International Journal of GEOMATE, Dec., 2020, Vol.19, Issue 76, pp. 197–204
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2020.76.90787
Special Issue on Science, Engineering and Environment

MAPPING FAULTS DISTRIBUTION BASED ON DEM DATA FOR REGIONAL SPATIAL PLAN ASSESSMENT OF SABANG MUNICIPALITY, INDONESIA

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ABSTRACT: Sabang Municipality is located on Weh Island. As a maritime gateway to Indonesia, the island has been inaugurated as an Integrated Economic Development Zone by the Government. A complete infrastructure has been planned and built to support the manufacturing and tourism industries in the region. On the other hand, the island is potentially affected by geological hazards. Tectonically, the island is crossed by the Great Sumatran Fault (GSF), but few studies have shown the fault trace on the island. To ensure sustainable development, such potential geological hazards have to be incorporated into the Regional Spatial Plan (RSP) of the city. In this study, fault distribution on the island were mapped using shaded relief, slope, lineament extraction, orientation, and Fault Fracture Density (FFD) distribution extracted from the National Digital Elevation Model (DEMNAS) data. The map shows that the island is crossed by several fault lines, but the one located along the eastern with northwest-southeast direction is considered tectonically active. However, according to the RSP, the eastern Weh Island is the most developed area. The city center, airport, seaports, dam, sewerage treatment plan, landfills, and diesel power electricity generator for the city are situated along this fault line. It seems that the RSP of Sabang Municipality was issued without taking into account potential geological hazard maps in it. Some recommendations have been proposed to reduce the impact of losses in the future.

Keywords: Remote sensing, Geological hazards, Regional spatial plan, Sustainable development, Disaster risk reduction.

1. INTRODUCTION

Most losses due to earthquakes which occurred in Aceh, Indonesia are related to the ignorance of the local community regarding the location of hazard sources. Indian Ocean earthquake and tsunami (2004) caused more than 130,000 people died [1]. However, this deadly natural disaster did not have a significant impact on the awareness of the public and local government. The earthquake near Takengon (2013) Mw 6.1 [2] and earthquake Mw 6.5 (2016) in Pidie Jaya have also caused casualties and property damage [3]. The source of the earthquakes was from on the land. The last event surprised the Indonesian Government since the area was abandoned in the Indonesian earthquake hazard map. The existence of an active fault passing the area was not observed by experts until the Pidie Jaya (2016) earthquake occurred. As a lesson learnt from the 2016 Pidie Jaya Earthquake, the Government revised the seismic hazard map of Indonesia by including new active faults recently found [4]. Mapping active faults that potentially generate an earthquake is important for saving people and settlement areas close to the active fault zones.

The Great Sumatran Fault (GSF) is an active strike-slip fault extending 1900 km [5] from the southern part of Sumatra to the Andaman Sea on the north [6]. The fault is divided into ~20 segments based on fault discontinuity such as step-overs [5]. The southern segments have broken within the last century due to earthquakes with magnitudes between 6.0 and 7.7 [7]. Based on GPS-derived slip rate, trench parallel component of convergence is 29 mm/year and most of it is accommodated by the GSF [8]. The northernmost GSF exhibits a GPS-derived slip rate of ~20 mm/year but it has not produced large earthquakes in the last 100 years and is considered to be a seismic gap [5,8]. However, there was no detailed geological research on the fault. Thus, the surface trace locations, late Quaternary slip rate, and rupture history along the Aceh and Seulimeum segments are still poorly known. Theoretically, for the GSF, each segment ruptures every 100-200 years [7], [8]. This seismic gap will potentially produce an earthquake magnitude of around 7.4 if there is no energy released during the time [8].

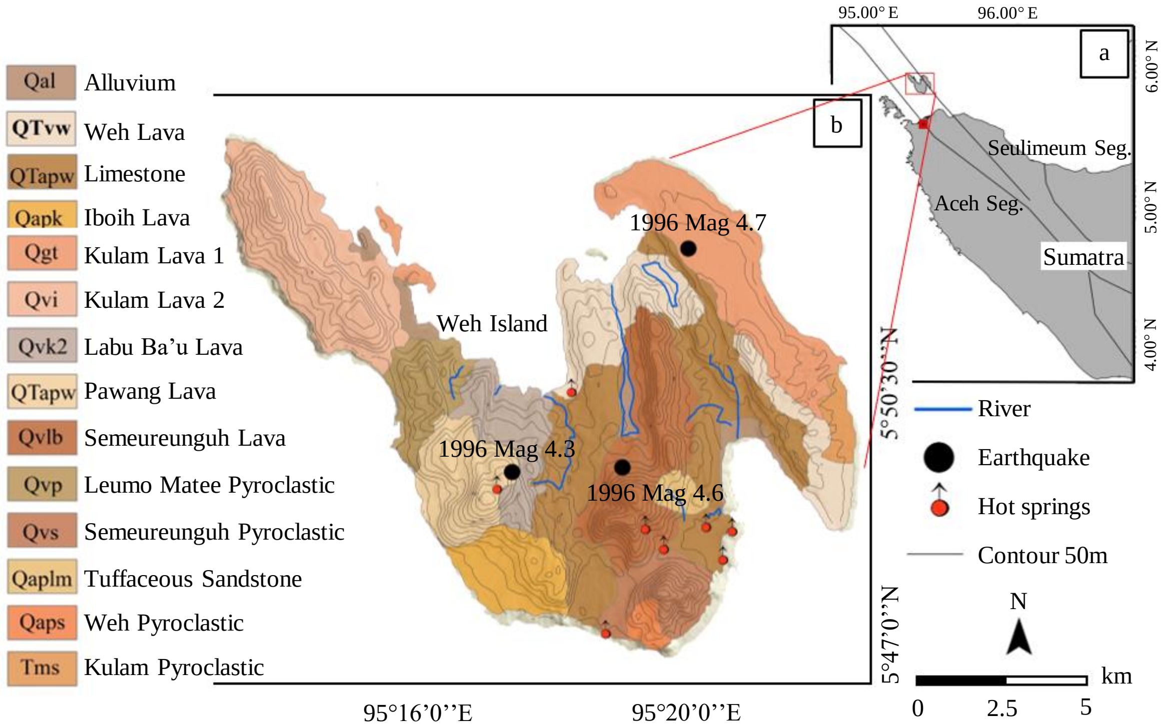

Fig. 1 (a) Tectonic setting of the research area. The research location is shown in the red box, i.e. Weh Island, Aceh Province (Indonesia) which is located off the coast of the Northwest part of Sumatra Island. The locations of the capital of Aceh Province in the red point mark. (b) The state of the geology of the unit and the geomorphology of Weh Island modified based on the previous study [9]. The figure also shows the distribution of earthquakes in Weh Island.

This condition may threaten Weh Island which is located on the fault line and inhabited by more than 40.000 people [10]. Sabang Municipality is also famous for tourism. In 2018, more than 30.000 tourists visited the island [11]. The number of visitors is three-fourths of the population [10]. As a maritime gateway to Indonesia, the island is situated in a very strategic position. Weh island has been inaugurated as an integrated economic development zone [12] and Indonesian free trade zone [13] by the Indonesian Government.

Complete infrastructure supporting industrial and tourism activities has been planned and some of them have been built on the island. To ensure sustainable development, additional information related to potential geological hazards has to be incorporated in regional spatial plan of the city. Some studies have been done in many developed countries [14-15]. However, studies conducted in developing countries, particularly in Indonesia, are still rare. Most studies on fault mapping of the island are not directly related to the spatial plans of the area, for example faults mapping based on geological units [9], DEM Aster data and kinematics study [16] as well as delineating the extension of the GSF along offshore zone situated between Sumatra and Weh Island [6]. In this study, the faults distribution was mapped using National DEM (DEMNAS) data produced by the Geospatial Information Agency of Indonesia. The DEMNAS data set is built from several data i.e. IFSAR data (5m resolution), TERRASAR-X data (5m resolution) and ALOS PALSAR data (11.25m resolution) [17]. The integrated data were added to the point mass through the assimilation process used the Generic Mapping Tools (GMT) - surface tension 0.32 [18]. The DEMNAS data has a spatial resolution of 0.27 arc-second for the territory of Indonesia [17].

The application of the Geographic Information System (GIS) technique by using remote sensing data was carried out as a preliminary study of mapping the fault distribution in Weh Island. The GIS technique plays a major and fundamental role in mapping surface geological features, especially lineaments [25]. The term lineament in geological features was first introduced in the early 20th century [19]. Today, studies related to lineament using of GIS techniques have been conducted for different objectives, such as structural weakness [20], valley [21], fractures [22], geomorphic [23], and fault mapping [24].

The extraction lineament method has been well developed. In this study, the automatic extraction approach was utilized for lineament identification. The results of the approach can be interpreted easily since the analysis process depends only on the appropriate algorithm and image quality when extracting [25]. It can be operated quickly by people with adequate experience and skills thus reducing the ambiguity of interpretation [23].

2. GEOLOGY OF THE STUDY AREA

Convergence of the Indo-Australian and Eurasian plates caused an oblique subduction along the western coast of Sumatra Island and Indian Ocean [5,8] called as Sunda Megathrust. This subduction leads to the formation of the GSF along Sumatra Island [5] in northwest – southeast direction [5,6,16]. At the northwest of Sumatra (i.e. in Tangse), the GSF splits in to 2 branches i.e. Aceh and Seulimeum Segments [5-6]. These two segments flank the capital city of Aceh Province, Banda Aceh, to the sea of northern Aceh (Fig. 1a). The Aceh Segment on the left side of Banda Aceh continues to the Andaman sea crossing along coastline of Pulo Aceh Island. On the left, the Seulimeum Segment passes through the sea, cutting off the east side of Weh Island, towards the Andaman Sea with a length of 120 km [5].

Tectonic settings in this region consist of trench, outer non-volcanic arc, forearc basin, inner volcanic arc, and back-arc or foreland basin. Weh Island is in the inner volcanic arc of the Sumatra Island [6,17]. The geological setting of Weh Island is influenced by the GSF [5,9,26]. Before the Pleistocene, Weh Island was a volcano and part of Sumatra; a big eruption of the volcanic island separated the two islands [9] (Fig. 1a). Weh Island has an area of 156.3 km^2 with a length of 15 km and a width of 10 km [27] the highest topographic is about 617 m [26]. Geomorphologically, Weh Island is mostly characterized by mountains and steep hills formed by fractures and erosion (see Fig. 1b).

Part of the Weh Island is a stratovolcano type located at the southeast (5.82° N 95.28° E) formed by andesitic and basaltic rocks (58%), volcanoclastic rocks (30%), and coral reefs and alluvium (12%) [27]. The high topographic area consists of andesitic, laharic breccias and sandy tuff lava. In some areas, low reliefs are found as in the north, Sabang Port, the northwest region, and the Balohan region in the south. On the east side, there is a mountain range which stretches from southeast to northwest, which is a morphological reflection of the fault strike-slip of the GSF. Meanwhile, the north-south part is dominated by other morphology indicated by the trend ridges, which are normal faults [9].

3. MATERIALS AND METHODS

3.1 Data Collections and Processing

Completion of lineament distribution mapping as identification of faults in Weh Island was used DEMNAS data. They are available free for all regions of Indonesia. The DEMNAS data have 32bit float Geo-tiff format, Earth Gravitational Model 2008 (EGM 2008) datum and scale map topography 1:50,000 [17]. Before further processing, sharpening process was applied to the DEMNAS data in order to increase the contrast of each pixel. The next steps are producing shaded relief and slope map, extract the lineament, Fault Fracture Density (FFD) map and orientation of the lineament. Fault distribution map was interpreted based on the extraction. The complete data processing steps are shown in Fig. 2.

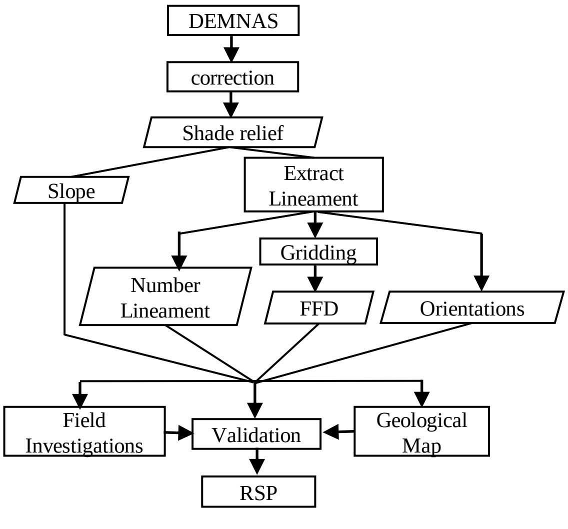

Fig. 2 Flow chart of data processing, evaluation and input parameters.

3.3 Lineament Extraction

In geological views, lineament can be interpreted as faults, fractures joints, structural weakness, cliffs, straight valley bottom, straight streams, or boundaries between stratigraphic formations, and contacts between natural or man-made geographic features [28]. The lineament is a mappable linear or curvilinear feature of a surface that align part in a straight or slightly curving relationship [21]. The lineament processes can be performed by several ways, for example (i) manual extraction [29], (ii) semi-automatic extraction [21], and (iii) automatic extraction [22]. In this paper, the process was carried out using an automatic extraction approach by the module Lineament Extraction (LINE) of PCI Geomatica [30]. The automatic extraction approach passed two main stages, i.e. using filters to detect edges or contours and using line detection [24,25].

3.3 Shade and Slop

Shade and slope maps play a fundamental role in the lineament analysis and extraction stages. The shaded reliefs were imaged based on different illumination angles (e.g. 0°, 45°, 90°, 135°) [30], an altitude of the sun (45°) and Z factor 1 as the scale factor for imaginary topography. According to illumination angles, the other 4 shaded relief maps were created with a contrast result (the results of this process are not attached in this article). The next step is to overlay all maps of shade relief to produce one shade relief maps with multi-illuminated directions (Fig 3a). This combining can improve image quality to better visual interpretation [32]. The shaded reliefs were extracted into lineament features so that direction of lineaments could be obtained.

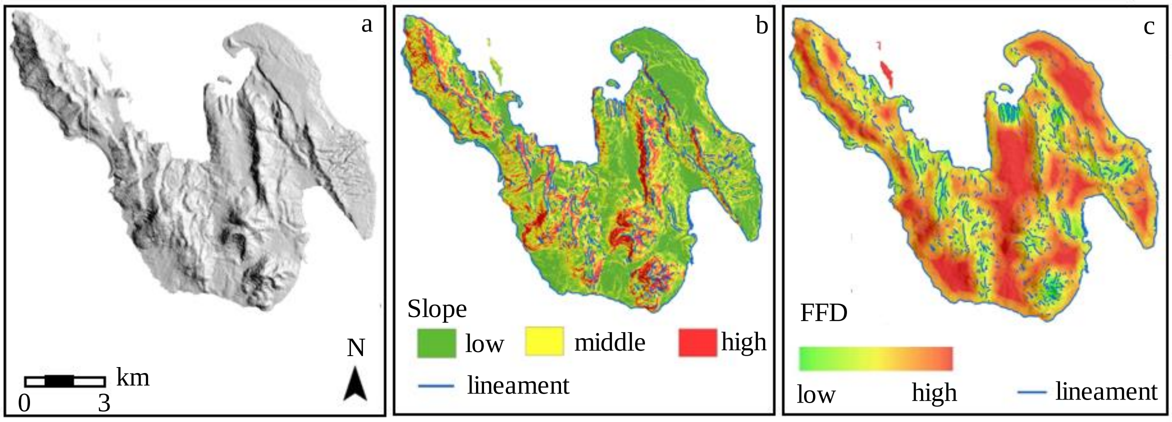

Fig. 3 (a) Shade Relief map (b) Slope map (c) FFD map

The angle orientation enhanced the features for further lineament extraction. The shaded relief map, shown in Fig. 3a is the result of the angle of illumination and the orientation of the angle that displays good features selected for the extraction process. Lineaments extraction were done by determining the edge between the shaded and unshaded areas [25]. After the map shading process was obtained, the slope mapping process was carried out as shown in Fig. 3b.

4. RESULTS

4.1 Fault and Fracture Density (FFD)

Lineament density or Fault and Fracture Density (FFD) is defined as the number of lines in one-unit area [N/km^2] or the total length (L) of each line unit area [km/km2] [21,25].

$$L=\sum_{i=1}^{N}\frac{x_i}{km^2}, \qquad (1)$$

N is number of lineaments and x_i is the length of lineament number i.

Lineament, which is associated with the structure, is a reflection of the topographic picture in the form of straightness of rivers, valleys, faults, rock fractures and contacts. The FFD analysis is commonly used to study geological and geomorphic structures [21, 24 and 25].

In this study, the FFD was used to correlate lineament concentration with lineament distribution for faults distribution analysis in Weh Island. As shown in Fig. 3c, the most intensively deformed areas are shown as high-density values caused by tectonic deformation.

4.2 Orientation

Analysis of direction or orientation was conducted by using a rose diagram. Rose diagrams from data sets for a specific distribution show alike trend of frequency and directions. In general, the dominant direction of the features is in NW-SE, NNW-SSE, NNE-SSW, and some of them are directed at ESE-WSW (Fig 4). Orientation depiction was carried out based on the most frequent linear features, in this case, lineament. Directions derived from the dataset, generally, show a similar pattern.

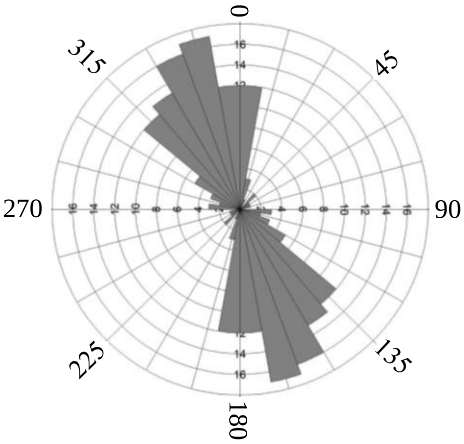

Fig. 4 Orientations of fault distributions

Based on Fig 4, most of them are directed to NW-SE and N-S orientation. There are some in NE-SW and E-W orientations but they are relatively few. The rose diagrams show that geological structures on Weh Island are mostly in this orientation, showing how the major effect of the GSF on the direction of distribution of the lineament in Weh Island (marked by the direction of NW-SE).

5. Discussion

Based on the distribution of lineament, shaded relief, FFD, slope, orientation and geological map, we interpret the fault distribution. There are 17 features that can be associated as faults, fractures, or bedding surfaces which are distributed throughout Weh Island.

The interpreted distribution of faults is shown in Fig 5. Labelled features 1, 2, and 3 are expected to be a main fault as an extension of the Seulimeum Segment, i.e. one of the two northernmost segments of the GSF. These features have NW-SE direction following the Seulimeum Segment direction. Therefore, the Seulimeum Segment extends from the Northern Sumatra, passing the northern sea toward the Sabang. Based on field observations, geomorphic of the area is characterized by graben on the west side with the east block rising (Fig. 5b, 5c, and 5d).

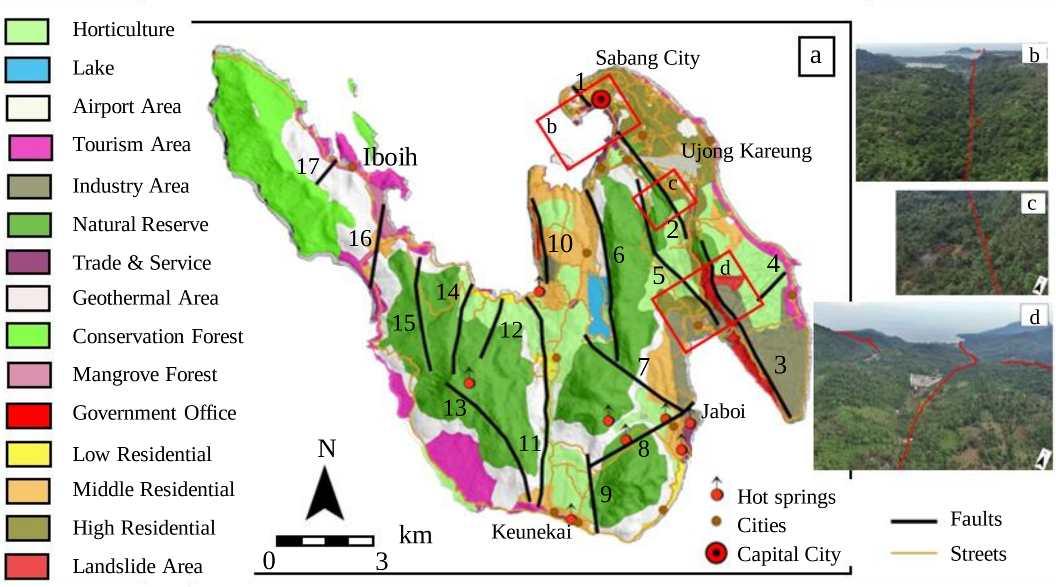

Fig. 5 (a) Interpretation distribution of fault fractures on Weh Island. (b) Aerial photographs showing geomorphic view at the northernmost (c), middle (d), and southernmost of the Segment Seulimeum on the Weh Island.

This major fault affected other parallel features located along the west side of the main fault. Labelled features 5, 6, 10, 11, 15, and 16 could be resulted from the main fault depression, since they also have northwest direction. The direction of active faults on Weh Island join the fault extension from the Seulimeum Segment along Sumatra Island [5,16]. However, labelled features 7, 8, and 13 could be subjected by geothermal activity where Jaboi volcano is situated around them (Fig. 5a). The main fault was formed in the early Tertiary period [9] and expected as an active fault [5], but no large seismicity has been recorded there [33]. However, several small-scale events have been recorded along the Seulimeum segment on Sumatra Island (Fig. 1a).

An active fault area is potentially subjected to geological hazards such as earthquakes, soil deformations, and landslides. Disasters occur when the hazards impact on lives, economic activities, facilities, and infrastructure. Most geological hazards cannot be stopped. However, the impact of the hazards due to active faults can be minimized. One of the ways is establishing regulations such as setting up rules for land use in active faults [14-15, 34]. Regional Spatial Planning Policy of Sabang Municipality has been established since 2012 [35] where the authorities related to development planning, regulation, determination and utilization of Regency/City spatial plans are managed by the Local Government [36]. In general, the RSP of Sabang municipality contains the objectives, policies, urban spatial planning strategies, urban spatial structure plans, urban spatial pattern plans, the determination of city strategic areas, direction of spatial use of city areas, and provisions for controlling spatial use of city areas.

Most Sabang area is conserved for vegetation, especially in the western part of the island, including conservation forest areas, natural resources, tourist areas, mangrove forests, and horticulture. Meanwhile, the eastern part of the island is intended for middle and upper settlements, government offices, trade, and industry. However, most RSP zones in the eastern intersect with fault lines, especially along the main fault. The main fault is located along northeast area with NW-SE direction. A densely populated government offices and trading areas are mostly located at the northwestern part along the fault. Along the middle of the fault, there are some facilities such as airport, plantation, and forest. Heading towards the southeastern, the industrial area and sea port can be found (Fig. 6). More ever, based on our observation, the main city, dam, drainage ponds, temporary garbage sites, landfills, tower providers, power plants, electrical substation, communication offices, military office, and schools are located less than 20 m from the main fault line. According to [15] the fault avoidance zone must be less than 20 m from either side of the known active fault line.

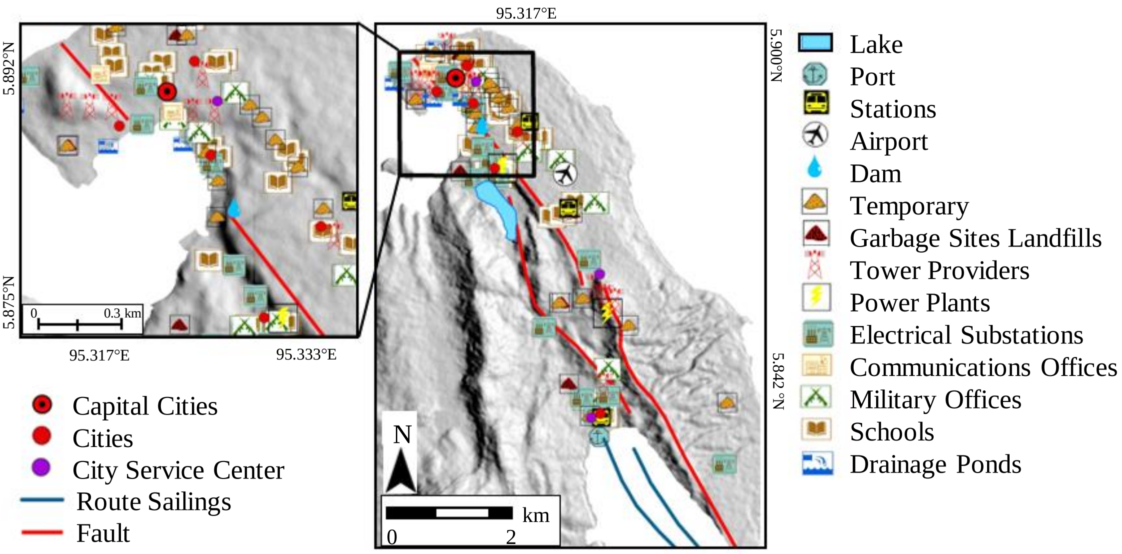

Fig. 6 Distribution of important sites that are in contact with active faults

Based on these findings, it seems the RSP has not considered the existence of the active fault, even though geological hazards issues have been mentioned in the RSP document. So far, the results of active fault studies related to potential future disasters are often underestimated [14, 15, 34] and have not been used optimally for disaster reduction, land use and construction design [34], Some recommendations to control population inflow and address development problems in Sabang have been formulated, such as limiting infrastructure development in fault areas and directing residents from potentially disaster-prone areas to safer areas. Meanwhile, some steps can also be taken to promote of population outflow, such as relocating buildings, prohibiting reconstruction, banning on leasing, requiring property owners to disclose zones/areas with active faults, prohibiting the construction of new buildings excluded from recommendations from comprehensive geological studies.

6. CONCLUSION

DEM derived from DEMNAS can be considered as promising methods for faults distribution mapping in developing countries. The methods are considered cost effective, fast, and reliable for regional scale. The faults map shown in this paper was produced by a quick method with medium resolution. However, it revealed that the potential hazards were not included in the city spatial plan. By this finding, we recommend that the municipality needs to solve the problem urgently by reassessing the city spatial plan by detecting and precisely tracing hazards on the map. The stakeholders need to know the hazard risks and how to mitigate them. In order to avoid hazard risks, any development should be done far from the active fault line. Even though the RSP is an official government regulation, this regulation needs to be reviewed by including an active fault map in it. The authority needs to establish a fault avoidance zone at least 20 m from either sides of the active fault line. The boundary represents a precaution to ensure the safety of life from the effects of material breaking and unpredictable surfaces structures. However, Sabang municipality is an urban area. Some constructions have already been erected on an active fault zone, long before the regulation was established. It is possible for the authority to protect areas from rebuilding without permission. People should also be educated to understand the risk they face in the future. Some buildings built across the faults need to be protected from damage when a catastrophic earthquake occurs.

7. ACKNOWLEDGMENTS

The authors would like to thank the Ministry of Research, Technology and Higher Education of the Republic of Indonesia for funding this research through the 2016-2018 PMDSU research grant.

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