Sains Malaysiana 55(7)(2026): 1119-1131
http://doi.org/10.17576/jsm-2026-5507-02

Structural Lineament Orientation Patterns in Eastern Sabah Derived from Sentinel-1 SAR Data

(Corak Orientasi Kelurusan Struktur di Timur Sabah Diperoleh daripada Data SAR Sentinel-1)

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Received: 13 February 2026/Accepted: 19 June 2026

ABSTRACT

Geological lineaments provide important insight into regional structural organisation, but their mapping remains challenging in humid tropical regions where dense vegetation, persistent cloud cover and limited bedrock exposure constrain conventional field mapping and optical remote sensing. This limitation is particularly important in Eastern Sabah, northern Borneo, where complex tectonic deformation and major fault systems are present, but spatially consistent regional-scale lineament characterisation remains limited. This study applies Sentinel-1 Synthetic Aperture Radar (SAR) data to investigate structural lineament orientation patterns in Eastern Sabah because SAR imagery is less affected by cloud cover and is sensitive to surface roughness, moisture variation and geomorphological discontinuities. Sentinel-1 GRDH imagery was pre-processed using radiometric calibration, terrain flattening, speckle filtering and terrain correction, followed by multi-directional Sobel edge enhancement and illumination-controlled visualisation. Lineaments were extracted through expert-guided manual digitisation using structural and geomorphological criteria, and were validated using optical imagery and existing geological information to reduce anthropogenic and non-tectonic features. A total of 10,746 validated negative lineaments were mapped and statistically analysed. The Rayleigh test confirms that the lineament orientation distribution is significantly non-uniform, while Kolmogorov–Smirnov tests indicate significant length-distribution differences between the main orientation classes. The extracted lineament network shows strong directional anisotropy, with four dominant orientation sets comprising N–S, NE–SW, NW–SE and E–W trends. The N–S and NE–SW sets form the principal structural trends, while NW–SE and E–W lineaments represent secondary components. NE–SW-oriented lineaments show the greatest apparent continuity, with a maximum length of 3.180 km, suggesting laterally persistent structural corridors. The dominant orientation patterns correspond with major fault trends reported in regional geological maps of Sabah, supporting the tectonic significance of the SAR-derived lineaments. Lineament-density and lithology-density comparisons further indicate that the mapped lineaments reflect the combined influence of structural discontinuities, lithological variation and geomorphological expression. This study demonstrates the usefulness of Sentinel-1 SAR for regional structural lineament mapping in densely vegetated tropical terrain and provides a spatially consistent lineament framework for Eastern Sabah.

Keywords: Eastern Sabah; lineament analysis; Sentinel-1 SAR; structural geology; tectonic fabric

ABSTRAK

Lineamen geologi memberikan maklumat penting tentang organisasi struktur serantau, namun pemetaannya masih mencabar di kawasan tropika lembap yang dilitupi vegetasi tebal, sering mengalami litupan awan dan mempunyai singkapan batuan yang terhad. Kekangan ini amat penting di Sabah Timur, utara Borneo, yang mempunyai deformasi tektonik yang kompleks dan sistem sesar utama, tetapi pencirian lineamen berskala wilayah yang tekal dari segi ruang masih terhad. Kajian ini menggunakan data Synthetic Aperture Radar (SAR) Sentinel-1 untuk menganalisis corak orientasi lineamen struktur di Sabah Timur kerana imej SAR kurang dipengaruhi oleh litupan awan dan peka terhadap kekasaran permukaan, variasi kelembapan serta ketakselanjaran geomorfologi. Imej Sentinel-1 GRDH diprapros melalui penentukuran radiometrik, perataan medan, penapisan hingar spekel dan pembetulan medan, diikuti dengan penambahbaikan tepi Sobel pelbagai arah dan visualisasi terkawal pencahayaan. Lineamen diekstrak melalui pendigitan manual berpandukan kepakaran menggunakan kriteria struktur dan geomorfologi, serta disahkan menggunakan imej optik dan maklumat geologi sedia ada bagi mengurangkan ciri antropogen dan bukan tektonik. Sebanyak 10,746 lineamen negatif yang telah disahkan dipetakan dan dianalisis secara statistik. Ujian Rayleigh mengesahkan bahawa taburan orientasi lineamen adalah tidak seragam secara signifikan, manakala ujian Kolmogorov–Smirnov menunjukkan perbezaan taburan panjang yang signifikan antara kelas orientasi utama. Rangkaian lineamen yang diekstrak menunjukkan anisotropi arah yang kuat dengan empat set orientasi dominan, iaitu N–S, NE–SW, NW–SE dan E–W. Set N–S dan NE–SW membentuk trend struktur utama, manakala lineamen NW–SE dan E–W mewakili komponen sekunder. Lineamen berorientasi NE–SW menunjukkan kesinambungan nyata yang paling tinggi, dengan panjang maksimum 3.180 km, mencadangkan koridor struktur yang berterusan secara lateral. Corak orientasi dominan ini berpadanan dengan trend sesar utama yang dilaporkan dalam peta geologi wilayah Sabah, sekali gus menyokong kepentingan tektonik lineamen yang diperoleh daripada data SAR. Perbandingan ketumpatan lineamen dan ketumpatan-litologi turut menunjukkan bahawa lineamen yang dipetakan mencerminkan pengaruh gabungan ketakselanjaran struktur, variasi litologi dan ekspresi geomorfologi. Kajian ini menunjukkan kegunaan Sentinel-1 SAR untuk pemetaan lineamen struktur berskala wilayah di kawasan tropika bervegetasi tebal dan menyediakan rangka kerja lineamen yang tekal dari segi ruang bagi Sabah Timur.

Kata kunci: Analisis lineamen; fabrik tektonik; geologi struktur; Sabah Timur; Sentinel-1 SAR

INTRODUCTION

Geological lineaments are commonly known as linear or curvilinear surface structures that reflect the presence of subsurface structural discontinuities such as faults, fracture zones, joints, and lithological boundaries (Baid et al. 2024; Gabrielsen & Olesen 2024; Strokova, Ezhkova & Leonova 2020). Lineament analysis has been applied to infer regional structures, particularly in regions where field observation is limited. With advances in remote sensing technologies, lineament analysis has become an established approach in structural geology for identifying deformation patterns and tectonic fabrics at regional scales (Gabrielsen & Olesen 2024). However, the interpretation of lineaments remains challenging because linear surface features may represent tectonic structures, lithological boundaries, drainage alignment, topographic effects, vegetation patterns or anthropogenic features. Therefore, a clear extraction procedure and careful validation are required to ensure that the mapped lineaments are geologically meaningful.

In structural interpretation, lineaments are considered to be surface expressions or proxies of underlying geological structures rather than structures themselves (Gabrielsen & Olesen 2024). Their scientific value lies in their orientation, continuity, and spatial organisation, which provide insight into stress-field evolution, structural inheritance, and deformation style. However, lineaments may also arise from non-tectonic factors such as geomorphological processes, lithological contrasts, and anthropogenic features (Menier et al. 2017; Tongkul 2017). Therefore, rigorous extraction criteria and independent validation are necessary to ensure that mapped lineaments reliably represent geological structures (Abdullah, Akhir & Abdullah 2010). This issue is particularly important in tropical regions, where dense vegetation, deep weathering profiles and limited bedrock exposure can obscure or modify the surface expression of geological structures.

Remote sensing provides a powerful means of mapping lineaments due to its synoptic coverage and ability to capture spatial patterns over large areas. Optical satellite imagery has been widely used for this purpose, particularly multispectral data such as Landsat, where linear features are detected through tonal and textural contrasts (Choudhury et al. 2025). However, in humid tropical regions, persistent cloud cover and dense vegetation significantly limit the effectiveness of optical imagery for structural mapping. Synthetic Aperture Radar (SAR) data represent a suitable alternative in such scenarios. SAR systems are less affected by cloud cover and atmospheric conditions, and they are sensitive to surface roughness, moisture variation and geometric discontinuities. These characteristics make SAR imagery useful for detecting linear geomorphological features that may reflect fault- or fracture-controlled structures in vegetated terrain. As presented by Baid et al. (2024) and Dhara, Baisantry and Prusty (2022), recent literature indicates that Sentinel-1 SAR data can effectively support the detection of regional-scale lineament patterns in complex terrains given suitable preprocessing and directional enhancement. Nevertheless, the systematic application of Sentinel-1 SAR for regional-scale structural lineament mapping in Eastern Sabah remains limited compared with conventional geological mapping, DEM-based interpretation and optical remote sensing approaches. This represents the main technological and methodological gap addressed in this study. These methodological advantages are particularly relevant for structurally complex and densely vegetated regions such as Sabah, where conventional field mapping and optical remote sensing are constrained by limited exposure and persistent cloud cover. In this context, SAR-based lineament mapping provides a suitable framework for investigating the regional structural fabric of Eastern Sabah.

Eastern Sabah occupies a tectonically complex zone at the junction of several marginal basins, including the South China Sea, Sulu Sea, and Celebes Sea. Its geological evolution has been shaped by multiple episodes of compression, extension, and strike-slip deformation since the Early Cretaceous, resulting in a structurally heterogeneous crust characterised by superimposed fault systems of different orientations. Regional structural syntheses indicate that the dominant structural trends in Sabah include NE–SW, NW–SE, and N–S fault and fold systems, reflecting successive tectonic phases linked to basin opening, subduction, and terrane accretion

(Tongkul 1991). More recent neotectonic studies further suggest that several of these inherited fault systems remain active or have been reactivated under the present-day stress regime, particularly in eastern and southeastern Sabah, where normal and strike-slip faulting continues to influence surface deformation patterns (Tongkul 2017). Eastern Sabah was selected because it contains major regional structures, including the Lahad Datu Fault, Tabin Fault, Segama Valley structures and Dent Peninsula fault systems, while also being affected by dense vegetation, rugged terrain and uneven field accessibility. These conditions make the area suitable for evaluating the usefulness of Sentinel-1 SAR in regional structural lineament mapping.

Despite the importance of these tectonic structures, a spatially consistent regional-scale characterisation of lineament orientations across Eastern Sabah remains limited. Previous studies have primarily relied on geological mapping and local structural measurements, while systematic integration of satellite-based structural mapping with regional tectonic models remains underdeveloped. This gap is particularly pronounced in tropical terrains, where field-based structural data are sparse and unevenly distributed. In addition, previous regional studies have established the broad tectonic framework of Sabah, but detailed spatial information on the distribution, orientation, length, density and lithological association of surface lineaments in Eastern Sabah remains insufficient. The present study addresses this gap by deriving a comprehensive lineament orientation framework for Eastern Sabah using Sentinel-1 SAR data and an integrated structural mapping workflow. The specific objectives are to: extract and validate a regional dataset of negative lineaments from Sentinel-1 SAR imagery; quantify the orientation, length, and spatial distribution of the extracted lineaments; assess the statistical significance of lineament orientation and length differences; examine lineament density and lithological association; and evaluate the tectonic significance of the dominant lineament trends by comparison with mapped fault systems and regional tectonic syntheses. By establishing a modern, spatially consistent lineament framework, this study contributes new insight into the structural fabric and deformation patterns of Eastern Sabah and demonstrates the utility of SAR-based lineament mapping for regional structural analysis in densely vegetated tropical regions. The specialty of this study lies in the integration of Sentinel-1 SAR directional enhancement, expert-guided validation, statistical testing and lineament-density analysis to provide a spatially consistent structural lineament dataset for Eastern Sabah.

STUDY AREA AND GEOLOGICAL SETTING

The study area is located in Eastern Sabah, northern Borneo, covering the Tawau–Lahad Datu region and adjacent areas (Figure 1). It extends approximately from 4.0°N to 5.5°N and 117.5°E to 119.5°E, encompassing an area of about 18,000 km^2. The region includes low-lying coastal plains, deltaic systems, and rugged interior highlands, forming part of the Eastern Lowlands and Central Highlands physiographic provinces. Dense tropical vegetation and limited bedrock exposure constrain conventional geological mapping in much of the area. These conditions make Eastern Sabah an appropriate area for evaluating the usefulness of Sentinel-1 SAR data in regional structural lineament mapping, particularly where optical imagery and field observation are limited by cloud cover, vegetation and accessibility.

Regional topography is characterised by structurally influenced ridges, linear valleys, and aligned drainage networks, reflecting strong structural control on landscape development. A shaded relief (hillshade) map of the study area (Figure 2) highlights the prevalence of linear geomorphological features, such as straight valleys and aligned drainage segments, that are commonly associated with underlying fault and fracture systems. These geomorphological features are important because negative lineaments are commonly expressed as linear depressions, valleys, aligned drainage segments and tonal discontinuities that may correspond to zones of structural weakness.

Sabah occupies a tectonically active domain at the northern margin of Borneo and has been shaped by interactions between oceanic and continental lithosphere since the Mesozoic. Unlike western Borneo, Sabah is not underlain by stable Sundaland continental crust but consists largely of accreted oceanic and marginal basin materials, resulting in a structurally heterogeneous crust. Its tectonic evolution involved multiple phases of subduction, accretion, basin development, and subsequent compression and uplift, influenced by major tectonic elements such as the Northwest Borneo Trough to the west and the Sulu Trench and associated volcanic arc system to the east.

The structural framework of Sabah reflects a multi-phase tectonic evolution involving compressional, extensional, and strike-slip deformation. Regional tectonic syntheses indicate that the dominant structural trends comprise NE–SW, NW–SE, and N–S oriented fault and fold systems, reflecting successive deformation phases linked to basin opening, terrane accretion, and post-orogenic reorganisation (Figure 3). In Eastern Sabah, this structural grain is further complicated by chaotic deposits, imbricated sedimentary sequences, and normal fault systems that cut earlier compressional structures, indicating post-orogenic extension and reactivation of inherited faults. This complex structural setting provides a strong geological basis for assessing whether SAR-derived lineaments correspond to major regional structural trends or are influenced by local geomorphological and lithological controls.

The study area is underlain by diverse lithological units, including sedimentary, volcanic, volcaniclastic, ultramafic, metamorphic, intrusive, and Quaternary alluvial or coastal deposits. These lithological differences are important because rock type can influence the surface expression of lineaments through variation in resistance to weathering, fracture development, drainage incision and topographic relief. For example, sedimentary and interbedded units may produce clear linear valleys or drainage alignments due to bedding, jointing and differential erosion, whereas unconsolidated alluvial or coastal deposits may produce weaker or more diffuse lineament expression. Therefore, lithological influence is considered in this study through a lithology–lineament density comparison rather than by interpreting the SAR-derived lineaments as faults alone.

Neotectonic studies suggest that several inherited structures remain active or have experienced recent reactivation, particularly in the Dent Peninsula, Kinabatangan, and Semporna regions. Major mapped structures in Eastern Sabah include the Lahad Datu Fault, Tabin Fault, and fault zones associated with the Segama Valley and Dent Peninsula. These structures exert strong control on regional geomorphology, influencing drainage alignment, valley orientation, and ridge development. Preferential erosion along fractured and faulted zones enhances their surface expression as negative lineaments, providing a strong basis for lineament-based structural analysis in the study area. The comparison between extracted lineaments, lineament-density zones, lithological units and known fault zones is therefore important for evaluating whether the mapped lineaments are structurally meaningful or mainly controlled by surface geomorphology and lithology.

METHODOLOGY

LINEAMENT MAPPING WORKFLOW

This study employs an integrated SAR-based structural mapping workflow to extract and analyse regional lineament patterns in Eastern Sabah. The workflow includes Sentinel-1 SAR preprocessing, directional image enhancement, expert-guided manual lineament extraction, validation and cleaning of extracted features, and statistical analysis of lineament orientation and spatial characteristics. In this study, ‘expert-guided’ refers to manual interpretation based on geological and geomorphological criteria, including linear valleys, aligned drainage segments, tonal or backscatter discontinuities, straight slope breaks, geomorphological continuity and consistency with regional structural trends. Each stage is designed to minimise orientation bias and non-tectonic artefacts while ensuring that the final dataset represents structurally meaningful lineaments. The overall workflow is summarised in Figure 4.

SENTINEL-1 SAR DATA AND PRE-PROCESSING

Sentinel-1 Ground Range Detected High Resolution (GRDH) SAR imagery was used due to its suitability for structural mapping in vegetated tropical environments. The dataset consists of C-band SAR scenes acquired in VV polarisation, selected to maximise sensitivity to surface roughness and structural discontinuities. VV polarisation was used because it provides useful backscatter response from surface roughness and terrain-related discontinuities, which are relevant for identifying linearly arranged geomorphological features. SAR preprocessing was performed using the Sentinel Application Platform (SNAP) and included radiometric calibration, terrain flattening, speckle filtering, and terrain correction. Radiometric calibration was applied to obtain backscatter coefficients, followed by terrain flattening to reduce topographic effects. Terrain correction was carried out using a digital elevation model to ensure accurate georeferencing. The processed SAR images were converted to Gamma^{0} backscatter for subsequent structural interpretation. These preprocessing steps were applied to reduce radiometric and geometric distortions before lineament interpretation, particularly in rugged terrain where topography can influence SAR backscatter.

DIRECTIONAL IMAGE ENHANCEMENT

To enhance the visibility of linear structural features, the preprocessed SAR imagery was subjected to multi-directional Sobel edge filtering. Directional kernels were applied along four principal azimuths (N–S, E–W, NE–SW, and NW–SE) to minimise orientation bias and to highlight anisotropic features corresponding to potential fault and fracture systems. The use of multiple directional filters was intended to reduce preferential enhancement of only one structural trend and to improve the detection of lineaments with different orientations. Directional filtering was complemented by illumination-controlled visualisation to improve contrast between linear features and background terrain. This combination proved effective in enhancing negative lineaments such as linear valleys, aligned drainage segments, and tonal discontinuities.

HILLSHADE INTEGRATION

Hillshade images derived from a digital elevation model were generated using multiple illumination azimuths and a fixed solar elevation. These hillshades were used solely as a visual aid during interpretation to support the identification of structurally controlled geomorphological features and to cross-check SAR-derived lineaments. Hillshade data were not used directly for lineament extraction. The hillshade images were used to confirm the persistence of geomorphological lineaments and to help distinguish genuine terrain-related linear features from local SAR artefacts or short discontinuous image textures.

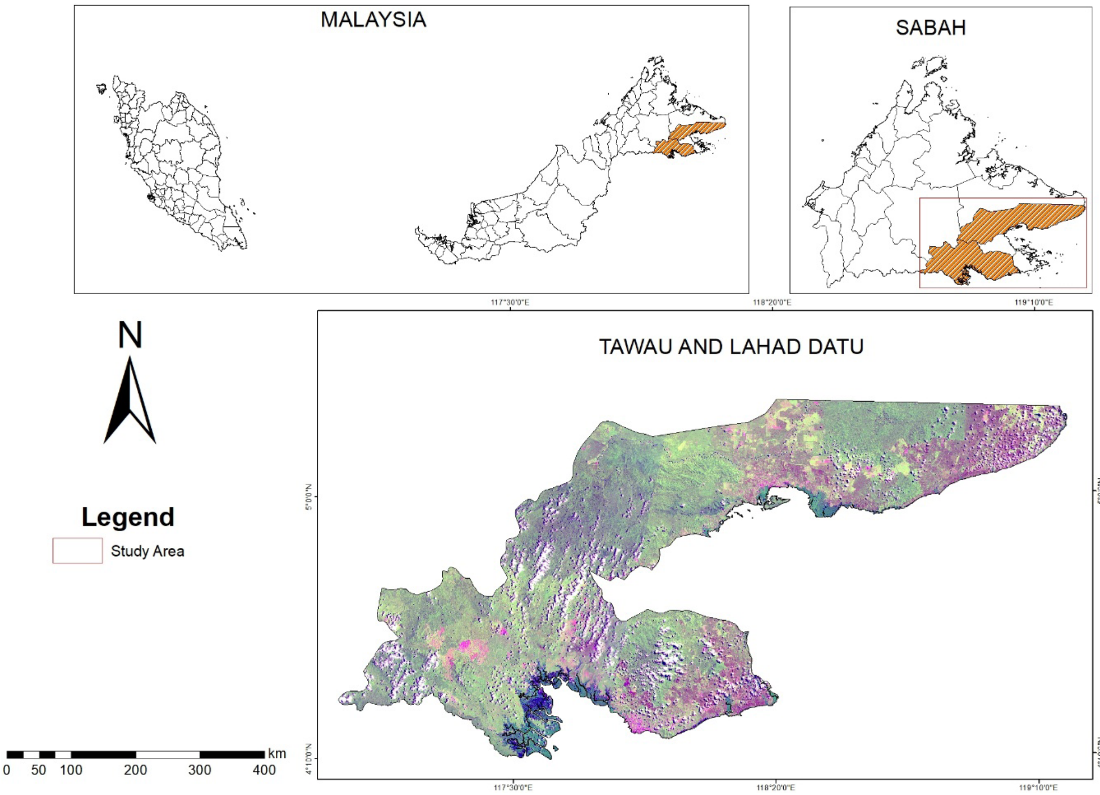

FIGURE 1. Location of the study area in Eastern Sabah, northern Borneo

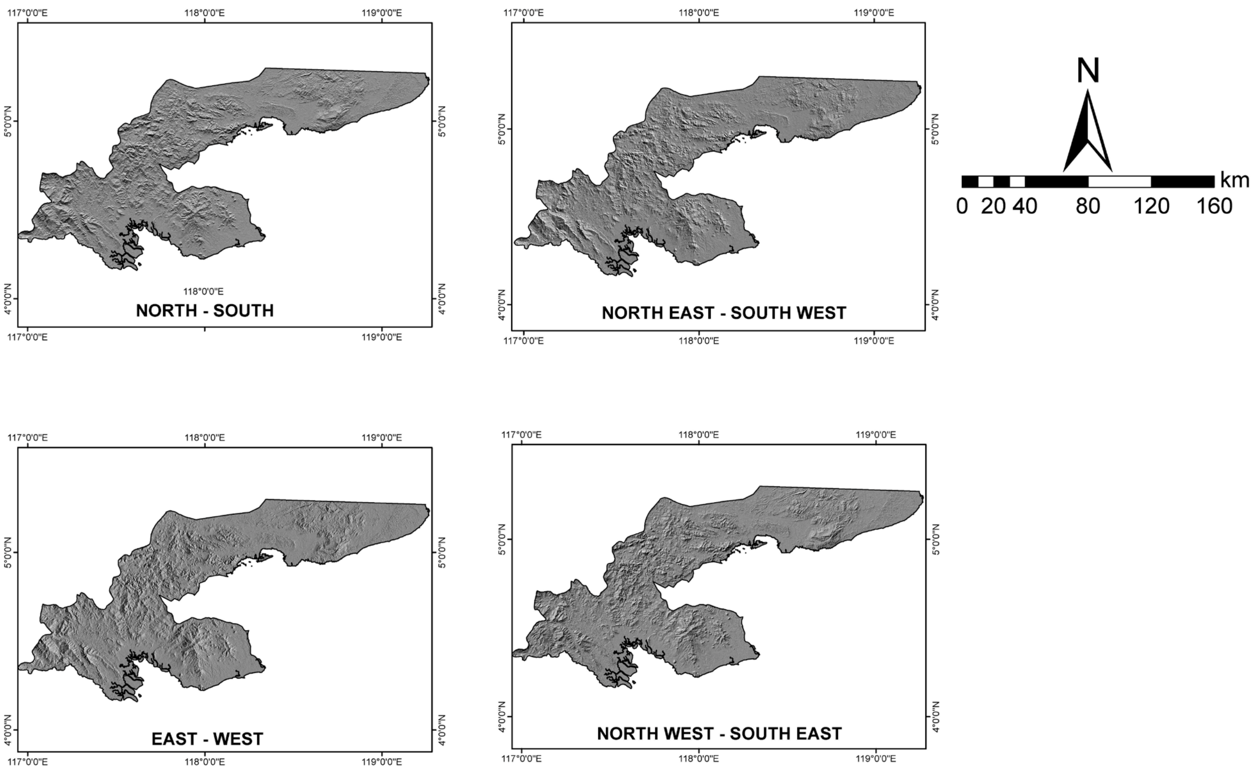

FIGURE 2. Hillshade map of Eastern Sabah showing regional topography and linear geomorphological features

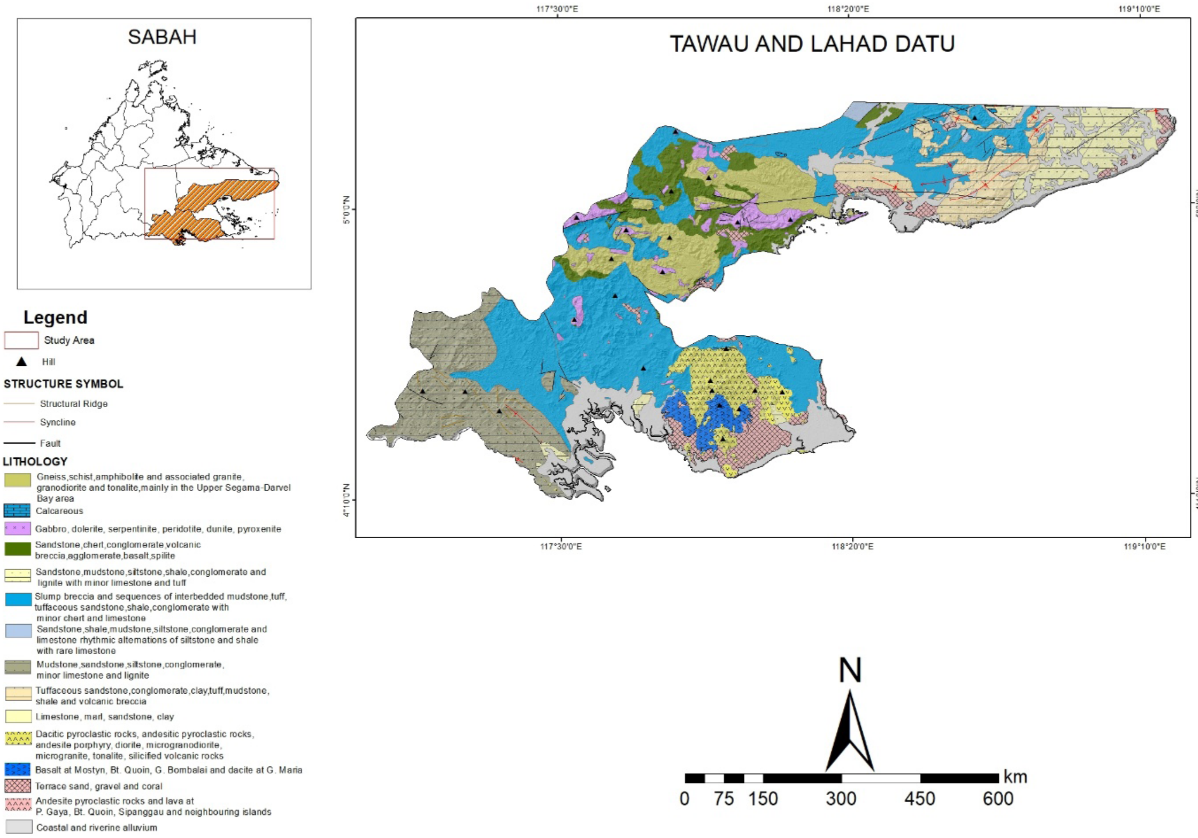

FIGURE 3. Simplified tectonic framework of Sabah showing major fault systems and structural trends

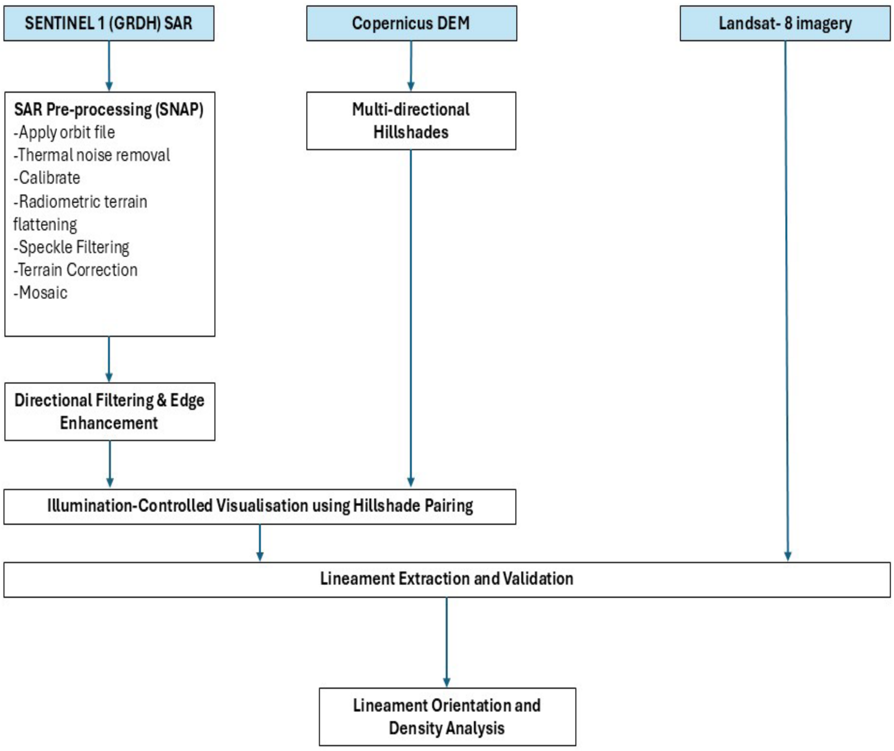

FIGURE 4. Workflow for Sentinel-1 SAR-based lineament extraction and analysis

LINEAMENT EXTRACTION AND VALIDATION

Lineaments were extracted through expert-guided manual digitisation using the directionally enhanced SAR imagery. Only negative lineaments, expressed as linear valleys, aligned drainage, or linear tonal depressions, were mapped. Digitisation was performed at multiple scales to ensure consistent identification of both short and laterally continuous features. A lineament was retained only when it showed clear linearity, geomorphological continuity and consistency across the enhanced SAR image and supporting topographic information. Features with unclear origin, irregular geometry or poor continuity were excluded to reduce interpretation uncertainty.

To ensure geological relevance, extracted lineaments were validated using optical satellite imagery to remove anthropogenic features such as roads and linear infrastructure. Additional non-tectonic features, including plantation boundaries, artificial drainage, settlement-related linear features and coastline-related features were also checked and removed where identifiable. Additional cleaning criteria included removal of closely spaced parallel features and selection of a single representative lineament where intersections occurred at very low angles. This validation process resulted in a final dataset of 10,746 cleaned negative lineaments. The final lineament dataset was then compared with existing geological information, lithological units and mapped regional fault systems to assess whether the extracted lineaments were structurally meaningful. Field verification was not conducted in this study; therefore, the mapped lineaments are interpreted as remotely sensed surface lineaments rather than confirmed fault traces.

LINEAMENT ORIENTATION AND SPATIAL ANALYSIS

Lineament orientation was quantified using azimuth measurements, grouped into four principal orientation classes (N–S, E–W, NE–SW, and NW–SE). Statistical analyses included frequency distribution, length statistics, and orientation–length relationships. Orientation patterns were visualised using rose diagrams, while lineament length distributions were examined using histograms and summary statistics. To strengthen the statistical interpretation, the Rayleigh test for circular uniformity was applied to evaluate whether the lineament orientation distribution was random or directionally concentrated. Since lineaments represent axial data, orientation values were treated accordingly before circular statistical testing.

Lineament length distributions among the four orientation classes were compared using the Kolmogorov–Smirnov test. This test was applied to determine whether the observed length differences among the N–S, NE–SW, NW–SE and E–W sets were statistically significant. Spatial organisation of the lineament network was further assessed through lineament density analysis to identify zones of enhanced structural intensity. Lineament density was calculated using the line density method, in which the total length of lineaments within a defined neighbourhood was computed per unit area and classified into very low, low, medium, high and very high-density classes. Lineament density was used as an indicator of surface structural intensity, where areas with higher lineament concentration were interpreted as zones of stronger structural or geomorphological expression. The density pattern was compared with known regional structures, including the Lahad Datu Fault, Tabin Fault, Segama Valley structures and Dent Peninsula fault systems.

A lithology–lineament density comparison was also conducted in table form to evaluate the relationship between lineament-density classes and major lithological units. This comparison was used to assess whether lineament expression is associated with particular rock types or reflects the combined influence of lithology, structural discontinuities, weathering, drainage development and topographic expression. These analyses form the basis for interpreting regional structural trends in Eastern Sabah while recognising that SAR-derived lineaments represent surface expressions and require field or geophysical validation for detailed subsurface interpretation.

RESULTS AND DISCUSSION

EXTRACTED LINEAMENT NETWORK

This represents one of the first regionally consistent SAR-based structural frameworks developed for Eastern Sabah. The lineament extraction and cleaning procedure yielded a total of 10,746 validated negative lineaments, distributed across four principal orientation sets (N–S, E–W, NE–SW, and NW–SE). Figure 5 shows the final validated lineament map derived from Sentinel-1 SAR imagery following directional filtering, illumination-controlled visualisation, and manual cleaning. These lineaments form the final structurally meaningful dataset used for subsequent statistical and spatial analyses. The large number of extracted lineaments reflects the ability of Sentinel-1 SAR directional enhancement to reveal subtle linear geomorphological features in densely vegetated terrain. However, the extracted features are interpreted as remotely sensed surface lineaments rather than confirmed fault traces, because field verification was not conducted in this study.

The extracted lineaments range in length from 0.003 km to 3.180 km, with mean lengths varying between 0.261 km and 0.574 km depending on orientation class (Table 1). The lineament network displays a non-random spatial organisation, with clusters of higher structural intensity evident in several parts of the study area. This spatial pattern suggests that the lineaments are not uniformly distributed across Eastern Sabah but are concentrated in zones that may reflect the combined influence of regional fault systems, lithological variation, drainage incision and topographic expression.

The updated length statistics were calculated from the same cleaned lineament shapefiles used for the statistical tests. The NE–SW set records the greatest maximum and mean length, whereas the E–W set records the shortest mean length. This provides an initial indication that lineament continuity varies according to orientation, although the statistical significance of these differences is evaluated further using the Kolmogorov–Smirnov test in the following section.

LINEAMENT LENGTH DISTRIBUTION

The statistical distribution of lineament lengths indicates that most extracted lineaments are short to intermediate in length. Across all orientation sets, minimum lengths range from 0.003 km to 0.071 km, while maximum lengths reach 3.180 km in the NE–SW orientation set. Mean lineament lengths vary systematically between orientation classes. The longest mean lengths occur in the NE–SW set (0.574 km), followed by the NW–SE set (0.371 km), the N–S set (0.297 km), and the E–W set (0.261 km) (Table 1). This pattern suggests that NE–SW-oriented lineaments are generally more continuous and laterally extensive than those of other orientations. However, this continuity is interpreted as apparent surface continuity rather than confirmed subsurface fracture connectivity.

The length–frequency histogram (Figure 6) shows that short lineaments (<0.5 km) dominate the dataset, whereas longer lineaments (>2 km) are less common but represent regionally significant structural alignments. The dominance of short lineaments is consistent with regional lineament datasets, where surface lineaments may be segmented by drainage development, lithological variation, vegetation cover, weathering and local geomorphological modification. In contrast, longer lineaments are more likely to reflect persistent zones of structural weakness, particularly where they are spatially consistent with mapped regional faults or dominant structural trends.

Kolmogorov–Smirnov tests were conducted to evaluate whether the observed length differences between orientation classes are statistically significant. The results show that lineament length distributions differ significantly between all orientation-class pairs ($p < 0.001$). The strongest difference occurs between the NE–SW and E–W sets ($D = 0.516$, $p < 0.001$), followed by the N–S and NE–SW sets ($D = 0.447$, $p < 0.001$). These results support the interpretation that lineament continuity varies systematically by orientation, with NE–SW lineaments showing greater apparent continuity than the shorter and more fragmented E–W lineaments.

LINEAMENT ORIENTATION ANALYSIS

Orientation analysis shows four dominant lineament sets of different population sizes (Figure 7). The most abundant set of lineaments includes the N–S trending lineament set (n = 3,541), followed by the NW–SE set (n = 2,486), NE–SW set (n = 2,434), and the E–W set (n = 2,285) (Table 1). The rose diagram for the entire study area (Figure 7) shows prominent peaks in the N–S and NE–SW directions, confirming high anisotropy in the regional structural fabric. Secondary maxima are reached in the NW–SE and E–W directions, indicating the influence of multiple structural trends and possible local geomorphological or lithological controls. The dominance of N–S and NE–SW indicates that they are the major structural configurations in Eastern Sabah.

The statistical significance of the orientation pattern was evaluated using the Rayleigh test for axial orientation data. The result indicates that the lineament orientation distribution is significantly non-uniform (n = 10,746, mean resultant length = 0.514, Rayleigh z = 2843.88, $p < 0.001$). This confirms that the extracted lineaments are not randomly oriented and supports the interpretation of preferred regional structural trends. However, because the dataset contains several dominant orientation sets, the Rayleigh test is used here to confirm departure from uniformity, while the specific modal trends are interpreted using the rose diagram and orientation-class statistics.

The dominance of N–S and NE–SW lineaments is consistent with the main structural grain of Sabah, where regional fault and fold systems have been linked to successive compressional, strike-slip and extensional deformation phases. The subordinate NW–SE and

TABLE 1. Summary statistics of extracted lineament length by orientation class

Orientation set	Number of lineaments (n)	Minimum length (km)	Maximum length (km)	Mean length (km)
N–S	3,541	0.039	2.000	0.297
NE–SW	2,434	0.071	3.180	0.574
NW–SE	2,486	0.029	2.429	0.371
E–W	2,285	0.003	2.357	0.261

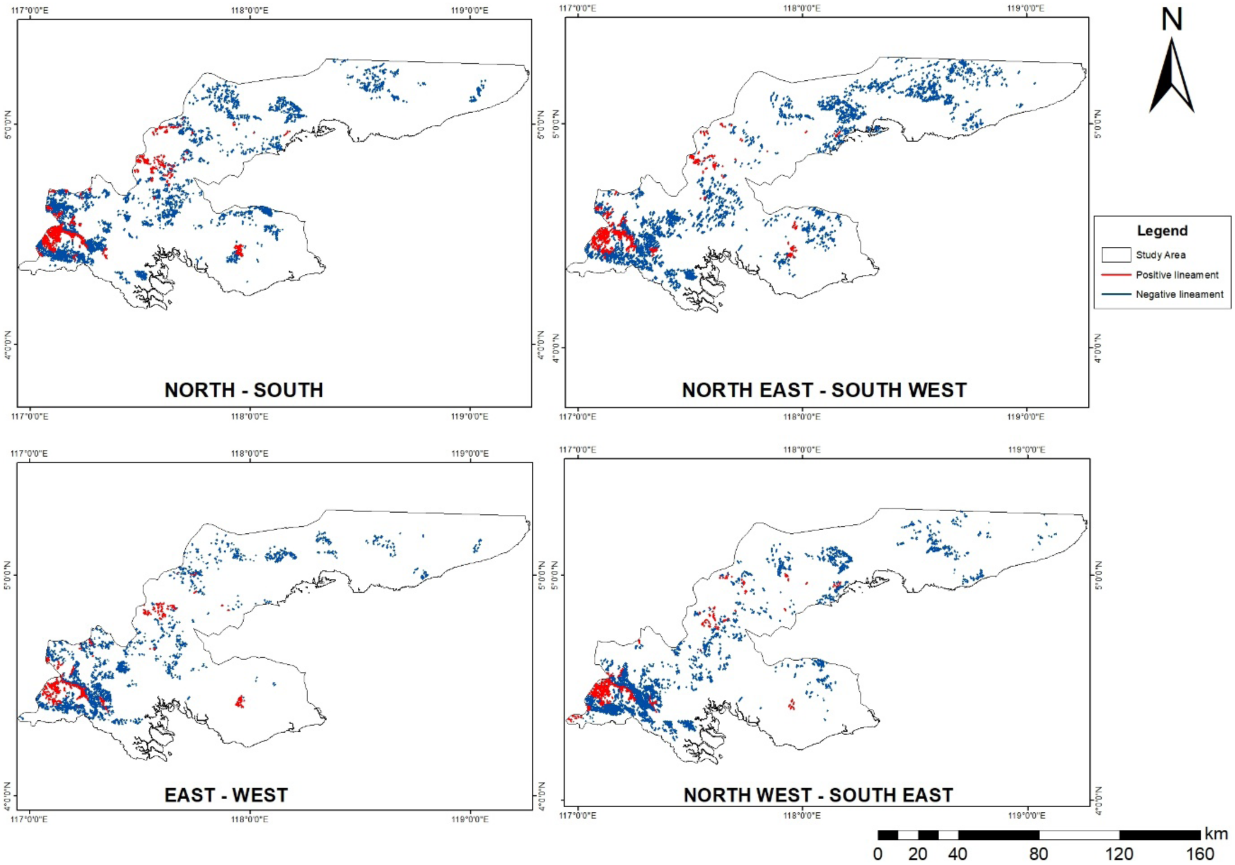

FIGURE 5. Final validated negative lineament map derived from Sentinel-1 SAR imagery

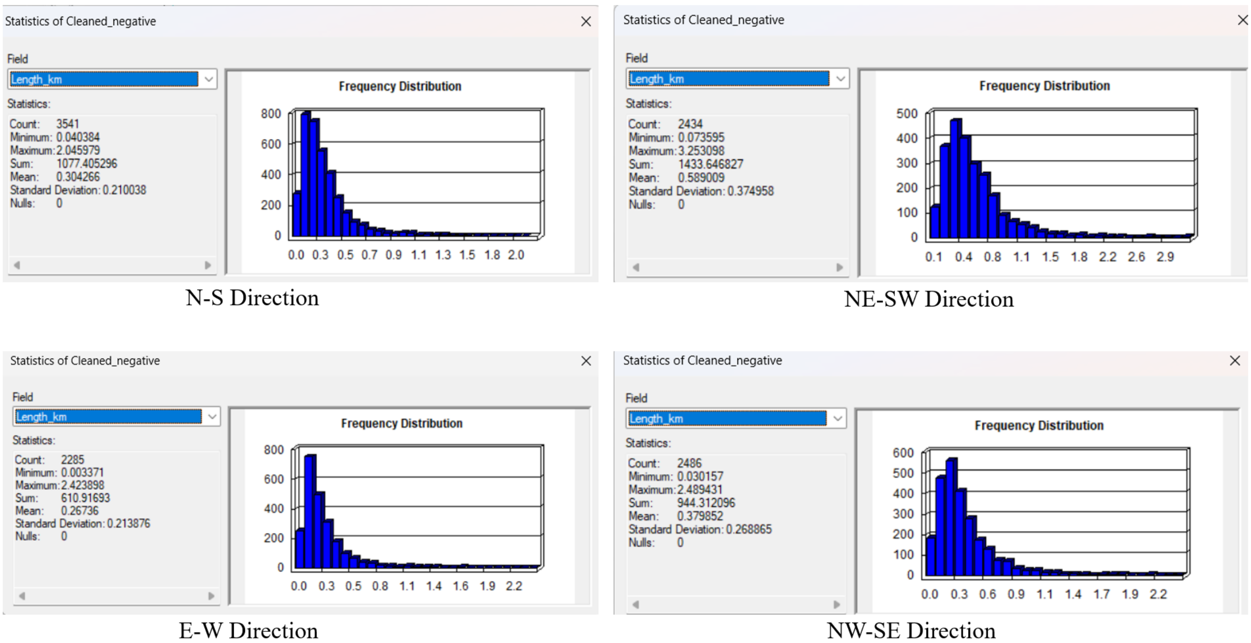

FIGURE 6. Length–frequency distribution of extracted lineaments

E–W sets may represent secondary structural trends, local reactivation features or lineaments influenced by lithological and geomorphological controls. Therefore, the orientation pattern is interpreted as a combined response to inherited tectonic structures, surface erosion, drainage development and lithological contrast.

ORIENTATION–LENGTH RELATIONSHIP

Analysis of lineament length as a function of orientation shows systematic differences between the structural sets (Figure 8). The NE–SW orientation set exhibits the greatest apparent surface continuity, with a mean length of 0.574 km and a maximum observed length of 3.180 km. In contrast, the E–W set displays shorter average lengths (mean = 0.261 km) and greater dispersion.

The NW–SE and N–S sets show intermediate mean lengths of 0.371 km and 0.297 km, respectively. These differences indicate that NE–SW trending structures are more laterally persistent, whereas E–W-oriented lineaments are more fragmented and locally developed. This interpretation is supported by the Kolmogorov–Smirnov test results, which show significant differences in length distribution between all orientation-class pairs ($p < 0.001$), with the strongest contrast between the NE–SW and E–W sets.

The greater apparent continuity of NE–SW lineaments suggests that this orientation may correspond to more regionally persistent structural corridors in Eastern Sabah. However, the term continuity is used here in a surface-mapping context and does not imply confirmed subsurface fracture connectivity. Confirmation of subsurface linkage or fault continuity would require additional field structural measurements, geophysical data or subsurface information. Therefore, the orientation–length relationship is interpreted as evidence of surface structural organisation rather than direct proof of deep or continuous fault systems.

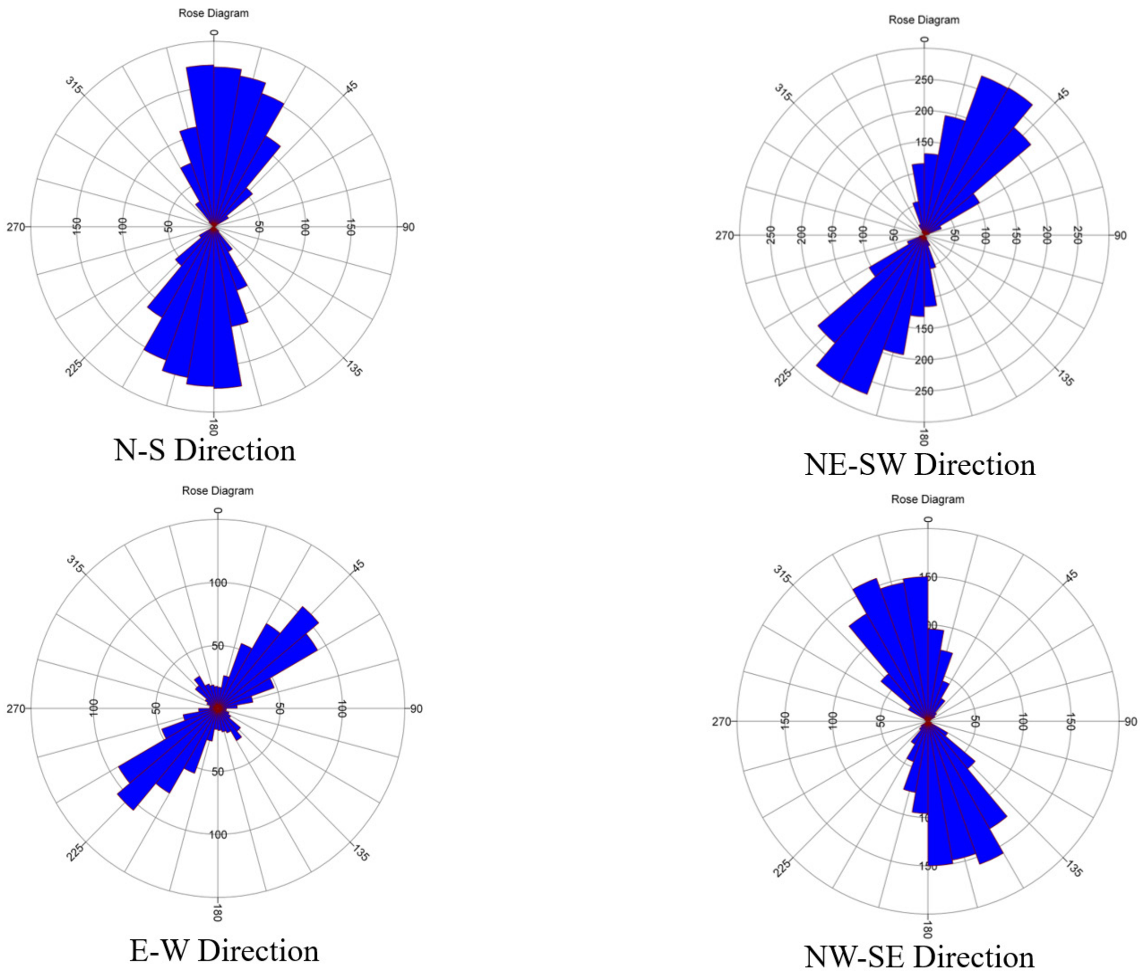

FIGURE 7. Rose diagram showing dominant lineament orientation trends

LINEAMENT DENSITY AND SPATIAL DISTRIBUTION

Lineament density analysis was conducted to identify zones of high surface structural intensity across Eastern Sabah (Figure 9). The density map shows that the extracted lineaments are not evenly distributed, but are concentrated in several zones of higher lineament density. These high-density zones are interpreted as areas of stronger surface structural or geomorphological expression, which may be related to fault zones, fracture corridors, lithological boundaries, drainage incision or topographic contrast.

The spatial distribution of high-density zones was compared with known regional structures, including the Lahad Datu Fault, Tabin Fault, Segama Valley structures and Dent Peninsula fault systems. Areas where high lineament density coincides with mapped structural zones support the tectonic relevance of the SAR-derived lineaments. However, high-density zones that do not clearly coincide with mapped faults should not be directly interpreted as new faults without further field or geophysical validation. Such areas may reflect unmapped surface lineament expressions, lithological contrast, drainage control or limitations in existing regional geological mapping.

Overall, the lineament density pattern supports the interpretation that the mapped lineaments are spatially organised rather than randomly distributed. The density map therefore provides additional evidence for regional structural control, while also highlighting the influence of surface geomorphology and lithology on lineament expression.

LITHOLOGICAL CONTROL ON LINEAMENT EXPRESSION

A lithology–lineament density comparison was conducted to assess whether lineament expression is associated with specific rock types (Table 2). The comparison shows that very high lineament-density zones are mainly associated with sedimentary and chaotic or interbedded units, particularly mudstone, sandstone, siltstone, conglomerate, minor limestone and lignite, as well as slump breccia with interbedded mudstone, tuff, tuffaceous sandstone, shale, conglomerate, minor chert and limestone. These lithologies may enhance lineament expression through bedding contrast, fracturing, differential weathering and drainage incision. High-density zones also occur across ultramafic, metamorphic, granitoid, sedimentary and interbedded units. This indicates that lineament density is not controlled by

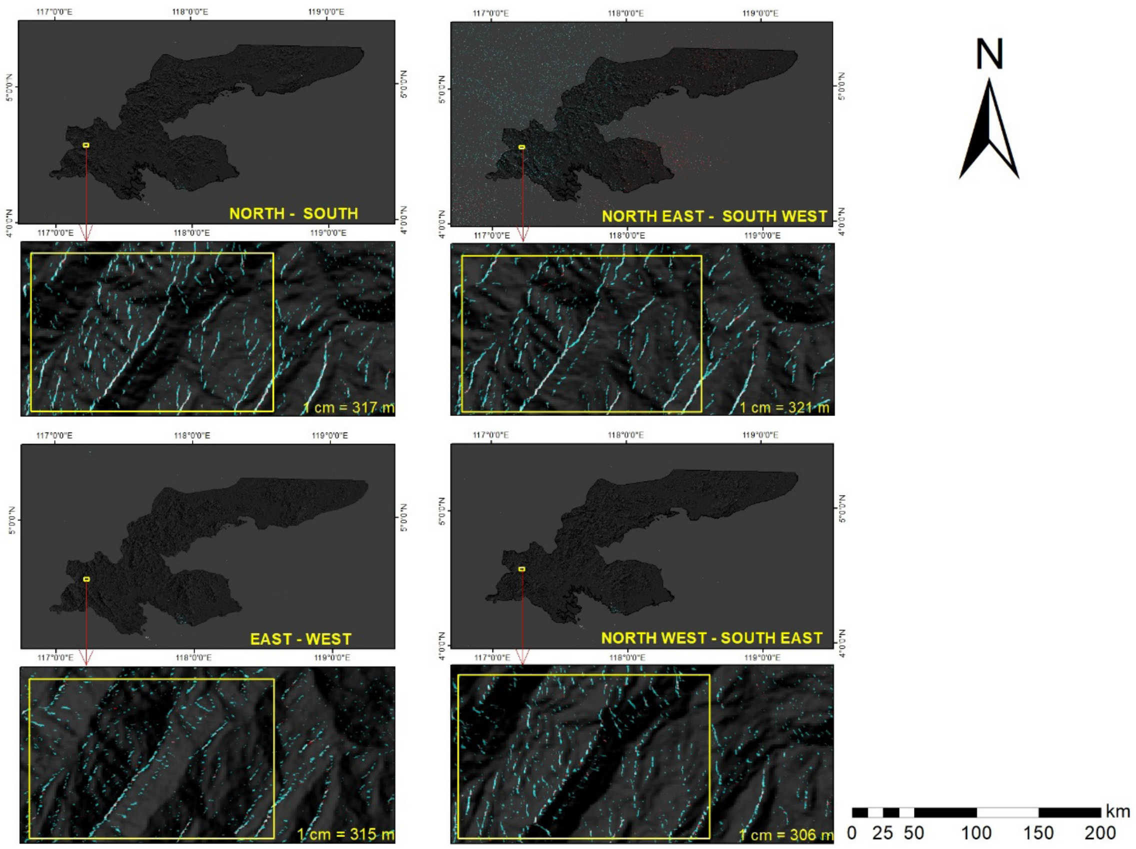

FIGURE 8. Relationship between lineament orientation and length

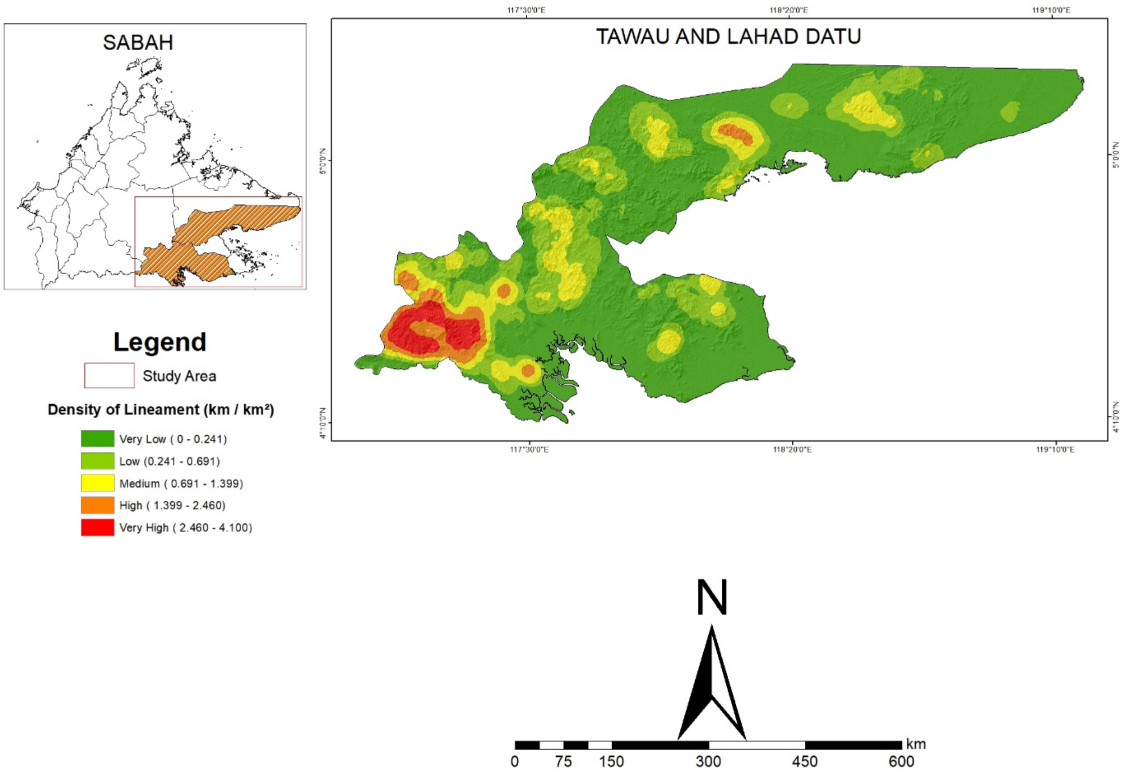

FIGURE 9. Lineament density map of Eastern Sabah showing zones of high lineament concentration

TABLE 2. Summary of lithological units associated with lineament-density classes in Eastern Sabah

Lineament density class	Main lithological units observed	Interpretation
Very high	Mudstone, sandstone, siltstone, conglomerate, minor limestone and lignite; slump breccia with interbedded mudstone, tuff, tuffaceous sandstone, shale, conglomerate, minor chert and limestone	Mainly associated with sedimentary and chaotic/interbedded units. Lineament expression may be enhanced by bedding, fracturing, differential weathering and drainage incision
High	Ultramafic rocks; metamorphic and granitoid rocks; sedimentary units; interbedded slump breccia, mudstone, tuff, tuffaceous sandstone, shale and conglomerate	Occurs across both crystalline and sedimentary/interbedded units, suggesting combined structural, lithological and geomorphological control
Medium	Basalt and dacite; alluvium; volcanic and intrusive rocks; ultramafic rocks; metamorphic and granitoid rocks; sedimentary units; terrace deposits; tuffaceous sandstone, conglomerate, clay, tuff, mudstone, shale and volcanic breccia	Widely distributed across different lithologies, indicating mixed control from lithology, topography, drainage and structural fabric
Low	Basalt and dacite; alluvium; volcanic and intrusive rocks; ultramafic rocks; metamorphic and granitoid rocks; sedimentary units; terrace deposits; tuffaceous sandstone, conglomerate, clay, tuff, mudstone, shale and volcanic breccia	May reflect weaker surface expression, lower fracture intensity, subdued relief, sediment cover or reduced SAR/ geomorphological contrast
Very low	Andesitic pyroclastic rocks and lava; basalt and dacite; alluvium; volcanic and intrusive rocks; ultramafic rocks; metamorphic and granitoid rocks; limestone, marl, sandstone and clay; sedimentary units; terrace deposits; tuffaceous sandstone, conglomerate, clay, tuff, mudstone, shale and volcanic breccia	Occurs across diverse lithologies, suggesting low expression may be due to surface cover, weathering, low relief, geomorphic smoothing or weak exposure of structural discontinuities

lithology alone. Instead, the mapped pattern likely reflects the combined influence of structural discontinuities, rock resistance, weathering behaviour, drainage development and topographic expression.

In contrast, low to very low lineament-density zones occur across a broader range of lithologies, including volcanic rocks, alluvium, ultramafic rocks, metamorphic rocks, limestone-bearing units, terrace deposits and tuffaceous sedimentary-volcanic units. This wide distribution suggests that low lineament density may reflect weaker surface expression of structures, lower fracture intensity, subdued relief, sediment or vegetation cover, or reduced contrast in SAR and geomorphological expression. Therefore, the SAR-derived lineament pattern should not be interpreted purely as a fault map, but rather as a surface structural-geomorphological dataset influenced by both tectonic and non-tectonic controls.

CONCLUSIONS

This study presents a regional-scale structural lineament analysis of Eastern Sabah using Sentinel-1 SAR data. Through directional filtering, hillshade integration and expert-guided manual digitisation, 10,746 validated negative lineaments were extracted and analysed. The lineament network is dominated by four orientation sets, with N–S and NE–SW trends forming the principal structural fabric, while NW–SE and E–W trends represent secondary components. The Rayleigh test confirms that the orientation distribution is significantly non-uniform, indicating that the extracted lineaments are directionally organised rather than randomly distributed. NE–SW lineaments show the greatest apparent surface continuity, and Kolmogorov–Smirnov tests confirm significant differences in length distribution between orientation classes. Lineament density analysis identifies zones of high structural intensity, while the lithology–density comparison indicates that lineament expression is influenced by both structural discontinuities and lithological variation. The close correspondence between SAR-derived lineament trends and mapped regional structures supports the tectonic significance of the extracted dataset. Overall, the adopted Sentinel-1 SAR workflow provides a robust and reproducible approach for regional structural lineament mapping in densely vegetated tropical terrain.

ACKNOWLEDGEMENTS

This research was supported by the Fundamental Research Grant Scheme – Early Career (FRGS-EC) from the Ministry of Higher Education, Malaysia under project code FRGSEC/1/2024/WAS07/UMS/02/1 and by the UMSGreat Research Grant (GUG0775-2/2025). We gratefully acknowledge the financial support provided by the Ministry of Higher Education Malaysia and Universiti Malaysia Sabah. We also sincerely thank the reviewers for their constructive comments and valuable suggestions, which have significantly improved the quality of this paper.

REFERENCES

Abdullah, A., Akhir, J.M. & Abdullah, I. 2010. Automatic mapping of lineaments using shaded relief images derived from digital elevation model (DEMs) in the Maran–Sungai Lembing area, Malaysia. *Electronic Journal of Geotechnical Engineering* 15: 949-957.

Baid, S., Tabit, A., Algouti, A., Ezzahzi, S. & Elghouat, A. 2024. Lineaments extraction and analysis using Sentinel-2B, Sentinel-1A data and ALOS PALSAR DEM: A case study of the Igoudrane region, Jbel Saghro, Eastern Anti-Atlas, Morocco. *Iraqi Geological Journal* 57(2A): 1-17.

Choudhury, N., Mitra, A.K., Nath, B. & Lindsay, M.D. 2025. Lineament extraction and structural mapping using Landsat-9 OLI and Sentinel-1 SAR data in the Proterozoic North Singhbhum Mobile Belt, Eastern India. *Geosystems and Geoenvironment* 4(3): 100392.

Dhara, M., Baisantry, M. & Prusty, G. 2022. Automatic extraction and analysis of lineament features using ASTER and Sentinel-1 SAR data. *Journal of Earth System Science* 131(2): 111.

Gabrielsen, R.H. & Olesen, O. 2024. The concept of lineaments in geological structural analysis: Principles and methods. *Geomatics* 4(2): 189-212.

Menier, D., Mathew, M., Pubellier, M., Sapin, F., Delcaillau, B., Siddiqui, N., Ramkumar, M. & Santosh, M. 2017. Landscape response to progressive tectonic and climatic forcing in NW Borneo. *Scientific Reports* 7: 457.

Strokova, L.A., Ezhkova, A.V. & Leonova, A.V. 2020. Application of lineament analysis to assess karst hazard in gas pipeline design in South Yakutia. *Bulletin of the Tomsk Polytechnic University* 331(11): 117-126.

Tongkul, F. 2017. Active tectonics in Sabah - seismicity and active faults. *Bulletin of the Geological Society of Malaysia* 64: 27-36. https://doi.org/10.7186/bgsm64201703

Tongkul, F. 1991. Tectonic evolution of Sabah, Malaysia. *Journal of Southeast Asian Earth Sciences* 6(3-4): 395-405.

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