Potentially active normal faulting zone identified in the eastern margin of Palu City, Central Sulawesi, Indonesia

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Abstract. The 2018 Mw 7.5 earthquake in Palu, Central Sulawesi, resulting in ~2,000 fatalities and estimated economic losses of ~22.8 trillion Indonesian Rupiahs, according to the report of BAPPENAS and Central Sulawesi Provincial-Government. Therefore, it is necessary to prevent similar disaster in the future by further detailed studies of any other potential sources that are capable of generating such hazards. Palu City is in the vast depression valley bordered by mountains in its eastern and western margins. The 2018 earthquake source is the Palukoro Fault, which runs through the western margin of onshore Palu Valley then continued under the bay. Along the eastern margin of the valley, we also identified a wide zone of many potentially active faults strands orienting N-S and NW-SE, showing predominantly normal faulting. These faults are observed from their normal fault scarps as inspected from Light Detection and Ranging Digital Terrain Model (LiDAR DTM) data with 90-cm resolution and field ground checks. The faults deformed the old terrace sediments (Late Pleistocene, ~125 kya), but it is unclear whether they also cut the Holocene young alluvial like the ruptured fault of 2018 event. Further paleoseismology investigation is then necessary to obtain further information about these potentially-active normal faults, including their slip-rate and the past ruptures.

1. Introduction

Palu City is located in the vast depression valley that is a very dynamic active tectonic region as it is in a triple junction between Australia, Eurasian, and Philippine Sea Plates [1-2]. North of Sulawesi, the Celebes Sea is being subducted beneath Sulawesi [1]. Hence, this region consist of complex arrays of active fault lines throughout the region (Figure 1). The Palukoro & Matano Fault zones, which cut Central Sulawesi, are the most dominant active fault of Sulawesi, and is of particular importance because it is straddled by Palu City (population around 340,000).

The 2018 Mw 7.5 earthquake in Palu City resulting in ~2,000 fatalities and estimated economic losses of about 22.8 trillion Indonesian Rupiahs (~USD 1.5 billion on current exchange rate), according to the report of BAPPENAS and Central Sulawesi Provincial-Government [3]. This event has lead the need for a better hazard risk evaluation of the 2018 earthquake surface ruptures and associated active faults to determine the strategy and policy in mitigating future earthquakes and their associated hazards and risks.

From geological point of view, a fault is evidently active if it cuts or deforms young landscape or sedimentary layers of Holocene to Late Pleistocene period [4]. For example, in New Zealand, the reference (maximum) age for active fault identification is 125,000 years old, which is related to the beginning of the previous warm-interglacial period or correlated with alluvial terraces and the Marine
Isotope Stage 5 (MIS 5) [5]. For an extremely high-risk project, the ‘capable or potential’ active faults that show any geomorphic-geologic evidences since early Pleistocene (1.8 million years old) should also be taken into considerations.

Active fault strands identification is rather tricky. As an example, in all old-rocks environment, sometimes it is hard to determine whether the identified fault line is active or not since there is no young geological deposits involved. Geological and landscape analysis is also limited by ratio between fault slip rates and rates of erosions and depositions. If a fault slip-rate is very low, lower than rates of deposition and/or erosion, than we may not be able to see surface-landscape expressions of fault movements since they will be erased by erosion or buried under geological deposits. Hence, identifications of active faults heavily depend on resolutions of used topographic/landscape (digital) maps. The higher the resolution will be the smaller morpho-tectonic features can be seen.

We implemented a combination of remote-sensed and field-based method active fault mapping to identify and analyze the earthquake-fault rupture traces of the 2018 earthquake (Mw 7.5) and we have acknowledged that the main source of the 2018 earthquake event is caused by the movement of Palu fault which runs through the western margin of the onshore Palu Valley then continued under the bay water striking relatively N-S direction. However, in this study we focus on fault scarps distributed in the eastern margin of Palu valley. The scarp was originally mapped as a lineament with no sense of fault-slip direction in the seismotectonic maps published by Center for Geological Survey [6]. Our investigation, however, indicates potentially active normal faulting. The fault displaced the Late Pleistocene unit. The distribution of these fault strands is located near the area of relocation housing plan for the 2018 earthquake victims and Tadulako University, highlighting the importance of characterizing these fault strands.

2. Methods
We use a combination of remotely sensed and field-based observations supported with comprehensive desk-study analysis on active fault mapping including evaluating previously published studies and geological maps. The Palukoro Fault is one of the major fault in Indonesia that have been studied rather intensively. However, in general, almost none of them had focus on mapping active fault lines in sufficient details. Most of paper-journal publications only studied the regional (active) tectonics from geological studies and from tectonic geodetic studies [1-2, 6-15].

Our remote mapping is based on LiDAR DTM 1-m grid data resolution developed by Geospatial Information Agency (BIG) after the 2018 Palu Earthquake and DEMNAS 8.5-m grid data resolution. The remotely based mapping was followed by field-based mapping to confirm the identified tectonic features by inputting the selected target sites into handheld Global Positioning System (GPS) and webGIS-based map as a guidance. To help robust and accurate interpretation of the fault line as complimentary to the LiDAR dataset, we also conducted Unmanned Aerial Vehicle (UAV) survey during the fieldwork using small drone (DJI Mavic) to develop Digital Elevation Models (DEM) and Orthophoto. The drone was flown at about 100 m high with overlapping images taken between 8-9 times. The image resolution produced from UAV survey have about 2-4 cm / pixel.

3. Results, Discussions, and Conclusions
In the eastern margin of Palu Valley, we identified numerous potentially active faults predominantly from the observation of normal fault scarps trending N-S and NW-SE in LiDAR, high-resolution orthophoto, as well as on the ground during fieldworks (black lines in Figure 2a, 2b, 3). These faults can be identified cutting and deforming the old Quaternary sediments, labeled as Qp (Quaternary-Pleistocene) in the Geology and Seismotectonic Map [6, 12] (Figure 2b). In some places, they are appeared to have also affected the Quaternary-Holocene landscapes or the young alluvial terraces and sediments. In general, the appearance of their active-tectonic-landscape signatures of the fault lines are rather obscure and spotty, not prominently continuous over long distances like the major active fault in the west side. Hence, it suggests that their rate of activities is significantly lower. Since they need to be
further studied in more details, here we assigned them as the potentially active faults, which are colored in black.

The prominent occurrences of the potentially active normal fault orienting N-S is in the Talise Area in the Eastern side of Palu Bay (Figure 2a). These faults are clearly observed by their relatively fresh linear (normal) fault scarps with predominantly west down movements. The trace of the faults gradually disappears northward when passing the young alluvial-fan sediments but reappearing again in the northern hilly areas. The fault seems to run around the west front of the Tadulako University. Hence, the fault is possibly buried under this Holocene sediment. The geological exposure key evidence of the fault was observed on at Site A at the cliffs of the quarry along southern side of the asphalt road (Figure 3). The outcrop clearly shows that the fault cut the old Quaternary sediments (labelled as Qp in the Geological Map and Seismotectonic Map) as shown in Figure 2b. A similar old Quaternary sediment on the western margin has been dated by Bellier [7] using the cosmogenic dating by the measurement of \textit{in situ} produced $^{10}$Be concentrations in quartz boulders on top of fan surfaces, which is about 125,000 years old (Figure 4). The maximum fault offsets observed along the main fault is about 2 meters. We called it as Tadulako Fault since it appears to run across the Tadulako University complex (Figure 2a & 2b).

We also plotted the fault map from Seismotectonic Map [6] and its revision by Soehaemi published from Center for Geological Survey (PSG) in 2018 for comparisons (Figure 2b). It is apparent that Soehaemi revised their previous Seismotectonic Map based on the same geological outcrop at Site-A. Hence, it considers the same fault, which is called here as the Tadulako Fault (Figure 2a). However, they did not consider the tectonic geomorphology of the surrounding area (numerous lineaments and fault scarps), and their measurement of the fault strike seems to be a bit off (more westerly).

Based on the available data, we still do not have clear evidence whether these normal faults in the eastern margin also cut or deformed the Holocene sediments (Qh). This is possibly because the slip rates of the faults are significantly lower than the rate of erosions and sedimentations. Consider that, even for the fast-moving Pulukoro fault on the western margin, its fault traces on surface were mostly not seen before exposed by the 2018 earthquake ruptures. Hence, further investigations are necessary to fully understand the characteristics and hazard potentials of these normal faults. Nonetheless, considering available data, then the fault slip rate is generally interpreted as between 125,000 (125ka) and 11Ka (early Holocene). However, according to the previous study along the western margin, these secondary faults cut the Holocene alluvial fan, dated ~11,000 years old [7] (see Figure 4); and thus the recurrent interval can be estimated to be about between the 125 ka and 5Ka (~Mid Holocene) or classified as Class IV to Class VI (>5,000 – 125,000 years) [16].
Figure 1. Active Fault Map of Central Sulawesi, modified from Daryono [17] and PuSGeN map [18]. Black rectangle is the research site.

Figure 2. (a) The potentially active fault trace in the Talise area, eastern side of the Palu City near the bay area. Site A is the key-site observation of the fault exposure on the mining cliff; (b) Comparisons of the potentially active faults trace mapped in this study and the fault trace which published in the Seismotectonic Map and its revision.
Figure 3. Site A in Talise showing the exposure of the potentially active fault (Tadulako Fault) cutting the Late Pleistocene sediments (Qp), dated about 125 ka [7]. The fault strike is N350E to N-S. The normal fault displacement on the main fault is up to 2 meters. The traces of the fault lines on the top of ground surfaces have mostly been eroded.

Figure 4. Fault map comparison of this study with Bellier [7]. Note that Bellier’s faults are coincided with the secondary normal faulting associated with the negative flower structures.
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