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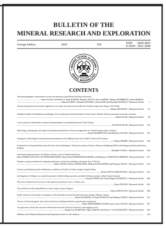

# An approach to obtain the structural information from the electrical resistivity well logging curves

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## ABSTRACT

In well logging measurements, the effect of the fluid in the well on the resistivity log curves and the investigation depth/distance for 16 and 64 inches logs were investigated in two-dimensional numerical modeling with the assumption that underground structures are symmetrical. Structural information was obtained via recovering the real resistivity values by using the inversion rather than empirical approaches. Generally, in the case of using the conductive fluid (1 ohm.m<) depending on the ratio of unit thickness (k) with respect to the length of log (l) (i.e. k/l), the insulating formations produce an “M” shaped signs for k/l<1 and appears as the conductive unit that cause fictitious structures in the data. The depth/distance of the research on the other hand causes deviations in the resistivity of structure due to tool length and distance. By the help of the inversion study one of the possible models is obtained. Contribution of this method to such studies is the reveal of compatibility of the resistivity model and data that usually neglected in other approaches.

## 1. Introduction

In well-logging studies, the physical properties of geological units are obtained. In resistivity logging, the current is applied directly into the geological unit and the real resistivity is obtained by measuring the voltage difference within the same geological unit as long as the unit is sufficiently thick (Figure 1). In practice, this case is very rarely encountered. Since the layer thickness is less than the logging device, the measured value is influenced by the resistivity of the layers on the lower and upper sides of the unit (so-called shoulder effect), as well as the real resistivity of the target unit. In addition, the boreholes itself filling fluid, invasion zones and the lateral transitions in the geological units also affect the measurements (Figure 2). The assessment of the complex data due to shoulder effect, the size of the measuring device and geological conditions has been the subjects of different studies (e.g. Woodhouse, 1978; Anderson, 2001; Nam et al 2010; Rodríguez-Rozas and Pardo, 2016). The

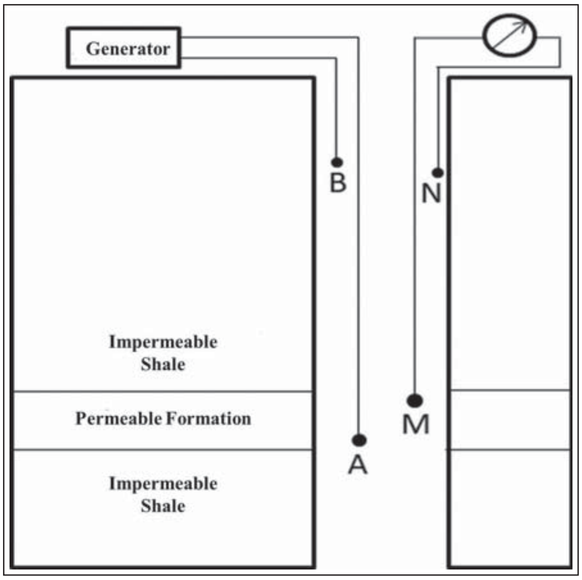

Figure 1- Simple schematic view of the normal electrical resistivity log.

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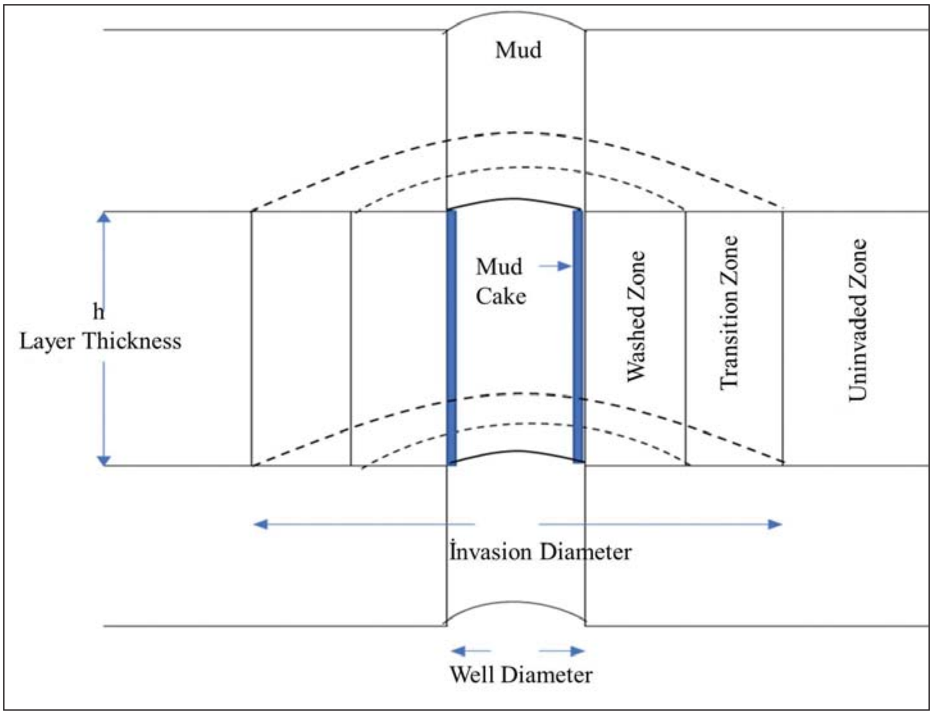

Figure 2- The view of layers that formed in well log study (Layers were shown as symmetrically with respect to well center).

behavior of the curves represents the filtered and simplified images of underground structures. In this sense, the values obtained from logging yield not real but apparent resistivity curves similar to those measured at the surface (e.g. Ulugergerli, 2011). As in many geophysical methods, the electric well logs often encounter with the problem of recovering the large number of parameters from a limited number of data. In practice, in order to obtain the resistivity of invasion zone and the formation either master curves or charts are utilized (e.g. Scott, 1978) or complex underground structures are imaged by multidimensional modeling (e.g. Liu et al., 1994; Yang and Ward, 1984; Pardo et al., 2008) from the apparent resistivity curves acquired in the well.

When charts are utilized, thin layered structures give erroneous results due to the applied corrections and assumptions. Most of the published charts have been produced for vertical drilling wells. As the charts became increasingly invalid, developing new approaches for the interpretation became crucial. Modeling has begun to develop from recognition of the non-functionality of the charts. Due to the development of computer technology, numerical modeling studies replaced the charts. Anderson (2001) outlined the historical development of the use of the modeling in well-logging. With the widespread use of digital modeling, the effect of both logging environment and device on the measurement has also been investigated through the researchers.

As an example, Dutta (1994) studied the calculation of resistivity and depth of invasion zones, formed by the drilling mud, from apparent resistivity curves via an infinitely thick layer. Modeling studies were followed by the inverse solution assessment studies and the inverse solution of both electric and electromagnetic logs has been the subject of various studies. One of the examples of these studies is Liu and Lin (2002). These authors have studied the joint inversion of induction, lateral and normal logs. They have described the joint inversion of induction and galvanic log measurements as an approach that needs to be carefully considered because of the problem of converging to local minima.

In the following years, Pardo et al. (2007), have studied the electrical resistivity log measurements, different electrode configuration and anisotropic effects using three-dimensional modeling of in deviated wells.

Both referred and also other studies in the literature indicated that the insufficient number of data obtained from the well-logs and the excess number of parameters that are desired to be solved have been main obstacles to numerical modeling studies. This obstacle has also opened the way to attempt to try different approaches in studies carried out in these kind and similar cases (e.g. Ahmadi et al., 2013). It is an undeniable fact that modeling studies are necessary to determine precise relationship between the measured data and wells and surrounding geology. In the following sections, the term modeling includes both the acquisition of observable data (forward solution) and the estimation of the parameters from measured data (inverse solution). The use of three-dimensional models that includes all structural changes in the forward solution studies, and the requirement of searching whole solution space in inverse solution create a heavy computation burden to the user. When the simplified model and the source points are considered, if the number of parameters to be solved per data in the symmetric model is n then it will be $n^2$ in three-dimensional model. An approach that does not require excessive computational power was chosen in this study. Geological structures in the well and the surrounding area were assumed to be symmetrical. With this approach, it is assumed that geological boundaries lay only horizontally and vertically and the number of parameters decreases. Geological units are defined as concentric cylindrical structures (Figure 2). This approach will provide a sufficient accuracy for the immediate vicinity of the well. This approach will continue to be valid in coal-bearing basins where electrical logs are widely used. On the other hand, it should be kept in mind that this approach will be invalid in fully complicated environments (e.g. conglomerate) or dipping beds.

Direct current (DC) logs have already been studied on the symmetrical environment. Ulugergerli (2011) jointly inverted the short (SN, 16 inches) and long (LN, 64 inches) normal log curves using the conjugate gradient (CG) relaxation and the conventional CG approach and obtained the underground model. The use of a vector-to-matrix multiplication instead of a partial derivatives matrix in CG inverse solutions reduces the memory requirement and provides a fast solution (e.g. Mackie and Madden, 1993; Zhdanov, 2002). Ulugergerli (2011), using the artificial and real well data, compared the advantage of log types on the inverse solution in addition to relative superiorities of the approaches used in the inversion. It was emphasized that, as expected, information about the formation could be obtained from long normal log while short normal log provides information about the invasion zone and around the well. The investigation depth/range of logs was defined as proportional to the device size. In addition to these issues, the effect of mud cakes has been mentioned.

In this article, how the research depths are affected by the mud cake will be investigated in DC resistivity curves. For this purpose, in the following sections, 2D modeling studies and simple but efficient models were used to quantify numerically the effect of mud and depth of investigation.

In the second part of the study, the well-logging data were modeled with the inversion program. Synthetic and real data were used for this purpose.

Although the physical changes occurring in the wells starting from the well itself are investigated, the definition of depth of investigation will be used in the place of the survey range or distance to provide the consensus in terminology with surface geophysical studies in the following sections.

## 2. Problem Definition

As mentioned in the previous section, during the resistivity logging survey, changes in the well diameter and the zones invaded by mud affect the normal electric resistivity curves. The SN and LN resistivity logs will be considered in this study. Measurements are taken with the help of four ring electrodes placed on the device lowered into the well. In practice, although different scales are used, the order is as B, N, M and A. The electrodes B and N are accepted to be positioned infinitely far from M and A. Although the values may vary depending on the manufacturer, the distance may be given in the following manner. Electrode B is 328 ft above the N electrode. The N electrode is 600 or 960” above the nearest electrode M. The measurement is named according to AM range; AM = 16’’ for SN and AM = 64” for LN. The KN interval was used to monitor the invasion areas, while the UN range was produced to determine the true resistivity of the clean section, but, due to the invasion zones, the measured value includes the effect of both the invasion zones and the clean unit (Zamansky, 1980; Gianzero, 1981; Anderson, 2001 and Pekin, 2002).

Theoretically, the investigation depths at which SN and LN curves are affected are given as twice the spacing of current and voltage electrodes located on the device (Pekiner, 2002). The investigation depth is estimated as ~80 cm (2.6 ft) for the SN log, and as ~320 cm (10.4 ft) for the LN log. It is generally thought that the SN log curve is influenced by layers of invasion originating from the well (Pekiner, 2002).

Since the values recorded with logs are equivalent to the apparent resistivity gathered from surface surveys, they cannot be used for interpretation directly. The true resistivity of the units should be obtained. The real formation resistivity values may not be obtained by modeling the logging data using only one measurement technique. Geological information and auxiliary logs may be needed.

The models to be used in this study include the layers formed due to the fluid in the well. Three models were created, namely the mud, the transition zone in which the fluid flows through the layer and the invasion zone in which the fluid is located. With these models, the effects of the fluid inside the well on the KN curves according to the regions were investigated.

### 2.1. Numerical Modeling

The Finite Element method was used to obtain the desired log from a symmetric underground model (Ulugergerli, 2011). In order to fully process the shoulder effect, B and N electrodes, which should be theoretically at infinite, are placed at the finite distances and all electrode positions are used in the geometric coefficient calculation. The mesh used in the modeling was initiated by rather fine cells (0.1”) then expanded to coarse cells while moving away from the well. To satisfy the boundary conditions, very large cells were added at the end of the mesh.

In the inverse solution phase, the reweighted conjugate derivative was used (e.g. Zhdanov, 2002). The program stops when either a predetermined number of iterations or the selected misfit value is reached or there is no significant improvement between two consecutive misfit values.

## 3. The Effects of Invaded Layers

The model considered includes fluid-filled wells and invaded zones on the target layer. For simplicity, the invasion zone in the host rock was not included. The addition of this unit will not provide any additional information since all resistivity values will be shifted with the same ratio.

Fluid-related models define cases; (a) when there is only the mud in the well wall, (b) the model in which the mud and the washed zone are present and (c) and all three components exist. The aim in this section is to examine the effect of the specified models on the resistivity log curves measured by the SN (16”) device (Figure 3 and figure 4).

Considering the model in the 16 ‘curves (Figure 3a), it is seen that the curve (-) shows the presence of the layer (Rt = 5 ohm.m) passing through the mud (0.2 ohm.m), but the value that should be 5 ohm.m is seen as 3.6 ohm.m. When the washed zone is added (Rxo = 0.5 ohm.m, figure 3b) to the model, it is seen that the curve (o) gives low resistivity values (3.2 ohm.m) under the influence of this belt. In the latter model (Figure 3c) it is also seen that the curve (+) gives lower resistivity value (2.85 ohm.m) with the addition of all zones (mud, washed and transition zone). When

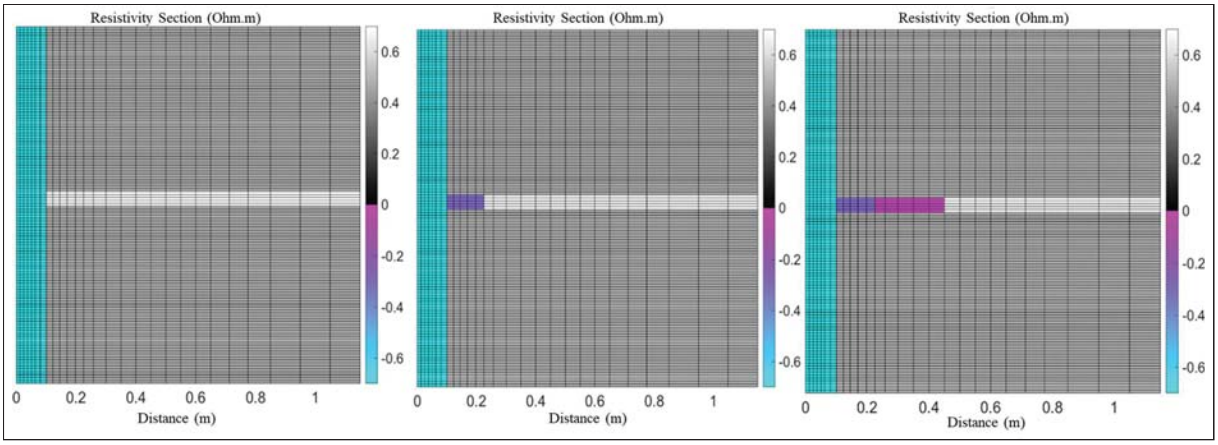

Figure 3- Underground models; a) well model, b) well and the washed zone and c) model consisting of the well, washed zone and transition belt.

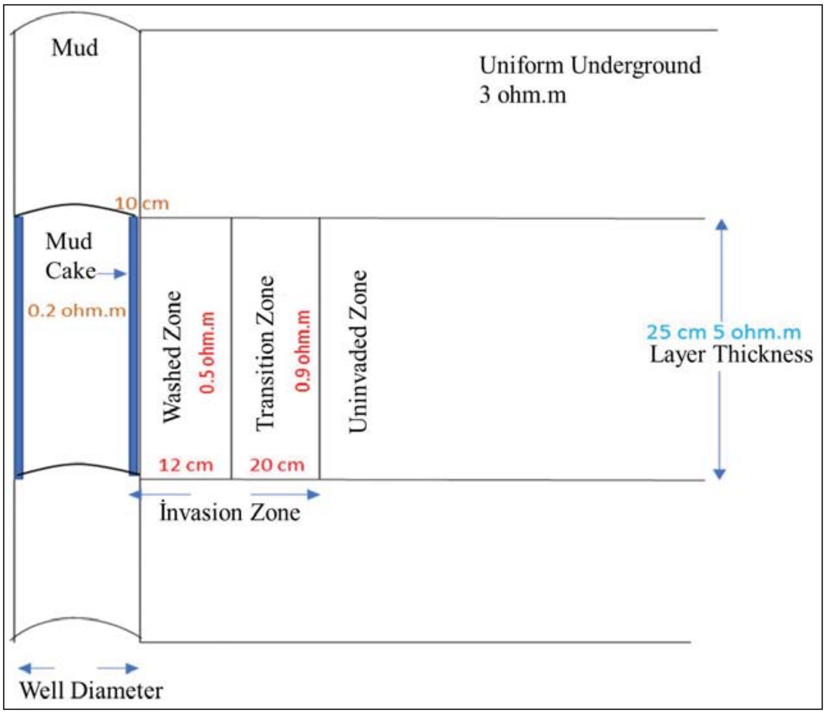

Figure 4- The representative view of the underground utilized in models.

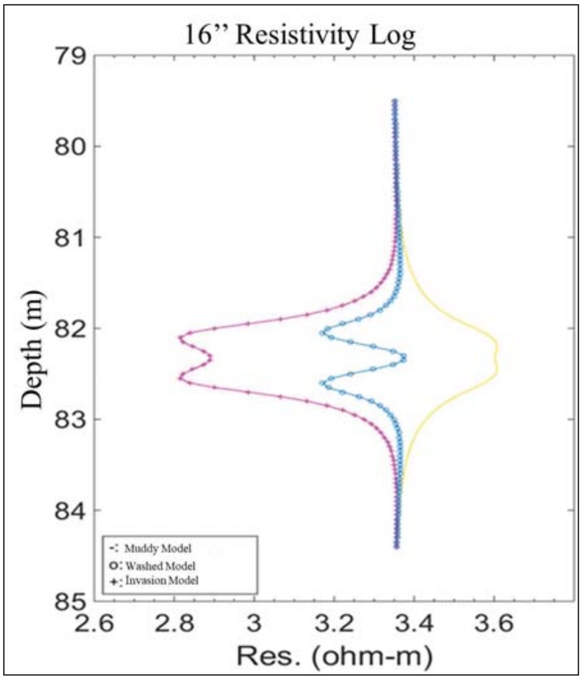

Figure 5- The variation of 16" normal log curves with mud effect and "M" shaped anomaly.

the models were examined, it was observed that, due to the artificial layering caused by the fluid, the SN log curves could not reach the layer resistivity (5 ohm.m) that was expected to be measured but remain at lower values (Figure 5).

Generally; charts are used in order to correct the effect of the fluid induced mud. (see Scott, 1978). The results obtained by these charts and our results were compared in figure 6, and it is not possible to make a prediction for the resistivity of the target layer in the correction using a chart, and it cannot be said that this correction has removed the effect of the mud.

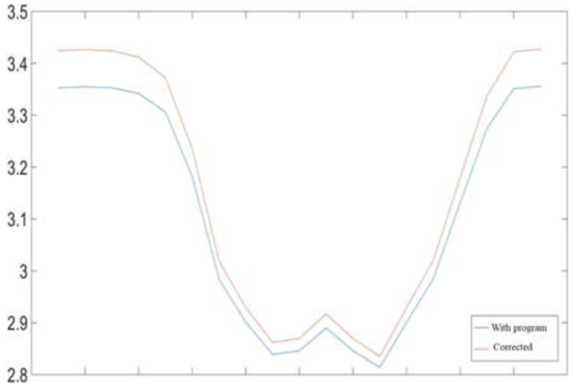

Figure 6- Mud-corrected data (yellow) and the data obtained from this study (blue) are shown. Vertical axis is ohm.m, horizontal axis is the depth.

## 4. Depth of Investigation

A series of models were used to examine the research depth of SN and LN logging devices. Models were prepared such that a unit with a resistivity of 10 ohm.m and infinite length inside the homogenous host of 1 ohm.m. In order to observe the effect to the research depth, the unit was gradually moved away from the well wall. In the first model created, the layer starts from the well. The theoretical investigation depth of the SN device is 80 cm, which is twice the instrument range. In the first four models, the unit remains in the depth of investigation of the short normal log tool. In subsequent models, the unit moves away from the investigation depth. In the used models, the distance of the unit to the well wall was taken as 0 cm, 20 cm, 40 cm, 78 cm, 155 cm, 325 cm, 550 cm and 750 cm, respectively (Figure 7).

When the models are compared; moving away from the semi-infinite unit of 10 ohm.m from the vertical measurement line inside the 1 ohm.m resistive underground causes proportional decrease in the resistivities of the 16 ‘’ curves. The reading for the first model (0 cm) converges to 10 ohm.m. As SN tool moves away from the boundary of the investigation depth, it deviates from the resistivity value of the target layer. When the theoretical investigation depth is approached, the reading gives the resistivity of the target unit as ~4.5 ohm.m. Very low values (<2.5 ohm.m) are observed after 1.5 m distance.

The theoretical investigation depth of the 64” tool includes the first six models, but the curves of the 20 cm and 40 cm models have opposite effects, giving more resistivity values than the LN curve produced by the adjacent unit (0 cm). When the theoretical investigation depth of the UN is approached, there is observed a resistivity value (<3.25 ohm.m) three times lower than the unit’s required value. When the theoretical investigation depth exceeded, then the values decreased below 1.7 ohm.m.

It is also seen that the curves obtained between the first and last models in both curves give a difference of about 10 ohm.m. In other words, the structure does not affect the data. With exceeding the theoretical investigation depth, the decrease in the SN and LN resistivity curves takes the form of increasing linear change with depth (trend) rather than structural effect.

## 5. Inversion of Real Data

In this section, two-dimensional models of underground were generated by inversion using short normal real resistivity well log data. Software developed by Ulugergerli (2011) which uses CG.

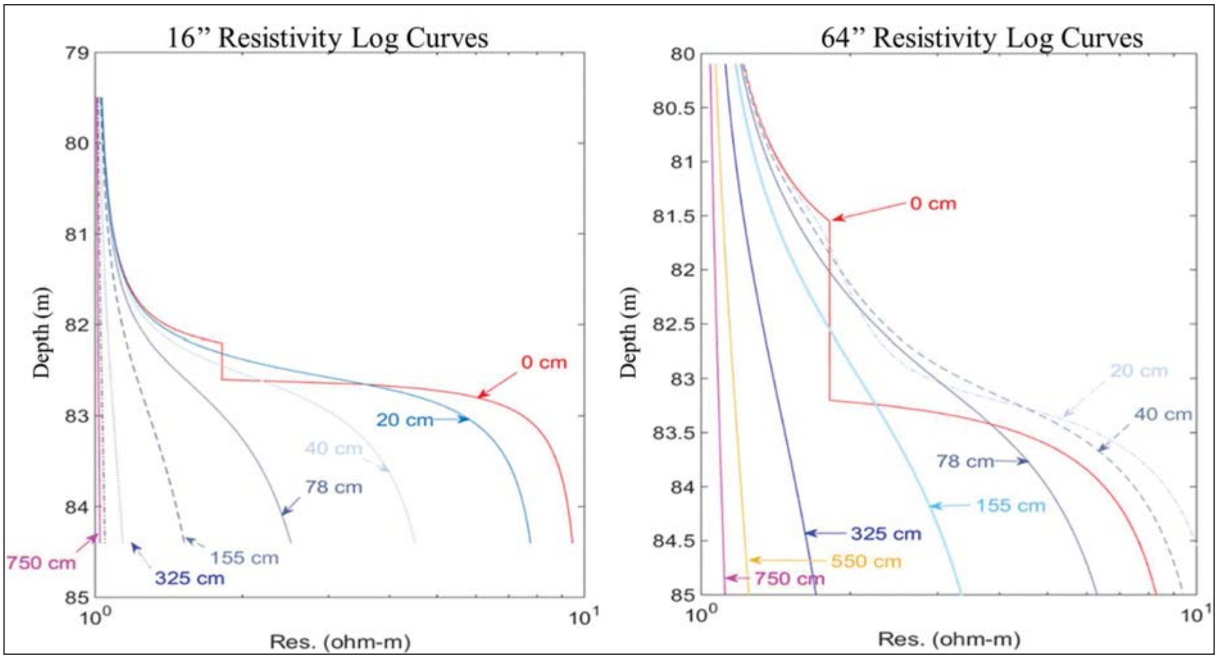

Figure 7- 16” (left) and 64” (right) log curves obtained by the removal of semi-infinite unit.

The section depth is 120 meters and the short normal resistivity values measured at every 0.5 meters were used. The number of data used is 240 and the mud was given as 4 cm thickness.

The resistivity data obtained from the well-logging survey were presented in figure 8. Real SN data (+) and calculated data (continuous line) were shown together for the inverse solution parameters are upgraded and fit between curves is improved at each iteration. The initial model has produced automatically. The inverse solution process made seven iterations and stopped at 0.0056357 misfit value.

The geological structure of the region was reported as volcanic rocks (Basalt, Andesite, Tuff) up to 1500 meters. It is known that the resistivity increase in the range of 230-260 m was interpreted as intact basalt.

When the obtained underground model is examined, it can be said that the resistivity values correspond to the basalt resistivity values (400 ohm.m). A sharp increase in the resistivity at about 233 meters forms a unit (dark blue) in the model which starts about 25 cm after the well wall and extends up to 2 meters.

The inversion study aims to recover the extremely large number of parameters, generally from insufficient and inadequate data. Such problems are encountered especially in surface studies with potential field methods. If comparison of calculated and measured data was assessed alone as the quality of the result the response of different models will provide similar misfit. The problem, defined as a multi-solution, point out that the inverse solution, as a mathematical sequence of operations, finds one of many possible models as a solution. Thus, in addition to the model found in this study, the response of many models will also provide similar misfit.

The validity of the results obtained due to the lack of data should be examined and interpreted in the direction of expectations.

## 6. Results

In the case of simple underground models, the effects of the mud and the drilling hole can be calculated and removed from the resistivity deviation curves by means of empirical formulas.

By means of modeling studies, the variation of the investigation depth based on the behaviors of normal curves can be revealed. In this study, the negative effect of the mud on the 16 ‘’ resistivity logging curves were investigated with mud formed layers. The

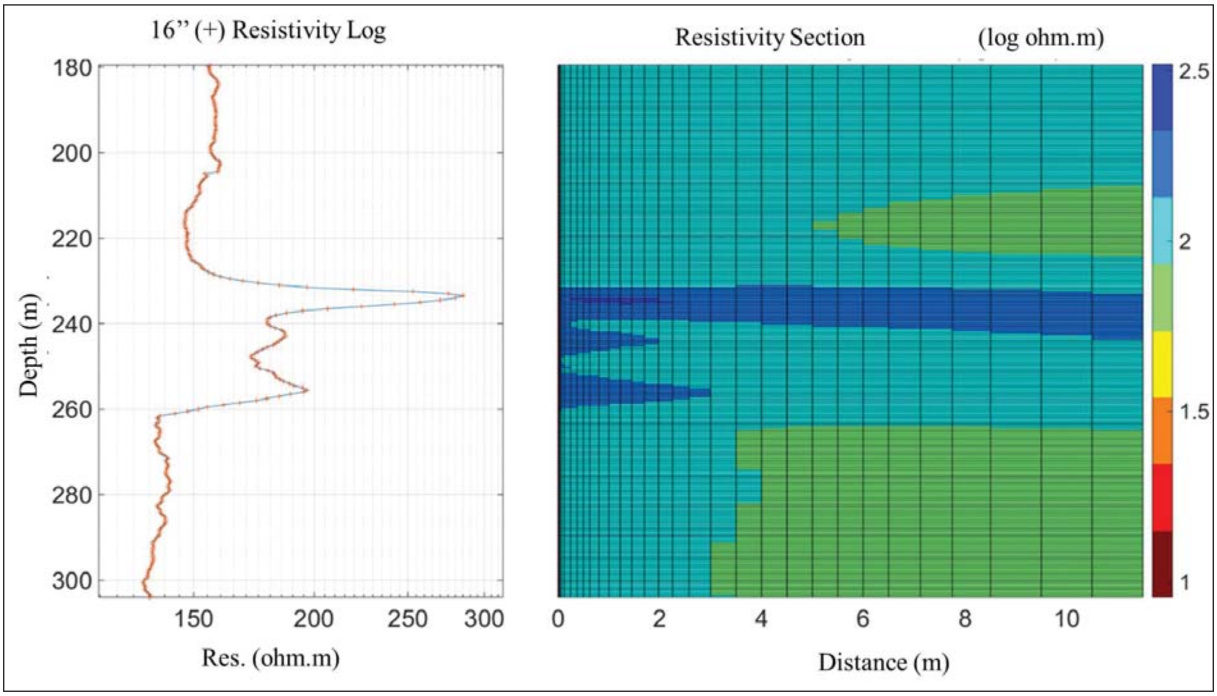

Figure 8- Short normal log data (+) and predicted model curve (straight blue line) on the left and two dimensional model of the underground with respect to the curve on the right.

negative effect of the washed and transition zones on the investigation depth is observed in the models.

The influence of the semi-infinite layer on the depth of investigation is also shown with the help of the models. Beyond the theoretical, the depth of investigation, the formal variation of the data is changed.

A representative model of the underground was produced from the real field data with the inversion program. The program produces a model for the underground in a shorter time than other manual methods do.

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