Optimization of 2-D Magnetotelluric (MT) Modes Based on Data Dimensionality to Delineate Potential Area for Shale Gas Prospect in Kutai Basin, East Kalimantan, Indonesia

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Abstract. We conducted a study using the magnetotelluric method in the Kutai Basin, which is one of the largest and deepest tertiary sedimentary basin located in the province of East Kalimantan, Indonesia. The Kutai Basin, which is one of the sedimentary basin that is proven to produce hydrocarbons in Indonesia, also has the potential for shale gas with all the complexities of its geological structure. Inversion of 2-D MT can generally be done in three modes with different sensitivity. We perform data processing objectively to obtain the best quality data. We continued our data processing to the inversion process with a range from 80.78% to 97.09% coherency data. We also performed sensitivity skewness calculations to determine the dimensionality of our data. The map of sensitivity skewness is shown for the vertical path A – A’ with direction N – S in our study area. Based on the calculation results, the skewness value below 0.3 is obtained around the frequency 320 - 0.002 Hz, and associated with the 2-D structure while value above 0.3 are obtained around the frequency 0.00198 - 0.00034 Hz at KT34 and KT36 stations. Based on dimensionality calculations, it is concluded that the MT data in the Kutai Basin is dominated by 2-D structural responses, so that the TE + TM (invariant) mode is the best measurement mode for inversion modeling. We also performed calculations to obtain the optimum smoothness factor (tau) using a trade-off curve. Based on the results of the inversion with the optimization of these data parameters, we obtained a subsurface geological structure pattern such as fault and fold structure along the vertical path of A – A’. The low resistivity anomaly is interpreted as a response to the presence of black shale which is part of the Pamaluan Formation. The top of the Pamaluan Formation is estimated at the depth that varies from 2000m to 4000m below the surface along the A – A’ vertical cross-section.

1. Introduction
Black Shale is thought to be a possible cause of the low resistivity anomaly found in the Earth’s upper mantle [1, 2, 3]. The high thermal maturity (> 4000) is the reason for the low resistivity value in black shale. The increase in temperature causes a change in the chemical composition of organic carbon found in
black shale which causes a decrease in the resistivity value of the rock [4]. A recent study was conducted to describe the black shale layer in South Africa as a continuous layer with low resistivity values mapped to hundreds of kilometres [5]. Based on this study, measurements in the laboratory were also carried out on black shale samples and confirmed that low resistivity values were found in some rock samples with high thermal maturation [6]. With the unique electrical resistivity properties of black shale, we conducted a study using magnetotelluric method that can depict subsurface geological structures based on electrical properties of rocks from shallow to very deep depths to delineate the potential for shale gas in the Kutai Basin.

2. Geology of Study Area

Based on the geological map of Samarinda sheet [7] shown in Figure 1, there are geological structures with fold pattern in the form of anticline and syncline with a relatively NE - SW oriented axis around this study area. Our A – A’ vertical cross section intersecting one axis of the anticline and Mahakam River in station KT36 and KT34 respectively. Based on the order of sedimentary rocks deposition around the study area, the Pamaluan Formation is the oldest rock formation which were deposited during the Oligocene to Early Miocene periods. Furthermore, it was continued with the deposition of the Pulaubalang Formation which was deposited unconformably with the Balikpapan Formation during the Middle Miocene to Late Miocene. The last one is the quaternary sediment deposited in a fluviatile, paludal, deltaic and coastal environment. It is estimated that the black shale in the Pemaluan Formation could be a potential source rock for the Kutai Basin petroleum system due to its high value of both TOC and thermal maturity.

Figure 1. Geological map of the Kutai Basin overlayed with magnetotelluric stations and vertical cross section A – A’ [7]
3. Data and Methods

In this study, we used the magnetotelluric data of the Kutai Basin consisting of 5 sounding points. Respectively from North to South are KT31, KT30, KT34, KT36, and KT37 along the section A – A’ with a ± 20 km-length section. We performed data processing to increase the quality of MT data based on the coherence value. The term coherence is quite popular to use to determine data quality. For MT data, high coherence value is one of an acceptance criteria and indicates a low contaminated coherent noise in signal [8]. A series of data processing techniques such as robust processing and cross power selection were also conducted in order to obtain an apparent resistivity curve as shown in Figure 2. Histogram comparison of the coherence of raw data and data processing results is shown in Figure 3.

![Figure 2](image1.png)

**Figure 2.** Apparent resistivity curve after performing data processing stages. Smooth curves of our MT data indicate high signal to noise ratio.

![Figure 3](image2.png)

**Figure 3.** Comparison of the coherence value between pre and post processing data. We managed to improve our quality data from 76.42 – 94.2% to 80.78 – 97.09%.
3.1 Dimensionality of MT Data

Dimensionality of MT data for regional electrical structures was originally introduced by [9] based on skewness data (S) which satisfies equation (1).

\[
S = \frac{|Z_{xx} - Z_{xy}|}{|Z_{yx} - Z_{yy}|}
\]  

(1)

Where \(Z_{xx}, Z_{xy}, Z_{yx}\) and \(Z_{yy}\) are the impedance tensor elements.

Skewness can be used to evaluate whether the subsurface electrical structure beneath the sounding point of MT qualitatively influence by 1-D, 2-D or 3-D distortion. However, the skewness value [9] in practice still deviates when it is exposed to telluric distortion in the impedance tensor components. [10] proposed a skewness (\(\eta\)) measurement formula that takes into account the effects of distortion on the impedance tensor components. The calculation of skewness (\(\eta\)) by Bahr is shown by equation (2).

\[
\eta = \frac{\sqrt{2} \left( \text{Re} Z_{xx} \cdot \text{Im} Z_{xy} - \text{Re} Z_{xy} \cdot \text{Im} Z_{xx} + \text{Re} Z_{yy} \cdot \text{Im} Z_{yx} - \text{Re} Z_{yx} \cdot \text{Im} Z_{yy} \right)}{|Z_{xy} - Z_{yx}|}
\]  

(2)

Where \(\text{Re}\) is the real component and \(\text{Im}\) is the imaginary component of a complex number. \(\eta\) values above 0.3 can be categorized as the response of the 3-D electric structure below the surface, \(\eta\) values below 0.3 are categorized as the response of 2-D electric structures, while the \(\eta = 0\) indicates the ideal 1-D or 2-D structure conditions [10, 11]. Previous studies of dimensionality and its effect on the sensitivity of MT measurement modes have been carried out by creating a 3-D synthetic model and testing the inversion results of each MT measurement mode which shows that TM is more sensitive to 3-D structures and TE+TM (invariant) is more sensitive to structure 2-D [12].

4. Result and Discussion

We used all frequencies (320 - 0.000034 Hz) in the data set to calculate sensitivity using the impedance tensor data decomposition. The plot of the calculation results is shown in Figure 4.
Figure 4. Map of the distribution of sensitivity on the vertical cross section A - A’ which shows the distribution of calculated values \( \eta \) is dominated by values in the range 0-0.3

It can be concluded that the 2-D structure is more dominant in the vertical section A – A’, so that the TE+TM mode is the most sensitive mode for the 2-D inversion model. We applied a 2-D inversion model based on the NLCG inversion algorithm [13]. For the purposes of making the inversion model, we used MT data with a frequency range of 320-0.01 Hz considering that data below 0.01 Hz is highly contaminated by coherent noise. Our model parametric test was carried out based on the Roughness and RMS plots on the trade-off curve as shown in Figure 5. The comparison between the 2 most optimal model parameterization values (tau) (1 and 5) is shown in Figure 6. Based on these comparisons it can be concluded that tau 1 shows the best results and is more sensitive to anticline in vertical sections A – A’.

Figure 5. The trade-off curve to find the optimum model parameterization for MT 2-D inversion
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The interpretation of the vertical section A – A’ (Figure 7) is validated by the geological map of the Samarinda sheet which shows the presence of an anticline and syncline fold structure pattern on the surface and crossed by A - A’ vertical section. Subsurface geological feature e.g. fault and fold structure can be well imaged based on the contrast of resistivity. The contrast of resistivity anomaly is interpreted as the top of the black shale bed which is characterized by low resistivity value (<5 ohm m).

The low resistivity anomaly are well resolved below the A – A’ vertical section which then interpreted as the response of matured organic black shale bed from the Pamaluan Formation at depths varying from 2000 m to 4000 m below the surface. Constraints on the geological map that show the outcropping of the Pamaluan Formation at the KT36 station can also be characterized well by the results of the 2-D vertical section inversion model A - A’.

![Figure 6. Comparison of 2-D MT inversion model (Respectively from above to below; TE, TM, TE+TM) at value of tau 1 and 5](image-url)
5. Conclusion
Optimization of parameters in 2-D MT inversion is very influential on 2-D MT inversion model, the wrong parameter selection will cause misinterpretation of subsurface geological information. We managed to determine the optimum parameters based on dimensionality data and optimum model parameterization values to obtain a vertical section that delineates the top black shale bed from the Pamaluan Formation and subsurface geological features such as the ramp anticline/fault-bend fold.

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