Identification of the structural trap of the hydrocarbon reservoir below volcanic rocks in Majalengka region, Indonesia, using the audio-magnetotelluric method

M T Alfiansyah and Supriyanto

Department of Physics, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia

Corresponding author’s email: supriyanto@sci.ui.ac.id

Abstract. The exploration of hydrocarbons below volcanic rock is a significant challenge in increasing oil and gas reserves in Indonesia. Because mapping using seismic waves does not produce data of good quality in areas of volcanic rock, in this study, the audio-magnetotelluric (AMT) method was used to map the structural trap of a hydrocarbon reservoir. Geophysical surveys were also used to determine the subsurface resistivity values and phase values. The raw data were in the form of time series measurement obtained using equipment from Phoenix Geophysics. The data were processed further into apparent resistivity and phase curves toward frequency. Data processing involved various filtering methods and corrections. The result was a two-dimensional cross-section of the AMT measurement line. The data from the AMT model were interpreted in an integrated manner using geological data. The results showed a relatively good relationship between the AMT data and the geological data. The results indicate a fault zone in the area of measurement and bedding formations that have produced a petroleum system. The lower part of the Cinambo Formation, which consists of shale-dark, acts as a source rock. While the upper part of the Cinambo Formation which consists of massive sandstone with very fine sand to silty above the shale-dark is thought to be a reservoir. The hydrocarbon trap could be of the structural type because there is a fault zone in the area of measurement.

Keywords: Structural trap, hydrocarbon reservoir, Majalengka region, audio-magnetotelluric method

1. Introduction

The exploration of hydrocarbons beneath volcanic rock has become a significant challenge in increasing oil and gas reserves in Indonesia. Usually, hydrocarbon exploration is performed on sedimentary rock formations using seismic methods. However, in mapping volcanic rocks, seismic methods suffer from the disadvantage of reverberation (multiple reflection) on structures owing to the nature of the volcanic rocks. As such, the seismic data captured does well represent the structure of the rocks beneath the surface. Alternatively, the magnetotelluric (MT) method is capable of mapping the structure of rocks by analyzing the resistivity of rock beneath volcanic regions.

The West Java area is an area located on the volcanic–magmatic groove that is part of the Sunda Arc [1, 4] The present research was carried out in the border area between Majalengka and Cirebon. This area is north of Mount Ceremai and south of Mount Kromong. The rock formation in
the area is dominated by volcanic rock sediment; young and old rocks are present in the volcanic zones [5].

Subsurface conditions were studied using the MT approach to determine hydrocarbon reservoir boundaries. Electromagnetic waves are very sensitive to conductive media. In a petroleum system, the conductive medium is a cap or seal rock because it usually consists of conductive clay minerals. While the resistive medium, in the petroleum system, is a hydrocarbon reservoir because reservoir rock and hydrocarbons fluid themselves have high resistivity values. The resistivity distribution of subsurface rock based on MT surveys can be modeled in several ways, one of which is through the data inversion process. Then, the cross-section of resistivity value is used to map the structure of the rocks at the base of the measuring area [6].

An MT survey was performed to determine the structure of the covered volcanic rock, which allowed the hydrocarbon reservoirs within to be identified. Based on this survey, the structure below the surface was determined based on volcanic rock resistivity values obtained at deep penetration. The data obtained were integrated with the geological data.

2. Experimental method

The research steps taken in this study were data acquisition, data processing, and data interpretation. Audio-magnetotelluric (AMT) data acquisition was conducted in October 2016. MT measurements were made at 15 points along one measurement line. For AMT data processing, several steps were followed. First, we used time series correction with SSMT2000 to reduce the noise signal. Second, we used crosspower correction with MT Editor to smooth the data and to identify the trends related to the structure. Finally, we used inversion of the corrected AMT data to produce a resistivity map and model using WinGLink.

We made an interpretation of the geological structure by combining the AMT data with the geological map data. A geological map can help elucidate structure and formation. The source rock potential was based on geochemical information, and the hydrocarbon reservoir potential was based on core samples, which showed the visual porosity in several formations. The geochemical information (kerogen type index, kerogen composition index and the maturity index; kerogen type index is obtained from TOC versus S2) was obtained from the additional data from paper.

3. Results and discussion

The geochemical data show the TOC results for the Cinambo formation. The kerogen type index (figure 1) [2] shows that the Cinambo Formation is of type III kerogen, which is derived primarily from terrigenous plant debris that has been deposited in shallow to deep marine environments.

The TOC value indicates the quantity, but not the quality, of the organic matter. The S2 value relates to the hydrocarbons evolved from the sample during the second programmed heating stage of pyrolysis. These hydrocarbons result from the cracking of heavy hydrocarbons and from the thermal breakdown of kerogen. S2 is given in milligrams of residual hydrocarbon per gram of rock, thus, indicating the potential amount of hydrocarbon that the source rock might produce if thermal maturation continued [3].

Figure 1 shows that the TOC can be classified as type III kerogen. It shows TOC versus S2 which have Type III kerogen that contain the residual hydrocarbon. Type III kerogen is derived mainly from land plants and contains little fat or wax. This kerogen type is also called vitrinite. Its main sources, terrestrial plants, are found in thick detrital sediments along the continental margin.

The results of the 2D inversion of the AMT data show the resistivity variations in the formation structure. We combined these data with the geological map and show the model that represents several main formations. We used the resistivity information presented in table 1 to interpret the results of the 2D inversion of the AMT data.
Figure 1. Hydrogen index versus thermal environment [2].

Table 1. Petrophysical properties of materials in the petroleum system.

| Property     | Resistivity, \( \rho \) (\( \Omega \cdot \text{m} \)) | Density, \( \sigma \) (\( \times 10^3 \text{ kg/m}^3 \)) | S-wave velocity \( V_s \) (m/s) | P-wave velocity \( V_p \) (m/s) |
|--------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Shale        | 10–1,000                        | 2.0–2.50                        | 780–2,300                       | 1,330–3,970                     |
| Limestone    | 10–10,000                       | 2.3                             | 1,450–3,500                     | 2,500–6,000                     |
| Oil          | \( \geq \) 10,000               | 2.93                            | 1,400                           | 2,600                           |
| Gas          | \( \geq \) 100,000,000          | 0.7–0.8                         | 1,400                           | 2,350                           |
| Groundwater  | 1–100                           | 1–1.02                          | 1,450                           | 2,700                           |

Based on this inversion, the results (figure 2) relate to three zones: (i) a zone of low resistivity termed “clay rocks”, which have a resistivity range of 1–16 \( \Omega \text{m} \), (ii) a zone termed the “intermediate reservoir” with a resistivity range of 20–65 \( \Omega \text{m} \), and (iii) a high resistivity zone with values \( \geq \) 100 \( \Omega \text{m} \).

The results of the second inversion indicate low resistivity from station AMT-02 to station AMT-13, and high resistivity at stations AMT-06 and AMT-07. Depletion of the low resistivity zone is seen in the 2-D inversion results at stations AMT-06 and AMT-07.

The medium resistivity zone at stations AMT-02 to AMT-05 is seen at a depth of 400–800 m, whereas at stations AMT-08 to AMT-12, it is located at a depth of 1000–1500 m in the 2D inversion results. In the zone of high resistivity (\( \Omega \text{m} \geq 100 \)), the 1D inversion results indicate a dome structure below stations AMT-06 and AMT-07 at shallow depth.

The 2D inversion, together with the interpretation of the line measurements (figure 2), indicate a normal fault that separated between AMT-06 and AMT-07. This fault serves as a fault trap for hydrocarbons generated in the Cimambo Formation. Maturity of source rock in the lower part of the Cimambo Formation will increase over time and the resulting hydrocarbon fluid flows into potential reservoir rocks such as the upper-part of Cimambo Formation which have sandstone as a reservoir.
The Kaliwangu Formation serves as a seal owing to the presence of clay rocks. Based on the results of the 2D inversion of the AMT data and the additional data supporting the interpretation, we can observe the evidence of a hydrocarbon reservoir in this geological area as shown in figure 3.

4. Conclusion
This study shows that the AMT method, together with the supporting geochemical and geological data, can be used effectively in hydrocarbon exploration. The AMT data yielded a resistivity mapping model that can be used for geological structure interpretation, especially in volcanic areas. The interpretation of the line measurements indicates a geological structure with source rock potential and a hydrocarbon reservoir around the area of interest. The identification of the hydrocarbon reservoir depended on source rock potential and the visual porosity of core samples. According to the limitations of the AMT method in the early days of its application to hydrocarbon exploration, the method will be more effective in certain environments.

Acknowledgments
This study was financially supported by Universitas Indonesia through Publikasi Internasional Terindeks 9 Grant 2019 with the contract number NKB-0033/UN2.R3.1/HKP.05.00/2019.
References
[1] Martodjojo 1984 *Evolusi Cekungan Bogor* (Bandung: Institut Teknologi Bandung)
[2] Praptisih dan Kamtono 2016 *Jurnal Geologi dan Sumberdaya Mineral* 17 1-11
[3] McCarthy K, Niemann M, Palmowski D, Peters K and Stankiewicz A 2011 *Oilfield Review* 23 32-43
[4] Armandita C, Mukti M, Satyana A 2009 *Proc. Indonesian Petroleum Association* 33rd Ann. Conference (Jakarta) (Jakarta: Indonesian Petroleum Association)
[5] Djuhaeni dan Martodjojo 1989 *Geologi Indonesia* 12 227-52
[6] Zhang K, Wei W, Lu Q, Dong H and Li Y 2014 *J. Appl. Geophys* 106 23-36