

Comparison of Window Scan and Digital Outcrop Model Approaches for Fracture Characterisation Along the Lampung–Panjang Fault Zone

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Abstract

Fracture characterisation is an important component of structural geological studies because fracture orientation and distribution provide insights into tectonic deformation and rock mass behaviour. However, conventional field-based fracture measurements are often constrained by limited outcrop accessibility and observation coverage. This study evaluated the applicability of Digital Outcrop Models generated from unmanned aerial vehicle photogrammetry for fracture characterisation within crystalline rocks along the Lampung–Panjang Fault zone, southern Sumatra, Indonesia. Fracture data were collected from four outcrops using both the window scan method and digital measurements derived from georeferenced three-dimensional outcrop models. The aerial imagery was processed to generate orthomosaics and digital outcrop models, from which fracture traces were identified and analyzed. A total of 124 fractures were measured using the window scan method, whereas 319 fractures were extracted from the digital outcrop models. Results showed that both approaches consistently identified dominant northwest–southeast and northeast–southwest fracture orientations across the study area. Although differences were observed in dip distributions and contour dispersion, the digital outcrop models preserved the principal fracture patterns recognized in the field while providing a larger dataset and broader spatial coverage. These findings demonstrated that digital outcrop models can reliably represent fracture geometries and serve as an effective alternative to conventional measurements, particularly in inaccessible outcrops. The study highlights the potential of drone-based photogrammetry to improve the efficiency and completeness of structural geological mapping and fracture characterisation.

Keywords: Fracture characterisation; Digital outcrop model; Photogrammetry; Structural geology

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Introduction

The Lampung–Panjang Fault is one of the strike-slip faults in Lampung Province, cutting across various lithologies distributed from South Lampung Regency through Bandar Lampung City to Metro City (Mangga et al., 2010). The fault exhibits a northwest–southeast (NW–SE) trend and is characterized by left-lateral displacement (Rasimeng et al., 2024; Sarkowi et al., 2025; Sulandari et al., 2023). Fault activity generated some kind of morphology for example elongate hills,

valleys, wavy flat, and mountains. This fault also developed fractures with high intensity especially on brittle rocks in the surrounding area of Fault. These fractures provide valuable records of tectonic processes and play an important role in structural geological investigations.

Fracture distributions are widely developed within crystalline rocks, including both igneous and metamorphic lithologies, along the Lampung–Panjang Fault zone (Haerudin et al., 2026). Traditionally, geologists have employed scanline and

window scan methods to assess fracture intensity, density, and spatial distribution in the field (Bistacchi et al., 2020; Koesmawardani et al., 2021; Watkins et al., 2015). However, the complex topography and variable outcrop accessibility associated with fault-related landscapes often limit the effectiveness of conventional measurements. Consequently, alternative approaches are required to obtain more comprehensive fracture datasets. One promising method is the use of Digital Outcrop Models (DOMs) or Digital Surface Models (DSMs) generated from unmanned aerial vehicle (UAV)-based photogrammetry, which enable detailed fracture mapping and analysis from high-resolution three-dimensional outcrop representations (Osterman, 2017; Panara et al., 2023; Rossi et al., 2017).

While previous digital discontinuity assessments in Indonesia (Koesmawardani et al., 2020) validated DOM applications against scanline/window measurements in granitic rocks at Muaro Silokek—reporting directional variances within $\pm 8^\circ$ —their evaluation focused primarily on homogenous basement exposures. The applicability and statistical consistency of DOM workflows across heterogeneous crystalline and metamorphic lithologies (e.g., Way Galih Schist) subjected to active strike-slip deformation along the Lampung–Panjang Fault Zone remain systematically unquantified. This study addresses this gap by implementing a nested multi-scale comparative framework (1×1 m field plots, co-located 3×3 m DOM windows, and full-outcrop DOMs) combined with 3D spherical statistics.

Photogrammetry is a method of acquiring information about physical objects by recording, measuring, and interpreting patterns from aerial photographs captured using drones (Bemis et al., 2014; Liu et al., 2022). The resulting aerial imagery is then processed to generate a DOM, which provides a detailed three-dimensional

representation of the outcrop (Liang et al., 2022). Numerous studies have demonstrated the capability of DSMs/DOMs to collect fracture-related data, including the automatic identification and extraction of fracture networks (Martinelli et al., 2020; Menegoni et al., 2023). DOM method should be applied at the study site to generate a three-dimensional outcrop model, which can subsequently be analyzed using specialized software for structural interpretation and fracture characterisation (Assali et al., 2014; Fardana et al., 2024; Panara et al., 2023; 2024; Triantafyllou et al., 2019).

Materials and Methods

The study area is part of the Way Galih Schist (Pzgs), which consists of greenschist-facies amphibole schist and orthogneissic dioritic amphibolite (Mangga et al., 2010). These rocks are distributed along a northwest–southeast trend that parallels both the Great Sumatran Fault system and the Lampung–Panjang Fault (Figure 1). This geological setting provides an excellent opportunity to investigate fracture characteristics associated with long-term tectonic processes.

DOM are digital representations of surface geometry derived from a collection of three-dimensional coordinate points, providing a detailed depiction of the shape and topography of a surface or rock outcrop (Caravaca et al., 2020; Nesbit et al., 2018). When accurately georeferenced in terms of location, orientation, and scale, DOMs enable the efficient extraction of lithological and structural data, particularly for the characterization of discontinuities such as faults, fractures, joints, and bedding planes (Triantafyllou et al., 2019). The increasing use of unmanned aerial vehicles (UAVs) in geological mapping has facilitated the generation of high-resolution DOMs, allowing researchers to identify and analyze structural features with greater precision (Burnham et al., 2022).

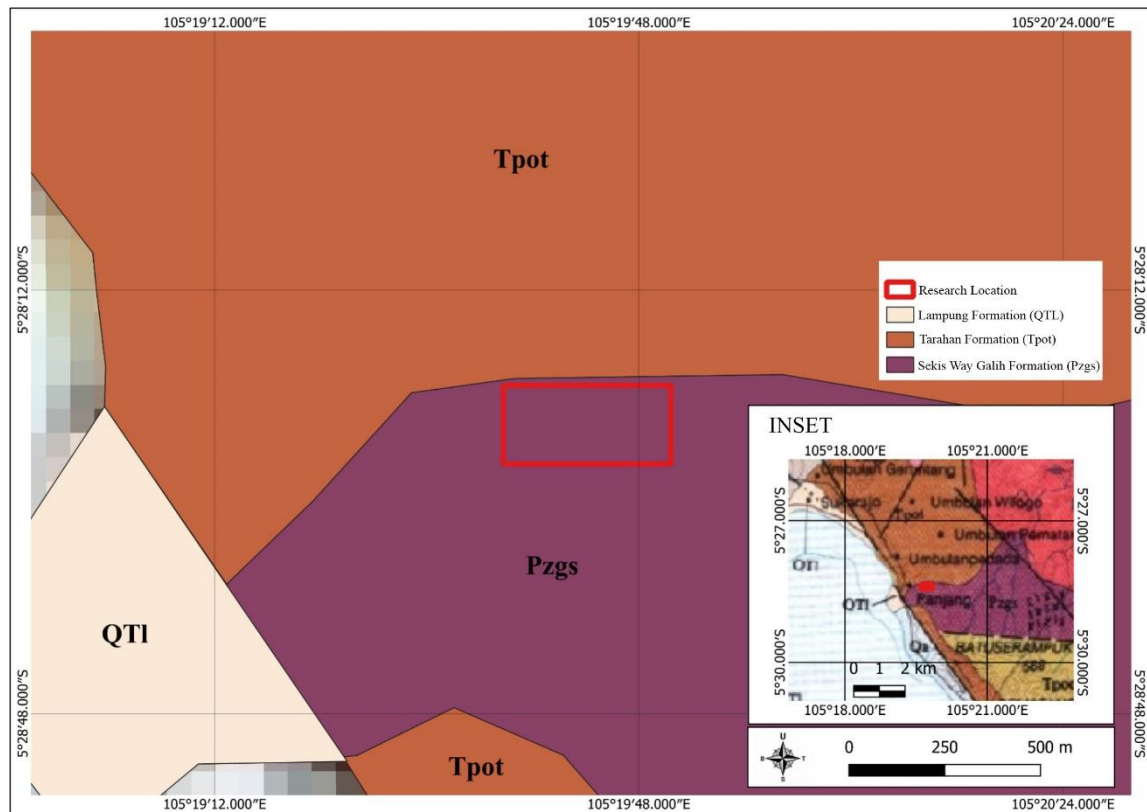


Figure 1. Section of geological map of Tanjungkarang (Mangga et al., 2010).

Previous studies have demonstrated the effectiveness of drone-based photogrammetry for automated fracture extraction and the mapping of various discontinuity surfaces within rock outcrops (Zeng et al., 2025). Compared to conventional field surveys, DOMs offer significant advantages by enabling measurements of orientation, thickness, and geometric relationships of structural features that may be inaccessible, poorly exposed, or too large to assess directly in the field (Menegoni et al., 2023). Fractures can be detected and mapped by interpreting linear features preserved within the digital models, providing a comprehensive framework for structural geological analysis (Perozzo et al., 2025).

The study commenced with the acquisition of fracture data through a combination of field measurements and aerial photogrammetric surveys. Field-based fracture measurements were conducted using the window scan method within a 1 m × 1 m sampling area (Figure 2a and Figure 2b), with observation sites selected based

on the abundance and intensity of fractures exposed on the outcrops (Farny, 2017; Koesmawardani et al., 2021; Watkins et al., 2015). Fracture mapping was performed concurrently with lithological observations to provide a geological context for the structural data. To support digital outcrop reconstruction, aerial imagery was collected using a DJI Mini 3 unmanned aerial vehicle, while an iPhone 15 Pro equipped with LiDAR technology was utilized to complement the data acquisition and improve three-dimensional surface characterisation.

Aerial imagery captured by a DJI Mini 3 drone was processed in Agisoft Metashape to generate georeferenced orthomosaics and 3D textured meshes, complemented by LiDAR close-range scans acquired via an iPhone 15 Pro Polycam (Figure 2c). Internal spatial scale accuracy was calibrated using physical scale bars (1.0 m × 1.0 m window frames) placed on the outcrop faces, yielding a mean relative distance residual of ≤1.8 cm (1.5% scale error). Fracture orientation extraction in

CloudCompare was performed using planar surface fitting with the Compass plugin, maintaining an angular orientation uncertainty within $\pm 2.5^\circ$.

To overcome area-dependent dataset discrepancies between manual field scans and digital models, fracture intensity was normalized using the two-dimensional areal lineation density parameter (P21, expressed in m/m^2 ; (Sanderson & Nixon, 2018)). For the field dataset, total cumulative fracture trace length (L) within each $1.0 \text{ m} \times 1.0 \text{ m}$ sampling frame ($A = 1.0 \text{ m}^2$) was digitized from high-resolution field orthophotos calibrated against physical tape measurements. For the digital outcrop models, co-located $3.0 \text{ m} \times 3.0 \text{ m}$ square sub-windows ($A = 9.0 \text{ m}^2$) centered on the

field scanplots were extracted. All visible discontinuity traces within the sub-windows were manually mapped on the georeferenced 3D meshes in CloudCompare to calculate total cumulative trace length. Fracture density P21 was then computed as the ratio of total trace length to observation area ($P21 = L / A$) (Andrews et al., 2019). Furthermore, spherical mean poles, Fisher concentration parameters (κ), and 3D angular misfits (γ) were calculated from lower-hemisphere normal vectors. Non-parametric two-sample Kolmogorov–Smirnov (K-S) tests were executed on circular-transformed axial strike angles ($\% 180$) and dip angles to evaluate statistical equivalence across methods.

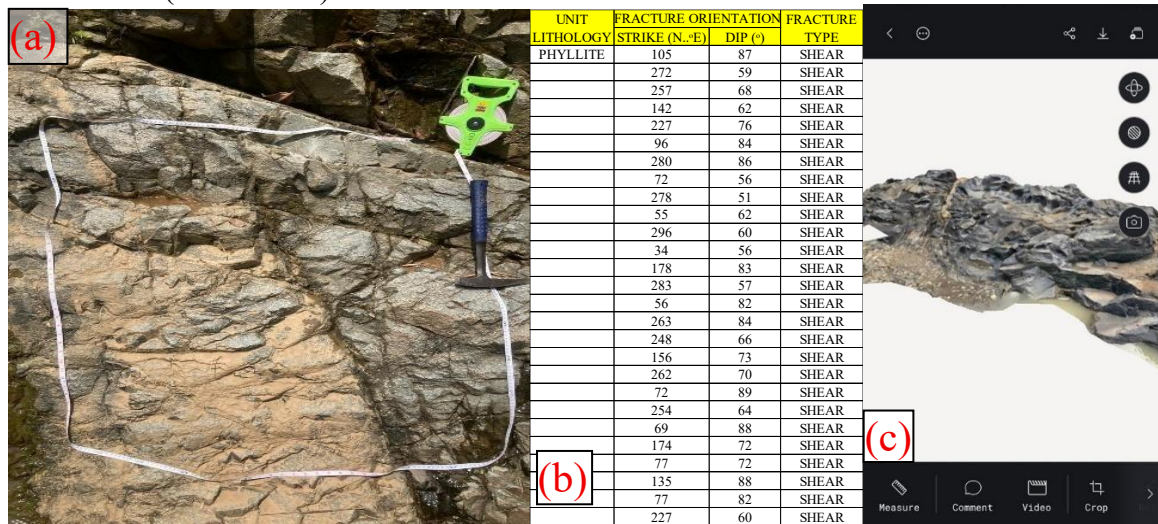


Figure 2. (a) Example of window scan method on outcrop; (b) fractures data list; (c) 3D model from Polycam.

Results

The study area is composed of crystalline rock units, including schist, phyllite, and andesite, exposed at four observation sites (Figure 3). Lithological characterization was carried out using two representative rock samples collected from outcrops DK1.1 and DK1.3. Petrographic analysis was conducted to determine the mineralogical composition, texture, and microstructural characteristics of the rocks, complementing field-based lithological observations. The combined field and microscopic analyses identified the DK1.1 outcrop as andesite, whereas the remaining

representative sample was classified as phyllite. These lithologies constitute the principal fractured rock units investigated in this study.

Fracture data were collected from four observation sites, where the dominant fracture type identified was shear fractures. A total of 124 fracture measurements were obtained using the window scan method. Stereonet contour analysis reveals that each observation site exhibits contour concentrations in different quadrants, indicating local variations in fracture orientation (Figure 4). However, when viewed collectively, the fracture population

displays a predominant northwest–southeast trend. These results are subsequently compared with fracture

orientation measurements derived from the DOM.

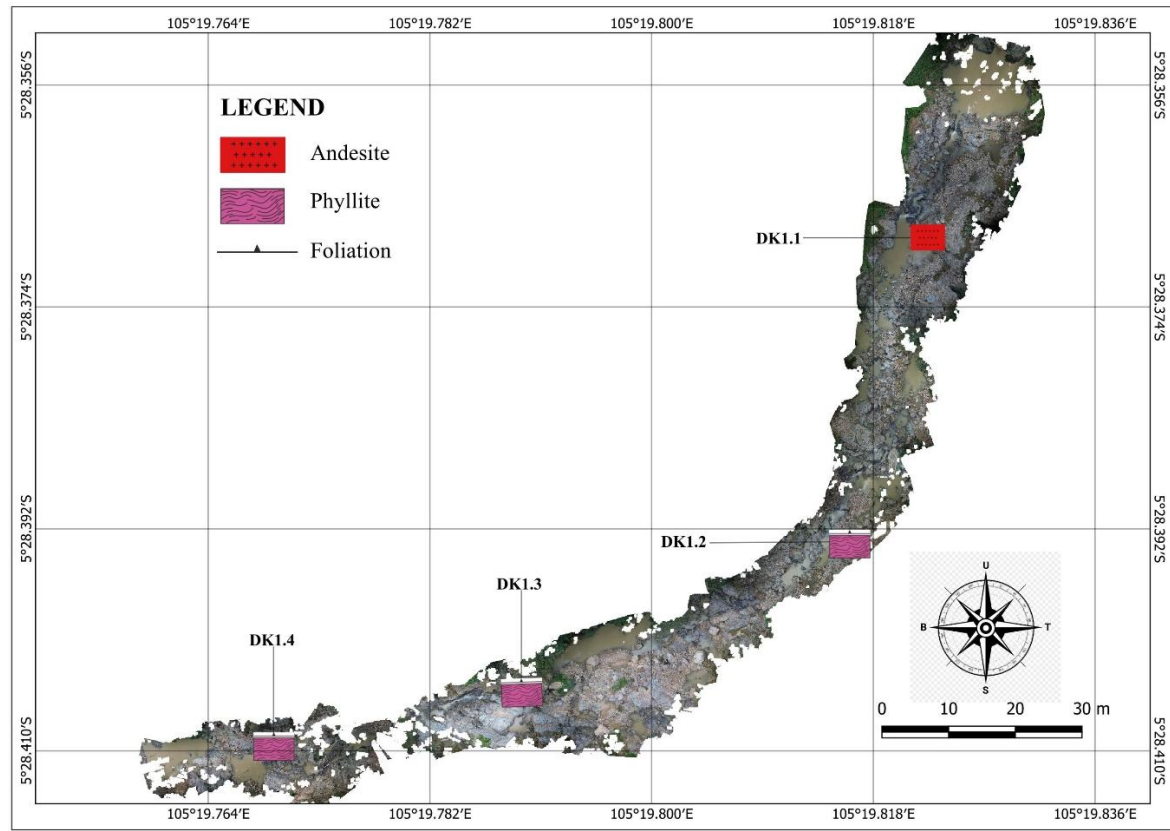


Figure 3. Lithology map in study area.

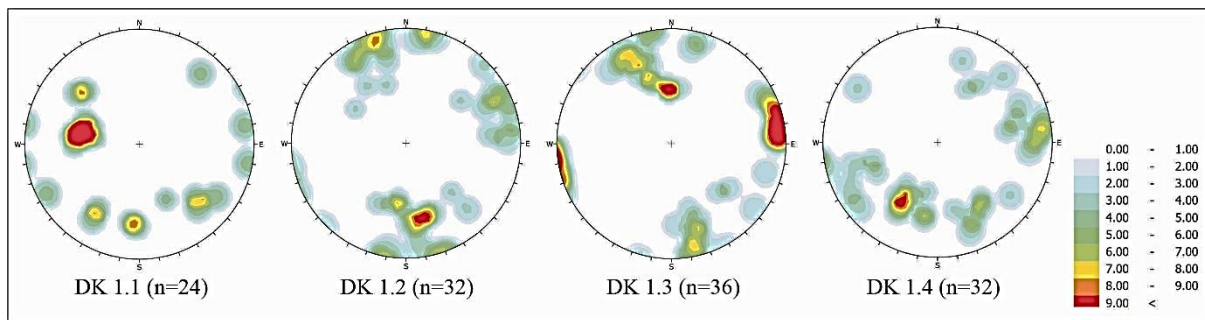


Figure 4. Fracture contours collected by window scan method at each site.

Digital outcrop modelling was conducted at all four observation sites (Figures 5). Fracture picking was performed after the outcrops had been reconstructed into georeferenced three-dimensional models. Fracture analysis on the DOMs covered the entire accessible outcrop surface, allowing a more comprehensive assessment than conventional field measurements. A total of 319 fractures were identified and mapped across the four sites. The orientation data from each site were subsequently presented using rose diagrams and analyzed through

stereonet contour plots (Figure 6) to characterize the dominant fracture patterns and their spatial distribution.

Across the four observation sites (DK1.1 to DK1.4) on Table 1, field window scans yielded normalized fracture density (P21) ranging from 10.00 m/m² (DK1.1) to 12.77 m/m² (DK1.3). Co-located 3 × 3 m DOM sub-windows yielded lower absolute P21 values, ranging from 3.73 m/m² (DK1.4) to 5.08 m/m² (DK1.3), establishing a systematic field-to-DOM offset ratio

between 2.11 and 2.86. Despite this offset, relative spatial variability was perfectly preserved, with site DK1.3 exhibiting the highest P21 intensity in both field (12.77 m/m^2) and DOM (5.08 m/m^2) datasets. Based on Table 2, 3D angular misfits between $3 \times 3 \text{ m}$ DOM and full-outcrop DOMs remained exceptionally low ($\gamma = 9.2^\circ$ to 17.4°). Two-sample K-S tests for strike distributions revealed no statistically

significant differences between field scans and local DOM windows at DK1.1 ($D = 0.239$, $p = 0.514$) and DK1.3 ($D = 0.361$, $p = 0.080$). Conversely, dip distributions exhibited statistically significant variance ($p < 0.001$) across all sites, with DOM measurements yielding systematically lower dip angles (mean dip 8.3° – 29.4°) than field compass readings (mean dip 30.5° – 54.1°).

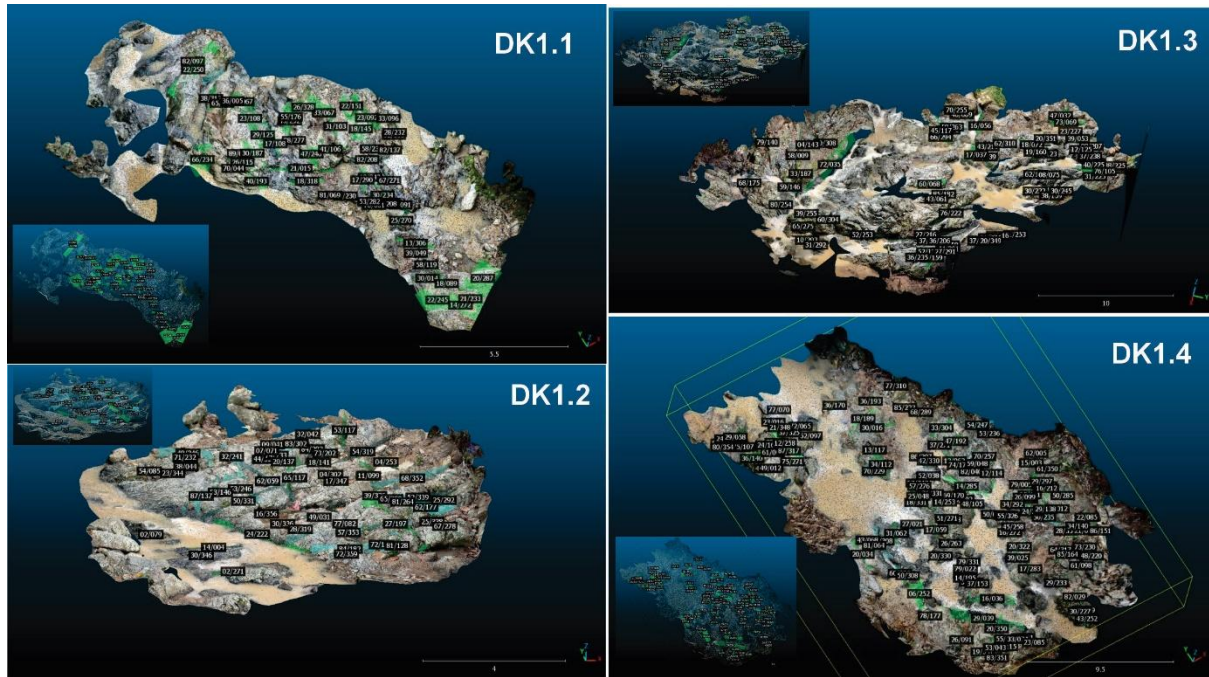


Figure 5 Digital Outcrop Model with Fracture Analysis at each site (inset: fracture distribution).

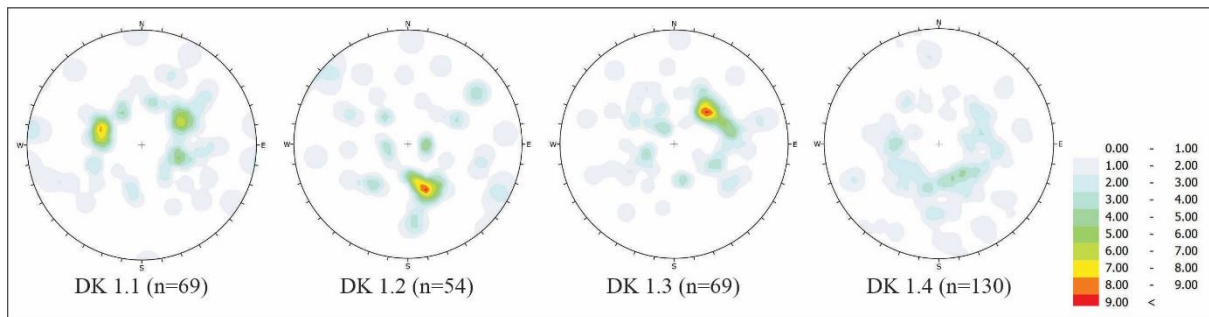


Figure 6. Fracture contours collected by picking from the DOM at each site.

Table 1. Fracture Density (P21).

Station	Scale	Area (A, m^2)	Length (L, m)	Density P21 (m/m^2)	Offset Ratio (P21 Field/ P21 DOM)
DK1.1	Field $1 \times 1 \text{ m}$	1.0	10.00	10.00	2.11
	DOM $3 \times 3 \text{ m}$	9.0	42.75	4.75	
DK1.2	Field $1 \times 1 \text{ m}$	1.0	10.85	10.85	2.28
	DOM $3 \times 3 \text{ m}$	9.0	42.84	4.76	
DK1.3	Field $1 \times 1 \text{ m}$	1.0	12.77	12.77	2.51
	DOM $3 \times 3 \text{ m}$	9.0	45.72	5.08	
DK1.4	Field $1 \times 1 \text{ m}$	1.0	10.66	10.66	2.86
	DOM $3 \times 3 \text{ m}$	9.0	33.57	3.73	

Table 2. Spatial orientation statistic result.

Sites	Scale	N	Strike Dip (RHR)	Fisher (κ)	Angular Misfit vs Field 1x1 (γ)	Angular Misfit (3x3 vs Full)	K-S Test Strike (D, p-value)	K-S Test Strike (D, p-value)
DK1.1	Field 1 × 1 m	23	N 328.3°E / 33.7°	1.86	–	–	–	–
	DOM 3 × 3 m	18	N 071.1°E / 10.8°	3.79	37.5°	9.2°	D=0.239, p=0.514	D=0.778, p<0.001
	DOM Full	69	N 125.9°E / 9.0°	3.15	42.2°	–	D=0.188, p=0.546	D=0.580, p<0.001
DK1.2	Field 1 × 1 m	32	N 166.8°E / 30.5°	1.44	–	–	–	–
	DOM 3 × 3 m	26	N 300.5°E / 11.2°	2.98	39.0°	11.5°	D=0.368, p=0.029	D=0.623, p<0.001
	DOM Full	54	N 229.5°E / 8.3°	2.81	27.6°	–	D=0.240, p=0.165	D=0.617, p<0.001
DK1.3	Field 1 × 1 m	36	N 138.2°E / 54.1°	1.76	–	–	–	–
	DOM 3 × 3 m	18	N 144.5°E / 29.4°	7.03	25.1°	17.4°	D=0.361, p=0.080	D=0.778, p<0.001
	DOM Full	69	N 130.6°E / 12.6°	3.66	41.7°	–	D=0.286, p=0.032	D=0.667, p<0.001
DK1.4	Field 1 × 1 m	32	N 250.4°E / 39.8°	1.79	–	–	–	–
	DOM 3 × 3 m	33	N 211.0°E / 16.4°	2.66	28.7°	10.6°	D=0.356, p=0.022	D=0.513, p<0.001
	DOM Full	130	N 251.7°E / 12.4°	3.06	27.4°	–	D=0.319, p=0.008	D=0.599, p<0.001

Discussion

The comparison of stereonet contour plots reveals that the primary difference between the two methods lies in the dip distribution and the degree of data dispersion. The DOM results generally exhibit a broader contour distribution than the window scan method. This difference is related to the wider observation coverage provided by DOM, which encompasses nearly the entire outcrop surface. As a result, in addition to recording shear fractures, the method may also capture other discontinuity surfaces, such as tension joints, foliation planes, and exposed bedding planes.

In contrast, field measurements using the window scan method were conducted within relatively small observation areas (1 × 1 m), resulting in datasets that are more focused on specific fracture populations. Furthermore, the use of a geological compass in the field may introduce measurement uncertainties due to limited access to fracture surfaces, irregular

outcrop geometries, and potential errors in orientation readings. These factors may explain why the dip values obtained from the two methods are not always identical, despite displaying similar orientation trends.

The results indicate that the window scan and DOM methods produce generally consistent fracture orientation patterns across the four investigated outcrops. This consistency suggests that the DOM approach is capable of representing fracture geometries with a level of reliability comparable to conventional field measurements. Therefore, DOM can serve as an effective alternative for acquiring fracture orientation data, particularly in areas that are difficult to access or have limited outcrop exposure.

At outcrops DK1.1, DK1.2, and DK1.3, both methods yield relatively similar dominant orientations, demonstrating a high degree of agreement. A notable difference is observed at DK1.4, where the

window scan method shows a contour pole concentration within the third quadrant, corresponding to a northwest–southeast orientation, whereas the DOM results display a more dispersed trend distributed across two different quadrants. This discrepancy is likely attributable to the larger dataset obtained through DOM, which provides a more representative characterisation of the overall fracture population within the outcrop. In contrast, the window scan method captures fractures only within a limited observation area and is therefore more susceptible to local-scale bias. This pattern suggests that DOM is capable of recording a broader range of fracture orientations than conventional field measurements.

Although differences in contour concentration positions are observed in several outcrops, both methods consistently indicate similar principal orientation trends. This demonstrates that DOM preserves the dominant fracture orientation characteristics identified through field measurements while simultaneously increasing the quantity of data and the spatial extent of observations. Consequently, the application of DOM can be considered an effective approach for fracture characterisation in crystalline rocks, particularly in studies requiring extensive spatial coverage and high-density structural datasets.

The systematic offset in normalized fracture illustrates the resolution censoring effect (truncation limit) inherent to photogrammetric 3D models. Field observations within 1×1 m plots allow human geologists to detect fine-scale micro-fractures (<5 cm length), whereas DOM trace mapping is constrained by mesh density and image pixel resolution, filtering out sub-centimetric discontinuities. Nevertheless, the preservation of relative density trends, where DK1.3 consistently exhibits peak P21 values across both methods confirms that DOM workflows

effectively capture spatial strain gradient variations along the fault zone.

The systematic divergence in dip angle distributions ($p < 0.001$) highlights fundamental sampling biases inherent to each observation technique. Aerial UAV photogrammetry operating from a top-down perspective preferentially exposes sub-horizontal to gently dipping fracture traces exposed on outcrop floors and bench surfaces. In contrast, manual field compass readings are constrained by physical reach, biasing field geologists toward steeply dipping to vertical fracture planes exposed on cliff faces. Consequently, DOM workflows should not be viewed as a standalone replacement for field measurements, but rather as a complementary system requiring targeted field compass calibration for dip orientation.

Conclusion

This study demonstrates that UAV-based Digital Outcrop Models provide a statistically reliable and highly efficient complementary framework for fracture orientation and intensity mapping in crystalline rocks along the Lampung–Pangajene Fault Zone. While DOM workflows accurately reproduce field strike distributions ($p > 0.05$) and preserve relative P21 density variations across sites, photogrammetric resolution cut-offs reduce absolute P21 values by a factor of ~ 2.1 to 2.8 relative to field plots. Systematic dip variations ($p < 0.001$) further underscore the need for targeted field compass calibration. Co-located 3×3 m DOM sub-windows effectively bridge the scale gap between localized field plots and macro-scale outcrop trends, confirming DOM photogrammetry as an essential upscaling tool for structural geology.

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Author Contribution

RNH: Conceptualization, visualization, writing; DK: data curation, investigation, software; MEJ: project administration, visualization; LPS: validation.

Conflict of Interest

The authors declare no conflict of interest.

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