Unlocking hidden potential in shallow water Gulf of Mexico legacy data for carbon capture and storage exploration

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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.

Introduction

In the shallow waters of the Gulf of Mexico (GOM), carbon capture and storage (CCS) is gaining increasing traction as a viable option for reaching net zero emissions. Critical to its development are high resolution seismic images to characterize the geologic framework around the target storage complex. This high-resolution seismic data will allow detailed mapping of the faulting framework in the area. Characterizing the capacity and containment of a carbon storage site is a part of the risk analysis of the larger CCS value chain. The shallow water and environmental regulations result in prohibitive costs and complexities for acquisition of new data. However, there is an abundance of vintage Ocean Bottom Cable (OBC) data available for reprocessing. In this study we show, that applying the latest technology solutions and workflows to these vintage datasets can unlock additional value and information producing results suitable for characterizing the capacity and containment of a carbon storage site.

Field Data

This study used single component hydrophone OBC data, acquired between 1994-1997 in Texas State waters, where the water bottom is between 3-15m depth. The seismic data was acquired in four tiers, with each tier representing a different phase of acquisition. There was overlap between the tiers and each tier was made up of multiple swaths. A single swath is comprised of 5 source lines, 110 feet apart, and 2 receiver lines, spaced 1650 feet apart. Each receiver line contained between 100-198 hydrophones spaced 330 feet apart. Due to the multiple phases of acquisition, the data was acquired with numerous recording systems with different configurations, as well as several source vessels. An 8 Hz 18 dB/oct low cut filter was applied to the data severely limiting the low frequencies. Maximum offset for this dataset ranges from 6 to 12 km.

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

Pre-Processing

Prior to commencing any processing, geometry correction errors were addressed. A first break geometry correction workflow was utilized, however the challenging data quality and shallow water depths complicated this process, as it relies on clear identification of first break energy. Consequently, only geometry errors exceeding 25 m from the correct position were resolved.

To prepare the data for imaging, we deployed a comprehensive wavelet processing workflow that included various denoising techniques, statics correction, surface consistent deconvolution, surface consistent amplitude compensation and source and receiver deghosting.

The process of removing the multiples within the data requires an iterative approach. First the extremely short period sea-bed reverberations are removed from the data by treating them as ghosts embedded within the source wavelet. Longer period multiples are dealt with using a combination of wavefield propagation and convolutional techniques.

At certain phases of processing, the sparsity of sources is addressed through regularization techniques to increase their density. For this, two types of approaches were used, one being an Anti Leakage Fourier Transform (ALFT) approach to prepare the data for Kirchhoff depth imaging, and a tau-p based matching pursuit methodology to increase the trace density within a receiver gather for wave equation imaging.

Imaging

To obtain a velocity model a novel seismic inversion workflow, that simultaneously updates both velocity model and reflectivity was implemented. The workflow utilizes a vector reflectivity parameterization of the wave equation (Whitmore et al., 2021) and an efficient scale separation of the Full Waveform Inversion (FWI) gradient using 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).

For the FWI workflow, observed data, velocity model, reflectivity cube and source wavelet are required. The observed data was the single component OBC data with the geometry and statics corrections applied, as well as suitable denoise to match the data to the modelled data. The starting model for FWI was the legacy model converted to anisotropic using 3% delta and 4.5% epsilon. For the source wavelet, minimal source information was available. Therefore, it was necessary to derive the source wavelet from the recorded data. A source wavelet was derived by averaging extracted wavelets from each shot. Then, a matching filter was derived for each shot to match it to the average source wavelet. The shot-by-shot matching filters were then applied to the recorded data prior to running FWI.

For the starting reflectivity cube, as the water depth in the survey area varied from 3 to 15 m, the near-offset seismic coverage from primary reflections was insufficient to estimate reflectivity. Therefore, imaging with multiples (Lu et al, 2015) was used to extend the near surface illumination and recover reflectivity information for imaging the shallow geology. Imaging with multiple works by treating 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 dataset 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. 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.

To obtain the resolution required to characterize the CCS storage site, a Least Squares Kirchhoff pre stack depth migration (LS-KPSDM) was run and combined with the image with multiples. Depth migrations produce a representation of the earth reflectivity. 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 geometry leads to 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 of images can be improved. Least Squares Migration (LSM) produces improved images of the sub-surface by correcting for distortions to the wavefield caused by limitations in acquisition and propagation effects. LSM explicitly solves for the earth reflectivity by use of Point Spread Functions (PSFs) (Valenciano et al., 2019).

Results

The subsurface geology of our area of interest is characterized by gently dipping depositional packages offset by - dipping growth faults. These faults range in depth from near the seafloor to approximately 6 km. Through application of the latest technology and workflows, understanding of the spatial distribution of these faults and subsequent impact on reservoir connectivity and seal integrity is possible.

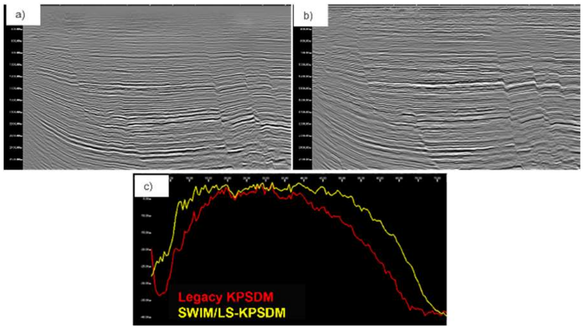

Figure 1: Comparison of the legacy Kirchoff volume (a) to the new LS-Kirchoff merged with the multiple imaging (b) with the corresponding frequency spectra (c). Imaging with multiples results in high resolution imaging of the water bottom and shallow reflectivity.

Figure 1a shows that the legacy Kirchhoff volume is of limited bandwidth and does not image any shallow reflectivity, meaning that hazards, such as faults and many challenges with the legacy volume the assessment at the reservoir is difficult. The increased resolution, data quality and accurate velocity in the new volume (Figure 1b) allows those assessments at reservoir interval to take place.

Figure 1c shows that an increased bandwidth of data was achieved with aggressive denoise techniques, proper wavelet conditioning and attenuation of both seabed and longer period multiple energies. This was further extended in the final imaging by utilizing Least Squares Kirchhoff Migration to properly compensate for imaging conditions at the reservoir. At the depth of the potential storage sites, the increased bandwidth aids the 3-D characterization, essential for extracting key storage attributes such as lithology, porosity, and thickness.

Figure 2 shows that imaging with multiples, using the derived FWI model, results in high resolution imaging of the shallow reflectivity, which reveals a network of channels, as well as shallow faults, which are critical for characterizing the geologic framework around the target storage complex. The increased bandwidth and spatial resolution of the new volume at the reservoir level, enables the spatial distribution of faults to be understood, allowing an assessment of the reservoir connectivity and potential seals to be made.

Results

We show that by applying the latest technology and workflows, as well as utilizing multiple energy for imaging, vintage single hydrophone OBC data acquired in a shallow water environment, is suitable for characterizing the capacity and containment of a carbon storage site.

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channels, which could act as potential leakage pathways or seals for injected CO2 plumes, are not identified. Due to

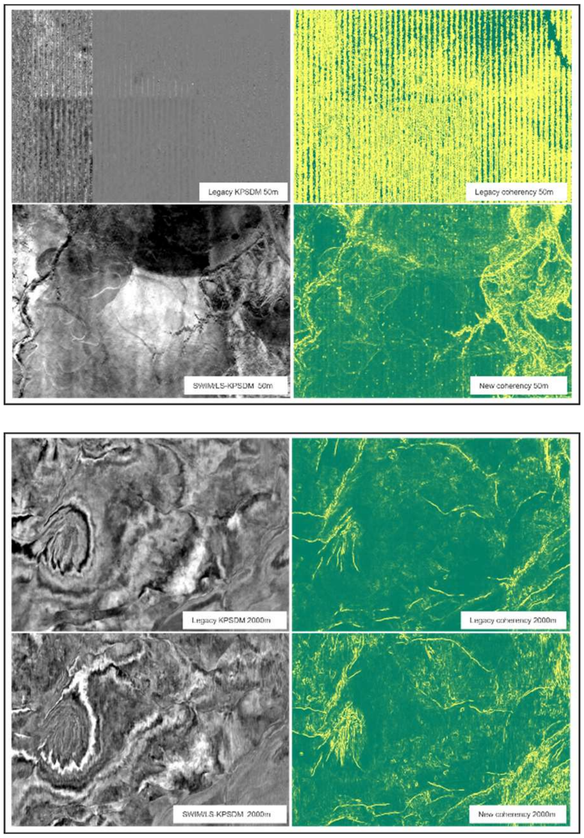

Figure 2: Top: Legacy KPSDM and corresponding coherency volume at 50 m depth compared to multiple image and corresponding coherency volume at 50 m depth. Imaging with multiples results in high resolution imaging of shallow channels and fault planes. Bottom: Legacy KPSDM and corresponding coherency volume at 2000m depth compared to LS-Kirchhoff and corresponding coherency volume at 2000m depth. Imaging with the LS-Kirchhoff results in high resolution imaging of the fault planes.