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Three Dimensional Modeling of Geological Parameters in Volcanic Geothermal Systems. Part I – Methods and Data.

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ABSTRACT

In this paper we discuss methods of generating three-dimensional models of geothermal systems in volcanic environments. The paper discusses how we can deal with variety of dataset some of which are incomplete and at different levels of interpretation. The parameters involved are for, example, alteration, tectonic features, feed zones, alteration temperature and indication of changes in the temperature state of the geothermal system. Case studies will be shown from geothermal systems in S-Iceland.

1. INTRODUCTION

The general conceptual model of geothermal systems is well known and documented (for example Dickson, M. and Fanelli, M., 2004) Figure 1 shows an example of this. In this paper we discuss the methods of developing site-specific 3D geological models that take into account the data gathered at various phases of exploration and drilling.

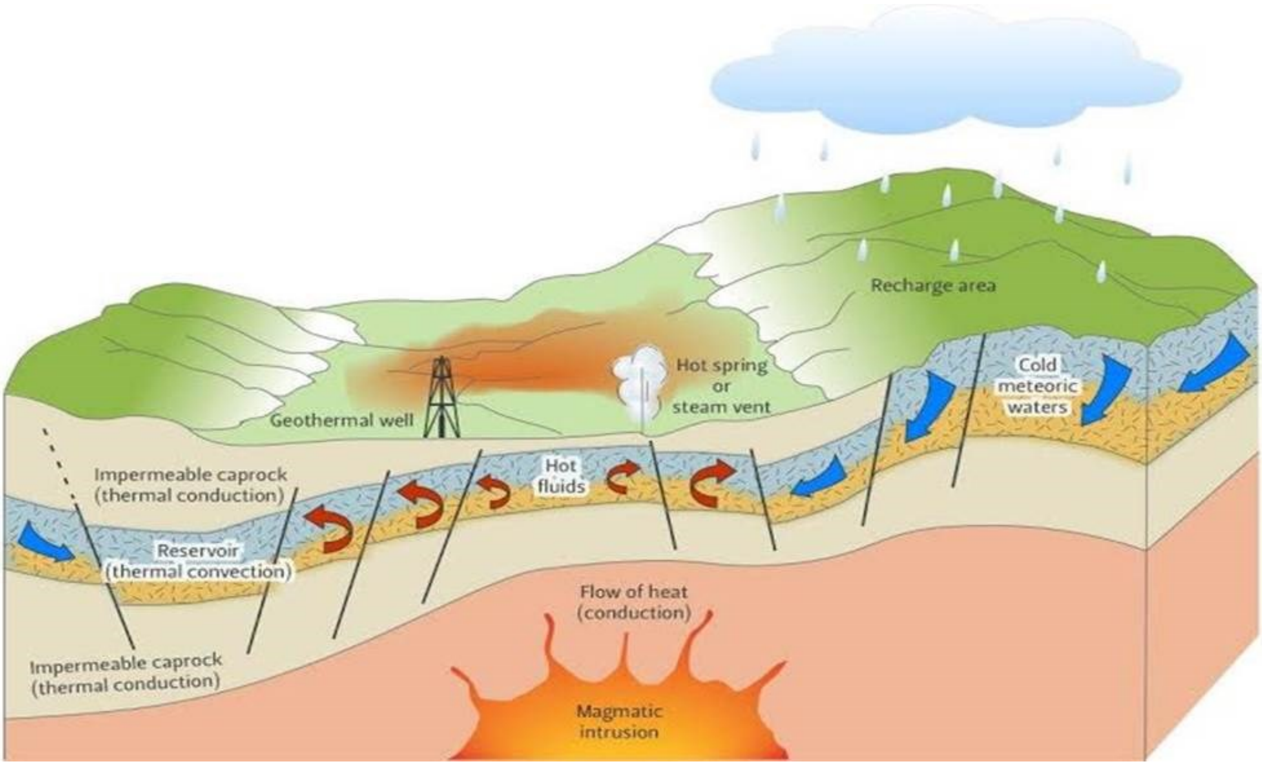

Figure 1: A conceptual model of a geothermal system, modified figure from Dickson and Fanelli 2004

This paper discusses the methods and processes for creating 3D geologic models of geothermal systems in volcanic environments. Here we want to focus on the data that is needed and the general methods used independent of software tools and packages. There are various software tools available the results obtained are always dependent on the quality of data.

Three-dimensional models of the geology of geothermal systems should enable comprehensive understanding of the geothermal system. This includes input from a team of specialists that each brings their unique view of the geothermal system whilst at the end reaching a consensus on the elements of the system. Then the model becomes a decision making tool which can be utilized when setting up a drilling program, developing an injection plan and can serve as input into the development of the conceptual and numerical models of the geothermal system.

Another important part of feature of the 3D model is the visual aspect of the 3d model. The model generated can be used to create visualizations and graphics. This is important for dissemination of results and the status of the geothermal system to different stakeholders, such as investors, the public and the scientific community.

The deliverables in projects such as need to be defined and agreed up on. The model itself should be the main deliverable, but the model should be accompanied by document describing the contents of the model as well as metadata that describe the source, processing parameters, and analysis carried out at each step of the analysis. Best practice would also be to include information about who carried out the work, and at what time as well as the time of the loading to the model.

Most successful projects have a plan that has been executed well. The same is true with modeling of the geology of geothermal systems. In our experience there are three (see Figure 2) distinct phases of work in these projects. Firstly it is the data-mining phase where existing data is compiled and the need for transformation between formats is determined. The second phase is the work of summarizing these datasets consolidating them into the modeling software. The last phase shown here is the data analysis and model development phase. In this phase data is analyzed and compiled in to a version of the model.

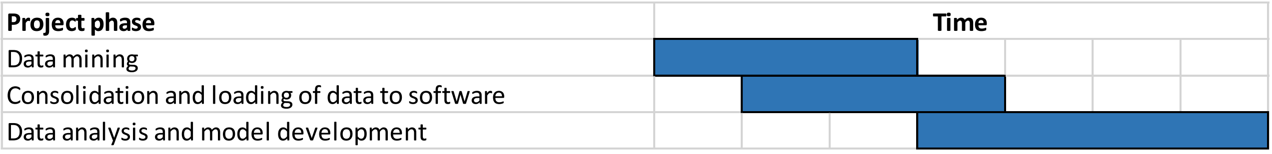

Figure 2: Gantt of the process of 3d modelling projects

Modeling the geology of geothermal systems is an iterative process. New data and ideas need to be incorporated as they become available and in our approach the modeling is hypothesis based. A hypothesis describing certain geology is put forward and then task is to prove or disprove it. This step often needs to be iterated many times before a consensus is reached about a particular model.

Creating a three dimensional model of geothermal system is a team effort. It is important that as many views as possible are discussed as the model is developed. The team needs at least to be composed of geoscientists able to integrate surface data such as geologic maps as well as interpretation of subsurface data such as borehole lithology and subsurface alteration. In addition interpretation of geophysical borehole logs is required. Input from reservoir engineers is important for compilation with the numerical model. Other important team members in the modeling work are reviewers who are not part of the team but can provide insights and point out sections of the model where things can be improved.

Geothermal areas and development concessions can be of various sizes ranging from very small (Reykjanes, Iceland <10 km2) to very big (Olkaria, Kenya >200 km2). It is quite easy to get dug in at the very small scale of a single borehole, but information about the geologic context in which the model is being developed is very important.

There are many software packages available that are designed for modeling geology in 3D but the methods and data discussed in this papers should be independent of any software package.

2. DATA TYPES

Any computerized model is only as good as the data that is used to generate it. In this chapter the objective is to briefly discuss the data that is the foundation of the geological model and what parameters attributes we use to accompany each dataset. In Figure 3 the main categories of data are shown on the left and the expected modeled outcomes are on the right.

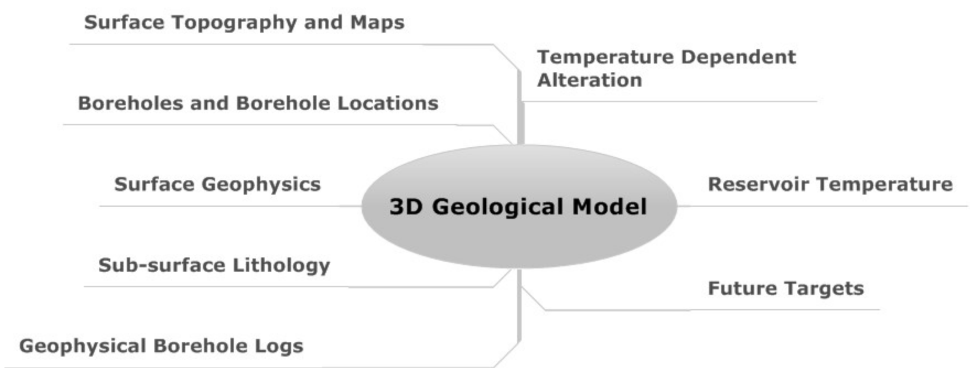

Figure 3: The categories of information used when developing a 3d geological model

First of all it is important to define a coordinate systems that is the will be used in the model. It is most appropriate to use a Cartesian coordinate system, were the coordinates are not in degrees. Most appropriate is to use the local national grid systems that are used in the study. Those can be the UTM zones or other projections as apply. It is however important to note which coordinate system is used and have this information accompanies the model.

The first datasets listed in Figure 3 is the surface topography and maps. Most 3d modeling software can import directly gridded elevation data. These Digital Elevation Models are raster images, where the value in each pixel is represents the elevation. The resolution of this type of data can vary significantly. Datasets like the ASTER GDEM and SRTM (downloadable form the Internet) have resolution of 30x30 m pixel sizes for the ASTER GDEM and 90x90 m SRTM. These dataset are very important as the represent the surface and the elevation of the top most layer in the geology model. In some instances specially when working in areas that are flat and do not have significant topographic features higher resolution data can provide additional information often highlighting topographic features that the lower resolution data misses. Figure 4 is a high-resolution elevation model of the very flat Reykjanes geothermal field.

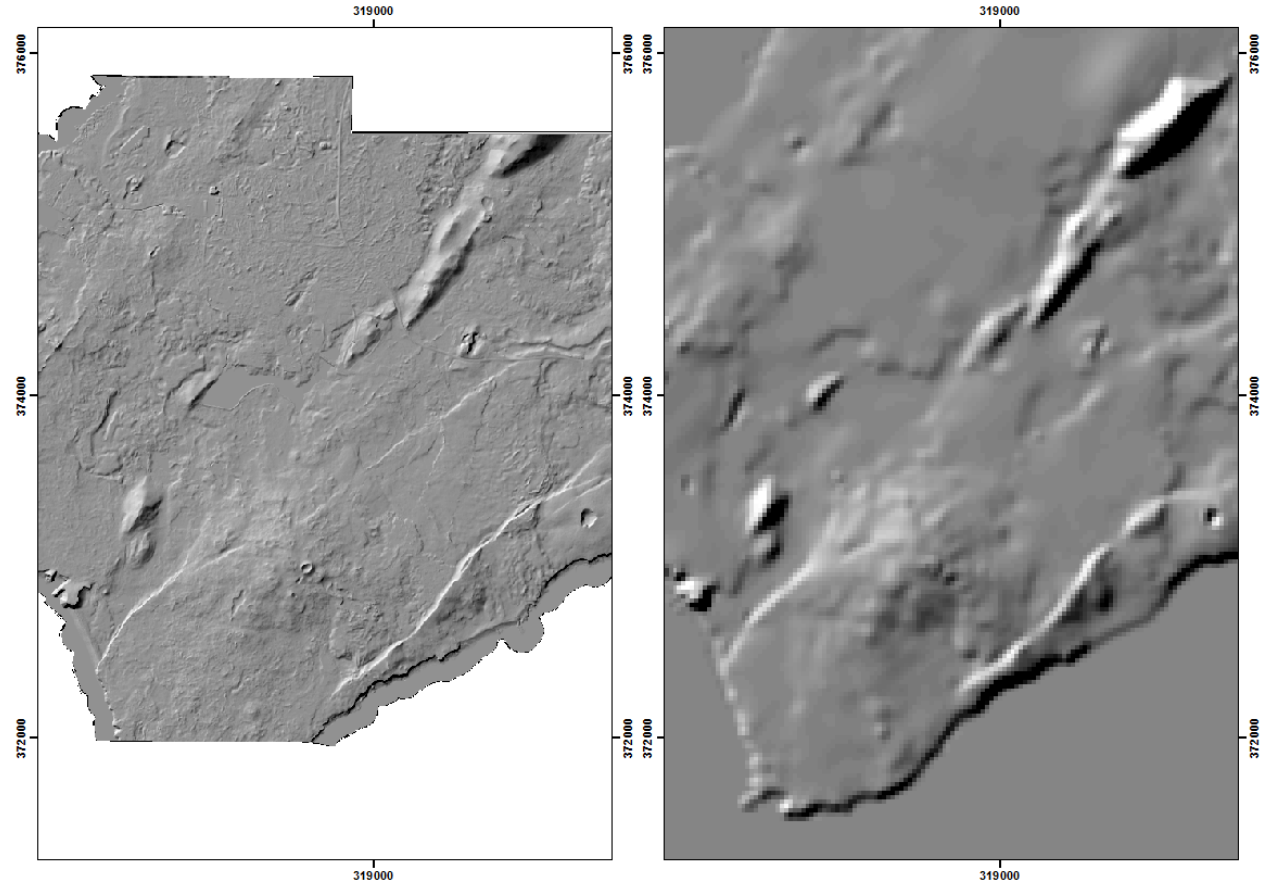

Figure 4: Example of resolution difference of the topographic surfaces. Left is a DEM with 2.5x2.5m but on the right the result is 25x25m.

Other surface maps should also be included they include the surface geology maps where locations of faults are shown as well as the surface rock types, as well as locations of surface geothermal activity. This can provide constraints to the topmost lithology layers and indicate the location of faults on the surface that can be extruded to into the geological model. Satellite images or aerial photographs of the study area should also be imported both for increased spatial awareness in the users creating the model. Draping an aerial photo on top of the surface of the model increases its dissemination impacts.

Data from boreholes are the foundation of the subsurface geology model. Locations of boreholes, described by three coordinates XY and Z, as well as their unique identifier (Name) as well as information about casing depths and widths. Information about the well path is also required for directional wells. Modeling software can either be used to calculate the well path from deviation data or the calculated well paths can be imported.

Data derived from samples of borehole cuttings and wire-line measurements are then related to the borehole to derive a location for samples, and positions of measured values from wire-line logs. Using depth as a primary key does this. The usual way is to annotate samples with the measured depth at which time they were collected and wire-line logs usually are collected using the length of the borehole or measured depth a key. By joining the measured depth calculated on the well path and measured depth of the log an absolute location can be derived. Then the software tools can be used to calculate true vertical depth (TVD) and elevation related to sea level.

This results in derived datasets where the absolute position of subsurface features is known. From all these, the surface maps and the sub-surface logs models of the geology are generate. A good first step is to look at temperature dependent alteration minerals. Compilations of data were the first occurrence of these minerals occurs is therefore important. This dataset needs to include the depth (in any domain) and an identifying name or number of well. Minerals might include epidote, calcite, pyrite and actinolite. Examples of this are shown by Níelsson et. al. (this volume).

Marker layers need to be identified and they generated, with their depth collected. Some 3D modeling software packages are providing ways of making connection directly, but others might require steps like generating the depths to horizons outside before the modeling begins.

In addition it is important to include data like resistivity models from TEM/MT data as well as reservoir temperature.

3. METHODS

Creating a 3d geological model is a methodical process. Our approach has is to start with what is simple and allow the model to grow into more complex tool.

The first step is to define boundaries and the study area. On approach that can work in many cases is to start very conservatively close to areas where there are boreholes and create a model that is representative of an area where data is dense and extrapolation is at a minimum. The step is to define the size of the grid that will be used to populate the properties of the geology model. The grid size needs to be small enough to show details in the subsurface but at the same time be large enough so that the computer system can process it without too many problems.

A big consideration is how fractures are at depth and how they control permeability. Generally there is not much known about how faults extend to depths in geothermal reservoirs our approach is to use faults mapped on the surface and extend them vertically to depths in the reservoir. Often dip is known from surface maps, and from that dip can be tested and modeled to depths. Another approach is to compare faults with locations of feeds in boreholes. As most big feed points relate to faults the insights of the geoscientist can be used to model the fault based on permeable feed zones in boreholes. Níelsson et. al. (this volume) shows examples of this from the Reykjanes field where permeability is observed in near a vertical fractures zones but no feed zones are found when boreholes reach west of it.

Some minerals have been shown to form at certain temperature. These temperature dependent minerals can be used to indicate that a certain temperature has been reached in the reservoir. By mapping the first occurrences of theses minerals in samples of borehole cuttings surfaces of possible higher temperatures can be generate. Interpolation methods are used to create the surfaces. Care has to be used when the surfaces are generated, as the interpolation method used will have an impact on how the surface will work. Our approach is to use the simplest form of interpolation by which we create a minimum area in which the point (borehole) has influence and assign that area the elevation of the mineral. Example of this Voronoi polygon method is shown in Figure 5.

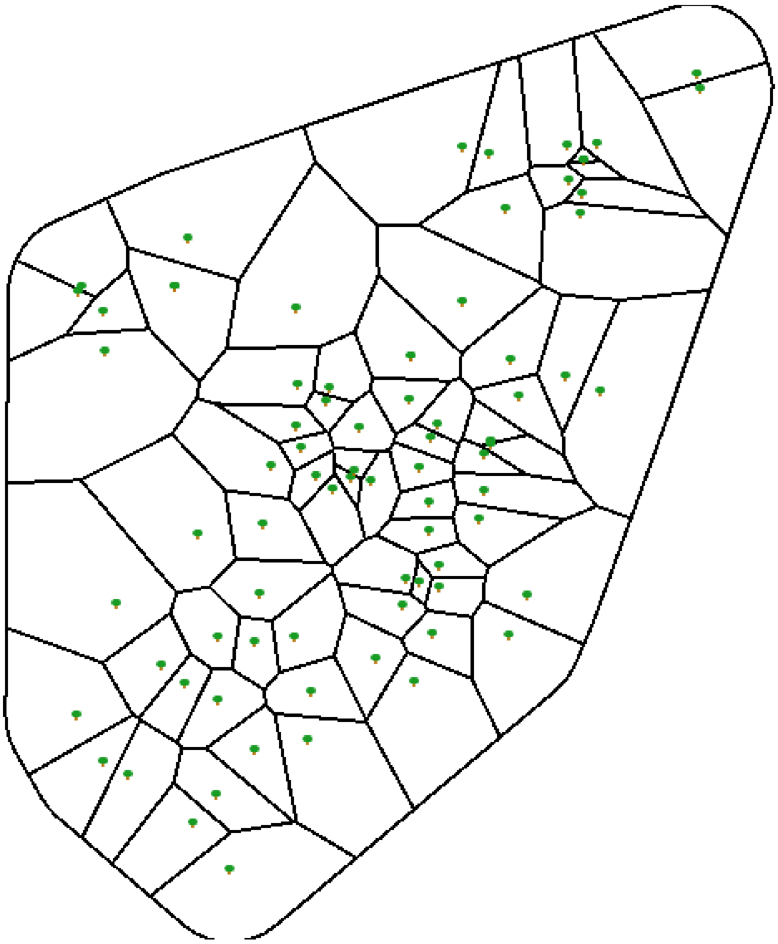

Figure 5: Example of a closest point interpolation. The points might represent an occurrence of alteration mineral at depth but the area represents the area influenced by each point.

This simple interpolation is useful for as a first step when creating alteration surfaces. Inconsistencies can quickly be identified, as abrupt changes in the elevation of alteration over short distances need to be checked for errors and explained if data seems to be accurate. When the data has been completed a more complex interpolation can be used to create more complicated surfaces, cross sections of the alteration surfaces. Figure 6 shows an example of this.

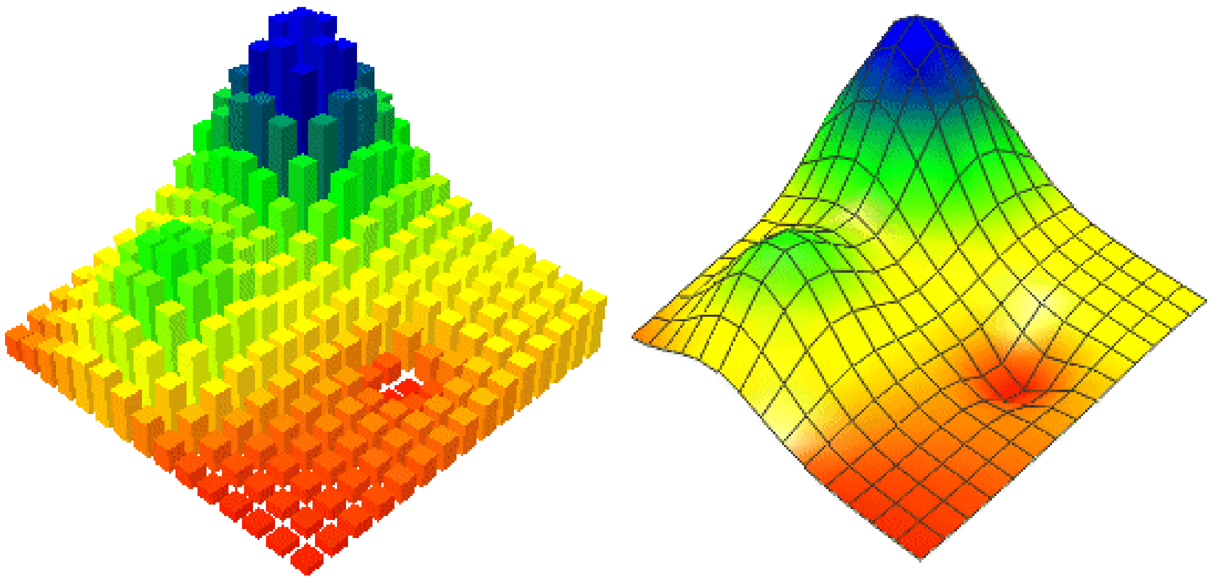

Figure 6: Example of a gridded surface using a smoothing algorithm

The subsurface geology also needs to be mapped. Input data is from multiple sources, all of which provide have high spatial density in the vertical domain but relatively low resolution in the horizontal domain. Subsurface geology is also heavily influenced by faults that lead to discontinuities when interpolating the surfaces that construct the geological model. Several software packages can handle these types of gridding functions taking into account faults as barriers for directional trends. Often quite detailed surface maps are used, that might contain many short faults as well as the inferred faults. In our experience often simplification is needed. This might consist of connecting faults that might be mapped in short segments, simplifying geometry and outlines of features. The same applies to the subsurface geology. In many instances the raw logs of well cutting show much detail that is beyond the purposes of the geologic model. Therefore simplification to easily defined marker horizons are needed to create the map. Marker layers can be for example boundary between hyaloclastite formations and lavas. A simplification can be done by aligning logs from wells side by side at the same scale and using the same depth datum. Geologic modeling software can do simplify this process. Figure 8 is an example of logs aligned together.

When the logs are aligned together at the same scale and depth domains connections between the wells can be generated. This results in data that shows depth of formations in each well that can be used to interpolate surface between the, calculate thicknesses and volumes of formations. This is combined together with the faults is the geological model. The volume between surfaces is then often used to create a voxel (http://en.wikipedia.org/wiki/Voxel) model that is aligned by faults and the formation tops. Níelsson et. al. 2015 shows examples of this.

The geology data from a geothermal system should not be viewed alone. Comparison between data from the reservoir models, such as formation temperature and surfaces geophysics needs to be incorporated to the model.

4. OUTCOMES

The outcomes of the 3d geologic model of the geothermal systems can be summarized as shown in figure 5. These eight pillars show the outcomes of the models.

Firstly the model documents the field development and can serve as the knowledge base of the conditions of the geothermal system. This documentation consists of how new data changes the understanding of the system as well as how the geothermal system responds to production, re-injection and usage. In order be able to do that the model has to have data describing the conditions of the reservoir at a pre productions state, data of past conditions (as discussed by Níelsson et. al. 2015) as well as the current state representing changes with production.

The model can also serve as a foundation for exploration plans, as it can be used to define weaknesses in data and formulate which questions need to be answered at any given time. That way data acquisition can be planned and the most important datasets collected at any given time. The model also can serve as a dissemination tool for all the different stakeholders, from the local population to investors and banker funding projects.

The geology model as well as other data is the foundation for a conceptual model a geothermal system. The geology model can provide information such where to expect permeability for example and can be used to assess the probabilities of drilling success. This is based on a clear and common understanding of the geothermal system modeled in a careful way. The geology model is data that is useful to constrain the numerical reservoir model.

5. OTHER CONSIDERATIONS

The data in that is used in when modeling the geology of the geothermal system there are other issues that need to be considered and viewed carefully. The main issues have to do with data quality and data integration. The data used is often based on interpretation of geoscientists of well cuttings, of surface manifestations of faults and of their geological insights into the geothermal area, which is under investigation. There are errors associated with all these steps. They may or may not be of significance of outcome of the model but they might show need to be considered and taken into account. These errors might be of definition, the depth datum might not be the same for all boreholes or between datasets in each borehole. Definitions' might be vague or ambiguous; there might be difficulty in determining the actual first occurrence of alteration mineral due the small sizes of well cuttings. There might also be calibration errors in the datasets such as what is used as control and what units of measurement are being used.

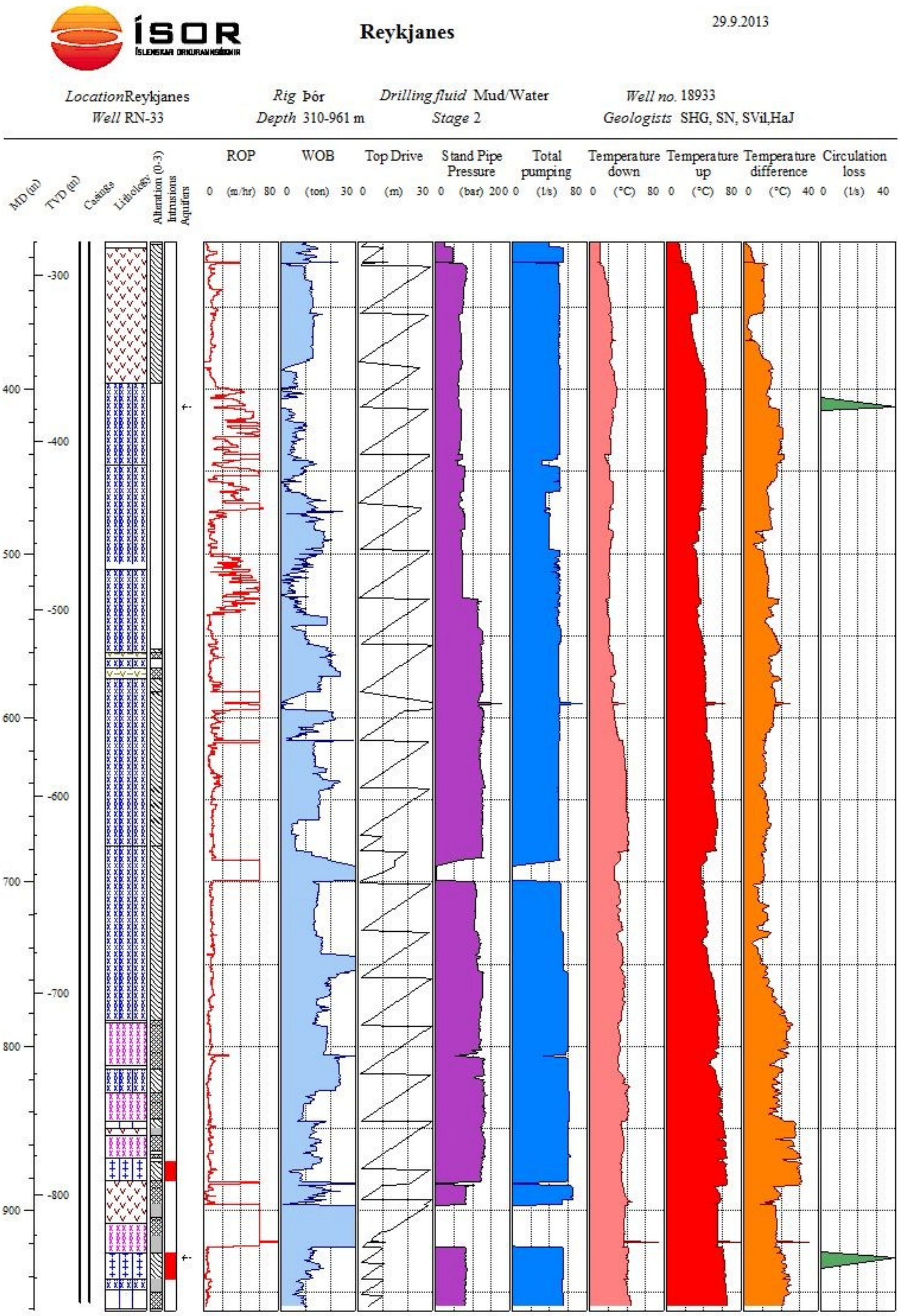

Figure 7: Example of combined well logs

While individually these examples of errors described above might seem insignificant they can when combined have an effect on the outcome of the model. Therefore it is very important in all modeling to document the data and its sources by creating a metadata about the datasets used. Standards exist for geospatial metadata, and those indicate what information the metadata should contain. However these are often very detailed and some required datasets might many fields collected. In our experience we try to keep the metadata as detailed as is helpful while keeping as few fields in the dataset as possible. By defying types of data, for example surface maps, borehole data, and surface geophysics, easily organize the metadata fields. It is also prudent to record the sources from which data originates the processing steps as well as the dates when data was collected and imported.

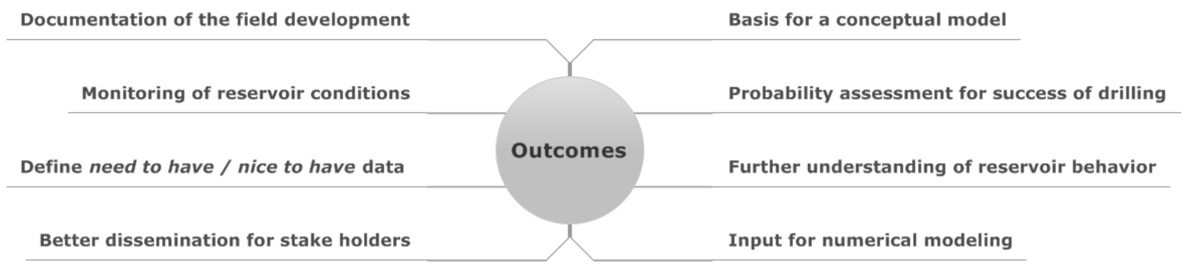

Figure 8: Expected outcomes of 3d modelling projects

In our experience projects where the objective is to create a geologic model of a geothermal system can be divided in to two phases, firstly the phase where data is collected and imported in to modeling software and secondly the phase where data is processed models refined and all data integrated in a uniform way. However the modeling process is a very iterative process when the model is updated frequently when new data becomes available. It can also take several iterations to create a model that everyone can agree-up-on, based on the preconceived ideas of the geothermal systems specially if they are been researched for a long time. One way to do this is to consider each iteration of the model as being a hypothesis on how the geothermal system might be. The then the work of the team is to test the hypothesis and either discards it, which leads to another iteration or confirm it which would then lead to a consensus about the model.

The cost of "getting it wrong" can be considerable in geothermal exploration and development. If compared to a single borehole costing upwards of 5M USD and the likelihood of a return on the investment increases as the decision is founded on quality data and understanding of the system. The cost of the generation of a concise and documented geological model is only a fraction of the cost of a single well. In our experience the a concise model can be created with approximately 1-6 man months of work depending on the status of data and preparation of the data that is needed. The rewards from work is not only the documentation of the data and research that has gone into the a geothermal field, but also a model that explains key parameters of a geothermal field, like structures, permeability and temperatures state of the geothermal field.

6. CONCLUSIONS

It is our experience that when 3d geologic modeling projects are carried out successfully they can provide insights into the geothermal systems when all the data from all the disciplines of geothermal research and development come together and look at all the their data in the same platform. For that there are several toolset available. Many of these software tools have been developed for other purposes than geothermal exploration, specially the oil and gas exploration. More often than not the processes are the same and the same or similar algorithms applicable for geothermal reservoirs as for oil and gas industries. With profit margins being significantly larger in the in oil and gas then in geothermal the pricing of software can be a barrier for entering into the realm of 3d modeling. We should consider 3d geologic modeling to be a new in the geothermal scientist's toolbox. If a considered decision based on sound 3d model can increase the success rate of geothermal drilling the cost of 3d modelling work and software will be saved on a single borehole.

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