Introduction

To meet the demands of monitoring geological storage of carbon in a cost-effective and efficient manner, we have developed an adaptive monitoring system, which is based on the use of the seismic method, but which is targeted, scalable, and responsive to the monitoring objectives of the project phase and risks identified. Using the SEG Advanced Modeling (SEAM) Corporation CO_2 model, the scenarios presented in the model demonstrate how the system responds for three potential results within a CO_2 storage project, including the conformance case, a nonconformance case, and a noncontainment case.

The Adaptive Monitoring Workflow

The adaptive monitoring system is contingent on the correct preplanning tasks being completed in advance of initiating the monitoring (Figure 1). The creation of an accurate subsurface model is important to the success of a storage project and due investment should be made early in the project. Qualitative risk analysis (QRA) should be undertaken to support the risk-based monitoring plan. Geophysical measurements should be assessed to establish their detectability threshold for the risks identified. If the outcome of this indicates that the risks can be monitored by the seismic method, then the adaptive monitoring workflow can be implemented (Figure 2).

Figure 1 *Key steps ahead of implementing the adaptive monitoring workflow, which uses the seismic method. MMV = measurement, monitoring and verification.*

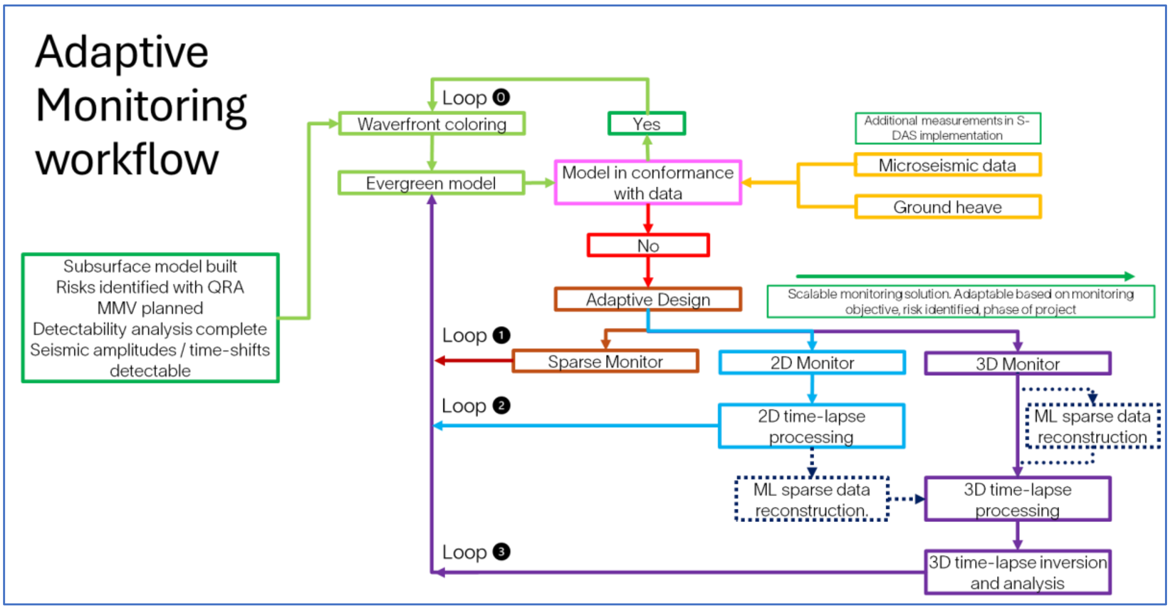

Figure 2 *The adaptive monitoring workflow. The prequalification steps are listed. Wavefield colouring is used to provide an early indication of divergence from model conformance (Loop 0). Once nonconformance is identified, the adaptive survey design process matches the acquisition effort to the risks identified by QRA. The acquisition effort can be scaled to meet the monitoring objective. Loop 1 is achieved with sparse shots, Loop 2 and Loop 3 are achieved with 2D and 3D shot grids, respectively. ML can be used to leverage 3D analysis from 2D data or sparse 3D shot grid. If the surface distributed acoustic sensing (S-DAS) implementation is used, additional measurements can be added to Loop 0 and recorded from the same system. ML = machine learning.*

SEG SEAM CO_2 Model

The SEAM CO_2 model was created by a consortium led by the Society of Exploration Geophysicists (SEG). This model is a highly realistic synthetic analogue of a CO_2 injection and storage project. Multiple scenarios have been considered and elastic finite element synthetic data generated for various geophysical acquisition methodologies. The model is fully described by Barranco et al. (2024) and Yoon et al. (2024). We use the conformance case (Figure 3a) and a nonconformance case (where the CO_2 migrates into the mid-aquifer but remains in the storage unit) (Figure 3b) and noncontainment case (where the CO_2 migrates up the open, subseismic fault, into the shallow aquifer) (Figure 3b) to demonstrate this workflow.

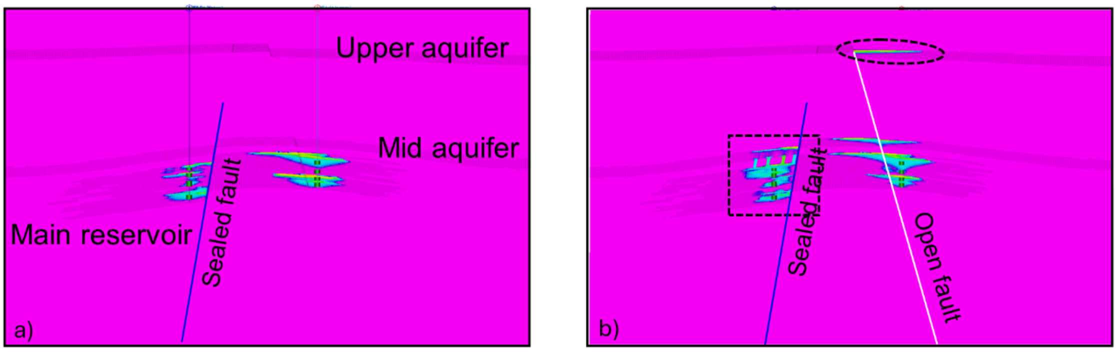

Figure 3 *The SEAM CO_2 model. (a) the conformance case with CO_2 migrating within the main reservoir; (b) the nonconformance case where CO_2 migrates into the mid-aquifer by means of permeability pipes in the caprock (left) and up an open fault (right). The open fault also allows for CO_2 to migrate into the shallow aquifer, which is the noncontainment case.*

QRA

QRA is a new approach that links advanced coupled modelling, sensitivity and uncertainty analysis, probabilistic analysis, and interactive 3D visualisation within risk quantification (Sorgi et al. 2024). The approach, which facilitates informed decision making and risk mitigation strategy, can be used to quantify risks such as fault reactivation, caprock failure or capillary breakthrough, loss of well integrity, unplanned lateral migration, induced seismicity, and seabed/surface elevation. This approach is used to plan the monitoring strategy by identifying areas of high risk.

Wavefield Colouring

Wavefield colouring is a full waveform modelling technique that links regions in the model domain to samples in the data domain. Using a baseline model, samples in the data (acquisition) domain are identified on which to compute statistics that detect changes from baseline data in monitor data. It has the potential to be used with ultralight acquisitions. This implementation is used to provide an early indication of divergence from model conformance (Figure 4).

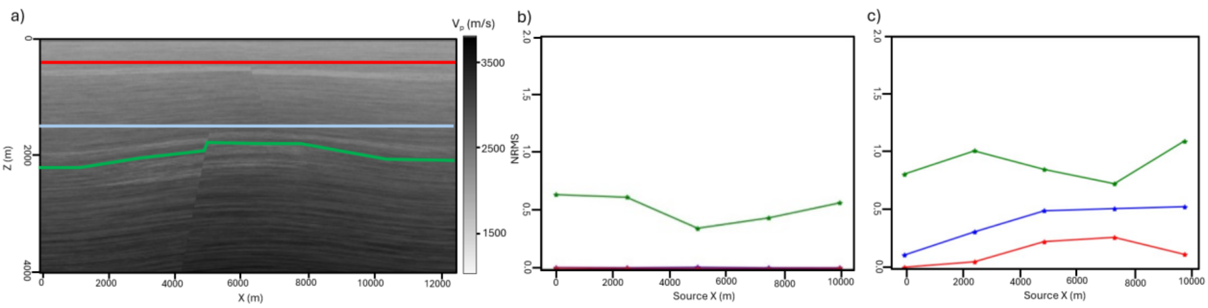

Figure 4 P-wave velocity model with markers indicating the top of zones delineated to track conformance (green), nonconformance (blue) and noncontainment (red). Output of the process indicates change within a given zone, for (b) conformance case and (c) nonconformance, and noncontainment cases.

The subsurface is divided into three zones. Isolating changes in the wavefield can qualify the location of the subsurface change over time and identify when that change is in the main aquifer (green), or when it is occurring in the mid-aquifer (blue) or shallow aquifer (red). This workflow is used in Loop 0 (see Figure 2).

Sparse Monitoring using Full-Waveform Inversion and Adaptive Survey Design

The adaptive survey design process (Halliday et al. 2024) uses predefined monitoring areas; (e.g., areas of risk identified in QRA) to determine the minimum level of effort required to quantify a property change in that area using 4D full-waveform inversion (FWI). The survey has been designed to probe for the conformance and nonconformance cases from Figure 3, and the property update is shown in Figure 5a and Figure 5b, respectively. This survey confirms the triggered warning from Loop 0. The process can be extended to identify whether a noncontainment scenario is present and help optimise additional targeted monitoring (e.g., in conjunction with the QRA output). The change is detected in the data domain but in this case projected into the model space via sparse 4D FWI to aid interpretation.

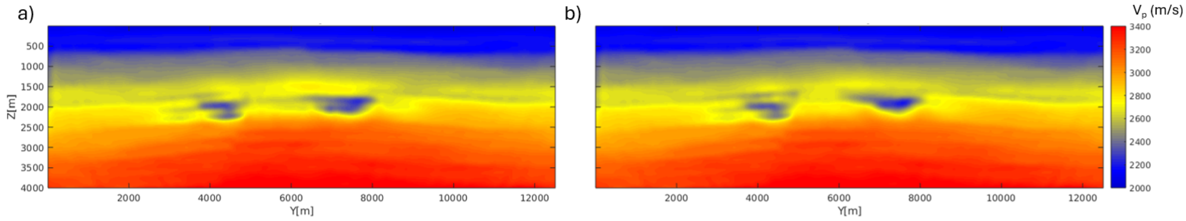

***Figure 5** Property updates achieved by means of sparse 4D FWI for (a) the conformance case and (b) the nonconformance case. The migration of CO_2 into the mid-aquifer is identifiable within the FWI velocity field (b) event for the sparse monitor geometry used in this adaptive survey design.*

Extending the Workflow to 2D and 3D Time-Lapse Seismic (including ML)

Should results of the sparse monitor, designed by the adaptive survey design process and implemented in Loop 1, identify the need for further mitigation and additional recalibration of the subsurface model, the source effort can be increased to record 2D or 3D time-lapse image data, providing access to established workflows for time-lapse characterisation and interpretation. This extended source effort can also be deployed, independent of a detected nonconformance event, at key monitoring milestones to help optimise conformance (e.g., management of injectivity and maximisation of capacity). The data acquisition effort can be further optimised when coupled with ML interpolation and analysis workflows. Hu et al. (2023) show how ML can be used to reconstruct sparse 2D and 3D data by utilising the data-rich environment presented by multiple datasets.

Implementation of Workflow using Surface DAS

This adaptive monitoring workflow is acquisition system agnostic. However, it has been developed to benefit from implementation within the surface distributed acoustic sensing (S-DAS) system (Branston et al. 2024). The benefits presented by the S-DAS system include high-receiver sampling, sensitivity to ultralow frequencies, excellent surface wave, P-wave and S-wave sensitivities and suitability for recording passive ambient or man-made noise (Bachrach et al. 2024). The low sensor cost, and ease of regular data harvesting provide additional benefits for deployment within an adaptive monitoring system, such as facilitating regular evergreening of the subsurface model through a digitally integrated installation. If the S-DAS system is deployed, then additional measurements can be recorded by the same sensor and integrated into the system to further improve cost-efficiency. These include seismicity data and ground upheave data. These measurements are established data inputs for CO_2 monitoring and can be integrated into Loop 0 (see Figure 2). Integration of borehole measurements (including DAS) can also improve the accuracy and cost-efficiency of the system.

Conclusions

An adaptive monitoring system has been developed to facilitate risk-based cost-efficient, multiobjective monitoring of geological storage of CO_2. The monitoring system uses a seismic method to acquire limited, but targeted data to confirm a lack of significant irregularities between the measured and predicted subsurface property change. Should a nonconformance event be detected, the adaptive survey design process can scale the acquisition effort to quantify and mitigate the identified risk. The SEAM CO_2 model has been used to demonstrate the adaptive nature of the system by showing how an unplanned deviation from the base conformance case triggers a response and scale-up of the monitoring system. The system is acquisition-hardware agnostic but has been designed to leverage the benefits of the S-DAS system.

Acknowledgements
The authors thank SLB for permission to present this work and their colleagues for their support, insight, innovation, and collaboration. The SEG Advanced Modeling Corporation (SEAM) is a not-for-profit research entity that manages collaborative projects between sponsoring stakeholders to further geophysical research by industry and academia. We gratefully acknowledge the SEAM CO_2 Project and all participating companies. Participants are Chevron, ConocoPhillips, Oxy, Saudi Aramco, Shell, SLB, Total Energies, and Woodside.

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