Indonesian Journal on Geoscience Vol. 4 No. 1 April 2017: 39-47

INDONESIAN JOURNAL ON GEOSCIENCE
Geological Agency
Ministry of Energy and Mineral Resources

Journal homepage: http://ijog.geologi.esdm.go.id
ISSN 2355-9314, e-ISSN 2355-9306

Audio-Magnetotelluric Modeling of Cimandiri Fault Zone at Cibeber, Cianjur

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Manuscript received: August 2, 2016; revised: October 10, 2016;
approved: January 9, 2017; available online: January 26, 2017

Abstract - The characteristic of Cimandiri Fault Zone has not been completely defined despite plenty of studies had already been accomplished. Therefore, an audio-magnetotelluric modeling was carried out. An audiomagnetotelluric survey was conducted at two parallel lines (N166°E) that intersected Cimandiri Fault Zone in Cibeber area, Cianjur. The distance between those two lines was 4.5 km and each line consisted of twenty-one stations with the distance between stations was 500 m. From the acquired forty-two apparent resistivity curves, inversion was executed to obtain two models. The models indicate layers with resistivity value of > 1000 ohm.m at about 500 m depth at both lines, which are associated to the basement layer. Columns of low resistivity zones in about the middle of each model represent fault zones as the weak zones of the area, and both models displayed them slightly dip southward as thrust faults.

Keywords: Cimandiri Fault Zone, audiomagnetotelluric, Cibeber, Cianjur, resistivity inverse modeling

How to cite this article:
Handayani, L., Maryati, Kamtono, Mukti, M.M., and Sudrajat, Y., 2017. Audio-Magnetotelluric Modeling of Cimandiri Fault Zone at Cibeber, Cianjur. *Indonesian Journal on Geoscience*, 4 (1), p.39-47. DOI: 10.17014/ijog.4.1.39-47

Introduction

The existence of Cimandiri Fault Zone has been recognized from the lineaments of topography maps, satellite images, and surface geology studies (*e.g*. van Bemmelen, 1949; Sudjatmiko, 1972; Abidin *et al*., 2009; Supartoyo *et al*., 2013). Several previous studies suggested that the Cimandiri Fault Zone was the eastern boundary of the Sunda Strait transition zone, where tectonic characteristics changed from the implication of the oblique subduction along Sumatra to that of the normal subduction along Java (Pramumijoyo and Sebrier, 1991; Malod *et al*., 1995; Susilohadi *et al*., 2005). Furthermore, Malod *et al.* (1995) suggested that Cimandiri Fault Zone was extended to offshore and connected to Sumatra Fault Zone in a forearc region and formed a conjugate dextral strike-slip fault. The argument was rather weak since several offshore seimic reflection surveys indicated that more complex structures existed in the Sunda Strait forearc region (Kopp *et al*., 2002; Susilohadi *et al*., 2005).

Throughout this paper, the term Cimandiri Fault Zone is used as a zone of long linear feature from Pelabuhan Ratu area (at southwest) to about the western limit of Lembang Fault (at northeast). There are at least two segments of Cimandiri Fault Zone: the first one is elongated from Pelabuhan Ratu to about the east of Suka-

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bumi along the Cimandiri River, and the second one is the one from about Cianjur to Padalarang region (Figure 1). They have slightly different course of lineament.

Besides those linear features, Cimandiri Fault Zone characteristic has not strongly defined yet. Since Hamilton (1979) suggested the existence of Cimandiri Fault at Pelabuhan Ratu area, several investigations had been conducted. However, there has not been an absolute agreement on the nature of the entire Cimandiri Fault Zone.

A field geological survey (Martodjojo, 1984) showed the Cimandiri Fault as a normal fault, but Dardji *et al*. (1994) through paleostress reconstruction concluded that the Cimandiri Fault was a sinistral strike-slip fault. On the other hand, an investigation by Hall *et al*. (2007) suggested that fault at about Cimandiri River area was a series of thrust faults. In addition, Supartoyo *et al.* (2013 and 2014) had a morphometric analysis that divided the Cimandiri Fault to four segments and concluded that all those segments were active faults, with southern part was less active than the northeastern part.

Global Positioning System (GPS) surveys conducted in 2006, 2007, and 2008 had not given enough information to define the property of Cimandiri Fault (Abidin *et al*., 2008). Those surveys indicated various directions of very small movements (0.5 - 1.7 cm/year) along the zone. Earthquake activities might indicate the existence of seismic activity along the zone, but the events were very sporadically distributed (Figure 1).

Several magnetotelluric surveys along Cimandiri Fault have been conducted previously. Widarto *et al.* (2000) and Arsadi *et al*. (2000) had a very wide area covered by a magnetotelluric survey, from about Bogor area to the southern coast of Ujung Genteng, Sukabumi. The subsurface images presented different basement characters at the northern and southern part of the Cimandiri Fault. Febriani *et al.* (2012 and 2014) carried out an audiomagnetotelluric survey at the southern end of Cimandiri Fault, in Pelabuhan Ratu area. The 2 km depth subsurface model displays a relatively low resistivity column that might represent a weak zone of the fault. This column separates two types of basements, where the basement at

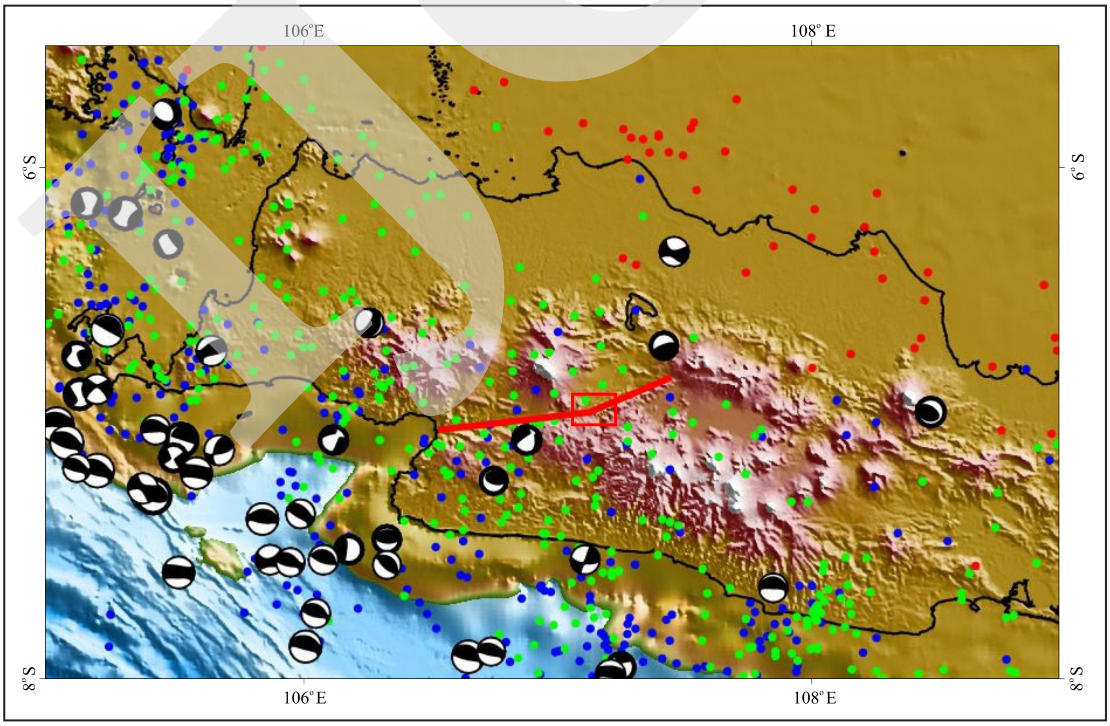

Figure 1. Earthquake epicentre distribution (red dots for deep, green for intermediate, and blue for shallow earthquakes, source: USGS/NEIC Catalog) and focal mechanism distribution of western Java (source: Global Centroid Moment Tensor Catalog). Red line indicated Cimandiri Fault Zone. Red box is the studied area.

the south of the fault has a higher resistivity than the northern part.

To understand the complex tectonic characteristic of Cimandiri Fault Zone, it is necessary to have a more subsurface mapping along the zone. This paper represents the current audio magnetotelluric survey in Cibeber, Cianjur. Cibeber is located at about the bend of the Cimandiri Fault Zone (red box in Figure 1). The survey lines crossed Cikondang River that separated the Quarternary volcanic rock deposits at the northwest to the Neogene - Miocene intermontane-intervolcanic rocks at the southeast (Hamilton, 1979). Geology outcrops that expose at the surface indicate the existence of a fault that could be deducted from the differences of the geological formations. However, the surface geology can not give enough information on the fault properties. Thus, the resulted subsurface models from the audiomagnetotelluric survey might give more insight on the subsurface structure of this fault zone.

Geology of the Area

The geologic map suggests that the formation at the southeastern part of the fault mostly consists of Oligocene to Holocene volcanic rocks (Figure 2). The northern part of the fault is mostly covered by more recent volcanic deposits. The oldest rock in this studied area is the Upper Oligocene Formation of Rajamandala, which comprises of two members: claystone, marl, sandstone (Omc), and limestone (Oml). Above Rajamandala Formation there is Jampang Formation (Md) of Lower Miocene that is composed of greenish tuffaceous sandstone and clay layers, calcareous tuffaceous breccia of dacite and andesite layers, and calcareous sandstones and marl layers.

On the top of Jampang Formation, there was deposited Citarum Formation of Middle Miocene age, composed of two members: Mts and Mtb. Sandstone and silt Member (Mts) consists of sandstones interspersed with claystone, and breccias. There is a turbidite deposition indication, shown by the sedimentary layering, convolute lamination, current ripple lamination, and traces of animal worms. The second one is Breccia and Sandstone Member (Mtb) of Citarum Formation composed of polymict breccia, which has components of andesite and limestone. In this member, there are also conglomeratic breccia, sandstone, and siltstone layers.

The Citarum Formation is overlain by Pumice tuff and Tuffaceous sandstones Unit (Mt) of Lower Pliocene age, consisting of pumice tuff breccia, tuff sand, and marl tuff containing small foraminifera. On top of Pumice tuff and Sandstone tuff Unit rest a Pliocene deposits which consists of breccia tuff, lava, sandstone, and conglomerate (Pb). There is also quite vast area of conglomerate and andesitic lava flows of (Pl).

The oldest Holocene rocks are made up of older volcanic product (QoT) consisting of pyroxene andesitic breccia with andesite insertion and forming a broad hill. In addition, there is also found basaltic rock (Qyc) that forms small hills in Cianjur plain. The youngest Holocene rocks are breccias and lava originated from Mount Gede (Qyg), that comprise tuffaceous sandstone, tuffaceous shale, tuffaceous breccias, and tuffaceous agglomerate also forming Cianjur plain.

Methods

Magnetotelluric (MT) is a passive geophysical method to investigate a resistivity structure of subsurface. This method depends on natural electromagnetic field variation, with a very wide range frequency (10000 - 0.00001 Hz) that induces electric currents of subsurface. With such a wide range of frequency, this method is suitable for subsurface investigation from the depth of a few meters to thousand meters. Lower frequency can be used for a deeper penetration (to the depth of upper mantle) while higher frequency is for the near surface observation. Data were acquired by a combination of electric sensors that determine the electric field and induction coil magnetometers that measure the magnetic field. The observed variations in electric and magnetic fields give information about the subsurface resistivity structure. The ratio of electric-magnetic field is represented as an apparent resistivity and phase as the function of frequency. The audiomagnetotelluric is the magnetotelluric survey using higher frequency (audio) that is suitable for relatively shallow subsurface mapping.

An audiomagnetotelluric (AMT) survey was conducted along two parallel lines (N166°E) in Cibeber area, Cianjur, that cross the Cikondang River (Figure 2). There was a 4.5 km distance between the two lines. Each line consists of twenty-one stations, with the distances between every two stations were about 500 m. However, distances between stations could not exactly uniform due to the difficulties in the field.

The measurements were to obtain the electric (E) and magnetic (H) fields for each station in time series. There are three components of magnetic fields and two components of electric field. During the measurement, the recorder main unit Phoenix MTU-5a was placed in the middle. Two pairs of porous post were placed (buried) in four directions, in about 40 - 50 m distances from the main unit. The north - south porous pots were to measure electric fields Ex, and the west - east porous pots were Ey. Three coils were used to acquire the magnetic fields. The first coil for measuring the Hx was placed in the middle between the north and west porous pots and lied in N - S direction. The second coil for Hy was placed between north and east porous pot in west - east direction, whilst third coil for measuring Hz was placed between the south and west porous pot, and placed (buried) standing up or perpendicular to the ground. All fields were measured simultaneously in a similar time axis to obtain time series data. For high frequency of audio-magnetotelluric, about three-hour acquisition time was needed. All data were recorded in the recorder main unit.

The placement of electric and magnetic sensors provides two dimension models, which show the distribution of resistivity in lateral and vertical direction (y,z). The combination of all obtained components then give two modes of data: TE (Transverse Electric) and TM (Transverse Magnetic). TE or xy mode comprised Ex, Hy, and Hz, where the electric field was parallel to the strike. While TM or yx mode was composed of Hx, Ey, and Ez, where the electric field was perpendicular to the strike.

The data processing consists of the transferring from time domain data to frequency domain data, editing noises by robust process, and signal sorting. All steps were done using MT Editor Software. After editing the process, apparent resistivity curves for each station were obtained. The last step of the work was an inversion to model the subsurface. The WinGLink software

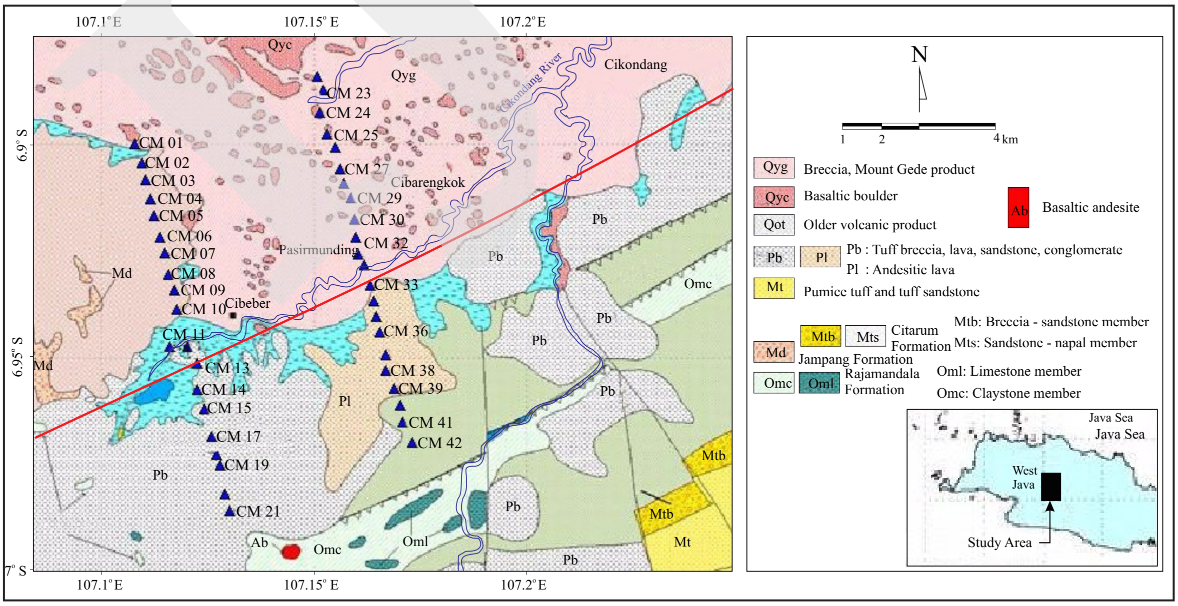

Figure 2. Geological map of the studied area (modification from Sudjatmiko, 1972) and audio-magnetotelluric survey stations (blue triangles). Red line is the Cimandiri Fault Zone traced from topography (Abidin *et al*., 2008).

was used, with the nonlinear conjugate gradient (NLGC) inversion method for forward and inverse modeling (Rodi and Mackie, 2001).

Result and Analysis

Figure 3 shows four out of forty-two apparent resistivity curves obtained from this survey. Each diagram shows the apparent resistivity which are parallel (Transverse Electric, TE) or perpendicular (Transverse Magnetic, TM) to the strike. Generally, decreasing apparent resistivity with increasing period indicates increasing electrical conductivity with depth. While increasing apparent resistivity indicates decreasing electrical conductivity. The flat curve suggests a homogenous subsurface. Gradient differences between TE and TM curves might indicate the complexity in the subsurface structure.

The 2D model or resistivity section along the two lines is derived from the inversion method using the WinGLink software. The results of inversions are subsurface resistivity distributions (Figure 4 and 5) for the two survey lines to the depth of 2 km.

These resistivity models display the subsurface of the north and south part of Cikondang River, at Cibeber, which is on the transition bend of Cimandiri Fault Zone. In general, both models indicate the existence of four main layers: low resistivity (less than 10 ohm.m), intermediate resistivity (10 - 100 ohm.m), high resistivity (100 - 1000 ohm.m), and very high resistivity (more than 1000 ohm.m). Near surface at about the river area there features low resistivity layer (10 - 100 ohm.m) that associated with uncompacted rocks. There are very low resistivity layers (< 10 ohm.m) at the northwestern and southeastern part of Line 1 that might be related to the loose sediment. This

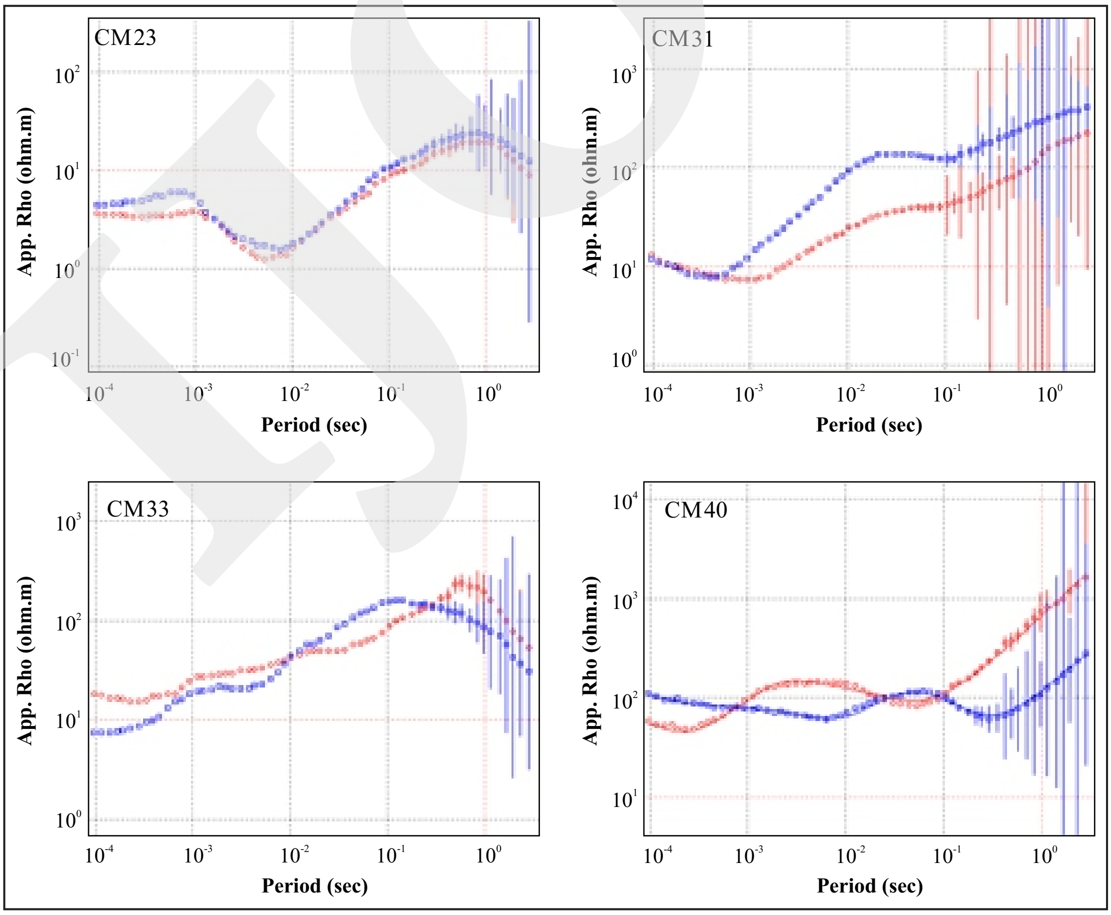

Figure 3. Apparent resistivity curves for the selected four stations (Red for TE and blue for TM).

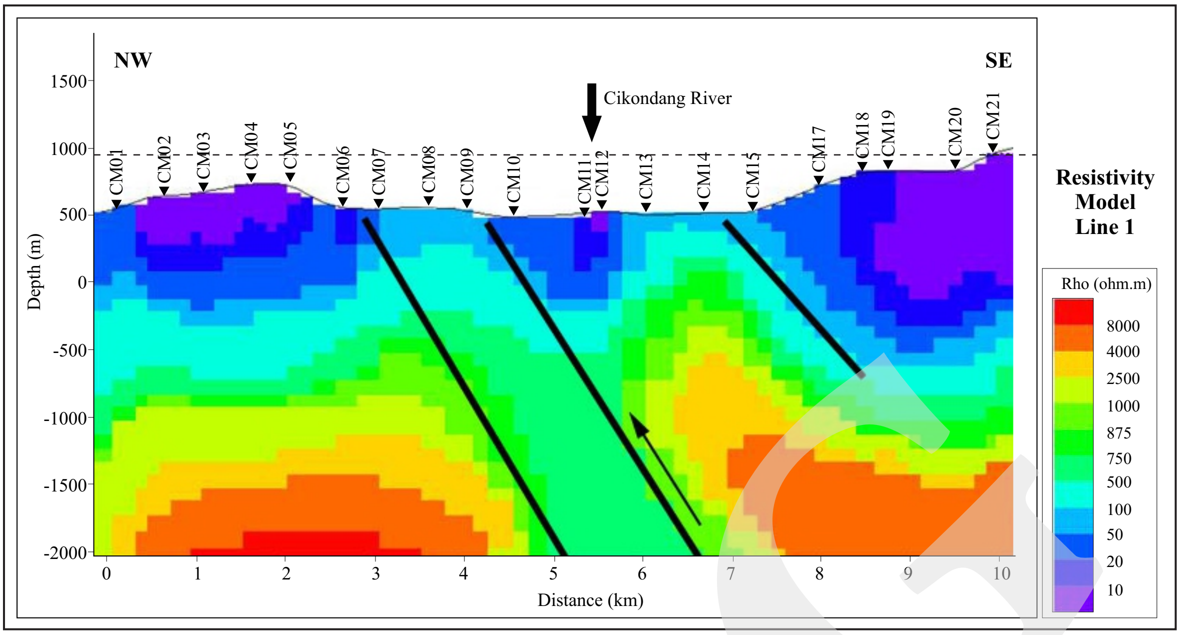

Figure 4. Inverted resistivity model of Line 1.

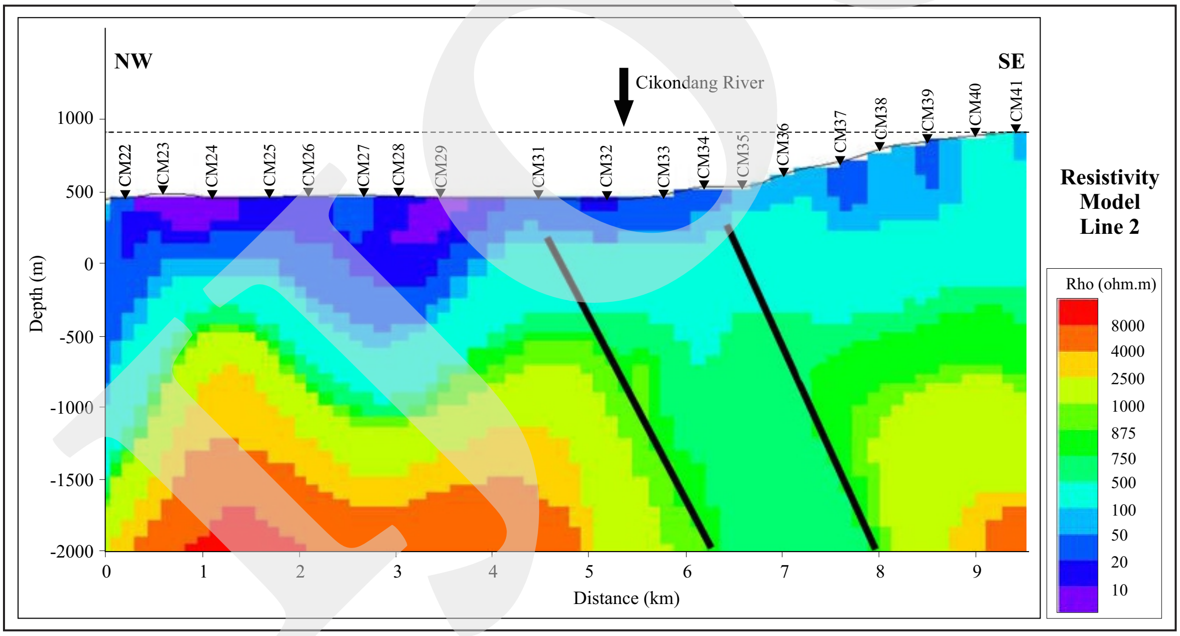

Figure 5. Inverted resistivity model of Line 2.

near surface resistivity distribution is consistent with the exposed lithologies consisting of breccia, tuff, conglomerate, and sandstone as volcanic products from Pliocene and Holocene. Near the surface, the resistivity of Line 2 is slightly different. The southeastern part of this line shows a relatively higher resistivity that correlates to the andesitic lava flow from Pliocene in this area. The basement of the area in both models is at about 1000 m depth, deducted from the high resistivity (> 1000 ohm.m) layers.

Models of Line 1 and 2 (Figure 4 and 5) indicate a low resistivity column in the middle with a higher resistivity at both opposite sides. The low resistivity column might indicate the weak zone that represents the fault zone. These weak zones dip southeastward in about 60°. In addition, the shape of a structure at about 500 m depth of southern part in Line 1 indicates a typical feature of a thrust fault. The tops of the weak zones in both models are located in between 500 and 1000 m depth.

The hill at the southeast of the Line 1 indicates very thick (~ 1500) sediments. The geological map indicates that the rock layer in this part of the area is Pliocene volcanic rock (Pb). This formation comprises breccia tuff, lava, sandstone, and conglomerate, which is consistent with its low resistivity value. From the subsurface model, it appears that the Pb deposition has formed a basin and a hill at the southeastern part. Although smaller and shallower, a basin feature is also indicated at the northwestern part of the line. Line 2 model also shows a basin feature at the northwestern part, but there is no similar basin feature at the southeast of this line.

Discussion

The existence of Cimandiri Fault might be correlated to the subduction zone geometry as the Sumatra Fault Zone to the oblique of the subduction along the Sumatra Island. The oblique subduction at the south of western Java area might affect the tectonic of the island in the same way as the oblique subduction along Sumatra which is responsible to the formation of Sumatra Fault Zone. However, the similar feature does not exist in this western Java region. Instead, there is the Cimandiri Fault Zone, which is not parralel to the trench. The Sunda Strait transition zone with an active extensional force might also give impact to this southwestern Java area as well. Therefore, the tectonic pattern in this area has a more complex origin.

A previous study has suggested that the Cimandiri Fault near Pelabuhan Ratu to Sukabumi area is a sinistral strike-slip fault (Dardji *et al*., 1994). Furthermore, in about the northern part of the fault zone at Cianjur area, there is the Rajamandala Formation with its thrusting complex (Sudjatmiko, 1972). The surveyed area of this study is located in the middle of the of Cimandiri Fault Zone, in Cibeber area across Cikondang River. The line along Cikondang River was presumed as the possible fault line due to its topographic contrast and surface geology differences at both sides.

Resistivity models from this study indicate the existence of weak zone columns from their low resistivity value beneath Cikondang River. The fault zone columns in both models are slightly dipping to the south. Compared to a previous study of similar survey of Cimandiri Fault on the western end (near Pelabuhan Ratu) (Widarto *et al*., 2000; Arsadi *et al*., 2000), the subsurface models displayed different characteristics. The weak zones in those previous studies are almost perpendicular to the surface. In addition, a resistivity model from Widarto *et al.* (2000) also suggested that the basements at the opposite side of the fault have different properties. While this current result does not show any significant differences.

Figure 6 presents a sketch of the subsurface structure of this studied area derived from both resistivity models. Some folds that involve Middle Miocene sedimentary rocks (Mts) are shown on the section. A thrust appears in the middle of the section, with the top of the fault covered by most recent alluvial deposition (Qa) in the region of Cikondang River. This area of Quarternary alluvial separates the Holocene volcanic rock (Qot) at the north and the Pliocene volcanic rock (Pb) at the south. This buried thrust should be a part of the thrusting complex in the northeast of Rajamandala Complex. Previous geological surveys

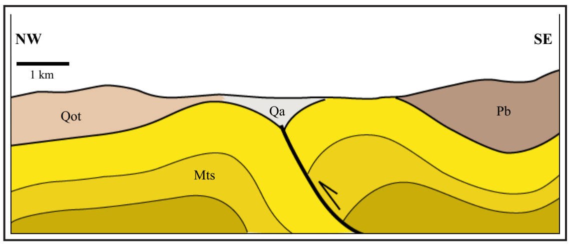

Figure 6. Cross section sketch of the surveyed area.

in the area of Cianjur - Padalarang have suggested that reverse motion is dominant, as indicated by the existence of fold and thrust complex (Hall *et al*., 2007; Marliyani and Arrowsmith, 2014). Fold and thrust complex is related to a continuous compression, which is consistent to the direct stress due to the perpendicular convergence direction of the India-Australian Plate towards the Java Island.

Besides stating that Cimandiri Fault is a thrust fault, Hall *et al.* (2007) has also suggested that it is not an active fault. His suggestion concurs to this present study of this particular area, since the model indicates that the fault is covered by recent deposition. However, the awareness of the existence of this buried fault should not be decreased, since it might trigger an earthquake anytime in the future.

Conclusion and Suggestion

Despite various previous researches have been carried out, the characteristics of the Cimandiri Fault Zone has not been known well. An addition of audio-magnetotelluric method was then applied in the middle of the zone. Two resistivity section models show the significant subsurface structure of Cimandiri Fault Zone at Cibeber, Cianjur. The low resistivity columns in both models indicate weak zones that represent the fault. The dipping fault zone in both models confirmed the previous theories of thrust faults in this northern part of Cimandiri Fault Zone.

Acknowledgements

The Audiomagnetotelluric Survey was possible with the fund from DIPA Research Center for Geotechnology in the fiscal year of 2015. The authors also recognized the hard work of their EM Team: Nyanjang, Sunardi, Dede Rusmana, and Sutarman. The authors gratefully acknowledge the helpful comments and suggestions of the two reviewers.

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