Garsela Fault and other NE-SW active faults along the southern part of Java Island

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Abstract. Most earthquake studies focus mainly on offshore subduction zones that often produce high-magnitude earthquakes. However, onshore active fault earthquakes also common to cause significant devastation, due to their proximity to human activity and their relatively shallow depth. Most of active faults in Java show a west-east (W-E) trending direction. However, the devastating Opak Fault ruptured in a NE-SW trend. Recent studies indicate that some shallow seismic clusters in Java cannot be associated with any known active fault traces. These seismic activities reported occurring in southern Garut, Cipamingkis (Sukabumi), Halimun-Salak Mountain (Bogor), and Grindulu in Pacitan. These seismic clusters show similar direction to the Opak Fault that ruptured an Mw6.4 earthquake in 2006 with thousands of fatalities. Here, we describe a brief review of the NE-SW trending active fault in the southern Garut area. Earthquake is a natural phenomenon with a repetitive mechanism. Therefore, we must be aware of the future hazard that has been demonstrated by recent seismic activities in this area.

1. Introduction
Java, one of the most densely populated island in the world is prone to seismic activity. This is a consequence of the converging margin between the Indo-Australian and Eurasian plates. Besides being potentially affected by earthquakes from subduction zones (interplate), Java also facing threat from earthquakes that may ruptured within its own plate (intraplate) [1,2]. Figure 1 shows a map of identified active faults in Java Island [3].

Recent research shows that the locations of shallow earthquake clusters cannot be associated with the identified active faults [4]. These earthquake clusters are indications of active faults in several places along the southern side of Java, even some of their activities have been reported in recent years. These active fault indications occurred in Halimun-Salak, Cipamingkis, southern Garut zones (West Java), and Pacitan (East Java) (Figure 1). These events show a NE-SW trending direction that parallels the Opak Fault. Several works suggested that Opak Fault was the source of the earthquake that shook Yogyakarta on May 27, 2006, with a magnitude of Mw6.4 and resulted in thousands of fatalities in Bantul [5–7].
Figure 1. Map of identified active faults in Java Island [3]. Blue ellipse represents NE-SW faults indications: 1 = Halimun-Salak, 2 = Cipamingkis, 3 = southern Garut zone, 4 = Pacitan.

The earthquakes that occurred in these several places along the southern side of Java had relatively low magnitudes. However, due to our limited knowledge of these faults, seismic activities that occurred in the last few years should certainly raise our awareness. This paper will discuss the indications of NE-SW trending faults in the southern part of Java Island that have not been well recognized, particularly in the southern Garut zone.

2. NE-SW Active Faults in Java Island

Java Island is part of the volcanic arc complex in the Sunda-Banda subduction system. The western part of Java is a transition zone between the oblique subduction in Sumatra and frontal subduction in Java. Subduction in southern Java shows an almost trench perpendicular direction with a rate of 67 mm/year [8]. The direction of the present-day regional maximum horizontal stress ($S_{Hmax}$) in Java is NNE-SSW [9] and is thought to have controlled the initiation of active faults in the island [10]. However, deformation in Java tends to have been accommodated by the widely spread small-scale active faults with lengths of up to tens of kilometers [2].

Fig 1 shows that most of the active faults in Java ruptured in a relatively west-east direction (W-E). However, one of the recently active fault, the Opak Fault, shows a NE-SW direction. This fault became a massive concern after the 2006 Yogyakarta earthquake. This event, which has caused 6,000 fatalities and destroyed hundreds of thousands of buildings, was believed to have ruptured along the Opak Fault [5–7]. The fault is located parallel to the Opak River which extends from Parangtritis, Bantul, and continued to Klaten farther north [11]. The Opak Fault is observed as a NE-SW escarpment that separated the Gunung Kidul high in the east and Yogyakarta graben in the west.

The estimation of hypocenter locations and focal mechanisms published by several research groups show significant discrepancies as shown in Figure 2. Furthermore, the recorded aftershock was located 5-10 km east of the surface trace of fault [7]. A subsurface resistivity model of 2D AMT-MT inversion shows a discontinuity in the form of low resistivity anomalies on fault escarpment with an eastward dipping geometry [12]. However, due to the model depth limitations which only reaches 1.5 km, we do not have a clear picture down to the hypocenter depth. A hypothesis proposes that the fault plane might have a slope of about 50 degrees to the east [13]. Coulomb stress change modeling supports this hypothesis and interprets the Opak Fault as an oblique reverse-slip as part of a flower structure (strike-slip) type [14]. A recent GPS study emphasizes Opak as a fault zone, instead of a single fault [15].
Figure 2. Left: Shaded relief map of digital elevation model (DEM) using DEMNAS elevation data from Geospatial Information Agency (BIG) around Opak Fault, with the epicenter of the 2006 Yogyakarta earthquake (CMT, NEIC-FMT, USGS, NIED [16]) and aftershock epicenters [7]. Right: Schematic cross-section of Opak Fault [13,14].

Recent researches indicate that Opak Fault may not be the only NE-SW active fault in the southern side of Java. Other NE-SW seismic activities were reported in several places in Java. A cluster of shallow depth (<20 km) low magnitude (Mw 2 – 4) earthquakes forms a lineament in a NE-SW direction in the Garut area [4]. Meteorology, Climatology, and Geophysical Agency (BMKG) have reported several low-magnitude shallow-earthquakes in this area over the past few years. Another area is Cipamingkis in southern Sukabumi, which shows a significant rate of compressional dilatation in NE-SW direction based on GPS data [17]. This GPS inferred deformation area coincides with low magnitude (<M4) shallow depth seismic activity that occurred along the lineament in January to July 2018 recorded by BMKG stations.

BMKG reports shallow swarms (M 2-4) occur in Mount Halimun Salak National Park area, Bogor, in August 2019 with an NNE-SSW direction. One of the biggest events was of magnitude M 4.0 on August 23, 2019, and damaged several buildings. Subsequently, another event occurred on March 10, 2020, with a magnitude M 4.9, 15 kilometers to the east of the swarm area. However, the relation between these two events is not yet clear. The last event occurred in Pacitan, East Java, where the Grindulu Fault ruptured a magnitude of Mw 3.1 at a depth of 11 km on November 7, 2019. BMKG announced that the source mechanism of this earthquake is a strike-slip movement with a NE-SW direction, indicating the activity of the Grindulu Fault.
3. Garsela Fault

This paper reviews and discusses the South Garut Zone (SGZ) that hosts one of the NE trending active faults in Java. Figure 3 shows shallow earthquake clusters extending in the NE-SW direction from south Bandung to south Garut in 2009-2015 [4]. Two shallow earthquakes occurred in this area, on November 6, 2016, and July 18, 2017. The first earthquake occurred at the border of Pangalengan-Sukasari (Bandung), with a magnitude of Mw4.2 and hypocenter depth at 17 km. The second earthquake occurred in the Samarang (Garut), with a magnitude of Mw3.9 and a depth of 10 km. Local newspapers reported that the first earthquake caused one person injured and damaged eight buildings, while the second earthquake caused minor damage to about 50 buildings.

Until the end of 2020, there were at least 9 other shallow earthquakes recorded by BMKG and felt by people around SGZ. The most recent occurred on November 1, 2020, with a magnitude of 4. Seismic activity in SGZ is suggested to be an indication of an active fault [18]. The national earthquake hazard map [3] lists the Garsela Fault as an active fault with two segments, the Kencana Segment in the southwest and the Rakutai Segment in the northeast. The naming of the Rakutai Segment itself seems a bit inappropriate, taking the name of a mountain in the fault line (geological map of Garut [19]) which is actually called Mount Rakutak. The Rakutai segment is also known as the Gagak fault in geothermal exploration [20,21].

Figure 3. A: Digital Elevation Model (DEM) around SGZ using DEMNAS data (BIG). Orange circles are shallow (<30 km) seismicity [4,22,23], crossed red circles are the location of the 2016 and 2017 earthquakes in SGZ. Red lines are traces of active faults [1,2,4]. Dash blue ellipse marks the NE-SW volcanic lineament. B and C are the DEM-only views for the indicated area in figure A.

Figure 3 is a Digital Elevation Model (DEM) around SGZ using DEMNAS elevation data from Geospatial Information Agency (BIG) which has a horizontal resolution of around 8m. It appears that SGZ is located in a NE-SW trending lineament of young volcanic bodies. The lineament stretches for
about 50 km from Sumedang to Garut. On the northeastern side (Figure 3B), the NE-SW lineament was observed to be crossed with the WNW-ESE lineament which might be part of the Baribis Fault. Several seismicity events were observed in the area dominated by oblique strike-slip thrust mechanism, with composite nodal planes NNE-SSW and WNW-ESE [4]. These events located about 20 km south of the identified Baribis fault traces [3]. It is unclear whether these events are related to the Baribis Fault or Garsela Fault. In the southern part of the SGZ (Figure 3C), in addition to the SE-NW directional alignments, the NNE-SSW directed topographic alignments were also observed. A regional geological study suggests that the NE-SW structure pattern in West Java is a basement structure pattern, while the surface structure is more diverse with the dominance of the N-S direction [24].

SGZ is located among several active volcanoes, such as Mount Papandayan and Mount Guntur, it is possible that the morphological expression of active deformation traces was masked by young volcanic products. On the other hand, the data from geothermal fields in the vicinity area might help to reveal the subsurface condition. The effective fracture in the Darajat reservoir shows the dominance of the strike direction N10-30E [20], in the same direction as the regional S_{Hmax} of Java Island which is directed at NNE-SSW [9]. The Wayang Windu shows a dominant geological structure directed at 30°-40° (NE) and 330°-340° (NW) [25]. The NE trending faults are thought to be regional shear faults that are reactivated as normal faults. This may be related to the results of 2D resistivity modeling based on MT data from Pangalengan to Garut, east-west line direction, which shows subsurface structures composed of horst and graben [26]. Stress regime in the Wayang Windu area shows that the magnitude of the S_{Hmax} component is only slightly greater than the S component (S_{Hmax} ≥ S, > S_{hmin}), indicating a transition condition of normal fault - shear fault [27].

4. Concluding Remarks
Shallow earthquakes caused by active fault often cause significant damage and fatalities, for example, earthquakes in Palu-2018 (>2000), Lombok-2018 (>500), and Yogyakarta-2006 (>6,000). Active fault earthquakes often occur relatively close (compared to subduction zones) to the center of human activity and at shallow depths. Several national vital objects are located in SGZ, in the form of geothermal power plant (PLTP), and hydroelectric power plant (PLTA), namely PLTP Wayang Windu, Darajat, Kamojang, and PLTA Lamajang. Disturbances in these vital objects certainly have the potential to disrupt the stability of the electricity supply for the community and the national industry sector.

Shallow earthquakes that occurred in the SGZ area in recent years show a relatively low magnitude but is located at a depth close to the surface. The surface geological conditions in the area are dominated by young volcanic products that tend to be uncompacted. This condition allows for low magnitude earthquakes to be amplified and then produce a big shocks. The intraslab earthquake of 2 September 2009 [28,29] can serve as an example. With a magnitude of Mw 6.8 and a distance of ~80 km from Pangalengan, this earthquake causing more than 100 deaths, thousands injured, and hundreds of thousands of buildings damaged. Most of the fatalities were from Cikangkareng (Cianjur) and Pangalengan, most of which were victims of landslides triggered by the earthquake. The lack of local community vigilance increases seismic risk as a result of our lack of knowledge regarding the potential sources of disasters. A further detailed investigation is needed to reveal the mechanism of the seismic activity in the SGZ area, particularly to map the subsurface geometry of the area.

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