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Beneath the scaly clay and clay breccia of Karangsambung area

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Abstract. Karangsambung area, Central Java-Indonesia, records tectonic evolution of the western part of Sundaland margin. The area is thought to have undergone a long tectonic evolution from paleosubduction, collision with the continental fragments of Gondwana, to the formation of the recent subduction zone. An interesting phenomenon in this area is the presence of the Late Cretaceous ophiolitic blocks with an east northeast (ENE) trending-direction surrounded by the east trend of Eocene - Oligocene sedimentary melange formation. There was also an ENE trending Dakah volcanic rocks unit found in this area, with approximately equivalent age with the sedimentary melange formation. There are two main interpretations regarding this volcanic unit, as an olistostrome and as an insitu shallow subduction magmatic product. Detailed mechanism of the emplacement of the Late Cretaceous ophiolite and the genesis of the volcanic rocks unit and their implications to the regional tectonic model is still open for discussion. Geophysical research in this key area may help to reveal the geometry, relationship among rocks units, and tectonic evolution. Unfortunately, geophysical studies in this area are still lacking. Previous geophysical work in Karangsambung still leaves uncertainty, especially in depth control and spatial resolution issue. Here we describe the results of previous works in Karangsambung as basic knowledge for the upcoming geophysical study.

1. Introduction
Karangsambung, Central Java, is a geologically unique and significant area in Indonesia that records the tectonic evolution of the Sundaland margin. This area, where we can find the Lukulo Melange Complex, is one of three places that expose pre-Tertiary rocks in Java Island. The other two places are Ciletuh in West Java and Jiwo Mountains - Bayat in Central Java. In general, the geology of the Karangsambung area can be divided into pre-Tertiary and Tertiary rocks. The basement of Luk-Ulo complex is believed to have formed in the Cretaceous subduction margin of Java [1-3]. This subduction zone is believed to have extent from Ciletuh in West Java, to Luk-Ulo, and Makasar Strait farther east [4,5]. The Cretaceous subduction zone has a northeast-southwest (NE-SW) direction, in contrast to the current east-west (E-W) trending subduction zone. Some researchers argued that the Cretaceous subduction ceased at the onset of the collision with the Gondwana fragment in the early Middle Eocene [6]. The initiation of the new subduction zone then began after the collision took place though some workers [7] argued that collisions occured in the Late Cretaceous.

An interesting geological feature in the Karangsambung area is the presence of the Late Cretaceous ophiolitic blocks in between the Eocene - Oligocene sedimentary formations [1,8]. These ophiolitic rocks were suggested as part of the Indo-Australian oceanic plate formed as a mid oceanic ridge (MOR) that was uplifted by a reverse fault at the end of subduction during Late Cretaceous to Paleocene [9]. Another interesting phenomenon is the presence of the Tertiary Dakah Volcanics. This
volcanic unit was found spotted and formed an ENE-WSW trend direction in the Karangsambung and Totogan formations. There are two different opinions about this volcanic unit, as an olistostrome \[1,10\] and as an insitu intrusion \[11,12,13\].

There are very few research publications about Karangsambung that is based on geophysical methods. A study based on gravity method \[13\] modeled the Karangsambung ophiolite as a dense body floating on a relatively lighter ground mass, and Dakah Volcanic Unit was modeled as an intrusion. Another study \[14\] was conducted using audio-magnetotelluric (AMT) and gravity methods. Based on these two types of data, they modeled the diabase of Mount Parang as a threshold and Jatibungkus limestone as olistolith. However, the limited number of measurement stations in this study raises the uncertainty on this diabase and limestone geometry.

A regional tomographic seismic publication of Central Java \[15\], interpreted the existence of mafic material in southern central Java that might be emplaced at or before the collision. But the narrow-spread dimension of Karangsambung ophiolite was not positioned well within the model due to the spatial resolution factor. This paper aims to review the geological conditions of Karangsambung, and the tectonic evolution models associated, as a basic knowledge for the upcoming geophysical research in this area.

2. Geology of Karangsambung Area

The Luk-Ulo Melange complex is a pre-Tertiary rocks, the oldest rock which is believed to be the basement of the Karangsambung area. The complex is composed of greywacke, chert, red limestone, basaltic lava, schist, phyllite, and eclogite. These components reside in the clay groundmass \[1\] and indicate the eastnortheast - westsouthwest (ENE - WSW) trend.

![Simplified Geological Map of Karangsambung Area](image)

**Figure 1.** Simplified geological map of Karangsambung area \[16\], divided into pre-Tertiary (light grey) and Tertiary formations (dark grey). The pre-Tertiary Luk-Ulo Melange Complex is surrounded by the Tertiary formations.
Age determination of the Melange Luk-Ulo Complex indicated the age of Early Cretaceous to Early Eocene [1] and Early Cretaceous - Late Cretaceous [8]. Several studies using radiometric methods had also been performed to determine the age of this complex: $117 \pm 1.1$ to $65$ Ma [17], $101.71 \pm 5.09$ Ma [9], $110 \pm 6$ Ma and $115 \pm 6$ Ma [18], and $124 \pm 2$ Ma and $119 \pm 2$ Ma [2].

Based on the petrographic and chemical analysis [9], the ophiolite at Luk-Ulo Melange Complex was interpreted to be derived from the tholeiite magma of the mid oceanic ridge (MOR). The author also suggested that the ophiolite in northern Karangsambung was part of the Indo-Australian oceanic plate that was uplifted by a reverse fault. This emplacement process was expected to occur at the end of the subduction process in Late Cretaceous to Paleocene.

Above the Melange Luk-Ulo Complex, tertiary rock formations were deposited unconformably. Stratigraphically, these Tertiary rocks are divided into Karangsambung Formation, Totogan Formation, Waturanda Formation, and Penosogan Formation in order from the earliest to the latest [1]. The Tertiary rock formations had been folded with the vertical axis in east-west (E-W) direction [8].

The Karangsambung Formation was interpreted as olistostrome with scaly clay groundmass or matrix [1]. In this formation, there were fragments of limestones, polymict conglomerates, and sandstones [8]. The age of this formation was predicted to be Late Eocene [1], Middle Eocene - Early Oligocene [19], or Middle Eocene to the Late Eocene [20]. Totogan Formations were deposited conformably on top of Karangsambung Formation. The formation is composed of clay breccia units, scaly clay units, and breccias units with limestone, sandstone, and conglomerate fragments. The age of this formation was estimated to be Early Oligocene to Miocene [1], Late Eocene - Oligocene to Oligocene - Early Miocene [20,21]. On the top of Totogan Formation, Waturanda Formation was also deposited conformably. The age of Waturanda Formation was thought to be Late Middle Miocene [16]. This formation is composed of breccia and greywacke sandstone intercalation.

The geological structure of the Karangsambung area is very complex. Three major deformation patterns are found in the Karangsambung area [16]. The first geological structures show ENE-WSW direction, specifically found in pre-Tertiary rocks. The second structural pattern has an E-W direction that involves a lot of Tertiary rock. The third pattern is north-south (N-S) trending direction and is considered as the latest pattern [10,22]. In addition, Eocene to Miocene volcanic and clastic rocks were also found in Karangsambung [8]. Tertiary volcanic rocks are commonly found in Karangsambung Formation and Totogan Formation, in the form of diabase intrusion and basalt lava. This rock unit was deposited in the island arc volcanic system [12].

There were two opinions about the Tertiary volcanic rocks exposed at the Luk-Ulo Mélange Complex. The first opinion [1] proposed that the Tertiary volcanic rocks were olistostrome, part of the Totogan Formation and Karangsambung Formation. Another publication [10] supported this opinion. Dakah Volcanic was interpreted as a result of large boulders mixing in the groundmass. This mixing process was interpreted to occur between Oligocene - Miocene.

On the other hand, a new name was introduced for Tertiary volcanic rock in Karangsambung area as "Dakah volcanic rock" [11]. The author proposed that the volcanic rocks were magmatic products of Paleocene subduction. Recent research finding [12] also supported this in-situ intrusion opinion and interpreted that the magma derived from shallow subduction. The age of Dakah volcanic unit [21] is concluded to be Late Eocene – Oligocene. Thus, the Tertiary volcanic activity that produced this volcanic unit might occur simultaneously with the sedimentation process of Karangsambung and Totogan Formation. This opinion was supported by the discovery of volcaniclastic fragments in scaly clay of Karangsambung Formation and clay breccia of Totogan Formation [12].

### 3. Geophysical Point of View

As discussed earlier in the introduction, geophysical research in Karangsambung area has been very limited in number. Based on the assumption that Karangsambung ophiolite was thin oceanic crust slices [9], this MOR product was estimated to have a small dimension and a narrow distribution [13]. Using the gravity method, this author modeled Karangsambung ophiolite as high-density rocks that float on a relatively lighter groundmass. The author also modeled Karangsambung ophiolite with a
southward dipping to a depth of less than 1 (one) kilometer, while the Volcanic Dakah unit was modeled as an intrusion unit that intruded the groundmass and the ophiolite. The gravity model uses the surface rocks distribution as the lateral distribution control. Unfortunately, this gravity modeling was not accompanied by any depth datum references (e.g. wellbore data). This reason, of course, makes the potential method modeling has high ambiguity.

A small piece snapshot of the Karangsambung sub-surface structure is presented from regional geophysical studies [15]. The author uses a tomographic method with seismicity data from the amphibious seismic network MERAMEX. The tomographic model showed the existence of high-velocity anomalies under Karangsambung and Bukit Jiwo. This anomaly was interpreted as mafic material (possibly mantle material) which is uplifted at the time of the collision. This anomaly has a thickness of about 20 kilometers with a southward dipping. This tomographic model also showed the existence of a low-velocity anomaly block in southern Java, which is interpreted as a continental fragment accreted to Sundaland. These findings support the previously proposed collision model [6,7]. Unfortunately, this tomography model has a regional resolution and strongly influenced by the occurrence of the natural earthquake events. This caused objects like Karangsambung ophiolite, with dimensions of about 10 kilometers wide and 2 kilometers thick [3] exposed on the surface, was difficult to map.

A preliminary result of audio-magnetotelluric (AMT) and gravity research in Karangsambung was published recently [14]. The author performed 1D forward modeling on 3 (three) AMT measurements. They modeled a rock body with resistivity value of 4000 Ohm.m at a depth of about 100-400 meters and interpreted it as diabase. They propose that the Gunung Parang diabase has a concordant geometry and probably a sill. However, since the result was based on only one AMT measurement, the modeled geometry of this diabase becomes less convincing.

Based on those three results [13,15,14], there are some disadvantages that leave uncertainties particularly with regard to depth datum control and spatial resolution issues. Geophysics is an indirect method to investigate earth by measuring its physical properties, so it complements each other among methods to reduce ambiguity. We propose the use of magnetotelluric (MT) and audio-magnetotelluric (AMT); methods which are electromagnetic (EM) methods.

MT and AMT are passive geophysical methods that have been widely used in earth-science, for example in the study of the fault zone [23,24], sub-surface structures of volcanic regions [25,26], to a continental scale regional structure [27,28]. This EM method produces time series data, which can then be transformed into frequency domains that represent depth control. Moreover, the independent measurement system in between measurement points in these methods provides an advantage in determining the expected spatial resolution. These two methods also have advantages in technical flexibility in the field, which is only distinguished by the use of induction coil types and their measurement duration. AMT can be used to target depths of up to 2 (two) kilometers, whereas MT up to 4-5 kilometers. Multi depth resolution might help to reveal the geometry, relationship among rocks units, and tectonic evolution of Karangsambung.

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