APPLYING INNOVATIONS IN MT TECHNOLOGY FOR REDUCING GEOTHERMAL EXPLORATION RISKS

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ABSTRACT

In the exploration stage (even in the development stage), geophysics is the most important surface method used to image the subsurface physical parameters associated with a geothermal system. Magnetotelluric (MT) imaging is the most powerful method to reconstruct a geothermal system model based on resistivity distribution. MT can be used to define top of reservoir, delineate geometry of reservoir and determine well target zones. The subsurface information derived from the MT data is then confirmed through drilling. Many geothermal fields in Indonesia have had wells drilled. The wellbore data (from both "successful" and "unsuccessful" drilling) contain valuable subsurface information that can be utilized for confirming the MT resistivity imaging data. Comparison between surface (MT resistivity) and subsurface (wellbore) data should be done iteratively in order to obtain more accurate MT imaging with higher resolution. This iterative process should be done continuously as new drilling data becomes available. Accordingly, such iteration contributes to innovation in MT technology that leads to better imaging and subsequently more accurate well targeting. Recent innovations of the MT technology such as applying advanced data processing, selection of a more appropriate modeling/inversion scheme, and joint interpretation with other geophysical methods, have been done and these should also be applied to the iterative process. The iterative process can be employed in many geothermal systems with different geological settings to improve the reservoir characterization and to increase drilling success ratio. Such innovations could provide a practical solution to mitigate the exploration risks.

1. INTRODUCTION

1.1 Problems of Disagreement between MT and Drilling Results

Magnetotelluric (MT), as the most powerful method for reconstructing geothermal system model has been frequently used to guide drilling targeting in the exploration and development stages (Cumming & Mackie, 2010). Many wells have been drilled on the basis of the MT resistivity guidance. However, some of the drilling results showed different subsurface geological conditions when compared to the MT resistivity indications. In other words, there is disagreement between drilling result and MT resistivity. As a result, questions may be raised as to the effectiveness of MT technology. This paper illustrates two cases related to the disagreements.

The first case deals with an unrealistic model derived from the mismatch between MT model and geological/geochemical indication impacting the drilling result. Subsurface geological conditions in a geothermal area are usually represented by low resistivity distribution above the reservoir with different thicknesses; thinning above the up-flow zone (up-dome shape), while thickening in the outflow zones. In this instance, fumarole (as an indication of up-flow zone on the surface) is not supported by thin conductive layer and updome-shape of the low resistive body in the subsurface. However, the MT model shows contradictive result (Figure 1). The thick conductive layer is observed beneath the fumarole. As a result, this led to an unsuccessful decision of the deep drilling target (i.e. thick clay alteration with low temperature at the bottom of the well) (Figure 1).

In the second case, a deep well has been drilled to the expected high temperature reservoir target as shown by MT model with thin conductive layer (up-dome shape). However, up to depth of 2300 meters, where the resistivity value reaches of about 100 ohm-m, the temperature is only less than 175^{o}C (Figure 1), which is theoretically still on the clay cap/conductive layer (Ussher et al, 2000).

These two cases indicate that MT results are positioned as the most blamed on the unsuccessful drillings. Therefore, we should carefully investigate the MT workflows to find out the possible misleadings that may have occurred (Daud, 2016).

In the following paragraphs we will discuss the workflow, the possible misleading and the need for problem-solving with iterative innovation.

1.2 Workflow of MT Applications

Figure 2 demonstrates workflow of MT applications. MT technology including survey design, data acquisition, data processing and modeling/inversion might be done properly or improperly. . Both MT imaging results conducted properly or improperly can be used to define the top of the reservoir, reservoir geometry, and well target zone. This information is then supported by geological and geochemical information including geological structure, inferred reservoir temperature, hydrogeology and volcano-stratigraphy to develop a conceptual model (Figure 2).

The conceptual model is then confirmed through drilling. The drilling result can be used to confirm whether the well targets as indicated by the conceptual model is appropriate or not. If the drilling reaches high temperature and high permeability zone, it can be categorized as a successful drilling. . The valuable subsurface information including lithology, structure or permeability indication, pressure and temperature profile could be yielded through both successful and unsuccessful drilling. In this stage, comparison between the surface data (MT resistivity) as well as the subsurface (wellbore) data should be done. When the correlation is poor, the process should not be stopped, but the MT data should be evaluated. The next iteration can be conducted by involving MT technology innovation, such as reprocessing, remodeling with constrained model as well as joint interpretation with Gravity/MEQ (Figure 2).

Detailed MT technology innovations are discussed in this paper, including the results of the two disagreement problems and the solutions (more accurate MT results after applying the MT innovations).

2. THE INNOVATIONS OF MT TECHNOLOGY

2.1 State of the Art

The main flow of the MT technology consists of representative survey design, well calibration of instrument and sensors, appropriate data acquisition, careful and proper data processing, suitable modeling/inversion scheme, 3-D visualization and joint interpretation (Figure 3).

The innovation discussed in this paper is focused on how to improve the quality of MT data by conducting careful and proper data processing and choosing appropriate modeling/inversion scheme (Figure 3). The result is then strengthened by joint interpretation with other geophysical data, especially Gravity and MEQ. This is further enhanced after applying similar appropriate processing and modeling/inversion innovations.

2.2 Applying Suitable Processing

Data processing is the most important and influential stage in applying MT technology. As a passive geophysical method (depending on the natural source), MT is very sensitive to electromagnetic noises. Szarka (1988) and Chave & Jones (2012discuss influences of electromagnetic noises to MT data. Accordingly, the first step in applying suitable processing is conducting time-series inspections and applying a noise filter (Ismail et al., 2015). Figure 4 shows the before and after results of noise filter applications.

After applying several filters and data conversion, the MT result is represented by both apparent resistivity vs. frequency curve and phase vs. frequency curve. However, the curves do not correlate. Accordingly, data selection (sometimes called cross power selection) should be performed. A different method of data selection may produce different curve trend (Figure 5). Manual selection, which is conducted with expert-judgement, is recommended rather than auto-processing (automatically processed by software).

Before conducting data inversion, a final data correction related to static shift effect should be thoroughly investigated (Arnason, 2015). Failure to do so will cause mis-interpretation of subsurface resistivity data, thereby increasing drilling risk, and consequently the financial risk. Static shift correction should be performed by conducting a TDEM survey. However, several geothermal fields in Indonesia have no TDEM data. An alternative solution is to apply a geostatistical method using an appropriate software tool (Daud, 2011). Based on several MT data sets, the results of static-shift corrections by using geostatistical data are comparable with those corrected by TDEM data. In addition, the inversion results of the both corrected MT data are comparable (Figure 6).

2.3 Choosing 3D Inversion Scheme

Choosing the most appropriate inversion scheme is also important. The actual geological conditions in which the geothermal area is located should be considered when selecting the proper modeling criteria for MT data. A 1-D inversion method can be used in a 1-D subsurface structure or stratified layer such as in sedimentary formation. A 2-D inversion method can be used in 2-D subsurface structure or single geoelectric strike direction. However, the geothermal systems in Indonesia are mainly associated with volcanic activity and are located in mountainous terrain with complex geological structure. Therefore, the most reliable approach is 3D inversion.

Before conducting 3-D inversion, the most important consideration is data input. An EDI file as a SEG standard format for MT data should be produced by appropriate MT data processing. After checking the data input, the workflow of 3-D inversion can be followed (Figure 7), from initial model construction to the most appropriate model selection. The basic principle for selecting the most appropriate model is understanding the geothermal system. A hypothetical model of the geothermal system should be considered by modeling engineers. In order to create better visualization of 3-D inversion result, 3-D visualization software (Daud & Saputra, 2010) can be utilized. Several features can be optimized within the resistivity section. These include resistivity map, 3-D cake model, and iso-value, as well as observed vs. calculated data curves.

2.4 Joint Interpretation with Gravity/Microearthquake

Joint interpretation between MT and other geophysical methods, such as Gravity and MEQ, could reduce the uncertainty of the well target zones. However, it should be done with one condition that is similar innovation workflow applied in MT need to be applied for Gravity and MEQ to guarantee the quality of data Otherwise, joint interpretation could not be effective or probably would produce contradictive results. When MT and Gravity/MEQ are processed properly, they will show good correlations (Figure 8). Similar correlations will increase level of confidence in imaging the subsurface condition.

3. APPLYING MT TECHNOLOGY INNOVATIONS FOR EVALUATING SUCCESSFUL AND UNSUCCESSFUL DRILLING PROGRAM

Innovations in reprocessing and 3-D inversion of MT data as described above have been applied in the previous two cases outlined in Section 1.1. The result of the first case shows that occurrence of the thick conductive layer below the fumarole as produced by previous researcher has been overcome. A thin conductive layer below the fumarole can be more acceptable and reasonable in geological and geochemical point of view (Figure 9). The low temperature found at the total depth (TD) of two existing wells can also be explained and well-correlated with the new resistivity distribution. The position of the well is inside the conductive clay cap which generally has temperature below 200^{o}C.

Similarly in the second case results show that a deep well drilled up to 2300 m depth with temperature below 175^{o}C and dominated by altered rock along the well is located inside the conductive clay cap (Figure 10). The distribution of subsurface temperature based on three wells presents a good correlation with the new MT model. The innovation of MT data processing in this case has been focused on static shift correction. The correction has been conducted using geostatistical method (Daud, 2011). In addition, 3-D inversion is performed with data space Occam's inversion (Siripunvaraporn & Sarakorn, 2011; Daud et al, 2012).

To better illustrate the benefit of the MT technology innovations, this paper also presents the application of the innovation of processing and modelling to green field MT data in East Java. This prospect area is situated inside the caldera where geothermal occurrence is indicated by unimpressive surface manifestations (i.e. bicarbonate hot springs at the northern margin of the caldera and the extremely acidic crater at the eastern margin). The geochemical data from such hot springs cannot be used for assessing origin of water and hydrogeology, since the geothermal water is mixing with shallow meteoric water. Further, as the surface is covered by thick lava, the surface geological structure cannot be mapped clearly. Therefore, the geochemical and geological data cannot be used for assessing the subsurface reservoir. The only tool for delineating reservoir location, depth and its geometry is geophysics (i.e. MT technology). MT is very helpful to delineate the reservoir zone in such “hidden” geothermal systems where geology and geochemistry data give poor indications. Basically, previous MT studies including processing and modelling have been conducted by several parties. However, each party indicated well target zones at different locations. Therefore, the MT data was then reprocessed by the authors following the above innovations and remodelled using 3-D inversion. The indication of promising well targeting is then used to guide the first deep slim hole drilling recommendation. The slim hole well drilled to a depth of 2000 m found high temperature of about 291°C at 1940 m depth and discharging two-phase fluids (76 % steam). This successful result demonstrates that the MT Technology innovation can be used to guide exploration drilling in such “hidden” geothermal reservoir.

4. DISCUSSIONS

MT is a technology, where “the man behind the gun” (engineers) become the most important thing. Special treatment to the MT technology and innovations to the processing and modelling of the MT data should be applied carefully and appropriately. Otherwise, misleading information can be generated leading to unsuccessful recommendations.

It should be a warning for geologist or interpreter wishing to use a MT model alone to describe a geothermal system and determine a drilling target. MT data provides a cross section that contributes to an overall process. Accordingly, it is important to reevaluate and reiterate existing MT data continuously before recommending further steps. Therefore, iteration is essential and should be applied in many geothermal fields to characterize reservoir based on MT data.

5. CONCLUSIONS

Resistivity distribution derived from Magnetotelluric (MT) imaging result is frequently applied to reconstruct a geothermal system as well as to guide drilling target. Many wells from many geothermal fields in Indonesia have been drilled by optimizing the MT data. Unfortunately, in others this has led to unsuccessful results. However, all the wellbore data (from both “successful” and “unsuccessful” drilling) contain valuable subsurface information that can be utilized for confirming the MT resistivity imaging data. If there is not a correlation between MT and drilling result (unsuccessful well), innovation of MT technology should be applied such as applying advanced data processing, choosing proper modeling/inversion scheme, and joint interpretation with other geophysical methods to get better results. MT technology innovation have been used to overcome the disagreement problem between MT and drilling result in the case 1 and case 2. The results become more accurate and corroborate with geological and geochemical indication. The temperature distribution is also confirmed with resistivity distribution. Accordingly, such evaluation should be performed in more geothermal fields to more accurately determine a reservoir characterization based on MT results.

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REFERENCES

Arnason, K. The Static Shift Problem in MT Soundings. *World Geothermal Congress*. Melbourne, Australia. (2015).

Chave, A. D., & Jones, A. G. *The Magnetotelluric: Theory and Practice*. Cambridge University Press. (2012).

Cumming, W., & Mackie, R. (2010). Resistivity Imaging of Geothermal Resources Using 1D, 2D and 3D MT Inversion and TDEM Static Shift Correction Illustrated by a Glass Mountain Case History. *World Geothermal Congress*. Bali.

Daud, Y. StaticShifter-X: A Static Shift Correction Software for MT Data. *Proceeding of API Annual Meeting 2011*. Lampung, Indonesia. (2011).

Daud, Y. *Misleading in Applying Geoscientific Technology for Geothermal Exploration*. Jakarta: INAGA - Luncheon Talk. (2016).

Daud, Y., & Saputra, R. GeoSlicer-X: A 3-D Interactive Software for Geothermal Data Analysis. *World Geothermal Congress*. Bali. (2010).

Daud, Y., Heditama, D., Agung, L., Amriyah, Q., Nuqramadha, W. A., Pratama, S. A., & Saputra, R. 3-D Inversion of MT Data Using MT3DInv-X Software. *The 12th Annual Indonesian Geothermal Association Meeting & Conference*. Lampung. (2012).

Ismail, M. L., Heditama, D. M., Dewi, R., Daud, Y., & Nuqramadha, W. A. Noise Elimination Technique in Magnetotelluric Data Using Digital Filter and Time Series Data Selection. *Indonesia International Geothermal Convention & Exhibition 2015*. Jakarta: INAGA. (2015).

Siripunvaraporn, W., & Sarakorn, W. An Efficient Data Space Conjugate Gradient Occam's Method for Three-dimensional Magnetotelluric Inversion. *Geophys J Int 186*, 567-579. (2011).

Sulistyo, A., Daud, Y., & Ningsih, N. U. Comparison between Geostatistical (Cokriging and Averaging) Methods and Time Domain Electromagnetic (TDEM) Method for Static Shift Correction of Magnetotelluric (MT) Data. *Indonesia International Geothermal Convention & Exhibition*. Jakarta: INAGA. (2015).

Szarka, L. Geophysical Aspects of Man-Made Electromagnetic Noise in the Earth - A Review. (1988).

Ussher, G., Harvey, C., Johnstone, R., & Anderson, E. Understanding The Resistivities Observed in Geothermal System. *World Geothermal Congress*. Kyushu - Tohoku. (2000).

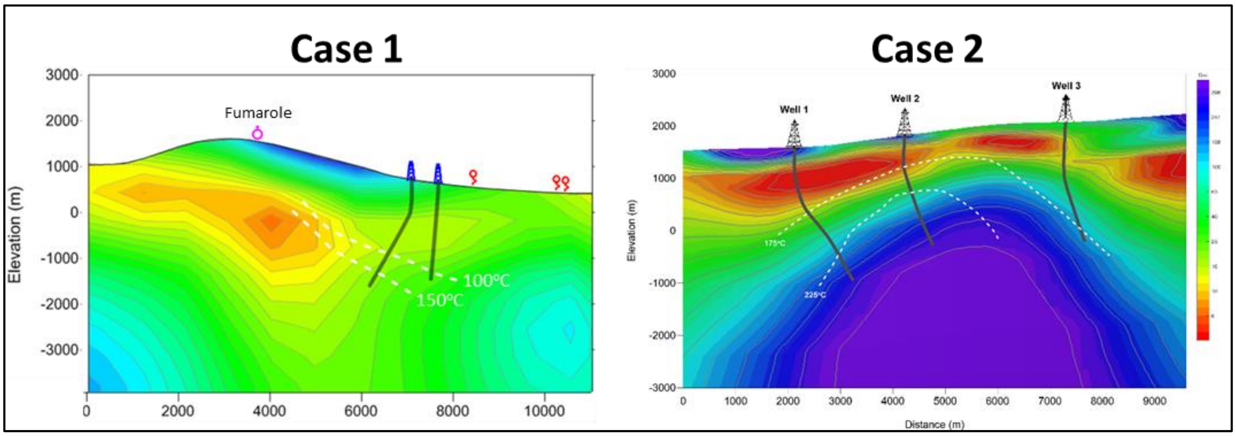

Figure 1. Problems of disagreement between MT result and drilling data for Case 1 and Case 2.

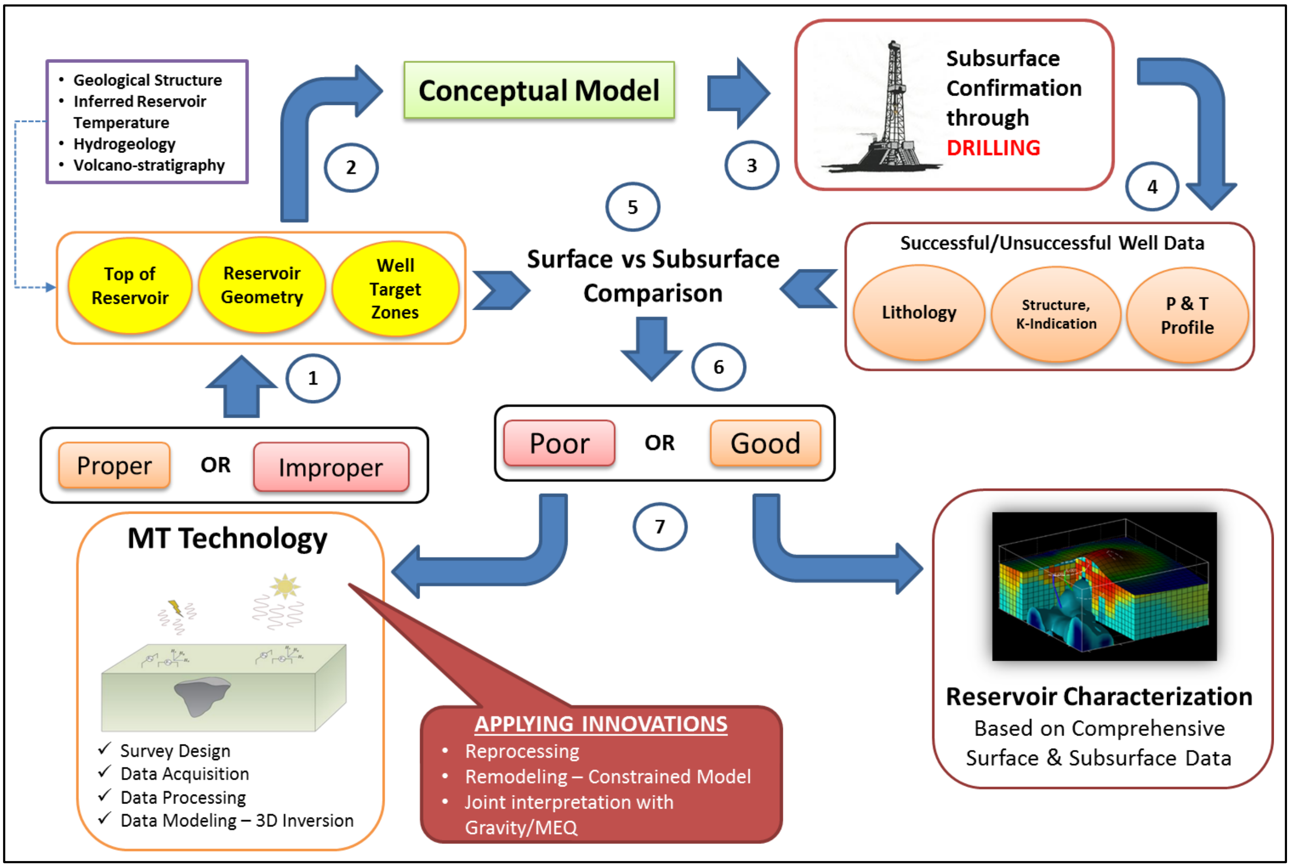

Figure 2. Workflow of MT application with or without applying innovations for drilling target recommendation.

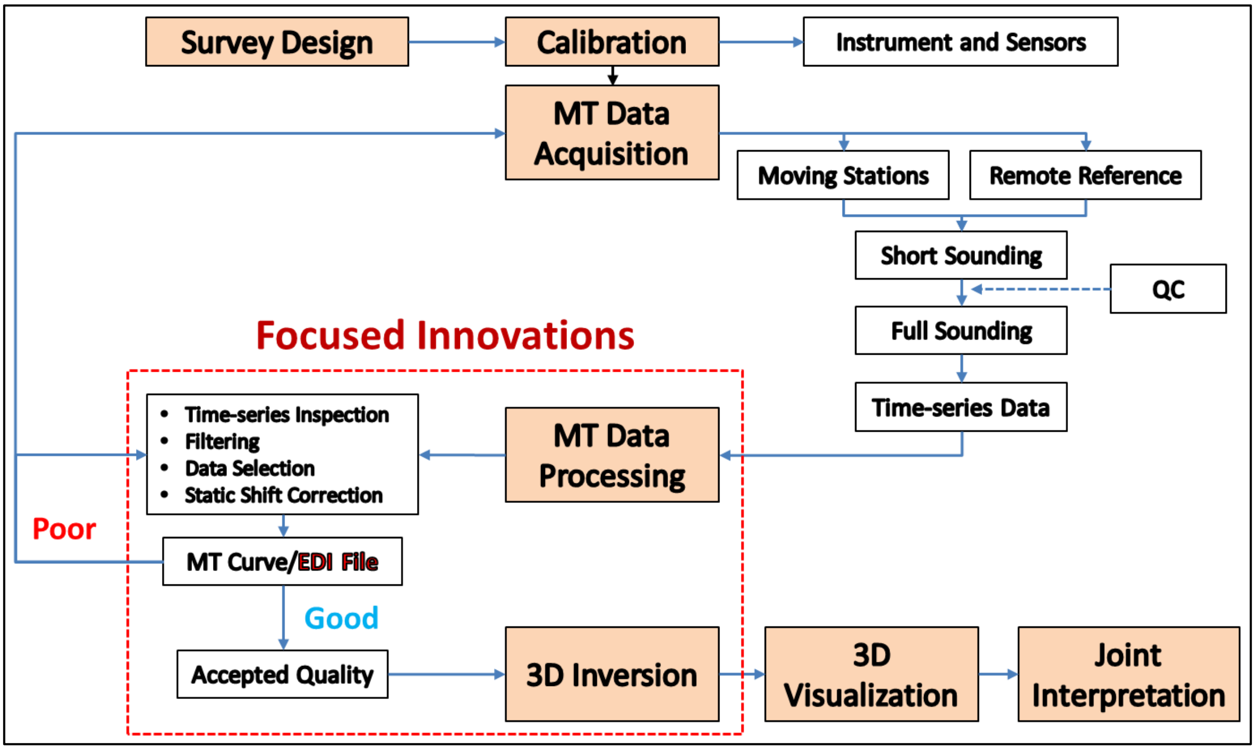

Figure 3. Workflow of MT technology.

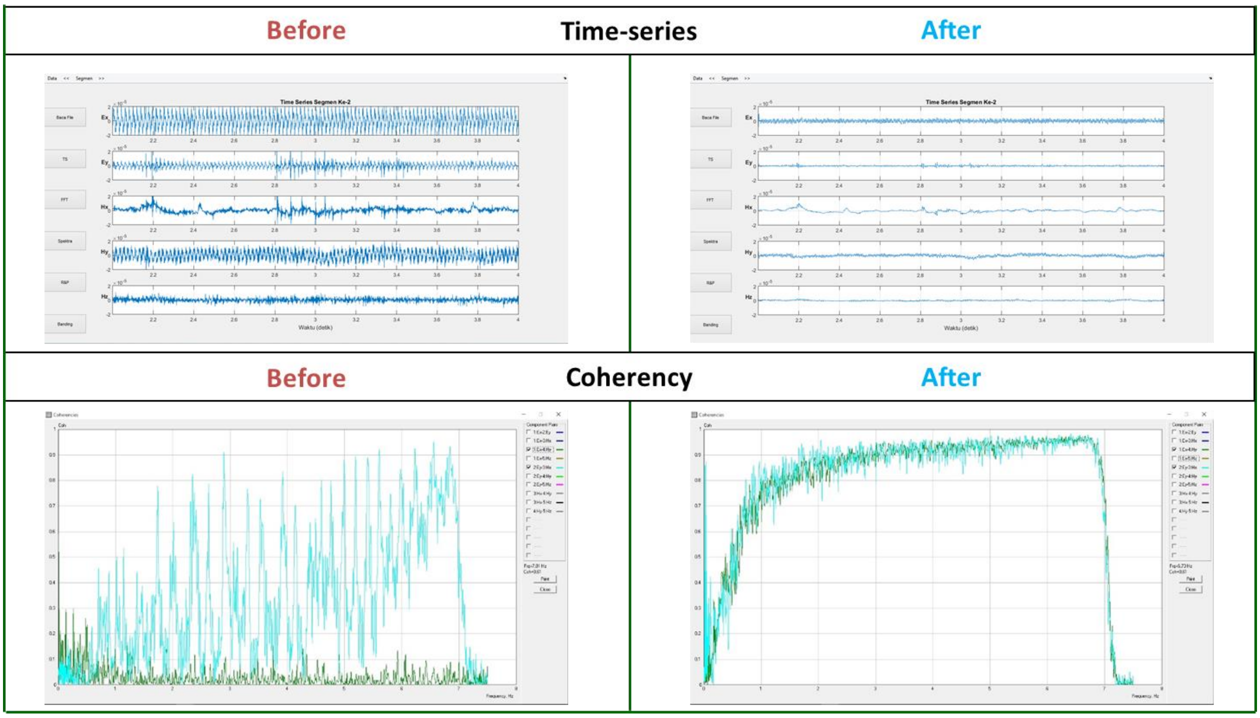

Figure 4. Condition of time-series and coherency before and after applying noise filters.

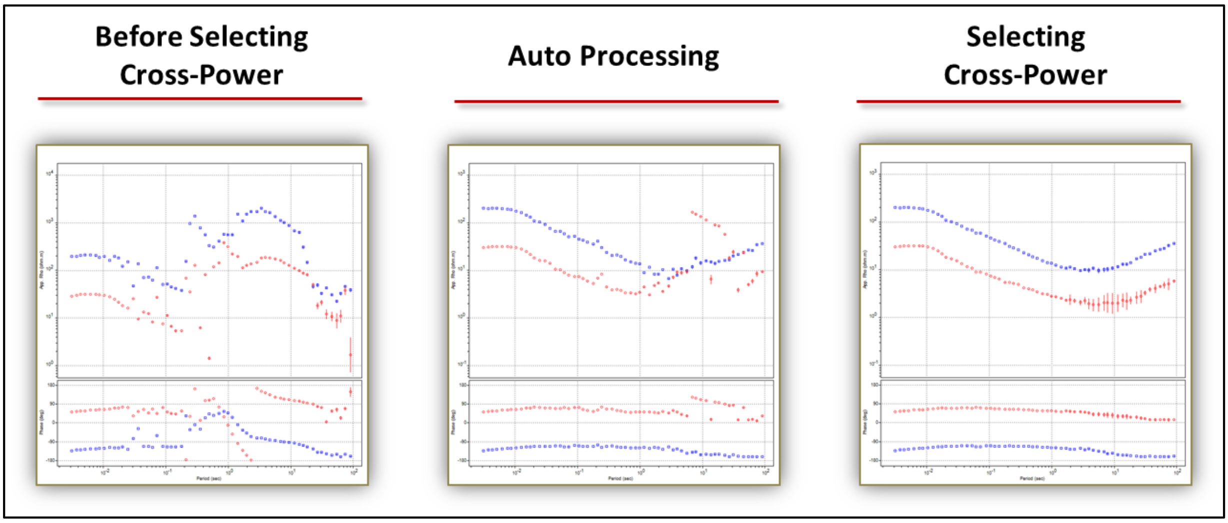

Figure 5. Comparison between before selecting cross power, auto-processing and "manual" selection.

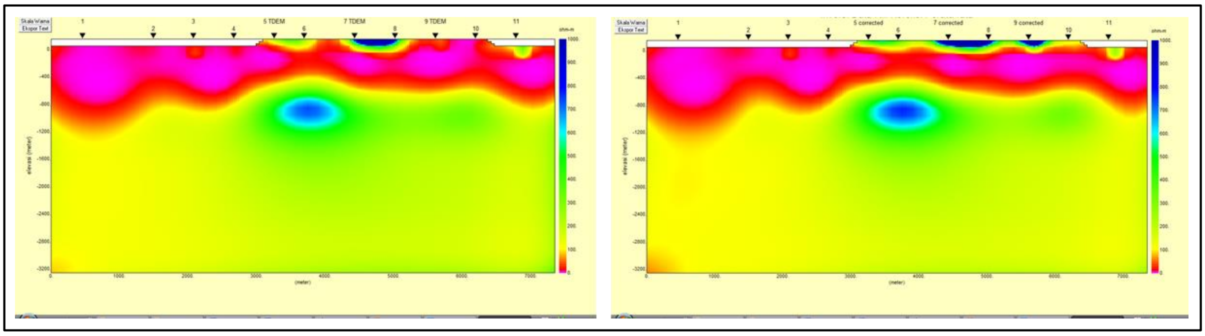

Figure 6. Comparison of inversion result of MT data after applying TDEM (left) and Geostatistic (right).

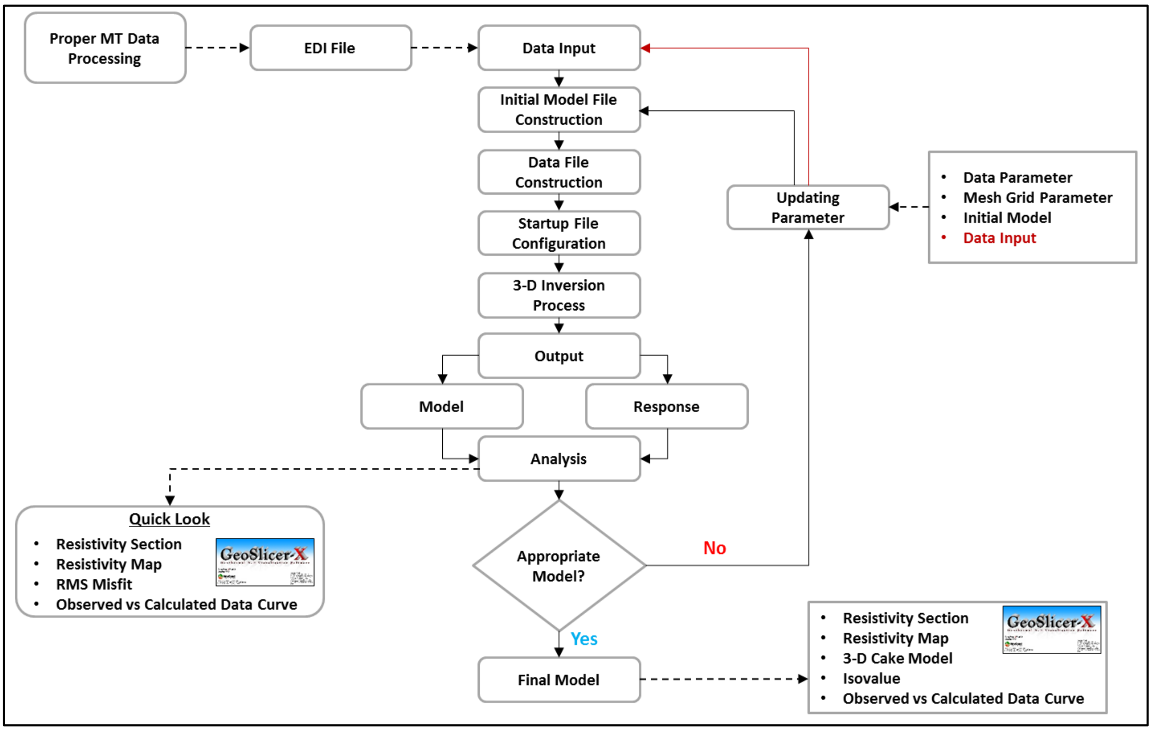

Figure 7. 3-D inversion flowchart using MT3DInv-X software.

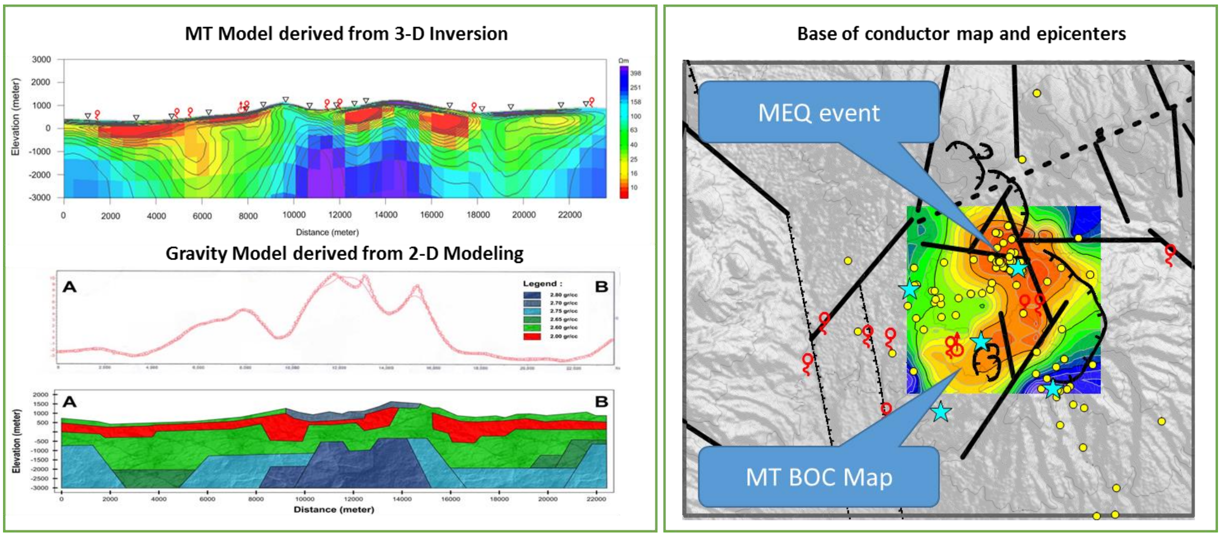

Figure 8. Correlation between MT and Gravity (left) as well as MT and MEQ (right)

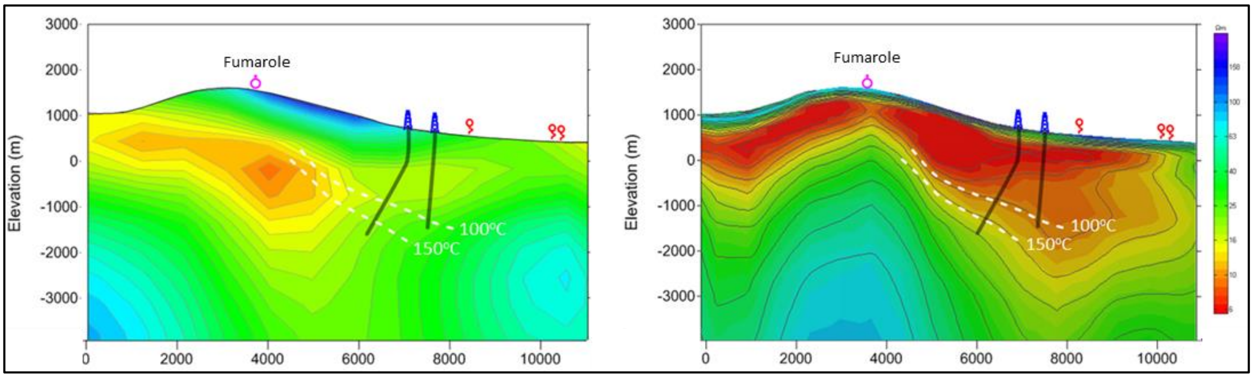

Figure 9. Correlation between MT and drilling result before (left) and after (right) applying the innovation to the case 1.

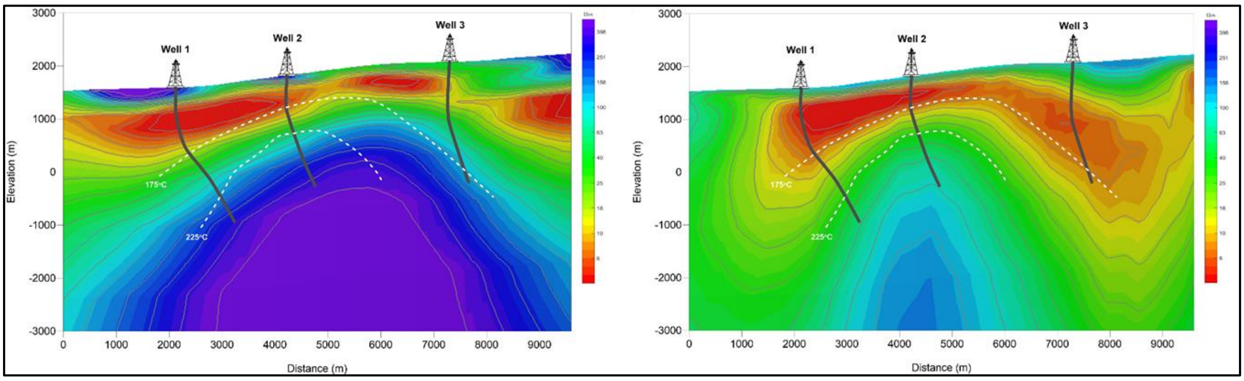

Figure 10. Correlation between MT and drilling result before (left) and after (right) applying the innovation to the case 2.

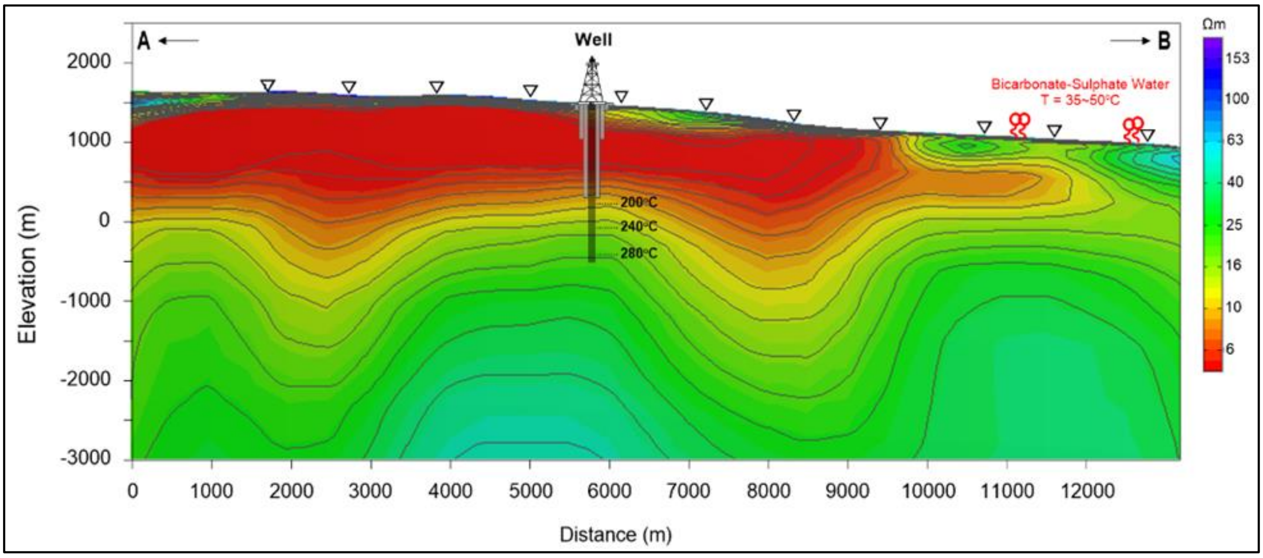

Figure 11. The result after applying the innovation for the Case 3. The example of successful drilling campaign in a green field.