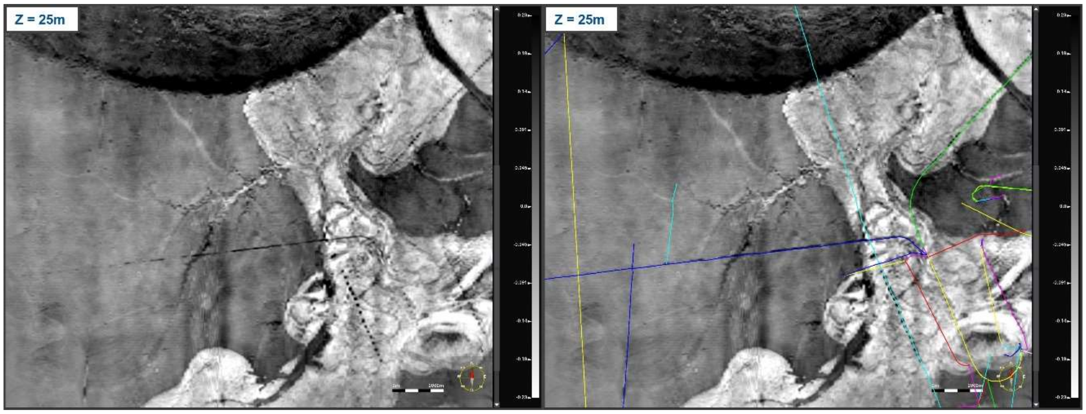

Figure 2 *Shallow (25 m depth) image offshore GoM, near Louisiana / Texas border. This 60 Hz SWIM image clearly shows Sabine River outflow and deltaic system. Pipelines present at time of acquisition are also visible. Left: SWIM image. Right: the same SWIM image with pipelines overlaid.*

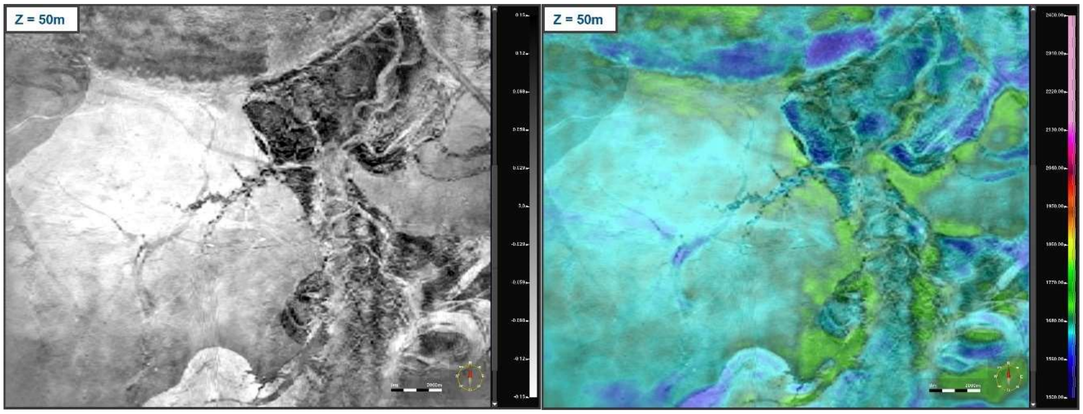

Figure 3 *Left: SWIM image at 50 m depth. Right: the same SWIM image with velocity model overlaid. Velocity variations seen in the shallow velocity model correlate to channels imaged using SWIM.*

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