Introduction

Each carbon capture and storage (CCS) site requires a measurement, monitoring, and verification (MMV) plan that provides assurance regarding containment of the CO_2 and conformance with regulations. This plan is informed by simulation modelling, qualitative risk analysis (QRA), and assessment of different monitoring techniques.

Time-lapse (4D) seismic monitoring is the main technology for 3D localisation of the CO_2; however, costs associated with conventional 4D seismic are high. To address these costs, Branston et al. (2024) introduced an adaptive monitoring scheme, which takes advantage of modelling and QRA conducted during the MMV planning process. This process enables monitoring to be tied to the MMV plan and evergreen subsurface model. The monitoring effort and frequency is adaptive, scaling appropriately with the evolution of the CO_2 plume. The scalability is enabled through a set of different monitoring solutions, which can include passive seismic methods (Bachrach et al., 2024), CO_2 tracking methods (Chapelle et al., 2024), targeted sparse 3D CO_2 localisation (Halliday et al., 2024), and conventional 4D monitoring.

This paper presents two components of adaptive monitoring, which are based on full-waveform modelling (FWM) and inversion (Figure 1). The first technique is a data-domain screening method that uses the subsurface model to map from subsurface zones to shot gathers, enabling detection and tracking of CO_2 in the subsurface. The second approach is an adaptive 4D full-waveform inversion (FWI) approach that can use the same model to design sparse 3D monitor surveys that target specific subsurface changes. These approaches are enabled by a high-quality baseline model created using FWI, and as the subsurface model is updated, the monitoring components can be adjusted to take this into account. This paper will present the approaches using the SEG Advanced Modeling (SEAM) Corporation CO_2 data set (Fehler 2024). This is a synthetic 3D land data set, providing baseline and monitor data for both CO_2 conformance and containment scenarios.

Wavefield Colouring

Wavefield colouring is an approach that uses FWM to understand how wavefields interact with zones in a model, tracking their progression over time (Fletcher and Halliday, 2025). This approach is performed by generating two wavefields from a standard modelling experiment and an experiment modified by a weight that discriminates events passing through the zone of interest. Division of the two wavefields enables separation of events that have interacted with the zone of interest.

If the output of these experiments is a set of shot gathers, then it is possible to generate shot gathers containing only those events that have passed through the zone of interest. This method has an obvious application in subsurface monitoring. With a high-quality baseline model (e.g., generated using FWI),

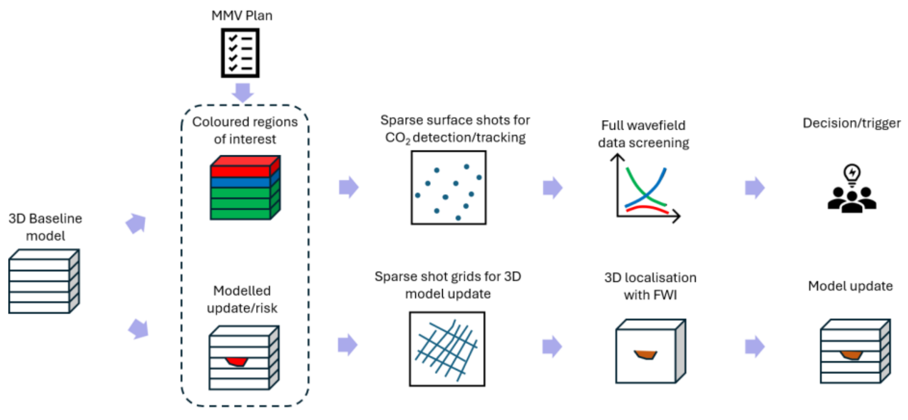

Figure 1 *Both methods conduct synthetic experiments in a baseline model using information from the MMV plan. Wavefield colouring defines subsurface zones of interest that are used to set up a sparse monitoring configuration to screen data for changes in each of the zones. Adaptive 4D FWI targets updates or risks defined by the MMV plan to design sparse monitoring surveys that enable 3D localization of the target.*

it is possible to identify subsurface zones that correspond to different monitoring scenarios and use wavefield colouring to show where data should change in response to a change in those subsurface zones. This method can be performed with just a few carefully selected shot gathers, providing a cheap and robust monitoring method.

Figure 2 shows how zones can be set up for a 2D section from the SEAM CO_2 model. Figure 2a shows the true P-wave velocity profile. It is possible to partition this model based on expected changes in the subsurface during CO_2 injection (where those changes can be defined by the MMV plan). The SEAM CO_2 data set provides scenarios, including a conformance case with CO_2 contained within a main reservoir, and a scenario with CO_2 migration into both a slightly shallower middle reservoir, and a shallow upper reservoir. Figure 2b shows the velocity model limited to the zone (coloured green) below the top of the main reservoir, Figure 2c shows the zone limited to main and middle reservoirs (blue), and Figure 2d shows the zone containing all three reservoirs (red).

Wavefield colouring can generate shot gathers for each of these zones indicating where those gathers are sensitive to changes in the different zones of interest; i.e., where the 4D difference should be expected due to changes in the subsurface. Masks are generated from those gathers for each zone and are differenced to show where events have passed through the green zone, passed through the blue zone but not green, and passed through the red zone, but not green or blue.

Thus, we can run synthetic experiments to design masks that can be used for 4D data screening during a CO_2 storage project, enabling quick identification of whether changes might have occurred in the different subsurface zones. Figure 3a shows examples of masks created in this way for one shot gather for the green, blue, and red zones. Note the detail in the masks, using a model that supports diving waves and reflections means we can use the full wavefield in the monitoring.

Synthetic data are modelled for the baseline case, and for the migration scenario after 30 years of injection. The 4D difference in the modelled data is screened using the different masks, and attributes

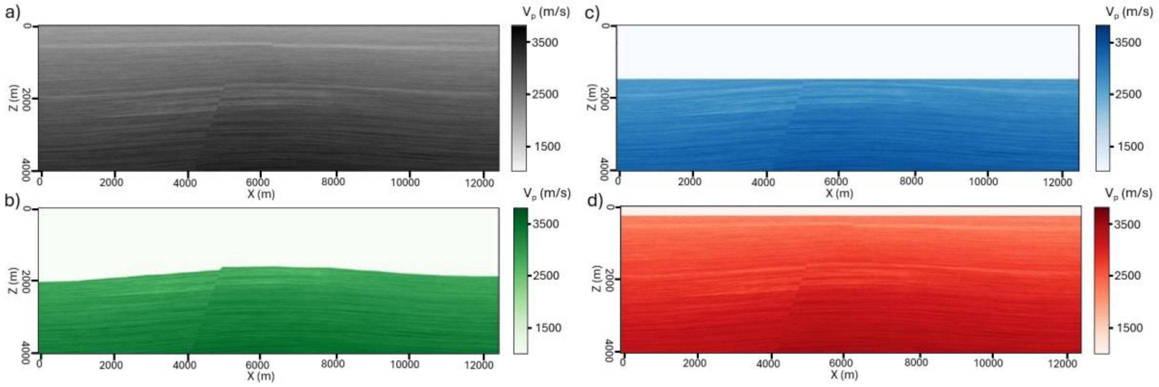

Figure 2 *2D section from the SEAM CO_2 model used for the wavefield colouring experiments. (a) the P-wave velocity. (b) to (d) Regions of the model denoted as the green, blue, and red zones, respectively.*

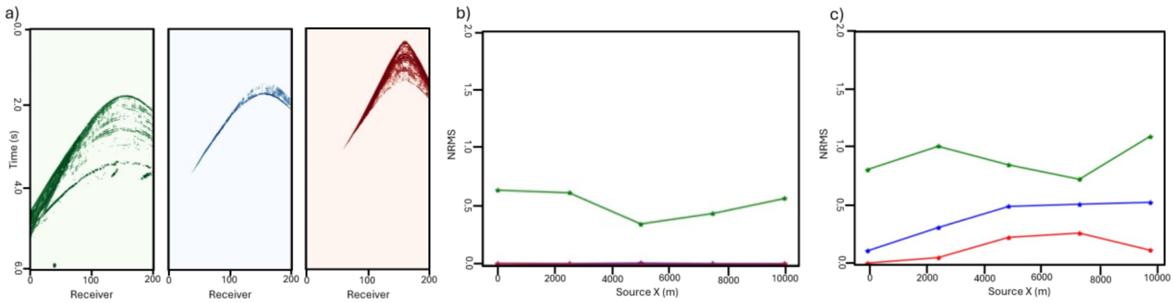

Figure 3 *(a) Masks created for the three zones in Figure 2 (after differencing to isolate each zone). NRMS values corresponding to the difference between baseline and monitor for each mask for a set of five monitor shots for (b) CO_2 containment within the main reservoir, and (c) CO_2 migration into the middle and upper reservoirs.*

such as the normalised root-mean square (NRMS) difference can be extracted to provide an indication of any 4D change. Figure 3b shows the NRMS difference for five different shots for the scenario where the CO_2 is contained within the main reservoir (green zone). Each of the five shots shows a significant change within the green mask, with little or no change within the blue and red masks, indicating the plume is in conformance. Figure 3c shows the same, but for the scenario where leakage has occurred into both the middle and upper reservoir, which is reflected in the change in all three zones. Thus, wavefield colouring has enabled us to use FWM for cost-effective CCS data screening that can discriminate between conformance and containment scenarios.

Adaptive Survey Design to Optimize the Cost of Model Updates

Wavefield colouring provides a cost-effective mechanism to track and detect CO_2 within a known subsurface. Having detected movement of the CO_2 within the subsurface makes it possible to scale the monitoring effort to localise the CO_2 and update the subsurface model in 3D. Rather than immediately scaling to a full 3D monitor survey, Halliday et al. (2024) introduced an approach to design sparse 3D surveys that target specific 4D changes in the subsurface. Using a perturbation analysis, based on FWI, the 4D target can be synthetically probed with different acquisition geometries, to determine which geometry provides the most cost-effective solution to detect and localise the targeted change. A metric-driven approach enables selection of the most cost-effective geometry that meets the 4D objective.

This approach is applied to the SEAM CO_2 data set. Figure 4a shows the baseline model (preinjection) generated with FWI using a dense baseline survey (300- by 150-m shot grid, with 150-by-50-m receiver grid). The adaptive FWI approach of Halliday et al. (2024) was used to identify a sparse acquisition geometry that will enable changes of interest to be localised. Here, both CO_2 contained in the main reservoir (Figure 4b) and the first of the migration scenarios are considered into the middle reservoir (Figure 4c). The best identified source geometry to monitor for these two potential changes is shown in Figure 4d. This is a subset of the source geometry used for the baseline survey, and the receiver system is assumed fixed. A 2D slice of the true velocity model, with CO_2 migration away from the main reservoir after 30 years of injection is shown in Figure 4a. This figure shows CO_2 within the main reservoir, and migration into the middle reservoir (this model also exhibits migration into the upper

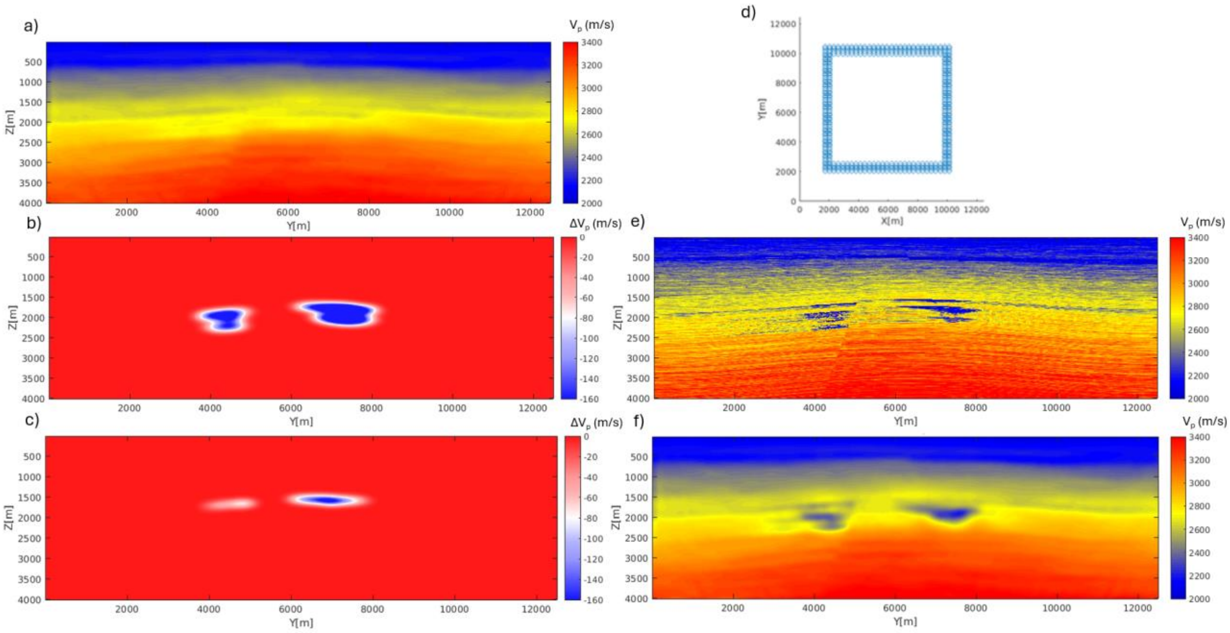

Figure 4 *(a) Baseline model generated with FWI using a dense baseline survey (300-by-150 m source grid). Perturbations used to probe the baseline model to determine sparse monitoring geometries for (b) CO_2 contained within the main reservoir and (c) CO_2 migration into the middle reservoir. (d) The source geometry selected to generate the 4D update. (e) Slice through the true 3D velocity model after 30 years of injection. (f) Velocity model updated using the sparse monitor survey.*

reservoir, but it is not considered here). The FWI updated baseline model using the sparse geometry in Figure 4d is shown in Figure 4f.

We can identify three reservoir compartments in the left region of the model, as well as the main changes in the right region. The upper of these three compartments corresponds to the middle reservoir, showing that they have been detected and localised the CO_2 migration. This method has been able to detect the targeted changes using FWI with just a fraction of the source effort (around 20% in this case) of the baseline survey. The results are for a single frequency band (centred on 6 Hz), with limited resolution. Progressing the inversion to higher frequencies will better differentiate between the different reservoir compartments. Extension to also consider leakage into the upper reservoir is the topic of ongoing work.

Conclusions

This paper has introduced FWM approaches for 4D CCS monitoring. The approaches rely on having a high-quality baseline model of the monitoring site. This model can be generated using FWI. FWM experiments are then conducted within this model. In the first instance, a wavefield colouring approach is used to map zones of interest in the model to masks in the data domain, enabling cost-effective CCS detection. This method can then be scaled through perturbation studies that enable sparse monitor surveys to be designed that provide cost-effective 3D CO_2 localisation using FWI.

These approaches form a portion of a modular adaptive monitoring system, in which wavefield colouring enables frequent surveys to detect and track CO_2 in different zones of the subsurface. Detection and tracking can then indicate when a model update is required. The monitoring effort can then be scaled up through adaptive 4D FWI to localise the CO_2 in 3D and provide a model update. Adaptive monitoring is not a replacement for full-density 4D seismic but will ensure that the full-density surveys are only acquired when a full-model update is required.

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