International Journal of Current Science Research and Review
ISSN: 2581-8341
Volume 07 Issue 05 May 2024
DOI: 10.47191/ijcsrr/V7-i5-08, Impact Factor: 7.943
IJCSRR @ 2024
www.ijcsrr.org

Morphotectonic Analysis in the Sombe Lewara Sub-Watershed in the Region of Palu City and Sigi Regency, Central Sulawesi Province

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ABSTRACT: A study on the tectonic activity index (IAT) was conducted in the Sombe Lewara Sub-Watershed, encompassing the area of Palu City and Sigi Regency, Central Sulawesi Province. The objective of this research was to determine the level of tectonic activity in the Sombe Lewara Sub-Watershed. The analysis employed in this study was morphotectonic analysis, utilizing parameters such as Hypsometric Integral (HI), Basin Shape (BS), Asymmetry Factor (AF), Stream Length-gradient Index (SL), Area Factor (AF), and Valley floor width-to-height ratio (Vf ratio). The tectonic activity index (IAT) value in the Sombe Lewara Sub-Watershed was 1.6, which classifies it within the high tectonic activity category. This high level of tectonic activity in the research area influences the landscape conditions and the types of rocks present. The predominant rock types in the study area are sedimentary rocks such as conglomerate deposits, sandstone, siltstone, and claystone. These rocks form the character of an expansive alluvial fan landscape that nearly covers the entire plain. One of the primary factors contributing to liquefaction in the Balaroa Region is that the area is composed of sand sediment deposits and granite boulders that constitute the alluvial fan.

KEYWORDS: Sombe Lewara Sub-Watershed, Morpotectonic, Level of Tectonic Activity, Alluvial fan.

INTRODUCTION

Sulawesi Island is the product of complex geological processes. Major tectonic plates of the world, such as the northward-moving Indo-Australian plate, the westward-moving Pacific plate, and the southeastward-moving Eurasian plate, along with smaller plates like the Philippine plate (Katili, 1970; Sompotan, 2012; Watkinson dan Hall, 2017) collectively shape the island of Sulawesi, which resembles a 'K' formation (Katili, 1978). In narrower regions, the impact of these tectonic forces is reflected by geological structures that can form unique geomorphological characteristics known as morphotectonics (Doornkamp, 1986). In addition to the formation of these landscapes, the Palu Valley is traversed by the active Palu-Koro fault line (Katili, 1970; Sukamto Et.al., 1973). this region particularly vulnerable to natural disasters, especially those caused by the movements of these plates, which drive the activity of the Palu-Koro fault (Badan Geologi, 2018).

The occurrence of these natural disasters is one of the manifestations of neotectonic events or tectonic processes that are active in the present era (Stewart dan Hancock, 1994; Van Hinsbergen, 2011). In this regard, to minimize the risk effects of such disasters, it is necessary to conduct research with a morphotectonic study approach. Morphotectonic studies investigate everything concerning the relationship between geological structures and landforms, or more specifically, the relationship between neotectonic structures and landforms (Stewart dan Hancock, 1994).

Morphotectonic research is expected to yield results and discussions regarding the zonation of tectonic activity levels in the Kawatuna Sub-Watershed and Sombe Lewara Sub-Watershed. Based on morphotectonic studies (El Hamdouni Et.al., 2007; Dehbozorgi Et.al., 2010; Tawil, 2019; Kumar Et.al., 2022), such research can determine the level of tectonic activity, ranging from very high tectonic activity classes, high tectonic activity classes, moderate tectonic activity classes to low tectonic activity class

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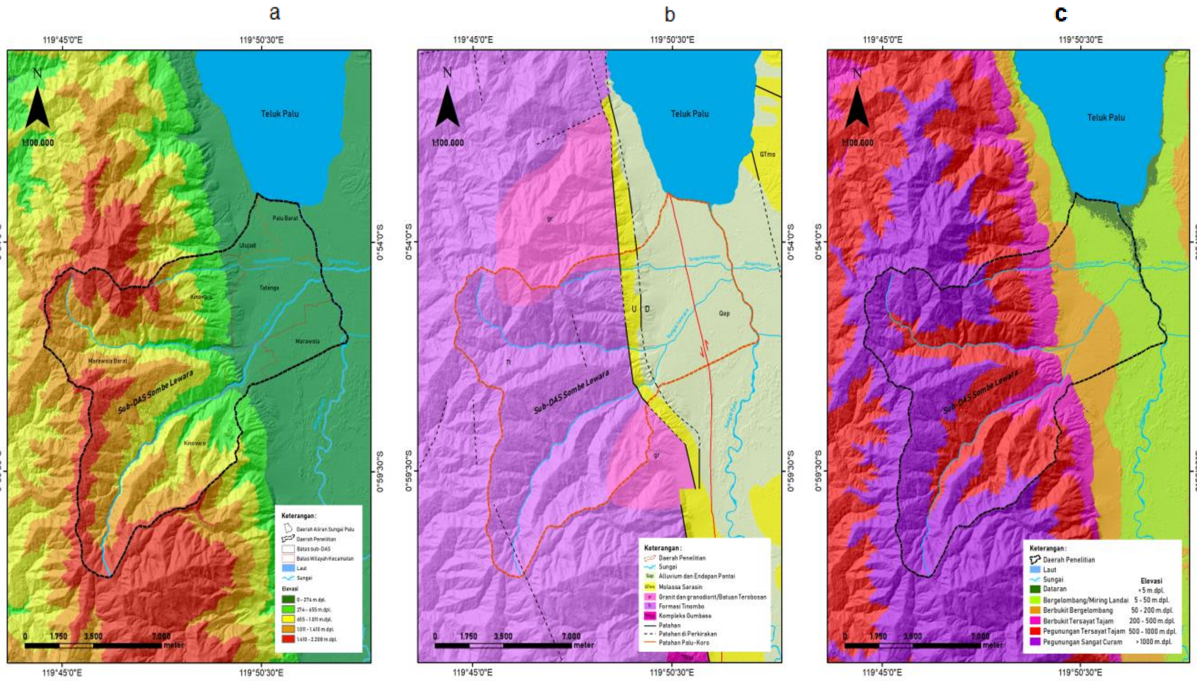

Figure 1. (a) The topographic map of the research area (Badan Informasi Geospasial, 2008), (b) The geological map of the research area (Sukamto Et.al., 1973; Sukido Et.al.,1993) and (c) The morphological map of the research area (Badan Informasi Geospasial, 2008).

Regional Geology of the Research Area

The research area is situated within the regional geological map zones of the Palu Sheet and the Pasangkayu Sheet (Sukamto Et.al., 1973; Sukido Et.al., 1993), which comprise generally of an alluvial plain extending in a relatively north-south direction and is bordered by slopes and ridges of mountains that belong to the Sarasin Molasse Formation in hilly areas, portions of Intrusive Rocks on the mountain sides, and the Tinombo Formation in mountainous regions. The research area is located in the Palu-Koro fault zone, which is one of the areas with active geological processes. The Palu-Koro fault system is a horizontal fault with movement of the strike-slip or transcurrent fault type (Katili J.A, 1970; Bellier Et.al., 2001). According to Sukamto et al (1973) and Sukido et al (1993) ,the regional geological stratigraphy of the research area is composed of the Tinombo Formation (Tt), Granite and Granodiorite (gr)/Intrusive Rocks (Tpkg), Sarasin Molasse (QTms), and Alluvium and Coastal deposits (Qap)

RESEARCH METHODOLOGY

The methods employed in this study encompass data acquisition and analysis techniques. Data acquisition methods are aligned with their scope, comprising studio and field collection techniques. Studio data procured include regional geological maps (Sukamto Et.al., 1973; Sukido Et.al., 1993), DEMNAS 8.5 m (Badan Informasi Geospasial, 2008), including river shapefiles at a 50_K scale, the Palu watershed boundary shapefiles, and the Sub-Watershed of Palu boundary shapefiles (BPDAS Palu-Poso, 2011), along with field data comprising visual descriptions of the landscape and the rock formations in the research area.

- **Research Location**

The research location is situated in the upper watershed area of the Palu River. Specifically, the research area is within the Sombe Lewara Sub-Watershed (BPDAS Palu-Poso, 2011). Geographically, it is located at coordinates 119°50'22.73"E - 0°56'23.20"S. Administratively, the research area is located in the Palu City region, encompassing the districts of West Palu, Tatanga, Ulujadi, and the Sigi Regency area, including parts of the Marawola, Kinovaro, and West Marawola districts, in the Central Sulawesi Province. The total area of the research site is approximately 130.04 km^2

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- **Equipment and Materials**

Equipment used during the research includes:

1. Geological compass
2. GPS (*Global Positioning System*)
3. Digital camera

Materials used during the research includes:

1. DEMNAS (National Digital Elevation Model) (Badan Informasi Geospasial, 2008)
2. Topographic map of Palu sheet 1 : 50.000 (BAKOSURTANAL, 1991)
3. Regional geological map of Palu sheet scale1 : 250.000 and regional geological map of Pasangkayu sheet scale 1 : 250.000 (Sukamto et al., 1973; Sukido et al., 1993).
4. River *Shapefile* 50_K, Palu Watershed Boundary *Shapefile*, and Palu Sub-Watershed Boundary *Shapefile* (BPDAS Palu-Poso, 2011).

- **Data Collection Phase**

The data collection phase encompasses both studio and field data gathering. Studio data collection obtained includes; regional geological data, topographic data (DEMNAS) (Geospatial Information Agency, 2008), Palu watershed river shapefiles 50_K, Palu watershed boundary shapefiles, and Palu Sub-Watershed boundary shapefiles (BPDAS Palu-Poso, 2011). Meanwhile, field data collection consists of rock layer data obtained from surveys or direct reviews of the research area.

- **Data Processing and Analysis Phase**

The data processing and analysis phase involved a variety of processes, including those derived from watershed morphometry and morphotectonic data. Data processing was conducted using ArcGIS 10.3 and *Globalmapper* 10 software.

- **Data Interpretation Phase**

The data interpretation phase employs morphotectonic analysis to ascertain the zonation of tectonic activity levels based on the classification by El Hamdouni et al. (2007) and Dehbozorgi et al. (2010). Field data consisting of rock layers are analyzed to understand the rock formations in sedimentary areas or alluvial fans.

RESULT

The research results in the Sombe Lewara Sub-Watershed include a discussion on morphotectonic analysis. The parameters of this analysis serve as references to explain tectonic activities in the research area. The parameters used include integral hypsometry (HI), stream area index (BS), stream area asymmetry factor (AF), mountain front sinuosity (Smf), stream length gradient index (SL), and the ratio of valley width to valley height (Vf ratio).

- **Hipsometri Intergral (HI)**

The Hypsometric Integral (HI) principally delineates the elevation distribution within a specified terrestrial area, predominantly within watersheds. The Integral Hypsometry represents the area located along the hypsometric curve portion. The computation of the HI value is derived from the following equation. (Keller dan Pinter, 1987, 1996).

$$HI = \frac{(Average\ Height)\ -\ (Minimum\ Height)}{(Maximum\ Height) -\ (Minimum\ HeIght}$$

Based on the classification of tectonic activity levels utilizing the Hypsometric Integral (HI) values (El Hamdouni et al., 2007; Dehbozorgi et al., 2010), the division of tectonic classes comprises class 1 with HI ≥ 0.5, class 2 with 0.4 ≤ HI < 0.5, and class 3 with HI < 0.4. From the measurements conducted in the study area, the Hypsometric Integral (HI) value was found to be 0.481. This value indicates that the area predominantly exhibits a level of tectonic activity corresponding to class 2.

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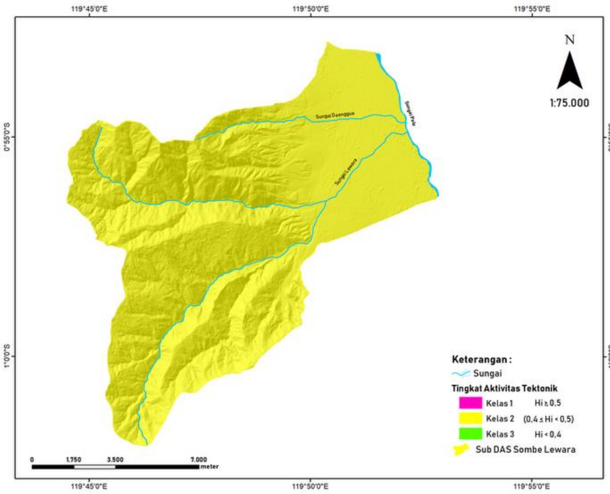

Figure 2. Map of Hypsometric Integral Tectonic Activity Levels (HI)

- **Basin Shape Index (BS)**

The Basin Shape (BS) index is defined as the ratio between the basin length (BI), which is the length of the watershed measured from the highest point, and the basin width (Bw), which is the width of the watershed measured at its widest point (Dehbozorgi et al., 2010). The measurement of the BS index in the research area is calculated based on the equation proposed by Bull and McFadden (1977).

$$BS = BI/Bw$$

Where:
BS = Basin Shape index (km^2)
BI = Basin Length (km)
Bw = Basin Width (km)

According to the classification by El Hamdouni et al. (2007) and Dehbozorgi et al. (2010), the levels of tectonic activity based on the Basin Shape (BS) index are divided into three categories: class 1 with BS ≥ 4, class 2 with 3 ≤ BS < 4, and class 3 with BS ≤ 3. The value of the tectonic activity level in the study area, based on the Basin Shape Index (BS), is 3.28, which falls within the category of class 2 tectonic activity level.

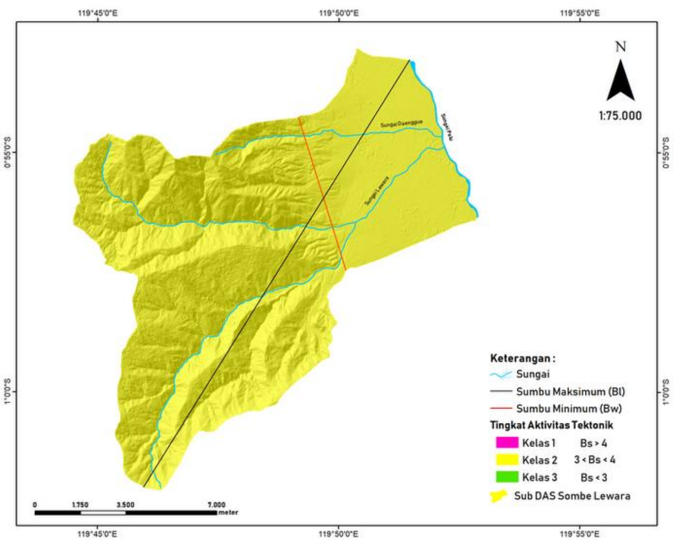

Figure 3. Map of Tectonic Activity Levels Based on the Basin Shape Index (BS)

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- **The Stream Area Asymmetry Factor (AF)**

The Stream Area Asymmetry Factor (AF) is a quantitative analysis tool for drainage basins used to detect tectonic tilting, applicable across both small and large drainage basin scales (Keller and Pinter, 1996). The asymmetry of a drainage area (AF) is determined by the ratio of the drainage basin or sub-basin area on one side to the total area of the drainage basin or sub-basin. The measurement of the AF in the study area was conducted on two rivers, namely the Daengguni and Lewara rivers. Subsequently, the results were calculated based on the equation (Keller dan Pinter, 1987, 1996).

$$AF = \left(\frac{Ar}{At}\right) x100$$

Where:
AF = Asymmetry Factor
Ar = Area of the right side of the drainage basin (direction of water flow downstream) (km^2).
At = Total area of the drainage basin (km^2)

The division of tectonic activity levels based on the Asymmetry Factor (AF) values is categorized into three classes, according to El Hamdouni et al. (2007) as cited by Dehbozorgi et al. (2010). These classes are defined as class 1 (AF values ≥ 65 or AF < 35), class 2 ($35 \leq$ AF < 43 or $57 \leq$ AF < 65), and class 3 ($43 \leq$ AF < 57). Based on the measurements conducted, the Asymmetry Factor (AF) value in the study area is 65.26. According to this value, the tectonic activity level in the research area is classified within class 1.

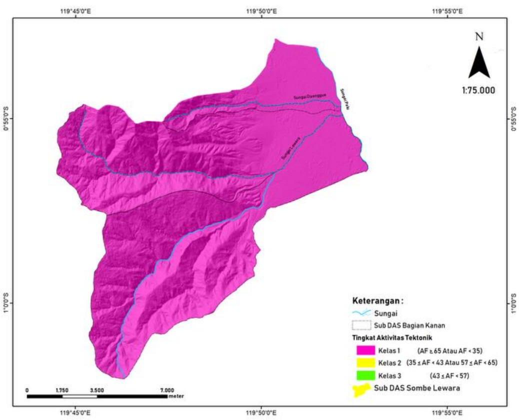

Figure 4. Map of Tectonic Levels Based on the Asymmetry Factor of Drainage Basins (AF).

- **Mountain Front Sinuosity (S_{mf})**

The Mountain Front Sinuosity (Smf) is an index that reflects the balance between the erosive forces, which tend to cut along the curves of the mountain front, and the tectonic forces that directly create the mountain front, coinciding with zones of active faults that reflect active tectonics (Keller and Pinter, 1996). From the measurements of the length of the mountain front surface (Lmf) and the straight length of the mountain front (Ls) in the Sombe Lewara Sub-Watershed, based on the boundary between the mountain front and alluvial fans(Bellier, 2001) and supported by topographic data (DEMNAS), the Smf value is obtained using the equation (Bull and McFadden, 1977, in Doornkamp, 1986).

$S_{mf} = L_{mf} / Ls$

Where:
Smf = Mountain Front Sinuosity
Lmf = Length of the mountain front surface (km)
Ls = Straight length of the mountain front (km)

According to El Hamdouni et al. (2007) and Dehbozorgi et al. (2010), the classification of tectonic classes based on the Mountain Front Sinuosity (Smf) value is divided into class 1 (Smf value < 1.1), class 2 (Smf value between 1.1 and 1.5), and class 3 (Smf

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value ≥ 1.5). Based on the measurements, the level of tectonic activity in the research area has a value of 1.20, which falls into class 2.

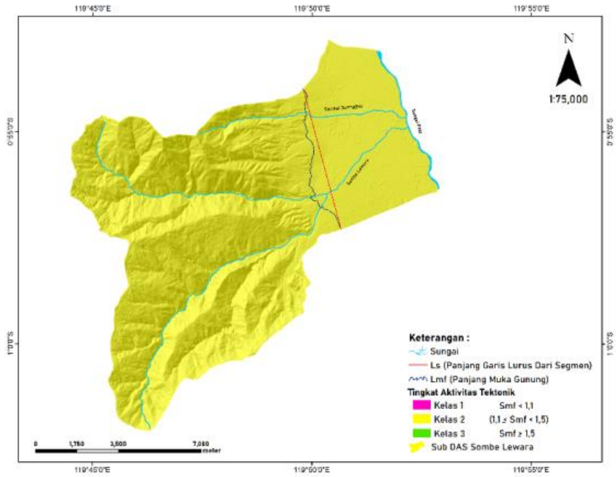

Figure 5. Map of Tectonic Levels Based on Mountain Front Sinuosity (Smf)

- **Stream Length Gradient Index (SL)**

The Stream Length Gradient Index (SL) is highly sensitive to changes in valley slope. This sensitivity of the SL values can be utilized to evaluate the relationship between active tectonics, rock resistance, and topography. The SL values can be employed for the identification of current active tectonics. The measurement of the stream length gradient index (SL) in the Sombe Lewara Sub-Watershed was obtained from the analysis of two rivers, namely the Daengguni and Lewara rivers. Subsequently, the results from these measurements were calculated based on the equation provided (Keller and Pinter, 1987, 1996).

$$SL = \left(\frac{\Delta H}{\Delta L}\right) xL$$

The classification of tectonic activity levels based on the Stream Length Gradient Index (SL) values is divided into three classes: class 1 with SL = 500, class 2 with 300 = SL < 500, and class 3 with SL < 300 (El Hamdouni et al. 2007; Dehbozorgi et al., 2010). From the measurement results of SL in the study area, a value of 539.44 was obtained. This value falls into the category of class 1 tectonic activity level.

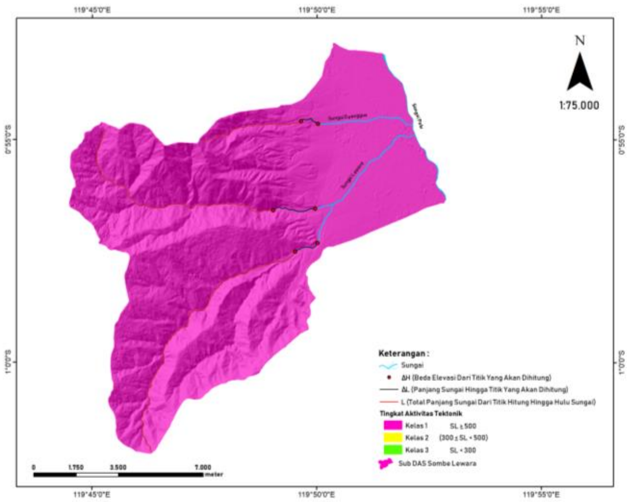

Figure 6. Map of Tectonic Levels Based on the Stream Length Gradient Index (SL) in the Study Area.

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- **Valley Width to Valley Height Ratio (Vf Ratio)**

The *Vf* ratio is an analysis of the uplift rate in a research area based on the comparison of the valley floor width to the valley height. A high Vf ratio is associated with a wide, flat valley floor, whereas a low Vf ratio is indicative of active uplift with a V-shaped valley form. The measurements of the Vf ratio cross-sections in the Sombe
Length Gradient Index (m)
Elevation difference from the point to be calculated (m))
Length of the river up to the point to be calculated (m)
Total length of the river from the calculation point to the river sourceses. (m)
Lewara Sub-Watershed were then calculated based on the equation provided by Bull and McFadden (1977).

$$V_f = 2V_f w/(Eld - Esc) + (Erd - Esc)$$

Where:
V_f = Ratio of valley floor width to valley height
$V_f w$ = Valley floor width (m)
Eld = Height of the valley's right side (m)
Erd = Height of the valley's left side (m)
Esc = Elevation of the valley floor (m)

According to Bull and McFadden (1977), Vf ratio values ranging from 0.055 – 0.5 constitute a highly active tectonic class (Class 1). The Vf ratio value ranges between 0.5 – 3.6 indicating moderate or less active tectonic activity (Class 2), while the Vf ratio value ranges between 2 – 47 indicating inactive tectonics (Class 3). Based on the measurement results, the Vf ratio value in the research area was found to be 1.19. The level of tectonic activity in this area is classified as class 2 tectonic activity.

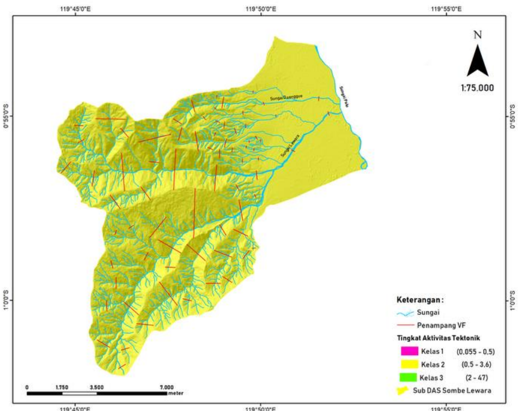

Figure 7. Map of Tectonic Activity Levels Based on the Valley Width to Valley Height Ratio (*Vf* Ratio)

DISCUSSION

- **Index Active Tectonic (IAT)**

The tectonic activity index of the research area, based on the average values from six morphometric parameters—Integral Hypsometry (HI), Stream Area Asymmetry Factor (AF), Stream Length Gradient Index (SL), Basin Shape Index (BS), Mountain Front Sinuosity (Smf), and the Valley Width to Valley Height Ratio (Vf Ratio)—refers to the work of El Hamdouni et al. (2007) and Dehbozorgi et al., 2010). The assessment of the index is divided into four classes to determine the level of active tectonics: 1-very high ($1.0 \leq IAT < 1.5$); 2-high ($1.5 \leq IAT < 2.0$); 3-moderate ($2.0 \leq IAT < 2.5$); and 4-low ($2.5 \leq IAT$).

$$IAT = S/N$$

Where:
S = Parameter Index
N = Total Parameter Index

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Based on the combined measurements and analysis of the parameters HI, AF, SL, BS, and Vf ratio, the active tectonic index value in the Sombe Lewara Sub-Watershed is 1.6. This value falls within the high tectonic activity class.

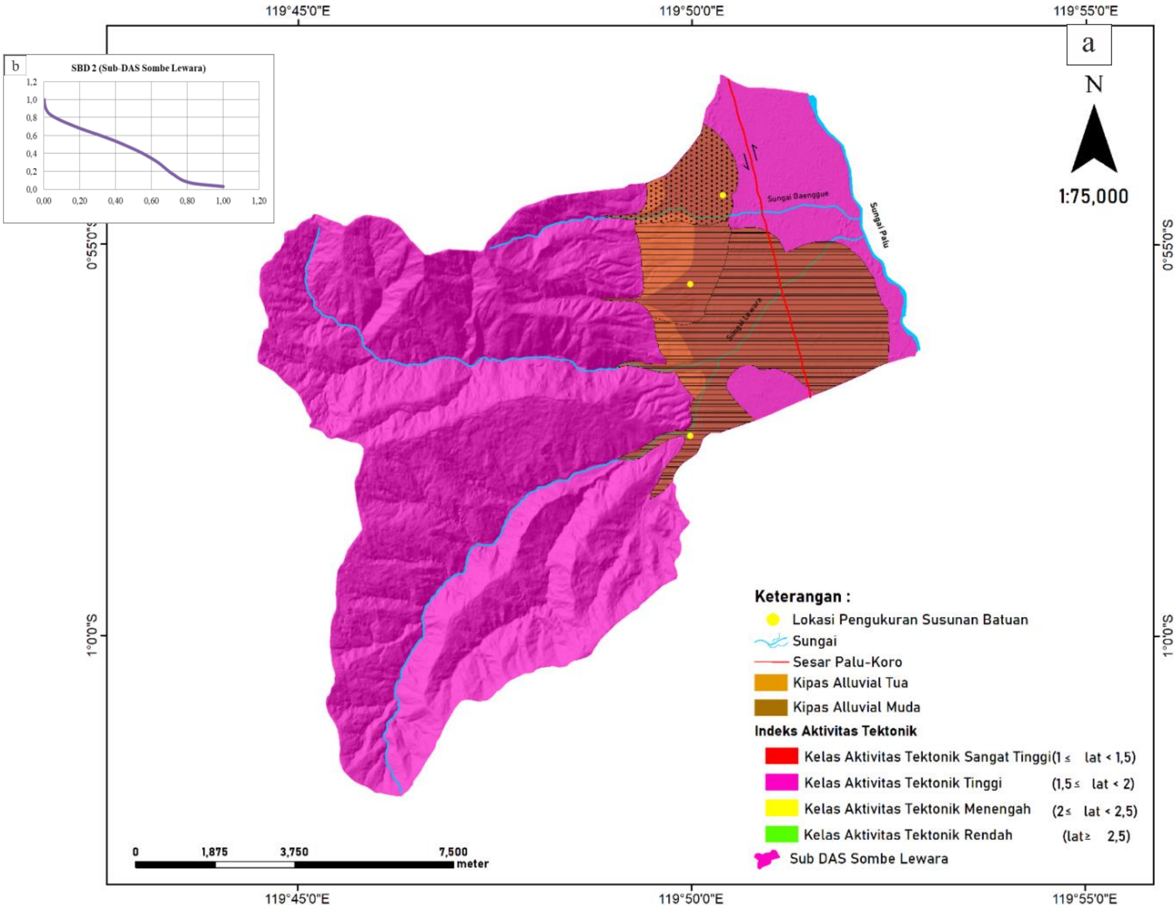
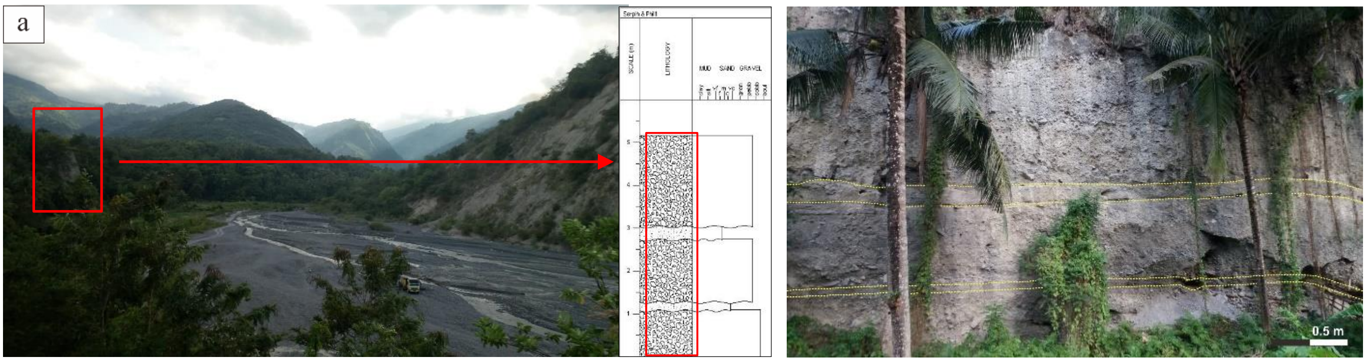


Figure 8. (a) Map of the Tectonic Activity Index (IAT) with the determination of the age of alluvial fans based on (Bellier, 2001) and (b) the shape of the hypsometric curve (Hc).

The sediment area in the Sombe Lewara Sub-Watershed is situated within the molasse formation on the regional geological map of the Palu sheet (Sukamto et al., 1973). The arrangement of sedimentary rocks in the molasse formation comprises both young alluvial fans and old alluvial fans (Bellier, 2001).



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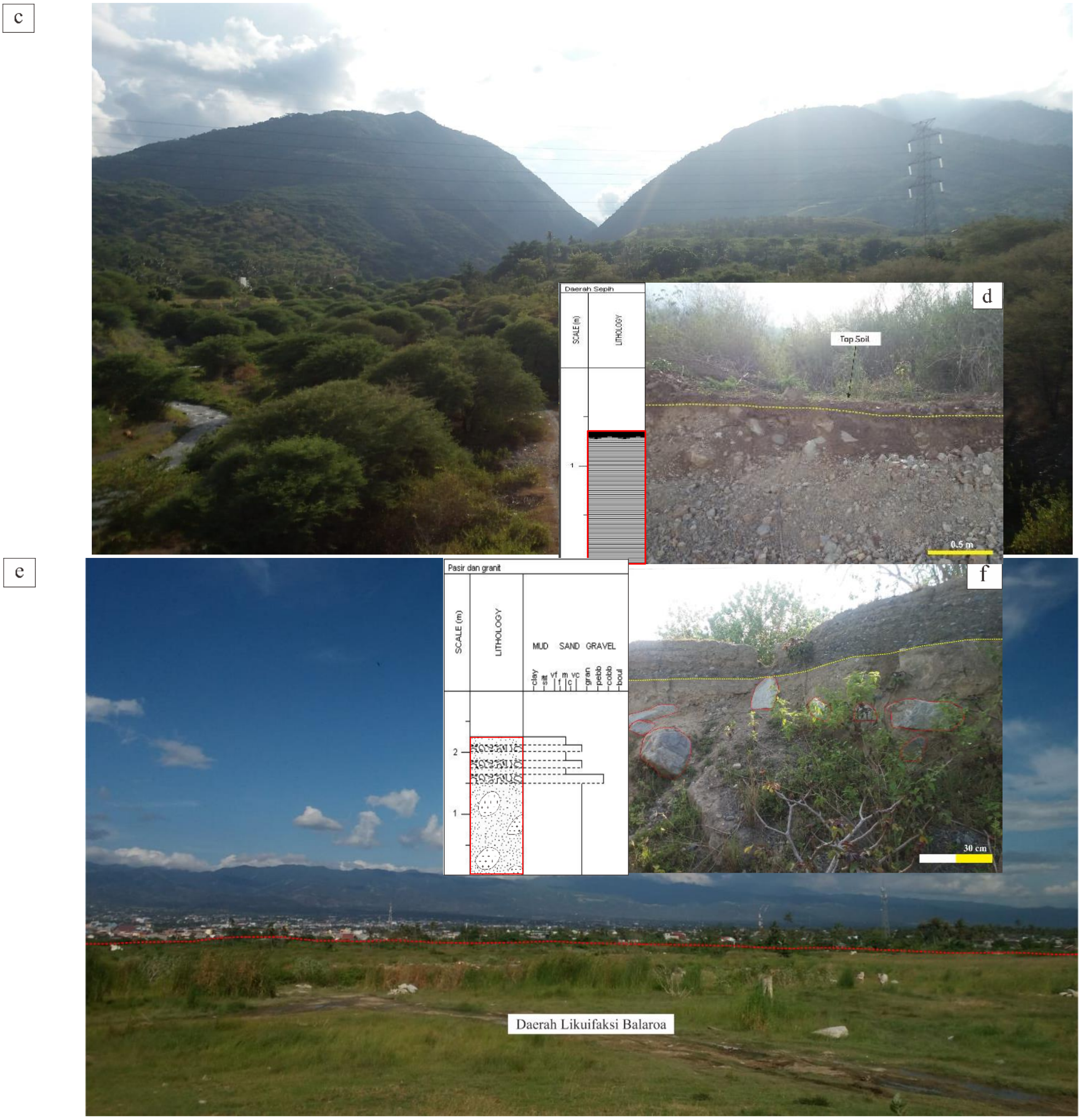

Figure 9. Sombe river area (a), outcrop of sedimentary rocks showing cross-bedding of sand and conglomerate deposits composed of shale and phyllite fragments (b), landscape appearance of the Lewara mountainous area (c), outcrop of shale deposits in the Duyu hilly area (d), Balaroa liquefaction disaster area (e), and the arrangement of sedimentary deposits in the crown area of the Balaroa liquefaction landslide composed of sand and granite (f).

The high tectonic activity in the area influences the landscape conditions and the sedimentation types of rocks. The sedimentary rock types in the research area are generally sedimentary rocks consisting of conglomerate, shale, phyllite, and sandstone deposits. The hypsometric curve indicates that this area is in an old stage, suggesting that it has reached a geomorphic equilibrium between uplift and erosion. The landscape formed in this area consists of extensive alluvial fans that nearly cover all plains and hills. The sediment materials of the alluvial fans are transported from the upstream areas (mountainous and hilly regions), carried to the downstream areas supported by the presence of main rivers in the area, namely the Daengguni River, Sombe River, and Lewara River. These sediment materials were formed due to erosion, rock weathering, and tectonic activities. The tectonic activity in this area is categorized as active, supported by the presence of the Palu-Koro Fault line traversing the area. The Balaroa region experienced liquefaction on September 28, 2018, caused by the movement of the Palu-Koro Fault. Research findings indicated that the materials at the landslide crown consist of sand deposits and granite boulders arranged in a young alluvial fan landscape, which supports the occurrence of liquefaction events. Meanwhile, in the southern area, the deposits are composed of metamorphic rocks that were formed by the deposition of shale, phyllite, and partially by sandstone lamination.

CONCLUSION

- The HI value in the study area is 0.481. This value indicates a level of tectonic activity classified as class 2.
- The BS value in the study area is 2.88, which falls within the level of tectonic activity classified as class 2.
- The AF value in the study area is 65.26. This value places the level of tectonic activity in the study area within class 1.
- The Smf value in the study area is 1.20. This value is classified within the level of tectonic activity as class 2.
- The SL value in the study area is 539.44. This value is classified within the level of tectonic activity as class 1.
- The Vf ratio value in the study area is 1.19. This value falls within the level of tectonic activity classified as class 2.
- Based on the combined values from the parameters (HI), (BS), (AF), (SL), and (Vf ratio), it can be interpreted that the (IAT) value in the study area is 1.6. This value falls within the high class of tectonic activity.

ACKNOWLEDGEMENT

Thank you to the fellow lecturers of the Geological Engineering Program at Tadulako University who provided advice and input in the writing of this scientific work, and to friends at the Wallacea Research Organization, especially Roland, Pribadi Ahmad, and friends from Tadulako geology, Alfian Zaini, who were willing to help during the data collection.

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