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Interpretation of Magnetotelluric Profile Data Using Multidimensional Inversion

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ABSTRACT

Commonly, survey design of magnetotelluric acquisition is in a form of profile and interpreted by using 1-dimensional inversion (1-D) or 2-dimensional inversion (2-D). The assumption used in 1-D and 2-D may lead potential pitfall during interpretation because real condition beneath the surface is 3-D. In other hand, 3-D inversion consumes processing time much longer than the other inversions. Therefore, 1-D, 2-D, and 3-D inversions are tested in 3D synthetic profile data for analyzing the influence of 3D effect and edge effect. 1-D and 2-D inversion results show an inability to maintain the geometry of 3D synthetic model, mainly in imaging edge boundary of 3D synthetic model. By using 3-D inversion profile synthetic data MT, it is proven that the use of 3-D inversion gives better result in showing the geometry of 3D synthetic model. Strike direction is also seen affecting the result of 2-D inversion. Analysis of multidimensional inversion of profile data is then performed on real magnetotelluric data in Tawau geothermal prospect area. From multidimensional inversion result, there is similarity of 1-D and 3-D inversion results in distributing low and high resistivity zone because both of the inversions are not influenced by strike direction. This result supports the suitability of synthetic model result where 1-D inversion can image subsurface resistivity at shallow depth.

INTRODUCTION

Geothermal system has complex structure which controls fluid flow in the system. Geothermal system consists of overburden rock, cap rock, reservoir rock, and source rock which have significant different resistivity value among them. Geophysical method which measures electrical resistivity method has effectively proven for geothermal exploration, such as magnetotellurics (MT) method. MT is a passive geophysical method that involves measuring fluctuations in the natural electric and magnetic field as a means of determining the resistivity structure of the Earth at depth to 600 km (Simpson dan Bahr, 2005).

3-D inversion is an effective technique to determine resistivity structure of geothermal system since geothermal systems are geologically located in volcanic region which have three-dimensional structure. However, industries rarely used 3-D inversion technique because its complexity and it needs more processing time. It also needs complex mathematical and computational formulations (Rosenkjaer dan Douglas, 2012).

In industry, usually , survey design of magnetotelluric acquisition is in form of profiles and the interpretation process is done by two-dimensional inversion result. 1-D and 2-D assumptions can affect misinterpretation because real dimensionality of subsurface is three-dimension. 2-D and 3-D inversions have been done through MT profile data using synthetic data. The result shows 3-D inversion with four impedance components gave better modeling than 2-D inversion. This is because the assumptions for 2-D model, e.g. strike direction, are rarely found in the field (Chang-Hong et al., 2011).

In this research, 1-D, 2-D, and 3-D inversions are carried out from 3-D synthetic data. The results then are compared to synthetic model. Strike direcion impact is tested toward inversion results of 1-D, 2-D, and 3D models. 1-D, 2-D, and 3-D inversion also have been performed to real data MT supported by synthetic model analysis.

SYNTHETIC MODEL

3-D synthetic models are made using MT3DFor-X. Discretization of resistivity structure into the mesh should be done in order to process forward calculation of synthetic data.

Interest area of the research is 36 km^2 with cell column space of 400 m. There are 36 stations with spacing 1.2 km between stations. It is also used 3 padding column with scaling factor of 1.5 for x-padding and y-padding (area outside interest zone). Each model consists of 10 layers which the first layer thickness is 50 m and increasing with scaling factor of 1.5 up to the depth is around 5666 m. The longest period is 100 s and the shortest is 0.01 s with 10 recorded frequencies.

The first synthetic model consists of a 10 Ωm conductive block with dimension 3.6 km x 8.85 km x 3 km inside a 100 Ωm host. Discretization of the model are carried out with 30 blocks in x-direction (N-S), 28 blocks in y-direction (E-W), and 10 blocks in z-direction. 1-D, 2-D, and 3-D inversion is performed toward profile A and B. Full impedance tensor (Z_{xx}, Z_{xy}, Z_{yx}, and Z_{yy}) are produced using forward calculation from the 36 stations with 10 periods (0.01, 0.028, 0.077, 0.22, 0.6, 1.67, 4.64, 12.92, 35.94 100 s).

The second synthetic model is identical with the first synthetic model, but resistivity value of the block is 500 Ωm.

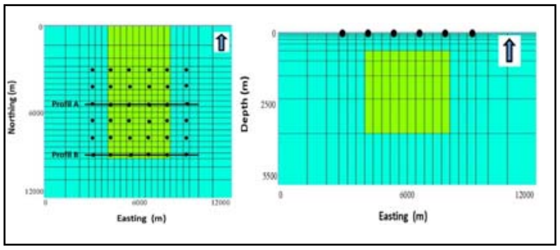

Figure 1. First synthethic model intersect z-axis with conductive block at depth of 660-3744 m (left); Cross section of first synthetic model in y-direction with conductive block at depth of 660-3744 m (right)

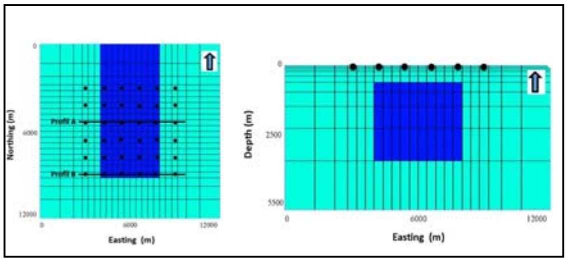

Figure 2. Second synthethic model intersect z-axis with conductive block at depth of 660-3744 m (left); Cross section of second synthetic model in y-direction with conductive blockt at depth of 660-3744 m (right)

INVERSION

1-D inversion is performed using Occam algorithms. 2-D inversion also performed using nonlinear conjugate gradient method to solve two-dimensional inversion problem.

3-D inversion is performed using MT3Dinv-X (Daud et.al., 2012) with data space Occam (Siripunvaraporn et. al., 2005). In using 3-D inversion, strike direction assumptions in 2-D inversion are not necessary.

The parameters that used in 3-D inversion are number of stations (N_s), number of periods (N_p), number of impedance response (N_r), and number of block in x, y, z direction. The amount of impedance response is 8 which consists of real and imaginary value from each impedance response.

RESULTS AND DISCUSSION

Inversion results of the first and second synthetic models are represented by profile A and B where profile A has 6 stations namely F19, F20, F21, F22, F23, and F24, profile B also consists of 6 stations namely F01, F02, F03, F04, F05, and F06.

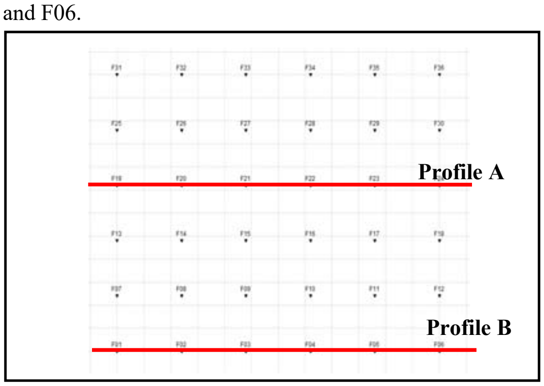

Figure 3. Profile A dan B synthetic MT data of synthetic model 1 and 2

1. 1-D Inversion Results of First Synthetic Model

Figure 4 shows 1-D inversion results of profile A which is located in the center of conductive block and profile B which is located in the edge of conductive block with RMS value less than 0.98.

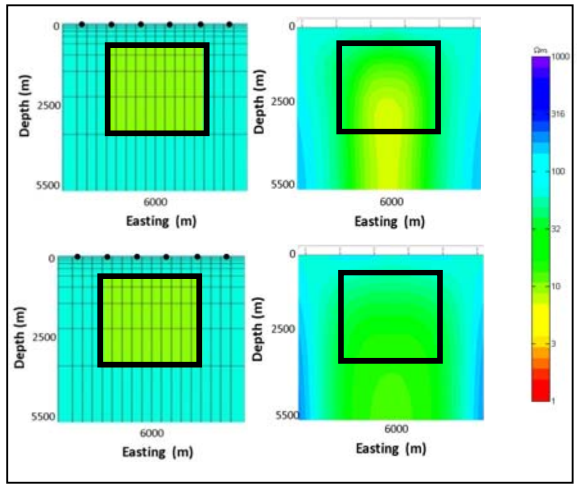

Figure 4. 1-D inversion result of profile A (first row) and profile B (second row)

Inversion result of profile A (first row) shows the existence of conductive block at depth of 500 m for the upper boundary. However, the results show varying values of resistivity, 7 Ωm in the center and increasing up to 15 Ωm near the left boundary and the right boundary of the conductive block. The results also show appropriate lateral length of the conductive block with length of 3.6 km (conductive block is located under F20-F23 stations). It is because this research used TM Mode which has high sensitivity in resistivity contrast laterally. 1-D inversion result shows the conductive block continues down to infinite depth while the lower boundary of the conductive block should be 3744 m depths so that 1-D inversion result can not show the lower boundary of the conductive block.

Inversion results of profile B is not able to show lateral length of the conductive block precisely. The result is also unable to show the lower boundary of the conductive block. The inversion result doesn't show the right resistivity of conductive block because of the influence from the edge effect. Both profiles aren't able to show surrounding resistivity value of 100 Ωm precisely.

2. 2-D Inversion Results of First Synthetic Model

Figure 5 shows 2-D inversion results of profile A located in the center of conductive block and profile B located in the edge of the conductive block with RMS values less than 1 using 100 Ωm homogeneous initial model.

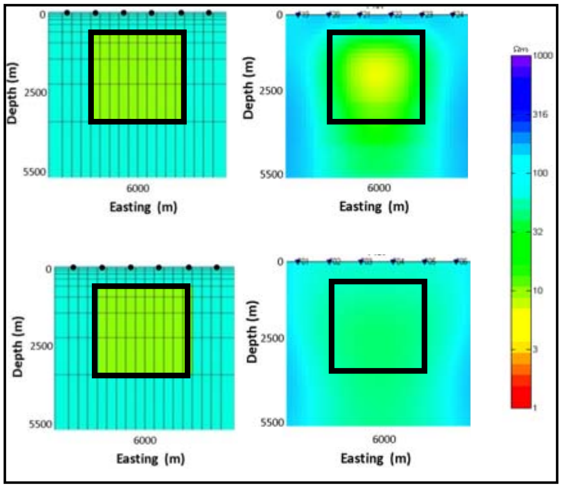

Figure 5. 2-D inversion results of profile A (first row) and profile B (second row)

Inversion result of profile A (first row) shows that conductive block is detected at depth of 500 m on the upper boundary, while the lower boundary is undetected because there is a spurious structure until depth of 5000 m. The results able to show the resisitivity value of conductive block (10 Ωm), but the inversion result shows variation in surrounding resistivity value from 100 Ωm to 110 Ωm which is imprecise.

Inversion results of profile B show resistivity value of the block increases up to 40 Ωm because of the influence from the edge effect at the edge profile. Furthermore, inversion result of profile B is unable to show the upper boundary, lower boundary, left boundary and right boundary of the conductive block so the inversion result can't show the block geometry correctly.

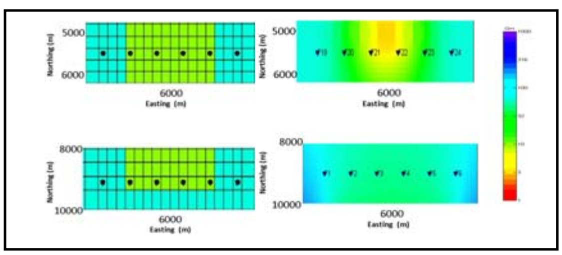

Figure 6. 2-D inversion results of profile A (first row) and profile B (second row) at depth of 1500 m

Figure 6 shows 2-D inversion results in mapping view at depth of 1500 m. 2-D inversion result of profile A is able to show the geometry of conductive block corresponding to the synthetic model. However, 2-D inversion result of the edge profile B is unable to image the suitability with the synthetic model where the edge geometry of the conductive block can not be seen.

3. 3-D Inversion Results of First Synthetic Model

3-D inversion of profile synthetic data is performed using 100 Ωm homogeneous initial model. Figure 7 shows 3-D inversion results of profile A and B. 3-D inversion results with full impedance tensor of profile A is showed at the first row and 3-D inversion result with full impedance tensor of profile B showed at the second row with RMS value less than 19% and less than 1% for profile A and profile B, respectively.

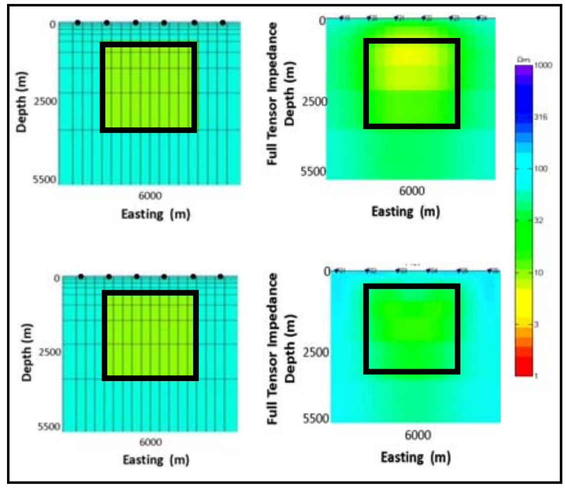

Figure 7. 3-D inversion results of profile A (first row) and profile B (second row)

3-D inversion result with full impedance tensor of profile A shows the conductive block is consistent to the synthetic models (9-10 Ωm at depths of 660 – 3744 m). 3-D inversion result with full impedance tensor of profile B also shows the conductive block with value of 10-15 Ωm and consistent to the geometry of conductive block at depth of 660 – 3744 m. Moreover, they are able to show the surrounding with resistivity of 100 Ωm.

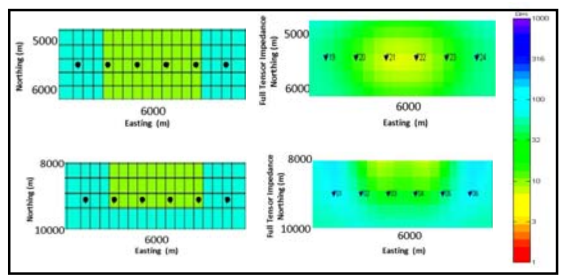

Figure 8. 3-D inversion results with full impedance tensor of profile A (first row) and profile B (second row) at depth of 1500 m

Figure 8 shows 3-D inversion results with full impedance tensor of profile A and B at depth of 1500 m. The 3-D inversion result of profile A shows that conductive block is symmetric and shows that conductive block is consistent with the synthetic model which ranging from 3 Ωm to 15 Ωm at length of 5000 m to 6000 m in north-south direction. This is indicating that edge effect of the profile A doesn't influence the resistivity value significantly. The 3-D inversion result of profile B shows the boundary geometry is approximately at length of 8850 - 9000 m in north-south direction which indicated as the encounter between the conductive block and the surrounding. Therefore, 3-D inversion is able to solve the edge effect.

4. 1-D Inversion Results of Second Synthetic Model

Figure 9 shows 1-D inversion result of profile A located in the center of conductive block and profile B located in the edge of conductive block with RMS value less than 0.98.

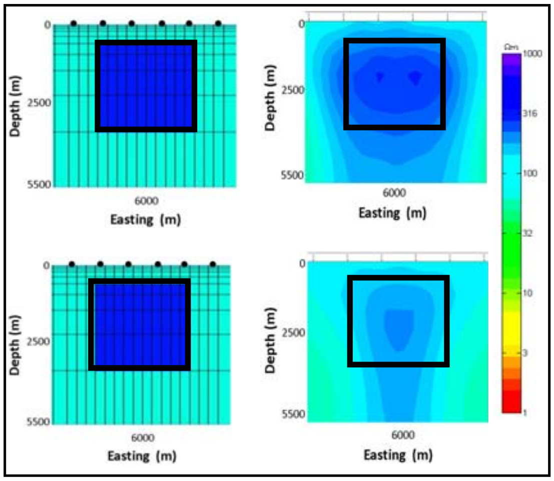

Figure 9. 1-D inversion results of profile A (first row) and profile B (second row)

In contrast to prior model, this synthetic model contains more resistive block than the surrounding (ρ background = 100 Ωm). Inversion result of profile A (first row) shows the existence of resistive block with lower boundary at depth of 5000 m while the real lower boundary of resistive block from synthetic model is at depth of 3744 m. However, the lower boundary is not clearly seen because there is unrealistic resisitivity value which indicating as a spurious structure. This spurious structure is exist in order to fit between inversion model (calculated data) and forward model (observed data) whereas observed data is influenced by 3-D effect.

Inversion result of profile B is unable to show the lower boundary of the resistive block, similar to the first synthetic model. Therefore, 1-D inversion is able to show lateral length of the resistive block correctly, but it is unable to show the lower boundary of the resistive block, similar to the inversion result of first synthetic model.

5. 2-D Inversion Results of Second Synthetic Model

2-D inversion results are produced using 100 Ωm homogeneous initial model and have RMS value less than 1.

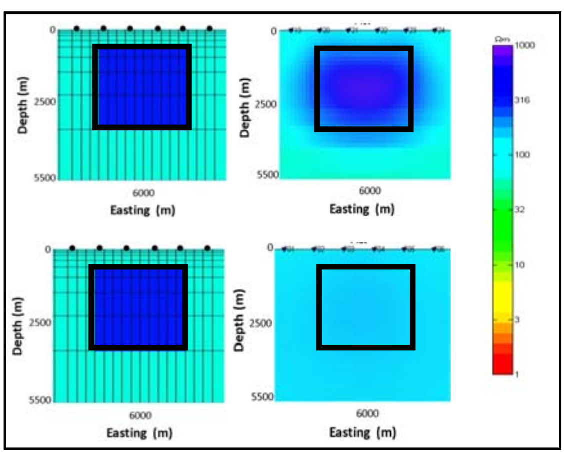

Figure 10. 2-D inversion results of profile A (first row) and profile B (second row)

Inversion result of profile A shows the lower and upper boundary of resistive block unclearly because there is unrealistic resistivity value around the block at depth of approximately 1000 m to 3500 m. Moreover, the inversion result of profile A is unable to show the boundary geometry of resistive block. It is found that resistivity of surrounding is 100 Ωm correctly, but the block resistivity is around 400 Ωm to 700 Ωm. 2-D inversion result of profile B is unable to show the resistive block geometry even unable to indicate the existence of a resistive block. This is because of the influence from edge effect.

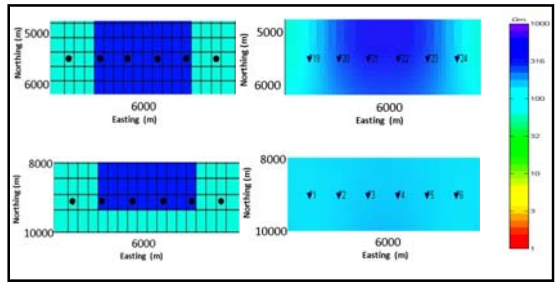

Figure 11. 2-D inversion results of profile A (first row) and profile B (second row) at depths of 1500 m

2-D inversion result of profile A shows that resistive block is consistent to the synthetic model which elongated to north-south direction. However, the 2-D inversion result at the edge profile B is not suitable with the synthetic model where the resistive block can not be seen due to the edge effect.

6. 3-D Inversion Results of Second Synthetic Model

3-D inversion synthetic data profile is performed using 100 Ωm homogeneous initial model. Figure 12 shows 3-D inversion results of profile A and B. 3-D inversion results with full impedance tensor of profile A is shown by the first row and 3-D inversion results with full impedance tensor of profile B is shown by the second row with RMS value less than 13% and less than 1% for profile A and profile B respectively.

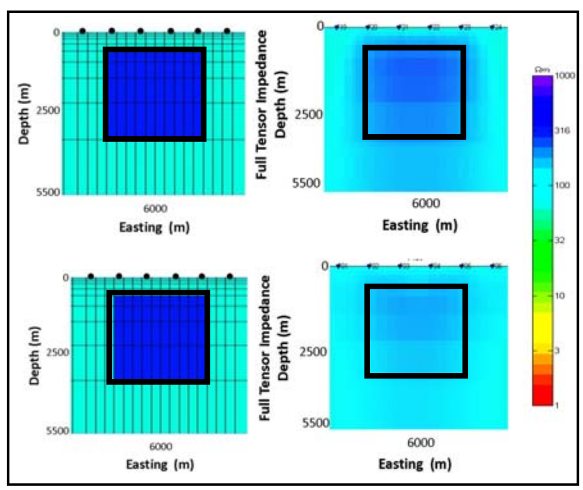

Figure 12. 3-D inversion results of profile A (first row) and profile B (second row)

3-D inversion result with full impedance tensor of profile A shows that resistive block is suitable with synthetic model value ranging from 300-500 Ωm at depths of 660 – 3744 m, but there is unrealistic resistivity value around the resistive block. 3-D inversion results of profile A shows the right surrounding resistivity value of 100 Ωm which is consistent with the synthetic model. Both inversion results show resistive block with value ranging from 300-400 Ωm, yet the upper boundary and lower boundary is hardly seen. It is may caused by MT method basically involves measuring fluctuations in the natural electromagnetic field which propagates in a conductor medium so that MT method is unable to give well responses in a resistive medium.

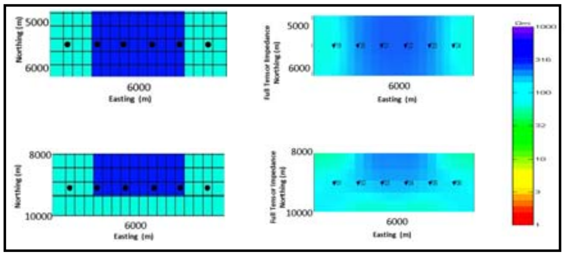

Figure 13. 3-D inversion results with full impedance tensor of profile A (first row) and profile B (second row) at depth of 1500 m

Figure 13 shows 3-D inversion results of profile A and B at depth of 1500 m. 3-D inversion result with full impedance tensor of profile A shows the resistive block with value of 300-500 Ωm along 5000 m to 6000 m in north-south direction and it is consistent to synthetic model. It is indicating that the result of profile A isn't influenced by the edge effect significantly. While 3-D inversion result with full impedance tensor of profile B shows the boundary geometry which indicates the encounter between block and surrounding resistivity. This research proves that the edge effect can be influenced not only between conductive-resistive object but also between resistive objects.

7. Influence of Strike Direction to Inversion Result

In 2-D inversion assumption, conductivity vary along z-axis (depth) and lateral axis (x-axis or y-axis). A line along constant conductivity value is called strike. Therefore, 2-D inversion is influenced by strike while 1-D and 3-D model aren't. This research is conducted to understand the influence of strike direction to 1-D, 2-D, and 3-D inversion results using first synthetic model (10 Ωm conductive block and and 100 Ωm surrounding).

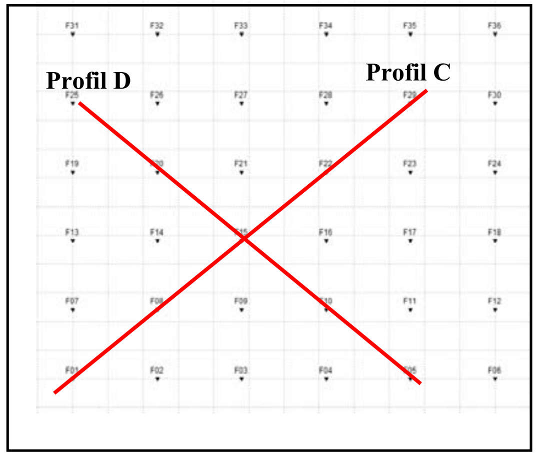

Figure 14. Profile C and D of MT synthetic data

Inversion results of profile C and D where profile C consists of F1, F8, F15, F22, and F29 stations and profile D consists of 5 stations namely F05, F10, F15, F20, and 25.

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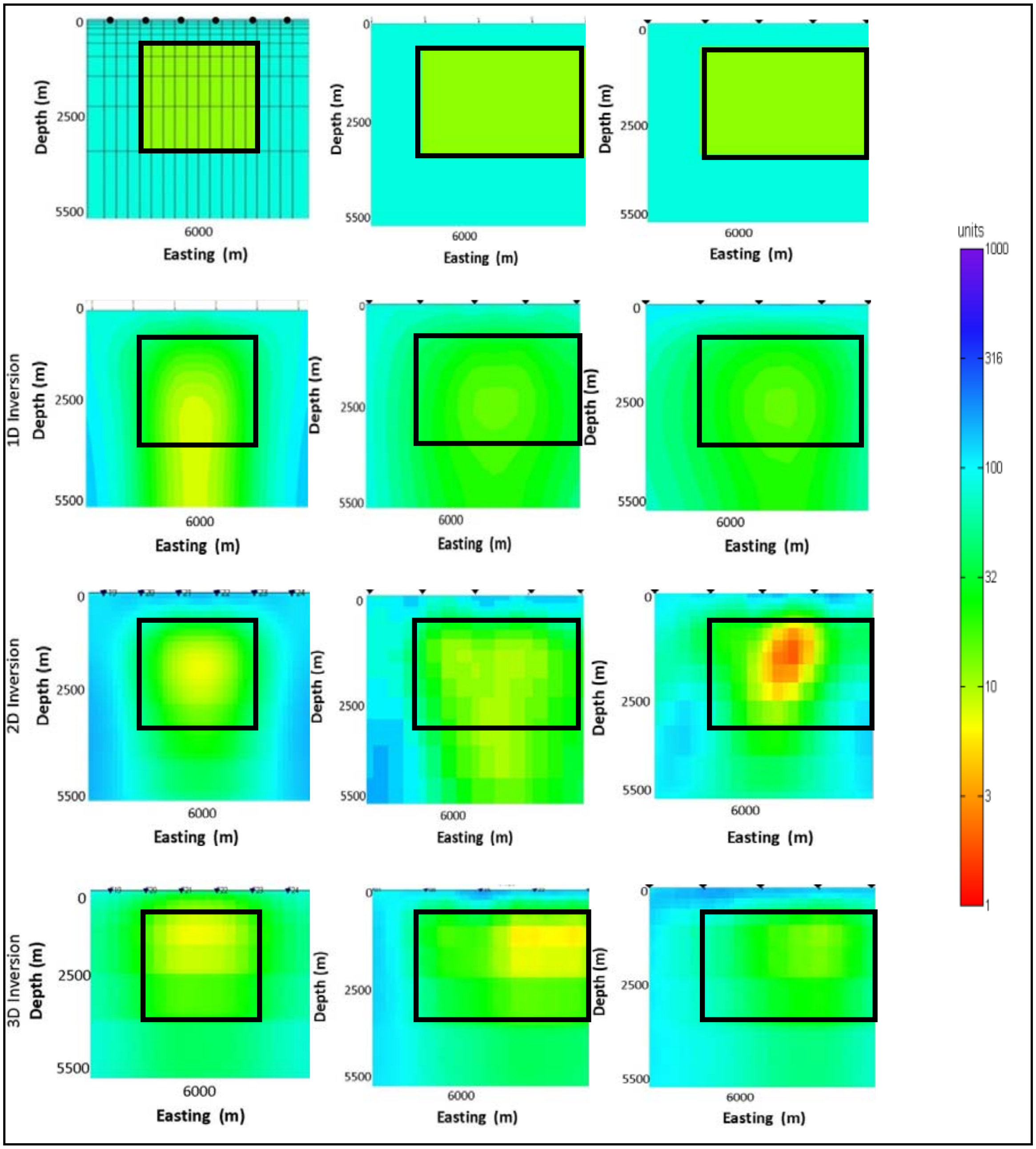

Figure 15. Multi-dimensional inversion results of parallel strike profile (first column); Multi-dimensional inversion result of profile C (second column); Multi-dimensional inversion result of profile D (third column)

3-D inversion result is able to show conductive block geometry than 1-D and 2-D. 3-D inversion result shows that both inversion of parallel strike profile and non-parallel strike profile are able to show 3-D synthetic model geometry correctly and the edge effect is not influence them.

Similar to non-parallel strike of profile C, 1-D inversion result of profile D shows the lateral boundary of conductive block correctly yet it is unable to show the lower boundary of conductive block precisely. This results show that both 1-D inversion of parallel strike profile and non-parallel strike profile are able to show lateral boundary of conductive block correctly, yet they are unable to show the lower boundary of conductive block correctly. Therefore we can say that 1-D inversion is not influenced by strike direction.

2-D inversion result of non-parallel strike for profile C and D show an inconsistency of pattern compared to 1-D and 3-D inversion results through the existence of spurious structure. Besides, compared to inversion result of parallel strike profile, quality of inversion result is very significantly different. This approves that 2-D inversion results are highly influenced by strike direction so that MT stations should be designed parallel or perpendicular to strike direction to avoid misinterpretation. Besides, determining of strike direction correctly is quite important in order to conduct rotation in processing data.

8. Muti-dimensional Inversion Results of Real MT Data Profile

1-D, 2-D and 3-D inversion of profle T is performed on southeast direction of Gunung Maria, Tawau, Malaysia. Determining of profile is based on the existence of hot spring manifestations A5, A1-A4 which give indication of the existence of geothermal system. A5 hot spring is indicated as a hot spring correlated to reservoir because it contains chloride and boron with higher pH rather than A1-A4 hot springs. A1-A4 hot springs are potentially indicated as an outflow zone of the geothermal system. Therefore, it is estimated that center of reservoir is located on southeast of Gunung Maria and the heat source is derived from Gunung Maria.

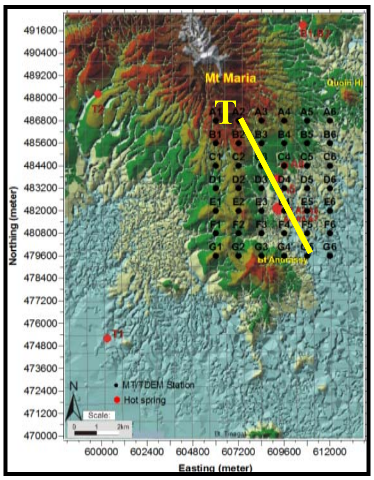

Figure 16. Area profile of Tawau

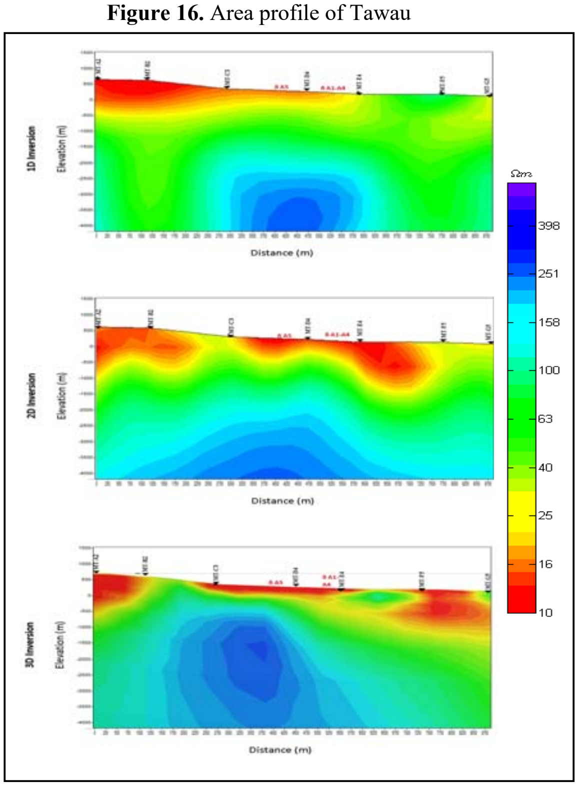

Figure 17. 1-D, 2-D and 3-D inversion of profile T

Figure 17 shows 1-D, 2-D and 3-D inversion results of profile T. All results show three contrast resistivity zones. Low resistivity zone with value ranging from 1-16 Ωm which is called as clay cap. Moderate resistivity zone with value of 20-65 Ωm which is indicated as reservoir zone. High resistivity zone with value of ≥ 100 Ωm is called as heat source zone (Ussher et al., 2010).

According to the results, it is seen that low resistivity zone is widen from A2 stations to G5 with depth of 500-1000 m. 1-D and 3-D inversion show a depletion of low resistivity zone under C3 to F4 stations.

2-D and 3-D inversion results show that moderate resistivity zone is located at elevations of -1000 m to -2000 m and -500 m to -1000 m, respectively. While 1-D inversion result shows that moderate resistivity zone is located at elevations of -500 m to 4000 m on B2 and F5 stations which indicated that 1-D inversion result is unable to image resistivity contrast in deeper depth and it has been proven in synthetic model.

1-D and 3-D inversion results tend to show high resistivity zone as a dome pattern at different depth between C3 to E4 stations. 1-D inversion result show a dome pattern at depth of 1500 m while 3-D inversion result show a dome pattern at shallow depth. In contrast to 1-D and 3-D inversion result, 2-D inversion result is unable to show dome pattern under C3 to E4 stations.

According to distribution pattern of low resistivity zone, moderate resistivity zone, and high resistivity zone of profile T, it is seen that 1-D and 3-D inversion results have similar distribution pattern of resistivity where there is a depletion of low resistivity zone on C3 and E4 stations and they also have similar dome pattern between C3 to E4 stations. This is similar to a research at Glass Mountain, California where 1-D and 3-D inversion results are more reliable to image subsurface resistivity they are correlated to well data, mainly in low resistivity zone (Cumming dan Randall, 2010).

2-D inversion result is unable to show appropriate distribution of low and high resistivity zone because of 2-D inversion assumptions that MT stations should be designed parallel or perpendicular to strike direction. This is proven by 2-D inversion result on 3-D synthetic model which conducted in this research. Inversion result of non-parallel strike profile gives bigger impact on 2-D inversion result than 1-D and 3-D. 2-D inversion result shows a spurious structure which can bring misinterpretation of real MT data. Besides, projection station is also influence 2-D inversion result. B2, D4, and F5 stations are projection stations in profile T.

The similarity of resistivity distribution pattern between 1-D and 3-D inversion results are proven by the inversion result of synthetic data that both 1-D and 3-D inversion results are able to show lateral resistivity of synthetic model precisely at shallow depth (± 1000 m). However, in synthetic model, 1-D inversion result is unable to image the lower boundary of 3-D synthetic model at deeper depth correctly. This is become an obstacle to interpret by using 1-D inversion.

3-D inversion result give more appropriate representation of subsurface which is proven by the existence of heat source at shallow depth between C3 to E4 stations. It is supported by A5 hot spring near D4 station which contains high concentration of chloride and boron indicated that the A5 hot springs is located nearer to the heat source (Javino et al., 2010). This is because at high temperature, heat source containing HCl dan H_3BO_3 evaporrated and mobilized to the surface with the result that manifestations near heat source will contain high chloride and boron. A1 hot spring has 7.4 pH, higher than A5 (Javino et al., 2010). It is indicating that A1-A4 hot springs are located more far form the reservoir than A5 hot spring.

Surface structure lines located at Tawau show a consistency with 3-D inversion results. 3-D inversion results show a presence of fault structure at C3 stations and A1-A4 hot springs.

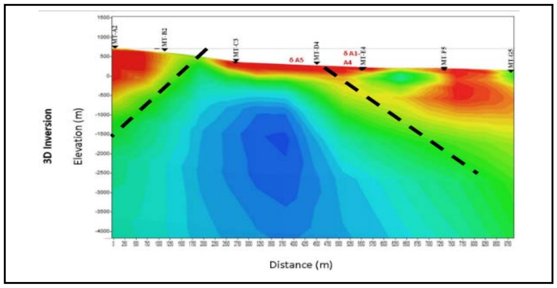

Figure 18. Matched surface structure lines on area near A1-A5 manifestations (Javino et al., 2010)

Furthermore, comparison between MT real data (observed data) and apparent resistivity value (calculated data) in each stations of profile T is shown by Figure 19. Figure 19 shows that apparent resistivity and phase (ρ_{xy} dan ρ_{yx}) value of inversion result (calculated data) has fitted with the observed data and has RMS value less than 7. Therefore, 3-D inversion result is able to image real conditions in the field.

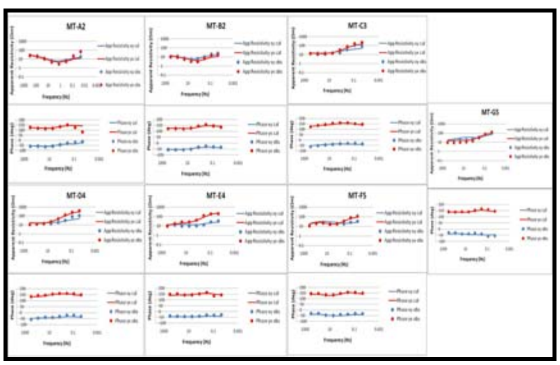

Figure 19. Fitting result between observed data and calculated data of profile T

CONCLUSION

1-D, 2-D, and 3-D inversion of MT data profiles have been performed which conclude that :

1. 1-D and 2-D inversion result of MT synthetic data profiles are unable to preserve 3-D synthetic model geometry, particularly at the edge profile of conductive and resistive objects.
2. 1-D inversion can image a good lateral resistivity at shallow depth, but it can not image resistivity at deeper depth.
3. The existence of spurious structure in 1-D and 2-D inversion results of MT synthetic data profiles is due to 3-D effect or edge effect.
4. Strike direction can affect 2-D inversion result however it doesn't affect 1-D and 3-D inversion results.

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