Geological Surface Conditions Mapping of 2021 Post-Earthquake of Mamuju-Majene using satellite images and field observations

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Abstract *Mamuju Regency, situated amidst active faults such as the Makassar Strait Thrust Fault and the Mamuju-Majene Thrust Fault, is a seismically prone region. This study aims to map the surface geological changes following the 6.2 magnitude earthquake that struck Mamuju Regency, West Sulawesi in 2021. The methodology involved satellite image analysis to identify linear geological structures and field surveys for rock sample collection and post-earthquake condition assessment. Results revealed a dominant northeast-southwest linear pattern, which field observations correlated with geological structures like faults cutting through coarse and fine tuff layers, crushed zones, and joints. These faults intersected rocks ranging from Miocene to Quaternary, indicating their active nature. The findings provide novel insights into the seismic potential of the Tapalang area, Mamuju.*

Keywords: *Earthquake, fault, geological Mapping, mamuju Regency, disaster mitigation*

Introduction

Indonesia's unique location at the convergence of four tectonic plates – the Eurasian, Indo-Australian, Pacific, and Philippine plates – has resulted in a geologically dynamic and diverse landscape. Sulawesi, one of Indonesia's largest islands, exemplifies this geological complexity. The interplay of these tectonic plates has given rise to a fascinating tapestry of rock formations, including ophiolite complexes, continental collisions, volcanic arcs, massive shear zones, and a myriad of other tectonic manifestations. (Katili, 1978; Bergman et al, 1996; Parkinson et al, 1998; Smyth et al, 2008; White, L.T et al 2017; Liu and Shi, 2021).

Sulawesi, is characterized by a complex geological makeup, divided into four distinct geological provinces: West, East, Central, and Southeast. The West and South Sulawesi regions belong to the West Sulawesi Geological province, predominantly composed of Miocene volcanic and plutonic rocks. These rocks originated from the Neogene subduction process from the east, forming a Tertiary volcanic arc known as the West Sulawesi Volcanic Arc (Surono and Hartono, 2013; Sukadana et al, 2015). This geological complexity and tectonic setting make Sulawesi Island one of the most earthquake-prone regions in Indonesia.

The 6.2 Mw earthquake that struck Mamuju Regency, West Sulawesi Province, on January 15, 2021, was one of the most significant earthquakes recorded on the island in recent years. The earthquake was triggered by tectonic movement along the Makassar Strait Normal Fault. Preceded by a 5.8 Mw foreshock, the earthquake resulted in over 100 fatalities and displaced more than 30,000 people (Meilano et al 2021, Gunawan et al, 2021).

Geologically, Mamuju lies within the West Sulawesi geological province and is characterized by active seismicity. It represents the convergence of several active faults, including the Makassar Thrust Fault and the Mamuju-Majene Thrust Fault. The region has experienced numerous earthquakes, both with and without tsunamis. The last destructive earthquake prior to the 2021 event occurred in 1984 (Hartono et al, 2021).

Extensive research focusing on seismicity, geophysical aspects, and disaster management has been conducted by several researchers (Priadi et al, 2022; Harimei and Massinai, 2019). However, geological studies related to field-based mapping and manifestations of geological structures remain limited. This paper presents an investigation of geological field manifestations integrated with satellite imagery data through remote sensing mapping, along with their relationship to the lithological units of the Mamuju region. The study focuses on the Tappalang area, the epicenter of the 6.2 mW earthquake in January 2021.

Literature Review

Mamuju is included in the western geological province of Sulawesi Island. Normal faults and thrust faults dominate the tectonics of this area with a west-east and northwest-south trend. Folds are found in several areas.

Six tectonic stages of Sulawesi have been identified based on seismic and gravity observations in the reconstruction of the Makassar Strait formation (Guntoro, 1999), In the middle Cretaceous, subduction of oceanic crust towards Southeast Kalimantan formed the accretionary complex; Late Cretaceous: the micro continent crust of SW Sulawesi collides with SE Kalimantan; Paleogene: block faulting occurs due to the uplift of the Meratus Mountains, accompanied by the movement of the Banggai-Sula micro continental crust in eastern Sulawesi.

In the Paleogene, the entire Meratus mountain range had been uplifted with the formation of block faulting, and in the eastern part the Banggai-Sula micro continental crust had approached. The opening process of the Makassar Strait occurred in the Eocene due to the vertical sinking process of the slab subducting into the subduction zone, which has implications for back-arc rifting. In the Oligocene, there was a collision of ophiolites in eastern Sulawesi with the SW Sulawesi micro continental crust. From the Middle to Late Miocene, there was a collision of the Banggai-Sula microplate with the eastern Sulawesi ophiolites. This process caused double subduction in the east and west, resulting in the emergence of West Sulawesi volcanism.

Four tectonic events have occurred in the Mamuju area, with the oldest event occurring during the Middle Cretaceous, coinciding with tectonic events in Southwest Sulawesi (van Leeuwen, 1981) manifested by folding, faulting, and low-grade regional metamorphism of metamorphic rocks. The Latimojong Formation was formed in the Late Cretaceous in a deep-sea depositional environment. The next process occurred in the Paleogene, resulting in folding of the metamorphic rock units and the Latimojong Formation undergoing low-grade regional metamorphism. These rocks are exposed in the Polewali and Enrekang areas and are part of the Latimojong Mountains in central of South Sulawesi.

During the Eocene and Oligocene, extensive marine inundation formed marine sediments, forming the Toraja Formation and Rantepao Member, which are dominated by carbonate rocks. Entering the Oligocene to Early Miocene, tectonic activity resumed, followed by the emergence of an island arc volcano, marking a phase of active volcanism. This volcanic activity produced the Lamasi Volcanic Rocks, which in some places are formed together with limestone.

Carbonate deposition continued until the Early Middle Miocene, after which volcanic activity ceased. This process formed the Riu Formation. Further tectonic activity occurred in the Middle Miocene to Early Late Miocene, accompanied by volcanic activity that formed the Talaya Volcanic Rocks, which are composed of andesite-basalt, and the Adang Volcano, composed of basalt-leucite. To the west, the Mamuju Formation carbonate rocks and the Tappalang Member reef limestones were also formed simultaneously.

The Mamuju and Tappalang areas are composed of several rock formations, namely the Mamuju Formation (Tmm) which is composed of marl, sandy limestone, tuffaceous marl, and sandy limestone interbedded with tuff, and volcanic rocks including Lamasi Volcanic Rocks (Toml) composed of various tuffs, lavas, and volcanic breccias of andesite-dacite composition, with local interbeds of sandy limestone and shale, and Adang Volcanic

Rocks (Tma) composed mainly of Adang Volcanic Rocks consisting of tuff, lapilli, volcanic breccia, and interbedded lava (basalt leucite), sandstone, and mudstone. The Adang volcanic rock unit has a thickness of 400 meters and is of Middle Miocene-Late Miocene age (Sukadana et al, 2015).

The Adang volcanic rock unit can be grouped into seven units, namely the Tapalang, Ampalas, Adang, Malunda, Karampuang, Sumare, and Labuan Rano complexes. These are composed of several types of rocks, including tephrite, tephriphonolite, phonotephrite, and phonolite, with tephrite being the most dominant type (Sukadana et al, 2015). We expected to find more detail types of lithology of these formations of regional geology.

Methodology

This research employed surface geological mapping to assess the post-earthquake conditions in Mamuju Regency. The methodology involved in the following stages. They are Satellite Image Analysis, and field geological survey to validate the findings from the satellite imagery lineaments. Digital Elevation Models (DEM) with a spatial resolution of 8 meters were used for remote sensing analysis and correlated with the Mamuju geological map (Ratman and Atmawinata, 1993). Surveys were conducted to verify the findings from satellite image analysis. Direct observations of rock outcrops and analysis of primary and secondary geological structures were carried out in the field. Soil and rock samples were collected with geological structure data measured in the field. Documentation of fault manifestations was also performed. Integrating the result from satellite imageries and data taken from the field enable the analysis to be confirmed.

Results and Discussion

The analysis of lineaments in the study area generally revealed a northeast-southwest (NE-SW) orientation. This linear pattern is dominant in the southeastern and southern parts of the study area, including Pebambaang, Uluserang, and Tappalang. These lineaments traverse several rock units, namely the Miocene Adang volcanic rocks (Tma) and the Miocene to Pliocene Talaya volcanic rocks (Tmtv). This linear pattern is also visible on the Mamuju geological map (Ratman and Atmawinata, 1993). The length of the observed lineaments, as determined using GIS, ranges between 6 to 7 km (Fig.1).

Field observations and surface geological mapping revealed evident manifestations of faulting within the study area's lithological unit, particularly in the volcanic rocks of the

Tappalang region. These faults include fault planes exhibiting offset or displacement of rock layers, crushed zone, joints, and slickensides. The distribution of these geological structures is closely associated with the identified lineament patterns. Additionally, several secondary geological structures such as springs, waterfalls, and altered rocks were observed in the field. Some signs and traces of infrastructure damage caused by the 2022 earthquake were still visible near the field observation stations.

Faults were observed intersecting various rock units within the Adang volcanic formation (Tma). These faults cut through coarse and fine tuff layers, with clear evidence of offset at outcrops in the Rantedoda area. At this observation area, multiple offsets were documented within alternating layers of coarse and dense fine tuffs. The observed faults exhibit a normal fault, with displacements ranging from 10 to 175 cm. (Fig.2) Associated with these faults are crushed zone and slickensides.

Displacement of rock layers and crushed zone were also identified in the Tapalang area along the Mamuju-Palu national road. Observations at this location revealed fault planes cutting through tuff units, with offsets ranging from 13 to 55 cm. The crushed zones in this area were quite extensive. In the limestone member of the Mamuju Formation, several crushed zones were also observed, resulting in significant deformation of the limestone into fragments.

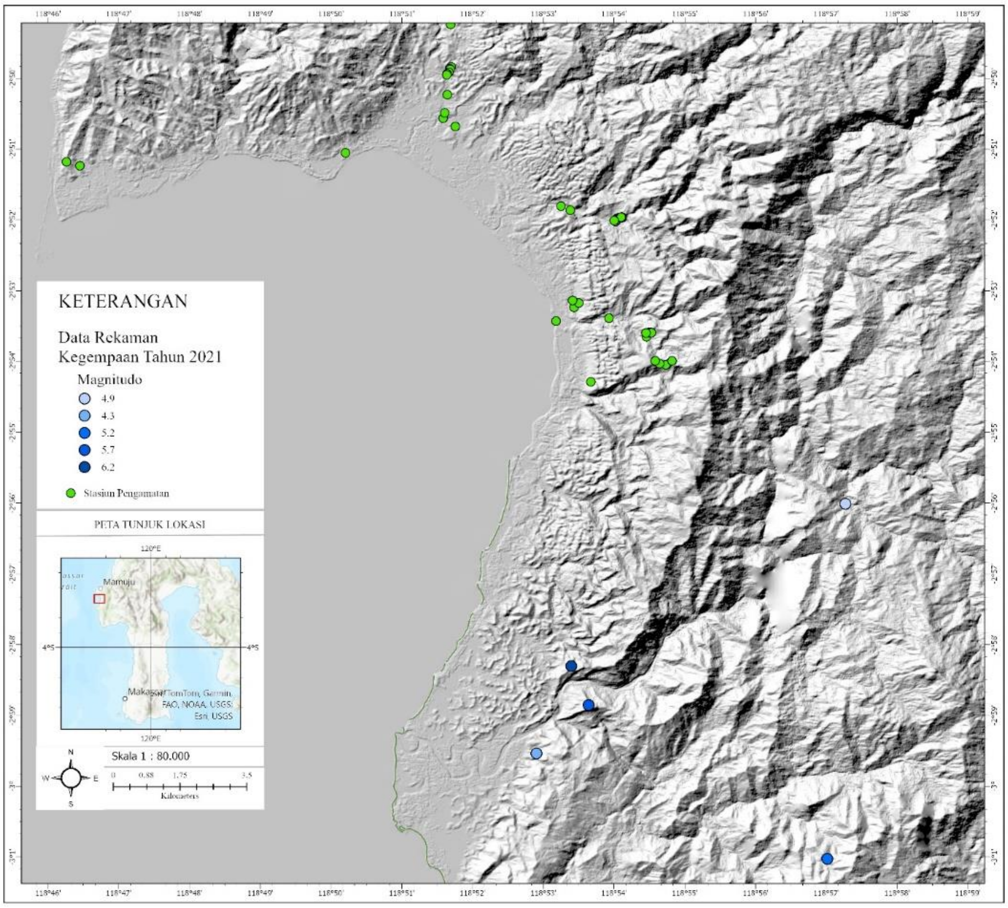

Fig 1. Recent earthquake distribution maps of the research area, and sampling locations.

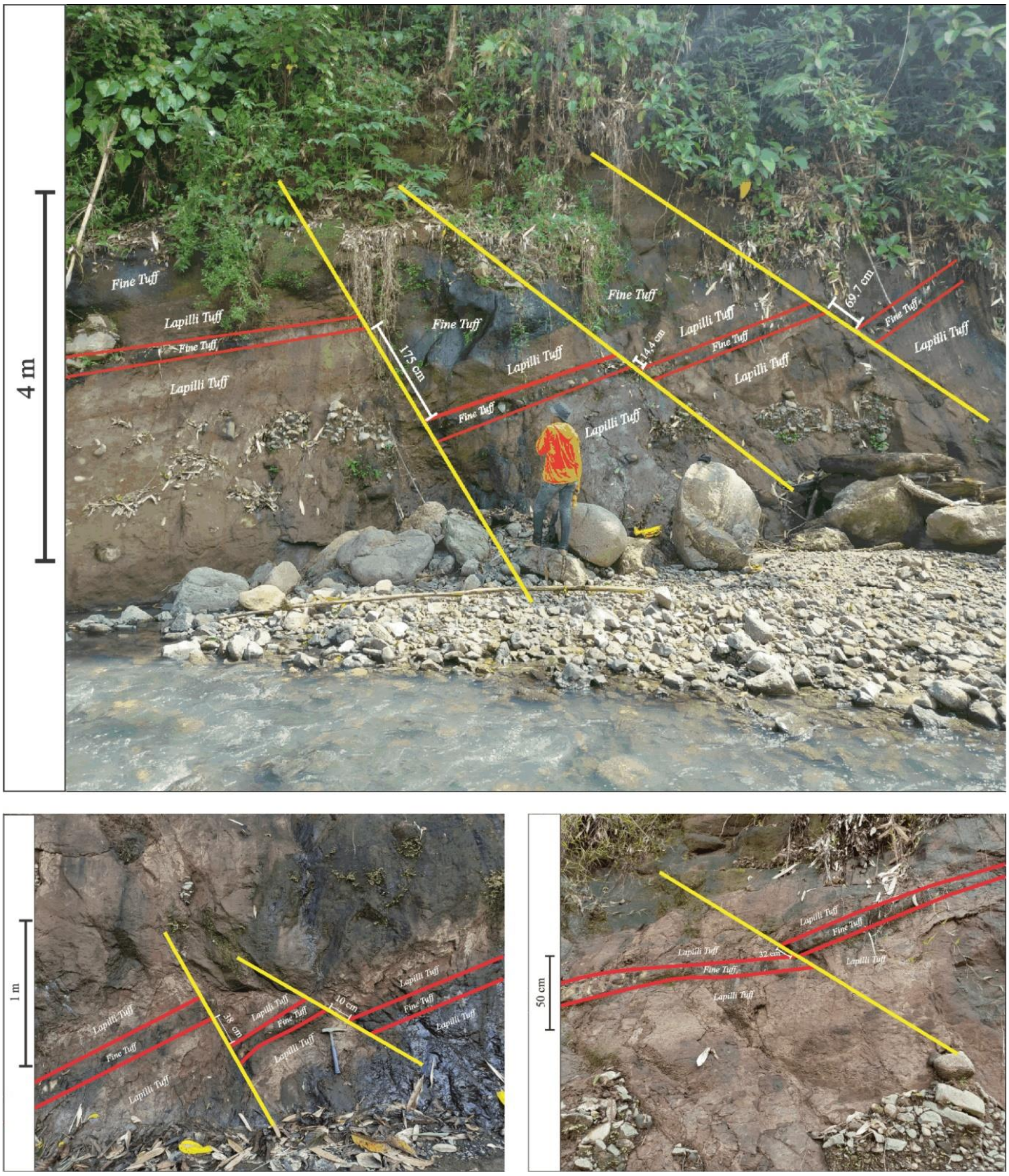

Figure 2. Outcrop of coarse tuff and fine tuff at the Rantedoda River, the fault cuts through the rock layer.

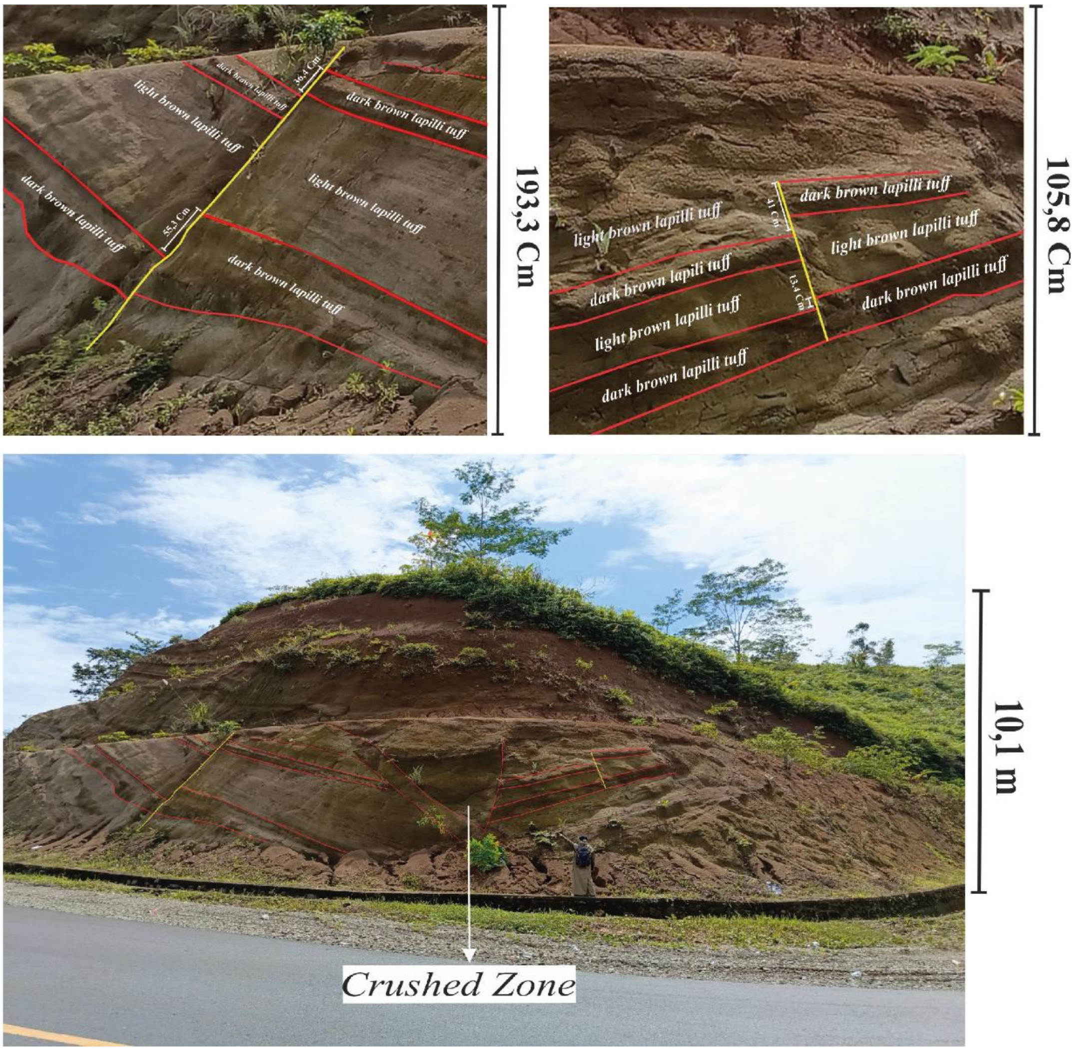

Figure 3. The outcrop of the intersection of coarse and fine tuff at Tapalang area, the fault cuts the rock layer (top). The crushed zone formed by fault activity in the tuff rock unit at the same observation location (bottom).

Extensional joints were observed in coarse and fine tuffs within the Rantedoda, Limbu, and Tapalang river areas (Fig. 4). These joints resulted in rock deformation and brecciation, and some slickensides with an orientation of N 346 and a pitch of 40° were also identified. The observed faults cut through rocks ranging from Miocene to Quaternary age.

Secondary geological structures, such as springs, waterfalls in the Rantedoda and Timbu rivers, and intense alteration of tuff units in Rantedoda and Tapalang, were observed. USGS earthquake data from 2021 showed four earthquakes with magnitudes ranging from 4.3 to 6.2 M, occurring near the study area and associated with the observed linear patterns. Post-6.2 M earthquake damage, including foundation failures and ground subsidence, was also observed. Both remote sensing and field mapping revealed fault manifestations such as cut tuff layers and crushed zone in volcanic and limestone rocks. These faults are associated with the observed lineaments and are located near earthquake epicenters, indicating that the fault in this area has been active since the post-Miocene.

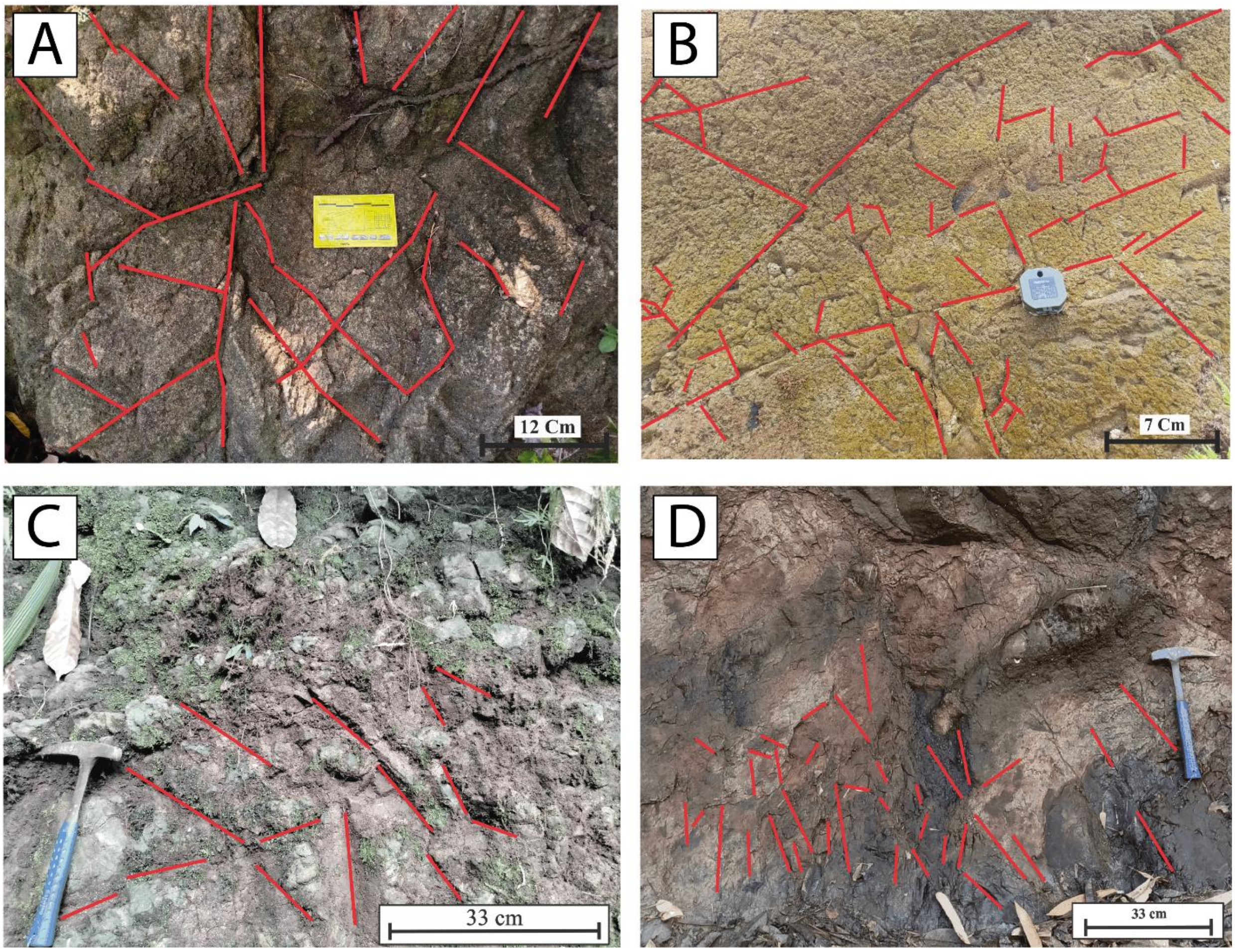

Figure 4. Extentional Joint found in the Tappalang area (A and B), Limbu River (C), and Rantedoda River (D).

Conclusion and Recommendation

This study reveals that the faults in the study area are associated with the observed lineament patterns oriented northeast-southwest. Field observations confirmed that these lineaments are associated with geological structures such as faults that cutting through coarse and fine tuff layers, crushed zones, and joints. These faults cut through rocks ranging from Miocene to Quaternary age, indicating that the faults in the study area are still active. The results of this study provide new insights into the seismic potential and disaster mitigation in the Tapalang, Mamuju area.

Based on the research findings, we recommend that building along the fault lines must be built according to the building code determined by the construction authority.

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