Introduction

The Penyu basin, located offshore of the Malaysia peninsula, is a geologically complex sedimentary basin situated south of the Malay Basin, and separated by the Tenggol Arch. Since the 1970s, hydrocarbon exploration in the region has yielded only modest discoveries, largely due to challenges related to complex charge and migration dynamics. However, insights from these exploration efforts suggest that the Penyu basin holds significant potential for geological carbon dioxide storage (GCS) within its Cenozoic aquifer systems. Recognizing this opportunity, Petronas, ADNOC, and Storegga have signed a joint agreement to study and develop carbon capture and storage (PETRONAS, 2024).

To support carbon storage screening, a basin-scale contemporary seismic database has been developed, incorporating 4050 km² of reprocessed and merged legacy data. This integrated seismic program was designed to enhance imaging of the Pari and Penyu sequences, which are expected to contain suitable reservoir and seal units for GCS. The new data set has enabled a detailed mapping of the sedimentary architecture of these units across the basin, facilitating the identification of high-potential GCS sites based on reservoir presence and seal integrity.

The study this paper presents is the first comprehensive assessment of aquifer-based GCS potential in the Penyu Basin, underscoring the important role of both legacy and contemporary seismic data sets play in the GCS screening process.

Basin framework

The Penyu Basin consists of a heavily deformed pre-Tertiary basement, reflecting the collision between the Sukhothai Arc and the Indochina Block. This basement includes granites, carbonates, and clastic metasediments. Overlying this basement, the Cenozoic succession consists of a shallow marine to coastal plain clastic sequence, broadly divided into Eocene to Oligocene syn-rift deposits, and Miocene to recent post-rift sediments (Madon et al., 2019).

A significant Late Miocene inversion event led to compressional folding and uplift, creating regional unconformities, including the Top Pari unconformity, which subdivides the post-rift succession into the Pari and Pilong formations.

The Pari formation has been a primary hydrocarbon exploration target, with previous efforts focusing on four-way closures associated with Sunda inversion structures and basement drapes. Drilling results confirm that the Pari formation contains high-quality fluvial to shallow marine sandstones, making it a suitable reservoir for GCS. Rumbia-1 records average permeabilities within Pari sands of 516 md and a hydrostatic pressure regime. Minimal brittle deformation and low-structural dips, making it well-suited for monoclinal, dip-slope GCS injection and containment.

The geological characteristics of the Pari formations, a high-quality, laterally extensive reservoir overlain by a thick, regionally continuous seal demonstrate strong potential for secure and effective geological carbon storage in the Penyu Basin.

Additional storage opportunities are considered present within the syn-rift Penyu sequence. Numerous reservoirs and a favorable stratigraphic situation beneath regional seals, including the Rhu Shale are positive indicators for a working GCS play. Risk factors include overpressure and faults affecting the syn-rift package.

Seismic processing and imaging

To support GCS, a seismic reprocessing of vintage streamer data was conducted. The legacy seismic data consisted of four surveys acquired between 2004 and 2012 using 5- to 6-km streamer lengths.

A contemporary broadband signal processing workflow was used to broaden the usable frequency range from shallow to deep by eliminating the source and receiver ghosts (Rickett et al. 2014) and attenuating the surface-related multiples.

The surface multiple prediction and attenuation process were separated into two distinct steps. The first step involves a model-based approach that uses a representation of the seafloor. This previous information is combined with the recorded seismic data in the form of 3D Green's functions over a predefined aperture. This method, known as general deterministic water-layer demultiple, effectively captures complex reverberations at and near the seafloor (Kostov et al. 2015). The second step attenuates the remaining surface multiples by using a cascaded implementation of 3D (Dragoset et al. 2008), which is designed to predict reverberations that did not interact with the water and/or sediment interface at and around the seafloor. Multiple models were adaptively subtracted, frequency-dependently, using a cascaded approach from the raw data.

The processed traces were regularised and interpolated using antialiased interpolation, improving the signal-to-noise ratio, and effectively constructing primary diffractions. The fast-track migration was run with the topographically updated 3D earth model and newly processed data. Currently, the goal is to update the velocity model through full waveform inversion and build high-resolution titled transversely isotropic velocity that enable refining the final image.

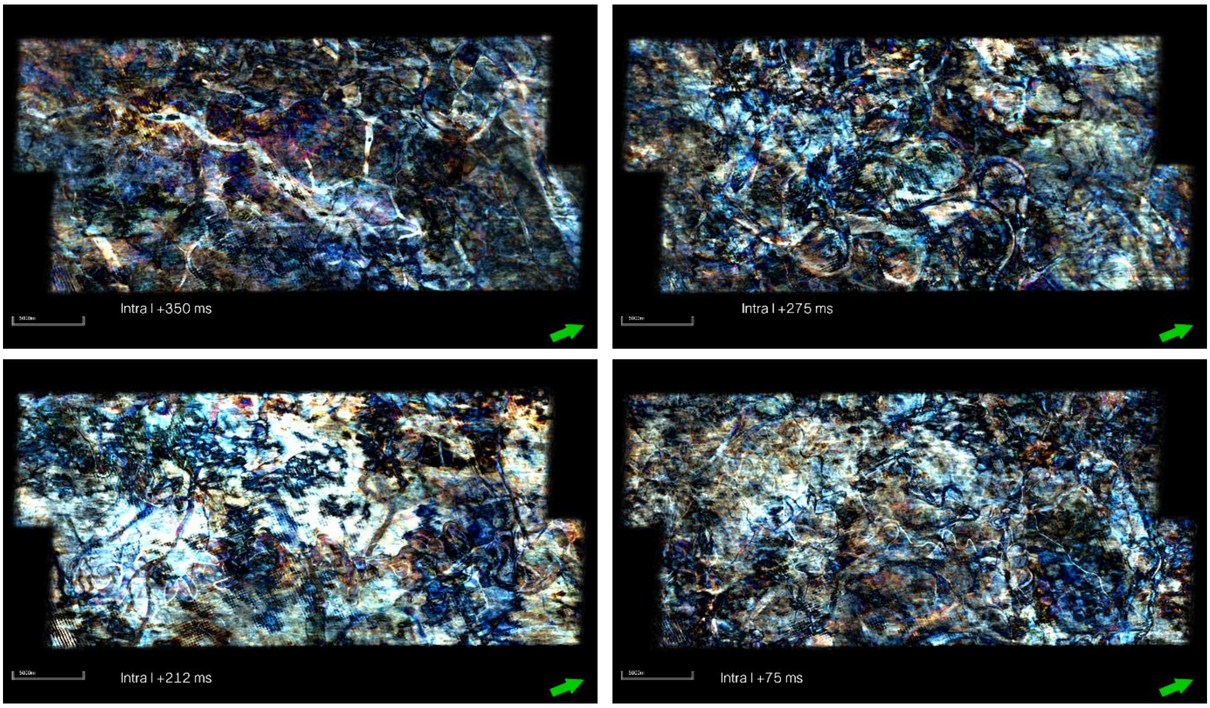

Figure 1- eXchroma sRGB attribute slices of the I Group within the Pari Formation illuminating the complex channel geometries through the sequence. Note the variable channel orientations and transport directions

Screening

We utilized blended RGB seismic attributes for stratigraphic mapping of the Pilong, Pari and Penyu formations to characterize sedimentary architecture and identify potential GCS sites (Figure 1).

The mapping revealed that Group I, representing the lower portion of the mid Pari formation, is highly sand-rich, with sinuous, short-lived distributary channels embedded in a highly heterogeneous package, indicative of a fluvial-dominated shoreline.

Initial basin modeling suggests that the Pilong and upper Pari formations might not achieve the necessary capillary entry pressure thresholds for long-term CO_2 storage. However, threshold entry pressures exceeding 0.8 MPa, which are conducive to CO_2 confinement, have been modelled within the

Lower Pari formation at depths greater than 1500 meters. This condition indicates that the lower portion of the Pari formation can support GCS (Tu et al. 2023).

Storage opportunities within the syn-rift sequences present different challenges. Hydrocarbon exploration and basin modelling indicate that both the Rhu and Terengganu shales can act as robust GCS seals. However, faults extending through these units pose potential leakage pathways. Additionally, reported overpressure within the Penyu formation may well limit its suitability for CO_2 injection and reduce the overall storage capacity at this level.

These geological models and maps were integrated into a common risk segment approach to pinpoint GCS sweet spots. Reservoir presence maps derived from seismic attribute analysis were combined with basin modelling results and structural and stratigraphic surfaces such as seal thickness and reservoir depth to identify viable GCS locations.

Summary

The mapping of the post- and syn-rift sequences using new seismic data in the Penyu Basin reaffirmed the area's potential for GCS. By integrating legacy well information and basin modelling, seismic mapping identified suitable reservoir characteristics, including presence, thickness, depth, and structure, within the Pari and Penyu formations. Storage risks such as shallow-seal validity particularly within the Pilong formation and deeper syn-rift overpressure have also been highlighted.

The analysis contained in this paper concurs with that of de-Jonge Anderson et al. (2024), which showed Groups I and H are promising for GCS within the Penyu Basin. The study presented in this paper also underscores the value of modern seismic data in the GCS screening process, particularly its capability to inform basin-scale depositional models.

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