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Three Dimensional Modeling of Geological Parameters in Volcanic Geothermal Systems. Part II – Case Studies and Examples

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ABSTRACT

The aim of this paper is to demonstrate several methods on how using modeling of different datasets in 3D can be used for better understanding of the sub-surface of volcanic geothermal systems. The paper shows examples of a variety of datasets and how they can be interpreted. Parameters that are discussed are for example, alteration, tectonic features, feed zones and alteration temperature. Examples will be shown from various utilized geothermal systems in Iceland.

1. INTRODUCTION

This paper is a follow up from the paper, *Three dimensional modelling of Geological parameters in volcanic geothermal systems* (Einarsson and Nielsson, 2015), which deals with methods of generating 3D models of geothermal systems in volcanic environments and various datasets gathered at various phases of exploration and drilling. It is the aim of this paper to demonstrate a few implications on using modeling of different datasets in 3D to create a better understanding of the sub-surface of different volcanic geothermal systems.

2. PHASES OF GEOTHERMAL EXPLORATION

During geothermal exploration multiple datasets are collected. Usually regional mapping of structures, stratigraphy, tectonics and volcanology is carried to begin with often accompanied with remote sensing; aerial photos, Lidar and mapping in the field. The next phase is to analyze fluids from, hot springs and fumaroles to determine the type of system and estimate resource temperatures by using geochemical geothermometers. The third exploration phase consists of surface geophysics f.eks. gravity measurements, magnetics, regional seismicity and use of TEM/MT electromagnetic surveys are carried out often to identify clay caps; a low resistivity cap covering a high resistivity core. When drilling in the geothermal field starts data on lithology, alteration minerals, wireline logging, feed point and loss zones are collected.

The conventional way of dealing with this kind of data is to view it in 2D, using maps and cross sections where layers of data are superimposed on each other. For example data such as the resistivity or formation temperature can be used as background and data from boreholes super imposed on top. In figure 1 an example of this data presentation is demonstrated. This limits the visualization to two dimensions and wells that are deviated cannot be plotted on a cross-section unless the cross-section is parallel to the deviated well.

By integrating various datasets available in 3D for visual and computational comparison it is possible to use different individual data sets to validate each other and see if they are showing the same results and if not what is the right scenario if data does not agree. Using multiple individual, quantitative datasets in 3D provides advanced understanding of the sub-surface. With a better understanding of the sub-surface the likelihood of drilling success increases. In the following paper examples of practical applications of using this method will be demonstrated.

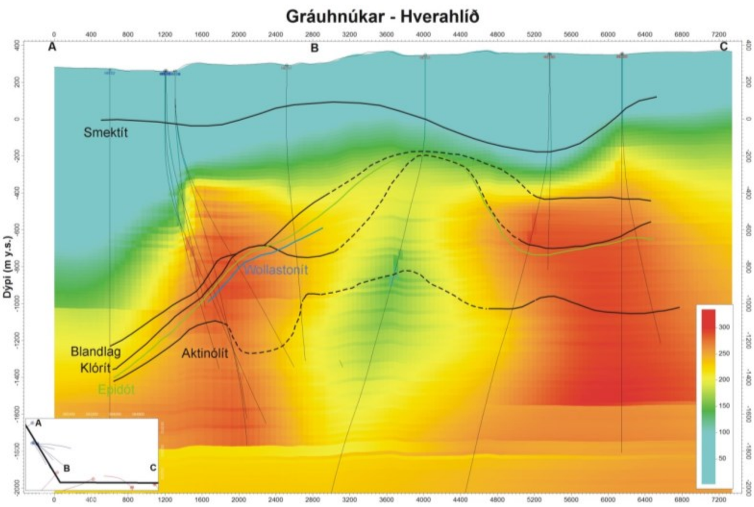

Figure 1. An example of a cross-section from the Hengill geothermal field, SW-Iceland, with formation temperature in the background and superimposed alteration data.

2. EXAMPLES OF DATA

Einarsson and Nielsson (2015) talk about datasets and methods of using that data in their paper. In this chapter we show examples of utilizing data from different datasets in order to gather valuable information on the geothermal system at hand.

2.1 Location of feed points compared with tectonic structure

In order to collect steam that can be used to power turbines that produce electricity one must hit a target that is a) hot and b) have permeability. One without the other is of no use in utilizing a volcanic geothermal system. Therefore it is highly important to have an understanding of the feed points that give fluid into boreholes. Information on feed points is derived from temperature logs, information on circulation losses during drilling, hydrothermal alteration and other relevant drilling data. Figure 2 is a map of the Reykjanes geothermal. These lines are the main tectonic feature that controls the permeability; well paths are shown in black. The yellow dots indicate the location of the main feed point in each well. For comparison the same tectonic structure is compared with total circulation loss in wells figure 3. When shown in 3D the relation between tectonic features and position of total circulation loss becomes apparent. On figure 4 a single borehole is shown with feed-points. This is then compared to known faults the well path bypasses. Feed points in the well correlate well with known near vertical fault. As the main permeability is often controlled by faults we emphasize that creating a detailed fault model of a geothermal system provides valuable information for targeting wells, as feed points in volcanic geothermal systems are often associated with tectonic structures.

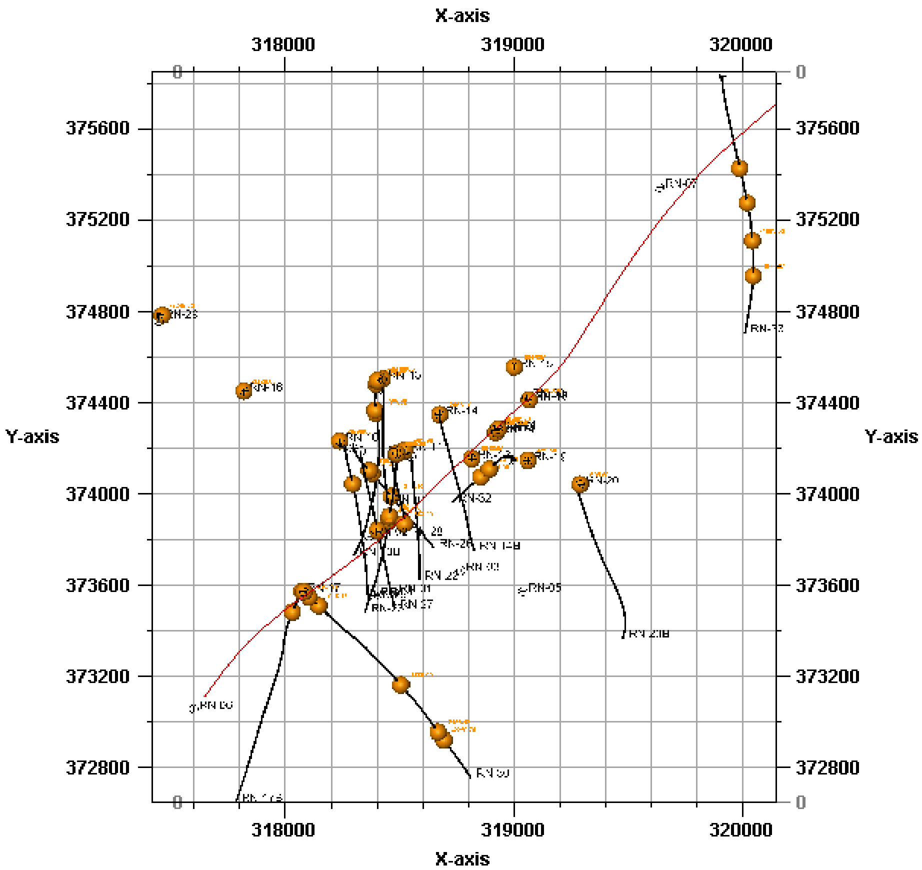

Figure 2. A map of the Reykjanes geothermal field, SW-Iceland, that shows wells, well paths with marked feed points (yellow dots). The red line shows a major tectonic structure of the area.

2.2 Mapping of alteration

While drilling hydrothermal alteration minerals are studied by observing drill cuttings. Temperature controlled alteration minerals can be used to indicate the maximum distribution of temperature in the geothermal system. By mapping the depth to first appearance of certain hydrothermal minerals it is possible to map the maximum boundary of the hydrothermal system. In the Reykjanes geothermal system three alteration minerals were used. They were selected based because they easily recognized in well cuttings. Those minerals are quartz, indicating temperatures of about 180°C, epidote indicating temperatures of about 250°C and actinolite indicating temperatures of about >300°C. By mapping the distribution of first appearance of those minerals it becomes apparent that the main up-flow zone of the Reykjanes field is confined to a small area. Figure 5 shows maps of the distribution of quartz, epidote and actinolite in 2D and figure 6 the mapping of those minerals is shown in 3D clearly marking the outlines of the geothermal field.

2.3 Mapping of lithology

Geological data in boreholes are mainly derived from cutting analysis of samples. Data is also collected from geophysical wire-line measurements in the well. Maker horizons are identified in the analysis of the drill cuttings as well a specific change in the character of a certain type of geophysical wire-line logs; resistivity, neutron-neutron, gamma. By mapping the lithology of a volcanic geothermal field and identifying the volcanic succession provides information on the development of the geothermal system. Figure 7 shows a cross-section of a geological model from the Reykjanes geothermal field, SW-Iceland and for comparison a down-hole resistivity logs are shown. In this particular example an increase in resistivity from the down-hole wire-line loggings were used as a marker horizon.

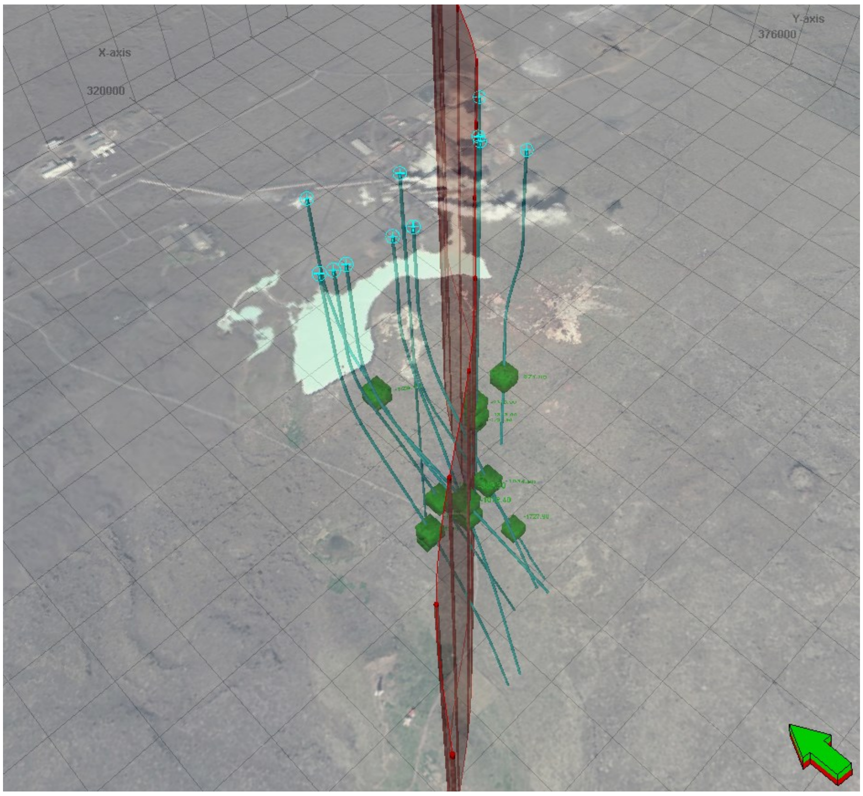

Figure 3

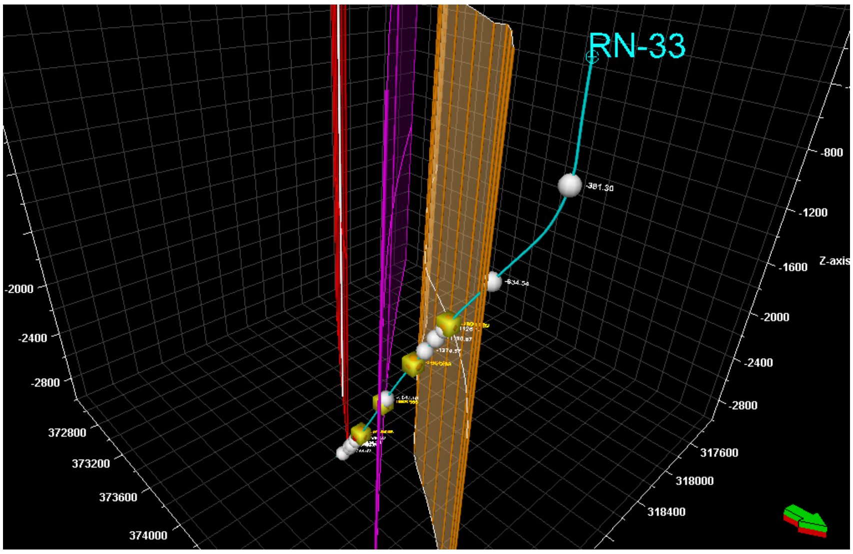

Figure 4. Well path of well RN-33 in the Reykjanes geothermal field, SW-Iceland, shown major feed points, places of loss of circulation and major tectonic features.

3. EXAMPLES OF RESULTS

This chapter gives an example of results.

3.1 Comparison between formation temperature and alteration temperature.

The difference between the present temperature state and level of temperature controlled alteration can vary and the difference can have an impact on the understanding of the geothermal system. A method to investigate this is to create an indicative temperature log based on the alteration minerals and their respective temperatures and compare those to formation temperatures in the geothermal reservoir. Then the gridded volume in the geothermal reservoir is populated with the two sets of temperatures. Then the two up-scaled datasets are subtracted from each other, formation temperature is subtracted from the alteration temperature. The results show areas where formation temperature is lower or higher than what is indicated by the alteration and therefore indicates either a heating up in the area or cooling. This could be of great value when it comes to plan further drilling in the field. Results of this work are shown in figure 8 for the Hellisheidi geothermal field, SW-Iceland along with major tectonic features of the area.

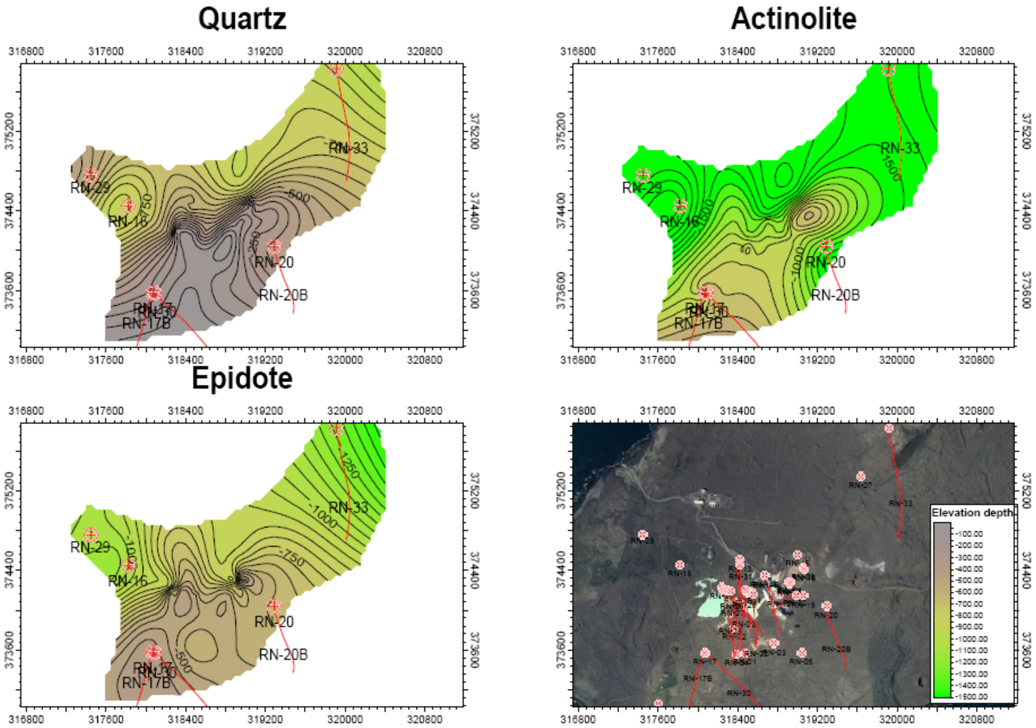

Figure 5. Map of distribution of quartz, epidote and actinolite in the Reykjanes geothermal field, SW-Iceland.

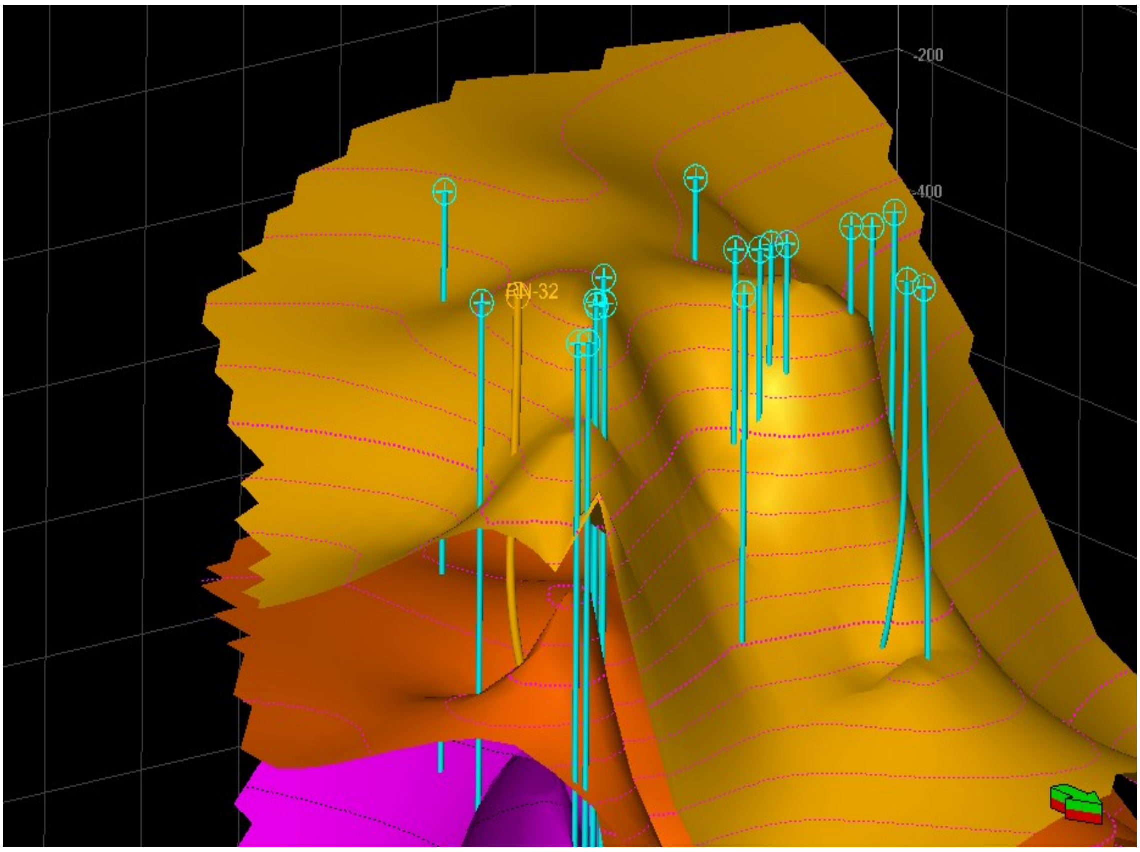

Figure 6. Mapping of quartz, epidote and actinolite in 3D in the Reykjanes geothermal field, SW-Iceland.

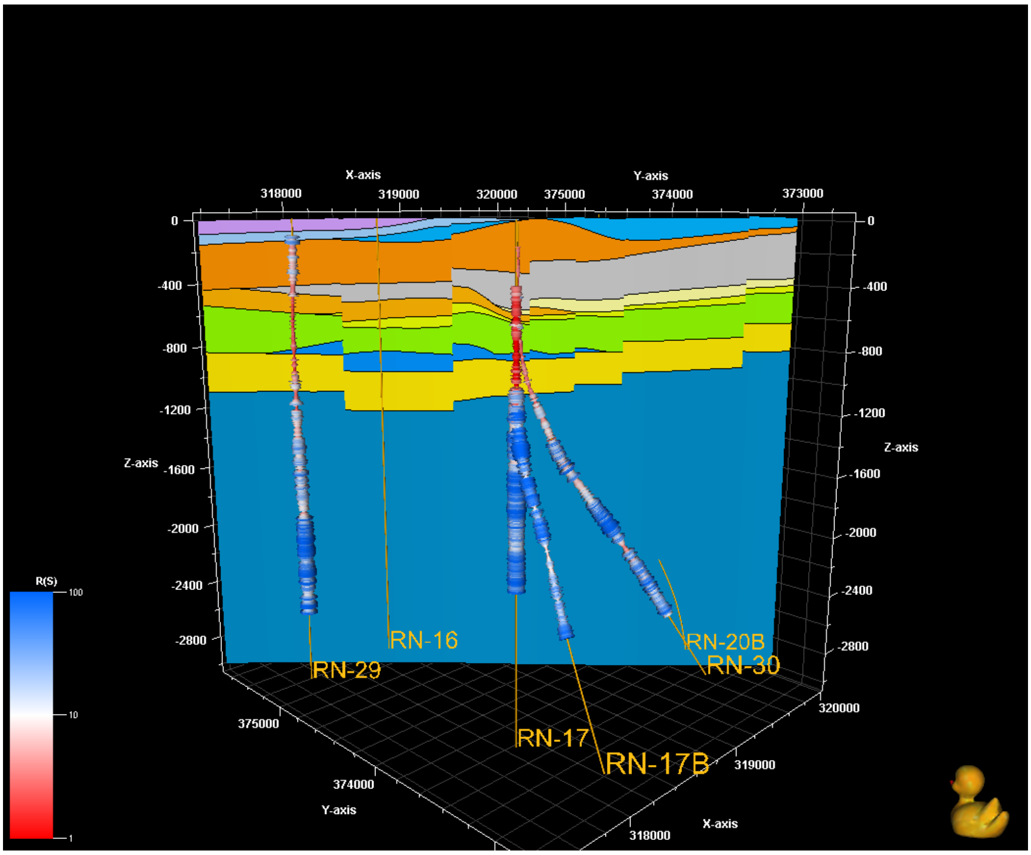

Figure 7

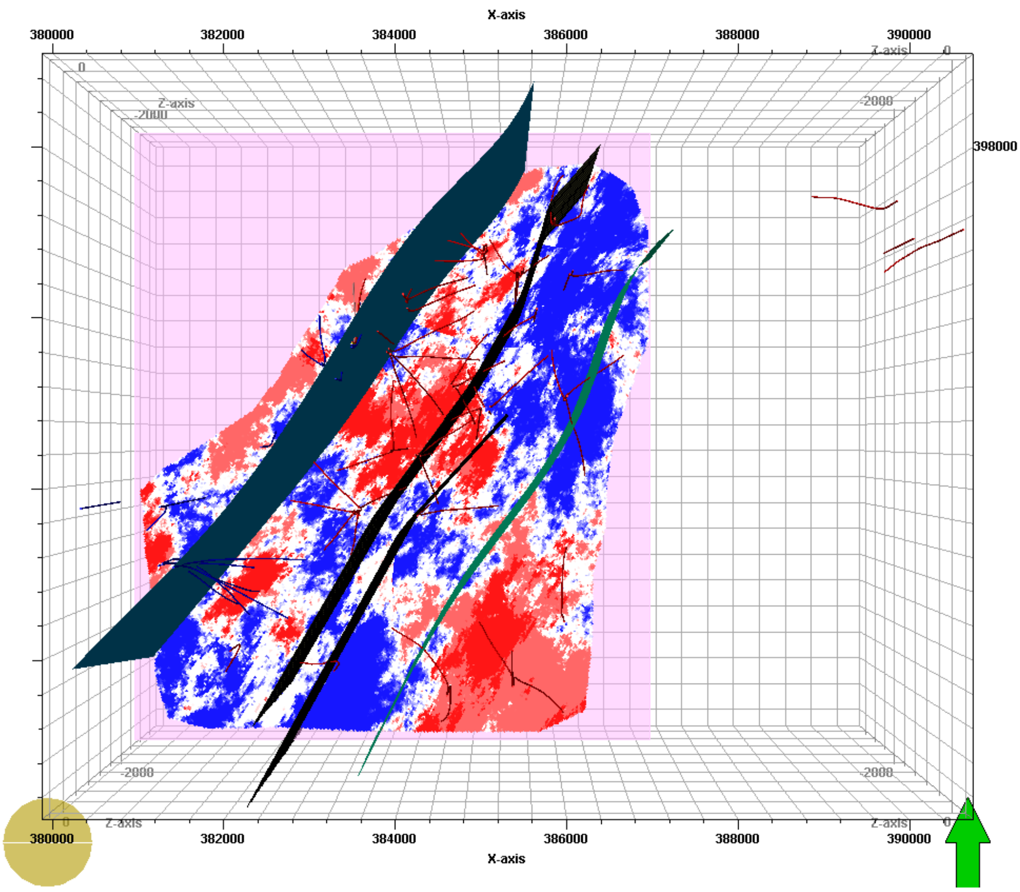

Figure 8. Comparison between formation temperature and alteration temperature in the Hellisheidi geothermal field, SW-Iceland.

4. CONCLUSIONS

The datasets cited in the text above are examples of data that can be used in 3D modeling of a volcanic geothermal system. There are other datasets that are not mentioned in this paper but are useful in interpreting the geothermal resource. The use of 3D modeling techniques can greatly enhance the understanding of a geothermal system and therefore increase the value of various datasets that can give precious information about the behavior of a geothermal system. We recommend using a methodical approach in building the 3D model from the beginning of an exploration a geothermal system and build up the model as more data is gathered. Information and knowledge gained from the quantitative 3D model should be used as a foundation for exploration and a tool for comparing different datasets and therefore enhancing the understanding of the geothermal resource.

REFERENCES

Einarsson, G.M. and Níelsson, S.: *Three dimensional Modelling of Geological Parameters in Volcanic Geothermal Systems Part I – Methods and data*. World Geothermal Congress 2015