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Fracture model and structural history of Gunung Keriang, Kedah

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Abstract: Gunung Keriang is a limestone hill in Kedah, northwest Peninsular Malaysia, with well-bedded limestones that gently dip towards the SW and SE, forming N-S trending gentle folds. Fractures are prevalent at both regional and local scales, with three major fracture sets identified: NW-SE, N-S, and NE-SW, all of which are steep to vertically dipping. These fracture sets and their characteristics have been thoroughly analyzed and summarized in this study. The NW-SE fractures have an average length of 137.2 m with a spacing of 92.3 m, the N-S fractures average 120 m in length with 81.3 m spacing, and the NE-SW fractures average 101.6 m in length with 72.7 m spacing. The limestone deposits in Gunung Keriang were formed in a partially unstable shallow marine environment during the Early Permian to Early Triassic period. Subsequently, the Late Triassic collision between the Sibumasu and Indochina terranes led to the formation of N-S trending gentle folds, N-S tension gashes, and potential conjugate fracture sets (NW-SE and NE-SW direction) due to E-W compression. The ensuing uplift exposed the Gunung Keriang limestone and caused extensive dissolution, particularly along fractures.

Keywords: Deformation, fracture sets, Gunung Keriang, structures

INTRODUCTION

Background

Limestones are abundant in Peninsular Malaysia, where the tropical climate often transforms the limestones into karst formations that manifest as isolated hills dramatically rising above the flat alluvial plains. The inherent brittleness of limestone, coupled with tectonic forces, causes extensive fracturing. Geohazard concerns, such as the risk of slope-related rockfalls and subsurface sinkholes, stimulate research on fractures within karstic limestone in tropical regions like Malaysia. Furthermore, these fractures have implications for mineral exploration (mining), fluid transport and storage (oil and gas, groundwater), and the paleo-stress interpretation for understanding geological evolution.

Notably, rockfalls in limestone terrains are frequently reported in Peninsular Malaysia, especially in the Kinta Valley area of Perak state, where limestone dominates the lithology and outcrops as majestic hills. The overhang blocks the limestone hills' steep flanks or caverns, poses the highest risk of rockfall due to gravity, and most likely detaches at existing fractures and areas of intense dissolution. The dissolution process within these rocks gives rise to karst features, including caverns and sinkholes, eventually leading to the enlargement of pores and the formation of molds and vugs (Ford & Williams, 2007). These phenomena can cause gradual weakening and collapse, posing a threat to nearby structures and residents. Consequently, these geological scenarios are recognized as significant geohazards, leading the Mineral and Geoscience Department (2015) to develop guidelines for identifying hazard zones around limestone areas to mitigate the associated risks.

Malaysia has accepted the Paris Agreement, an international climate change treaty, as part of its commitment to the effort and has initiated an offshore Carbon Capture and Storage (CCS) project. Successful CO_2 injection and storage in subsurface reservoirs necessitate a thorough understanding of existing fractures and mechanical properties within the rocks, as these parameters profoundly impact fluid flow and sealing capacity. Furthermore, they are intricately linked to geohazard considerations. While fracture analysis is crucial for the effective deployment of CCS, it also contributes to comprehensive knowledge of potential geological risks, such as subsidence.

Malaysia may foster environmentally conscious practices while tackling geological challenges by recognizing the interdependence of CCS optimization and geohazard

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mitigation. Therefore, an onshore analogue is a valuable tool for comprehending the evolution of fracture networks within rock formations, allowing for thorough research across various dimensions and scales.

Motivation of the study

Gunung Keriang, a Permo-Triassic limestone deposit in the NW region of Peninsular Malaysia, has remained unmetamorphosed, preserving its original textures and structures. Remarkably, satellite images show that systematic fractures have developed on a regional scale within this limestone. Today, this hill serves a dual purpose as a recreational park and a geosite, emphasising the importance of a comprehensive study of these fractures to ensure the safety of both residents and visitors, particularly regarding rockfall and sinkhole hazards.

The regional fracture networks within the limestone hill offer vital insights, potentially serving as analogues for subsurface formations that operate as reservoirs for water, hydrocarbons, and even CO_2. Our ongoing research is committed to characterizing the fractures within Gunung Keriang at both regional and local scales. Our objective is to reveal their significance in structural evolution and their potential as fracture analogues for limestone formations through an in-depth investigation of the extensive fracture data.

GEOLOGICAL SETTING

Peninsular Malaysia is divided into three longitudinal belts, each distinguished by unique geological characteristics and evolutionary paths. These belts are known as the Western, Central, and Eastern Belts (as illustrated in Figure 1B). Limestone deposits such as the Kodiang Limestone and Chuping Limestone within the Western Belt play a prominent role. Notably, the Gunung Keriang limestone correlates to the Chuping Limestone and Kodiang Formation.

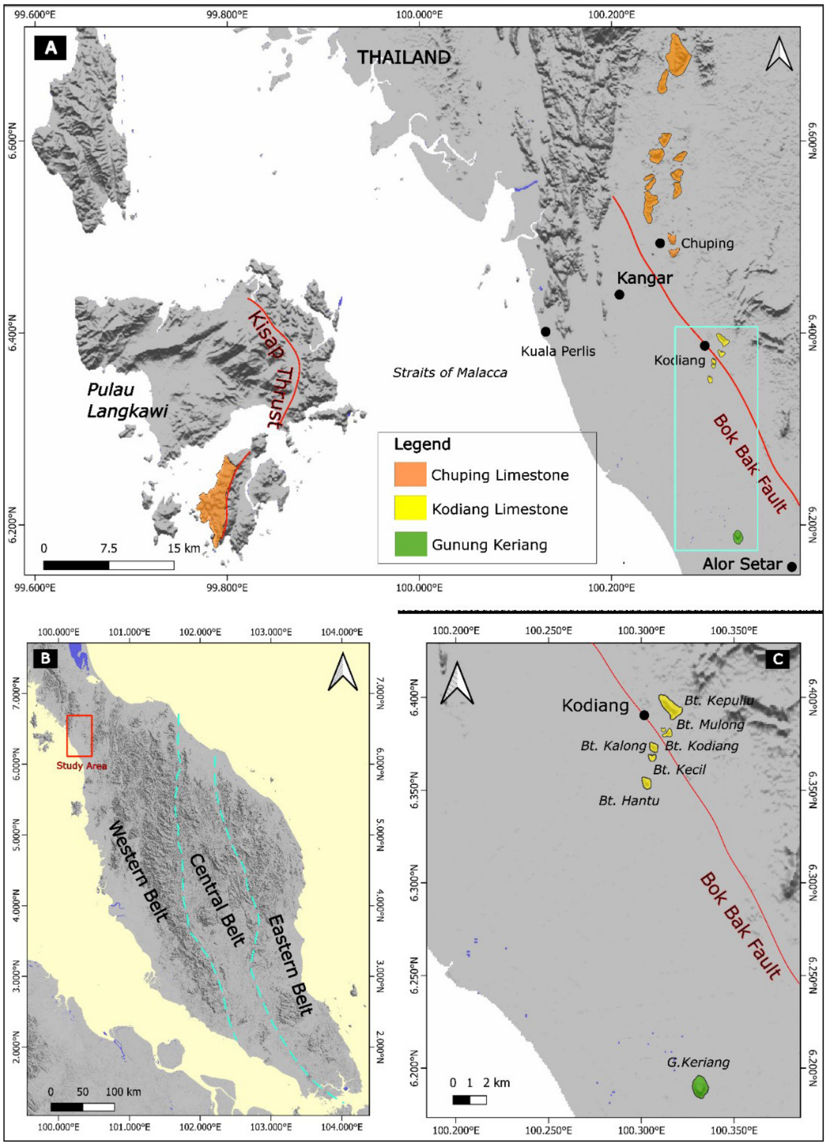

Figure 1: [A] A regional map of the northwestern area of Peninsular Malaysia displaying the primary distribution of Permo-Triassic limestone along major fault lines (Bok Bak Fault and Kisap Thrust). [B] An overview map of Peninsular Malaysia delineating three longitudinal belts (Western, Central, and Eastern Belt). [C] A depiction of the distribution of seven limestone hills within the Kodiang Limestone area.

Sedimentology and stratigraphy of Chuping Limestone and Kodiang Limestone

Chuping Limestone

The Chuping Limestone (Figure 1A), named after Bukit Chuping in Perlis, lies immediately NNE of the Kodiang Limestone and extends from Perlis to northern Kedah. This steep-sided karst hill is exposed in central Perlis, northern Kedah, and on Pulau Dayang Bunting, Pulau Jong, and Pulau Singa Besar in Langkawi (Hutchison & Tan, 2009). Fontaine *et al*. (1988) reported that the limestone appears massive, displaying hues ranging from light to dark gray. The Chuping Limestone is characterized as fine-grained and devoid of fossils.

Meanwhile, Fontaine & Metcalfe (1988) and Metcalfe (1990) discovered abundant fossil evidence in the southern part of the Chuping Limestone belt, such as foraminiferas, conodonts, and algae. The fossils, which include blue-green algae (*Aelisaccus*) and foraminifera (*Pilammina Generica*), suggest an age range of Ladinian to Carnian and possibly early Norian (Hutchison & Tan, 2009). Therefore, the Chuping Limestone is believed to span from the Lower Permian to the Upper Triassic period. As a result, the Triassic Chuping Limestone is regarded as a depositional unit within the Kodiang-Semanggol depocenter, merging the lithostratigraphic units of the Chuping and Kodiang Limestones due to their deposition on the same shelf/platform.

Kodiang Limestone

The Kodiang Limestone (Figure 1A) was named after Kodiang town in north Kedah. Jasin & Harun (2001) noted that Burton (1973) employed the term 'Kodiang limestone' to describe seven limestone hills in the Kodiang area (Figure 1C), including Bukit Kepelu, Bukit Mulong, Bukit Kodiang, Bukit Kalong, Bukit Kecil, Bukit Hantu, and Gunung Keriang. Based on a composite stratotype section, De Coo & Smith (1975) formally classified the Kodiang Limestone as a new lithostratigraphic unit with a 125 m thickness. The lower part of the Kodiang Formation corresponds to the basal section of Bukit Kecil, while the upper part relates to the basal part of Bukit Kalong. The limestone gently dips 20°–30° towards the NE, trending progressively younger to the north. It comprises well-bedded limestone sequences with repeated units of massive or relatively thick and

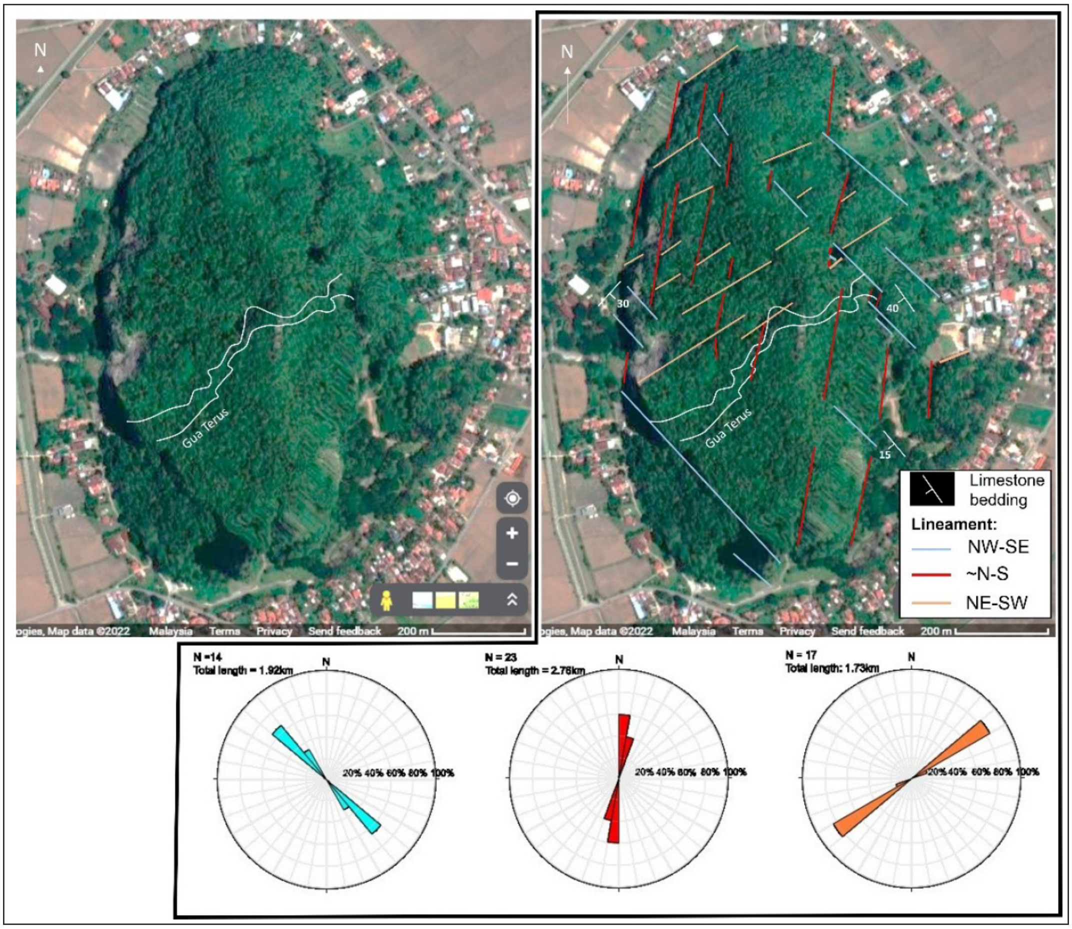

Figure 2: The negative lineaments or major fractures traced in the Gunung Keriang and their corresponding rose diagrams for each lineament set. Note: The data in the rose diagram is based on the total length of the particular fracture set.

thinly bedded dark grey limestone, finely laminated black shale, chert lenses, and nodules (Hutchison & Tan, 2009). Additionally, several limestone conglomerate and breccia horizons are present at Bukit Kalong, Bukit Kecil, Bukit Mulong, and Bukit Kodiang.

Metcalfe (1984b) identified Late Permian conodonts in the lower section of the limestone at Bukit Hantu, indicating continuous deposition from the Upper Permian to the Lower Triassic. The top section of the limestone, discovered at Bukit Mulong and Bukit Kepelu, yielded Late Carnian to Middle Norian conodonts (Metcalfe, 1992), implying an age ranging from Upper Permian to Upper Triassic. Furthermore, Serasa *et al*. (2017) noted that Jones (1976) reclassified all limestone hills in the Kodiang Formation deposited in the Permian as the Chuping Formation. Hutchison & Tan (2009) outlined its depositional environment, which ranges from the shelf to slope and basin.

The limestone exposed as a hill at Gunung Keriang and throughout the Kodiang area was previously identified as the Permian Chuping Limestone (Alexander, 1965; Burton, 1965). Metcalfe (1981) documented a total thickness of 182 m of limestone strata in Gunung Keriang (Figure 2), comprising massive limestone, bedded limestone, bedded dolomitic limestone, slumped bedded limestone, and chert. Metcalfe (1981) also discovered Late Wolfcampian (Early Permian) and Smithian (Early Triassic) conodonts in the massive dolomitic limestone and slumped bedded limestone. The Early Permian and Early Triassic strata are separated by only eight meters of strata, which Metcalfe (1981) interpreted as either an extremely thin Middle to Late Permian section or an unconformity. Slumping in the bedded limestone reflects the overall instability of the depositional setting (Hutchinson &Tan, 2009).

Deformation and fractures / faults in Kedah-Perlis area

Koopmans (1965) and Ibrahim Abdullah (1997) documented three distinct deformation episodes that have significantly impacted the Palaeozoic rock formations in NW Peninsular Malaysia, specifically on Langkawi Island. A similar deformation pattern is evident in the Kedah and Perlis regions, affecting both the Lower and Upper Palaeozoic rock layers (Yancey, 1975; Hutchison & Tan, 2009). The dominant compressive force was oriented NE-SW during this geological activity, evident from the presence of overturned and recumbent folds across Langkawi. This tectonic activity caused the separation of the Setul Limestone in the east and the Chuping Formation in the west, as delineated by the Kisap Thrust (Figure 1A). During the Upper Triassic period, another deformation phase ensued following intrusive events, resulting in the refolding of earlier tight folds and the development of crenulation cleavage within the Palaeozoic strata (Hutchison & Tan, 2009). The third phase of deformation introduced E-W-directed compression, leading to minor refolding of existing folds and the formation of brittle structures.

In the Kedah-Perlis area, the Bok Bak Fault (Figure 1A) is a prominent NW-SE trending sinistral strike-slip fault that Burton (1965) meticulously traced from Baling to Jeneri. The deformation along the fault zone exhibited brittle-ductile characteristics, with mylonites near the Kedah-Perak border serving as compelling evidence of the ductile deformation associated with the Bok Bak fault. Salmanfarsi *et al*. (2018) conducted radiometric dating using Ar/Ar dating techniques to date these mylonites to approximately 136.1 ± 1.4 Ma. Notably, Salmanfarsi *et al*. (2018) ascribe the 150 million-year-old Kupang Gneiss, which bounds the Bok Bak fault, is attributed to faulting events rather than metamorphic processes.

The northern segment of the Bok Bak fault exhibits a prevalence of NW-SE trending faults with oblique sinistral to reverse slip, a pattern strikingly reminiscent of the Bukit Tinggi Fault Zone, which dates back to 83.6 million years ago during the Late Cretaceous period, as reported by Zaiton (2002).

FRACTURE ANALYSIS METHODS

This part details the regional- and local-scale fracture analysis to compile comprehensive fracture data from Gunung Keriang.

Regional lineament study

As a competent rock type, limestone is prone to fracturing, particularly when subjected to tectonic forces. Satellite imagery revealed extensive fractures within the rock, characterized by features like valleys and troughs. These fractures occur along natural planes of weakness, facilitating the movement of solvents and occasionally leading to the formation of narrow valleys within limestone formations. Furthermore, the landscape exhibits lineaments, which are straight and extensive, spanning several kilometers, and may potentially represent faults. Satellite imagery readily identifies numerous prominent lineaments and deep, narrow valleys within the rock formations. These lineaments are interpreted as major fractures, and their attributes, such as azimuths and lengths, are extracted from satellite imagery such as Google Maps through geographical software.

Upon recording all relevant fracture information, these fractures are categorized based on their azimuths or strikes, typically in 10^o increments. The cumulative length of fractures within each category is used as input data for constructing a comprehensive rose diagram. This analytical technique enables a detailed comparison of the major fracture sets within the limestone with those observed at the outcrop scale, providing valuable insights into their relationships and patterns.

Local outcrop analysis

To validate the virtual observations derived from the regional analysis, a systematic geological data collection effort was carried out at numerous outcrops around

Gunung Keriang (Figure 5). These outcrops were selected based on their accessibility and the presence of notable geological structures. Geological data and hand specimens were methodically collected at these chosen sites, such as recording dominant strike and dip measurements of fractures and bedding, documenting cross-cutting relationships, and identifying fracture-filling materials. Kinematic indicators, such as slickenside fabrics and marker-bed offsets, were specifically noted in the outcrops as they are essential in reconstructing paleo-kinematics.

Major geological structures, including bedding and faults, were digitally captured and stored in a geo-database as a GIS layer to facilitate integrated analysis. The fracture data acquired was processed utilizing the "Stereonet" software (Cardozo & Allmendinger, 2013). All data points were plotted on a lower hemisphere, equal-area projection, enabling the computation of the paleo-stress field for each deformation event.

Data intergration

The regional and local fracture data from Gunung Keriang were thoroughly analyzed and assessed to construct a comprehensive fracture model that shed light on the structural history of the site. This model is constructed and digitized utilizing the open-source graphical software, "Inkscape."

RESULTS

The subsequent sections present the findings of the regional and outcrop fracture study of Gunung Keriang. In summary, three prominent fracture sets were discerned and categorized based on their respective strike directions: the NE-SW, N-S, and NW-SE. The geometrical characteristics of each fracture set are detailed below.

Regional fracture study

The regional fracture study of Gunung Keriang utilized Google Maps satellite imagery (Figure 2). On the satellite images, 54 negative lineaments, interpreted as fractures, were identified and traced. These lineaments were classified into three distinctive sets: NW-SE, N-S, and NE-SW.

The first fracture set exhibited a NW-SE orientation and comprised 14 lineaments. The length of the lineaments ranged from 16 to 503 meters, with an average length of 137.2 meters. A N-S direction characterizes the second fracture set and includes 23 lineaments, ranging in length from 27 to 241 meters, with an average length of 120.0 meters. Finally, the third fracture set trends in the NE-SW direction and encompasses 17 lineaments, with lengths ranging from 34 to 273 meters, averaging 101.6 meters. A comprehensive summary of the fracture data is displayed in Table 1.

Local fracture study

Five locations (Figure 3) were specifically chosen for a localized fracture analysis: the recreational park (L2), the southern end of Gunung Keriang (L3), the western flank of Gunung Keriang (L4), the hiking trail (L5a & L5b), and the entrances of Gua Terus (L6a & L6b). Detailed records of bedding orientations and rock characteristics were documented from each site.

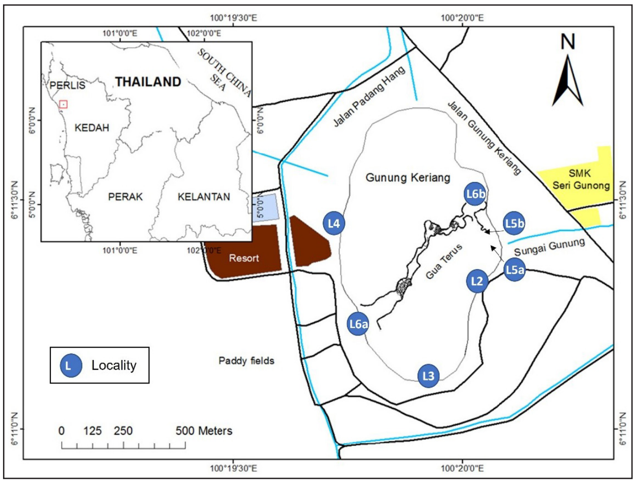

Figure 3: Map of Gunung Keriang showing the localities of the studied outcrops.

Table 1: Information on the regional fracture sets in the Gunung Keriang.

Fracture information		**Fracture set**		
	NW-SE	**N-S**	**NE-SW**	
Bearing	**Range**			
Length	**Number of readings**	14	23	17
	Range	16–503 m	27–241 m	34–273 m
	Total	1921.3 m	2761.2 m	1726.7 m
	Average	137.2 m	120.0 m	101.6 m
Spacing	**Number of readings**	7	12	6
	Range	38–212 m	30–156 m	50–98 m
	Average	92.3 m	81.3 m	72.7 m

Locality 2 (L2)

Locality 2 (L2) is a recreational park located in the eastern region of Gunung Keriang. The limestone cliff here displays gently dipping beds, characterized by an average orientation of 135/30, and are intersected by vertical fractures. These fractures have played a pivotal role in shaping the landscape, creating steep cliffs and narrow valleys within the limestone hill. Notably, we have identified two prominent sets of vertical fractures, one oriented N-S (bearing between 350–020) and the other NW-SE (bearing between 140–155), with dips ranging between 80°and 90° (refer to Figure 4A for visual representation).

Locality 3 (L3)

Locality 3 (L3) is located at the southern extremity of Gunung Keriang. The rocks in this area exhibit significant deformation, primarily attributed to the prevalence of NW-SE fractures. These steeply dipping fractures have significantly impacted the shape of the hill slope. Furthermore, the intersections of the NW-SE fractures have undergone intense dissolution, facilitating the formation of caves within this region (see Figure 4B). It is worth noting that one of the prominent regional NW-SE fractures traverses through this particular locality.

Locality 4 (L4)

Locality 4 (L4) is located on the western flank of Gunung Keriang, featuring a limestone cliff that spans less than 400 meters in width with distinct bedding oriented at 042/30 degrees. These exposed cliffs bear the imprint of steeply dipping NW-SE fractures that NE-SW fractures have intersected. Towards the northern section of L4, the cliff is impacted by a roughly N-S-oriented fracture (as depicted in Figure 5A). Importantly, all of these outcrop fractures are readily discernible in satellite imagery. Additionally, a minor set of steeply dipping E-W striking fractures are

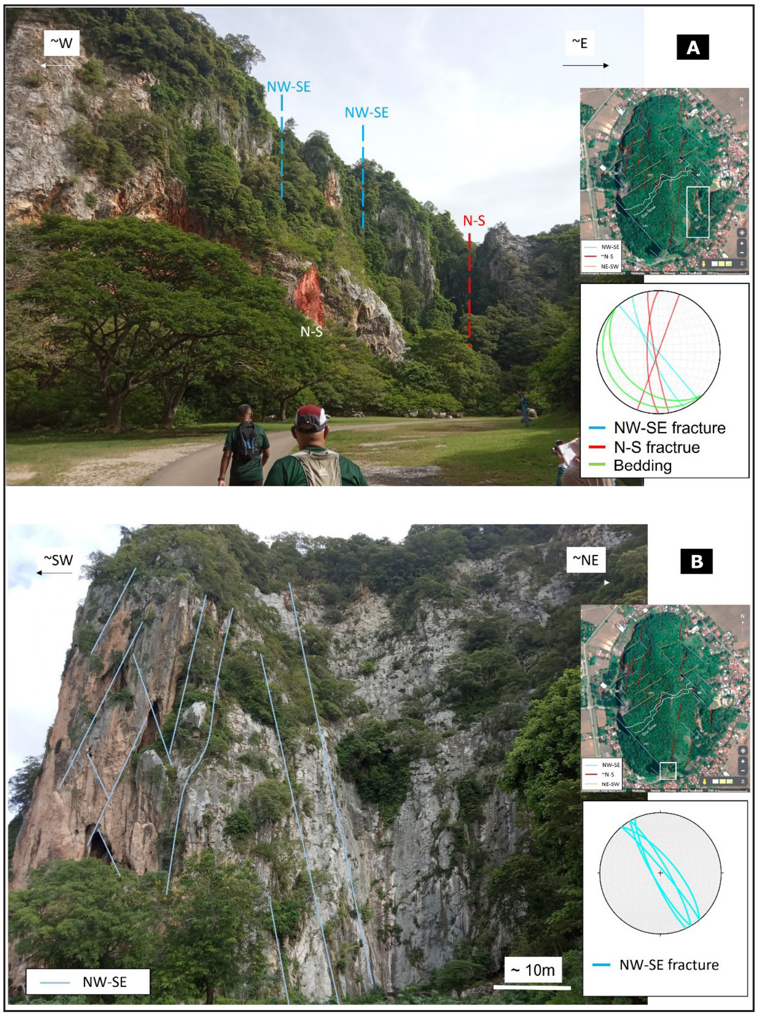

Figure 4: [A] Steeply dipping fractures (NW-SE and N-S striking) cut the limestone beds at the recreational park (L2). N-S fractures control part of the hill's steep flanks. [B] Steeply dipping NW-SE fractures in Locality 3. Caves have developed at the intersections of the fractures.

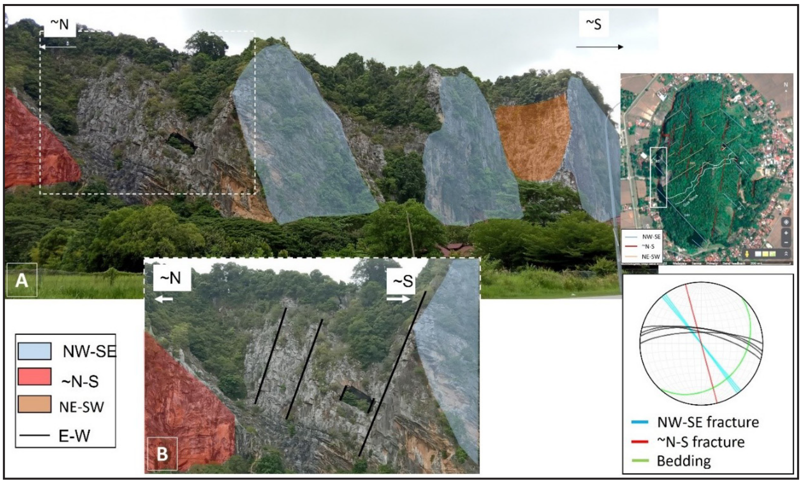

Figure 5: [A] ~N-S (red highlighted area) and NW-SE (blue highlighted area) fracture planes formed the cliff of the limestone hill at L4. A NE-SW fracture cuts/separates the NW-SE fractures. [B] A minor E-W fracture set (black lines) occurred in the thick limestone beds and probably controlled the cave development.

notably present within the thicker limestone beds of the local area (as illustrated in Figure 5B).

Locality 5 (L5)

Locality 5 (L5) encompasses a hiking trail leading to the hill peak in the eastern part of Gunung Keriang. Two sub-localities are distinguished along this trail, denoted as L5a and L5c, with L5a at a lower elevation and L5c at a higher elevation. Interestingly, the bedding orientation is consistent throughout the hiking trail, measuring 135/35.

L5a (Figure 6A) is characterised by light grey, thinly bedded limestone with potential stylolites forming along the bedding planes. Vertical fractures with orientations along the N-S, NW-SE, and E-W directions are prominent within the limestone. Some of the N-S and NW-SE fractures contain calcite mineral infillings, and the spacing between fractures is uniform throughout all fracture sets, within the 5–10 cm range.

On the other hand, L5c (Figure 6B) is located near the lower peak of Gunung Keriang and exhibits signs of intense dissolution, resulting in steeply dipping fractures predominantly striking between 288–300 degrees. The dissolution process has resulted in fracture apertures ranging from 1 to 5 cm, with fracture spacing averaging approximately 20 cm.

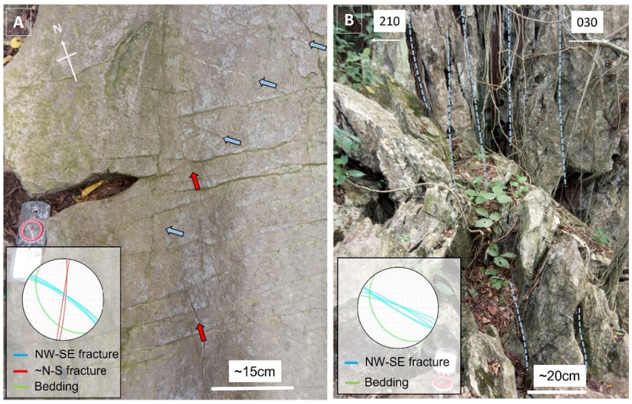

Figure 6: [A] N-S fractures (indicated by red arrows) and NW-SE fractures (marked with blue arrows) intersected by E-W fractures at L5a, offering a top view of the limestone. [B] Notice the broader aperture of NW-SE fractures at L5c, resulting from significant dissolution.

Locality 6 (L6)

Locality 6 (L6) encompasses the entire traversing route of Gua Terus, a NW-SE-oriented cave that spans from the western to the eastern flank of Gunung Keriang. Notably, the middle segment of the Gua Terus path aligns and coincides with the NE-SW and ~N-S negative lineaments (highlighted by orange and red lines overlapping the cave path in Figure 2), revealing a compelling correlation between cave development and the underlying fracture network within the limestone. Carbonate reprecipitation mostly conceals the internal sections of the cave, including both the host rock surface and structures. As a result, we focused on the fractures near the cave entrances on the western (referred to as L6a) and eastern flanks (designated as L6b) of the hill, owing to their superior exposure.

The intersection between N-S and NW-SE vertical fractures is evident (as depicted in Figure 7A) along the limestone cliff faces adjacent to the western cave entrance (L6a), aligning seamlessly with the lineament orientations observed precisely at that location on the satellite image. At the western cave entrance (L6a), steeply dipping in nature, the NE-SW striking fractures have considerably altered the cave's roof structure (as illustrated in Figure 7B).

Meanwhile, the limestone layers at the eastern cave entrance (L6b) are notably thickly bedded (~5 m thick per

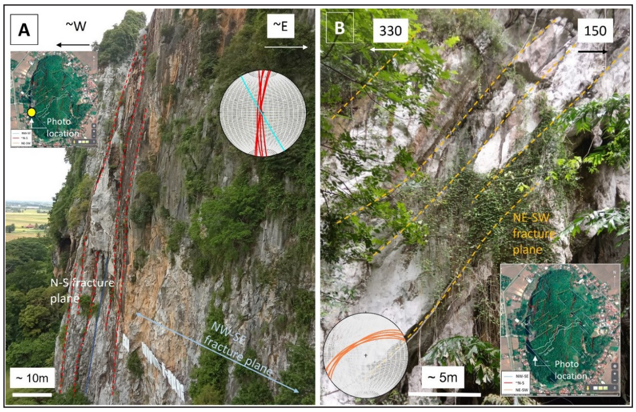

Figure 7: [A] Confluence of N-S (blue line) and NW-SE (red dashed lines) vertical fractures shaping the western cliff face of Gunung Keriang. [B] NE-SW fractures (orange dashed lines) observed at the entrance of the western cave (L6a).

bed) and laminated, with a bedding orientation of 160/20. As depicted in Figure 8, the limestone has been intersected by nearly vertical N-S-striking fractures. Some of these N-S fractures have undergone intense dissolution, resulting in extensive karstification.

Fracture sets and model of the Gunung Keriang

Gunung Keriang features a southward, gently plunging, synclinal limestone formation with a high degree of fracturing (Figure 9). Four fracture sets have been documented within Gunung Keriang, striking in the N-S, NW-SE, NE-SW, and E-W directions. During the regional study, the N-S fracture set is noted for its steep dip and extensive occurrence along the western and eastern flanks of Gunung Keriang. At the local scale, outcrop fractures were specifically identified at L2 and L6b, with the N-S fractures at L6b displaying significant dissolution and some transitioning into tension gashes at L5a, indicative of an E-W extension.

On the regional scale, the steeply dipping NE-SW and NW-SE fractures traversed the limestone formations. Meanwhile, during outcrop observations, NE-SW fractures were observed at L4 and L6a, and NW-SE fractures manifested as calcite veins at L5a and were susceptible to dissolution at L5c. However, most of these NE-SW and NW-SE fractures lack clear kinematic indicators. Satellite imagery (Google Maps) revealed the occurrence of E-W fractures, predominantly localized to specific outcrops such as L4, but are not directly associated with the primary deformation event.

Although the NE-SW and NW-SE fractures display limited cross-cutting relationships, they suggest an E-W compression when examined in the context of the N-S trending syncline limestone. Consequently, it is presumed that the NE-SW and NW-SE fractures form a conjugate fracture set corresponding to the compressional event previously mentioned.

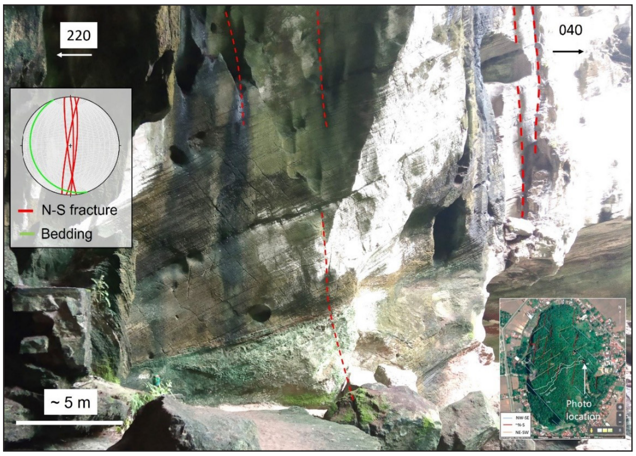

Figure 8: Eastern cave entrance (L6b) reveals thick-bedded limestone with distinct lamination structures intersected by prominent ~N-S fractures (indicated by red dashed lines).

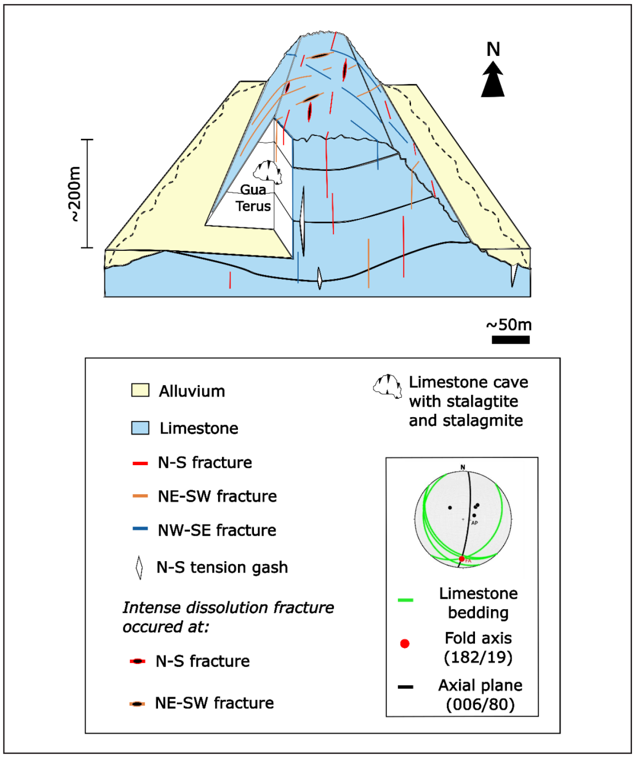

Figure 9: Fracture Model of Gunung Keriang: Utilizing stereonets, the limestone beddings reveal the fold axis (182/19) and axial plane (006/80), while certain fractures display signs of significant dissolution. Notably, there is a discernible alignment between the NE-SW fractures and Gua Terus. Fracture densities within each set have been scaled down in this model to enhance clarity.

A detailed fracture model (Figure 9) illustrates all major fracture sets in Gunung Keriang, incorporating the limestone bedding orientations. Additionally, the fracture model emphasises the alignment of fracture orientation with Gua Terus, suggesting a potential linkage between the two.

STRUCTURAL HISTORY OF THE GUNUNG KERIANG

During the Early Permian to Middle Permian, the Gunung Keriang limestone began to deposit in a shallow marine shelf environment, with carbonate sediments accumulating horizontally (Figure 10). Subsequently, the limestone strata underwent deformation, resulting in N-S trending open folds due to E-W compression. It is important to note that the N-S vertical fractures and tension gashes can develop in the high strain zone of the fold hinge (Figure 10). While no distinct cross-cutting relationships or kinematic indicators were identified for the NE-SW and NW-SE fractures, the two fracture sets may have formed as a conjugate fracture set assuming a simplified scenario of a single E-W compressional event in Gunung Keriang (Figure 10). Locally, E-W fractures intersected the limestone and other fractures in the area during a late-stage deformation. Eventually, during the Jurassic period, the Gunung Keriang limestone was uplifted above sea level. The present morphology of the limestone has been significantly impacted by intense dissolution, with fractures playing a controlling role, as evidenced by the alignment of NE-SW lineaments and features like Gua Terus (Figure 10).

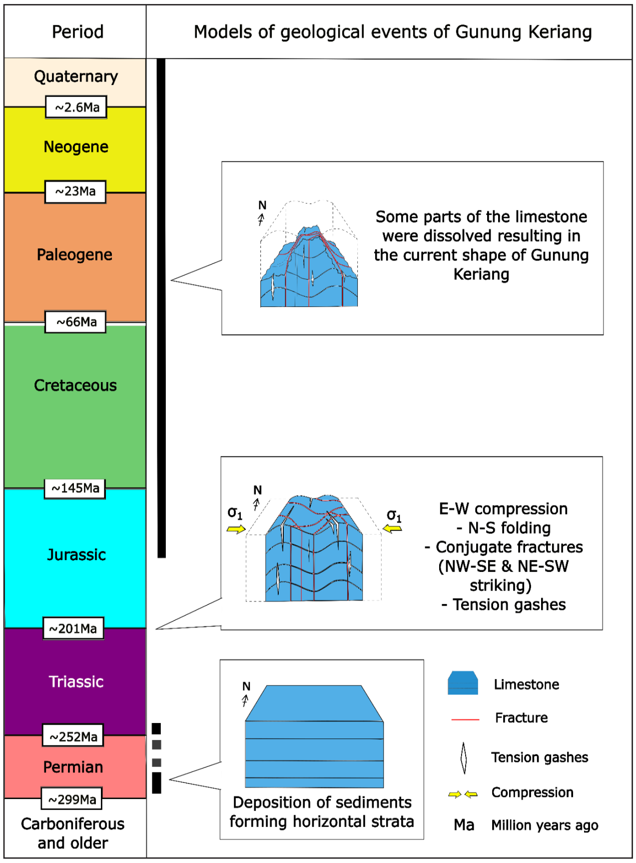

Figure 10: The interpreted geological events and history of Gunung Keriang including stages of deposition, E-W compression, and dissolution.

CONCLUSION

The Gunung Keriang limestone exhibits a gently folded syncline pattern intersected by systematic fractures. These fractures are organized into four sets, discernible at both regional and local scales, striking in the NW-SE, NE-SW, N-S, and E-W directions, with steep to vertical dips. Comprehensive analysis of these fractures includes three major sets: NW-SE fractures with an average length of 137.2 m and spacing of 92.3 m, N-S fractures with an average length of 120 m and spacing of 81.3 m, and NE-SW fractures with an average length of 101.6 m and spacing of 72.7 m. The southward plunging N-S trending syncline is interpreted as a consequence of E-W compression, with N-S tension gashes forming at the high strain zone of the fold hinge. Deposited in a shallow marine environment during the Early Permian to Early Triassic period, the Gunung Keriang limestones underwent E-W compression during the Late Triassic collision between the Sibumasu and Indochina terranes. This compression created gentle N-S trending folds, N-S tension gashes, and likely conjugate fractures striking NW-SE and NE-SW. Subsequent uplift raised the limestone above sea level, leading to dissolution processes, especially along the fractures, which shaped the current morphology of Gunung Keriang.

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AUTHOR CONTRIBUTIONS

CCM, SSAR, MAMY and MAM conceived and planned the research. Both MAMY and MAM provided support for the project's funding. CCM, SSAR, MAA and NAM carried out the fieldwork. CCM designed and performed the data analysis assisted by MAA and NAM. MAA wrote the manuscript with support from NAM, CCM and SSAR. Both MAA and CCM contributed to the final version of the manuscript. CCM supervised the project. All authors provided critical feedback and helped shape the research, analysis and manuscript.

CONFLICT OF INTEREST

This manuscript has not been submitted to, nor is it under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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