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Structural analysis using 3D digital outcrop model: A case study in Kebun 500 outcrop, Kedah, Peninsular Malaysia

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Abstract: Photogrammetry and digital outcrop modelling are the latest techniques used by various geoscience groups for Earth visualisation and research. This study showcases the structural analysis of a digital outcrop model in the Kebun 500 area, Kedah, involving drone photo collection, digital model construction, structural data extraction, and geological interpretation. The outcrop represents folded and fractured sedimentary rocks of the Permian-Triassic Semanggol Formation, situated adjacent to a major fault, the Bok Bak Fault. The digital model revealed a N-S strike direction and steep dips to the east in the sedimentary beds at the Kebun 500 outcrop. The rocks experienced flexural slipping on the bedding planes and locally folded into close-to-open folds. They can also be further classified into gently plunging-upright folds, gently plunging and moderately inclined folds, and moderately plunging and steeply inclined folds. The beds/folds are cross-cut by N-S striking, steeply dipping fractures, and NNW-SSE striking, inclined dipping reverse faults. The folds that occurred in the Kebun 500 outcrop are interpreted as parasitic folds. The identified fractures are also potentially associated with the Bok Bak fault system.

Keywords: Digital outcrop model, fold, fracture, photogrammetry, Semanggol Formation

Abstrak: Fotogrametri dan pemodelan singkapan digital adalah teknik terbaru yang telah banyak digunakan oleh pelbagai bidang geosains untuk visualisasi dan penyelidikan bumi. Kajian ini mempamerkan penganalisaan struktur geologi secara digital di kawasan Kebun 500, Kedah melalui pengambilan foto udara, pembinaan model singkapan digital, pengekstrakan data struktur, dan tafsiran geologi. Kawasan ini mewakili batuan sedimen berlipat dan berretak Formasi Semanggol yang berusia Perm - Trias, dan ia terletak bersebelahan dengan Sesar Bok Bak. Batuan sedimen dalam model singkapan digital berjurus utara-selatan dengan kemiringan curam ke arah timur. Lapisan sedimen ditafsirkan mengalami *flexural slipping* dan terlipat secara tempatan, kemudian membentuk lipatan jenis *close-to-open*. Lipatan ini juga dapat dikelaskan sebagai *gently plunging-upright fold*, *gently plunging and moderately inclined*, dan *moderately plunging and steeply inclined*. Lapisan/lipatan sedimen juga dipotong oleh retakan berjurus utara-selatan dan sesar berjurus NNW-SSE. Maka, lipatan di singkapan Kebun 500 boleh ditafsirkan sebagai lipatan parasit dan pembentukan retakan berpotensi berkait dengan sistem sesar Bok Bak.

Kata kunci: Model singkapan digital, lipatan, sesar, fotogrametri, Formasi Semanggol

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INTRODUCTION

The application of digital outcrop models (DOMs) has become increasingly popular in Earth Science. The advancement in Earth visualisation technology has improved geological research in terms of data gathering and interpretation. Geological studies are shifting from traditional field-based and 2D visualisation (map or photo) work to more computer-based and 3D visualisation (digital model) output. Satellite imagery and photogrammetry are two remote techniques that are widely used for geological studies, especially in areas that are inaccessible or challenging to reach. They are beneficial when field data acquisition time is limited, allowing for the geological study and analysis to start immediately. Previous studies in NW Peninsular Malaysia (Salmanfarsi, 2017; Azman *et al*., 2018) have proved that remote sensing techniques can be used to extract higher accuracy lineament/ structural information and reconstruct deformation history.

This study aims to present capability of drone-based photogrammetry can improve structural analysis by extracting precise and sufficient digital geological data on a high-relief and steep rocky slope at Kebun 500, Kedah (Figure 1). This abandoned quarry exposes an extensive folded and fractured outcrop of the Semanggol Formation, providing the opportunity to demonstrate the workflow for structural analysis.

GEOLOGICAL SETTING OF NORTH KEDAH

Major rock formations

Geologically, the north Kedah region is mainly covered by the Paleozoic - Early Mesozoic sedimentary sequences of the Sibumasu Block. The oldest sequences comprise clastic rocks of the Lower Silurian Sungai Patani Formation and the Mahang Formation (Lower Ordovician-Upper Devonian), which are overlain conformably by the Carboniferous to Lower Permian Kubang Pasu Formation. The Kubang Pasu Formation conformably overlies the Permian to Triassic carbonates of Kodiang Formations and Chuping Formation at different locations in central and north Kedah (Jones, 1981; Shashida *et al*., 1995), as well as the Semanggol Formation clastic rock, which are later locally intruded by Triassic granite.

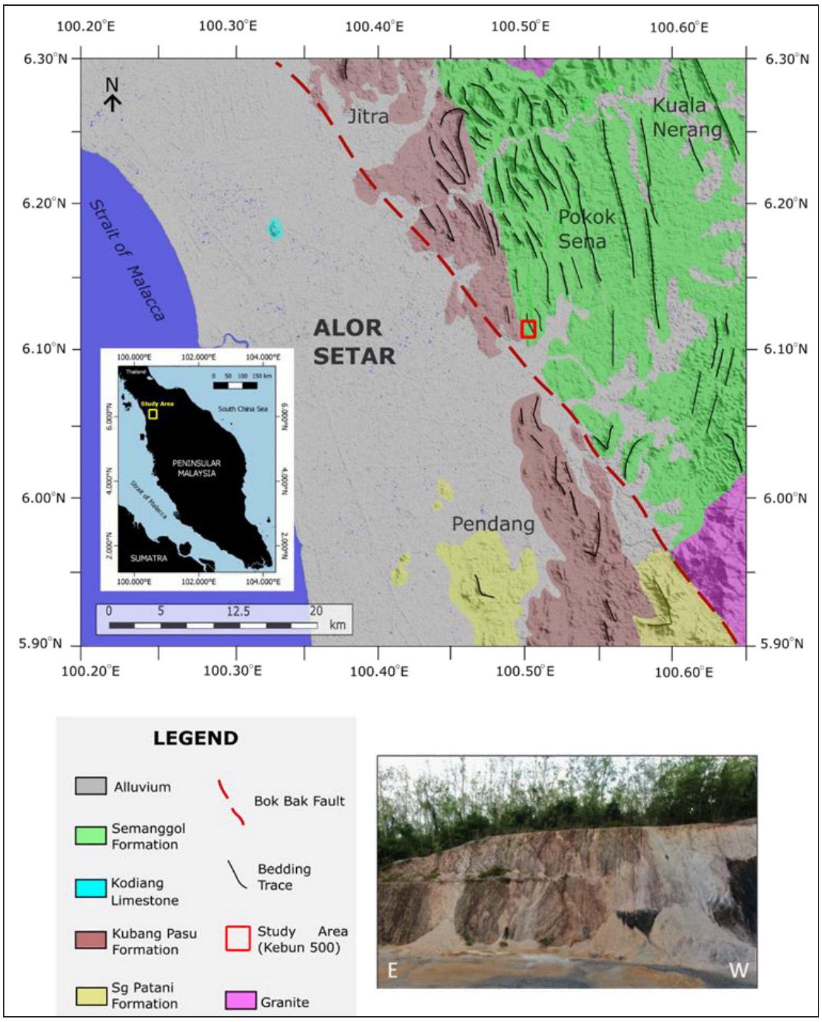

Figure 1: The Kebun 500 outcrop is located east of Alor Setar, Kedah, northwest of Peninsular Malaysia. [Top] Geological map of north Kedah. [Inset] Location of study area (Kebun 500 outcrop) in Peninsular Malaysia. [Bottom Right] Photograph of part of the rocky cliff at Kebun 500. The overall exposed outcrop is roughly 120 m long with an average height of 20 m.

The Sungai Patani Formation is mainly distributed further south in Kedah, consisting of argillaceous rock (Hassan, 1989) with Llandovery (Lower Silurian) graptolites (Courtier, 1974), which was later identified as Lower Devonian in age (Jones, 1973b). The formation was initially correlated to the Mahang Formation (Lower Ordovician-Upper Devonian) and separated by a granite body (Courtier, 1974). However, the name was no longer used and was included in the Mahang Formation by Burton (1988). Meanwhile, Burton (1967) identified the Kubang Pasu Formation as the Kampong Sena Formation, which is equivalent to the Singa Formation on Langkawi Island (Jones, 1973a). It comprises thick-bedded quartz and feldspathic grey, red or purple sandstone interbedded with subordinate varicoloured mudstone. The red mudstone near the base is where most Carboniferous fossils from the Kubang Pasu Formation are reported (Jones, 1973a). Numerous isolated limestone hills to the northwest of Kedah, known as Triassic limestone, were formally established by de Coo & Smit (1975). They were named Kodiang Limestone prior to the formalisation (Jones *et al*., 1966). The limestone hills are believed to be localised in the Kodiang area and are lithologically different from the other limestone overlying the Kubang Pasu Formation, i.e., Chuping Limestone in Bukit Barak, Pokok Sena (Shashida *et al*., 1995). De Coo & Smit (1975) reported that the Kodiang Limestone consists of repetitive units of thickly- and thinly-bedded limestone with several horizons of limestone conglomerate and breccia. The thickly-bedded limestone is composed of algal laminate and skeletal wackestone-packstone, while the thinly-bedded limestone comprises shell fragments, sponge spicules, ostracods, and foraminifers wackestone or mudstone. Semanggol Formation was named after Gunong Semanggol (Alexander, 1959) for the Triassic clastic rocks that extend from the northern border of Kedah southward to northwest Perak (Courtier, 1974). Sandstone, shale, and mudstone with turbiditic characteristics are the most abundant rocks in the Semanggol Formation. The sediments were also reported to contain a wide distribution of chert clasts in the turbidites and conglomerate, where some clasts are radiolarian-bearing (Hutchison & Tan, 2009).

Semanggol Formation

The Semanggol Formation stretches from the northern border of Kedah southwards to north Perak (Alexander, 1959). The chert unit of this formation is widely exposed in Kedah, while its contacts are either faulted or unexposed (Hutchison & Tan, 2009). Burton (1973a) initially subdivided the Semanggol Formation into chert, rhythmite, and conglomerate members, which Teoh (1992) later referred to as a unit. Jasin (1997) interpreted the three units as having a lateral and interfingering contact, representing lateral facies variation. The chert unit was described as alternations of black, carbonaceous mudstone with chert, siltstone, and greywacke (Burton, 1973a). The age of the siliceous rocks of the Semanggol Formation was interpreted to be Permian-Triassic based on the radiolarian assemblage in the chert unit (Shashida *et al*., 1992; Jasin, 1997, 2008; Jasin & Harun, 2007).

The sedimentary rocks of the Semanggol Formation were deposited in a post-collision basin, corresponding to the collision between Sibumasu and Sukhothai Arc during the Triassic (Metcalfe, 2013). The Semanggol Formation mapped in the NW Peninsular was suggested to initially be a continuous basin that was later truncated by wrench faults and separated into three sedimentary accumulations (Burton, 1973a; Ahmad Jantan *et al*., 1989). Burton (1973a) reported that the beds exhibited repeated and tight folds. Mustaffa (1994a) interpreted a single deformation phase resulting in regional N-S trending, slightly asymmetric drag folds that were superimposed by the E-W trending folds and strike-slip related structures at the southern part of the formation in north Kedah. This complexity is believed to have been created by reverse fault drags along the N-S striking steeply dipping faults due to granite intrusions and movement along the Bok-Bak fault. In the adjacent area of Pokok Sena, Harun & Jasin (1999b) also reported evidence of combined movements of lateral faults with reverse components on the moderate to steeply dipping NW-NNE striking beds, which resulted in the development of fault-related gentle, open folds, tight folds, and a positive flower structure. Overall, the Semanggol Formation of Pokok Sena has N-S striking chert beds with distinct folding and faulted structures (Jasin, 1997).

METHODOLOGY

The study was divided into three stages: (1) data acquisition, (2) digital outcrop model (DOM) generation, and (3) interpretation and analysis using DOM. The main workflow for this study is summarised in Figure 2.

Data acquisition

High-resolution digital aerial photographs of the outcrop were acquired in 2022 using a DJI Mavic 2

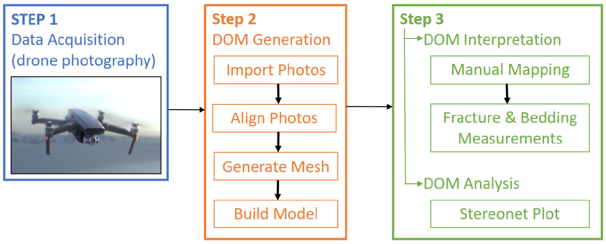

Figure 2: Basic workflow diagram showing the three main steps of the study: Step 1 - data acquisition using a drone, Step 2 - DOM building in photogrammetry software, and Step 3 - structural data extraction and analysis.

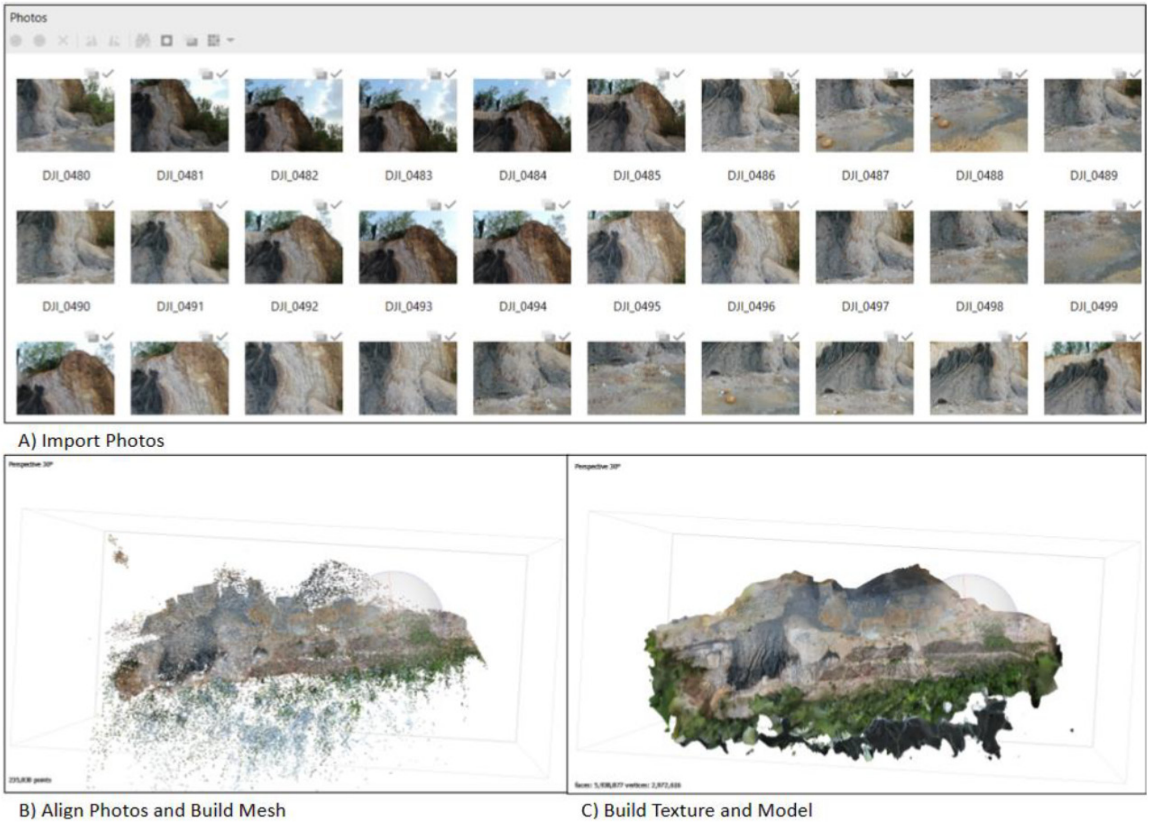

Figure 3: DOM photogrammetry processing steps. The workflow in sequential order: [A] Import outcrop's aerial photos, [B] Matching mutual points in photos and estimating photo's locations, then build depth map and mesh, [C] Texture atlas parameterization, blend textures and tiled model building.

Zoom drone camera (camera model FC2204). The drone camera was fitted with a 1/ 2.3-inch 12MP CMOS sensor which shot up to two-times optical zoom (24–48 mm) photos. The aircraft flew back and forth from a position perpendicular and at an angle to the strike of the rock layer to cover the full extent of the outcrop at an altitude of 23–56 m. The aircraft was equipped with a positioning algorithm using signals from GPS and GLONASS satellite positioning systems to precisely geo-reference the images taken. Each digital photograph has 4000 × 3000 pixels and was taken at slightly different angles from each other in overlapping series around the outcrop to capture all the detailed geometry of the outcrop for a precise DOM generation (Figure 3A).

Digital outcrop model (DOM) building

A 3D outcrop model was constructed using the Agisoft Metashape Professional 2.0.1 photogrammetry software. The photogrammetry processing steps from importing photos to model building are shown in Figure 3. A total of 235,830 tie points in different dimensions were created from 354 aligned images. A point cloud was used to define the faces and shapes which make up the depth maps and mesh. Lastly, model texturing was applied to give colour and detail to the 3D model after applying the mesh via the mosaic blending model.

DOM validation

The quality of the photogrammetric product was assessed following the guidelines outlined in the accuracy standards set by the American Society for Photogrammetry and Remote Sensing (2023) (Table 1). Notably, results obtained from a few checkpoints (both from field and Google Maps) are considered photogrammetrically accurate, falling within the defined accuracy window for the x, y, and z coordinates.

Table 1: Aerial triangulation and ground control accuracy requirements, orthoimagery and/or planimetric data and elevation data. (*RMSE: root-mean-square error)*

Product Accuracy ($RMSE_x$, $RMSE_y$) (cm)	A/T Accuracy		Ground Control Accuracy	
	$RMSE_x$ and $RMSE_y$ (cm)	RMSEz (cm)	$RMSE_x$ and $RMSE_y$ (cm)	RMSEz (cm)
50	25	25	12.5	12.5

Interpretation and analysis using DOM

The generated DOM was analysed in the Lidar Interpretation and Manipulation Environment (LIME) software of Virtual Outcrop Geology Group that allows 3D visualisation of outcrop models, manual mapping, and digital measurements (Buckley, 2019). Lines and planes representing structural features were mapped manually by point-picking the intersection of the selected structural features and the 3D model's surface (Figure 4). The best-fit planes representing each bedding and fracture plane were calculated from three picked points, and their orientations, positions, and lengths were recorded. Then, the extracted structural readings were plotted in the Stereonet software version 11.5.1 (Cardozo & Allmendinger, 2013) for illustration and further analysis.

RESULTS AND DISCUSSION

This study focused on the observation and interpretation of structural elements, particularly on folds and fractures on the Kebun 500 outcrop DOM.

General geology of Kebun 500 outcrop

The Kebun 500 outcrop is an exposed sedimentary sequence of the Semanggol Formation. The outcrop extends 120 m in the east-west direction. Earlier studies have reported the nearly vertical dip of chert beds interbedded with shale and mudstone, as well as the occurrence of radiolaria in the chert unit. A large section of a black-coloured sequence at the western end of the Kebun 500 outcrop is interpreted to be related to a post-deposit thermal process (Mohammad, 2016) (Figure 5).

Geological structures of the Kebun 500 DOM

Bedding

Eight representative bedding planes were sampled at a distance away from the highly folded zones. The interpreted bedding planes generally recorded a N-S strike direction, predominantly dipping at 65°–87° towards the east (average: 011/76) (Figure 5 and Table 2).

Table 2: Readings of bedding planes extracted from Kebun 500 DOM.

Bedding	
Number of readings	8
Strike	002 - 019 182 - 195
Dip	65 - 87°

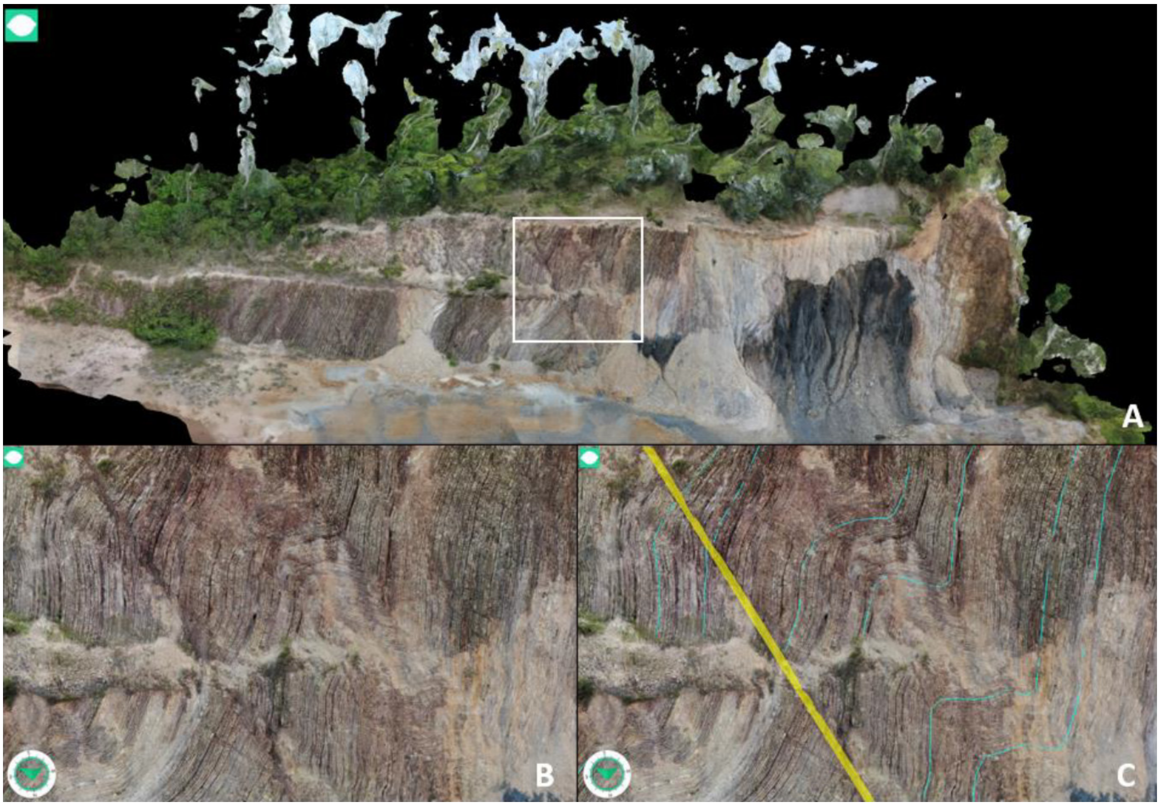

Figure 4: 3D DOM of Kebun 500 outcrop. [A] Model visualisation in LIME software. The white box indicates the location shown in "B" and "C". [B] High-resolution outcrop model illustrates the distinct beddings and structural features. [C] Interpretation of lines (cyan) and planes (yellow) in LIME software environment.

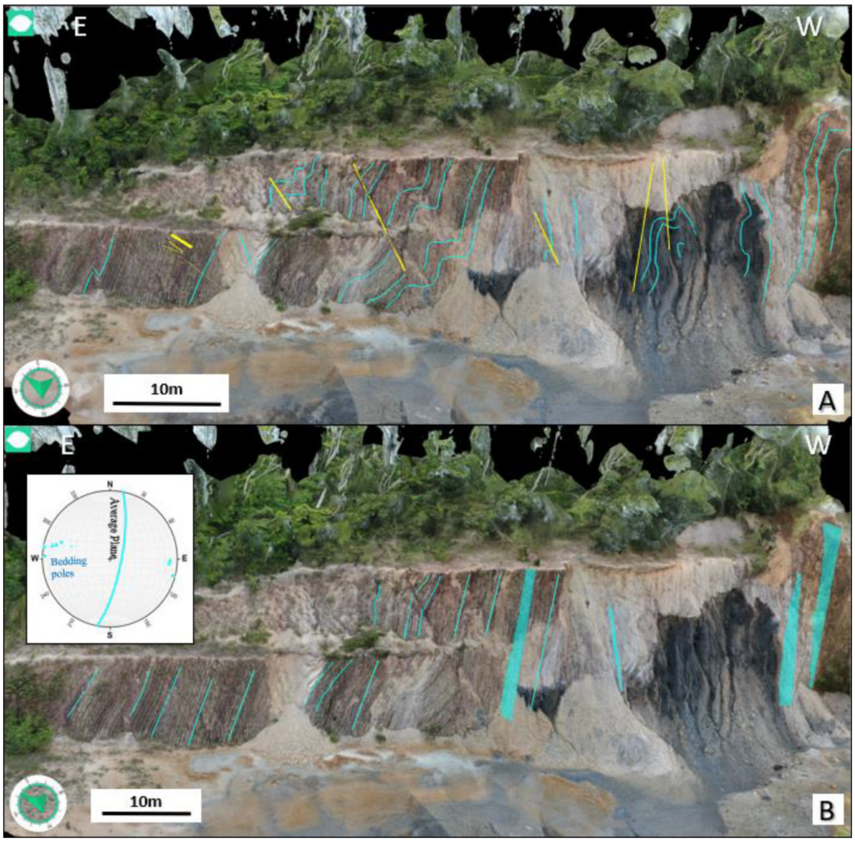

Figure 5: [A] Key geological structures observed on the Kebun 500 DOM. Bedding (cyan) and fracture/fault planes (yellow) were interpreted in LIME. [B] The beds generally strike in a N-S direction and steeply dip eastward. The readings of the bedding planes (cyan) are plotted on a stereonet.

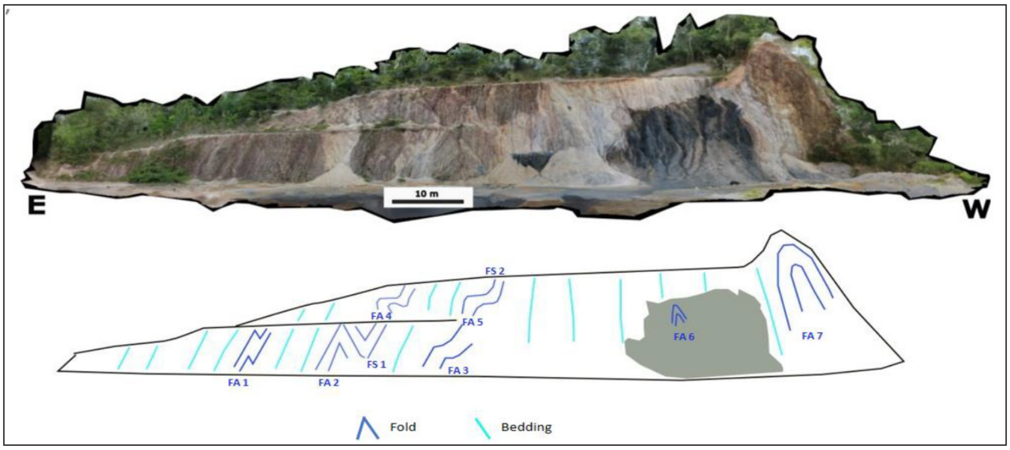

Figure 6: [Top] DOM of the Kebun 500 outcrop. [Bottom] Sketch of interpreted bedding (cyan) and folds (dark blue) in outcrop. There were seven anticlines and two synclines identified. [FA: anticline; FS: syncline]

Folds

Folds are prominent secondary structures at the Kebun 500 outcrop. A total of nine folds (seven anticlines and two synclines) were mapped and analysed via visual interpretation on the DOM (Figure 6 and Table 3). Three bedding planes were sampled on each fold limb to obtain the mean reading of each limb. The mean bedding plane (dip, strike) of each fold limb allows the calculation of the orientation of the fold axial plane and hinge line.

The mapped folds were further classified based on their different geometric features. Based on the interlimb angle, these folds can be classified into two types: close

Table 3: Information of the studied folds in Kebun 500 outcrop.

Folds	Average Limbs (Strike/ Dip)	Hinge Line (Trend/ Plunge)	Axial Plane (Strike/Dip)	Interlimb Angle		Fold Classification	
				Range	Average	Interlimb Angle	Hinge Line-Axial Plane
FA1	007/71° 172/64°	181/18°	180/87°	32-67°	56°	Close fold	Gently plunging, upright fold
FA2	172/59° 001/70°	178/10°	177/85°	44-63°	58°	Close fold	Gently plunging, upright fold
FS1	172/59° 020/65°	188/24°	186/87°	48-77°	65°	Close fold	Gently plunging, upright fold
FA3	005/74° 061/25°	178/23°	159/52°	109-120°	119°	Open fold	Gently plunging, mod. inclined fold
FA4	095/37° 185/76°	196/37°	037/64°	73-87°	79°	Open fold	Mod. plunging, steeply inclined fold
FA5	003/86° 103/27°	181/27°	160/55°	73-91°	89°	Open fold	Gently plunging, mod. inclined fold
FA6	005/68° 117/50°	164/41°	154/80°	70-86°	75°	Open fold	Mod. plunging, steeply inclined fold
FA7	179/63° 081/32°	197/30 °	028/71°	75-83°	79°	Open fold	Mod. plunging, steeply inclined fold
FS2	359/85° 104/28°	177/27°	157/56°	79-92°	87°	Open fold	Gently plunging, mod. inclined fold

folds (30°–70°) at the eastern side of the outcrop and open folds (70°–120°) on the western cliff (Figure 7). Additionally, the fold classification based on the plunge of the hinge line and dip of the axial plane (Fleuty, 1964) has grouped the observed folds into (Figure 8): gently plunging-upright folds (FA1, FA2, and FS1), gently plunging and moderately inclined folds (FA3, FA5, and FS2), and moderately plunging and steeply inclined folds (FA6, FA7, and FA4). The folds at the eastern part of the outcrop had a vertical axial plane and gently plunging fold axis geometric position. Towards the central and west sections, the axial planes became more inclined, possibly indicating plunging folds. In general, the folds at Kebun 500 outcrop have an acute interlimb angle with axial planes striking nearly in the N-S direction. In addition, these folds changed from symmetrical folds on the eastern side to asymmetrical folds towards the west.

Fractures / faults

Eleven major fracture planes were mapped and measured on the Kebun 500 DOM. The identified fractures can be subdivided into two sets (Figure 9 and Table 4). Three fractures were non-displaced with a nearly vertical fracture plane (dip angle 67°–88°), while the remaining eight were reverse faults with measured slip ranging from 6 cm to 32 cm and moderately steeply dipping (30°–58°) (Figure 9).

The reverse faults strike from the SSE to S direction and dip towards SW. Most of the fracture planes are sub-parallel to the fold axial planes and the bedding planes. The rocks were displaced discretely without any significant changes to the bed thickness under faulting. (Figure 9B).

Discussion

Structural geology of Kebun 500 area

Generally, the bedding, folds, and fractures interpreted on the Kebun 500 DOM are ~N-S directed. The rocks strike N-S and dip steeply toward the E or W. Most of the folds in the study area are asymmetrical and trend N-S. The folds are mainly classified into close to open folds based on interlimb angles and grouped into gently plunging-upright, gently plunging and moderately inclined, and moderately plunging and steeply inclined folds, based on the plunge of the hinge line and dip of the axial surface. There are two groups of fractures observed on the DOM. The first group represents non-displacement fractures that strike in the N-S direction and dip steeply towards E or W. The second group is the reverse faults with strikes ranging from SSE to S and inclined dips (30º–58º) toward the W. These fractures and faults have orientations parallel to sub-parallel with the axial planes and outcrop bedding, as well as the major morphological features in the NW Peninsular Malaysia region. Besides, the study area is located next to the NW striking sinistral Bok Bak Fault Zone. The ~N-S folds of

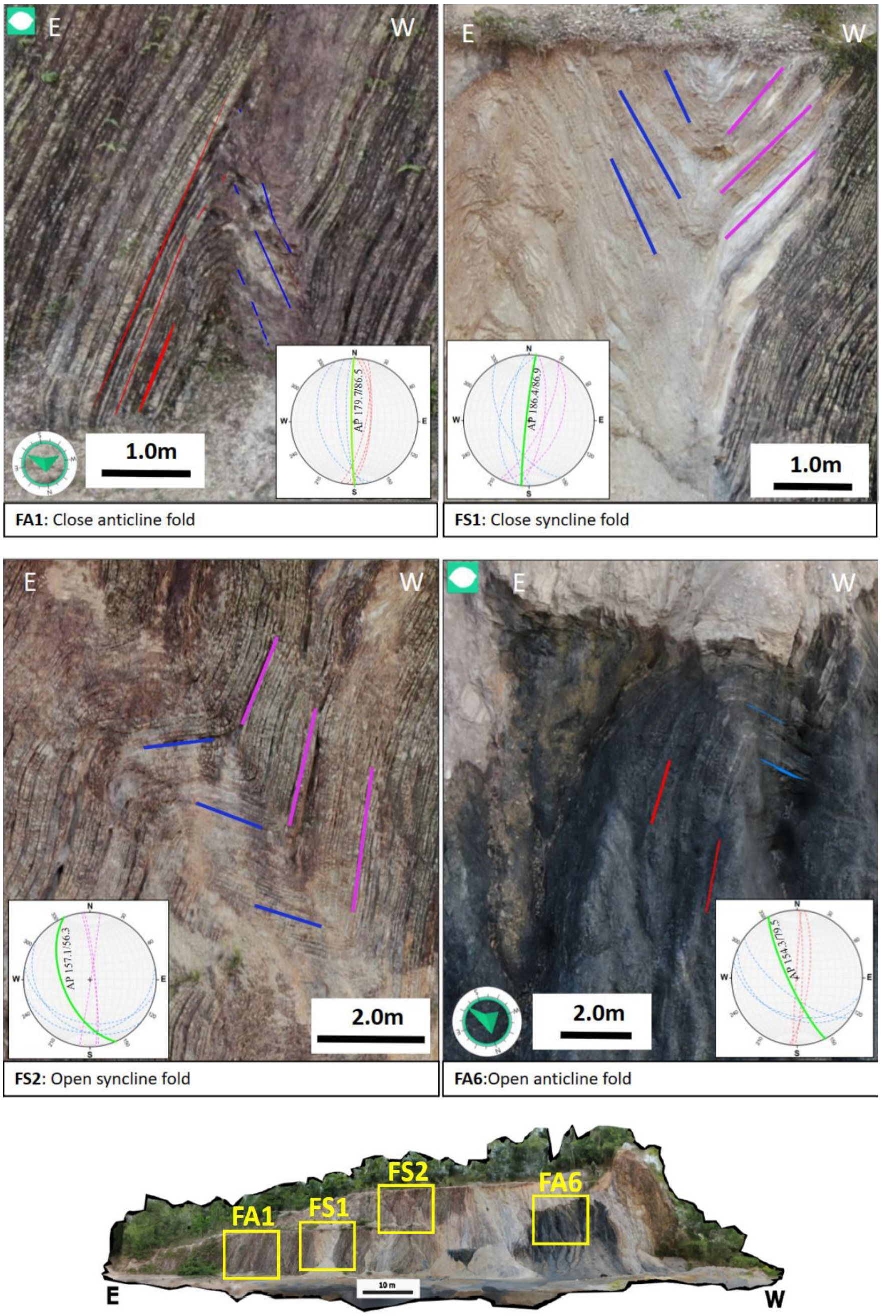

Figure 7: Folds on the Kebun 500 DOM are classified based on the interlimb angle: close folds (30°–70°) and open folds (70°–120°). FA1: close fold. FS1: close fold. FS2: open fold. FA6: open fold.

the Semanggol Formation and NW sinistral movement of the Bok Bak Fault both deduce an ~E-W compressional event, which suggests that the structures in Kebun 500 and Bok Bak Fault activity were likely formed during the same deformation episode, which was also reported in the nearby outcrops of Bukit Jabi and Cheong Chong Kaw estate (Harun & Jasin, 1999b; 2000).

The sedimentary layers of the Semanggol Formation (chert and mudstone) with contrasting mechanical properties were folded when flexural slip occurred at the boundary during a shortening or compressional event. It can be observed that the local outcrop folds appear like parasitic structures relative to the regional-scale fold. Minor folds parasitic to the major fold usually have S and Z asymmetrical profiles on the limbs of the major fold and M profiles in the hinge region (Figure 10 [Top]). The western outcrop with an M fold-profile is interpreted as the core of the fold and fracture/fault system. In contrast,

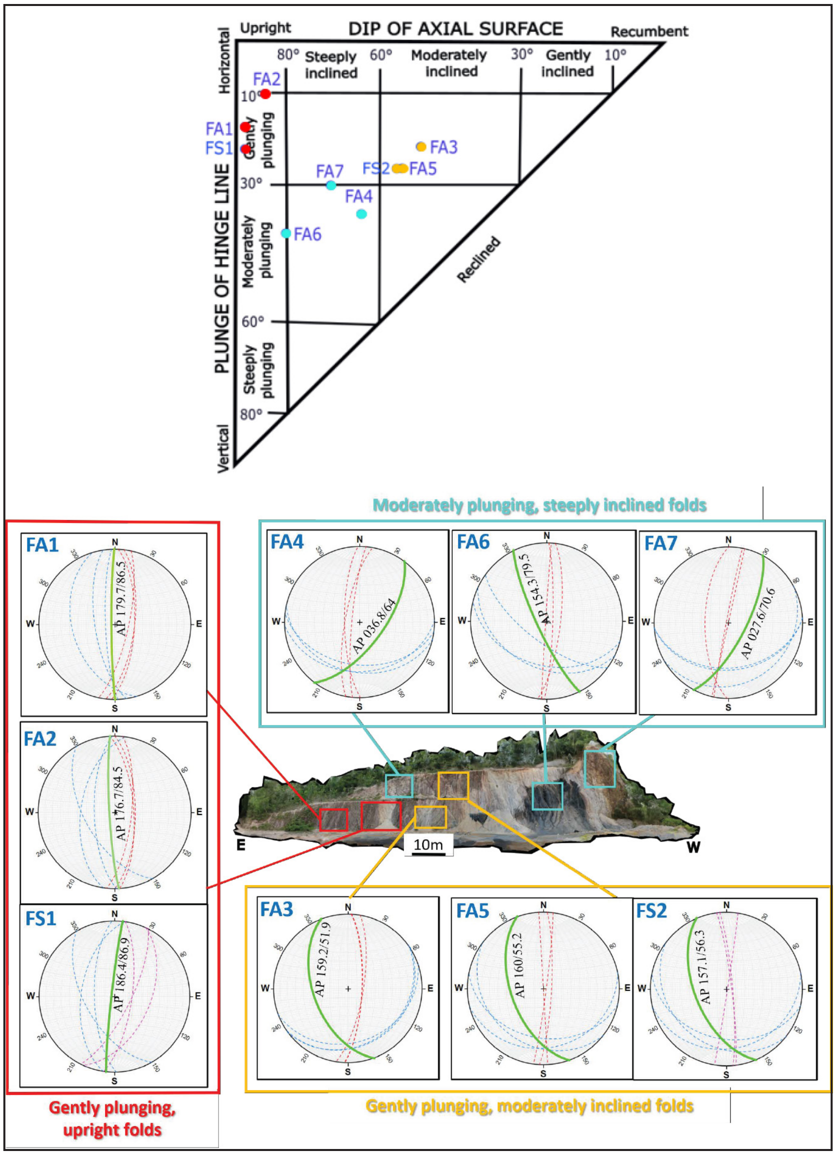

Figure 8: Fold classification (Fleuty, 1964) based on the axial plane dip and the plunge of the hinge line. Three types of fold were identified in the Kebun 500 DOM: (1) gently plunging-upright; (2) gently plunging-moderately inclined; (3) moderately plunging-steeply inclined.

the fractures in the western outcrop did not display any displacement, possibly due to the lack of marker beds. The fractures branch out from the core of the fracture/fault system to the east with lower dip angles and cross-cut the earlier formed folds. The deformation in the Kebun 500 outcrop is explained with a structural model in Figure 10 [Bottom].

Usage of digital outcrop model as study material

The integration of digital inspection within 3D models has revolutionized the tracing and interpretation of structural planes, offering several key advantages. Firstly, it has markedly reduced the time required for data collection in the field, streamlining the process and enhancing efficiency. Moreover, this technology enables the extraction of geological insights, such as precise structural orientations, with unprecedented levels of accuracy. Additionally, digital inspection facilitates the collection of data from inaccessible or remote areas, expanding the scope of geological studies. Lastly, it accelerates the interpretation and analysis phase, allowing geoscientists to quickly derive meaningful conclusions and make informed decisions.

The results from this study align with the existing knowledge regarding the structural geology of the Kebun 500 area. The general strike trends north-south and compression forces are believed to originate from the east-west direction (Ahmad, 2016). Additionally, unique features such as folds have been reported (Ahmad, 2016). However, this study, utilising DOM reveals additional

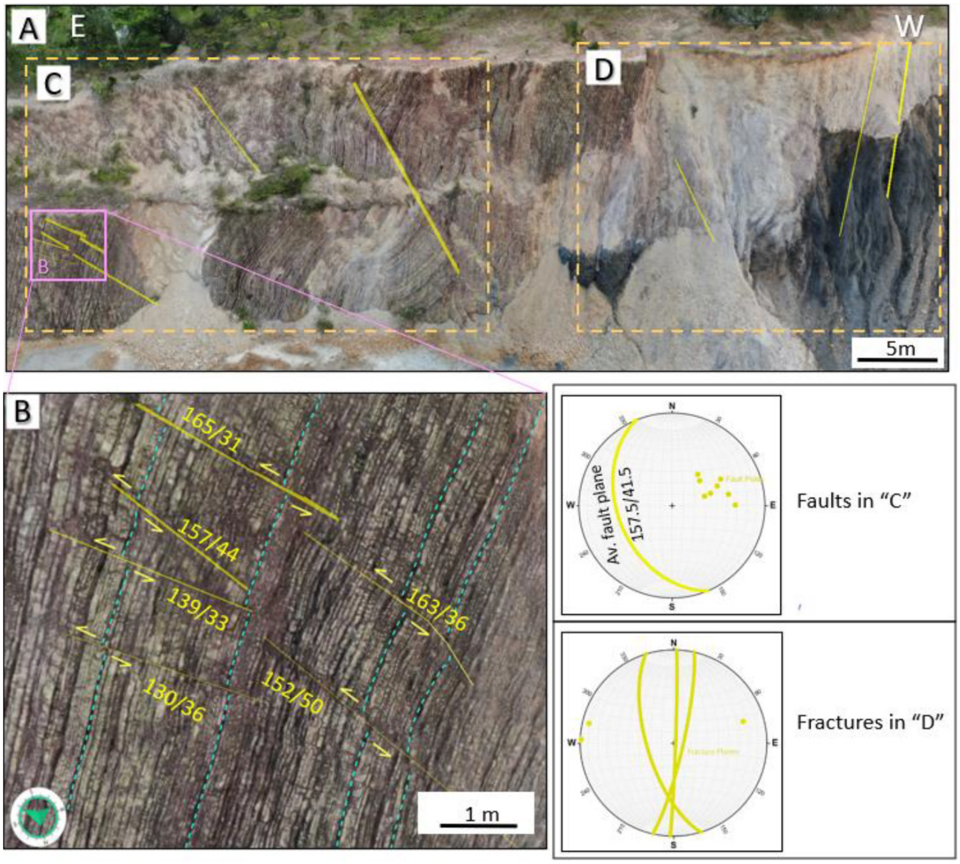

Figure 9: Fracture interpretation on the Kebun 500 DOM. [A] Eleven distinct fractures were identified, of which three had no displacement, and eight were reverse faults. Stereonets show the faults that occurred in area "C" and the fractures that occurred in area "D". [B] Local fractures observed at the eastern part of the Kebun 500 digital outcrop. The bed displacements showed a fault system with consistent reverse motion.

Table 4: Fracture information of Kebun 500 outcrop.

	Fracture	
Displacement	no	yes
Number of readings	3	8
Strike	002-013; 163	130-180
Dip	67°-88°	30°-58°
Mapped Length (m)	7-14	2-14
Displacement (cm)	-	6-32
Motion	-	Reverse

insights. Compared to traditional field study, DOM provides a broader view of fold features, allowing us to zoom in, zoom out and explore different angles. This enhanced perspective aids in understanding the direction, connections between bends and the overall formation of this geological structure. Furthermore, other case studies in different regions have also demonstrated that UAV-based photogrammetry approaches enable precise detection of geological features, enhancing fieldwork and advancing in the field of structural geology (Colica *et al.*, 2021; Peace & Jess, 2023).

CONCLUSION

A 3D digital outcrop model (DOM) of the Semanggol Formation in the Kebun 500 area of Kedah was constructed to collect high-accuracy geological data and analyse its structural style and deformation. The rocks of the Semanggol Formation in Kebun 500 are observed to

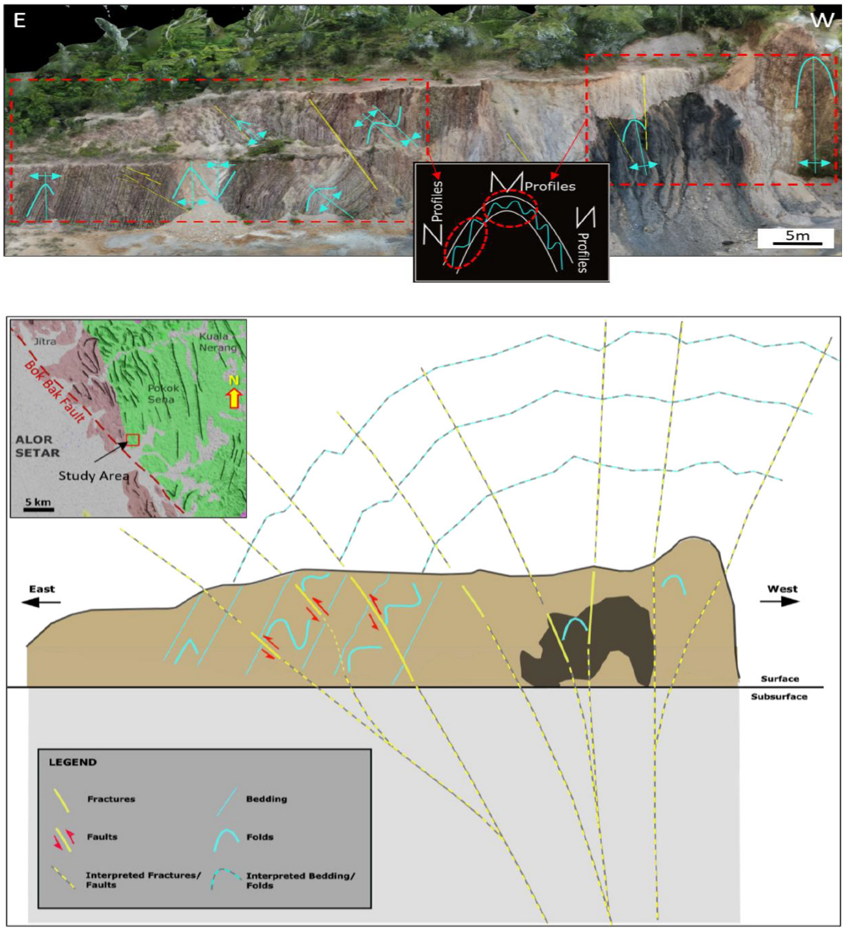

Figure 10: [Top] The eastern cliff exhibits Z-profile folds, while the western side has M-profile folds, which are characteristic of parasitic folds. [Bottom] A proposed model of the structural setting in Kebun 500 sedimentary rocks. Inset at left, the geological map of northern Kedah shows that the study area (Kebun 500) is located next to the Bok Bak Fault zone and ~N-S trend morphology features (bedding traces) in the surrounding area.

be folded and fractured. Based on the interlimb angles, the folds are classified as close to open folds and can also be grouped into gently plunging-upright folds, gently plunging and moderately inclined folds, and moderately plunging and steeply inclined folds. These folds are part of a series of minor/parasitic folds that form when flexural slip occurs in sedimentary layers with contrasting mechanical properties during a shortening or compressional event. The N-S striking beds and folds of the Kebun 500 sedimentary rocks are cross-cut by N-S striking, steeply dipping fractures and NNW-SSE striking, inclined dipping reverse faults. These fractures could be associated with the adjacent NW striking Bok Bak fault.

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AUTHORS CONTRIBUTION

TYE performed interpretation, analysis, drafted and wrote the manuscript with input from the other authors. NHMJ conducted field data collection using drone. CCM, MAMY, and NHMJ provided technical oversight. CCM, NHMJ and MAMY reviewed the writing.

CONFLICT OF INTEREST

This paper has never been published and is not in the process of being published by any journal. The authors declare that there are no competing interests or conflicts of interest associated with this work.

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