JGSM
Jurnal Geologi dan Sumberdaya Mineral
Journal of Geology and Mineral Resources
Center for Geological Survey, Geological Agency, Ministry of Energy and Mineral Resources
Journal homepage: http://jgsm.geologi.esdm.go.id
ISSN 0853 - 9634, e-ISSN 2549 - 4759

The uplift rate of Sulawesi East Arm and the activity of Batui Fault using a tectonic geomorphology approach in the Luwuk Area, Sulawesi

Laju pengangkatan Lengan Timur Sulawesi dan aktivitas Sesar Batui dengan pendekatan geomorfologi tektonik di Daerah Luwuk, Sulawesi

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Naskah diterima: 15 Desember 2021, Revisi terakhir: 03 Desember 2024, Disetujui: 02 Februari 2025 Online: 06 Februari 2025
DOI: http://dx.doi.org/10.33332/jgsm.geologi.v26i1.663

Abstract- *Sulawesi is a tectonically active area with convergent triple-junction amidst Eurasian, Indo-Australian and Pacific Plate. The study area is located in the suture zone of sedimentary Banggai-Sula Microcontinent and East Sulawesi Ophiolite. This research is aimed to determine fault activity and rate of tectonic uplift of Luwuk mountainous area. Field geological mapping had been done to determine lithology and geological structure along with morphometric analysis to measure definitive result of tectonic activities. Geological structure features which encountered in this area are Batui Thrust, Pasini Thrust, Lobu Balongan Fault Zone, and Lambangan Anticline. The sedimentary rocks have average N315°E dip direction with angle of 41°. Based on tectonic geomorphology and morphometric analyses are resulting the most active tectonic areas passed by the Batui and Pasini Thrust which have NE-SW direction and Lobu Balolang Fault Zone relative to others. The Batui Thrust is considered as active fault intersected the East Sulawesi Ophiolite and Banggai-Sula Microcontinent which segmented with wrench faults. Number of thrust faults parallel to the Batui Thrust generate Batui Thrust Belt which propagate from the ultramafic rocks to the sedimentary rocks within the suture zone. As a result, the presence of active fault is uplifting the East Arm of Sulawesi with 0.408 ± 0.008 mm and 0.213 ± 0.046 mm uplift rate per year by the presence of high altitude Celebes Molasses. These rates are getting higher to the west.*

Keywords: *Batui Thrust, East Sulawesi Ophiolite, Luwuk, morphometry, tectonic geomorphology, uplift rate*

Abstrak-*Sulawesi secara tektonik adalah daerah aktif yang terletak di antara pertemuan tiga lempeng yaitu Lempeng Eurasia, Indo-Australia, dan Pasifik. Lokasi penelitian berada di zona suture antara Mikrokontinen Banggai-Sula dan Ofiolit Sulawesi Timur. Penelitian ini bertujuan untuk mengetahui aktivitas sesar di daerah pegunungan Luwuk. Survei lapangan dilakukan untuk menentukan sebaran litologi dan struktur geologi. Pendekatan geomorfologi tektonik melalui analisis morfometri digunakan untuk mendapatkan hasil yang terukur terkait aktivitas tektonik di daerah ini. Jejak struktur geologi yang hadir di daerah penelitian yaitu Sesar Naik Batui, Sesar Naik Pasini, Zona Sesar Lobu Balongan, dan Antiklin Lambangan. Batuan sedimen yang tersingkap secara umum menunjukkan perlapisan berarah N315°E dengan kemiringan 41°. Berdasarkan pendekatan geomorfologi tektonik dan analisis morfometri diketahui bahwa daerah yang dilalui oleh Sesar Naik Batui dan Sesar Naik Pasini yang berarah timur laut-barat daya, serta Zona Sesar Lobu Balolang secara tektonik paling aktif dibandingkan daerah lainnya. Sesar Naik Batui adalah sesar naik aktif yang membagi Ofiolit Sulawesi Timur dan Mikrokontinen Banggai-Sula yang tersegementasi oleh sesar geser. Sekelompok sesar dengan arah yang sama di sekitar Sesar Batui menghasilkan Sabuk Sesar Batui yang tersebar dari batuan ultramafik hingga batuan sedimen dalam zona suture. Keberadaan sesar-sesar aktif tersebut menyebabkan pengangkatan Lengan Timur Sulawesi dengan laju 0,408 ± 0,008 mm dan 0,213 ± 0,046 mm per tahun dilihat dari kehadiran Molase Sulawesi pada elevasi yang tinggi dan memiliki laju pengangkatan yang semakin tinggi ke arah barat.*

Kata kunci: Sesar Naik Batui, Ofiolit Sulawesi Timur, Luwuk, morfometri, geomorfologi tektonik , laju pengangkatan

INTRODUCTION

Eastern Indonesia especially Sulawesi, at the tip of Eastern Arm and Banggai-Sula microcontinent geologically have a very complex structure. Development of the structure in the location affected by three major plates convergent between Eurasian Plate, Indo-Australian Plate, and Pacific Plate (Rudyawan & Hall, 2012). Recently, tectonic activity of Sulawesi is extremely active which show a lot of scattered earthquakes occur. Including a triggered tsunami on Mw7.5 Palu earthquake in 2018, and Mw6.6 Poso earthquake in 2017.

Geological hazard potentials are widely range covering eastern Indonesia from earthquake and triggered *tsunamis*, and volcano eruptions. Up to 216,744 fatalities and 11,932,560 were injured and affected since 1900 to 2020 geological hazards. Excluding the Tambora tragedy in 1815 buried Bima Emperor and created no-season for several years in the world and the tsunami-triggered-volcano eruption of Krakatoa in 1883 which cost totally more than 300,000 killed (Wood, 2014).

Pusat Studi Gempa Nasional (2017) released an updated active fault map across Indonesia, including two active faults lie in the East Arm of Sulawesi, named as the Batui Thrust and Balantak Fault with 84 and 149 kilometres maximum length respectively. Those active fault generated latest recorded earthquake on July 25th, 1998 with M4.4 and 33 km epicentre depth correspond to Batui Thrust and April 26th, 2018 with M4.1 and 33.6 km epicentre depth correlate to presence of Balantak Strike-Slip to the east.

This research is aimed to understand the tectonics activities of the Luwuk mountainous area by defining the presence of active faults and its effect on the mountainous uplift rate. This study also could be a pre-warning of potential earthquakes on its area in the future.

This study took place in the East Arm of Sulawesi, registered as the Banggai Regency in the Central Sulawesi Province, especially in Pagimana District. The place is comprising sedimentary rocks from the Banggai-Sula Microcontinent and Ophiolite Rocks. In this study, several methods are used to approach the tectonic uplift rate including regional and detailed geological fieldwork, biostratigraphy and petrography analysis, and landscape analysis which related to tectonic geomorphology. The study of tectonic geomorphology has been extremely developed since last decade. Morphometric analysis can be applied to any mountainous landform or even a valley. It is also useful to analyse rough mountainous landform and very limited access. Tectonic geomorphology gives guidance tectonic activity which associate to structural geology based on geomorphic indices.

Geographically, Sulawesi Island has a unique "K" shape located among Sunda Shelf on the west and Australian Shelf on the east. Sulawesi is divided into four lithotectonics (Figure.1). Geologically, Sulawesi is located on the triple junction convergent boundary between Eurasian Plate, Indo-Australian Plate and Pacific Plate. The Pacific Plate then developed into Philippine Plate on the northeast Sulawesi.

Sompotan (2012) and Baillie & Decker (2022) stated that litho-tectonically regional geology of Sulawesi can be divided into: i) West and North Sulawesi Volcano-Plutonic Arc as magmatic belt whose tip of Sunda Shelf, ii) Central Sulawesi Metamorphic Belt consists of metamorphic rocks overlain by melange complex, iii) East Sulawesi Ophiolite Belt (ESO) which segmented and imbricated oceanic crust and, iv) Banggai-Sula and Tukangbesi Microcontinent a discrete Australian Continent which moved along the New Guinea Wrench Fault.

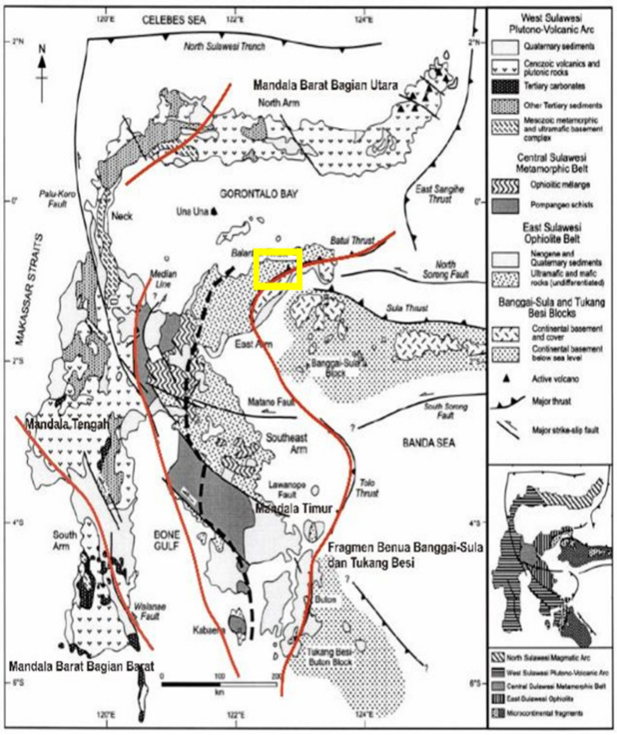

Figure 1. Research area within the yellow box. Lithotectonics of Sulawesi, comprising i) West and North Sulawesi Volcano-Plutonic Arc ii) Central Sulawesi Metamorphic Belt iii) East Sulawesi Ophiolite Belt (ESO) iv) Banggai-Sula and Tukangbesi Microcontinent fragments (Hall and Wilson, 2000).

It is controlled by regional structure of the Banggai-Sula Microcontinent and East Sulawesi Ophiolite convergent. Resulting a lot of thrust faults in NE-SW direction including Batui Thrust which is tectonic border between the convergent. Tip of East Arm of Sulawesi develop dextral fault which divide Poh Head and mainland named Balantak Fault. The fault is also bordering Poh Fault which develops ENE-WSW from Poh segment to the east shore of the Poh Head's (Rudyawan & Hall, 2012).

METHODS

The research is covered the East Arm of Sulawesi regionally and detailed geological mapping at the body of the Luwuk mountainous area. Geological fieldwork had been conducted for about two months. The fieldwork was divided into regional and detailed area. In the first week, regional fieldwork was covered the tip and neck of Sulawesi East Arm, including transect the body of the arm. It covered several formations from the Ultramafic Pra-Tertiary rocks for Quaternary Limestone. The rest of weeks were utilized to detailing 12 x 8 km^2 geological map of Pagimana area which located in the mountainous of the Luwuk region at the north of the ESO. Lithology, structure, and geomorphological data had also been collected.

Tectonic geomorphology is the study of the interplay between tectonic and surface processes that shape the landscape in regions of active deformation and at time scales ranging from days to millions of years (Burbank & Anderson, 2011). Whilst morphometry analysis is a quantitative measurement on external shape and dimension of objects. In this case is earth expressions. Burbank & Anderson (2011) say rates of the surface process tends to have a negative value to the rate built up by tectonic processes in an area. Measurement of deformations that occur due to tectonic processes requires a marker that must be identified before it had been deformed, the so-called geomorphic marker. The best geomorphic marker is a span shape, surface, or known linear trends, and has three characteristics: i) geometry before its deformed, ii) known age, iii) high resistance morphology relative to tectonic process that will be applied. Other things which considered to be acquired are topographic response, sediment flux, isostatic uplift, steady-state and non-steady-state topography.

Based on the topography response theory, every model has different characteristics based on the time, tectonic lift rate (rock uplift), and the result of topographies (Burbank & Anderson, 2011). Garefalakis & Schlunegger (2019) stated a process-responses model that put flux and time as parameters resulting in tectonic flux has rapid erosion rather than sediment flux.

There are three measurements to measure landscape features of tectonic activity in an area they are i) continent to orogenic scale range between 10^7-10^4 km as a result of plate margin, ii) moderate scale range between 10^4-10 km as the result of regional endogenic and exogenic force in term of different time and place, iii) minor scale range between 10-10^{-2} km as a result of tectonic activity such fault and erosion-sedimentation landscape process-response such as fluvial, colluvium, moraine, fjord, and glacier (Enrico & Tomasso, 2010, Whittaker, 2012).

To measure the landscape features quantitatively, we use Geographic Information System (GIS) based study and run by seven geomorphic indices as parameters. They are i) Mountain Front Sinousity (Smf), ii) Drainage Basin: Asymmetry Factor (AF), Transverse Topographic Symmetry (T), iii) Hypsometric Integral (HI), iv) Channel Sinuosity (S), v) Ratio of Valley Floor Width to Valley Height (Vf), vi) Stream Length-Gradient Index (SL), vii) Basin Elongation Ratio (Re). Those parameters are quantitatively applied to seven watersheds in research area using 3rd and 4th river order. Each parameter has been measured to each watershed and evaluate the correlation between watersheds to get the lowest sensitivity data. Total value and the lowest sensitivity data then are classified to each watershed based on tectonic activity and overlain by geological map.

Mountain Front Sinousity (Smf) Index reflects equilibrium between river flow and its valley process resulting mountain front which irregular or sinous. Vertical tectonic activity which is shows dominant straight front (Bull & Fadden, 1997, Elias *et al*., 2019), as formula:

$$Smf = \frac{Lmf}{Ls} \quad (1)$$

Where Smf is mountain front sinuosity index, Lmf is mountain front total length, and Ls is a straight line from mountain front.

Drainage basin asymmetry is showing river flow direction and watershed asymmetrical area. It is divided into Asymmetric Factor (AF), a quantitative cross-section gradient of a watershed as formula:

$$AF = 100\left(\frac{Ar}{At}\right) \quad (2)$$

Where Ar is an area of inclined watershed to main river stream, and At is watershed area. If AF value is greater or less than 50, significantly indicates presence of tectonic activity and uplift (Keller & Pinter, 2002, Khalifa *et al.,* 2018).

The second is Transverse Topographic Symmetry Factor (T-index) Index, as formula (Cox *et al.*, 2001, Radaideh & Mosar, 2019):

$$T = \frac{Da}{Dd} \quad (3)$$

Where Da is distance between outermost border of watershed to main river, and Dd is distance between watershed outermost border to watershed central imaginer line. If T-index value is greater or less than 1, it indicates the presence of tectonic activity and uplift.

Hypsomteric Integral (HI) is used to analyse difference of erosional landform each stage during its evolution (Strahler, 1952, Schumm, 1956, Duan *et al.,* 2022), as formula:

$$HI = \frac{\bar{h} - h_{min}}{h_{max} - h_{min}} \quad (4)$$

Where $\bar{h}$ is mean elevation, and h is elevation. Keller and Pinter (2002) stated HI < 0.3 is old stage, 0.3 ≤ HI ≤ 0.6 is mature stage, and HI > is immature stage of erosion.

Channel Sinuosity (S) is used to identify river stream which affected by landform evolution (Bhatt *et al.,* 2007, Masurkar *et al.,* 2019), as formula:

$$S = \frac{SL}{VL} \quad (5)$$

Where SL is river length, and VL is codirection valley length. S value is 1 when it has straight river stream, 1.0 < S < 1.5 is bended river, and S ≥ 1.5 is meandering river.

Ratio of Valley Floor Width to Valley Height (Vf) is measurement between V-shape valley cause of uplift and tectonic activity, and U-shape span floodplain valley with lateral erosion indicate tectonic stability and low activity (Clubb *et al.*, 2022), as formula:

$$Vf = \frac{2V_{fw}}{[(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})]} \quad (6)$$

Where V_{fw} is width of valley floor, E_{sc} is elevation of valley floor, E_{ld} and E_{rd} are elevation of left side and right side of valley. Vf ≤ 0.2 is categorized as high fault activity and Vf > 0.2 is categorized as less fault activity.

Stream Length-Gradient (SL) Index proposed by Hack (1973) is change of river stream sensitivity. It is great correlated between tectonic activity, lithology resistant, topography, and river stream, as formula:

$$SL = \frac{\Delta H}{\Delta L} \cdot L \quad (7)$$

Where (ΔH/ΔL) is river gradient at specific interval, ΔH is elevation interval, and ΔL is distance interval, and L is river stream total length from the specific point (Doranti-Tiritan *et al.,* 2014).

Basin Elongation Ratio (Re) is gradient difference of the watershed. It is classified based on elongation ratio (Pareta & Pareta, 2011). Elongation variation is tightly correlate to fault activity on the watershed, mainly thrust (Pareta & Pareta, 2011), as formula:

$$Re = \frac{\left(2\sqrt{\frac{A}{\pi}}\right)}{L} \quad (8)$$

Where A is an area of watershed and L is the longest side of watershed's length. Re is classified into circular at 0.9-1.0, oval at 0.8-0.9, less elongated at 0.7-0.8, and elongated at < 0.7.

Along with the geomorphic indices, we use regional focal mechanism data to support regional tectonic synthesis at the suture zone between Banggai-Sula Microcontinent and East Sulawesi Ophiolite.

Data Measurement *Tim Pusat Studi Gempa Nasional* (2017) stated Batui Thrust is one of active fault which lies in the East Arm ofSulawesi with 2 mm per year slip rate and maximum 7.3Mw earthquake. The fault has maximum segment of 84 kilometer, and meets another active fault right lateral strike slip fault of the Balantak in the east of Poh Head.

Multiple analysis of sub-watershed in the detailed mapping area. Lobu is the main watershed which has 4th as the highest order river. To the east, located smaller Pakowa watershed. Both of them have downstream to the north plunging into Tomini Bay. The Lobu Watershed can be divided into six different sub-Watersheds, in order to get more detail effect from the fault which tear along the shape (Figure. 2). We also generate the slope map of watershed to comprehend slope rising in percent and orientation of river streams and regional lineaments.

West region of elongated Lobu Watershed has 15 to more than 140 percent slope, is mainly composed by ultramafic rocks, including serpentinite, peridotite, and small amount of basalt and gabbro. Special in the small north area is also constructed by ultramafic rock mainly serpentinite. The Batui Thrust is turning from NE-SW to W-E orientation come up with right lateral strike-slip fault in the north. East region generally has lower slope rise ranging from 0-2 per cent to narrow area of 70 – 140 per cent indicates presence of Pasini Thrust. This region is mainly composed by limestone and moderate amounts of clastic sedimentary rocks at the tip of microcontinent.

Longitudinal profile of Lobu, Senseiyan, Hako, and Luwaan River within Lobu Watershed is shown on (Figure 3). The profiles aim to indicate the Batui Thrust which intersected by them. Only Hako longitudinal profile has knickpoint showing the existence of Batui Thrust. Senseiyan and Luwaan profile are not showing the knickpoint, showing that the thrust is confirmed being segmented. Right lateral strike slip fault is present at the end of Senseiyan River, within one kilometre before stream joins higher order Lobu River. While the downstream of Luwaan River is bisected by left lateral strike slip fault. Both proven on the field as lithological offset during fieldwork between serpentinite and sandstone-limestone.

The presence of Batui Thrust is also confirmed from transect elevation which had been confirmed during fieldwork. The Thrust is located range between 400 to 500 meter to the east of Lobu River, not at the river indicated by ridge appearing. In the southern to middle north area, the Batui thrust is parallel to Lobu River. In the north where the Lobu River is curved to the north, the thrust mantains its orientation of NE-SW and shows the thrusting indicators (Figure 4).

Morphometry analysis is applied to Lobu, Pakowa and Lambangan Watershed which have different river stream at the highest order. Then Lobu is divided into six smaller regions as sub-watershed. All of morphometry data is plotted as box plot diagram with defined threshold value based on classification reference (Figure 5).

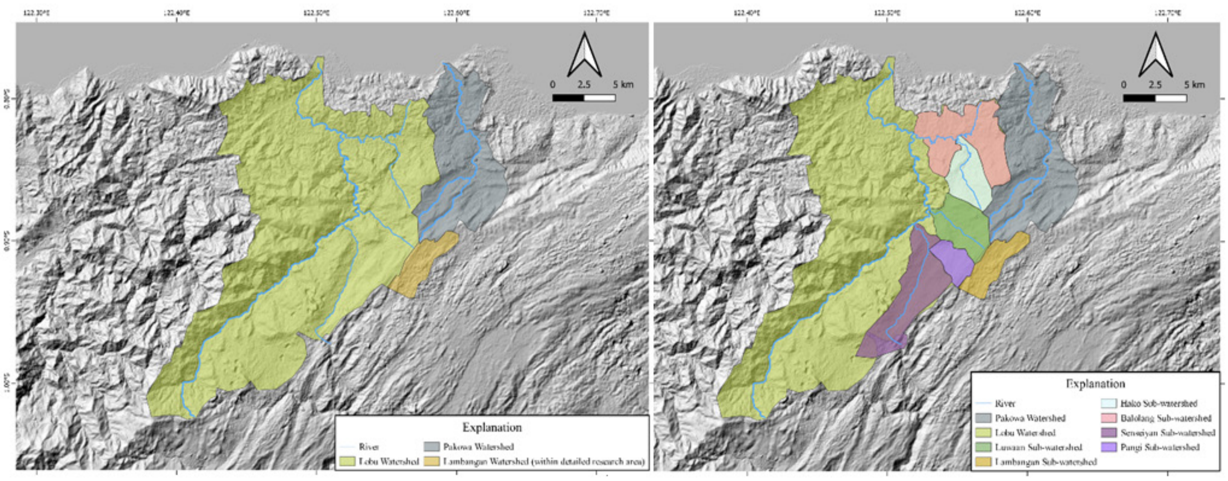

Figure 2. Watershed division of research area. Eight sub-watersheds are Lo = Lobu, Se = Senseiyan, Pan = Pangi, La = Lambangan, Lu = Luwaan, Pak = Pakowa, Ha = Hako, Ba = Balolang. Except Pakowa and Lambangan Sub-watershed, rest of them are constructing Lobu Watershed and its streams empty to Lobu main river.

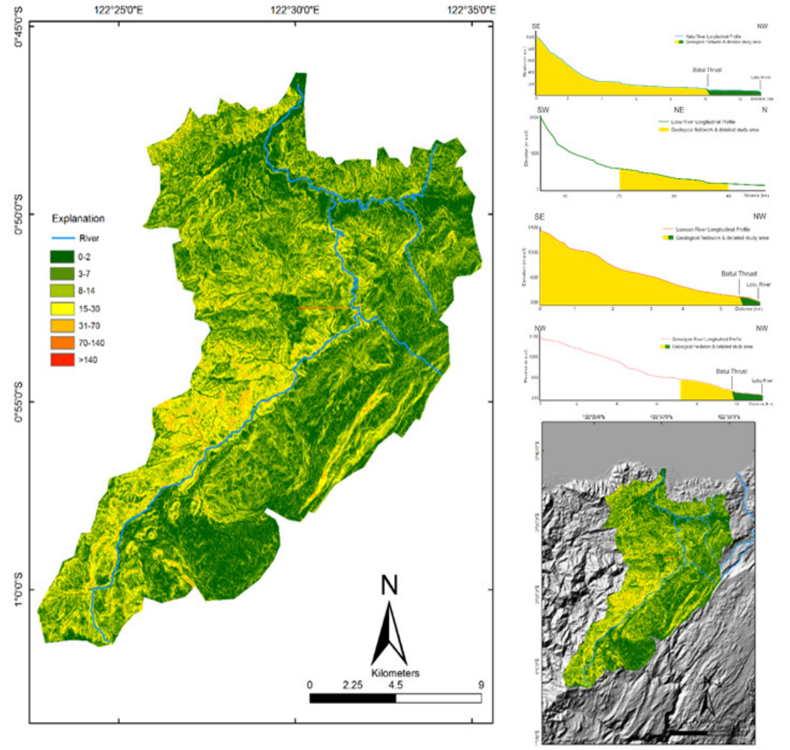

Figure 3. Slope map of Lobu Watershed, including Senseiyan, Hako, Luwaan River longitudinal profile (above). Cross-sections which transect East Sulawesi Ophiolite and Banggai Sula Micrcontinent are showing Batui Thrust escarpment.

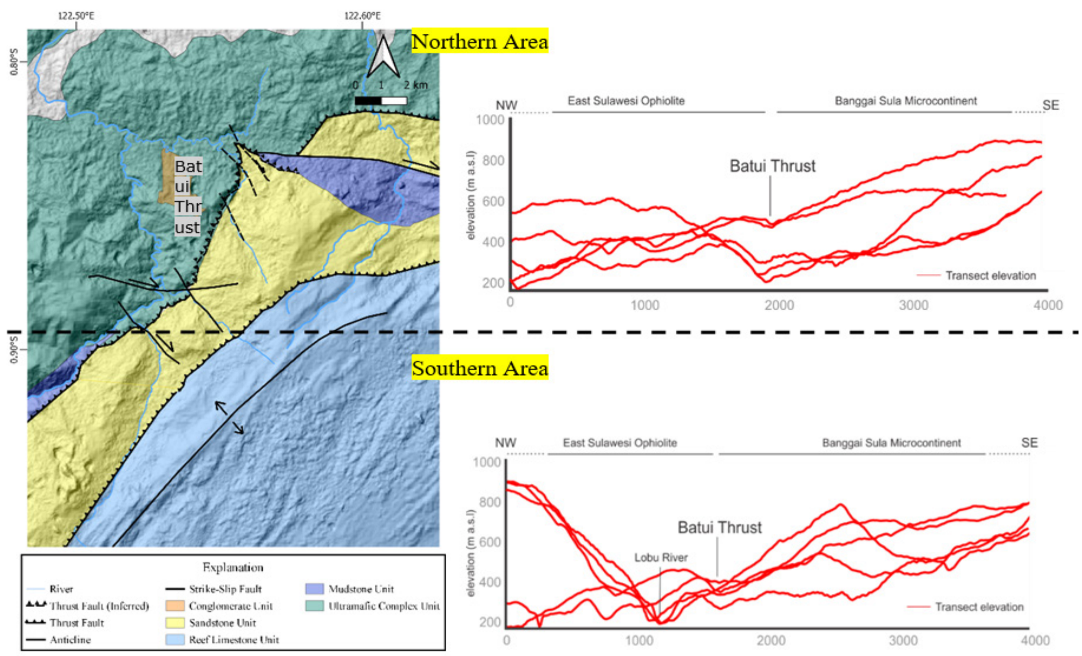

Figure 4. Knickpoints indicate presence of Batui Thrust next to Lobu River in the northern and southern areas. The profile is generated from DEMNAS 30 (2019) with 12.5 meter vertical resolution.

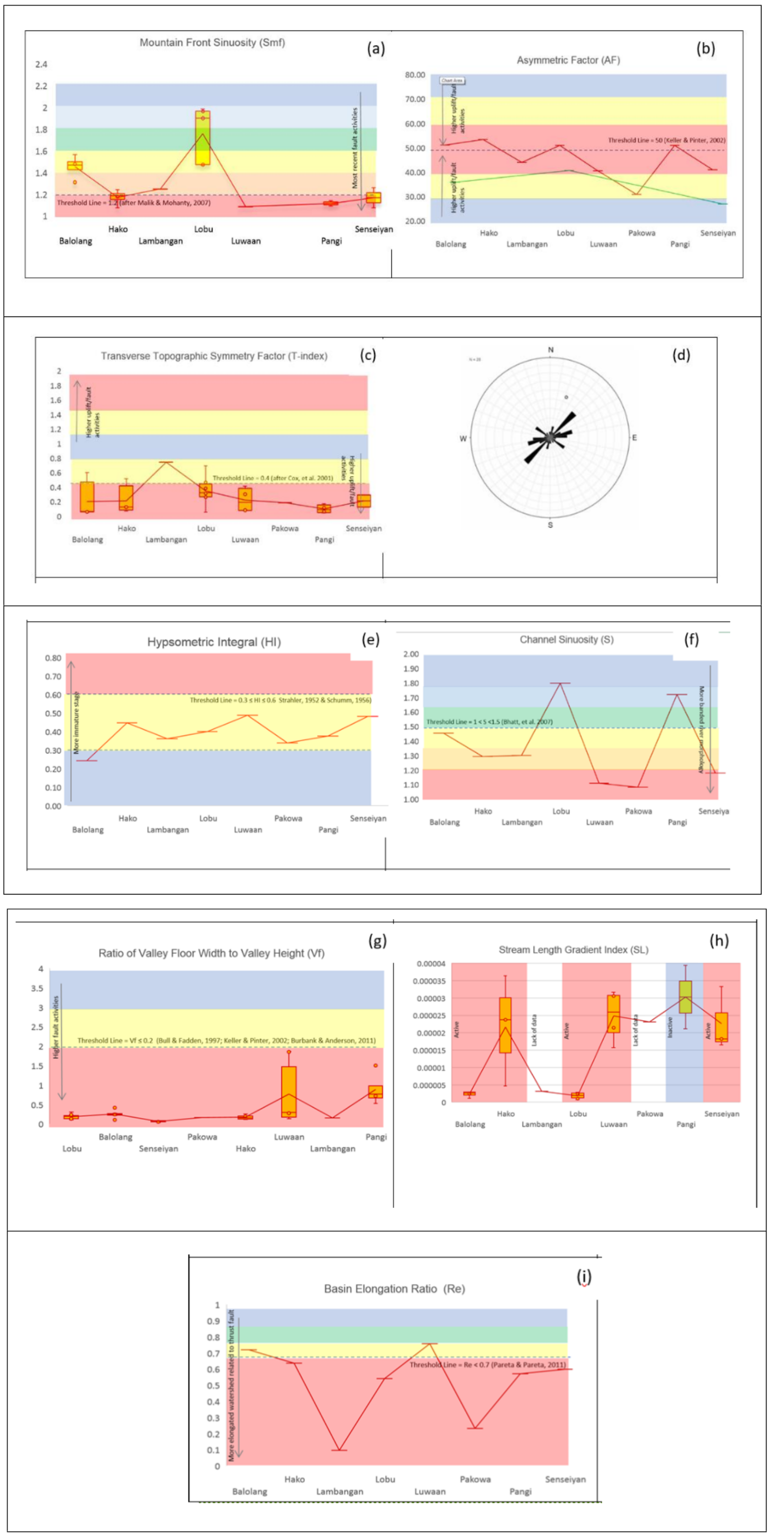

Figure 5. Summary of quantitative analysis based on morphometry indices. From the top left (a) Smf-index result which values close to 1.00 are highly considered to recent fault activities, (b) AF-index result which alues far from 50 are highly considered to recent fault and/or tectonic activities, (c) T-index result shows only Lambangan watershed has relatively equal tectonic activity, (d) The T-index rose diagram is showing relative shifting of the main river to mid-line watershed, (e) HI-index result, most of them are considered as rapid to moderate uplift relative to the erosion rate, (f) S-index result shows the most of watersheds are affected by mature morphology, but the values close to one interpreted as fault-related morphology, (g) Vf-Index result, all of the watershed is grouped which have high fault activity, (h) SL-index shows that the Balolang, Hako, Lobu, Luwaan, and Sensiyan considered to have active fault. The value is equal to channel steepness index which correlates to the thrusts, (i) Re-index result, the Lambangan and Pakowa are classified to oval and others are moderately oval to circle.

The Smf is analysed to all watersheds but Pakowa because unavailability mountain front measurement. Value classification based on Malik & Mohanty (2007) resulting Senseiyan, Hako, Luwaan, Lambangan, and Pangi have high tectonic activity. It is caused by less Smf value which interpret recent tectonic activity and no significant erosion rate close to 1.00. The threshold line at 1.20 is minimum value which can be considered has the most recent fault activity. Thus, the fault movement was relatively young and active. Balolang and Lobu have moderate tectonic activity based on 1.5 and 1.7 averaged value and interval respectively. However, it can be adjusted to high tectonic activity because the sinuosity on the mountain front is extremely affected by wrench fault which lie and across ultramafic rocks. Least, Pakowa Watershed cannot be measured due to unclear hill border as a mountain front.

Calculation of AF and T-index from show watersheds which had been tilted and shifted from normal position. Rose diagram on (Figure. 5 (d)) shows that main river streams are drifting relative to midline watershed (Zhang *et al.,* 2019). Curve pattern of AF and T-index explain Lobu, Senseiyan, Hako, Luwaan, and Lambangan are tilted watersheds.

The HI analysis calculation based on Beg (2020) categorizes Hako, Lambangan, Lobu, Luwaan, Pakowa, Pangi, and Senseiyan have active tectonic activity. Otherwise, Balolang is classified into inactive and old erosion stage. Generally, HI calculation of the research area has active tectonic activity

Analysis and calculation of S based on Bhatt *et al.,* (2007) and Barman & Goswami (2015) indicates Luwaan, Pakowa, Senseiyan have high fault activity and associate with severe faults parallel and across watersheds. Moderate fault activity presence on Balolang, Hako, and Lambangan interpret either lesser number of fault or no fault across main river. But S-shape of the Balolang river created by faults along river. Less active fault is located on Lobu and Pangi. Especially the Lobu faults along main river create bended-shape and river knickpoint above ultramafic unit

Analysis and calculation of Vf based on Gupta *et al.,* (2022) are resulting Hako, Lambangan, Pakowa, Senseiyan have high fault activity. These watersheds associated with uplift which occur on the side of main river. In the other hand, Balolang, Lobu, Luwaan, and Pangi have moderate to less fault activity.

Calculation of SL based on Jaiswara *et al.,* (2020) is resulting anomaly value for each watershed dataset that indicates different lithologies, massive erosion or fault presence at location. The yellow on the table is anomaly value in a dataset. These anomalies within each dataset indicate presence of either thrust or normal fault. It is critical points to confirm the NE-SW Batui Thrust and Pasini Thrust are active faults.

The Re calculation based on relief classification (Sukristiyanti *et al.,* 2018) shows that high fault activity is Lambangan and Pakowa which controlled by fold structure. The moderate fault activity is Hako, Lobu, Pangi, and Senseiyan which controlled by fault activity. And the inactive fault activity is Balolang and Luwaan.

After seven morphometric indices are applied to eight sub-watersheds, the tectonic geomorphology indices value in the research areas are: Mountain Front Sinuosity (Smf) 1.09-1.76; Drainage Basin Asymmetry as Asymmetry Factor (AF) 26.81-53.33 and Transverse topographic symmetry factor (T-index) 0.10 - 0.77; Hypsometric Integral (HI) 0.24 -0.49; Channel Sinuosity (S) 1.08-1.80; The Ratio of Valley Floor Width to Valley Height (Vf) 0.06 - 0.89; Stream Length-Gradient Index (SL) 187.57 - 3027.10; Basin Elongation Ratio (Re) 0.10 - 0.76.

DISCUSSION

After conducting fieldworks for weeks and analyzing samples, the Pagimana and adjacent area can be is divided into four geomorphological units named i) Lobu-Balolang Fault Zone Ridge, ii) Hoho Karst Mountains, iii) Homoclinic Kolobias Ridge, and iv) Dolom Aluvial Plain. Stratigraphy of research area divided into six unofficial units, namely Ultramafic Complex, Mudstone, Reef Limestone, Sandstone, Conglomerate, and Alluvium Units. Geological structures of Pagimana are the Batui Thrust, Pasini Thrust, and the Lambangan Anticline with similarly NE-SW direction and Balolang Normal Fault with NW-SE direction (Hikmy, 2019).

As a result, update is applied to the geological regional map from Geological Research and Development Centre published in 1993. Hikmy (2019) generated from this fieldwork, a detailed location and tectonic contact between the ESO and Banggai Sula Microcontinent as a thrust. The Batui Thrust is confirming border between them, with fault plane is dipping to the ultramafic rocks. In Boimbin River located at the curve of regional thrust, a huge 12 meters throw and 3 meters heave separates between sandstone unit the Poh

Formation which derived from the microcontinent and serpentinite unit of ophiolite complex which come from oceanic crust of Sulawesi. Whilst in Senseiyan River, the thrust was observed dividing marl intercalation of Poh Formation and serpentinite. Fault kinematics were running 400m away from the fault which observed in Senseiyan River. There are slickensides, fault breccias and shear fractures data resulting Left Thrust Slip Fault (Rickard, 1972) with attitude of fault plane N256°E/58° NW, net slip 53°, N19°E, and pitch 71°.

About 2.7 km to the southeastern of the Batui Thrust, the Pasini Thrust is present, given obvious different morphology between the hanging and footwall. The vertical throw is up from 10 to 25 meters high and lie up to 300 m. The ridges are dissected with NNE-SSW orientation, and recover after 2.5 km away along the orientation.

Sandstone unit comprises lithic wacke, marl, packstone, wackestone, and grainstone intercalation is considered as the Poh Formation. Based on the biostratigraphy analysis, the unit was deposited during Middle Miocene to Late Miocene in the fore-reef environment. The unit is conformably overlying the Limestone Unit of Salodik Formation. These clastic outcrops have average dip value of 41° and N315 ° E dip direction.

The limestone unit is considered as Salodik Formation. Comprising packestone, wackestone, rudstone, grainstone, and minor marl intercalation. Based on the petrography analysis, shown larger foraminifera as follows *Discocyclina sp., Miogypsina sp., Miogypsinoides sp., Heterostegina sp.* and *Assilina sp*. which determine not later than Middle Miocene age. In this fieldwork, the highest elevation of Salodik Formation reached up to 1469 m asl. However, Prabawa *et al.,* (2020) said based on facies, reef system, and diagenetic environment distribution, a paleogeographic model were interpreted in every age from Middle Eocene to Early Pliocene. The Early Pliocene of the group is upper Salodik Group, known as Minahaki Formation.

Close to neck of the Poh Head, we found a massif conglomerate outcrop comprises cobble conglomerate polymict within the Kintom Formation at 512 m asl. The cobble fragment is pegmatite with 3-4 cm crystal size as phenocrsyt. This unit is unconformably underlain Poh Formation and Ultramafic Rock, probably deposited in Pliocene (Simandjuntak *et al.,* 1993) shown by Figure 6.

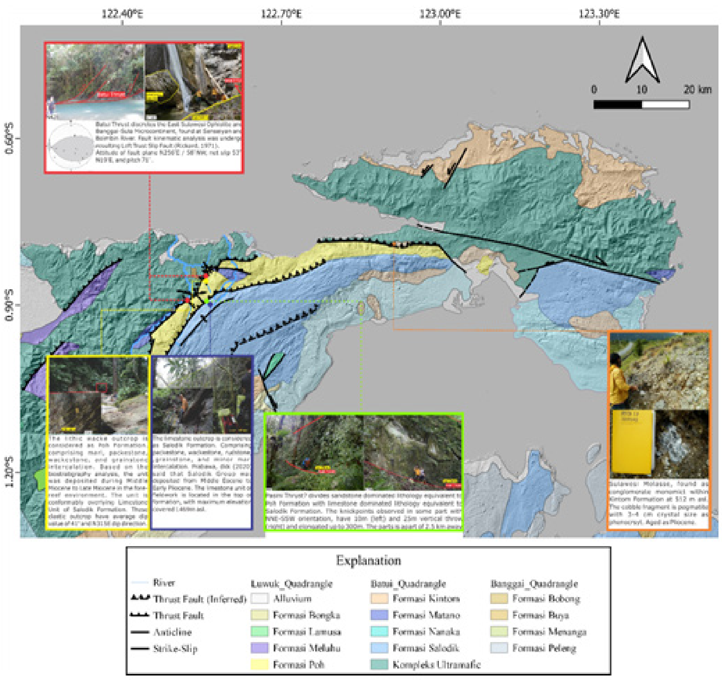

Figure 6. Photo montage during fieldwork. This regional geological map (Rusmana *et al,* 1993) is slightly updated after fieldwork. Fault kinematic of the Batui Thrust is shown on the top corner of the map, while highest elevation from the fieldwork is Salodik Formation in the body of the arm. The Celebes or Sulawesi Molasse was found as conglomerate in cobble size and pegmatite fragment.

The summary of average value for each morphometry parameter and calculation shows the influence of faults on each watershed (Table. 1). Thus, the research area can be divided into three classes of tectonic activities, there are Most Active Tectonics, Moderate Active Tectonics, and Less Active Tectonics. Most of area are considered as most active tectonics which correlate to recent fault activities, specifically the Batui Thrust which overlay Hako, Lambangan, Luwaan, and Senseiyan Sub-Watersheds whilst Pakowa is influenced by the presence of the Pasini Thrust. Lobu watershed has moderate active tectonic due to no field data suggests the presence of the Batui Thrust in the detailed study area. However, it strongly shapes the southern area off from fieldwork confirmed by GIS-based data. Most of the sub-watershed also empty to the Lobu River as main watershed, and should be influenced the final score of watershed. Anomalies value of SL index on the disperse sample map and AF & T-index value on the drainage basin pattern map are directly connected to fault structure in the research area which considered as the Batui Thrust, Pasini Thrust, and Lambangan Anticline. Only Pangi sub-watershed is having lesser active tectonics, it correlates to the position of the Pasini Thrust that only affect the northwestern area and changed small portion of sub-watershed. The tectonics activities of each sub-watersheds can be seen on Table 2.

Hence, the final tectonic activity map rush on the research area is generated and confirms that the Batui Thrust is an active fault. High activity of the southeastern area comprising the Pasini Thrust and Lambangan Anticline also might be activated by the Batui Thrust Belt (Figure 7).

Another supporting data is the earthquakes within 100 km radius from detailed geological study happened 362 times since 1975 to 2021. The biggest magnitude is 7.4Mw in Tomini Bay with hypocenter 242.3 km depth, off coast of Sulawesi on 6th August, 1984. As near as 1.2 km is the nearest earthquake from Batui Thrust to the northwest was happened on 25th July, 1998 with magnitude 4.4Mw and 33.0 km depth categorized as medium earthquake. This earthquake is considerably causing the movement of Batui Thrust. And 4.9Mw earthquake hit 3 km southeast the Pasini Thrust with 66.5 depth on 11th November, 1983 (Figure. 8).

For tectonic uplifts and regional syntesis, a regional 2D seismic line was published by Wahyudiyono (2017) after joint study between Indonesia Ministry of Energi and Mineral Resources and oil & gas company in Banggai Basin. The line recorded off southern coast of Morowali. The Batui Thrust Belt comprises series of thrust within ultramafic rocks, and partially made thrust of sedimentary rocks during collision during Late Pliocene. The ultramafic rocks, is a member of ophiolite series, being made in the oceanic crust of East Arm of Sulawesi during Cretaceous age. To the east, also in Cretaceous age deposited crystalline limestone of the Matano Formation in the deepwater depositional environment. These rock units then collided and mixed, became Pre-Tertiary basement of western Banggai Basin (Figure. 9). The structures are evidence of compression regime which conducting convergent with W-E direction between the Banggai-Sula microcontinent and East Sulawesi Ophiolite.

Table 1. Morphometric measurements on each watersheds and sub-watersheds

	Morphometrics parameter								
Watershed & Sub-watershed	Major rock type based on fieldwork	Mountain Front Sinuosity (Smf)	Asymmetric Factor (AF)	Transverse Topographic Symmetry Factor (T-index)	Hypsometric Integral (HI)	Channel Sinuosity (S)	Valley floor width to valley height (Vf)	Stream Length-Gradient Index (SL)	Basin Elongation Ratio (Re)
Balolang	Serpentinite, Gabbro	1.45	35.70	0.07	0.24	1.45	0.25	1.10E-06	0.72
Hako	Serpentinite, Sandstone	1.17	53.33	0.13	0.45	1.29	0.17	4.69E-06	0.64
Lambangan	Limestone	1.25	43.96	0.74	0.36	1.30	0.15	N/A	0.10
Lobu	Serpentinite, Peridotite	1.76	40.65	0.35	0.40	1.80	0.19	7.18E-07	0.54
Luwaan	Sandstone, Limestone	1.09	40.50	0.30	0.49	1.11	1.87	1.57E-05	0.76
Pakowa	Sandstone, Serpentinite	N/A	30.83	0.19	0.34	1.08	0.48	N/A	0.23
Pangi	Limestone	1.14	50.93	0.12	0.38	1.72	0.89	3.95E-05	0.57
Senseiyan	Limestone, Sandstone	1.17	26.81	0.29	0.48	1.18	0.07	3.33E-05	0.60

Table 2. Final score of tectonic activity after weighing using geomorphic indices value.

	Morphometrics parameter								
Water-shed and Sub-wa-tershed	Mountain Front Sinousity (Smf)	Drainage Basin Asymme-try (AF)	Transverse Topographic Asymmetry Factor (T)	Hypso-metric Integral (HI)	Channel Sinousity (S)	The ratio of valley floor width to valey height (Vf)	Stream length-gra-dient index (SL)	Basin elon-gation ratio (Re)	Tectonic Activ-ities
Balolang	Moderate Fronts	Tilting	Normal	Less Active	Active	Moderate	Active	Moderate	Moderate Active Tectonics
Hako	Most Active Fronts	Tilting	Tilting	Active	Active	Most Active	Active	Moderate	Most Active Tectonics
Lamban-gan	Most Active Fronts	Tilting	Tilting	Active	Active	Most Active	N/A	Most Active	Most Active Tectonics
Lobu	Moderate Fronts	Tilting	Tilting	Active	Less Active	Moderate	Active	Moderate	Moderate Active Tectonics
Luwaan	Most Active Fronts	Tilting	Tilting	Active	Most Active	Moderate	Active	Less Active	Most Active Tectonics
Pakowa	N/A	Tilting	Normal	Active	Most Active	Most Active	N/A	Most Active	Most Active Tectonics
Pangi	Most Active Fronts	Normal	Normal	Active	Less Active	Moderate	Inactive	Moderate	Less Active Tectonics
Senseiyan	Most Active Fronts	Tilting	Tilting	Active	Most Active	Most Active	Active	Moderate	Most Active Tectonics

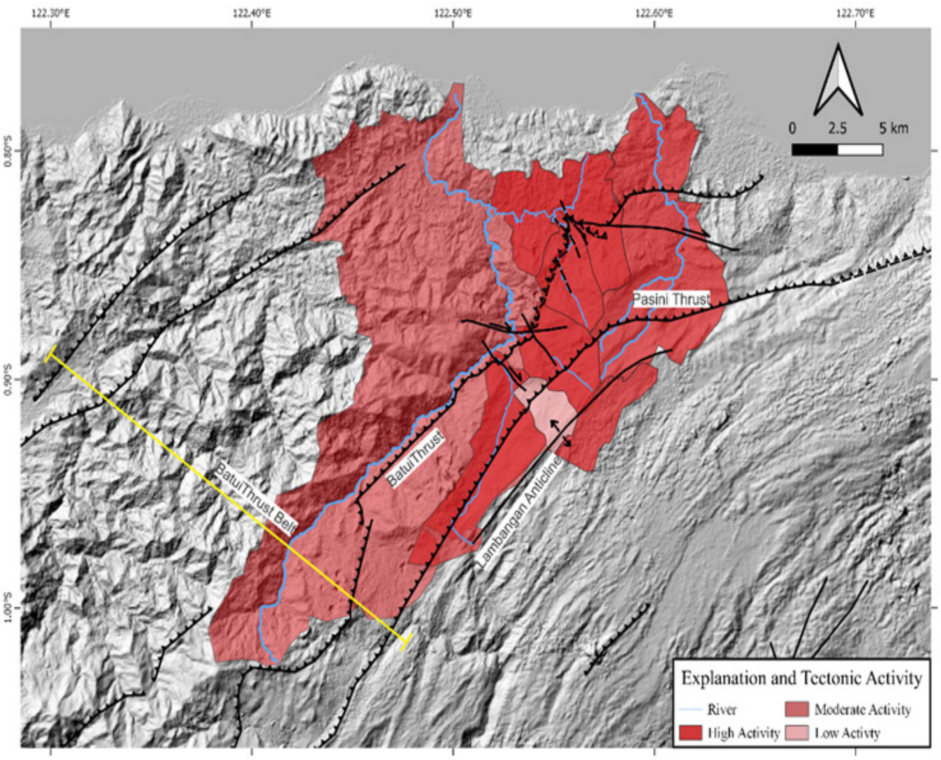

Figure 7. Tectonic activity research area after adjusting the watersheds connection and weighing from presence matrix. It shows tectonic activity is mostly active related to the last activity of the Batui and Pasini Thrust.

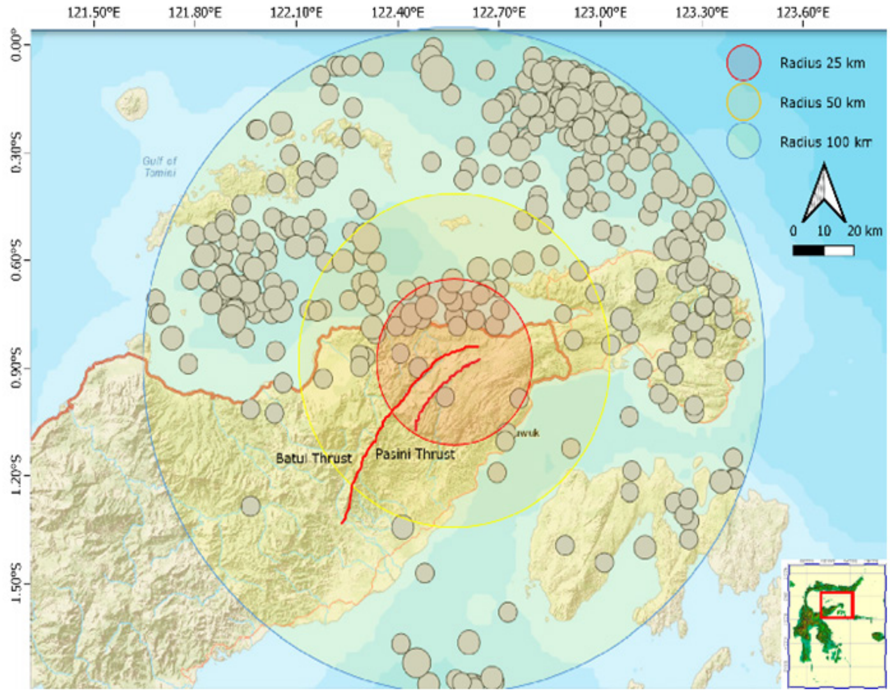

Figure 8. Earthquake catalog of East Arm of Sulawesi since 1975 to 2021 with magnitude more than 2.5Mw (earthquake.usgs.gov, accessed on September 24, 2021). Radius 25 km from detailed study is indicated by red circle line, 50 km yellow line, and blue line for 100 km radius. The red line is Batui Thrust and Pasini Thrust.

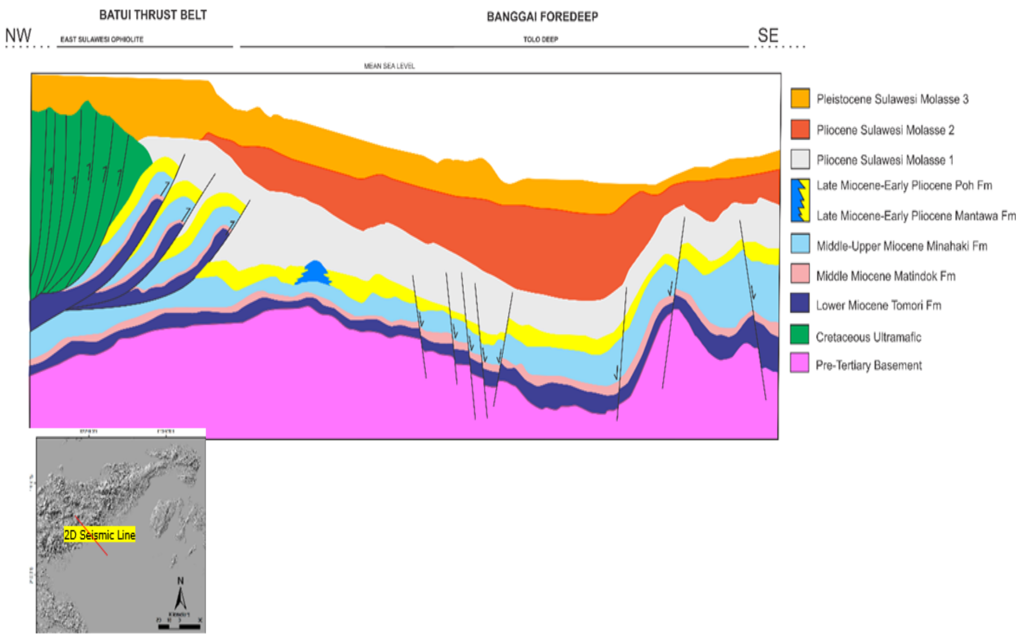

Figure 9. Modified regional cross section from seismic line (Hartanto, 2019) offshore of southern coast of the arm. It shows thrust belt known as Batui Thrust at the border between East Sulawesi Ophiolite and Banggai-Sula Microcontinent

During Middle Eocene to Middle Miocene, the reefal limestone of Salodik Group was deposited reefal limestone of Salodik which unconformably overlying the basement. The reefal limestone constructs the Tomori Formation, as the oldest and lower part of Salodik Group. The group is consisted of wide and thick carbonate platform from back-reef, reef crest and fore-reef. Later, Middle Miocene of Matindok Formation was deposited bringing up clastic and coal bearing formation. The top Salodik Group is referred to the Minahaki Formation consisting of carbonate platform with approximately 270 meters thickness having an age of Middle to Upper Miocene (Wahyudiyono, 2017). A reefal build up was emerged in Upper Miocene to Pliocene of the Mantawa Member up to 200 meters (Wahyudiyono, 2017), which interfingering with the calcareous sedimentary clastic of the Poh Formation.

The upper part of Salodik Group is equal to the Minahaki Formation, and spotted carbonate build up Mantawa Member having an age of Pliocene. However, there is no clear publication about detailed least age of the Salodik Group, so this paper assumes Late Pliocene 3.6 Ma is the age of the youngest group. Based on geological fieldwork in the southern mountainous Pagimana region, the highest Salodik Group is located at 1469 m above sea level. The outcrop is right at the contact between the clastic dominated sedimentary Poh Formation and the upper part of Salodik Group. The reef limestone and carbonate build up environment are well developed in shallow marine water, from maximum 30 meter below sea level to mean sea level (Pomar & Kendall, 2008). So the normal uplift rate of East Sulawesi Ophiolite from the view of youngest Salodik Formation is formulated as fraction of maximum elevation and the age resulting 0.408 ± 0.008 mm uplift per year.

After the diagenesis of Salodik and Poh Formation, these different lithotectonics collided in Late Pliocene, forming rigorous suture zone East Arm of Sulawesi. During this quick period, when the ultramafic rocks and Tertiary sedimentary rock uplifted through sea level, Celebes Molasse consisting of conglomerate, conglomeratic sandstone and marl was deposited during Late Pliocene. So far, there is no publication which dated the molasse, so this paper assumes the uppermost border 2.4 Ma is the age of the youngest molasse. In this fieldwork, polymict conglomerate was found consisting cobble-size-dominated pegmatite fragment equivalent to the Kintom Formation at 512 m above sea level near the Poh Head in the east. The molasses was deposited in a marine environment from an outer sublittoral to upper bathyal as channel pattern (Kurniawan *et al.,* 2018) which converted to 20-250 m below sea level (Kingsford, 2010). Sayre *et al.*(2017) stated that bathyal is a zone that rely on 200 to 2000 m below sea level, even there is no guidance to classify border of upper bathyal. Sea level is used as pessimistic datum to measure the normal rate of uplift to this view. As a fraction between elevation and time, the uplift of the east Arm of Sulawesi is 0.213 ± 0.046 mm per year.

The normal uplift rate of the region is getting higher to the west, before the Pompangeo Schist Complex in the Central of Sulawesi. The elevation of Celebes Molasse reach up to 2000 m asl of the Bongka Formation based on Geological Research and Development Center of the Batui Quadrangle.

CONCLUSION

Analysis of tectonic geomorphology using morphometric analysis in the mountainous Luwuk area indicates that Batui Thrust, Pasini Thrust, and Balolang Fault Zone are active faults overlying the region. These thrusts and fault zone are products of the Batui Thrust Belt covers East Arm of Sulawesi based on existing seismic line of regional cross section in the southwestern part of the area. The Batui Thrust is an active fault stands as a border between the East Sulawesi Ophiolite and the Banggai-Sula microcontinent and segmented with wrench faults. Number of thrust faults parallel to the Batui Thrust generate Batui Thrust Belt which propagates from the ultramafic rocks of East Sulawesi Ophiolite to the sedimentary rocks of Banggai-Sula Microcontinent within the suture zone. Earthquake clusters located far from the active faults are indicating docking phenomena between the East Sulawesi Ophiolite and the Banggai-Sula microcontinent while numbers of earthquakes at the fault lines support the movement of faults. The results of morphometric analysis shows that the most active tectonics occupy the area traversed by the Batui Thrust and Pasini Thrust with having a NE-SW direction and the Lobu Balolang Fault Zone. As a result, the presence of active faults are uplifting the Arm of Sulawesi with rate of uplift 0.408 ± 0.008 mm per year and 0.213 ± 0.046 mm per year which is getting higher to the west considered from present elevation polymict conglomerate deposits of Celebes Molasse.

ACKNOWLEDGMENT

The authors thank to Geodynamics Research

Group of ITB for funding the fieldwork; to Ferdi Endinanda and Guntur Ghiffari as well for discussions and their assistance within the heavy rainforest of Sulawesi. The authors responsibilities were as follows- IGH and AR wrote the manuscript; BS and IG advised the content on the pre-manuscript as a thesis; BSP added field data. The authors also express a gratitude for the reviewers and editors who gave constructive comments and well-prepared editing to publish the article.

REFERENCES

Baillie, P., and Decker, J., 2022, Enigmatic Sulawesi: The Tectonic Collage, Berita Sedimentologi, 2022 V. 48(1), DOI: 10.51835/bsed.2022.48.1.388.

Barman, P., and Goswami, D. C. 2015. Evaluation of Sinuosity Index of Dhansiri (South) River Channel and Bank Erosion, *Assam in GIS. IARJSET. 2. 111-114.* 10.17148/IARJSET.2015.2523.

Beg, A. A. F. 2020. Spatial analysis of the geomorphic evolution of Tigris River basin using developed ArcGIS-Morphometric toolbox. IOP Conf. Series: Materials Science and Engineering 737 (2020) 012235. *doi:10.1088/1757-899X/737/1/012235*

Bhatt, C.M., Chopra, R., and Sharma, P.K. 2007. Morphotectonic analysis in Anandpur Sahib area, Punjab (India) using remote sensing and GIS approach. *Journal of the Indian Society of Remote Sensing 35*(2), p.129-139.

Bull, W.B., and McFadden, L.D. 1977. Tectonic geomorphology north and south of the Garlock fault, California. *Geomorphology in arid regions,* p. 115–138.

Burbank, D.W., and Anderson, R.S. 2011. *Tectonic Geomorphology, 2nd edition*. Willey-Blackwell Publishing: UK.

Clubb, F. J., Weir, E. F., Mudd, S. M. 2022. Continuous measurements of valley floor width in mountainous landscapes. *Earth Surface Dynamics, Volume 10, Issue 3, 2022, pp.437-456.* https://doi.org/10.5194/esurf-10-437-2022.

Cox, R.T. 1994. Analysis of drainage basin symmetry as a rapid technique to identify areas of possible Quaternary tilt block tectonics: an example from the Mississippi Embayment. *Geological Society American Bulletin*, 106, 571-581.

DEMNAS 30. 2019. *DEMNAS*. http://tides.big.go.id/DEMNAS/. Diakses pada 17 Januari 2019.

Doranti-Tiritan, C., Hackspacher, P. C., de Souza, D. H., and Siqueira-Ribeiro, M.C. 2014. The Use of the Stream Length-Gradient Index in Morphotectonic Analysis of Drainage Basins in Poços de Caldas Plateau, SE Brazil. . International Journal of Geosciences, 5, 1383-1394. http://dx.doi.org/10.4236/ijg.2014.511112

Duan, Y., Pei, X., and Zhang, X. 2022. The Hypsometric Integral Based on Digital Elevation Model for the Area West of Lvliang Mountains in Loess Plateau, Shanxi, China. Front. Earth Sci., Sec. Geohazards and Georisks Vol. 10 https://doi.org/10.3389/feart.2022.827836

Elias, Z., Sissakian, V.K. and Al-Ansari, N. 2019 Assessment of the Tectonic Activity in Northwestern Part of the Zagros Mountains, Northeastern Iraq by Using Geomorphic Indices. Geotech Geol Eng 37, 3995–4007. https://doi.org/10.1007/s10706-019-00888-z

Enrico, M., and Tommaso, P. 2010. Two tectonic geomorphology studies on the landscape and drainage network of chain and piedmont areas of the Abruzzi Region Central Apennines, Italy. *New Frontiers in Tectonic Research - At the Midst of Plate Convergence.* doi: 10.5772/18969.

Garefalakis, P. and Schlunegger, F. 2019. Tectonic processes, variations in sediment flux, and eustaticsea level recorded by the 20 Myr old Burdigalian transgressionin the Swiss Molasse basin. Solid Earth, 10, 2045–2072. https://doi.org/10.5194/se-10-2045-2019.

Gupta, M., Devadas, D., Sahni, C., Nayak, A., Tiwari, P.K., and Mishra, A. Morphometric Analysis of the Proximal Femur With Its Clinical Correlation in Eastern Uttar Pradesh Region. *Cureus. 2022 Sep 4;14(9):e28780. doi: 10.7759/cureus.28780.*

Hack, J.T. 1973. Stream profile analysis and stream-gradient index. *Journal of Research of the U.S. Geoloogical Survey*, vol 1, 4, p.421-429.

Hall, R. and Wilson, M.E.J. 2000. Neogene sutures in eastern Indonesia. *Journal of Asian Earth Sciences, 18,* 781–808.

Hartanto, S. 2019. *Pengaruh Eksplorasi Migas di Cekungan Banggai Terhadap Area Perbatasan KRI.* Jakarta: Kementerian Energi dan Sumberdaya Mineral.

Hikmy, I.G., 2019. *Pemetaan Geologi dan Analisis Geomorfologi Tektonik Menggunakan Pendekatan Morfometri Daerah Pagimana dan Sekitarnya, Kabupaten Banggai, Sulawesi Tengah.* Tugas Akhir A. Bandung: Institut Teknologi Bandung (*unpublished*).

Jaiswara, N. K., Kotluri, S. K., Pandey, P., and Pandey, A.K. 2020. MATLAB functions for extracting hypsometry, stream-length gradient index, steepness index, chi gradient of channel and swath profiles from digital elevation model (DEM) and other spatial data for landscape characterisation. *Applied Computing and Geosciences, Volume 7, 2020, 100033.* https://doi.org/10.1016/j.acags.2020.100033

Keller, E.A., and Pinter, N. 2002. *Active Tectonics: Earthquakes, Uplift, and Landscape, 2nd edition.* Prentice Hall: Upper Saddle River.

Khalifa, A., Çakir, Z., Owen, L.A., and Kaya, Ş., 2019. Evaluation of the Relative Tectonic Activity of the Adıyaman fault within the Arabian-Anatolian plate boundary (eastern Turkey). *Geologica Acta, 17.6, 1-17*. DOI: 10.1344/GeologicaActa2019.17.6

Kingsford, M. J. 2010. *"Marine ecosystem". Encyclopedia Britannica.* https://www.britannica.com/science/marine-ecosystem. Accessed 25 September 2021.

Kurniawan, A.P., Adi, G.P., Sundari, W.T., Arifin, M., Panguriseng, M.J., Hartanto, S. and Herawati, N. 2018. Pliocene Deep Water Channel System of Celebes Molasse as New Exploration Play In Banggai Sula Foreland Basin, Eastern Sulawesi-Indonesia. *IOP Conf. Series: Earth and Environmental Science 132* doi :10.1088/1755-1315/132/1/012005.

Malik, J.N., and Mohanty, C. 2007. Active tectonic influence on the evolution of drainage and landscape: Geomorphic signatures from frontal and hinterland areas along the Northwestern Himalaya, India. *Journal of Asian Earth Sciences 29*, p.604–618.

Masurkar, S., Manjare, B., and Anusha, N. 2019. Morphotectonics of Wan River Sub-basin Using Remote Sensing and GIS Approach. *JGSR Vol. 4, No.2, July 2019 163-172.*

Pareta, K., and Pareta U. 2011. Quantitative Geomorphological Analysis of a Watershed of Ravi River Basin, H.P. India, *International Journal of Remote Sensing and GIS vol 1* p.47-62 .

Prabawa, G., Jambak, M.A., Harnest, B., Irano, T., and Ibrahim, I. 2020. Rejuvenating the concept of The Salodik Group Reservoir of The Banggai Basin through Surface Geological Mapping and multi-method analyses, Proceedings of Indonesian Petroleum Association Digital Technical Conference.

Pomar, L. and Kendall, C.G.S.T., 2008. Architecture of Carbonate Platforms: A Response to Hydrodinamycs Evolving Ecology. *SEPM Special Publication No. 89 p.* 187-216.

Radaideh, O. M. A., and Mosar, J. 2019. Tectonics controls on fluvial landscapes and drainage development in the westernmost part of Switzerland: Insights from DEM-derived geomorphic indices, *Tectonophysics, Volume 768, 2019, 228179, ISSN 0040-1951,* https://doi.org/10.1016/j.tecto.2019.228179.

Rickard, M. J., 1972. Fault Classification: Discussion. *Geological Society of America Bulletin, 83(8),* pp.2545-2546.

Rudyawan, A., and Hall, R. 2012. Structural reassessment of the South Banggai-Sula area: no Sorong Fault Zone. *Proceedings of the Indonesian Petroleum Association, 36th Annual Convention, Indonesian Petroleum Association,* IPA12-G-030 1–17.

Rusmana, E., Koswara, A., and Simandjuntak, T.O. 1993. *Peta Geologi Lembar Luwuk, Sulawesi.* Bandung: Laporan Terbuka Pusat Penelitian dan Pengembangan Geologi, skala 1:250.000.

Sayre, R. G., Wright, D. J., Breyer, S. P., Butler, K. A., Van Graafeiland, K., Costello, M. J., Harris, P. T., Goodin, K. L., Guinotte, J. M., Basher, Z., Kavanaugh, M. T., Halpin, P. N., Monaco, M. E., Cressie, N., Aniello, P., Frye, C. E., and Stephens, D. 2017. A Three-Dimensional Mapping of the Ocean Based on Environmental Data. Oceanography, 30(1), 90–103. *http://www.jstor.org/stable/24897845*

Schumm, S.A. 1956. Evolution of drainage systems & slopes in Badlands at Perth Anboy, New Jersey, *Bulletin of the Geological Society of America*, 67, p.597-646.

Sompotan, A. F. 2012. *Struktur Geologi Sulawesi.* Bandung: Penerbit ITB.

Strahler, A. N. 1952. Hypsometric (area–altitude) analysis of erosional topography. *Geological Society of America Bulletin* 63. p.1117–1142.

Sukristiyanti, S., Maria, R., and Lestiana, H. 2018. Watershed-based Morphometric Analysis: A Review. *IOP Conf. Ser.: Earth Environ. Sci.* 118 012028

Simandjuntak, T. O., Situmorang, R. L., and Sukido. 1993. *Peta Geologi Lembar Batui, Sulawesi.* Bandung: Laporan Terbuka Pusat Penelitian dan Pengembangan Geologi, skala 1:250.000.

Tim Pusat Studi Gempa Nasional. 2017. *Peta Sumber dan Bahaya Gempa Indonesia Tahun 2017*. Bandung: Kementerian Pekerjaan Umum dan Perumahan Rakyat

Wahyudiyono, J. 2017. *Geologi & Potensi Migas di Wilayah Balantak, Tomori, dan Morowali Selatan, Sulawesi Tengah*. Bandung: Pusat Survei Geologi (unpublished).

Whittaker, A. C., and Boulton, S. J. 2012. Tectonic and climatic controls on knickpoint retreat rates and landscaperesponse times, J. Geophys. Res.,117, F02024, *doi:10.1029/2011JF002157.*

Wood, G. D. 2014. *Tambora: The Eruption That Changed the World*. New Jersey: Princeton University Press.

Zhang, K., Gann, D., Ross, M., Robertson, Q., Sarmiento, J., Santana, S., Rhome, J., and Fritz, C.: Accuracy assessment of 1035 ASTER, SRTM, ALOS, and TDX DEMs for Hispaniola and implications for mapping vulnerability to coastal flooding, Remote Sens. Environ., 225, 290–306. https://doi.org/10.1016/j.rse.2019.02.028, 2019.