Introduction

Limestone reservoirs are prone to karstification. Karst often develops extensive connectivity within aquifers forming paleo-drainage systems. While such connectivity can enhance fluid flow in exploration and production, it also introduces significant challenges. Paleo-karst features may lead to pore collapse, disrupt reservoir integrity, and increase the risk of contaminant migration. This study aims to develop a comprehensive workflow and algorithm to assess and predict geohazard risks associated with paleo-karst within the Cycle IV-V limestone of the Central Luconia Province.

The approach involves converting seismic attributes to map horizons dominated by paleo-karst, tabulating risk-factors, and conducting statistical analyses to assess the severity of hazards potentially induced by these paleo-karsts. The resulting algorithm, derived from the statistical analysis, is tested on both pinnacle and flat-top limestone build-ups, with the goal of accurately modeling the paleo-karst system. The outcomes of this study are intended to mitigate potential hazards during drilling or carbon gas injection for storage within limestone reservoirs, thereby enhancing operational safety and efficiency.

Karst formations, characterized by dissolution features such as caves, sinkholes, and fractures, pose significant challenges for carbon capture and storage (CCS). Their inherent heterogeneity can increase leakage risks, compromise structural stability, reservoir heterogeneity, seismic hazards, and induced fracturing, contributing to reservoir unpredictability. The presence of high-permeability pathways within karst systems further amplifies the risk of carbon dioxide (CO_2) migration. Therefore, understanding karst-related geohazards is crucial for evaluating the viability and safety of CO_2 storage in these reservoirs.

The Central Luconia Province, offshore Sarawak, Malaysia (Figure 1), evolved in a tectonically active setting from the late Oligocene to mid-Miocene. Carbonate platform development in this region was driven by nutrient availability, eustatic sea-level fluctuations, and basinal tectonics. Tectonics played a crucial role in creating horst and graben structures, which served as the foundation for carbonate deposition, influencing platform morphology (Hassan et al., 2024). Karstification in Central Luconia was first detected in the early days of exploration when many drilled wells experienced mud losses and other drilling complications (Kosters et al., 2008). High-frequency sea-level fluctuations during the Miocene further intensified karst formation through repeated subaerial exposure re-submergence of the carbonate platforms (Kiat et al., 2016). Central Luconia Province is ranked as the second most suitable site for CO_2 sequestration in sedimentary basins of Malaysia, based on criteria such as tectonic stability, faulting intensity, reservoir-seal integrity, depth, and hydrocarbon maturity (Hasbollah & Junin, 2015), following Bachu (2003) classification.

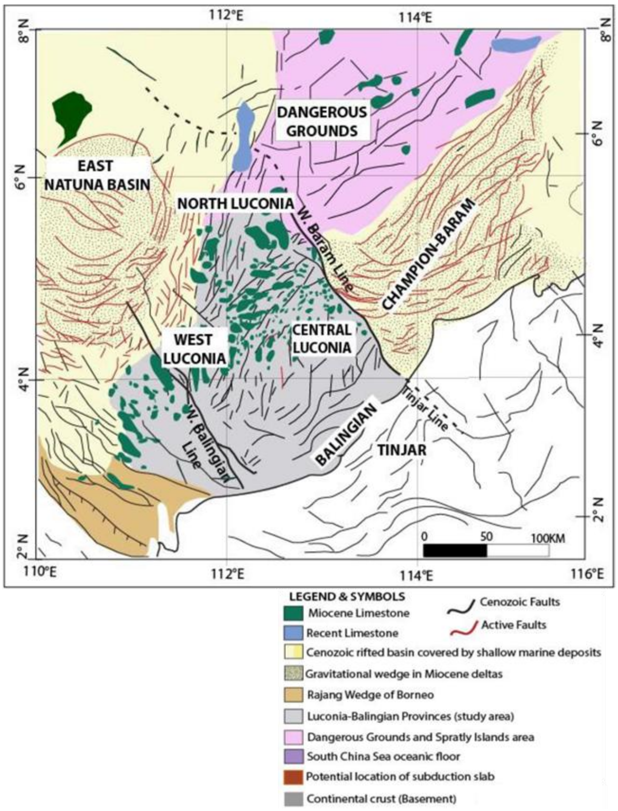

Figure 1: *Map of the study area, Central Luconia, and its surrounding geological provinces, highlighting the dominance of Miocene limestone buildups in Central Luconia. Modified from Hassan et al. (2024), based on Jamaludin et al. (2021).*

Methodology

This study utilizes seismic attributes, including variance and spectral decomposition, to enhance the interpretation of karst geobodies. A region with high karst intensity has been selected and cropped from the original seismic data for the testing (Figure 2a). The interpreted karst features were then used as input for a deep-learning-based prediction model employing a convolutional neural network (CNN). The CNN-generated prediction cube distinguishes karst from non-karst areas, improving automation and accuracy in feature identification using a confusion matrix. Only the karst zones identified through deep learning were further processed for geohazard prediction mapping (Figure 2b).

The prediction cube was further refined to generate a geohazard map, where the risk associated with karst bodies was evaluated and color-coded based on their size and spatial distribution. For size-based risk, the total number of karst features was first calculated, followed by determining their sizes based on voxel counts. For spatial distribution-based risk, clustering parameters were defined, and clustering analysis was performed using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm. This analysis helps in identifying groups of karst features that may pose greater hazards due to their proximity and potential interaction. The basis of the DBSCAN clustering algorithm is the density between the objects in the dataset (Li et al., 2023). The DBSCAN algorithm enables the clustering of dense datasets of arbitrary shapes.

Subsequently, the karst features identified in the prediction cube were mapped onto a risk cube, where each feature was assigned to a risk level based on its size and spatial distribution. These risk levels were visually represented in a 3D plotting tool using distinct color mapping to differentiate hazard severity (Figure 2c). The volume of each risk level was quantified by defining specific risk ranges and counting the corresponding voxels. The risk scale was categorized into three levels: Level 1 (low risk), Level 2 (moderate risk), and Level 3(high risk).

Results and Discussion

The risk cube provides a 3D visualization of karst geohazard predictions, categorizing risk levels into low (1), medium (2) and high (3), each represented by distinct color codes. The analysis indicates that high-risk zones are predominantly concentrated in the northeastern part of the tested volume, where multiple large and spatially dispersed karst bodies were detected. The total volume for high-risk zones (risk level 2.5-3.0) is 4.05% from the total karst zone detected by the deep-learning technique. These areas are likely to correspond to regions of active karstification. Such zones pose significant challenges for subsurface activities, including drilling, carbon storage, and reservoir management, due to increased structural instability and potential fluid migration pathways.

Conversely, low-risk zones (risk level 1.0–1.5) contribute only 0.90% of the total karst volume. These areas are more uniformly distributed, consisting of smaller and more isolated karst features. Their limited connectivity and reduced spatial extent suggest lower complexity and fewer operational risks, making them potentially safer zones for subsurface activities.

The risk cube for the cropped section of the study area reveals that most of the identified karst formations are classified as high risk. However, despite the high-risk classification, their overall volumetric contribution remains relatively small. This is because most of the surrounding area is composed of non-karst formations, which reduces the overall impact of these high-risk zones in the context of the entire geological volume. These findings indicate that while certain localized areas within the study region pose significant risks due to karstification, the overall geological setting is largely composed of less hazardous formations. This insight is critical for subsurface planning and risk mitigation, particularly in optimizing safe drilling paths and assessing the feasibility of carbon storage in the region.

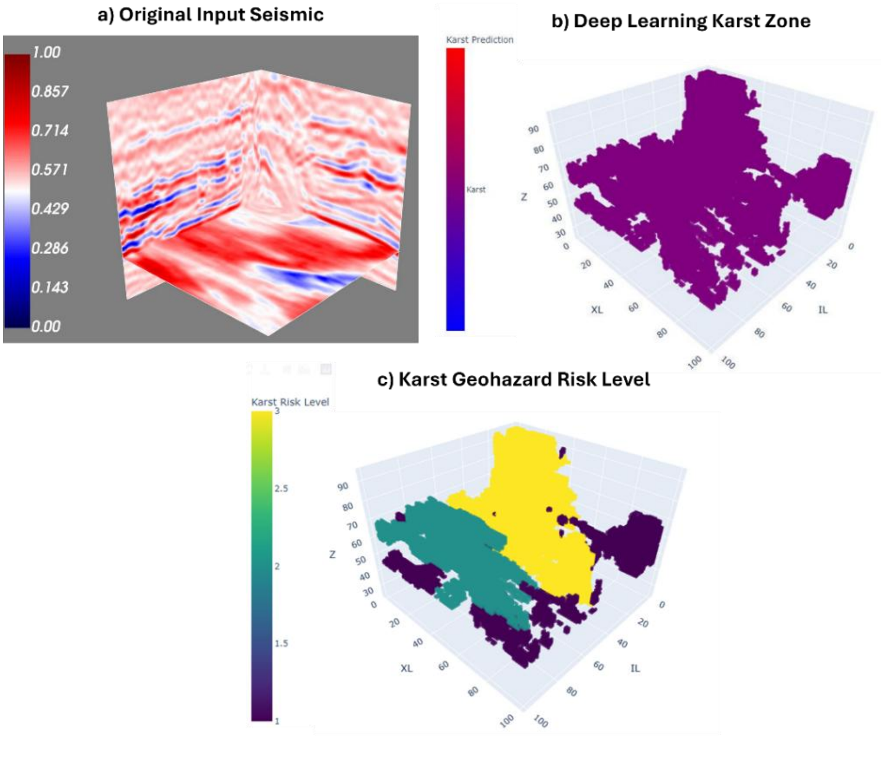

Figure 2: *a) The original seismic cropped to the zone with highest karst section. b) Identified karst zone (both dendritic and dolines/sinkholes) from deep-learning technique as input for karst geohazard risk mapping in c) Risk level of karst geohazard within the identified karst zone with level 1: low risk; level 2: medium risk and level 3: high risk.*

Conclusions

This study effectively integrates seismic interpretation, deep learning, and geohazard mapping to address challenges posed by subsurface karst formations. The research demonstrates that advanced seismic attributes significantly enhance the identification and interpretation of karst geobodies. The application of CNN further automates the detection of these features, producing a reliable prediction cube that distinguishes karst from non-karst areas. The subsequent geohazard mapping of karst using DBSCAN, based on their size and spatial distribution, offers critical insights into potential risks associated with subsurface activities, particularly drilling and hydrocarbon extraction. The findings underscore the importance of accurate karst characterization in ensuring safe and efficient field development, as well as the value of integrating advanced geophysical techniques with machine learning to improve subsurface understanding.

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