Active Fault Delineation Using Magnetotelluric Data in The Western Region of East Java

W Lestari1,*, A Widodo1, D D Warnana1, F Syaifuddin1, J P G N Rochman1, A Zarkasyi2 and N S Setiawan1
1Geophysical Engineering Department, Faculty of Civil Engineering, Planning and Geoengineering, Institut Teknologi Sepuluh Nopember, Surabaya
2Geothermal, Coal and Mineral Resources Centre, Bandung, Indonesia
*Corresponding author’s e-mail: wien@geofisika.its.ac.id

Abstract. The subsurface geological condition of East Java is an area that is crossed by an active fault geological structure. The National Earthquake Center revised the Indonesian Earthquake Hazard and Source Map of 2017 with the discovery of new active faults surrounding the Kendeng Zone, East Java. This research was conducted using Magnetotelluric (MT) method which has high penetration therefore it was able to map the geometry of active deep fault structures beneath the surface. Measurements were made at 11 measuring points focusing on the Blumbang Fault (M6.6) in Lamongan District. 4 (four) lines were made from 11 existing measuring points. The lines were then modelled in 2D to describe the distribution of subsurface resistivity. The results showed an anomaly with low resistivity value which was indicated as Blumbang Fault in 4 section models. Section of line 1 and 2 indicated a fault in the NS-SE direction continuity to the northwest which became deeper to the south from 6 km to 9 km. Lines 3 predicted the fault with low resistivity value (<30 Ωm) close to M07 point with a depth of 8 km. However, it did not clearly show its continuity. Line 4 assumed the suspected structure as Blumbang Fault with a resistivity value below 30 Ωm that is shallower to the west with 6 km of depth.

1. Introduction
The interactions between tectonic plates has made Indonesia an active tectonic region which is very vulnerable to earthquakes’ activities [2][7]. Material loss and human casualties due to earthquakes were mostly caused by ignorance of faults in an area. Mapping of active faults is really needed in spatial development because recent building construction must consider aspects of hazards, one of which being an earthquake. Geodetic studies using Global Positioning System (GPS) were conducted by Koulali et al. in 2016 [11] [12] that identified an active extension of the Flores back-arc thrust to the west for 300 km along the land to East Java. The results pointed out the threat of a new major earthquake for East Java and the threat of tsunamis to Bali, Lombok, and Nusa Tenggara. The National Earthquake Center revised the Indonesian Earthquake Hazard and Source Map of 2017 with numerous inventions of new active faults particularly throughout the Kendeng Zone in East Java [14]. The faults are Surabaya, Waru, Blumbang, and Cepu Faults with a slip rate about 0.05 mm/year and a magnitude up to M5. A preliminary regional study was performed using magnetotelluric to delineate the major active fault with north to south direction in East Java [13]. It can be concluded that more specific spacing in the survey is needed to reach satisfying data besides integration with other geophysical methods to present high quality data about geological subsurface information [3][8]. This
study using the Magnetotelluric method is expected to be able to provide comprehensive information about the existence of active geological structures beneath the Kendeng Zone particularly the Blumbang Fault which can be seen from the distribution of resistivity value.

The Magnetotelluric method is a passive electromagnetic (EM) method that measures the fluctuations in electric field (E) and magnetic field (B) naturally in the orthogonal direction of the earth's surface in order to determine the subsurface conductivity of the earth's surface from depths of tens to thousands of meters [3][15]. The frequency range of natural electromagnetic field recorded by the instrument was 320-0.001 Hz which used natural electromagnetic fields (primary electromagnetic fields) as sources i.e. lightning (high frequency) and solar wind (low frequency). This method has been proven to characterize a deep active fault with high resolution represented by low resistivity anomaly [5][17][19].

2. Regional Geology

There are three general structural patterns in Java, namely Northeast-Southwest (NE-SW) called the Meratus Pattern, North-South Direction (N-S) or Sundanese pattern, and East-Western Direction (E-W). The change in the line of subduction through lime age where the Northeast - Southwest direction (NE-SW) became relatively East - West (E-W) since the Oligocene until now has produced a complex tertiary geological order on the island of Java [4][16][18].

At the end of Cretasius, a subduction zone was constructed from the Karangsambung region continuously to the Meratus Mountains in Kalimantan. This zone created a northeast-southwest-directed geological structure. Afterward, the subduction zone was in the south of Java during tertiary formed east-west direction. The collision between the Asian plate and the Australian plate produced a major force of north-south compression that developed an oblique wrench fault pattern of northwest-southeast direction, which was more or less in the same direction as the final Cretasius mountain pattern [7][18].

The physiography of study area is located in the Rembang Anticlinorium / Rembang Zone which stretches from Tuban to the east through Lamongan, Gresik, and almost the entire Madura Island which is illustrated on Figure 1 [9][10][18]. Rock formations in the area consist of shallow marine deposits, clastic sediments, and carbonate rocks. Rembang High, several east-west trending folds and the Kendeng Anticlinorium / Kendeng Zone were formed in this zone where the rock formations consist of volcanogenic and pelagic sediments [9][10]. Stratigraphically, the rock formations that constructed this zone according to the Geological Map of Rembang Zone are, from the oldest to youngest formation, composed by [16]:

- Tawun Formation: claystone and limestone with sandstone inserts, siltstone and calcarenite.
- Ngrayong Formation: sandstone, shale, clay and siltstone with limestone, coal and lignite insertions.
- Bulu Formation: gray white limestone, sandstone is thinly layered.
- Wonocolo Formation: claystone with limestone inserts.
- Ledok Formation: sandy marl with claystone, sandstone and limestone insertion.
- Mundu Formation: sandy marl and limestone.
- Paciran Formation: massive limestone with weathered surfaces, dominantly dolomite.
- Selorejo Member: interlocking limestone and sandstone which is rich in plankton foraminifera fossils.
- Lidah Formation: blackish gray clay with insertion of rocky sandstone.
- Muria Volcanic Rock: lava tuff and sandy tuff, lava is composed by fragments of leusite, basalt, andesite, limestone, and metamorphic rocks
- Lasem Vulcanic Rock: andesite, anglomerate, breccia, lapillary tuff, and lava.
- Alluvium Deposit: crust, gravel, sand, silt, and clay
3. Methodology
The Magnetotellurik method is applied to a map of geologically active structures in the study area. Primary data were obtained from the acquisition that surrounded Lamongan Regency, East Java in July 2019. 11 (eleven) data points acquired using MT tools of phoenix geophysics are scattered around the Blumbang Fault from the map issued by National Earthquake Centre in 2017 as in Figure 2 and details of measurement points are outlined in Table 1. The target of this research is to delineate regional active geological structure, so we utilized space in 5 until 10 km from one measurement station to the next station. Four research lines were made, i.e. 2 lines oriented Northwest-Southeast (NW-SE), 2 lines North-South (N-S), and each line intersects Blumbang Fault from the fault distribution map issued by the National Earthquake Centre. The purpose of making a research line that indicated the fault was to describe the active geological structure in the cross section of the resulting model.

Figure 1. East Java Physiography

Figure 2. Distribution of MT measurement stations

The data obtained from the measurement results are time series data with a minimum measurement time of 7 hours and a maximum of 22 hours. Data for each measurement point consist of 5 data in the form of magnetic field (Hx Hy and Hz) and electric field (Ex Ey). The time series data obtained were then processed to obtain a pseudo resistivity curve. The data were then converted in 2D so that a cross-sectional 2D model of the subsurface resistivity was obtained. The flowchart of MT data processing in this study is shown in Figure 3.
Table 1. Details of MT measurement stations

| Stations | Latitude (Km) | Longitude (Km) | Elevation (m) |
|----------|---------------|----------------|---------------|
| MT-06    | 27721.380     | 1592.124       | 71            |
| MT-07    | 27700.227     | 1644.940       | 45            |
| MT-08    | 27674.260     | 1643.600       | 63            |
| MT-09    | 27641.989     | 1678.451       | 25            |
| MT-10    | 27618.316     | 1647.864       | 64            |
| MT-11    | 27633.732     | 1621.891       | 129           |
| MT-12    | 27658.349     | 1592.224       | 127           |
| MT-13    | 27676.558     | 1549.627       | 114           |
| MT-14    | 27702.836     | 1531.446       | 108           |
| MT-24    | 27710.099     | 1688.572       | 32            |
| MT-26    | 27603.959     | 1559.118       | 94            |

Figure 3. Flowchart of MT data processing
4. Results and Discussion
The expected results after the MT data processing were 2D sections of subsurface resistivity from 4 measurements lines. The following results were acquired:

4.1 Line 1
In line 1, a low resistivity structure below 30 Ωm was found with a depth below 5 km beneath ground level. This structure is estimated to be a continuation of the Meratus pattern structure with the northwest-southeast (NW-SE) trend. Identification of the structure in the form of a fault is considered between the points MT07 and MT08 which are around 700 m to the southeast of the point MT08. It is represented by contrast resistivity patterned down to the northwest with a depth of up to 6 km. These results were in accordance with the fault distribution map that was issued by the National Earthquake Centre where the Blumbang Fault passed through MT07 and MT08. The southeastern part is Ledok Formation that is composed of sandy marl with claystone and sandstone insertion. Meanwhile, in the northwester part are Lidah Formation consisting of claystone with sandstone insertion and Kabuh Formation containing sandstone.

![LINE 1](image)

**Figure 4.** 2D section model of line 1

4.2 Line 2
Obviously, the Meratus pattern structure is not detected in line 2. Figure 5 shows two contrasted zones, the northwestern part with low resistivity (< 30 Ωm) which is pointed to be the Mundu Formation which is composed of sandy marl, and the southeast zone with high resistivity (> 1000 Ωm) which is represented by Ledok Formation (sandy marl with dominant limestone insertion). Whereas the identification of faults assumed them to be between the MT10 and MT11 points, precisely around 1 km northwest of the MT11 point. This assumption was based on the existence of resistivity contrast anomaly in the low resistivity area with a downward pattern to the northwest as suspected fault on line 1 with depths up to 9 km below ground level. This fault identification was also in accordance with the fault distribution map issued by the National Earthquake Centre.
Figure 5. 2D section model of line 2

4.3 Line 3
Line 3 as illustrated in figure 2 is a line that lay from north to south (N-S). The 2D model cross section in Figure 5 resulted the estimation of the fault to be around 2 km north of the MT11 point while the depth was estimated to be up to 8 km below sea level. Unfortunately, the continuity of the fault was not really clear, due to the large range of spaces of the measurement points. This fault location was also still in accordance with the map issued by the National Earthquake Centre.

Figure 6. 2D section model of line 3

4.4 Line 4
2D cross section on line 4 (Figure 4) reflected 2 different resistivity parts as in line 2. However, line 4 presented that the low resistivity section (< 30 Ωm) was on the north side and the high resistivity part (> 1000 Ωm) on the south side. This high resistivity value was controlled by the MT13 point which
was estimated as Ledok Formation (sandy marl and limestone). The fault was identified around 500 m north of point M07. The fault was assumed to have a depth of 6 km below sea level. The direction of fault continuity was assumed to tend be in the west side of M07 point.

5. Conclusions
2D sections of subsurface resistivity Magnetotelluric data on 4 research lines identified the active fault structures (Blumbang Fault) according to the research information of Indonesian earthquake hazard and source map revised by the National Earthquake Centre in 2017. Line 1 and line 2 in the northwest-southeast (NW-SE) direction indicated the Blumbang Fault with its continuity to the northwest, where line 1 was located at 6 km of depth and became deeper to the south while line 2 was 9 km deep. Lines 3 and 4 which were extended in the north-south direction (N-S) while line 3 predicted the fault with low resistivity value (<30 Ωm) close to M07 point with a depth of 8 km though it did not clearly show its continuity. Line 4 assumed the suspected structure as Blumbang Fault with a resistivity value below 30 Ωm that is shallower to the west at 6 km deep.

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