

Machine-Learning-Assisted Seismic Facies Screening of Reservoir-Seal Architecture for CO₂ Storage in the Nong Phak Chi Field, Thailand

Rattanaorn Thongson^{1*} and Sukonmeth Jitmahantakul²

¹ M.Sc. Program in Energy Geosciences, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

² Center of Excellence in Applied Mineral and Petrology, Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok, 10330 Thailand

*Corresponding author: rattanaorn.thongson@gmail.com

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Abstract

Geological carbon capture and storage (CCS) requires secure reservoir-seal systems and robust assessment of additional containment. This study screens for potential secondary CO₂-containment pairs and additional reservoir candidates in the depleted Nong Phak Chi field, Suphan Buri Basin, Thailand. The workflow integrates Relative Geological Time (RGT) modelling, horizon-stack interpretation, multi-attribute seismic facies classification using an Unsupervised Vector Quantizer (UVQ) neural network, and Lithological interpretation using well calibration across four wells. A seven-attribute dataset derived from the conditioned 3D seismic volume was partitioned into three seismic facies classes. After calibration with well-log data, the classes were interpreted as sandstone prone, silty sandstone prone, and shale prone facies. The UVQ model produced a 94% average vector-matching score, which indicates internal classification consistency rather than independent lithological prediction accuracy. Horizon24/S5 (H24/S5) is the preferred primary reservoir candidate for CO₂ injection, and the overlying shale-rich H53 is the interpreted primary seal. H58 is a potential CO₂ accumulation interval above the primary reservoir-seal system, and H62 is a potential upper seal. Together, H58-H62 form the most plausible candidate additional containment pair. In contrast, H9/D6 lies below S5 and is therefore treated as a separate deeper reservoir candidate for dedicated CO₂ injection, not as a secondary trap or additional containment interval. The results indicate a multilayer reservoir-seal architecture in the Nong Phak Chi field. Confirmation of long-term storage performance will require petrophysical analysis, fault-seal assessment, static reservoir modelling, dynamic CO₂ flow simulation, and geochemical and geomechanically evaluation.

Keywords: Geological CO₂ storage; seismic facies classification; additional containment; Relative Geological Time modelling; Nong Phak Chi field.

1. Introduction

Carbon capture and storage (CCS) is widely recognized as an important option for reducing anthropogenic CO₂ emissions, particularly in industrial sectors in which direct emissions reduction is technically or economically challenging. Geological CO₂ can be stored in several types of deep subsurface formations, including deep saline aquifers, depleted oil and gas reservoirs, coal seams, and basalt formations. Depleted oil and gas reservoirs are widely considered suitable storage sites because they have retained hydrocarbons over geological timescales, are supported by extensive geological and production data, and often have existing infrastructure that can be used for CO₂ storage operations (Bachu, 2000; Massarweh & Abushaikh, 2024).

The long-term effectiveness of geological CO₂ storage depends on reservoir capacity and injectivity, caprock integrity, and the absence of transmissive leakage pathways. Structural, residual, solubility, and mineral trapping all contribute to storage security, although structural and stratigraphic trapping generally dominate immediately after injection (Massarweh and Abushaikh, 2024). Key uncertainties include reservoir heterogeneity, fault connectivity, and pressure-driven migration. Consequently, screening for additional containment is an important component of site evaluation and risk management (Bachu, 2008). Here, a candidate additional containment pair is defined as a reservoir prone interval outside the primary reservoir-seal system together with a plausible overlying seal prone interval along a credible

CO₂-migration pathway. Neither component in isolation constitutes a trap.

Seismic facies analysis is widely used to characterize subsurface heterogeneity and map reservoir prone lithologies from seismic reflection data (Owusu et al., 2024). Machine-learning methods can improve the speed and reproducibility of facies interpretation across large 3D datasets and reduce interpreter-dependent variability. However, seismic facies classes are indirect geophysical responses, not lithologies. They require calibration with well logs and should be reported with appropriate uncertainty.

In this study, the D5 or S5 sandstone was selected as the primary CO₂ storage reservoir because it has a proven hydrocarbon accumulation and production history in the Nong Phak Chi field and favorable reservoir characteristics documented in the available well data. Machine-learning-assisted seismic facies analysis has been widely applied to reservoir characterization and lithological interpretation (Jin, 2018; Owusu et al., 2024). This study applies the approach to support the geological screening of potential reservoir-seal pairs for additional containment of CO₂ migrating beyond the primary storage reservoir (S5) in the Nong Phak Chi depleted hydrocarbon field. The study integrates Relative Geological Time (RGT) modelling, horizon-stack interpretation, multi-attribute seismic facies classification using an Unsupervised Vector Quantizer (UVQ), and seismic facies interpretation using well-log correlation. The conceptual framework for the additional containment systems evaluated in this study is illustrated in Figure 1.

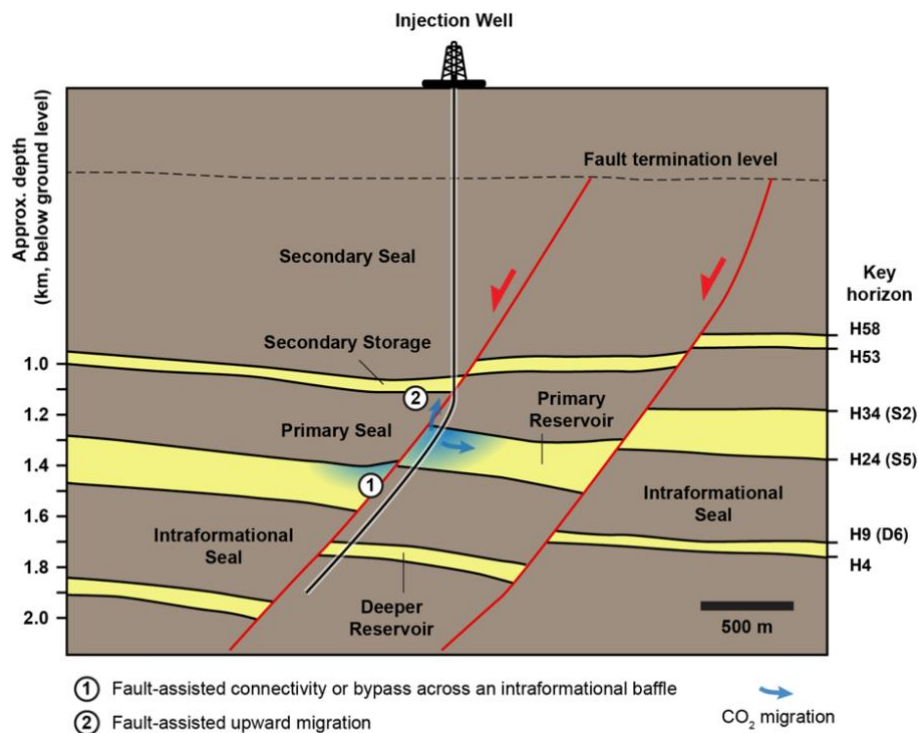


Figure 1. Conceptual, not simulated, storage architecture. H24/S5 is the preferred primary reservoir candidate for CO₂ injection, H53 is the interpreted primary seal, H58 is a potential CO₂ accumulation interval with H62 as a potential upper seal, and H9/D6 is a separate deeper reservoir candidate requiring dedicated injection and its own containment assessment. Faults may act as barriers or conduits; CO₂ plumes and arrows are schematic.

2. Geological Setting

The Nong Phak Chi (NPI) field lies in the southern Suphan Buri Basin, approximately 85 km northwest of Bangkok in Thailand's lower Central Plain (Fig. 2a). The basin is one of several Cenozoic continental rifts in central Thailand and forms part of an established onshore petroleum province. Hydrocarbons in the NPI field occur in Miocene sandstones of Unit D, including the D2 (or S2), D5 (or S5), D6, and D7 intervals (Morley and Racey, 2011)

The Suphan Buri Basin developed during Late Eocene-Miocene extension associated with regional tectonic reorganization after the India-Eurasia collision. It is a north-south trending half-graben bounded by major normal

faults between the Mae Ping and Three Pagodas fault zones. Basin evolution was influenced by both high-angle and low-angle boundary fault systems, which controlled accommodation, sediment distribution, and reservoir architecture (Fig. 2b).

The basin fill comprises Late Oligocene to Recent continental strata divided into five lithostratigraphic units (A-E; Fig. 3). Units A to C represent the early syn-rift succession and consist predominantly of conglomerate, sandstone, siltstone, mudstone, and shale deposited in alluvial, lacustrine, and fluvio-deltaic environments. Middle to Late Miocene

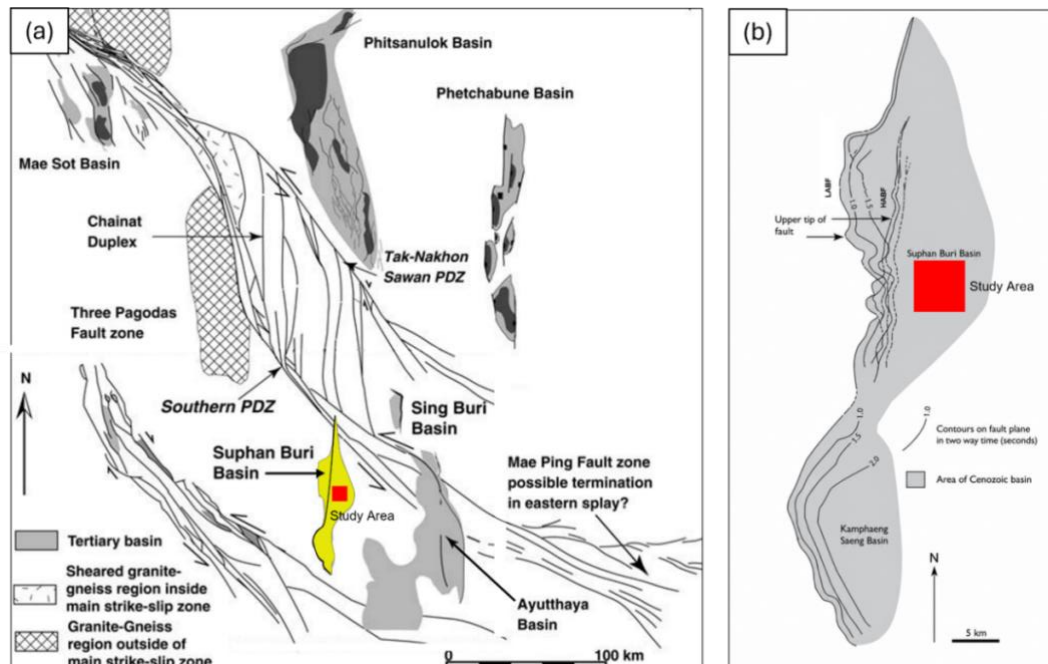


Figure 2. (a) Location of the Suphan Buri Basin in central Thailand relative to the Mae Ping and Three Pagodas fault zones. (b) Interpreted boundary faults of the Suphan Buri and Kamphaeng Saeng basins based on 2D seismic-reflection data. LABF, low-angle boundary fault; HABF, high-angle boundary fault. Modified from Morley et al. (2011).

Unit D comprises interbedded sandstone, siltstone, and mudstone deposited in fluvio-lacustrine settings and hosts the principal hydrocarbon reservoirs. Unit E records the transition from syn-rift to post-rift sedimentation, with a lower mudstone- and siltstone-dominated interval overlain by predominantly fluvio-alluvial sands and gravels (Morley and Racey, 2011).

Unit D contains multiple sandstone reservoirs interbedded with mudstone and siltstone rich intervals (Fig. 3). This heterolytic succession creates a vertically stacked reservoir-seal architecture that could partition fluid flow and influence CO₂ containment. Accordingly, storage security may depend not only on the regional caprock but also on the continuity and capillary properties of intraformational shale- and mudstone-rich units.

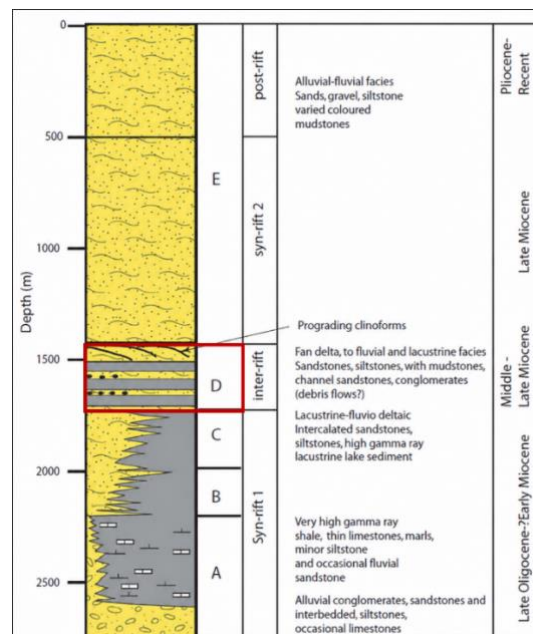


Figure 3. Stratigraphic column of the Suphan Buri Basin; Unit D, which contains the principal reservoir succession, is outlined in red. Modified from Morley and Racey (2011).

3. Methodology

This study used a 3D seismic survey covering approximately 36.5 km² in Block L54/43, Nong Phak Chi area. The volume has a 2 ms sample interval, a 6.0 s two-way-time record length, a 25 m × 50 m bin size, and the vertical seismic resolution is estimated to be approximately 10-20 m. Gamma-ray, density, neutron-porosity, sonic, and resistivity logs from four wells were integrated with the seismic data for facies calibration and seismic-to-well correlation. The workflow is summarized in Figure 4

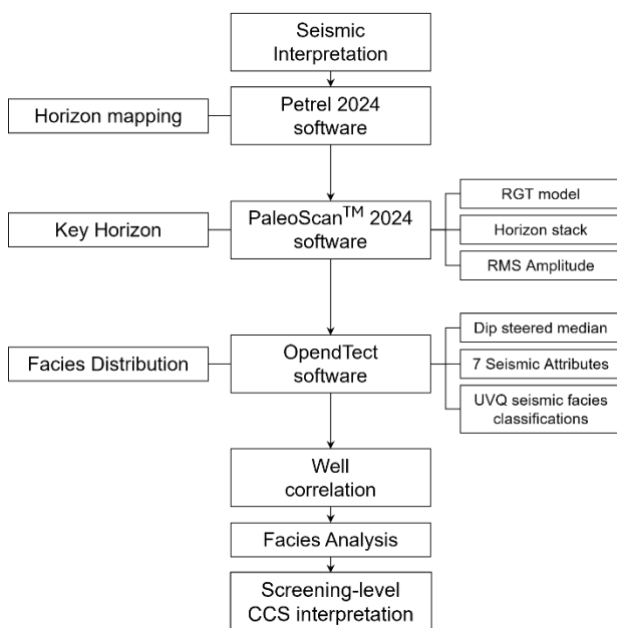


Figure 4. Study workflow: seismic interpretation and conditioning; RGT-model and horizon-stack generation; extraction of seven seismic attributes; UVQ facies classification; seismic facies interpretation using well-log correlation; and screening of the preferred primary injection reservoir candidate, a candidate additional containment, and a separate deeper reservoir candidate.

3.1. RGT modelling and horizon-stack generation

An RGT model was generated in PaleoScan™ 2024 to establish a chronostratigraphic framework. Approximately 100 chronostratigraphic surfaces were extracted as a horizon stack. Root Mean Square (RMS) Amplitude was calculated along each surface to screen for intervals with distinct amplitude responses and to select representative horizons for detailed facies analysis. Selection considered both RMS amplitude character and stratigraphic position relative to known reservoir and seal markers.

3.2. Seismic facies classification

The selected horizons and seismic volume were exported to OpendTect. A dip-steered median filter (Owusu et al., 2024) was applied to improve reflector continuity and suppress random noise (Fig. 5). Seven attributes were computed from the conditioned volume: instantaneous bandwidth, energy, RMS amplitude, instantaneous quality factor, sweetness, instantaneous amplitude, and the natural logarithm of instantaneous frequency. Together, these attributes describe variations in amplitude, frequency, attenuation, and reflector continuity that may be associated with changes in lithology or depositional architecture.

Seismic facies were classified using an Unsupervised Vector Quantizer (UVQ) neural network, which performs competitive-learning clustering without lithological labels during model training (Ross and Cole, 2017; Owusu et al., 2024). The number of output clusters was predefined as three to represent the dominant lithological variability inferred from the available well-log data. This prior geological knowledge was used only to specify the model

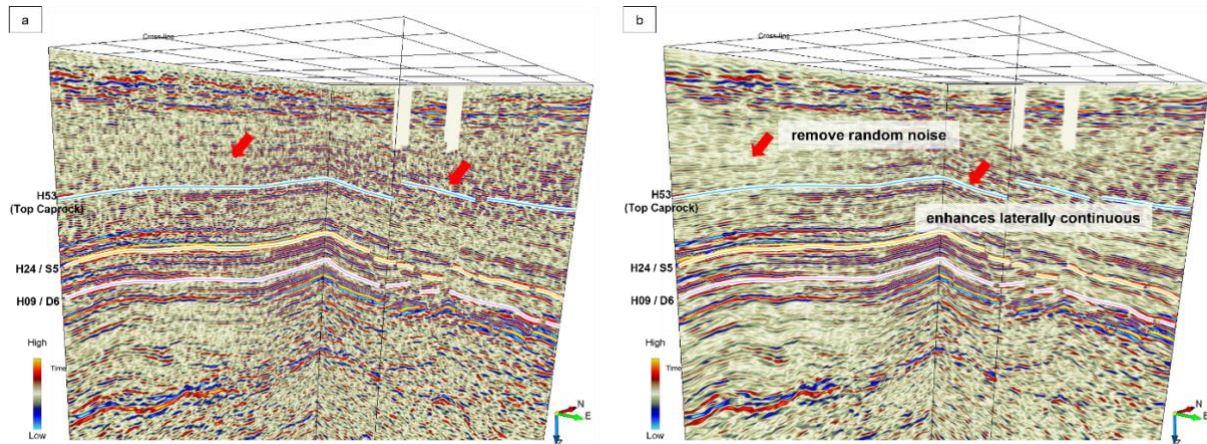


Figure 5. Seismic volume (a) before and (b) after dip-steered median filtering. The conditioned volume shows reduced random noise and improved lateral reflector continuity at the locations marked by red arrows.

parameter (number of clusters) and did not guide or supervise the clustering process. Consequently, the clustering remained unsupervised. Following classification, the resulting clusters were calibrated against gamma-ray, density, neutron-porosity, sonic, and resistivity logs from wells A–D to assign their geological significance as sandstone, silty sandstone, and shale. Model convergence was monitored using the average vector-matching percentage reported by the UVQ algorithm. During training, the cluster prototypes were iteratively updated until the average matching score stabilized. This metric was used to assess the internal convergence of the clustering process and does not represent an independent measure of lithological classification accuracy.

3.3. Seismic facies interpretation using well-log correlation

Following seismic facies classification, the interpreted facies were correlated with available well logs from four exploration wells (NPI-A, NPI-B, NPI-C, and NPI-D) to establish their geological significance. The classified seismic facies were compared with the corresponding stratigraphic intervals at each well using formation markers together with gamma-ray (GR), bulk density (RHOB), neutron porosity (NPHI), compressional sonic (DT), and resistivity logs. Lithological descriptions from the final well reports were used to support the interpretation of each facies class. Characteristic log responses were used to interpret the seismic facies as sandstone dominated, silty sandstone, or shale dominated intervals. The interpreted facies distribution was then used to delineate reservoir prone and seal prone intervals and to identify intervals with potential for additional containment of CO₂ within the study area.

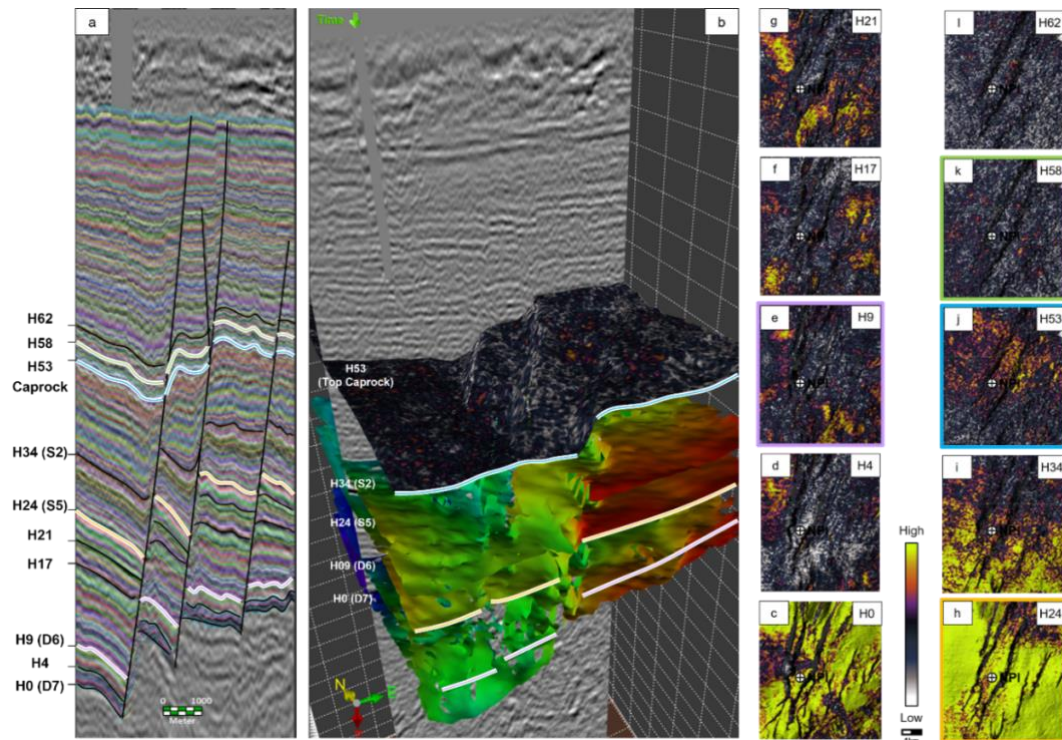


Figure 6. Relative geological time (RGT) framework and selected RMS amplitude horizon slices. (a) RGT horizon stack along inline 1950; (b) 3D stratigraphic surfaces; and RMS amplitude slices for (c) H0/D7, (d) H4, (e) H9/D6, (f) H17, (g) H21, (h) H24/S5, (i) H34/S2, (j) H53, (k) H58, and (l) H62. Colored outlines indicate the key reservoir and seal intervals discussed in this study.

4. Results

4.1. RGT modelling and horizon-stack selection

The RGT model generated approximately 100 chronostratigraphic horizon-stack surfaces. Examination of RMS amplitude extracted along these surfaces revealed distinct lateral variations in seismic response throughout the stratigraphic succession. Calibration with the four exploration wells showed that these amplitude patterns were consistently associated with different lithological intervals. Relatively high amplitude responses corresponded predominantly to sandstone prone intervals, whereas lower-amplitude and more uniform responses were associated with shale prone

intervals. Based on these calibrated seismic responses, ten representative horizons were selected to capture the principal reservoir and sealing intervals within the study area. These comprise H62, H58, H53, H34/S2, H24/S5, H21, H17, H9/D6, H4, and H0/D7 (Fig. 6).

4.2. Seismic facies classification

The UVQ network integrated the seven seismic attributes and partitioned the selected horizons into three output clusters with similar multi attribute responses (Fig. 7). The clusters were initially numerical and acquired geological meaning only after calibration with the available well-log data. The average vector-matching

percentage increased progressively during training and stabilized at 94% (Fig. 8),

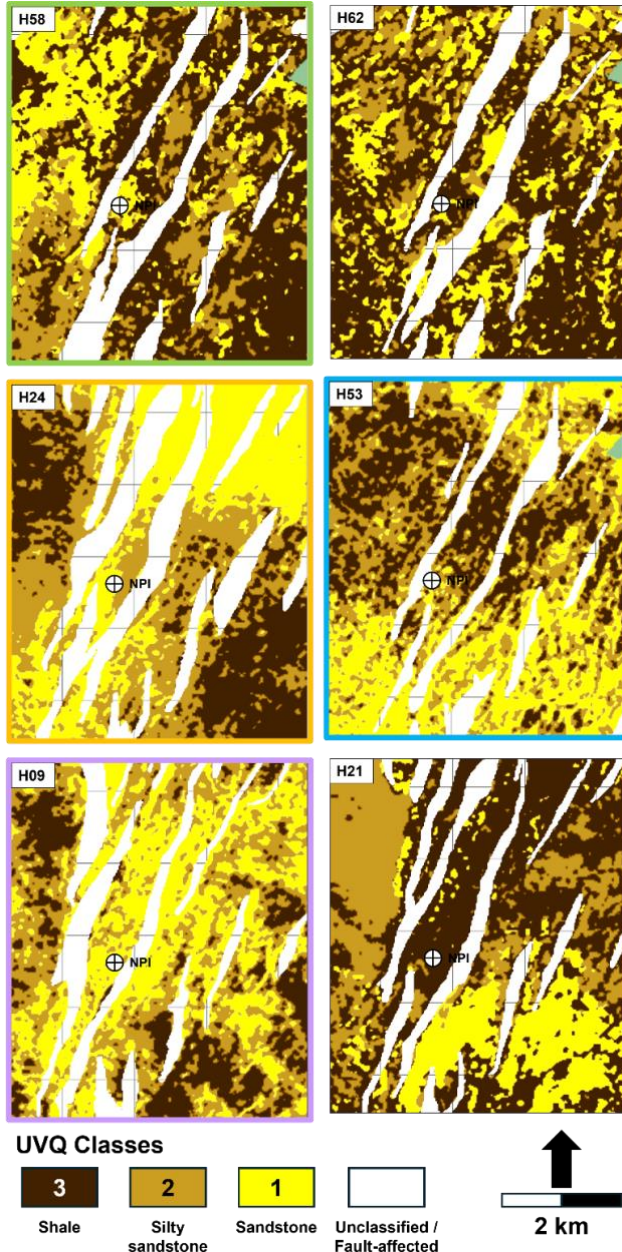


Figure 7. UVQ facies maps for H9/D6, H21, H24/S5, H53, H58, and H62. After well calibration, yellow, light brown, and dark brown indicate sandstone, silty sandstone, and shale prone facies, respectively; white areas are unclassified or fault affected.

indicating stable convergence of the clustering process. This metric reflects the internal consistency of the clustering process and should not be interpreted as an independent measure of lithological classification accuracy. The classified horizons exhibit systematic vertical variations in cluster distribution. Cluster 3 (dark brown) dominates horizons H62, H21, and H4, Cluster 2 (light brown) is prevalent on H53, H17, and H0/D7, whereas Cluster 1 (yellow) predominates on H58, H34/S2, H24/S5, and H9/D6. The resulting cluster distribution formed the basis for subsequent geological interpretation.

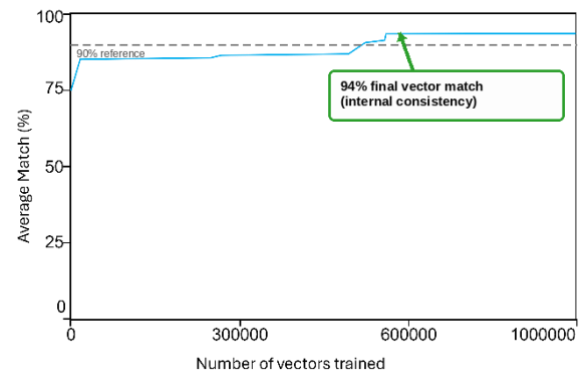


Figure 8. UVQ training curve shows average vector match versus the number of training vectors. The model stabilizes at approximately 94%; the dashed 90% line is a visual reference. The score measures internal classification consistency, not independent lithological accuracy.

4.3. Lithological interpretation using well-log correlation

Calibration against the four available wells (NPI-A, NPI-B, NPI-C, and NPI-D) established the lithological interpretation of the three UVQ-derived facies classes. Figure 9 shows Well NPI-A as a representative example of the calibration. Petrophysical log calibration identified Facies Class 1 (yellow) as sandstone

prone, Facies Class 2 (light brown) as silty sandstone prone with locally carbonate bearing intervals, and Facies Class 3 (dark brown) as shale prone. The interpreted facies classes were subsequently mapped across the study area to characterize their spatial distribution.

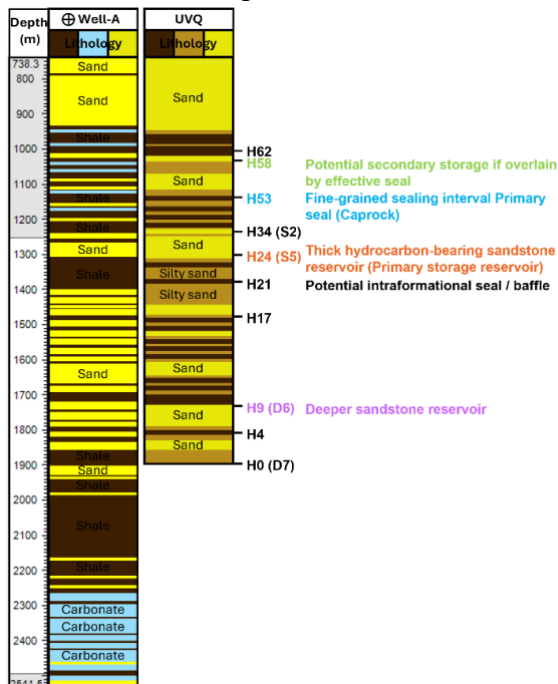


Figure 9. Comparison between interpreted lithology in Well NPI-A and the corresponding UVQ facies column, with key horizons marked.

5. Discussion

5.1. Reservoir and seal interpretation

Well-log calibration established three seismic-response facies comprising sandstone prone, silty sandstone prone with locally carbonate bearing intervals, and shale prone facies. Sandstone prone facies dominate H58, H34/S2, H24/S5, and H9/D6, whereas shale prone facies characterize H62, H21, and H4. Silty sandstone prone facies with locally carbonate bearing intervals are predominant on H53, H17, and H0/D7. These interpretations represent the dominant seismic response facies

within the calibrated area surrounding the available wells and the proposed CO₂ storage interval, rather than implying uniform lithology across the entire interpreted horizons.

Among the interpreted intervals, H24/S5 is identified as the most prospective storage reservoir because it corresponds to the producing S5 sandstone and is associated with relatively thick sandstone, high hydrocarbon net pay, and favorable porosity and permeability reported from the available well data. The correspondence between the sandstone prone seismic facies and the reservoir interval identified from the well data further supports its selection as the primary storage reservoir for geological CO₂ storage.

H53 directly overlies the H24/S5 reservoir and corresponds to the interpreted top caprock horizon. Although the UVQ classification indicates predominantly silty sandstone prone facies at this level, the horizon was selected as the principal sealing interval based on its stratigraphic position immediately above the primary reservoir and its correlation with the interpreted top caprock identified from the available well data. This interpretation therefore integrates seismic facies classification with geological and stratigraphic interpretation rather than relying solely on seismic facies.

The interpreted reservoir-seal architecture demonstrates that machine-learning-assisted seismic facies classification provides an effective screening tool for identifying potential storage intervals in the Nong Phak Chi field. However, the interpreted facies represent seismic-response facies calibrated with limited well control and should not be regarded as direct lithological classifications. Consequently, the reservoir and sealing intervals identified in this

study represent geological screening results that require further validation through detailed petrophysical evaluation, caprock characterization, and seal-capacity assessment.

5.2. Reservoir-seal architecture and implications for additional containment

A key outcome of this study is that the geological role of an interpreted horizon cannot be determined from seismic facies classification alone. Instead, the screening interpretation depends on integrating seismic facies, well-log calibration, and stratigraphic relationships within the three-dimensional geological framework (Table 1; Fig. 1). This integrated approach allows horizons with similar seismic-response facies to be assigned different geological roles according to their position within the storage system, providing a more robust basis for evaluating potential CO₂ storage architecture.

This relationship is particularly evident for sandstone prone horizons. Although H24/S5, H34/S2, H58, and H9/D6 are all classified as sandstone prone, they represent different components of the interpreted storage system (Table 1). H24/S5 is interpreted as the preferred primary storage reservoir, whereas H34/S2 forms an additional sandstone interval within the primary storage succession. H58 is interpreted as a potential CO₂ accumulation interval because it occurs above the primary storage system, while H9/D6 represents a separate deeper storage candidate. These differences demonstrate that the geological significance of a reservoir interval is controlled by its structural and stratigraphic context rather than by seismic facies alone.

A similar observation applies to H53. Although the UVQ classification identifies this

horizon predominantly as silty sandstone prone, it is interpreted as the primary caprock because it directly overlies the S5 reservoir and corresponds to the mapped top caprock horizon identified from seismic interpretation and well-log calibration. This finding demonstrates that machine-learning-assisted seismic facies classification provides an effective framework for geological screening, but the interpretation of reservoir and sealing intervals requires integration with independent geological constraints.

The conceptual storage architecture shown in Figure 1 further illustrates that the potential for additional containment depends primarily on the vertical arrangement of reservoir and overlying sealing intervals rather than on the occurrence of an individual sandstone or shale unit. Consequently, the H58 to H62 succession is interpreted as a potential additional containment system because it forms an upper reservoir-seal association above the primary storage interval. However, this interpretation remains conceptual because the storage performance of H58 and the sealing effectiveness of H62 were not evaluated in the present study.

H9/D6 is interpreted primarily as a separate deeper storage candidate because of its position beneath the primary storage system. Nevertheless, in structurally complex rift basins, downward migration into deeper reservoirs cannot be excluded if fault connectivity modifies the expected migration pathway. This possibility was not evaluated in the present study and therefore remains beyond the scope of this screening assessment. Accordingly, H9/D6 should be regarded as a potential alternative storage target rather than part of the additional containment system proposed above the primary storage reservoir.

The integrated interpretation developed in this study is consistent with the geological storage-screening framework proposed by Metz et al. (2005), which emphasizes the integration of reservoir, seal, and structural relationships during site evaluation. By combining relative geological time modelling, horizon-based seismic facies classification, well-log calibration, and geological interpretation, this study extends that framework by identifying both the primary storage system and potential additional containment within the Nong Phak Chi field. Nevertheless, the geological roles summarized in Table 1 and illustrated in Figure 1 represent screening-level interpretations and should be regarded as hypotheses requiring further validation. Additional petrophysical characterization, caprock assessment, fault-seal analysis, and dynamic reservoir simulation will be required before the proposed storage architecture can be

confirmed for long-term geological CO₂ storage (Metz et al., 2005; NETL, 2017).

5.3. Study limitations and future work

The present study represents a geological screening assessment and should be interpreted within that context. Although the integrated workflow successfully identifies potential reservoir, seal, and additional containment intervals, it does not evaluate storage capacity, injectivity, seal performance, fault behavior, or long-term CO₂ migration.

Future studies should focus on quantitative reservoir characterization through detailed petrophysical analysis, caprock evaluation, fault-seal assessment, static geological modelling, and dynamic reservoir simulation. Incorporating additional well and core data would further improve the geological interpretation and reduce uncertainty in evaluating the CO₂ storage potential of the Nong Phak Chi field.

Table 1. Screening-level interpretation of key horizons and their potential CCS significance. Terminology follows Metz et al. (2005), NETL (2017), and ISO (2026). Reservoir, seal, baffle, and accumulation labels are provisional and require the listed validation; no horizon is confirmed as a trap or injection reservoir.

Horizon	Dominant facies	Screening interpretation	Screening level CCS role	Confidence/key uncertainty
H62	Shale-dominated	Seal prone	Potential secondary seal above H58	High: shale prone facies are well supported; thickness, lateral continuity, capillary entry pressure, and fault integrity require confirmation.

Horizon	Dominant facies	Screening interpretation	Screening level CCS role	Confidence/key uncertainty
H58	Mixed sandstone, limestone conglomerate	Heterogeneous ; locally reservoir prone	Potential secondary CO ₂ accumulation/storage interval beneath H62, conditional on reservoir quality and an effective overlying seal	Moderate: mixed lithology, porosity/permeability, structural or stratigraphic closure, migration connectivity, and seal continuity are unverified.
H53	Shale rich with silty sandstone interbeds	Seal prone	Primary caprock candidate above H24/S5	High: facies and stratigraphic position are well supported; capillary entry pressure, thickness/continuity, and fault/well integrity require evaluation.
H34/S2	Sandstone dominated	Reservoir prone	Additional upper reservoir interval within the storage complex; possible internal accumulation interval beneath H53	Moderate: local closure, connectivity to S5, reservoir quality, and internal seals require assessment.
H24/S5	Sandstone dominated; known hydrocarbon pay	Reservoir prone	Primary CO ₂ storage-reservoir candidate and intended injection target	High: reservoir occurrence is well supported; capacity, injectivity, pressure limits, fluid-rock interactions, and well integrity require quantification.
H21	Shale-dominated	Seal- or baffle prone	Potential intraformational seal or baffle within the lower storage succession	Moderate: thickness, continuity, fault juxtaposition, and capillary sealing capacity remain uncertain.
H17	Silty sandstone dominated	Transitional; baffle prone	Potential flow-retarding baffle or low-quality reservoir interval	Low-moderate: permeability contrast, reservoir quality, and lateral continuity are poorly constrained.
H9/D6	Sandstone dominated	Reservoir prone	Deeper alternative storage-reservoir candidate for dedicated injection; not an additional containment interval	Moderate: an independent seal, capacity/injectivity, pressure regime, fault connectivity, and well integrity require assessment.
H4	Shale dominated	Seal or baffle prone	Potential intraformational seal above H0/D7	Moderate: lateral continuity, thickness, and capillary sealing capacity are unverified.

Horizon	Dominant facies	Screening interpretation	Screening level CCS role	Confidence/key uncertainty
H0/D7	Sandstone dominated	Reservoir prone	Additional deeper reservoir interval within the storage complex	Low-moderate: calibration is limited; reservoir quality, connectivity, and an independent seal require assessment.

6. Conclusion

This study integrated RGT modelling, horizon-stack analysis, seven-attribute UVQ classification, and calibration with four wells to screen potential reservoir- and seal prone intervals in the Nong Phak Chi field.

The UVQ model produced three seismic facies classes and a 94% average vector-matching score. After well calibration, the classes were interpreted as sandstone prone, silty sandstone prone, and shale prone; the score indicates internal cluster consistency rather than independent lithological accuracy. H24/S5 is the preferred primary reservoir candidate for CO₂ injection and H53/top caprock is the interpreted primary seal. H34/S2 is an additional reservoir prone unit within the primary reservoir-seal system, H58 is a potential CO₂ accumulation interval, and H62 is its potential upper seal.

Together, H58-H62 form the most plausible candidate additional containment because they lie above the primary reservoir-seal system and are positioned to intercept buoyancy-driven upward migration. By contrast, H9/D6 lies below S5 and should be treated as a separate deeper reservoir candidate for dedicated CO₂ injection, not as a secondary trap or additional containment.

These interpretations remain screening hypotheses. Storage capacity, injectivity, capillary sealing, fault behavior, pressure evolution, geochemical compatibility, and geomechanically stability must be tested

through integrated petrophysical, structural, static, dynamic, geochemical, and geomechanically studies before the field's long-term CO₂ storage performance can be assessed.

7. Acknowledgments

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8. Data availability

The data used in this study are proprietary and were obtained from PTT Exploration and Production Public Company Limited. Therefore, the seismic and well-log datasets cannot be shared publicly.

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