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A Study of The Late Neogene Tectonic Deformation of the Kayu Ajaran Region, South Bengkulu, Bengkulu

Fikri Andrian[1], Edy Sutriyono[1]

[1] *Geological Engineering Study Program, Sriwijaya University, Jl. Srijaya Negara, Palembang, South Sumatra, 30139, Indonesia*

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Corresponding author:
Fikri Andrian
Email: fikrandr@gmail.com

ABSTRACT

This study investigates the tectonic deformation history of the Kayu Ajaran area in South Bengkulu through integrated geological structure mapping and Digital Elevation Model (DEM)-based lineament interpretation. The research focuses on reconstructing the sequence of tectonic events that occurred during the Late Neogene within the Bengkulu Forearc Basin, a region known for its complex tectonic setting. Fieldwork and remote sensing analysis identified twelve major structural features, comprising eight folds and four faults. These structures predominantly trend northwest–southeast (NW–SE), indicating a compressional stress regime oriented northeast–southwest (NE–SW). The fold geometries, ranging from upright to steeply inclined types, and fault types, including thrust, reverse, and strike-slip, suggest the reactivation of earlier Paleogene extensional structures during the Neogene compressional phase. Stereographic and kinematic analyses were used to determine the orientation of principal stress axes (σ1, σ2, σ3), supporting the interpretation of inversion tectonics. DEM-based lineament analysis enhanced the identification of structural trends and fault zones, especially in areas with limited outcrop exposure. The study provides a clearer understanding of the progressive tectonic deformation in the region and fills critical gaps in the structural characterization of the Kayu Ajaran area. These results contribute to broader regional tectonic models of southwest Sumatra.

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1. INTRODUCTION

The Bengkulu Basin, located along the southwestern margin of Sumatra, represents a significant segment of the forearc system of the Sunda Plate, where active tectonic processes have shaped its geological evolution since the Paleogene (Susantoro et al., 2022). This region is a vital area of study due to its complex tectonic history involving multiple deformation phases and its potential as a hydrocarbon-bearing basin . Previous works have highlighted the role of rifting and strike-slip tectonics in the formation of pull-apart basins within this region. Recent advances in remote sensing and geospatial analysis, particularly using Digital Elevation Model (DEM) interpretation, have improved the detection and analysis of structural lineaments, aiding regional-scale geological studies (Meixner et al., 2018; Yatini & Getsimany, 2024).

Despite numerous tectonic studies, the Late Neogene deformation history of the Kayu Ajaran region in South Bengkulu remains undercharacterized. There is a lack of detailed documentation and analysis of geological structures that record the sequential development of tectonic events in this part of the Bengkulu Basin (Fajri et al., 2019). Understanding the interplay between inherited structures and recent tectonic forces is critical for reconstructing regional geodynamics (Zuhair et al., 2022). This study addresses this gap by conducting an integrated structural analysis combining field-based geological mapping and lineament interpretation using DEM imagery to clarify the deformation stages and stress regimes of the area (Meixner et al., 2018).

The structural configuration of the Bengkulu Forearc Basin, including the development of the Manna Sub-basin, has been interpreted as the result of both Palaeogene extensional and Neogene compressional regimes. The transition from rift-controlled sedimentation to compressional tectonics led to the inversion of pre-existing faults and the formation of complex fold and thrust belts (Mondy et al., 2023). This phenomenon is further supported by studies that demonstrate the utility of integrating geological fieldwork with DEM-based lineament analysis in delineating structural trends and reconstructing deformation phases (Fajri et al., 2019; Putri & Setiawan, 2023). The classification of fold geometries, particularly the scheme proposed by Fleuty and cited in Fossen, has been pivotal in understanding the kinematics of folding in compressional regimes (Pechlivanidou et al., 2022).

Although many researchers have contributed to the general understanding of Sumatra's tectonic evolution, detailed structural analyses specific to the Kayu Ajaran area remain limited. Prior studies have mostly focused on broader basin-scale interpretations without concentrating on local fold-fault relationships and their chronological development (Zuhri & Sutriyono, 2020). There is a paucity of integrated field and remote sensing data in existing literature that specifically addresses the progressive tectonic stages of this region (Saputra et al., 2023). This limitation presents an opportunity to apply modern structural geology techniques to unravel the deformation chronology and provide insights into regional tectonics (Fajri et al., 2019).

This study aims to reconstruct the Late Neogene tectonic deformation history of the Kayu Ajaran area through detailed geological structure mapping and DEM-based lineament interpretation. The novelty lies in its comprehensive approach that combines classical structural mapping with modern geospatial techniques to delineate fold and fault geometries and interpret stress field orientations (Florinsky, 2016; Markwick et al., 2024). With the use of DEM-based lineament interpretation, this study leverages advanced geospatial technologies to identify and analyze geological structures that are difficult to observe directly in the field, which is particularly effective in regions with complex tectonic settings like Kayu Ajaran (Fayyaz., 2024). This research aims to fill critical gaps in current knowledge regarding the tectonic deformation history of the Kayu Ajaran region by synthesizing field observations and structural data into a regional tectonic model (Karig et al., 1980; Maulin et al., 2019).

The scope includes extensive field observations across an 81 km² area, which are essential to understanding the geological history and current tectonic activity of the region. This approach builds on foundational geological mapping techniques and supports a thorough assessment of structural evolution in the field (Maulin et al., 2019). Structural data collected from the field are analyzed using stereographic techniques, aiding in the interpretation of the orientation and nature of geological structures (Fayyaz., 2024; Markwick et al., 2024). These findings are synthesized into a regional tectonic model that offers insights into the deformation processes affecting the forearc basin in southwest Sumatra, thereby contributing to broader tectonic understanding (Maulin et al., 2019). While this study introduces a novel approach to understanding tectonic deformation, it also acknowledges the limitations of integrating classical and modern techniques. For instance, the accuracy of DEM-based lineament interpretations can be influenced by DEM resolution and terrain complexity (Mshiu, 2020). Moreover, synthesizing field data into regional models requires careful consideration of diverse geological factors, including sedimentation and fault dynamics, which may vary significantly across different settings (Qureshi et al., 2020). Despite these challenges, the integrative methodology of this study holds promise for advancing the understanding of tectonic processes in geologically complex environments.

2. METHOD

2.1. Materials

This research was conducted in Kayu Ajaran, South Bengkulu Regency, Bengkulu Province. Materials included geological maps, DEM data, stereonets, compass clinometers, GPS devices, and topographic maps. Software like Global Mapper, ArcGIS, PCI Geomatica, Dips, WinTensor, and CorelDRAW supported structure interpretation and mapping.

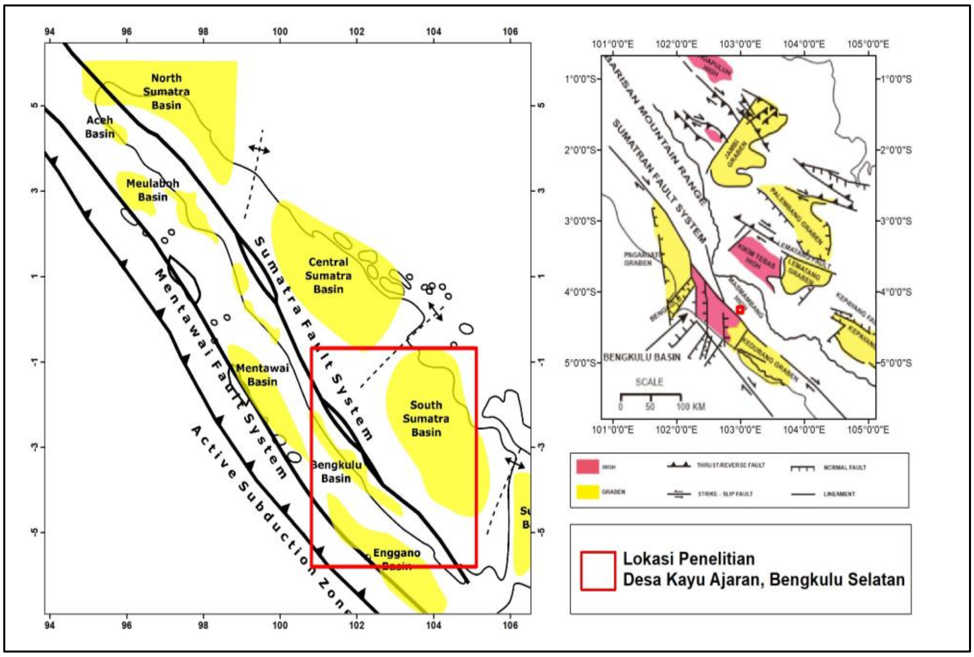

Figure 1. Map of the research area with development of tectonic deformation.

2.2. Sample Preparation

Field surveys were carried out to observe and measure lithological and structural characteristics at selected outcrop sites. Rock samples were not the primary focus of this structural study; rather, emphasis was placed on detailed recording of bedding planes, fold geometries, and fault traces. Each measurement was documented with respect to its geospatial position using GPS, and photographed for subsequent interpretation. Lithological descriptions, structural orientations, and textural properties were systematically recorded in field notebooks and digital databases.

2.3. Structural Mapping Procedure

The geological mapping was executed across an area of approximately 81 km² with a mapping resolution aligned to 1:25,000 scale. Data acquisition involved measuring orientations of bedding, joints, folds, and faults using compass clinometers. Structural elements such as fold axes and fault planes were analyzed using stereographic projection (McClay, 1988). DEM analysis was used to delineate lineaments, drainage patterns, and geomorphological features. The interpretation of structural data was supported by stereonets and rose diagrams. Lineament extraction and visualization were performed using Global Mapper and ArcGIS, while figures were refined using CorelDRAW.

2.4. Parameters

The parameters measured and analyzed in this study include strike and dip of bedding planes, fold hinge orientation, axial plane inclination, net-slip vector of faults, and pitch. Stereographic analysis enabled identification of principal stress axes ($\sigma1$, $\sigma2$, $\sigma3$). The classification of folds and faults followed standard criteria as presented (Fleuty, 1964; Fossen, 2010). Fold geometries were categorized into upright, inclined, and steeply inclined horizontal folds, whereas fault types were classified into thrust, reverse, and strike-slip based on dip and movement vectors.

2.5. Data Analysis

Quantitative analysis was carried out by plotting orientation data on stereonets and rose diagrams to evaluate the directional patterns of tectonic features. Stereonet plotting helped establish kinematic relationships among measured structures and interpret the prevailing stress fields. DEM-based lineament density mapping further supported the recognition of fault zones and areas with high structural intensity. These analytical methods provided a robust framework for reconstructing the tectonic deformation chronology of the study area.

3. RESULTS AND DISCUSSION

3.1. Results

DEM lineament analysis revealed NW–SE and NE–SW structural trends in Kayu Ajaran region. Fold and thrust structures trend NW–SE, with normal faults in NE–SW direction. Oblique-slip faults deviate 30° from principal stress. DEM data showed Late Neogene folding patterns, as in Figure 2.

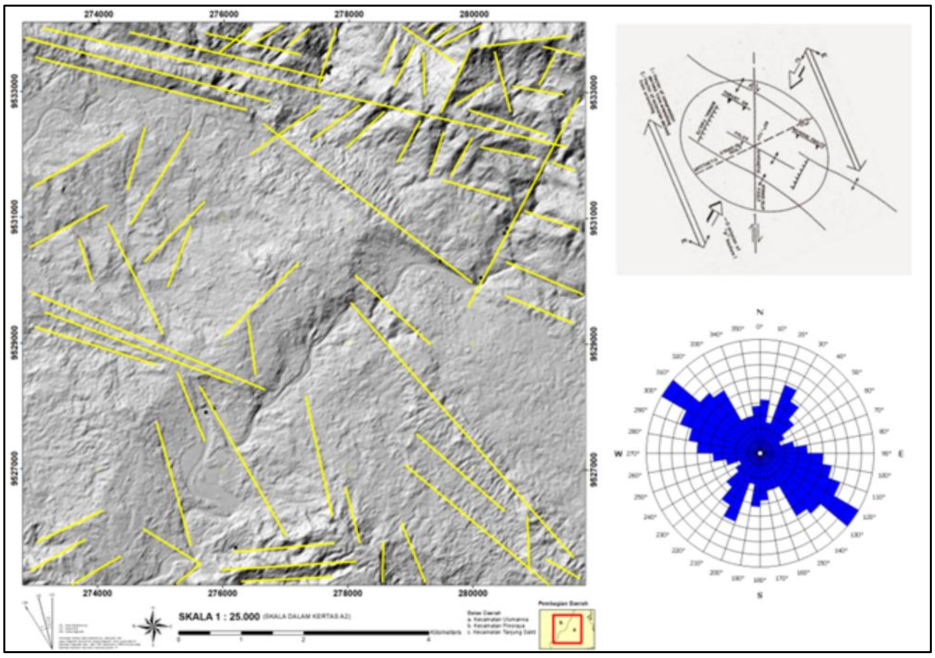

Figure 2. Map of lineament distribution in research area.

The stratigraphy comprises the Seblat Formation (Late Oligocene-Early Miocene) of claystone and sandstone from upper bathyal-outer neritic environments, and the Lemau Formation (Middle-Late Miocene) of interbedded sandstone and claystone from middle neritic-transitional settings. Eight folds and four faults exist, evidenced by displaced bedding, slickensides, and fold geometries. Stereographic analyses determined fold types and fault orientations.

The fold within the Lemau Formation trends NW–SE. The northeastern limb dips 37° towards NE (N320°E), while the southwestern limb dips 14° towards SW (N124°E). The hinge surface trends N135°E and dips 70°SW. Stereographic projection shows a steeply inclined fold with axis plunging 3° SE. Principal stress orientations are: σ1=19°, N045°E; σ2=03˚, N136˚E; σ3=69°, N233°E.

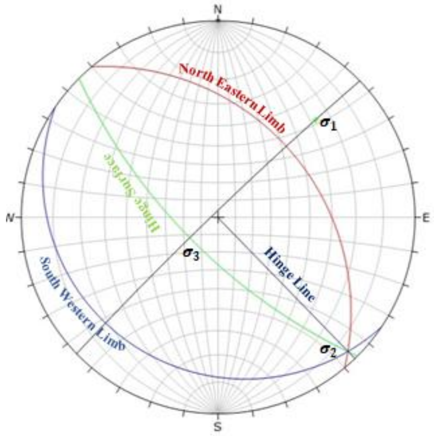

Figure 3. Stereographic analysis of Keban Jati Anticline Fold.

Figure 4. Lubuk Tapi Syncline Outcrop.

Located in Lubuk Tapi Village along the Air Manna River within the Lemau Formation. It exhibits interbedded sandstone and claystone. The fold trends NW–SE. Northeastern limb: N111°E/11°SW; southwestern limb: N291°E/32°NE. Hinge surface: N111°E/79°SW. Stereonet shows a steeply inclined fold; fold axis plunges 0° toward N290°E. Stress field: σ1=10°, N020°E; σ2=00˚, N290˚E; σ3=78°, N201°E.

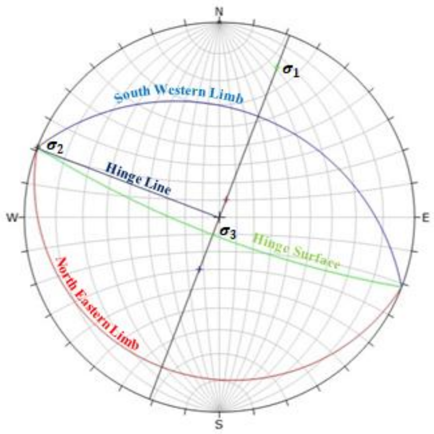

Figure 5. Stereographic analysis of Lubuk Tapi.

Situated along the Air Serdangan River in Kayu Ajaran Village. Composed of carbonate-rich grey sandstone (Seblat Formation). NE limb: N307°E/59°NE; SW limb: N118°E/57°SW; hinge: N123°E/80°SW. Fold axis plunges 5° to the SE. Stress orientations: σ1 = 02°, N032°E; σ3 = 82°, N282°E. Classified as upright horizontal fold.

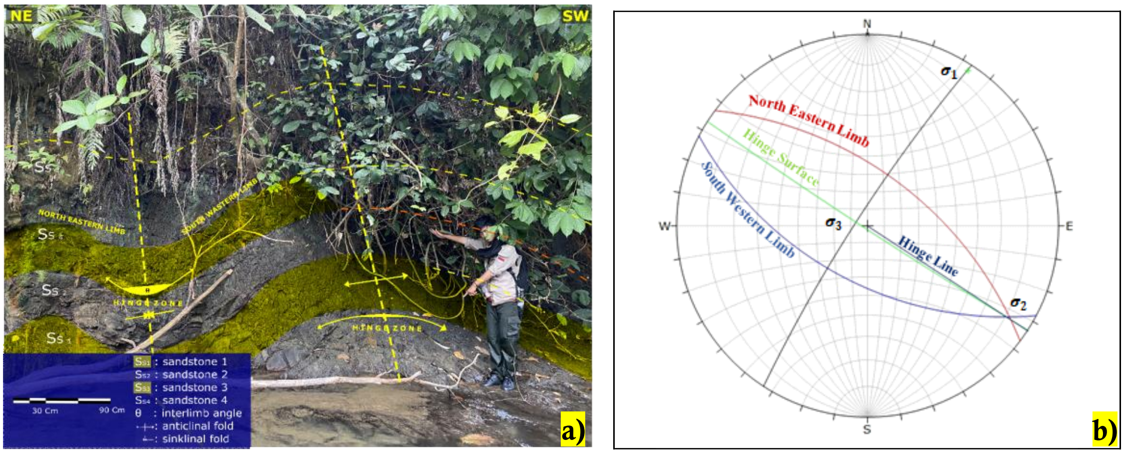

Figure 6. a) Air Serdangan I Anticline, b) Stereographic analysis of Air Serdangan I Anticline.

Co-located with the Air Serdangan I Anticline. Fold trends NW–SE. NE limb: N115°E/61°SW; SW limb: N305°E/60°NE; hinge: N120°E/89°SW. Fold axis plunges 8° SE. Stress: σ1=01°, N029°E; σ2=08˚, N119˚E; σ3=80°, N292°E.

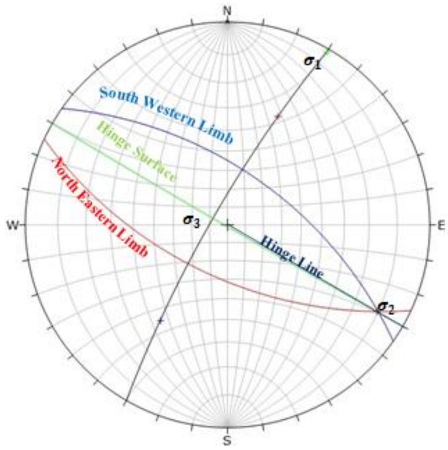

Figure 7. Stereographic analysis of Air Serdangan I Syncline Fold.

Derived from Lemau Formation. NE limb: N291°E/61°NE; SW limb: N130°E/29°SW; hinge: N117°E/74°SW. Fold axis plunges 7° NW. Stress: σ1=15°, N027°E; σ2=07˚, N295˚E; σ3=71°, N178°E.

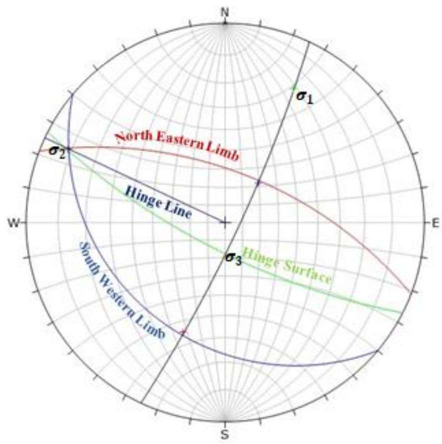

Figure 7. Stereographic analysis of Air Serdangan I Syncline Fold.

Data from ten measurements (Lemau Formation). NE limb: N106°E/50°SW; SW limb: N292°E/40°NE; hinge: N288°E/86°NE. Axis plunges 3° SE. Stress: σ1=04°, N198°E; σ2=03°, N108˚E; σ3=84°, N341°E.

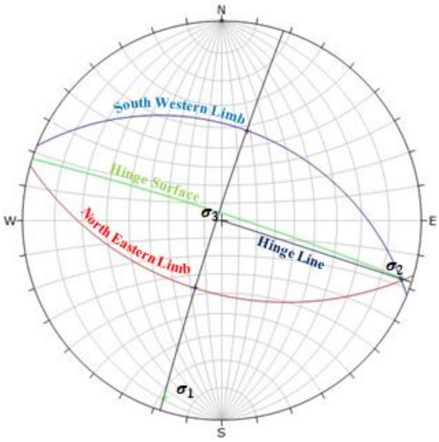

Figure 8. Stereographic analysis of Kayu Ajaran Syncline Fold.

Located in Tanjung Aur II Village. Lithology: grey sandstone (Seblat Formation). NE limb: N306°E/62°NE; SW limb: N117°E/41°SW; hinge: N122°E/81°SW. Axis plunges 5° SE. Stress: σ1 = 08°, N032°E; σ3 = 79°, N242°E.

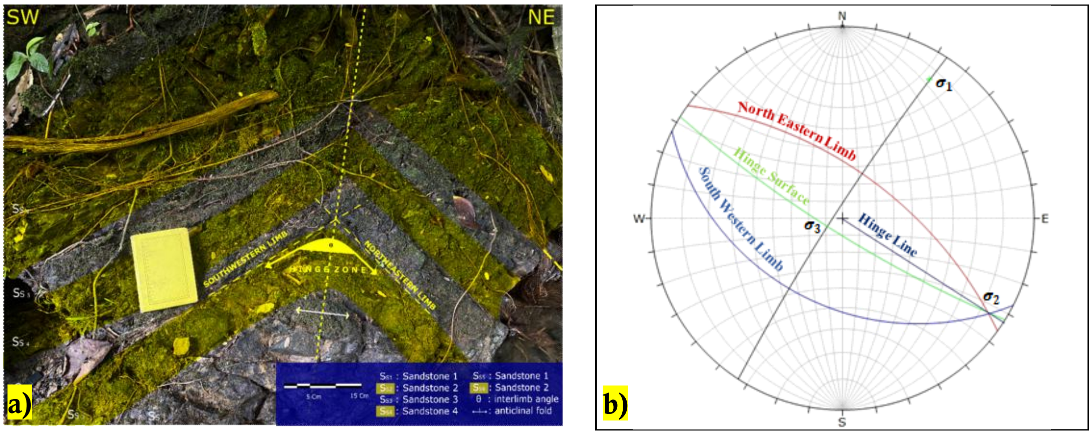

Figure 9. a) Appearance of Air Kemumuan Anticline, b) stereographic analysis.

Located along Air Serdangan Kiri River. Lithology: beige sandstone (Seblat Formation). NE limb: N108°E/58°SW; SW limb: N318°E/48°NE; hinge: N302°E/85°NE. Axis plunges 18° SE. Stress: σ1=04°, N211°E; σ2=18˚, N120˚E; σ3=70°, N315°E.

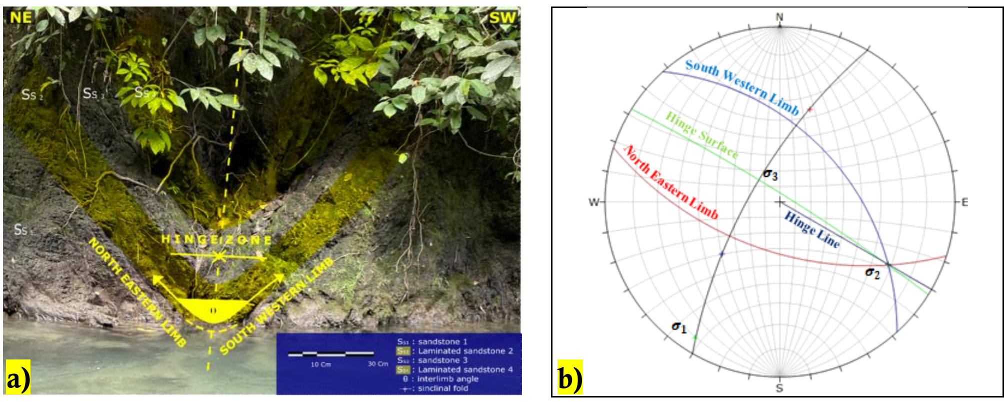

Figure 10. a) Appearance of Air Serdangan II Syncline, b) stereographic analysis.

Thrust fault in Talang Tinggi Village. Fault plane dips 56°SW, strike N126°E. Net-slip: 49°, pitch 65°. Stress: σ1=06°, N195°E; σ2=19˚, N287˚E; σ3=70°, N088°E. Right reverse slip fault.

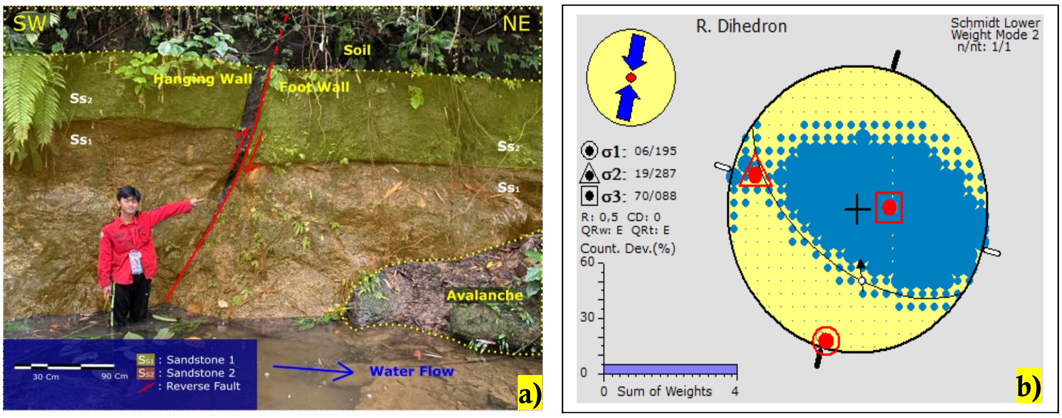

Figure 11. a) Appearance of Talang Tinggi Fault, b) stereographic analysis.

Located on Air Luguran River. Strike: N310°E, dip 79°NE, net-slip 47°, pitch 48°. Stress: σ1=25°, N009°E; σ2=44˚, N123˚E; σ3=38°, N258°E. Left reverse slip fault.

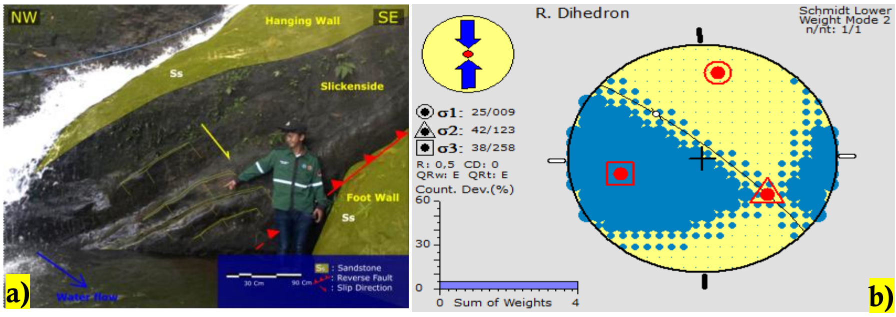

Figure 12. a) Appearance of Air Luguran Fault outcrop, (b) stereographic analysis.

Found along Air Serdangan River. Strike: N308°E, dip 71°NE, net-slip 48°, pitch 52°. Stress: σ1=23°, N054°E; σ2=20˚, N315˚E; σ3=59°, N187°E. Left reverse slip fault.

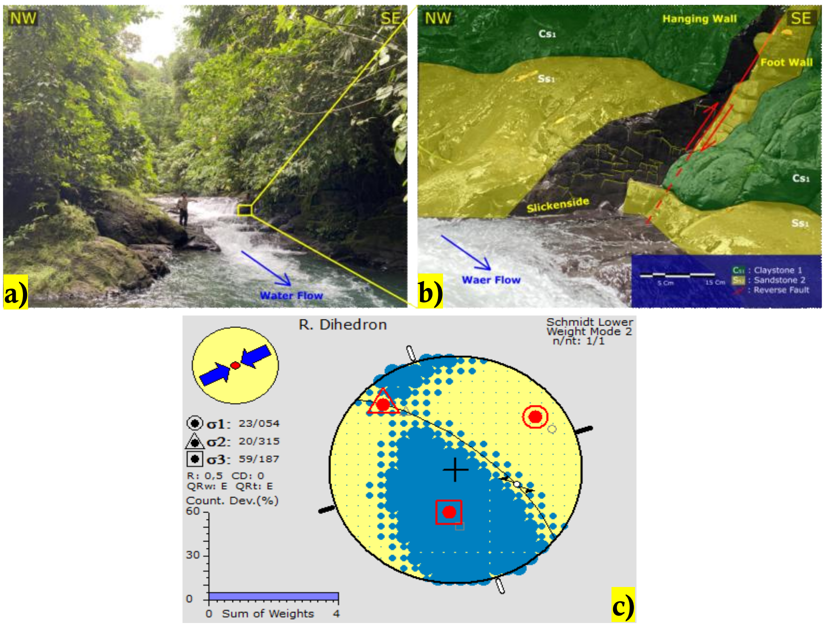

Figure 13. a) Air Serdangan I Fault outcrop, (b) slickenside, c) stereographic analysis.

Observed on Air Serdangan Kiri River. Strike: N078°E, dip 88°SW, net-slip and pitch: 04°. Stress: σ1 = 08°, N033°E; σ3 = 02°, N303°E. Left strike-slip fault.

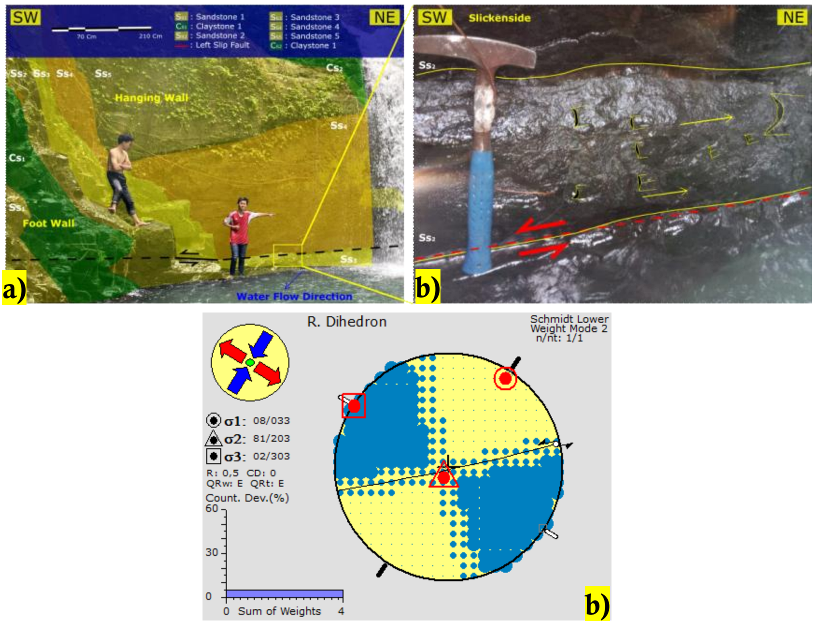

Figure 13. a) Air Serdangan II Fault outcrop, (b) slickenside, c) stereographic analysis.

The Late Oligocene Seblat Formation of sandstone and claystone formed during marine transgression, showing shelf to shoreface deposition and submarine fans with Bouma sequences. This formation was deposited from outer neritic to upper bathyal zones until Early Miocene regression. The Middle Miocene Lemau Formation lies paraconformably above, representing shallow marine environments with carbonate sandstones and mudstones. The lithology shows transgressive-regressive cycles, with high carbonate content below and decreased carbonate above. Post-depositional features include NW-SE trending folds, thrust faults, and NE-SW strike-slip faults aligned with Neogene tectonics..

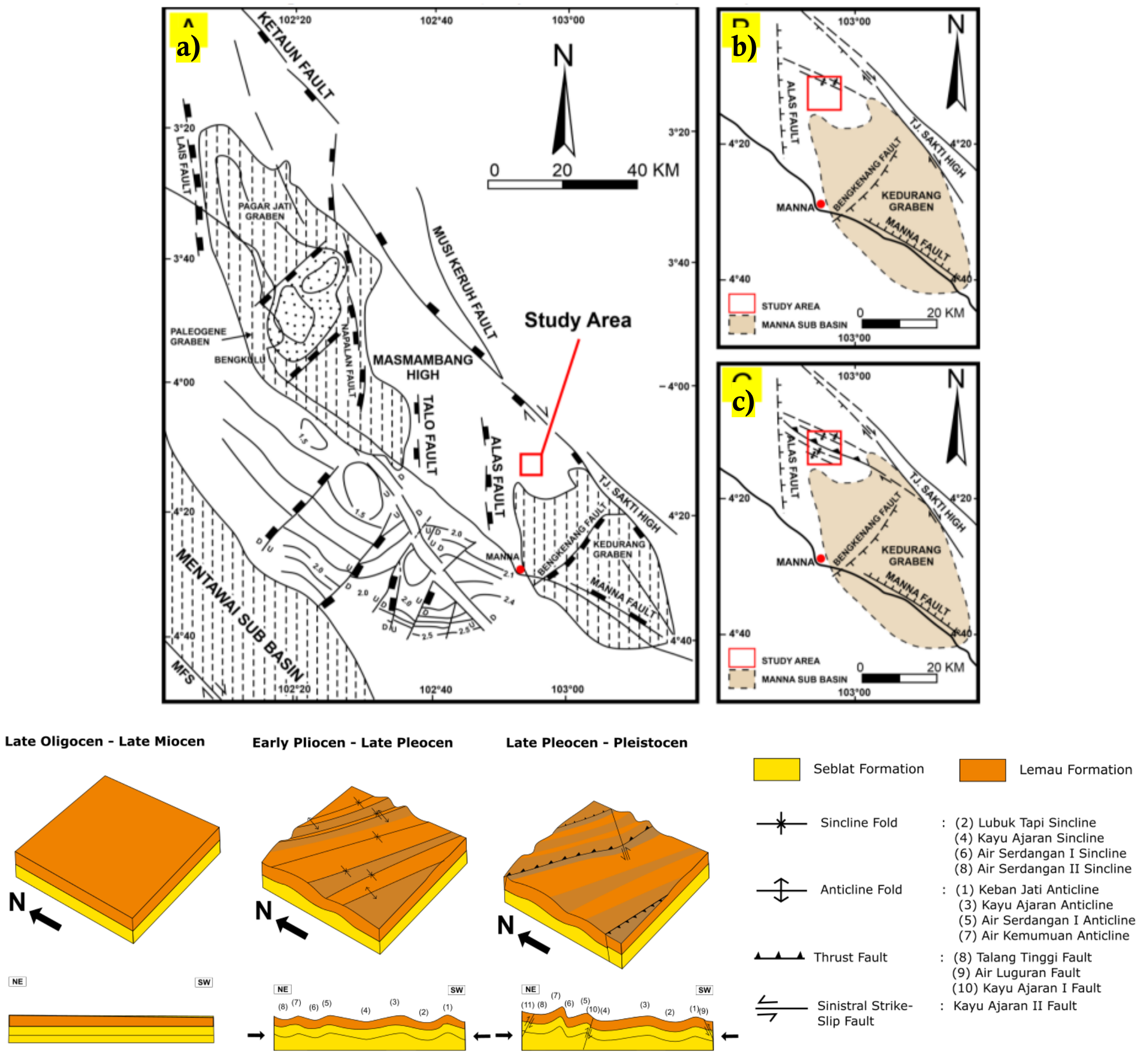

Figure 15. a) Geological Structure of the Bengkulu Basin through Pliocene; bFormation of asymmetric to overturned folds in Late Pliocene; c) Fold conditions develop into faults from continued deformation forces.

The Neogene tectonic development was influenced by reactivated Paleogene extensional features through a transtensional duplex system with northwest-southeast faults, primarily the Sumatra and Mentawai Fault Systems. This created a pull-apart basin with graben structures - Pagarjati in northwest and Kedurang in southeast - aligned NW-SE and connected to N-S elements bordered by Masmambang High (Yulihanto et al., 1995). Late Neogene tectonics occurred in three phases: Late Pliocene, Late Pliocene to Pleistocene, and Pleistocene to Resen (figure 15). Post-Simpang Aur Formation deformation shifted from basin subsidence to structural inversion, with N-S compression forming NW-SE folds that evolved from symmetrical to overturned. These folds became faults, forming the Talang Tinggi, Air Luguran, and Kayu Ajaran I reverse faults, ultimately leading to imbricate thrust faults and mountain morphology.

3.2. Discussion

The results of the structural mapping and DEM-based lineament interpretation reveal that the deformation structures in the Kayu Ajaran region developed under a dominant compressional tectonic regime trending NE–SW. This finding aligns with the broader tectonic evolution of the Bengkulu Basin, which has undergone both Paleogene rifting and Neogene compressional phases (Mondy et al., 2023; Susantoro et al., 2022). The orientation of the observed folds and faults, predominantly NW–SE, supports the hypothesis of reactivated Paleogene fault systems due to subsequent Neogene compressional stress fields.

The identified fold structures, including synclines and anticlines such as the Keban Jati Anticline and Lubuk Tapi Syncline, exhibit upright to steeply inclined geometries. These geometries are consistent with the classification by Fleuty and reflect deformation under high differential stress (Fleuty, 1964; Pechlivanidou et al., 2022). Stereographic analyses confirm the presence of gently plunging fold axes and steep axial planes, indicating significant tectonic shortening. Such structural styles are typical of inversion tectonics where earlier extensional faults are later compressed and reactivated (Maulin et al., 2019).

The fault structures, including the Talang Tinggi, Kayu Ajaran I and II, and Air Luguran faults, further substantiate the post-depositional compressional deformation phase. The kinematic indicators, such as slickensides and fault mirrors, as well as stereonet-derived stress orientations ($\sigma 1$ and $\sigma 3$), confirm reverse and strike-slip mechanisms. These fault patterns resemble those in other segments of the Sumatra Fault System, indicating that the Kayu Ajaran region shares tectonic characteristics with the broader forearc basin of southwestern Sumatra (Zuhair et al., 2022).

DEM analysis has proven instrumental in identifying linear features that correlate with field-mapped faults and fold trends. The alignment of geomorphic elements, such as ridges and drainage systems, with the interpreted lineaments enhances the validity of the structural model. Similar methodologies have been applied successfully in other geologically complex settings and validate the integration of DEM in structural studies (Meixner et al., 2018; Yatini & Getsimany, 2024).

The progression of deformation identified in this studyfrom initial folding to eventual faulting illustrates a tectonic evolution consistent with structural inversion models. The observed transition from symmetrical to asymmetrical and overturned folds, followed by thrust and strike-slip faulting, demonstrates the increasing intensity of compressional stress over time. This sequential development confirms that tectonic deformation in the Kayu Ajaran region occurred through a progressive and dynamic process influenced by reactivated regional structures (Fajri et al., 2019).

Overall, the integration of classical structural mapping and modern geospatial techniques has successfully addressed the knowledge gap regarding the tectonic history of the Kayu Ajaran region. The methods used allowed for the reconstruction of a coherent deformation chronology and established the structural link between local features and regional tectonic trends. Despite limitations such as DEM resolution and terrain complexity, the approach demonstrated in this study offers a robust framework for further tectonic research in similar forearc settings (Mshiu, 2020; Qureshi et al., 2020).

4. CONCLUSIONS

This study reconstructed the tectonic deformation history of the Kayu Ajaran region using geological mapping and DEM-based analysis. The results show that deformation progressed during the Late Neogene from folding to faulting, with twelve structures trending NW–SE, reflecting NE–SW compressional stress. Fold and fault geometries confirm the reactivation of older Paleogene structures under Neogene compression.

Stereographic and kinematic analysis aligned well with regional tectonic trends, and geospatial methods proved effective in identifying and interpreting structural features. This research addresses existing knowledge gaps and provides a basis for future studies incorporating geochronology, seismic profiling, and 3D modeling.

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