Introduction

Geological carbon dioxide storage (GCS) is recognised as a key strategy for reducing anthropogenic CO_2 emissions in India (IEA, 2006; Bachu, 2008; Pingping, Xinwei, & Qiujie, 2009). Assam, being the country's oldest hydrocarbon-producing province, offers a favourable environment for GCS due to its mature, depleted reservoirs, robust subsurface datasets, and existing oil and gas infrastructure. These attributes position Assam as a viable candidate for secure and long-term CO_2 sequestration. Within the wider scope of Carbon Capture, Utilisation, and Storage (CCUS), GCS is increasingly viewed as a critical component of India's climate mitigation framework (IEAGHG, 2022).
However, ensuring containment security in structurally complex basins such as the Upper Assam Basin requires a detailed understanding of fault systems and stress regimes. The region is characterised by extensional and strike-slip fault networks that present potential pathways for leakage and induced seismicity if fault reactivation occurs. A key technical challenge is controlling pore pressure increases linked to CO_2 injection, which can reduce normal stresses on faults and promote shear failure. Further complications arise from uncertainties in well-log interpretation due to measurement inaccuracies, resolution constraints, borehole conditions, and variable fluid compositions. Mitigating these risks demands integrated workflows that combine high-resolution seismic data, advanced geomechanical modelling, and iterative updates to structural frameworks for reliable CO_2 storage assessments.

Method

This study applies a multidisciplinary approach to assess the fault slip potential and associated risks of CO_2 storage in the Naharkatiya field, Upper Assam Basin, India. The methodology combines seismic data interpretation, structural analysis, and quantitative geomechanical modelling through Fault Slip Potential (FSP) analysis to evaluate fault stability under various injection scenarios.
1. Seismic Data Acquisition and Processing

- Conventional 3D pre-stack time-migrated (PreSTM) seismic data from the Naharkatiya field were utilised, covering an area of approximately 230 km². The seismic survey was conducted using a bin size of 50 m x 25 m, with inlines oriented north-south and crosslines east-west.
- Seismic data underwent several enhancement processes:
- Amplitude Balancing: Corrected amplitude variations using RMS amplitude scaling to achieve trace-to-trace amplitude consistency.
- Spectral Blueing: Enhanced high-frequency content to increase resolution and match the spectrum to well-log data.
- Coherency Filtering: Applied structure-oriented filters to preserve faults and reduce random noise, improving fault delineation.
- Fault Attribute Analysis: Employed advanced algorithms (e.g., semblance-based and gradient structure tensor methods) to generate fault likelihood volumes, highlighting fault networks critical for structural interpretation.

2. Structural Interpretation
The processed seismic data were analysed to delineate major and minor faults within two principal reservoir formations, one of which is depicted in Figure 1. Structural interpretation identified normal and strike-slip faults using seismic sections and attribute maps. The major faults were classified by orientation (NE-SW and N-S trends), dip angles (60° to 80°), and sigmoidal, relay ramp, horse-splay geometries, exhibiting listric profiles at depth and minor faults trending orthogonally in map view (Figure 1). Particular focus was placed on zones exhibiting fault reactivation potential, focusing on areas with complex fault interactions and sediment compartmentalisation.
3. Geomechanical Model Development
The geomechanical model integrates:
Fault Geometry: Strike and dip angles derived from seismic data.
Reservoir Properties: Porosity, permeability, and thickness data from well-log interpretation.

In-Situ Stress Regime: Assumed normal and strike-slip faulting regimes based on regional tectonics, using values for vertical stress (Sv), maximum horizontal stress (Shmax), and minimum horizontal stress (Shmin).
Material Properties: Parameters such as rock friction coefficient (assumed default of 0.6), rock compressibility, and fault gouge properties were incorporated.

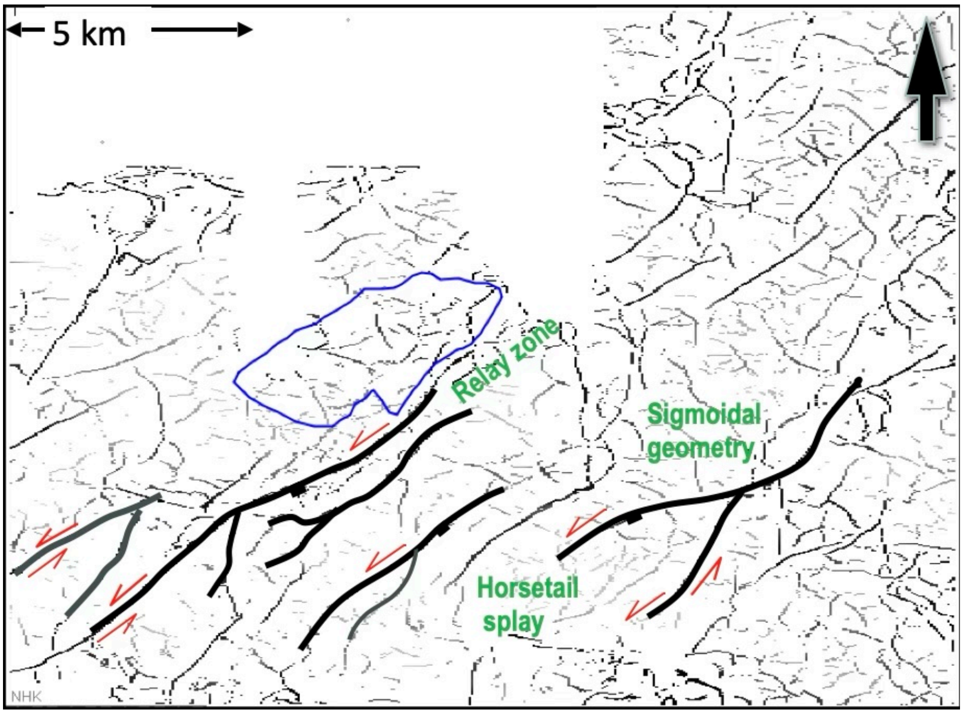

Figure 1 Attribute map from a key reservoir zone illustrating major (dark grey to black) and minor (light grey) fault systems. The major faults trend predominantly northeast-southwest, while the minor faults are primarily oriented orthogonally to them. The major faults exhibit sigmoidal geometries, with minor faults splaying from their tips and sometimes forming relay structures. Red arrows indicate the direction of fault movement.

4. Fault Slip Potential (FSP) Modelling
FSP analysis was conducted using a Monte Carlo-based probabilistic model (Walsh & Zoback, 2016), accounting for uncertainties in input parameters. The model calculates the likelihood of fault reactivation based on Mohr-Coulomb slip criteria.
Pore Pressure Calculations: Pore pressure increases due to fluid injection were estimated using the Hsieh and Bredehoeft (1981) radial flow model. Injection scenarios were simulated over a 75-year period (2025–2100).
Hydrology-Geomechanics Coupling: The model combined hydrological (pressure buildup due to injection) and geomechanical (fault stress state) components to assess slip potential for each identified fault.
Injection Scenarios: Eight cases were modelled, including water and CO_2 injections at various rates (ranging from 150,000 to 50 million barrels per year), under both normal and strike-slip regimes.
5. Sensitivity Analysis
A sensitivity analysis was performed to evaluate the impact of uncertainties in key geomechanical parameters (e.g., Shmin gradient, pore pressure gradient) on fault stability. Tornado diagrams were generated to rank parameter sensitivities.
6. Fault Risk Zonation

Based on FSP outputs, fault slip potential was mapped across the study area, identifying high-risk and low-risk zones. This risk zoning provided insights into where fault reactivation is most likely under different operational scenarios.
7. Reservoir Characterisation
Reservoir properties of the major formations were summarised:
Tipam Formation: Characterised by fine-grained sandstones with varying lithologies (feldspathic arenite, lithic arenite, wackes) deposited in fluvial settings.
Barail Formation: Predominantly deltaic deposits with interbedded shale and sandstones, forming the main reservoir.
Both the reservoirs are provided with the secondary seals by overlying Girujan claystones.

Conclusions

The containment assessment for CO_2 geological storage in the Naharkatiya field of Upper Assam provides critical insights into both the feasibility and risks associated with long-term CO_2 sequestration in a structurally complex setting. The geological containment capacity of the region is strongly influenced by the interplay of fault systems, lithological heterogeneity, and subsurface stress regimes.

The Barail and Tipam formations, targeted for CO_2 storage, exhibit favourable reservoir characteristics, including adequate porosity and permeability, complemented by overlying regional seals such as the Kopili shale and Girujan claystones. These caprocks play a pivotal role in vertical containment, restricting upward CO_2 migration. However, the presence of numerous faults, particularly normal and strike-slip faults, introduces lateral and vertical leakage risks that require rigorous evaluation.

The FSP analysis reveals that containment integrity is most challenged under high-pressure scenarios, especially with supercritical CO_2 injection rates at or exceeding 50 million barrels per year. The shorter faults demonstrate an elevated risk of reactivation due to their proximity to injection wells and unfavourable orientation within the regional stress field. Fault reactivation could compromise caprock integrity, leading to potential CO_2 migration beyond the designated storage complex. Further, sensitivity analysis further identifies minimum horizontal stress gradient (Shmin) as a critical driver of containment integrity, influencing fault stability more significantly than other variables.

In conclusion, while the Naharkatiya field offers a technically feasible CO_2 storage site with sufficient geological containment structures, its long-term security depends on careful injection planning, continuous monitoring, and adaptive management strategies. Injection rates should be optimised to prevent excessive pore pressure build-up, and detailed geomechanical assessments should be integrated into operational workflows. Ultimately, maintaining the integrity of caprocks and minimising fault reactivation are essential to ensuring that the containment system performs effectively over the storage project's lifetime, supporting broader climate change mitigation goals.

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