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The Application of Magneto Telluric Method to Identified Petrology System of Pre-tertiary Sediment at Bintuni Gulf, West Papua Indonesia

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Abstract

Objectives: To identify and analyze the petrology system of pre-teriary sediment at Bintuni Gulf Area of West Papua Indonesia**. Methods/Statistical**: To identify the petrology system, we utilize the magnetotellurique exploration method to obtain the resistivity value of the reservoir of hydrocarbon. There are 14 sounding points purpose to identify and detect the reservoir hydrocabon trapped at Bintuni basin. Then the reservoir location was mapping in 2D modeling. To get the best quality of the data, we performed coherence analysis of data on every stage processing. The stage of data analysis begins with the robust processing, cross power selection, resistivity analysis, skin depth analysis, and 1-D and 2-D Modeling. **Results**: The coherence analysis shows that the quality of coherence at least achieved at 70% and the highest coherence 9%. The hydrocarbon in Bintuni basin area resulted by sedimentary rock with the Total Organic Carbon (TOC) of about 0.51 % to 88%. The exploration by magneto telluric method showed that the Bintuni basin is the new potential reservoir in West Papua. From the analysis and interpretation of data, it is shown that rocks cover with low resist vitas (3 – 13 Ωm) interpreted as the clay Kembelangan formation. Reservoir with moderate resistivity (13 -70 Ωm) as sand stone at Tipuma formation. The source by rocks with high resistivity (70 - 200 Ωm) indicated as black shale of Ainim formation. The improvement of the research shows that one more again potential location of hydrocarbon in Papua Indonesia. **Application**: The application of magneto telluric method is reducing if there are aquifer of hydrocarbon was trapped under the layer of hard rock that cannot be detected with the seismic method then the magneto telluric method who use electromagnetic waves can handle it.

Keywords: Hydrocarbon, Magneto Telluric, Petrology System, Reservoir, Resistivity

1. Introduction

The Bintuni Basin is one of the potential basins of the hydrocarbon in Papua, Eastern Indonesia and has been producing with the working areas located on the south coast the gulf of Berau. Based on the research about potential hydrocarbon in the Bintuni basin, it was found that the potential of hydrocarbon that derived from the sediment Pre-tertiary[1–3]. The potential hydrocarbon was found in the sediment at the Ainim formation. Survey of geophysical exploration was made to find the possibility of petroleum system from pra-tersier sediment (formations ainim) at the Bintuni basin. The Ainim Formation estimated is at a depth of thousands of meters under the surface of the earth. It Required the Geophysical method who able to provide information until at the depth of thousands of meters under surface of the earth. One method that has been used is the seismic method. But exploration with this method does not work, because Kais Formation consisting of limestone at the depth of 1600 is a powerful reflector, so that seismic data under the Kais Formation of kais considered being lacking accurate. The seismic reflection method has become a standard tool in oil and gas exploration for decades, and almost all of resources were found by extensive use of the seismic method. The trend towards increasingly difficult exploration targets where seismic is less effective led explorationists to consider other geophysical techniques in a multi-disciplinary

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exploration program. Among supplementary geophysical techniques in petroleum exploration, the Magneto Telluric (MT) method has been known for its capability in resolving geological structures less favorable for seismic method (e.g. volcanic or basaltic high-velocity cover, complex over thrust structures etc.). However, the magneto telluric (MT) method has not been employed for oil and gas exploration in Indonesia. Therefore, the objective of this paper is to introduce the MT method and its application for exploration petroleum system in Bituni Basin at east Papua Indonesia. The MT method is a frequency-domain Electromagnetic (EM) sounding technique used to investigate the electrical structure of the earth's subsurface. The method exploits naturally existing EM fields (typically in frequency bands that span from 0.001 Hz to 10 kHz) as signal source. These primary fields induce secondary electric and magnetic fields in the conductive earth. The transient variation of the EM fields recorded at the surface of the earth is therefore diagnostic to the subsurface electrical properties, i.e. conductivity or resistivity. Electric currents caused to flow in the earth by earth's changing magnetic field are called "telluric currents. The EM waves which constitute the signal for MT arise from (a) distant lightning (above 1 Hz) and (b) electric currents flowing in the ionosphere (below 1 Hz). The EM field caused by these changing currents radiates around the earth (as do radio waves), reflected repeatedly between the conductive ionosphere and the relatively conductive earth. The MT method has a wide range of applications, from shallow investigations (geotechnics, groundwater and environment) to moderate and deep target in exploration of natural resources (mineral, geothermal and petroleum) depending on the frequency band used. However, the MT method had been long known as the preferred method in geothermal exploration due to its great investigation depth and its effectiveness in delineating low conductivity zones associated with high temperature effects, e.g. alteration. The Maxwell's equations define the fundamental relationship between EM field vectors, i.e. E (electric) and H (magnetic). Diffusion equation of EM waves in a homogeneous medium leads to solution with exponential decay of EM wave's amplitude with depth. In this case, skin depth is defined as the depth at which the amplitude of EM waves becomes e-1 of that at the surface. Skin depth (in meters) is expressed as:

$$\delta \approx 500\ (\rho T)^{1/2} \qquad 1$$

Where ρ is resistivity (in Ohm.m) and T is period (in second). The equation (1) shows that slower attenuation of EM wave is obtained for longer period and higher resistivity of the medium. Therefore, the skin depth is associated with the penetration depth of EM waves. It also describes the principle of MT sounding, i.e. information on variation of resistivity with depth is obtained by recording MT signals from a wide frequency band. Model response (forward modeling) of more complicated resistivity distribution is obtained by resolving diffusion equation of EM waves in 1-D or 2-D media. The ratio of electric and magnetic fields, either from forward modeling and from measurement, is the impedance (Z) and usually expressed as apparent resistivity and phase:

$$\rho_0 = \frac{1}{\mu_0 \omega} Z^2 \qquad 2$$

$$\varnothing = tan^{-1} \frac{Im\,Z}{Re\,Z} \qquad 3$$

MT sounding curves are log apparent resistivity versus log period and phase versus log period.

EM field's variation with time is measured by using coil magnetometers and nonpolarizable (porous-pot) electrodes. Two horizontal components of electric field (E_x *and* E_y) and three components of magnetic field (H_x, H_y *and* H_z) are recorded. Signals are subject to filtering and amplification in an analog unit, while the recording s performed in the digital unit that consists of multi-channel Analog to Digital Converters (ADCs) and data storage. Typically, the frequency between 0.003 Hz to 1 kHz is subdivided into three overlapping frequency bands, i.e. High Frequency (48 - 1024 Hz), Medium Frequency (3 - 64 Hz) and LF (0.005 - 4 Hz). High and medium frequency variations are recorded first, continued by low and very low frequencies with longer recording time.

At each frequency band, real-time quality control of data is done by analyzing raw sounding curves obtained from data processing performed in the receiver unit. Based on coherency and outlier limit tests, bad data are discarded and Signal to Noise ratio (S/N) is increased by application of analogue filters and amplifiers and also by accumulating stacked data. Field processing capabilities allow data quality control, immediate re-recording of poor quality site and optimization of MT survey grid.

Measurements are preferably conducted during minimum anthropogenic noise since sensitive sensors are used to measure very small EM field variations. MT signals are usually of good quality and strength after midnight and just before dawn. Although distant lightning is the main EM signal source for MT, heavy rain and thunderstorm occurred at or close to measurement sites will saturate the data with noise. In such case, the measurement is usually postponed, in general, one-day and up to two-day measurement is necessary to record complete MT signals (from high to low frequency) at each site. This includes deployment and set-up of the equipment in the morning, measurement of MT signals from noon to morning of the next day, removing the equipment and moving to the next site. In difficult areas, measurements are usually performed by flying camp.

2. Material and Method

The basic principle of magneto telluric method is the propagation of electromagnetic wave in conductive medium. The electromagnetic waves can be obtained from Maxwell equations as

$$\nabla . \boldsymbol{E} = \frac{\rho}{\varepsilon_0} \qquad 4.a$$

$$\nabla . \boldsymbol{B} = 0 \qquad 4.b$$

$$\nabla x \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial \boldsymbol{t}} \qquad 4.c$$

$$\nabla x \boldsymbol{B} = \mu_0 \sigma \boldsymbol{E} + \mu_0 \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial \boldsymbol{t}} \qquad 4.d$$

And by doing curl operation on similarities Maxwell equation on obtained the equation of electromagnetic waver as

$$\nabla^2 \boldsymbol{E} - \mu_0 \sigma \frac{\partial \boldsymbol{E}}{\partial \boldsymbol{t}} - \mu_0 \varepsilon_0 \frac{\partial^2 \boldsymbol{E}}{\partial \boldsymbol{t}^2} = 0 \qquad 5.a$$

$$\nabla^2 \boldsymbol{B} - \mu_0 \sigma \frac{\partial \boldsymbol{B}}{\partial \boldsymbol{t}} - \mu_0 \varepsilon_0 \frac{\partial^2 \boldsymbol{B}}{\partial \boldsymbol{t}^2} = 0 \qquad 5.b$$

And solutions of the equation are

$$\vec{\boldsymbol{E}}(\boldsymbol{r},\boldsymbol{t}) = \vec{\boldsymbol{E}}_0 \boldsymbol{e}^{\boldsymbol{i}(\boldsymbol{wt}-\boldsymbol{kr})} = \vec{\boldsymbol{E}}(\boldsymbol{r}) \boldsymbol{e}^{\boldsymbol{iwt}} \qquad 6.a$$

$$\boldsymbol{B}(\boldsymbol{r},\boldsymbol{t}) = \boldsymbol{B}_0 \boldsymbol{e}^{\boldsymbol{i}(\boldsymbol{wt}-\boldsymbol{kr})} = \vec{\boldsymbol{B}}(\boldsymbol{r}) \boldsymbol{e}^{\boldsymbol{iwt}} \qquad 6,b$$

where,

$$\vec{B}(r) = B_o e^{-ikr} \qquad 7.a$$

$$E(r) = E_o e^{-ikr} \qquad 7.b$$

In this equation the wave number of k is a complex number given by:

$$k^2 = (i\mu\omega\sigma - \mu\varepsilon\omega^2) \text{ or}$$

$$k = \sqrt{\left(i\mu\omega\sigma - \mu\grave{o}\omega^2\right)} \qquad 8$$

In geophysical exploration, electromagnetic method commonly used to investigate the conductor medium where $\mu\sigma\omega \gg \omega^2 \mu\varepsilon \, or \, \sigma \gg \omega\varepsilon$ in so that $\omega^2\mu\varepsilon$ can be ignored. Thus the number of waves is $k = \pm\sqrt{i\omega\mu\sigma}$. In a coomplex variable form, the wave number can be written as: $k = \alpha + i\beta$ where $\alpha = \beta = \sqrt{\frac{\mu\omega\sigma}{2}}$ So that a solution the wave equation electrical magnetic field obtained as:

$$\vec{E}(r,t) = E_0 e^{-\sqrt{\frac{\mu\omega\sigma}{2}} r} e^{i\left(\omega t - \sqrt{\frac{\mu\omega\sigma}{2}} r\right)} \qquad 9.a$$

$$\vec{B}(r,t) = B_0 e^{-\sqrt{\frac{\mu\omega\sigma}{2}} r} e^{i\left(\omega t - \sqrt{\frac{\mu\omega\sigma}{2}} r\right)} \qquad 9b$$

The penetration depth (skin depth) is the depth capable of being penetrated by electromagnetic wave until to 1/e of the initial amplitudonya. Based on these remarks then the skin depth obtained as[4–7]. The characteristics impedance of electromagnetic wave is obtained as:

$$Z_{xy} \equiv \frac{E_x}{H_y} = \left(i\mu\omega\rho\right)^{0.5} \qquad 10$$

And the resistivity of earth is given by:

$$\rho = \frac{1}{\mu\omega} \left| Z_{xy} \right|^2 \qquad 11$$

Magnetotelluric method is one of geophysical exploration methods use the natural electromagnetic field for the investigation of natural resources under the surface of the earth[8]. This Electromagnetic fields inflicted by various processes of physics, so that the spectrum frequency very wide (10-5 hz -- 104 hz The data acquisition was undertaken in the basin Bintuni at West Papua[9].

2.1 Magneto Telluric Data Processing

The recorded data are stored in the receiver's hard disk or flash memory capable for storage of data for several sites or several days of measurement. The time series data are then downloaded to the personal computer at the basecamp for preliminary data processing. In frequency domain, horizontal components of electric and magnetic fields are related by the following equation

$$\begin{vmatrix} E_x \\ E_y \end{vmatrix} = \begin{vmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{vmatrix} = \mathbf{E} = \mathbf{Z} * \mathbf{H} \quad \mathbf{10}$$

where, each component is function of frequency or period. The MT data processing is essentially spectral analysis of electric and magnetic fields time series data from which the transfer function or impedance tensor is estimated. The readers are referred to standard textbooks and published papers for detailed description of MT data processing. The impedance tensor obtained from data processing is associated with the measurement coordinate system, where x-and y- axes are conventionally set to North and East respectively. The impedance tensor represents the subsurface resistivity distribution at each site in a 3-D way, i.e. it varies as function of the coordinate system. A tensor can be rotated mathematically in order to obtain the tensor associated with any different coordinate system. A clockwise rotation of an angle α will results in an impedance tensor in a new coordinate system as follows

$$Z^* = RZR^T.R = \begin{Bmatrix} \cos\alpha & S\sin\alpha \\ -\sin\alpha & \cos\alpha \end{Bmatrix} \qquad 12$$

Where is a rotation matrix and $(.)^T$ is matrix transpose notation By assuming that in 1-D or layered medium the impedance is scalar (it does not depend on the coordinate system) then the so-called invariant parameters can be extracted from the impedance tensor. The invariant parameters that do not vary with the angle of rotation represent overall resistivity distribution at each sounding site. One of the invariant parameters is the well-known determinant of the impedance tensor.

If the structure is purely 2-D and the rotated coordinate system is parallel or perpendicular to the strike of the structure, then the impedance tensor will take a simpler form.

$$Z_{2D} = \begin{pmatrix} 0 & Z_{xy} \\ Z_{yx} & 0 \end{pmatrix} \qquad 13$$

In equation (13) are termed TE-mode (transverse electric) and TM-mode (transverse magnetic) impedances respectively if x-axes is parallel to the strike. The impedance tensor can be rotated incrementally to obtain impedance tensor close to the one expressed in equation (13) and to estimate the strike directionOn a regional basis, the basin of Bintuni are in the around area of 3 collisions of tectonic plate namely the Eurasian plates, Pacific plates and Indo-Australia plates procedure of research at location area is show in Figures 1 and 2.

The data consisting of electrical (TE) and magnetic fields data (TM). Because the data recording is always with noise and influence the quality data. To reduce the influence of noise done with calculated the coherence each data. the next step of data processing was transformation of data from time domain to frequency of data the next step was the calculated the resistivity for every value of frequency, cross power and calculated the resistivity average and robust processing. The final of data processing is skin depth analysis and done the resistivity inversion modeling in 1 and 2 dimensional modeling (1- D and 2- D)[8–10]. From 1-D and 2-D modeling can be identified the kind of rock reservoir as the petroleum system. The main structure of the Bintuni Basin consisting of a horizontal fault, the block normal fault. Generally, the pre tertiary Stratigraphy the Bintuni basin cannot be separated from the stratigraphy of West Papua. The data used in this research represents the used to determine the characteristic impedance, resistivity and skin depth of electromagnetic wave at the research area. The elevation of the research area, can be explained as inverse modeling located in lowland valley, with an altitude between 19 m -25 m from the mean sea level (msl), and there are two areas which are located in highlands with an altitude between 80 -100 m from msl namely the east and the western part of the research area. And between the highlands there is an area with the height of 60 m as shown in Figures 3 and 4.

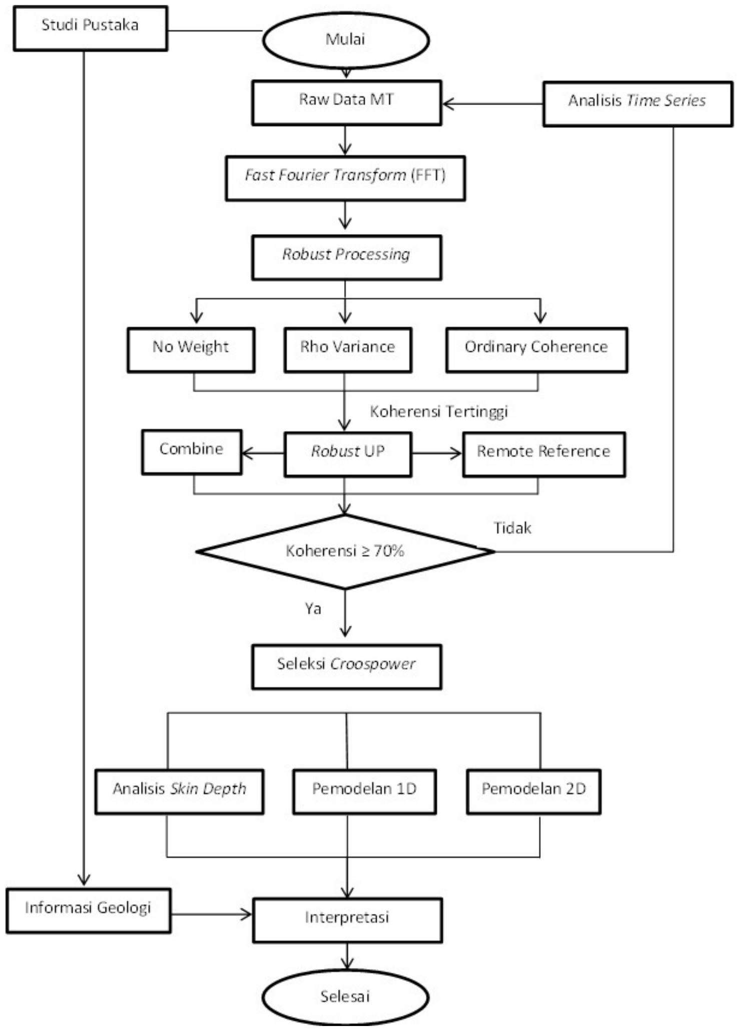

Figure 1. Flowchart.

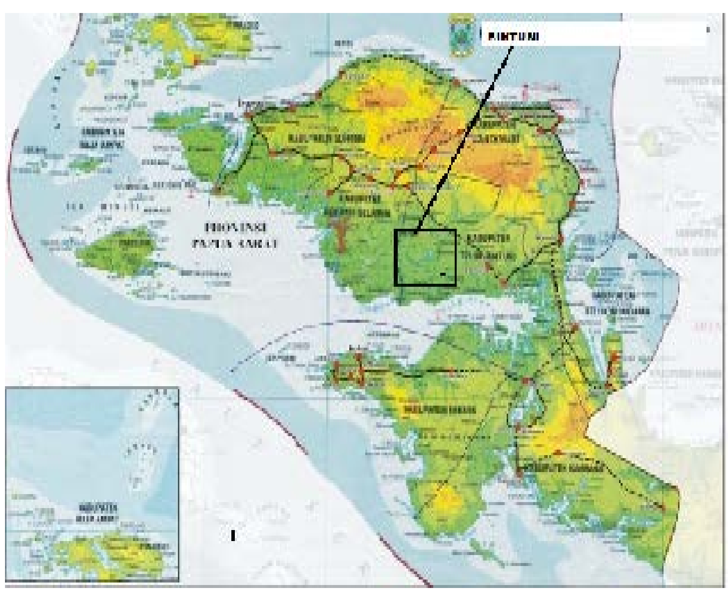

Figure 2. Research location.

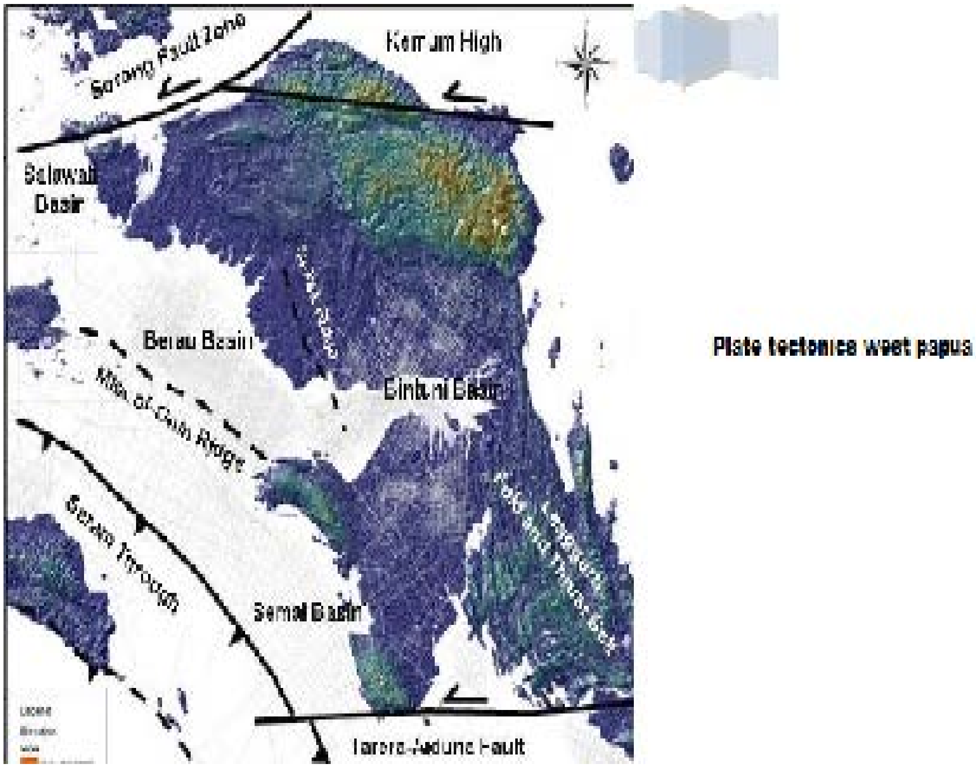

Figure 3. The Tectonic Plate of West Papua.

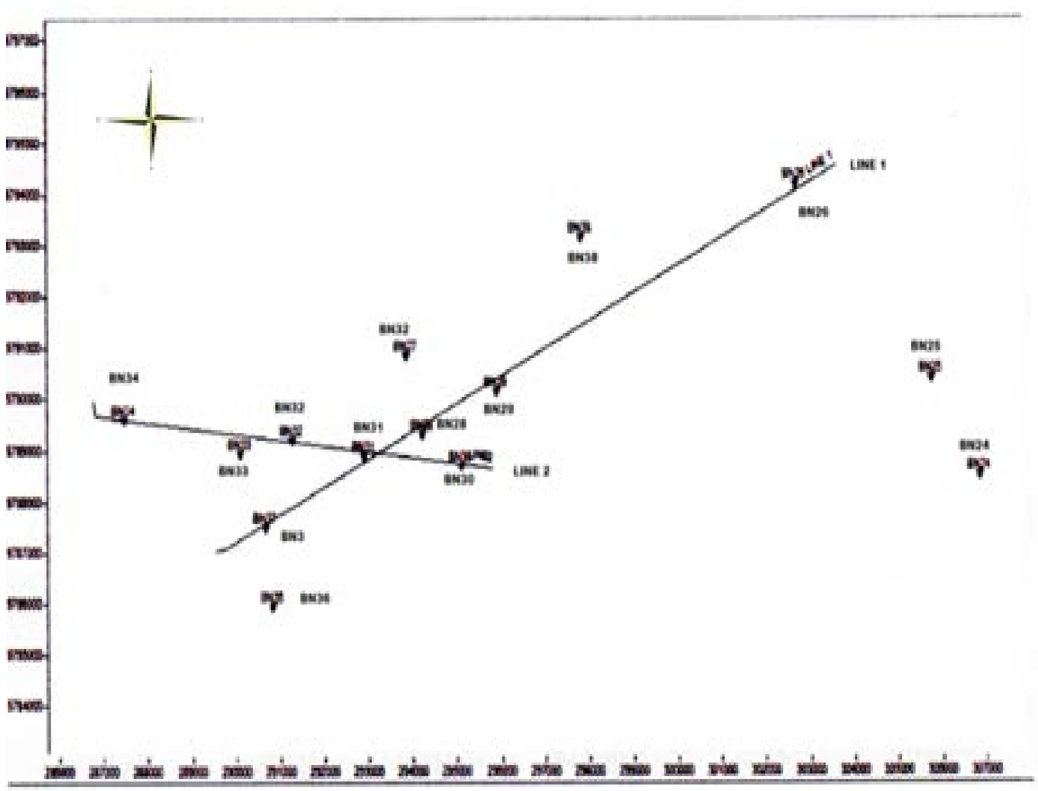

Figure 4. The trajectory and measurement points at research area.

3. Result and Discussion

3.1 Modelling and Interpretation of Magneto Telluric

Comprehensive 1-D and 2-D MT forward and inverse modeling are routinely performed to obtain the resistivity structure of the earth, while 3-D MT modeling is still in the research stage. We have developed a smoothness-constrained inversion technique which results in smooth 1-D and 2-D resistivity model of the subsurface. The inversion method is similar to Occam's inversion developed by for 1-D model and de Groot-Hedlin and Constable (1990) for 2-D model. The 1-D MT inversion modeling is used to infer horizontally layered model from invariant (or one of TM- and TE-mode) sounding curve at each site. By employing different inversion techniques and constraints, a model representing blocky (discrete) or smooth variation of resistivity with depth can be obtained. 2-D resistivity section is formed by joining 1-D models from contiguous sites along a profile. This pseudo 2-D model can be used for preliminary interpretation or as a starting model for a full 2-D MT inversion modeling. In the model obtained from inversion, the resistivity units are related to various rock units and structures in the survey area. Obviously, it is important that any other available geophysical or geological data be integrated to reduce the ambiguities in the final interpretation of the Magneto telluric data.

Data analysis were beginning with calculated the skin depth at any point of measurements. The results of the skin dept analysis indicates that smallest frequency full filling is 4.6 mHz, because at the frequency lower than 4.6 mHz the penetration depth to be. The skin depth analysis is done to see the efficacy of cross power selection. With a depth of its prophets shall be increased if the frequency be smaller. To know the quality of data we calculated the coherence of data at all measurement points, namely the coherence of TE mode, TM Mode and the average mode of TE and TM. From the result of reckoning it was discovered that the coherence value of all data ranged from 63.23% to 92.47%. The penetration depth (skin depth) obtained by using equation (1). The Skin depth obtained were a result of cross power selection. There are two values of skin depth obtained namely the minimum skin depth and the maximum skin depth. Any point Resistivity were the very important geophysical parameters in geophysical exploration, because from the resistivity parameters can be seen the existence the type and characteristic of rock under the surface of the earth.

3.2 Resistivity 1D Sounding

In magneto telluric method the Resistivity were the very important geophysical parameters in geophysical exploration, because from the resistivity parameters can be seen the existence the type and characteristic of rock under the surface of the earth. In magneto telluric the resistivity layers at all points measurement

Calculated by applying the equation (11) as shown in Table 1.

3.3 2D Modeling

To identify the petroleum reservoir system in the research area were conducted resistivity model on two tracks of the measurements. The distance of the first track about 14 km and 6 km of depth. The measurement on this track pass through 6 measurement points namely BN26, BN38, BN29, BN28, BN31 and BN37. The second track also pass through 6 measurements points namely BN30, BN28, BN31, BN32, BN33 and Bn34 with the distances about 8 km. The distribution of the resistivity on both tracks; be divided into 3 groups of rock base on the value of its resistivity. The first group were the zone of low resistivity (3 – 13) Ωm, described in blue purple, the second group is the zone of middle resistivity (14 – 17) Ωm, described in yellow- green colors, and the last group is the zone of high resistivity (18 -200) Ωm, described in orange – red color. The cross section resistivity on both tracks of such measurements in 2D model presented in Figures 5 and 6.

Based on 2D model, obtained that the, rocks cover identified spread at BN26, BN29, BN38 at the first line with the thickness about 1000 km to 200 km. At the second line the low resistivity is found in BN31, BN32, BN33, and BN34 at the depth of 2 km. the thickness of the rock cover at line 2, the thickness of the rock cover, between 1 km to 2 km and it's also expected as rocks cover. The Zones with the middle resistivity presented at all measurement points. The zones with middle resistivity were estimated as the reservoir zone. Under layer of rock cover at BN38, a reservoir zone spread from the depth of 3 km to 6 km under the surface of ground, and forming syncline structure. And below the measuring points BN26 and BN29, the reservoir zone spread from the depth of 1.5 km to 3 km and form anticline structure. Zone with high resistivity under the reservoir zone identified as

Table 1. D Resistivity Model

(a) Sounding point BN 24 (d) Sounding point BN 28

Layers number	Resistivity (Wm)	thickness (m)
1	9.27	27.9
2	1.29	21.55
3	4.29	40.34
4	2.04	117.65
5	3.3	209.15
6	2.12	391.01
7	31.9	2263.01
8	49.51	

Layers number	Resistivity (Wm)	thickness(m)
1	144.34	119.29
2	18.15	81.47
3	45.29	110.6
4	16.51	227.24
5	22.31	1055.66
6	300.12	3030.08
7	16.71	4911.67
8	4.36	

(b) Sounding point BN 25e) Sounding point BN 29

Layers number	Resistivity (Wm)	thickness (m)
1	9.63	20.49
2	2.77	37.89
3	1.51	47.64
4	3.00	55.32
5	1.03	204.19
6	6.96	302.92
7	12.13	2384.24
8	663.34	

Layers number	Resistivity (Wm)	thickness(m)
1	8.4	51.1
2	17.9	13.5
3	68.5	42.6
4	11.0	42.1
5	4.5	230.5
6	1.7	498.2
7	22.3	230.0
8	59.2	

(C) Sounding point BN 27(f) Sounding point BN 30

Layers number	Resistivity (Wm)	thickness (m)
1	5.3	33.3
2	1.8	23.9
3	4.1	32.4
4	2.1	371.1
5	34.9	1021.7
6	7.6	1564.8
7	89.3	4416.1
8	6.0	

Layers number	Resistivity (Wm)	Thickness (m)
1	20.2	50.40
2	3.4	60.1
3	2.0	144.5
4	0.7	685.1
5	19.4	2532.4
6	1.0	3485.7
7	11.1	
8		

(g) Sounding point BN 31 (j) Sounding point BN 34

Layers number	Resistivity (Wm)	thickness (m)
1	16.4	32.5
2	40.2	104.8
3	8.9	226.1
4	3.5	474.3
5	143.3	1295.3
6	8.4	4862.9

Layers number	Resistivity (Wm)	Thickness (m)
1	21.2	55.6
2	7.5	46.3
3	25.6	131.5
4	7.5	347.8
5	2.5	445.8
6	11.0	1338.6

(h) Sounding point BN 32(k) sounding point BN 39

Layers umber	Resistivity (Wm)	thickness (m)
1	49.2	79.0
2	11.1	59.7
3	24.3	109.3
4	6.2	198.3
5	8.2	183.1
6	2.1	377.4
7	339.2	2796.3
8	8.53	

Layers number	Resistivity (Wm)	Thickness (m)
1	25.95	64.45
2	11.24	83.41
3	17.27	106.94
4	9.16	241.2
5	2.18	634.41
6	19.33	2167.92
7	0.9	1286.59
8	7.07	

(i) Sounding point BN 33**(l) sounding point** BN **37**

Layers number	Resistivity (Wm)	thickness (m)
1	16.8	61.1
2	920.5	72.2
3	10.8	287.7
4	3.0	1154.3
5	172.4	890.0
6	0.2	3216.8
7	14.5	

Layers number	Resistivity (Wm)	Thickness (m)
1	28.7	39.9
2	12.4	26.7
3	29.5	62.8
4	14.7	160.6
5	6.5	300.7
6	2.9	594.1
7	13.7	1347.1
8	0.5	

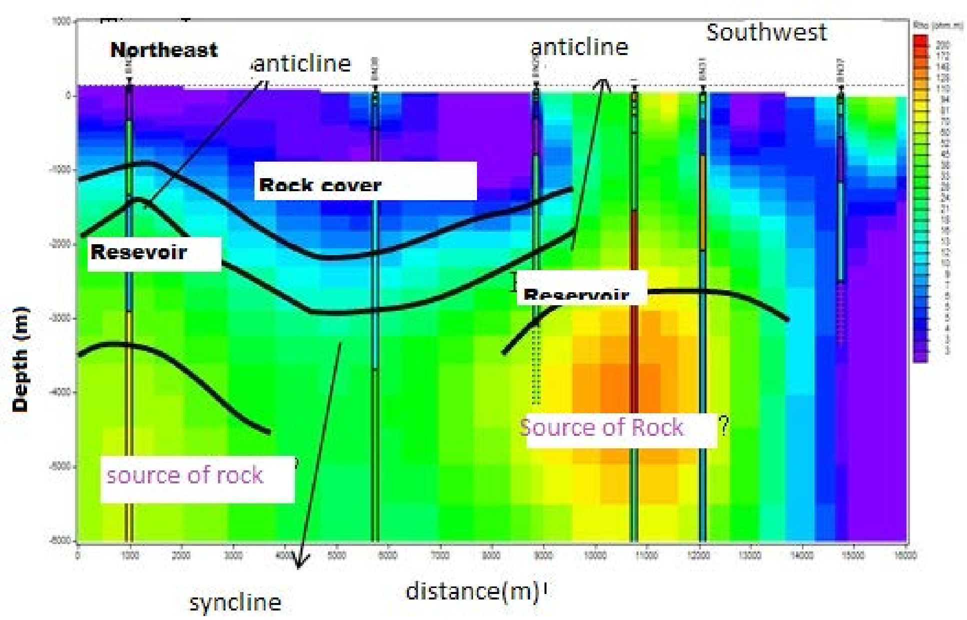

Figure 5. 2 D Resistivity Model for the first line.

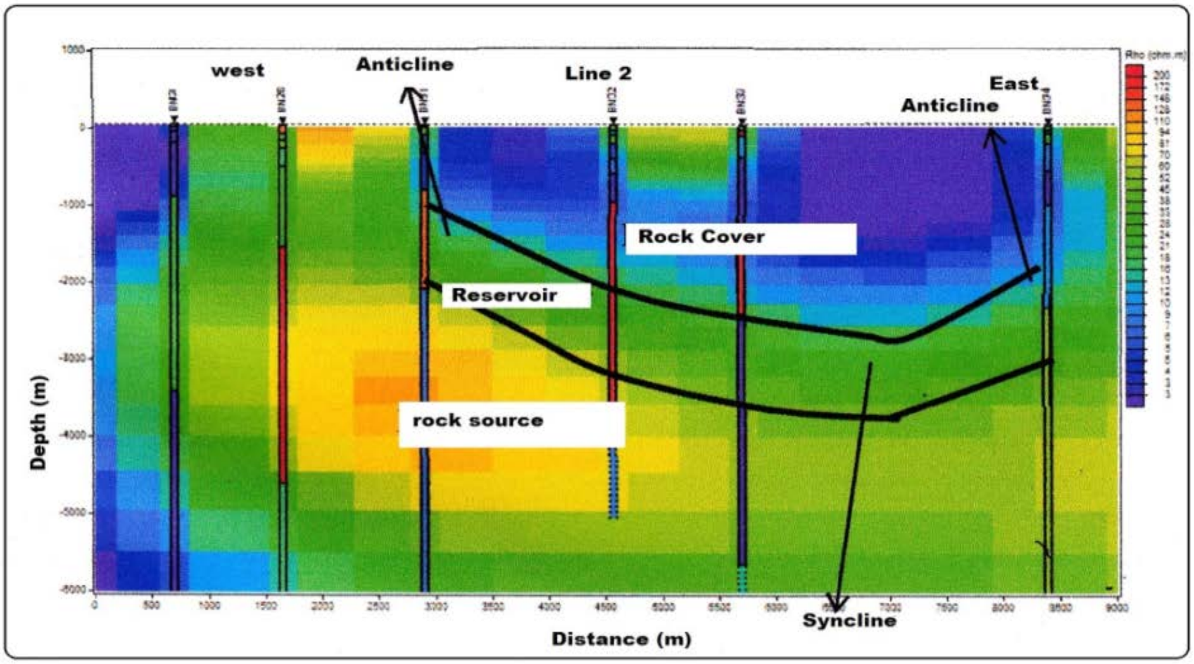

Figure 6. 2D Resistivity Model for the second line.

source rocks. On the first truck expected there are petroleum systems that may be trapped, were at BN26, BN38 and BN29 zone. On the second truck expected there are petroleum system that may be trapped at the zone around of BN31 There Are, BN32, B33 and BN33. In addition, the structure under surface, also form a structure syncline; and anticline, so it is thought that hydrocarbon reservoir trapped on the structure of anticline.

4. Conclusions

From the results of the analysis and interpretation of data the conclusion is drawn as follows:

1. The coherence analysis of data on every processing shows increase in quality of MT data.
2. There are three categories represented the resistivity value: the petroleum system, the low resistivity, middle resistivity and high resistivity. The middle or moderate resistivity (13- 70) Ωm suspected as rock reservoirs from sandstone at tipuma formation. The rocks with high resistivity (70-200) Ωm suspected as rock source which produces the hydrocarbon from the flakes rock Ainuim Formation.
3. The kind of the petroleum trap in the research area allegedly as a trap structure from the syncline and anticline structure.

5. References

1. Utomo W. Potensi permian akhir - Trias awal formasi ainim sebagai batuan induk pada lapangan ran, cekungan bintuni, papua barat. Universitas Gadjah Mada; 2016.
2. Alamsyah A. Seismic analysis of rock properties from center of reservoir at bintuni. Bassin Thesis of Geophysis hasanuddin University; 2012.
3. Dong Z, Tang J, Unsworth M, Chen X. Electrical resistivity structure of the upper mantle beneath Northeastern China: Implications for rheology and mechanism of craton destruction. Journal of Asian Earth Sciences. 2015; 100:115–31. https://doi.org/10.1016/j.jseaes.2015.01.008
4. Erdiansyah E, Iryanti M, Wardhana DD. Analisis potensi longsoran tanah akibat zona jenuh air menggunakan metode geolistrik resistivitas di daerah pelabuhan ratu k. fibusi. Journal Online Fisika. 2007; 3(1):3–13.
5. Grandis H. Magnetotelluric (MT) method. Faculty of Mining and Petroleum Engineering Institute Technology of Bandung; 2012.
6. Jiracek G. Geological sciences. San Diego: San Diego State University; 2002.

7. Lantu. Geosciences. Geophysics Program Study, Faculty of Mathematics and Natural Sciences, Hasanuddin University; 2014.
8. Eaton WD, Darbhysire F, Evans RL. The elusive Lithosphere–Asthenosphere Boundary (LAB) beneath cratons. Lithos. 2009; 109:1–22. https://doi.org/10.1016/j.lithos.2008.05.009
9. Muddasir F, Ismail LM, Daud Y. Magnetotelluric Time series data processing of metronix instrument based on Matlab. Proceedings the 4th Indonesian International Geothermal Convention & Exhibitions; 2016. p. 1–6.
10. Simpson F, Bahr K. Practical Magnetotelluric. United Kindom Cambridge University Press; 2005.