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RESEARCH ARTICLE

Morphotectonic Identification of the Active Ransiki Fault Zone as a Source of Shallow Seismicity in South Manokwari, West Papua: Integrating Stream Length–Gradient Index and Lineament Analysis

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Abstract

The Ransiki area, which is in South Manokwari, West Papua, lies in a tectonically active transition zone related to the oblique convergence between the Indo-Australian and Pacific plates. Although shallow seismic activity has already been detected, the geometry and seismo-tectonic behavior of local fault structures have not been characterized yet. This work aims to explore the morphotectonic framework of the region by combining quantitative geomorphic indices and structural evidence. From 8–30 m resolution DEMNAS data multi-azimuth lineaments were extracted and Stream Length–Gradient Index (SLI) was derived on 42 river segments. The distribution of lineament density and SLI anomalies were correlated using Pearson coefficient and verified with field observation of fault scarps, triangular facets and slickensides. The results show relevant NNW–SSE lineaments (N330°-N340°E) having high local SLI values (>500) that are more concentrated in the eastern sector of Ransiki. Field evidences evidence envisage an active sinistral strike-slip deformation along this trend. These combined geomorphic- and structural-based indicators attest the actively deforming character of the Ransiki Fault Zone as a transpressional shear corridor that transfers deformation between the Sorong Fault System and the Arfak upliftement. The methodology applied in this case study offers an efficient tool to identify active faults in tropical regions with sparse geophysical ground data and provides valuable input for seismic hazard assessment in eastern Indonesia.

Keywords: active tectonics, morphotectonics, SLI, lineament mapping, Ransiki Fault Zone, West Papua

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1. Introduction

The study site, in the Ransiki area of South Manokwari, has a key location in the obliquely convergent boundary between the IndoAustralian and Pacific plates with structured strain partitioning across strike-slip and transpressional structures (Hall et al., 2002; Hall & Spakman, 2015; Degroot & Hall, 2020). This zone is able to accommodate large amounts of crustal shortening and lateral shear resulting in highly complex morphotectonic features (Fisher & Brandon, 2021; Moucha & Forte, 2023). Although superficial earthquakes have been observed in the area (BMKG, 2023), the exact sources of seismicity are under-evaluated due to lack in detailed structural mapping and limited geophysical studies.

Quantitative geomorphic metrics have been useful in identifying active crustal deformation where instrumental data are sparse (El Hamdouni et al. (2008) ; Cox & Barrell, 2020). Of these, the Stream Length–Gradient Index (SLI) is widely used to detect knickpoints and steepened river reaches, which indicate ongoing uplift and fault activity (Hack, 1973; Bishop, 2017; Brardinoni et al., 2022; Wobus et al., 2021). Remote sensing, as a major tool for extracting lineaments, has now overtaken it in delineating subsurface structural discontinuities (Chorowicz, 2005; Gomes et al., 2019). Combined, these methods enhance interpretation of active landforms as tectonic responses and assist with field validation (El Hamdouni et al., 2008; Li et al., 2022).

In eastern Indonesia similar studies have led to successful in the mapping of previously unmapped active faults, such as those reported by Sulistiyono et al. (2019), and Wirastuti et al. (2021), which have been applied to structures associated with major left-lateral shear zones along the Sorong Fault System (SFS) that transfer plate-boundary strain across northern New Guinea (Hill et al., 2015; Baldwin et al, 2012). Yet, knowledge of the tectonic role of secondary faults south off the SFS, notably in Ransiki area, is limited. Local structures are not interpreted as being active in current geological maps (Atmawinata et al, 1989), with these faults absent from the Indonesian national seismic hazard model (PUSGEN, 2017), highlighting a major deficiency in knowledge with implications for regional hazard assessment.

For these reasons, the objective of this study is to recognize and define active fault traces in the Ransiki area using a multi-approach analysis based on SLI, lineament mapping, space associativity linked with field validation. This is the first well-documented evidence for active faulting in Ransiki and, hence, better constrains crustal deformation and seismic hazard in east Indonesia.

2. Geological and Tectonic Setting

The tectonic setting of West Papua is the result of the convergence between Indo-Australian, Pacific and smaller microplates, giving rise to an extensively deformed zone (Hall, 2002; Pubellier & Hall, 2014). This area is a place for oblique convergence, between the northward-advancing

Indo-Australian Plate and the westward-moving Pacific Plate where strike-slip shearing, thrust faulting, and regional uplift is combined on this region (Nugraha et al., 2020). The Sorong Fault System (SFS), a major active tectonic zone occurs in this region and represents well documented left-lateral shear-earthquake prone belt that stretches over 1,000 km from eastern Halmahera to the Bird's Head area (Tjia, 1972; Baldwin et al, 2012). The SFS is a main strain-transfer zone between the two largest plates.

South of the SFS are the Arfak Mountains, which rise tectonically at a rapid rate and are subjected to transpressional thickening or crustal shortening (Pigram & Panggabean, 1984; Pertamina, 2010). The Ransiki area falls in the transitional zone between these two principal tectonic terrains, where distributed shear is shared by several minor faults that are incompletely mapped. The steep topography, triangular faceted spurs and linear valleys in the region imply the activity of faulting in landscape evolution.

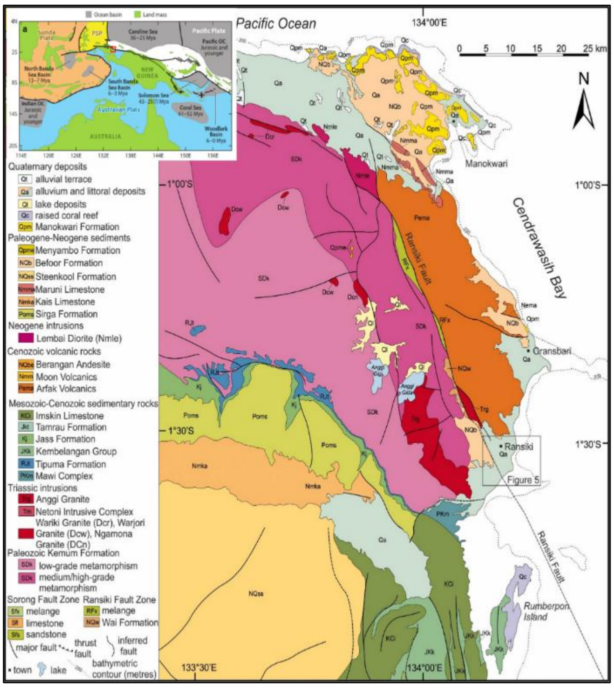

Fig 1. Geological map and location of the Ransiki area, South Manokwari, West Papua. The inset shows the regional tectonic framework of eastern Indonesia and New Guinea, highlighting the interaction between the Indo-Australian Plate, Pacific Plate, and associated microplates, including the Bird's Head block (modified after Atmawinata et al, 1989; Hall, 2002; Baldwin et al., 2012).

Previous geological studies carried out in Ransiki area previously emphasized mainly on rock lithology and regional mapping as indicated in figure 1 (Atmawinata et al, 1989). While the structural observations and local deformation were detected by these studies, they like wise did not interpret them as evidence for active recent faulting. In addition, PSHAs based on instrumental seismic records show the existence of several shallow earthquakes; however, in official current seismic hazard estimates (PUSGEN, 2017; BMKG, 2023), no fault has been established as a source. This contrast is demonstrative of a poor understanding of active crustal deformation in the region.

Morphotectonic features present in the landscape of Ransiki, such as aligned river valleys, sudden elevation changes and fault-scarp-like slopes suggest ongoing deformation related to previously not delineated active fault system. Distinguishing the geometry, nature, and kinematics of such structure is a key step to enhance the seismic hazard assessment in South Manokwari and its neighborhood.

3. Data and Methods

3.1 Data Sources

This study used high-resolution Digital Elevation Model Nasional (DEMNAS) data with 8–30 m spatial resolution that compiles elevation data from IFSAR, TERRASAR-X and ALOS-PALSAR satellite sensors (BIG, 2021). The DEMNAS data set was chosen because it is appropriate for an in depth geomorphic analysis, as the study area belongs to tropical regions with dense vegetation and scarce access for geophysical surveys. Active river networks were derived from DEM for morphometric analysis. Field validation Site visits were made at a limited number of test sites in the study area to check the geomorphic and structural signatures (Fig. 2).

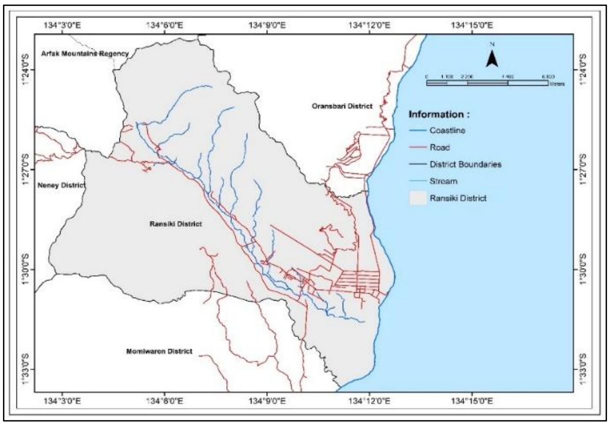

Fig 2. Research map area

3.2 Lineament Extraction and Structural Orientation Analysis

To emphasize linear topographic discontinuities and to reduce directional bias, we used a multi-azimuth hillshade visualization. Hillshade products were obtained in 0°, 45°, 90° and 135° illumination azimuths through QGIS processing. The lineament features were digitized and then statistically filtered to eliminate drainage artifacts and cultivation-induced lineaments. Direction of the lineament was examined in rose diagrams for recognizing main structural trends. The lineament density was determined by processing a fixed-radius kernel to compare clustered distribution of potential fault-related bands.

3.3 Stream Length–Gradient Index (SLI) Calculation

SLI values were calculated following the formulation of Hack (1973), where:

$$SL = \frac{\Delta H}{\Delta L} \cdot L_{tot}$$

ΔH is the channel length of the river segment, and is total inflow channel length to that upstream from this point. Inspection of 42 river segments within their database revealed locations with anomalous steepness due to tectonic uplift or fault movement (table 1). The rivers were extracted automatically based on a change in streamline curvatures, and then manually edited to fit steep terrain.

Table 1. Calculation of SLI value

Activity Category	SLI Value Range	Number of Segments	Percentage
Low	< 300	26	45.60%
Moderate	300–500	14	24.60%
High	500–1,000	11	19.30%
Very High	> 1,000	6	10.50%

3.4 Spatial Correlation Analysis

To evaluate the relationship between crustal deformation and landscape response, a spatial correlation analysis was conducted between SLI anomalies and lineament density using Pearson's correlation coefficient:

$$r = \frac{\sum(xi-\bar{x})(yi-\bar{y})}{\sqrt{\sum(xi-\bar{x})^2 . \sum(yi-\bar{y})^2}}$$

where x represents SLI values and y represents lineament density within equal-sized grid cells. Zones exhibiting both high SLI values and high lineament density were interpreted as areas potentially influenced by active faulting.

3.5 Field Verification

Field surveys concentrated on representative sites detected by remote sensing data, such as triangular facets, linear valleys, fault scarps and polished slickenside surfaces. Field measurements (orientation of strike, dip and slickenline) were measured using a Brunton compass. This could be verified by identifying the kinematics and surface expression of the newly found lineaments.

4. Results

4.1 Lineament Characteristics

Altogether, 186 topographic control lineaments were recognized in the study region. The rose diagram analysis indicates a dominant trend N330°–N340°E and less significant ENE–WSW trends. The lineaments are denser in the eastern part of Ransiki. Lineament density mapping indicates a number of linear zones with more than 2–3 lineaments/km^2, which appear to be along an oblique distribution striking NW–SE in accordance with a major structural corridor.

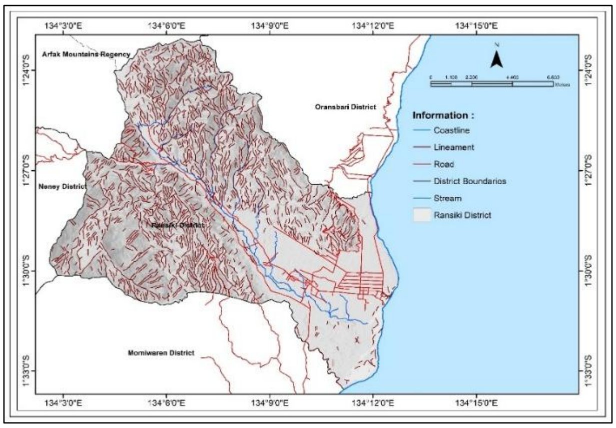

Fig 3. Lineament map of study area

4.2 River Profile Anomalies Based on SLI

The SLI values range from 50 to >500. Most of the low (to moderate) SLI values (500) concentrated along the major tributaries, which flow oblique to the main lineament trend. These steepened river segments are associated with large changes in local river gradients and the development of knickzones (figure 4).

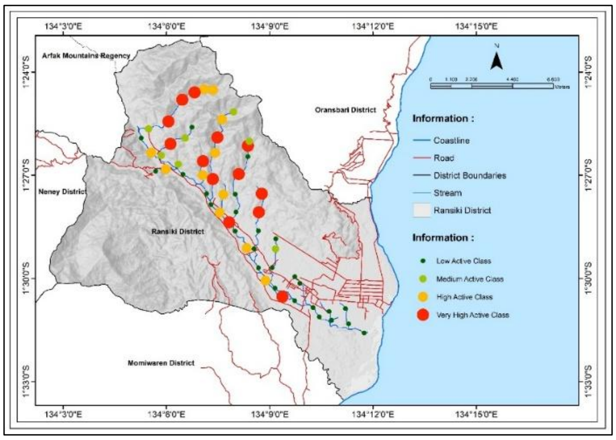

Fig 4. Stream length-gradient index

4.3 Spatial Correlation Between SLI and Lineament Density

The spatial correlation analysis reveals a consistent, positive relationship between SLI anomalies and lineament density (r = 0.63), indicating that regions affected by structural disturbances are also characterised by increased fluvial steepness. The overlapping of high-value sub-domains describes a continuous linear band in the NNW–SSE direction shown approximately 20 km in figure 5.

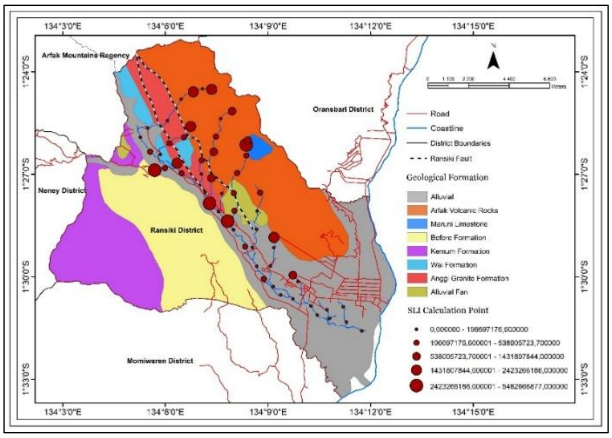

Fig 5. SLI calculations point in geological formation of study area

4.4 Field Observations

Field confirmation was achieved for geomorphic and structural markers at locations of interest. These include:

- well-defined fault scarps up to 3–5 m in height,
- triangular facets developed along linear mountain fronts,
- aligned valley axes following NNW–SSE trends, and
- polished slickenside surfaces preserved in exposed bedrock.

Plotting slickenline direction trends gives N150°–N170°E for measured trends and close to vertical plunges indicating strike-slip kinematics. Outcrops at shattered slopes and down from the riverbanks reveal a marked break that indicates a fault trace (Figure 6).

Fig 6. Shown the triangular facets developed along linear mountain fronts. Photo takes heading to NNW.

5. Discussion

The orientation of the dominant NNW–SSE lineaments have close similarities with major structural trends in others oblique moving terranes in New Guinea deformation zone (Hill et al., 2015; Degroot & Hall, 2020) suggesting that Ransiki is a source of part of strain partitioning that may occur related to channeling/space/S-strain associated with oblique convergence processes in this segment of plate boundary (Hall & Spakman, 2015;Pubellier & Hall, 2014; Fisher & Brandon, 2021). Similar strike-slip-dominated topographic patterns are found in other transpressional fault systems worldwide (Raimondo & Steer, 2020; Ramos, 2021).

The pronounced spatial clustering of high SLI values (>500) proximal to the belt-mapped corridor is indicative of ongoing tectonic uplift that supports models for knickpoint-propagation in deforming landscapes (Bishop, 2017; Brardinoni et al., 2022; Wobus et al., 2021). These river steepness anomalies are commonly interpreted as reflecting ongoing fault propagation and lithosphere motion during crustal thinning (Li et al., 2022; Cox & Barrell, 2020; Moucha & Forte, 2023).

Field observations attest to sinistral strike-slip faulting as a kinematic style consistent with the regional Sorong Fault System (Tjia, 1972; Hill et al., 2015) and other strike-slip systems accommodating similar plate-motion vectors in transpressional margins (Sapkota et al., 2018;Duvall et al., 2021). These pieces of evidence suggest that the imaged structure is an active constituent in the Papua tectonic network rather than a 'dead' paleo-fault.

From a seismic hazard point-of-view, the identification of the Ransiki Fault Zone is a large step forward in comparison with actually-used models. Smaller faults of equivalent magnitude have generated destructive shallow earthquakes in similar tectonic settings (Ramos, 2021; Nugraha et al., 2020). The distance from a populated area of the RFZ highlights the need to factor RFZ into subsequent hazard evaluations and infrastructure development.

In addition, the longitudinal distribution of SLI values along the river channels helps to identify the trend of variation along the river channels, further illustrating the spatial pattern of active deformation. As illustrated in Figure 4, the channels show a trend of variation from low to high activity, with the SLI values increasing along the channel course towards the segments that intersect the area of high lineament density. This pattern suggests that the tectonic effect increases towards the area of structural control of the drainage network. However, other channels show the opposite trend of variation, where the SLI values decrease from high to low along the course of the channel, moving away from the area of main deformation (Figures 4 and 5). This suggests that the tectonic effect decreases away from the area of main deformation. The presence of abrupt changes in the classes of SLI values, as illustrated in Figure 5, further supports the suggestion that the rivers show responses to localized uplift and strike-slip tectonic activities related to the presence of the Ransiki Fault Zone, acting as a strain transfer structure related to the Sorong Fault System.

6. Conclusion

This paper is the first in introducing morphotectonic studies on Ransiki area in South Manokwari, West Papua. The combined outcomes are summarized as follows:

1. Lineament analysis reveals a prominent NNW–SSE trending structures corridor, characterised by unusually high clustering, in the eastern Ransiki region.
2. High Stream Length–Gradient Index (SLI) anomalies (>500) are spatially coterminous with high lineament density, representing active tectonic uplift and fault-controlled river incision.
3. Field relationships validate sinistral strike-slip kinematics due to fault scarps, triangular facets, and slickensided surfaces that are defined parallel to the dominant structural trend.
4. The combined datasets define the Ransiki Fault Zone (RFZ), an active transpressional shear zone serving as the transfer point for strain between the Sorong Fault System and Arfak uplift.
5. The identification of the RFZ as a potential shallow seismogenic source has important implications in seismic hazard assessments for South Manokwari and its surrounding areas.

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