Coast effects on 3-D inversion of magnetotelluric data for geothermal exploration in East Flores, Indonesia

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Abstract. Nowadays geothermal exploration in Indonesia is beginning to reach small islands, most of which have a prospect in the coastal area. This has influences on the MT data modelling due to the distortion of the electric field component caused by the extreme contrast of resistivity between land and sea. In these conditions, it is necessary to apply the correction of the coast effects. The seawater resistivity (0.3 Ωm) must be included in the 3-D MT modelling. A simulation was conducted to observe coast effects on 3-D MT modelling. Forward 3-D MT modelling is done to obtain synthetic data to compare homogeneous model and coast effects model. The simulation results show that the presence of seawater affects all MT data frequencies, but the most significant distortion occurs in the low frequency. The affected frequency range correlates with the distance between the MT station and seawater. If the distance of MT station to the sea is getting closer, then the disturbed frequency range is greater, and vice versa. The results of 3-D inversion of MT real data with the coast effects model are used to construct a conceptual model for geothermal systems in East Flores. The interpretation shows that the geothermal prospect area in the field is around Mount Anging. This research is expected to be a consideration for drilling recommendations and further development.

Keywords: Coast effects, 3-D inversion, magnetotelluric, geothermal

1. Introduction
Ministry of Energy and Mineral Resources (MEMR) Republic of Indonesia released that the geothermal energy development nowadays is focused on the Eastern Indonesia region, which is mostly located on small islands and coastal areas. The existence of geothermal prospects bordering the coastal area will affect the modeling of Magnetotelluric (MT) data so it needs to be done carefully. MT is a passive electromagnetic (EM) technique that measures orthogonal components of the electric and magnetic fields on the earth's surface as a means of determining the conductivity structure at depths ranging from a few tens of meters to several hundreds of kilometers [1]. The conductive areas (low resistivity) are the main targets in geothermal exploration. 1-D and 2-D inversion modeling of MT data are less precise in describing subsurface structures in complex geothermal fields. Therefore, it is necessary to apply 3-D inversion modeling that can representatively delineate the reservoir structure of a geothermal system [2].

In the interpretation of MT data from a coastal environment, sea effects must be correctly included because seawater is a strong conductor [3]. In other words, MT data obtained near the seashore are not free from sea effects. Conventionally, the term ‘sea effect’ or in some literature called ‘coast effects’
was used to describe the effect of induced currents flowing along land-ocean boundary [4]. The boundaries between the ocean and inland induce severe distortion of electrical fields due to its extremely high conductivity contrast. One way to overcome this influence is to correct coast effects in MT 3-D inversion modeling [5].

2. Methodology

The method used in this research is Magnetotelluric (MT), a geophysical method which involves measuring fluctuations in the natural electric and magnetic fields (E and B) on the earth to determine the subsurface resistivity distribution. The MT method make use of the response of the ground to the propagation of electromagnetic fields that interact with a medium that has certain electrical properties or conductive body [6]. Forward 3-D modeling is a simulation to produce synthetic data from several models which will then be carried out with 3-D inversion with coast effects correction. The real MT data was processed according to the procedures to eliminate the recorded noise and to obtain good quality data. Furthermore, a geothermal system model was designed based on 3-D inversion result of MT data to discover the resistivity structure.

MT 3-D inversion is very important to study and to apply in 3-D earth modeling [7]. It can solve ambiguity, we do not make assumption of strike direction, high degrees of freedom, and spreading data location can be inverted easily without projecting data to some certain straight line. MT 3-D inversion was conducted using MT3DInv-X. Then the output in the form of data $x$, $y$, $z$ and value is used as input in the GeoSlicer-X software to visualize the 3-D model. The result is a conceptual model was constructed based on 3-D inversion of MT data and supported by geology and geochemistry data.

3. Results and discussion

The research area is located in East Flores Regency, East Nusa Tenggara (NTT) and in regional tectonic setting, it is in the middle Banda Arc [8]. The Banda Arc is an active subduction system with parallel subduction, outer back arc, outer arc basin, and magmatic arc that leads to the east 2000 Km from Java anticlockwise to the U-shaped [9] (figure 1). Several volcano complexes are Mt. Anging, Mt. Lekung, Mt. Lereboleng, etc. The observed geological structures are grouped into three types: fault structure, caldera structure, and barangko structure. The several fault structures become permeable zone in a geothermal reservoir as well as at the surface they control the discharge of thermal manifestations.

There are 3 clusters of thermal manifestations:

- APWO hot spring, FWO fumaroles, and alterations in caldera structure or around Mt. Anging.
- APBK, APLM and APHD hot spring on the northern area.
- APMO hot spring on the eastern area.

The water samples in APWO cluster are steam heated water or volcanic water which are related to the up flow zone (upper reservoir), while the rest clusters are outflow zones. Reservoir temperature based on several geothermometers and mixing models is 220 °C.

The coast effects simulation on MT data is done by forward modelling to produce synthetic data. Two models (figure 2) have been made: model 1 for a homogeneous model (without coast effect) and model 2 for the coast effects model. Model 1 is a homogeneous model showing subsurface layers with a certain resistivity distribution as generally in geothermal fields. These layers are overburden layer (resistivity 100 $\Omega$m), clay layer (resistivity 10 $\Omega$m), reservoir (resistivity 50–100 $\Omega$m), and basement layer (resistivity 200 $\Omega$m). While model 2 is a variation of model 1 by adding sea on the east side with a resistivity value of 0.3 $\Omega$m. The depth of sea water is gradual to the east in 2000 meters depth.

These two models are then compared to see the effect of the presence of the sea on the MT curve.
Figure 1. Banda Arc tectonic setting with seismotectonic and history of seismicity. The research area is marked with a yellow box.

Figure 2. Cross section, (a) Model 1 (homogeneous model), and (b) Model 2 (coast effects model).
MT measurement in research area were 45 stations spread especially in areas within the caldera zone of Mt. Anging and around fumarole manifestations. The spacing is 500–1500 m. The closest distance to sea is 800 m and the furthest is 4 km. MT data processing has been carried out according to the procedure to obtain the apparent resistivity and phase curves. Then the static correction process using geostatistical method of averaging is done in order to eliminate the static shift effect.

The 3-D inversion process is applied with two schemes. The first scheme uses a homogeneous initial model with a value of 100 Ωm resistivity on all blocks. Whereas the second scheme includes the coast effects model with a resistivity value of 0.3 Ωm on the block which intersects with the sea area (figure 3). 3-D inversion modelling with coast effects requires bathymetry data to determine the depth of sea water, especially those directly adjacent to the mesh grid design (northwest and southeast sides). The bathymetry data is taken from the Geospatial Information Agency (BIG).

The results obtained from the forward modelling of the two models show a fairly good trend in the MT curve. Model 1 can be used as a benchmark for model 2 which illustrates the influence of the existence of the sea on the MT curve. If the distance of MT station to the sea is getting closer, then the disturbed frequency range is greater, and vice versa (table 1).

Coast effects appear on the MT curve obtained from model 2, namely the presence of a TE and TM curve splitting. In general, coast effects are observed on all MT data frequencies, but the most significant effects occur in the low frequency. The disturbed frequency range correlates with the distance between the MT station and the sea. The closer the MT station to the sea is, the greater the frequency range that is disturbed. As for the MT station which is relatively far from the sea, the disturbed frequency range is getting shorter and only appears in the low frequency. As for data at high frequencies, it is relatively not much affected by the existence of the sea. The MT-001 (7 km from sea) curve starts to be affected by the coast effects at a frequency of 0.1 Hz, whereas on the MT-007 (1 km from sea) curve the frequency of 10 Hz has begun to be affected.

The results of real MT 3-D inversion are displayed as a cross section (figure 4 and figure 5) for homogeneous model (left) and coast effects model (right). In general, the differences between two models are not too significant. It is since some MT data are not available at a low frequency of 0.001 Hz. In addition, it is possible because the sea in this region is strait or shallow sea (Hading Bay in the north and Larantuka Strait in the south), so that coast effects are not very influential. The differences can be observed are the thickness of clay layer, reservoir area, and heat source body. Cross section of coast effects model is quite representative so that it can be used to construct a conceptual model supported by geological and geochemical data (figure 6).
### Table 1. Comparison of MT curves from model 1 and model 2.

| MT Station | Model 1 | Model 2 |
|------------|---------|---------|
| MT-001     | ![Graph](image1) | ![Graph](image2) |
| MT-007     | ![Graph](image3) | ![Graph](image4) |

**Figure 4.** Resistivity cross section on Line 1 (S-N).
4. Conclusion

The simulation results show that MT data can be affected by the presence of seawater which causes the splitting of TE & TM curve. The presence of seawater can influence all MT data frequencies, but the most significant occurs in the low frequency range. The disturbed frequency range correlates with the
distance between the MT station and sea water. The closer the distance between MT station and sea water the greater the frequency range that is disrupted. Geochemical analysis shows the upflow zone is on Mt Anging, while hot waters that discharge on the east and north coasts are an outflow zone. The 3-D inversion results from the two models have different resistivity patterns, especially in clay layer thickness and reservoir boundary. Interpretation of MT data corrected by coast effects is supported by geological and geochemical data which results are quite good and mutually supportive to build a conceptual model. The conceptual model describes the geothermal system in East Flores, the promising zone is inside the caldera.

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