Project Poseidon CCS site assessment through legacy 3D seismic reprocessing

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Summary

This paper shows that legacy 3D seismic data can be reprocessed with modern seismic reprocessing workflows to produce high-resolution seismic images suitable for CCS site assessment. Using the Poseidon project as a case study, three 1990s surveys of different acquisition geometries, including OBC, were reprocessed through DW-FWI and a TTI pre-stack depth migration. Despite challenges such as limited offsets, source wavelet uncertainties, complex shallow water seabed conditions, and thin, variable velocity layers, the workflow delivered significant improvement over legacy datasets in the structural and fault imaging of the Leman field. The uplift in fault imaging along with the greater confidence in the velocity model and associated event depthing allowed for the reconstruction of the static model for Leman from scratch. The result therefore demonstrates that reprocessing existing seismic data is a quick and cost-effective way to reduce risks and increase confidence in the evaluation of depleted reservoirs prior to CO_2 injection and storage.

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Introduction

Carbon Capture and Storage (CCS) captures CO_2, transports it and stores it deep underground in geological formations. Key storage candidates for CO_2 are depleted oil and gas reservoirs, where existing 3D seismic data is already available. The most cost-effective way to assess whether a depleted reservoir is suitable for CO_2 storage is to reprocess existing data. This paper demonstrates that high-resolution seismic images for CCS site assessment can be produced from legacy data using modern processing and imaging workflows.

Our case study comes from the Poseidon project covering the Leman field in the Southern North Sea, where the legacy seismic data comprised two 3D towed-streamer surveys acquired in 1991 and 1995 and one two-component ocean bottom cable (OBC) seismic survey acquired in 1996. The data was processed from field tapes using a broadband TTI Kirchhoff pre-stack depth migration sequence, including diving wave full-waveform inversion (DW-FWI). 1152 km^2 of input data was used, with water depths ranging from 6 to 54 m, with several large sandbar structures running across the survey area. 1002 km^2 of fully imaged data was output, covering the large ~230 km^2 depleted Leman field. Potential challenges for the processing and imaging workflow included limited offsets, narrow azimuths (1990s acquisition), thin variable-velocity layers above the target and the very shallow water with a complex seabed due to sandbar features.

The highly compartmentalised nature of the CCS site under consideration exhibited three major fault regimes, meaning that the processing objectives focused on improved structural imaging and fault definition. The overall aim was to produce an imaged dataset of the highest possible quality, focusing on improved resolution throughout, but primarily at the intended Rotliegend storage unit and Zechstein caprock. Achieving this goal would increase confidence in the subsequent interpretation ahead of planned CO_2 injection testing.

This case study illustrates the use of advanced deghosting and demultiple workflows, alongside DW-FWI, to generate high-resolution velocity models and enhanced depth images. Reprocessing of multiple seismic surveys will be shown to yield substantial seismic image improvements, thereby reducing risks in CCS site evaluation and subsequent injection test planning. The increased fidelity of the velocity model and seismic processing will also enhance any subsequent monitoring efforts, like those discussed at Poseidon in Festucci et al. (2024).

Method

Key processing steps were applied to generate a high-resolution broadband image that is seamless across all legacy surveys. These included:

- Source and receiver deghosting to help improve resolution through a broader bandwidth
- Multiple attenuation using a combination of Surface-related Multiple Elimination (SRME) related techniques, Tau-P deconvolution and high-resolution Radon demultiple
- An iterative denoising approach (pre- and post-migration)
- 4D interpolation and regularisation to aid in the signal-to-noise ratio enhancement. Particular attention was given to addressing acquisition coverage gaps and identifying areas where spatial resolution may be compromised.

In addition to the pre-processing steps above, velocity model-building played a crucial role in the reprocessing of these legacy seismic data. The best of the legacy models for each of the surveys were combined, generating a legacy field over the full area. A total of four tomography updates to the velocity model were completed, in addition to DW-FWI. The first two tomographic updates were isotropic. Refraction first-break picks were included to stabilise the shallow part of the model, for the first pass of tomography - a joint reflection and refraction tomographic update. Initial anisotropy models were generated after the second pass of reflection tomography through well marker to horizon mis-tie analysis (delta model) and depth varying ratios of delta assessed through PreSDM gather analysis at far offsets (epsilon model). This was followed by an anisotropic third pass of reflection tomography and those velocities, in addition to the derived anisotropy models, were input into DW-FWI.

DW-FWI was performed up to a maximum frequency of 17 Hz to capture lateral velocity variation in the shallow section, with particular emphasis on the shallow channel features. The legacy 1990s data, however, posed several limitations: short maximum offsets of approximately 2.2 km limited the depth of penetration of the diving waves to approximately 400 m and there was a lack of low frequencies in the data due to recording filters (variable across the different surveys). Source signatures were generated using modelling software and subsequently updated using an FWI source inversion scheme for each survey. The raw seismic data with minimal processing applied was input to the inversion along with updated survey-appropriate inverted signatures. A DW-FWI starting frequency of 5 Hz was deemed as an appropriate compromise across all three surveys. Updates were undertaken using a multiscale frequency stepping approach in four passes: up to 7 Hz, 10 Hz, 13 Hz, and 17 Hz; using all the available offsets.

Following DW-FWI, an update was performed on the delta model through well to horizon mistie analysis using updated horizon information, and on the epsilon model through PreSDM gather analysis. This was undertaken to better constrain the delta model based on the more advanced DW-FWI velocity information. The final tomography update, for the full trace length, was then performed using the regularised pre-processed gathers as input.

Results

The extensive velocity model building sequence resulted in a higher resolution, geologically conformable velocity model and subsequently, a better migrated image compared to the legacy datasets. Incorporating DW-FWI improved the spatial resolution of lateral velocity variations, which resolved image distortions related to shallow channel features (Figure 1 and Figure 2 (yellow arrows)). When compared to the legacy velocity model, a seamless velocity model across the three surveys with high resolution detail was obtained (Figure 2).

The application of the key processing steps resolved the strong multiple energy present from the shallow seabed and sandbars and normalised the differences resulting from the various survey geometries. This processing, together with the improved model building, has provided a superior image with enhanced imaging of the shallow channel and the Rotliegend CO_2 store, (Figure 3, Figure 4 (yellow arrows)).

Conclusions

The final result achieved the project aims and resulted in a seamless merge of the two towed streamer surveys and the OBC survey, creating a single continuous, consistent volume. The reprocessing achieved a significant improvement in resolution, coupled with a depth model that produced a simplified overburden and higher fidelity at the intended CO_2 store target level. The Leman static model was rebuilt from first principles using this reprocessed seismic volume as the primary input. The previous static model was based on a post-stack Kirchhoff time migration and in-house velocity modelling. Relative to this previous static model, a major improvement was an increased confidence in the interpreted fault network, resulting in a more robust and geologically consistent structural grid. The reprocessed dataset therefore delivered improved velocity modelling and depth conversion. Following this reprocessing, the UK's first offshore CO_2 injection test for CCS was successfully concluded.

Acknowledgements

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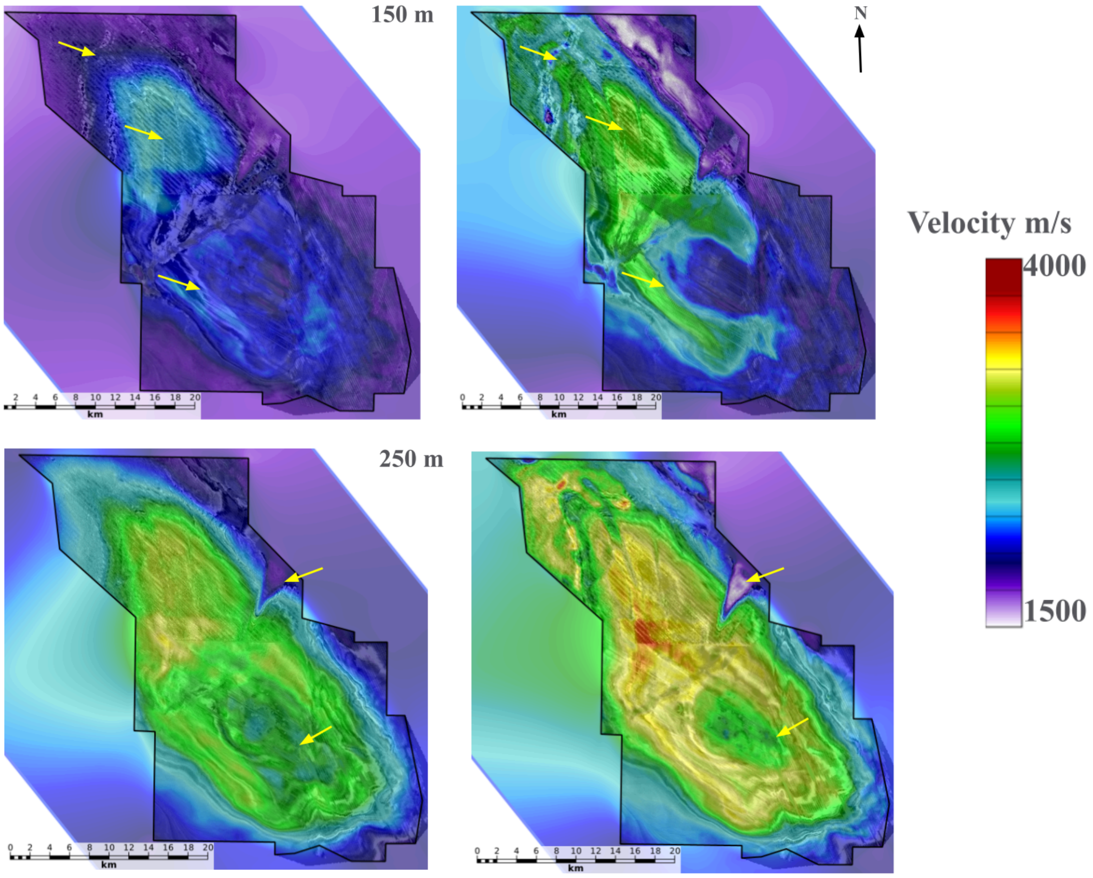

Figure 1 *Depth slices showing a comparison between the input velocity model to DW-FWI (left) to the DW-FWI output velocity model (right); both co-rendered with their corresponding stacks.*

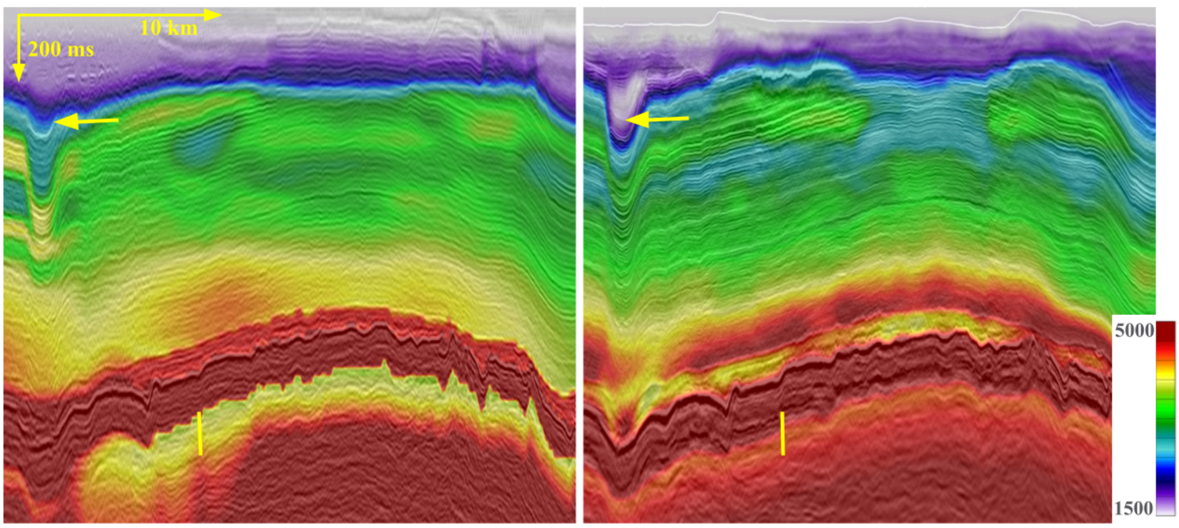

Figure 2 *Arbitrary line through the legacy interval velocity in time (left) and the final PreSDM interval velocity model in time (right), both co-rendered with their respective stacks. The Rotliegend storage unit (vertical yellow line) and improved shallow channel velocities (yellow arrow) are shown.*

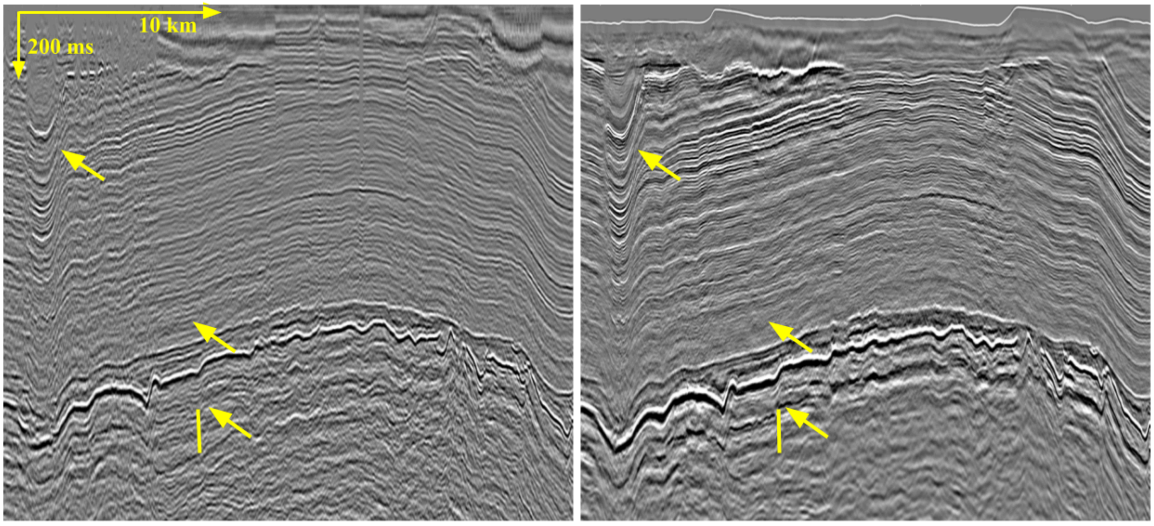

Figure 3 *Arbitrary line across the depleted gas reservoir through the legacy stack in time (left) and the final reprocessed PreSDM stack stretched to time (right). The Rotliegend storage unit (vertical yellow line) is indicated.*

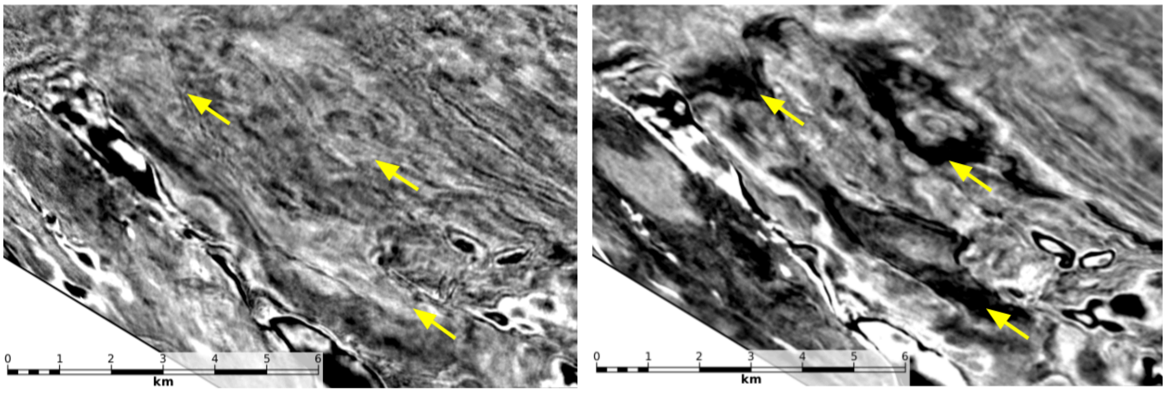

Figure 4 *Time slice at the depleted gas reservoir level through the legacy stack in time (left) and the final reprocessed PreSDM stack stretched to time (right).*

References

Festucci, A., Puig, M., Furby C., Morris, H., Brun, V., and Morgan, E. [2024]. Overcome Structural Challenges and Enabling Focused Seismic CCS Monitoring: the North Sea Leman Field Example. Fifth EAGE Global Energy Transition Conference & Exhibition, Extended abstracts, 1 - 4.