Click to view oral presentation.

3D Inversion of Crosswell Electromagnetic Data Collected between Extremely Spaced Horizontal Wells*

Ping Zhang[1], Alberto Marsala[2], Stig Lyngra[2], Wael Abdallah[1], and Mike Wilt[3]

Search and Discovery Article #41860 (2016)
Posted August 15, 2016

*Adapted from extended abstract prepared in relation to oral presentation and from the presentation itself given at GEO 2016, 12th Middle East Geosciences Conference and Exhibition, Manama, Bahrain, March 7-10, 2016. Bahrain:

[1]Schlumberger (PZhang@slb.com)
[2]Saudi Aramco
[3]Groundmetrcis

Abstract

A crosswell electromagnetics (called DeepLook EM) survey was applied to map oil and water saturation in a naturally fractured reservoir in Saudi Arabia between a 1-km-long horizontal water injection well and a 1-km-long horizontal producer 1.3 km away. Although high-quality data provide a solid foundation for interpretation, 3D inversions of DeepLook EM data collected from horizontal wells are very challenging. Many factors can affect the inversion results, especially the starting model and the inversion constraints. This article reports the process to select and refine the starting models and choose constraints based on existing geological and geophysical information. We also demonstrate the impact of starting models and constraints on the final inverted conductivity structure.

Introduction

DeepLook EM, initially developed in the 1990's, involves applying inductive physics and 2D inversion to vertical and sub-vertical wells to define the inter-well conductivity distribution. The method has developed into a mature technology in the oil and gas community, especially for enhanced oil recovery (EOR) and time-lapse studies (Wilt et al., 1995). However, applying the technology to horizontal wells involves an entirely new set of challenges. First, because the wells are oriented horizontally the sensors are sensitive to variations both vertically and horizontally, the problem becomes 3D. Second, because the measurements are confined to a limited set of vertical levels, the problem is extremely under-determined for 3D inversions, meaning that there are far fewer observations than required to properly define the conductivity of a 3D model. Starting model and inversion constraints must be carefully chosen to achieve useful inversion results.

This study is part of a larger effort by Saudi Aramco to understand the saturation distribution in fracture-controlled reservoirs and to thereby devise strategies for improving production and recovery. The general description of the project and preliminary interpretation of the inversion results are presented in Marsala, et al. (2015).

In this article we mainly focus on technical details of how to achieve stable and useful 3D inversions. In particular, we have studied starting models and inversion constrains in detail. After a brief description of the data collection and processing, the role played by the starting model in the inversion results is examined. We demonstrate that if the starting model is too far away from the formation being investigated, then the inversion may fall into a local minimum and cannot find a useful conductivity model. On the other hand, a starting model defined based on known geological and geophysical information may lead the inversion to a global minimum; and, therefore, a properly defined conductivity model. Inversion constraint is another powerful tool to guide the model searching process. How to select a correct constraint depends on the problem being studied. The general rule is that any constraint must be consistent and justifiable with known structure knowledge. A properly selected constraint not only reduces the uncertainty of an inversion, but may also enhance the resolution of the final model. Finally we discovered that testing the sensitivity of an inversion with different starting models and constraints may increase the confidence and provide deep understanding of inverted models reliability.

Data Collection

The selected fractured carbonate field is a giant mature oilfield in Saudi Arabia. One of the main producing reservoirs has been under water flooding since the 1970s, but there are indications that considerable oil still remains. The selected reservoir is approximately 100m thick and has a moderate porosity (around 20%) but low matrix permeability. The reservoir is known to be connected via through-going clustered fractures, or fracture corridors which provide easy passage to the injected water. However, the connections and their impact on saturation and recovery are poorly understood in the inter-well volumes, where a direct measurement of saturation is not possible with conventional well logging.

The DeepLook EM technology was chosen to map the inter-well saturation due to its sensitivity to the high conductivity salt water used for water flooding. Two horizontal wells, an injector and a producer, about 1.3 km far apart, were chosen for DeepLook EM survey. The wells are roughly parallel although at different vertical levels. The injection well was completed as an open hole over its entire 900m length. The production logs indicate that much of the injected water exited the well through an extensive fracture corridor encountered in the initial 100m. The producing well was also completed as an open hole over 900m, but the initial 350m was later cased off with a steel liner to eliminate water production from fracture zones crossed near the well heel. The DeepLook EM data were collected during a 6-day period in April, 2014, using a transmitter frequency of 91 Hz. The data quality is excellent. The details about the data collection and processing can be found in Marsala, et al. (2015). A sample of the data used for 3D inversions is presented in Figure 1.

Inversion Practice

Field data were interpreted with a 3D finite difference inversion code (Mackie and Rodi, 2008). We noted that for DeepLook EM survey in horizontal wells (Figure 2), the induced current is perpendicular to the tool axis (both transmitter and receivers are axial magnetic dipoles).

Although this provides a good sensitivity to vertical structure, the inversion is inevitably 3D. In general a 3D inversion from data collected in a single well pair is severely under-determined for even a simple 3D model. Especially in this case, both wells are confined within the reservoir, and the distribution of measurements is insufficient to resolve much in 3D. We need extra information to guide the inversions. Many factors can influence the outcome of an inversion. We will examine the role played by the starting model and constraint in the following section.

Impact of Starting Model

A good starting model is extremely useful to define the conductivity structure between the two wells. To study the impact of a starting model to inversion results, three different models are tested:

1. A model with uniform conductivity
2. A background model constructed by using available logs and geophysical data in which the conductivity within the reservoir is constant
3. A model using the same background model as model (2), but with conductivity values within the reservoir defined from the conductivity logs of both the injection and producing wells.

The purpose of using different starting models is to study the dependence of the inversion results from the initial background model guess and to investigate which inverted features are common among different starting models. We believe that those features are probably not biased by the starting model, but are required to fit the measured EM field data. Figure 3 shows three different starting models that are used as the initial guess to invert the measured crosswell EM data in Figure 1. With the same inversion parameters and constraints the inverted models are presented in Figure 4.

The inversion using a uniform starting model (model 1) does not lead to any adequate 3D structure. The other inversions started with models 2 and 3 define sensible 3D conductivity structures. It seems that the uniform starting model is too far away from the true formation structure; therefore, the inversion is unable to reach a global minimum. Instead, it may fall into a local minimum.

On the other hand, models 2 and 3 are constructed from the existing geological and geophysical information, so they are closer to the true formation structures and properties. As a result, the inversions are easily converged, perhaps to a global minimum. In fact, the best data misfit start with model 1 is approximately 4%, and with models 2 and 3, the data misfit is reduced to approximately 1%, which is a very significant improvement.

Figure 5 shows a depth section of the inverted models started with models 2 and 3. Although the two starting models are very different within the reservoir section, the inverted structures share a similar pattern. The conductive blocks (purple) are well defined in both cases, although the values of the conductivity are different. We may conclude that those conductive blocks are required by the data and should be interpreted with high confidence.

Constraints of 3D Inversion

Another important factor that has profound impact on the inversion results is the constraint. It is well known that inversion is a non-unique process. Many different models can fit the field data equally well. One way to solve the non-uniqueness is to apply inversion constraints. The most common is the smooth constraint, which requires the attribute of the inverted model to be varied smoothly across the entire model space. One can also add other constraints so long as they can be justified with our knowledge about the area being investigated.

For this particular oil field, local geology and borehole logging data indicate that two conditions should be considered to make the constraints more meaningful. The first is that target reservoir is a low-resistivity volume confined by thicker high-resistivity (low porosity) layers; that is, the induced signal is almost fully confined into the reservoir volume, within well defined upper and lower boundaries. This means that most of the sensitivity of inversion is within the reservoir. Secondly, the injected water is mostly confined within the reservoir, and very little water is expected to leak into the layers above and below the reservoir due to their low porosity. Therefore, almost all the conductivity changes are expected within the reservoir boundary. A most straight forward constraint limits the inversion area entirely within the reservoir.

Both starting models 2 and 3 were constructed from linear interpretation of the borehole conductivity logs at the survey area. Clearly these models, at the best, are only approximations of the true formation structure. As mentioned before, 3D inversion is sensitive to the layers above and below the reservoir. These layers only have constant conductivity inferred from the borehole logs (see models 2 and 3). Therefore, we cannot fix these layers at the beginning of the inversion. Instead, we perform the inversion in two phases. Initially we fit the data using a predefined starting model (model 3) by inverting the entire model space. Only smooth constraint is applied; so the inversion is free to adjust the conductive values iteratively both inside and outside of the reservoir. Exactly 100 iterations were required to reach the best data misfit (approximately 1.2%). We then start another inversion with an initial model extracted from the previous inversion at the 20th iteration. The data misfit at the 20th iteration is approximately 5%. An additional constraint is applied to the new inversion. This constraint requires that the conductivity values outside the reservoir are fixed, and the remaining cells within the reservoir are allowed to adjust to fit the data.
The final iteration of the new inversion is able to reduce the data misfit from 5% to approximately 1%. In other words, by changing only the conductivity values within the reservoir, the inversion is able to fit the data within our threshold (1%). Choosing the initial model at 20th iteration of the previous un-constrained inversion is somewhat subjective. The goal is that the conductivity values outside the reservoir have been sufficiently adjusted that by fixing them in the remaining inversion will not degrade the data misfit. A good justification for doing this is that we are able to reduce the misfit from 5% to around 1%. That means the influence to the data misfit due to the fixed background is insignificant. Figure 6 shows the inverted models with and without the new constraint.

Discussion

Field data were interpreted with a 3D finite difference inversion code (Mackie and Rodi, 2008). The workflow consists of using different starting models and constraints to reduce the non-uniqueness and to define adequate models.

The 3D inversion of DeepLook EM data presented in this article is a very challenging problem. Many factors can alter the output of an inversion. We investigate two important ones: starting model and constraint with limited inversion area. Inversion normally starts with an initial guess of the attributes being investigated. It then iteratively adjusts the attributes until the field data fit within predefined threshold. If the initial guess is too far away from the ground truth, the inversion probably will never reach an adequate model and may fall into a local minimum. A good starting model should be consistent with known structure information, and thereby be somewhat close to ground truth. An inversion starting with such defined initial model may avoid the local minimum trap and reach a global minimum. Model 1, in this study, is the easiest model to construct, but it is very far away from the ground truth. So it is not surprising to see that the inversion starting with model 1 does not converge and cannot give an adequate final model either. Models 2 and 3, on the other hand, require extra effort to build. We must assemble the known geological and geophysical data to construct the subsurface structure. In this study, these extra efforts paid off in terms of inversion results. The inversions starting from either model 2 or model 3 are able to fit data very well and also define adequate conductive structures. The purpose of applying constraints on inversion is to minimize the uncertainty and enhance the resolving power. The justification behind any constraint is that it is consistent with our knowledge about the structure being investigated. In this specific oil field, we knew that the target reservoir is a low-resistivity volume confined by thicker high-resistivity and low-porosity layers and that almost all the injected water is confined within the reservoir. Therefore, the induced EM signal is almost fully confined within the reservoir volume. Limiting the inversion area within the reservoir is fully justified in this case.

The inverted results with and without the above-mentioned constraint (Figure 6) reveal similar conductive features inside the reservoir. However, there are important differences. Although unconstrained inversion defines conductive blocks with similar shapes, those are less confined and lack of details compared those in the constrained inversion. This particular constraint seems to be well justified, and it provides a better defined model. Inverting only the reservoir area is a very different process compared with inverting the entire model space. Although there are some important differences between the two inverted models, two major conductive blocks (one at center and another one at the front) are resolved by both inversions. These two conductive blocks seem to be less dependent on the constraints, but they are mostly required by the measured EM data. Similar results are also achieved using the starting model 2. This may provide an effective way to investigate the uniqueness of the inversions. If some features revealed in the final model have minimum or no dependence on the starting models and constraints; then they are robust and required by the data. Therefore, they should be treated with more confidence in the interpretation stage. In our case, the central and front conductors in Figure 6 are considered more realistic in the final interpretation (Marsala, et al., 2015).

Conclusions

3D inversions using DeepLook EM data collected from horizontal wells are a challenging and very non-unique problem. Both starting model and constraints have profound impact on the outcome of the inversions. A model with a uniform conductivity is an easy initial guess, but it is far from the ground truth; therefore it does not lead to a useful inversion result. A model constructed with a priori geological and geophysical knowledge, based on well logs and structural information, provides an excellent initial guess; as a result, realistic models can be defined by the inversions. Carefully selected constraints can enhance the resolving power of the inversion. However, any constraint applied to an inversion must be geologically, geophysically and petrophysically justified. Appropriate screening and selection of starting models and constraints can provide important knowledge regarding the robustness and confidence of the inverted models.

Acknowledgements

This project is the result of a collaborative multidisciplinary project between Saudi Aramco and Schlumberger. Thanks to all the colleagues that made this success possible; among whom we mention: Stig Lyngra, Danang Widjaja, Sanggam Hutabarat, Mark Ma, Keshab Baruah, Nashi Al-Otaibi, Moemen Ramadan, Steve Crary, Pablo Saldungaray, Khaled Hadj-Sassi, and Joseph Khoury.

References Cited

Mackie, R., M D. Watts, and W. Rodi, 2008, Joint 3D inversion of marine CSEM and MT data (abstract): 77th Annual International Meeting, SEG, Expanded Abstracts, p. 574–578.

Marsala, A., S. Lyngra, M. Safdar, P. Zhang, and M. Wilt, 2015, Crosswell electromagnetic induction between two widely spaced horizontal wells: Coil-tubing conveyed data collection and 3D inversion from a carbonate reservoir in Saudi Arabia(abstract): 85th Annual International Meeting, SEG, Expanded Abstracts.

Wilt, M., D.L. Alumbaugh, H.F. Morrison, A. Becker, K.H. Lee, and M. Deszcz-Pan, 1995, Crosshole electromagnetic tomography: system design considerations and field results: Geophysics, v. 60, p. 871-885.

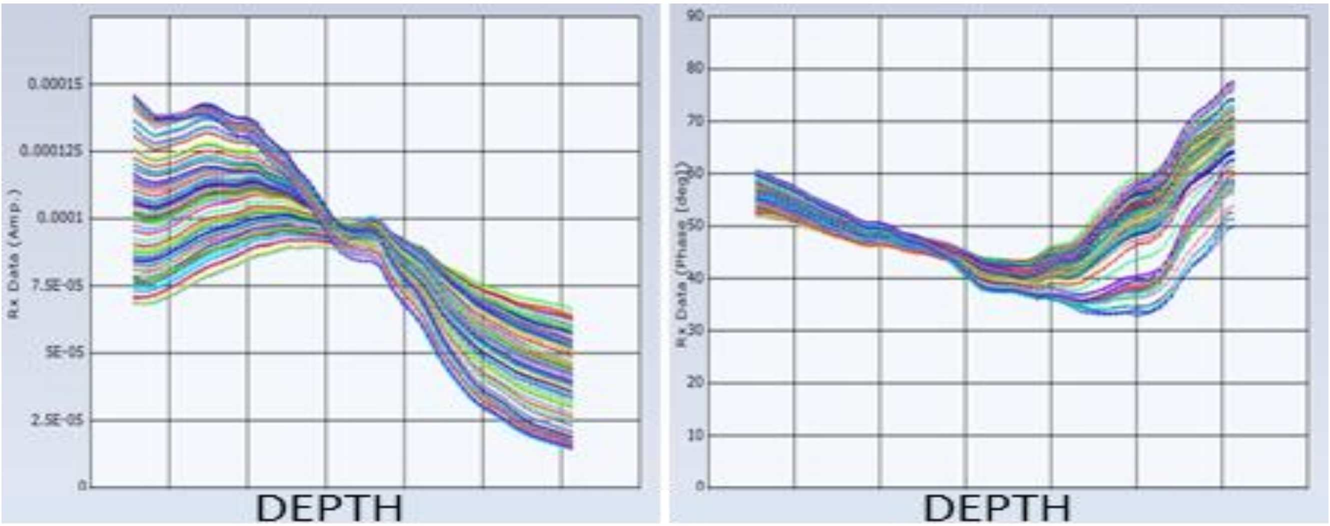

Figure 1. Amplitude (left panel) and phase (right panel) gathers for DeepLook EM data. The x axis is transmitter depth. The x axis in the left panel is in field units (voltage) and in degrees in the right panel.

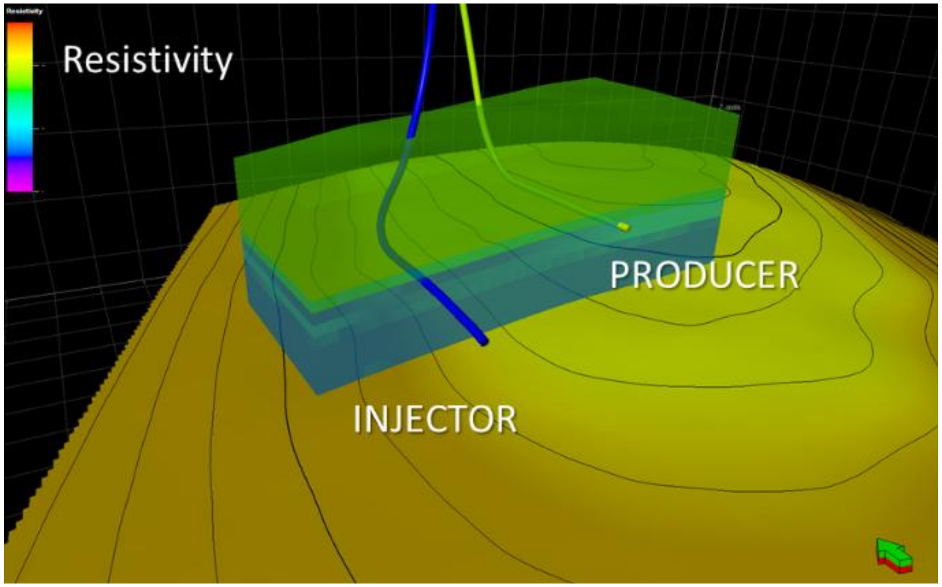

Figure 2. Configuration of the DeepLook EM survey in horizontal wells.

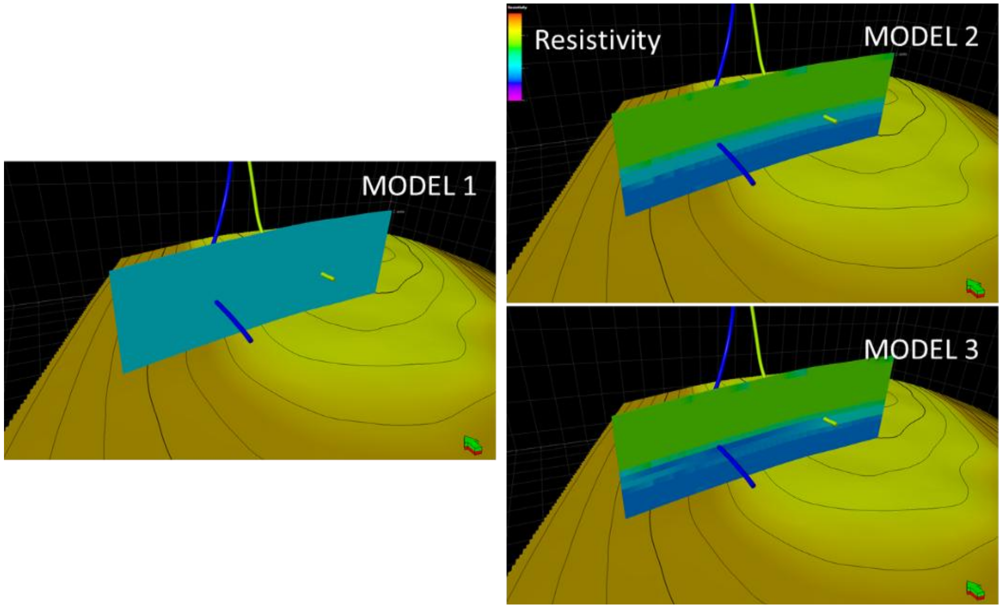

Figure 3. Three different starting models with injection well and producing well. The separation between the wells is approximately 1.3km (section map).

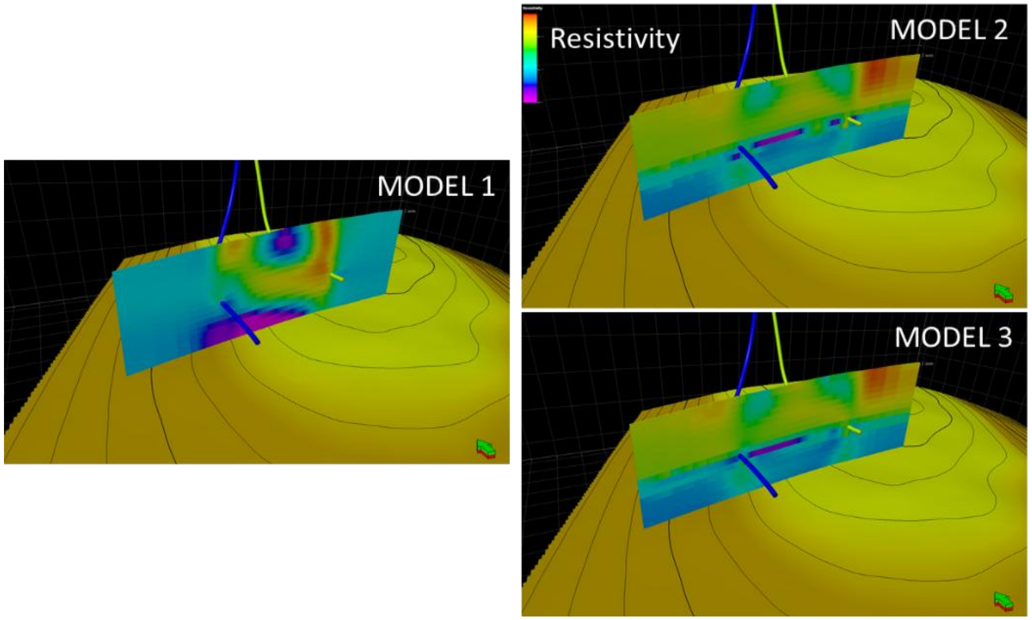

Figure 4. Inverted models from starting model 1, 2 and 3 (section map).

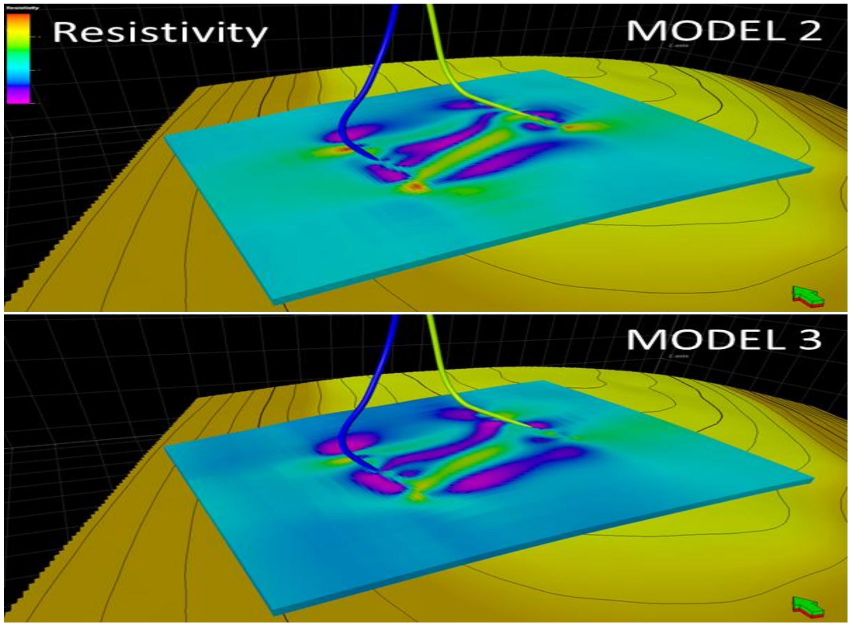

Figure 5. Depth section of inverted models from starting models 2 and 3. Purple indicates a high conductivity.

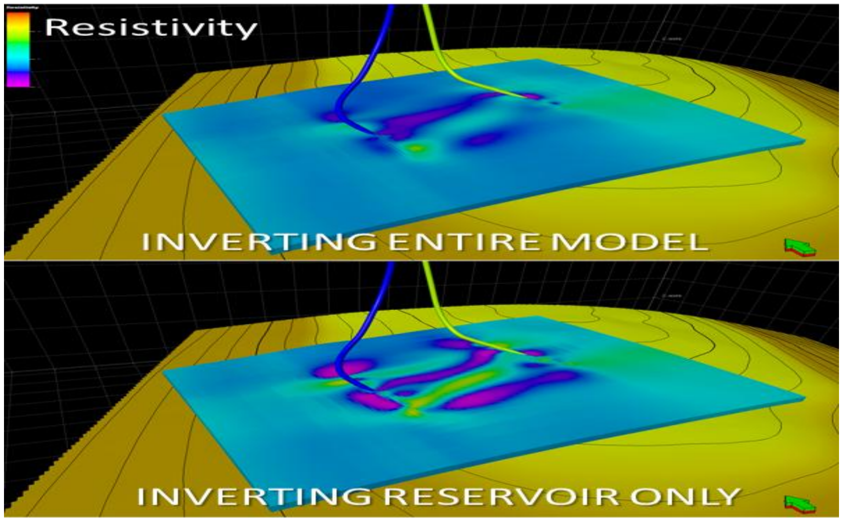

Figure 6. Inverted models with different constraints (depth map).