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# Conceptual modelling of the Krafla geothermal area, NE-Iceland and lessons on constructing a workflow

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## ABSTRACT

The Krafla high temperature geothermal area is located within the Krafla caldera in the Neovolcanic zone in NE-Iceland. The caldera was formed around 100.000 years ago. An extensive activity in the area has since filled it with volcanic material. Geothermal exploration in Krafla was initiated in 1969 and the first wells were drilled in 1974. The power plant was commissioned in 1978, currently producing 60 MWe. Conceptual modelling of the Krafla brownfield has gone through a few phases since geothermal research began (a brownfield is a geothermal field that has been subject to extensive exploration and drilling). The first model was presented in 1977, another two models were published in the eighties. These models are still valid today in many respects. The most recent revision of the conceptual model is from 2015. This extensive experience provides the basis within the IMAGE project (Integrated Methods for Advanced Geothermal Exploration) for a workflow of a 3D model representation and visualization which will be applied to the Pico Alto geothermal greenfield in Terceira island in the Azores (a greenfield is a geothermal field that has not been subject to extensive exploration and drilling).

ISOR applies the Petrel 3D software platform to incorporate into the Krafla conceptual model data from both the exploration phase and from the development/production phase. This has resulted in various 3D models; a geological facies model, a temperature model based on well data, an alteration model and a resistivity model. The 3D petrophysical model will e.g. be updated with recent seismic velocity models which are partly based on IMAGE's Vertical Seismic Profile experiment (VSP) done in mid-2014 to test if zones of magma, supercritical fluid, superheated steam and high permeability can be revealed.

The first step of geothermal conceptual modelling is to incorporate data from the exploration phase. These data include surface data such as geological mapping (surface geology, faults and fractures, geothermal surface manifestations), aerial images and topography and geophysical data such as resistivity, results based on magnetic and gravity studies and location of micro-earthquakes. Data from the development phase such as well paths and eventually data from boreholes (cutting analysis, lithological logs, and pressure and temperature logs) are incorporated as well. These data include lithology (stratigraphy) from each well resulting in a geological facies model; alteration (alteration zones, appearance of temperature dependent alteration minerals) leading to an alteration model; aquifers in relation to the structural mapping, intrusions and lithological contacts; temperature logs which with time result in a formation temperature model and geophysical logs such as resistivity, neutron-neutron, gamma and sonic log, as well as televiewer data.

A well-organized workflow leading to a conceptual model is based on the alternative models resulting from all the different geothermal disciplines. Its purpose is a better understanding of the properties and processes taking place in the reservoir with the aim of finding high temperature and high permeability for successful well siting. A conceptual model is subject to constant recalibration and to be updated as new and additional knowledge is acquired – there is no such thing as a final conceptual model.

## 1. INTRODUCTION

A workflow for constructing a conceptual model will be developed by practical experience from Krafla geothermal area in NE-Iceland. A total of 43 wells have been drilled within the area sofar and various data have been collected over the last decades. Datasets, from geochemistry, geology, geophysics and remote sensing, provide a base for the Krafla conceptual model. By recording the work and estimating the importance, uncertainty and reliability of the results, a well-organized workflow can offer an opportunity to implement the geological and physical situation of the system. The extensive experience from Krafla provides a lesson for the making of a workflow for a 3D model for other geothermal fields. Krafla is an example of a *brownfield* which is defined as a well known geothermal field based on exploration and utilization experience. With improved understanding and experience, the workflow from the Krafla geothermal brownfield will be applied within the IMAGE project to the less known geothermal field, Pico Alto, in the Azores. Pico Alto is an example of a *greenfield*, a field that is in the early stages of development.

This paper outlines approaches in data acquisition and interpretation from the Krafla geothermal area. It demonstrates how different datasets relate to and support each other. The main emphasis is on how available data are used, although recently acquired data have also been added to enhance the understanding of the geothermal system.

## 2. KRAFLA GEOTHERMAL SYSTEM

### 2.1 Geological setting

The Krafla geothermal system is located in NE-Iceland. It consists of a central volcano and a NNE-SSW trending fissure swarm running through it (Fig. 1). Due to its tectonic location, on the divergent plate boundary, the system has been very active for the last 200.000 years. The volcanic activity is episodic and in historical time two rifting episodes have occurred – the Mývatn fires in 1724-1729 and the Krafla rifting episode in 1975-1984. Stress distribution is also caused by the tectonic location of the system resulting in WNW- ESE trending fissures and faults within the area (Sæmundsson, 1991).

The lava pile consists mainly of hyaloclastite and basaltic lavas, but rhyolite is also present. Hyaloclastite formed during glacial periods, but basaltic lavas in postglacial times. Intrusions cut the lava pile at greater depth, but they are believed to have been formed mainly by a pressure drop at the end of the last glaciation period.

The caldera is thought to have been formed about 100.000 years ago in an eruption producing semi-acidic welded tuff. It is about 8 km in diameter but is not visible at the surface because it has been filled with volcanic material (Sæmundsson, 1991).

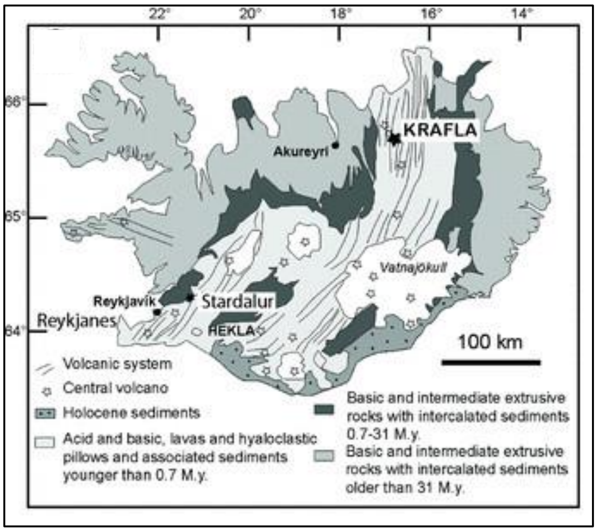


**Figure 1: Map showing the location of Krafla geothermal system inside the volcanic system in NE-Iceland (Oliva-Urcia et al., 2011).**

### 2.2 Utilization and exploration

Exploration in Krafla started in 1974, and since then, 43 wells have been drilled. Currently the plant produces 60 MWe from 19 production wells (Weisenberger et al., 2015). Through the utilization development, analyses and exploration have revealed the complexity of the system, with respect to geochemistry and structure (Stefánsson, 1980). The area is divided into subareas according to the chemical characteristics (Ármannsson et al., 1987). The siting of wells depends to a large extent on fissures, faults and intrusions. Directional drilling has been used to cut through these features, where feed zones are more common.

### 2.3 Published conceptual models

Four comprehensive conceptual models of the Krafla geothermal area have been made. The first one, presented in 1977, was mainly based on surface exploration data and data from the first 11 wells (Stefánsson, 1977). A revised conceptual model was presented by Guðmundur S. Böðvarsson in the eighties (Böðvarsson and Pruess, 1982). At that time more detailed explorations had been carried out. In many respects, that model is still valid today (Weisenberger et al., 2015).

In the nineties, a conceptual model was presented in the context of a numerical model. New modelling software created an opportunity to estimate the volume of the reservoir more accurately as well as the capacity and reaction of the reservoir (Tulinius and Sigurðsson, 1991; Björnsson et al., 1997).

A proposed expansion of the Krafla power plant required further exploration and drilling. Following that a reassessment of the conceptual model was presented in 2009 where size, temperature and capacity of the reservoir were recalculated. More focus was put on certain subareas that were more likely to be productive than other parts of the system (Mortensen et al., 2009).

The latest revision of the conceptual model was published in 2015. Only two new wells had been completed between 2009 and 2015. Some reinterpretation was made on alteration and resistivity data in addition to the 3D visualization being upgraded and developed (Weisenberger et al., 2015). The latest revision was partially based on 3D models that were developed in Petrel. Petrel is a 3D software program that allows interpretation and analysis of data in the context of the geothermal field. It also allows an insight into complex reservoirs and better understanding of the system.

## 3. DATA ACQUISITION

Since the publication of the latest conceptual model, some geophysical and geological data have been added and interpreted. In January 2016 a seismic report was presented, where earthquakes from the Krafla geothermal area, spanning the period November 2014 to October 2015, were located. The location was based on a seismic network run by Landsvirkjun and the Icelandic Meteorological Office (IMO). During this period, two stations were moved and five stations from the Icelandic Meteorological Office were added which allows location with more precision than before (Blanck et al., 2014; 2016).

The lithological model was updated in Petrel by adding information from a number of older wells. Geophysical logs that had not been included in the 2015 revision of the conceptual model were also added as an aid in determining different lithological units. Alteration data were also updated since a few wells were missing in the previous models.

In 2015 and 2016, new velocity data were acquired as a part of the IMAGE (Integrated Methods for Advanced Geothermal Exploration) and VMAPP (Volcanic Margin Petroleum Prospectivity) projects (Millett et al., 2015). VSP (vertical seismic profile), televiewer and sonic logging were part of measurements that were conducted in well K-18 in Krafla (Árnadóttir, 2014; Hersir et al., 2016).

During the acquisition of available and recently acquired data and in the making of a preliminary version of a workflow to be used in the Pico Alto geothermal area it was decided to divide the data into two groups, surface data and subsurface data. Subdivisions of these groups are listed below.

### 3.1 Surface geology

Geological exploration of the Krafla geothermal area has resulted in a geological map and a geothermal map in different scales. The geological map represents different rock formations, age and name of postglacial lavas, surface tectonic features and topography while geothermal maps show geothermal manifestations and surface alteration (Sæmundsson, 2008a; 2008b). Mapping has been done from field observations and aerial photographs. These data are used as a base for a structural model as well as comparison with various data that have been collected from the exploration phase.

### 3.2 Surface geochemistry

Surface temperature measurements, $CO_2$ flux measurements and stable isotope analysis are available for the Krafla geothermal area (Mortensen et al., 2009; Weisenberger et al., 2015). Temperature distribution and $CO_2$ flux distribution are interpreted with respect to each other and used to determine location of magma chambers and intrusions. A comparison between temperature of the fluid and temperature from $CO_2$ geothermometry has been used to infer whether magmatic volatiles were present in the fluid. Geothermometers are also used in stable isotope analysis to indicate inflow or circulation of colder fluids (Mortensen et al., 2009; Weisenberger et al., 2015).

### 3.3 Surface geophysics

Surface geophysics include measurement made at the surface but reflect the structure of the subsurface. Seismic data, active and passive earthquakes, result in a 2D and 3D earthquake distribution model. The distribution shows effects of injection and production but is also used to estimate the location of the brittle/ductile boundary, tectonic features, heat sources as well as depth to magma chamber. These data are compared to lithology, formation temperature, structural maps and resistivity. Seismic studies within the Krafla geothermal area have been carried out and show seismic attenuation of S-waves within the caldera which reflect the crustal structure of the system; crustal thickness and location of magma chambers (Brandsdóttir and Menke, 2008; Einarsson, 1978).

Resistivity measurements have been conducted in Krafla using a variety of methods. The most valid data are from MT and TEM measurements, but DC and SP methods have also been used (e.g. Mortensen et al., 2009). All these measurements reflect thermal conditions and evolution of the system. These data are, therefore, really important but need to be interpreted with respect to other data such as formation temperature and alteration minerals. The resulting data give inference to the location of heat sources, size of the reservoir and upflow and outflow zones.

Gravity data are visualized by Bouguer gravity maps (Fig. 2). Results show density differences on a lateral scale. The anomalies can be caused by tectonic features (faults and fissures), lithology, magma chambers or possibly magma pockets. Interpreted gravity data are compared to resistivity, structural model and lithology. Aeromagnetic survey from Krafla and surroundings has been performed and presented as a magnetic map. Magnetic anomalies can indicate demagnetization of magnetic minerals in geothermal areas. These results are compared to resistivity, structural model and lithology (Mortensen et al., 2009; Weisenberger et al., 2015).

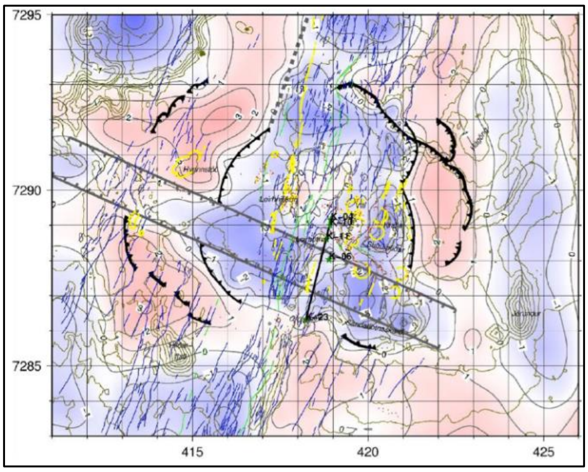


**Figure 2: A Bouguer gravity map of the Krafla area. The rims of the caldera are shown as well as ESE-WNW low gravity lineament (Weisenberger et al., 2015).**

### 3.4 Subsurface geology

Analyses of borehole cuttings result in alteration temperature and alteration models and a geological facies model. The alteration minerals are temperature dependent and become stable at a certain temperature. By recording the depth of first appearance of the minerals, alteration temperature model can be developed. The depth of the first appearance of smectite, mixed layer clay, chlorite, quartz, epidote and amphibole is used in the current alteration model (Fig. 3). Zones where epidote becomes more common and zones where calcite disappears are also mapped. When comparing alteration temperature to formation temperature the thermal evolution of the reservoir can be recorded. Resistivity is dependent on alteration minerals (namely the clay minerals), and alteration minerals are dependent on permeability. Therefore, alteration temperature is interpreted with respect to resistivity and aspects affecting permeability (fractures, faults etc.).

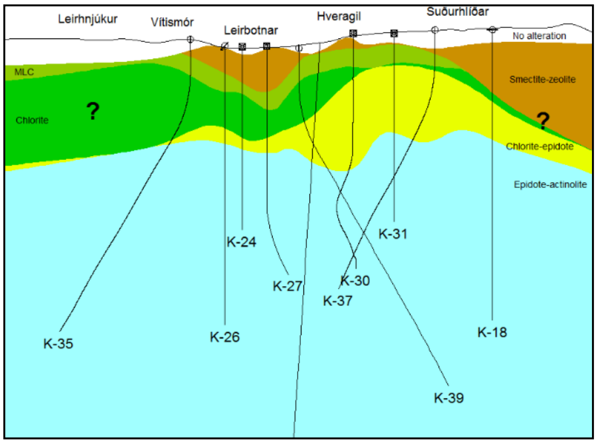


**Figure 3: Alteration model of the Krafla geothermal field, based on cutting analysis from the wells and X–Ray diffraction of clays. The alteration gives evidence of the thermal evolution of the reservoir (Weisenberger et al., 2015).**

By making a lithology log of each well, it is possible to correlate wells and infer which formations are most dominant. This is sometimes done with the aid of geophysical logs (wireline logs). The formations vary in permeability, therefore the correlation can be an indicator of flow paths, outflow and upflow zones. When a 3D lithological model has been developed, it can be compared to VSP data, structural features and the resistivity model.

### 3.5 Subsurface geophysics

Geophysical logs are available for the Krafla geothermal area. Gamma, neutron, resistivity and caliper logs are used for lithological correlations. With increasing silica content of rock, gamma values increase. Neutron values reflect density of the rock, as porous and fluid rich rocks absorb neutrons. Resistivity reflects, as mentioned above, the alteration state of the bedrock. Caliper logs reflect the hardness of the surrounding rock, high values of caliper indicate low hardness resulting in increased diameter of the hole.

VSP data have recently become available in geothermal exploration. They have been used to compare the cutting analyses and other logging data to recognize different volcanic facies. The data reflect the character of rock formations and alteration, supercritical zones and intrusion density (Millett et al., 2015).

In 2014, televiewer logging was performed in well K-18 in Krafla (Árnadóttir, 2014). The aim was to improve the structural and facies interpretation. The well was sonic logged in 2014 (Hersir et al., 2016).

### 3.6 Subsurface geochemistry

To be able to estimate the behavior of the system, subsurface geochemistry has to be analysed. Tracer tests have been carried out to record injection and utilization effects. Chemical analyses are performed, where concentration is measured during a certain period of time. If some changes are seen in the system, it is likely that flow paths have changed or there has been a drawdown in the system. Two phase analyses are useful to estimate the chemical composition of deep liquid. Changes can indicate steam cap, felsic feed points, supercritical fluid or superheated steam. These data are compared to temperature logs to locate feed zones as well as to resistivity to locate outflow and upflow zones. Geochemical analysis from the Krafla geothermal area have been used to classify the system into subsystems (Mortensen et al., 2009; Weisenberger et al., 2015).

## 4. 3D MODELLING IN KRAFLA

The data mentioned above have been collected and imported into Petrel, a 3D software that is used to visualize and incorporate various data. Since the data are from different eras within the research history of the Krafla system (from the 1970s to 2015) they require estimation of quality and in many cases preprocessing.

Lithological model has been derived from the correlation of lithology between wells (Fig 4). Krafla geothermal area is not homogeneous, neither with respect to geochemistry nor lithology. Therefore, correlation throughout the area is not straight forward. Hyaloclastite and basalt lavas are the dominant rock formations and their distribution is not easy to translate into a 3D model, especially hyaloclastite formations from different areas (Mortensen et al., 2009; Weisenberger et al., 2015).

Formation temperature model has been developed, based on temperature profiles. The temperature model is compared to the alteration temperature, based on depth to alteration minerals, to estimate the temperature evolution of the system.

Resistivity model has been developed with a few different approaches (see e.g. Mortensen et al., 2009; Weisenberger et al., 2015). TEM and MT methods are suitable in high temperature fields. TEM soundings show the resistivity distribution of the uppermost 1 km of the system while MT measurements reveal the resistivity distribution at greater depths (Hersir, 2015).

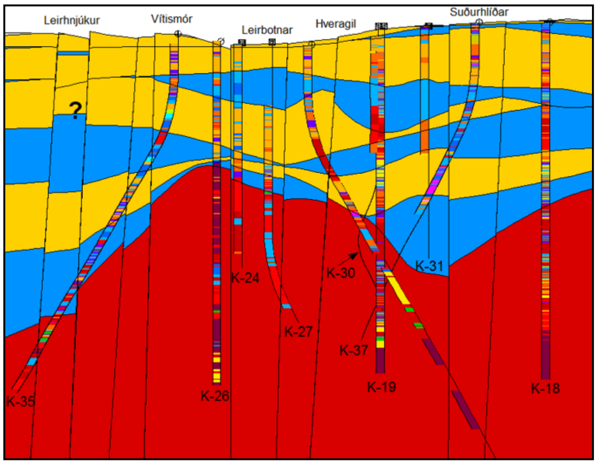


**Figure 4: Geological facies model of the Krafla geothermal field, based on cutting analysis from the wells. Repeated dyke formation at shallow depths where groundwater is present creates geothermal field such as the Krafla high temperature field (Weisenberger et al., 2015).**

A 3D structural model, based on surface tectonic features, has been developed in Petrel. Strike and dip of faults, fractures and volcanic fissures have been mapped within the area and they are extended to greater depths (Fig 5). Geothermal map can also be used as an indicator of subsurface tectonic features, but fluid flow to the surface is often controlled by tectonics (Sæmundsson, 2008a; 2008b).

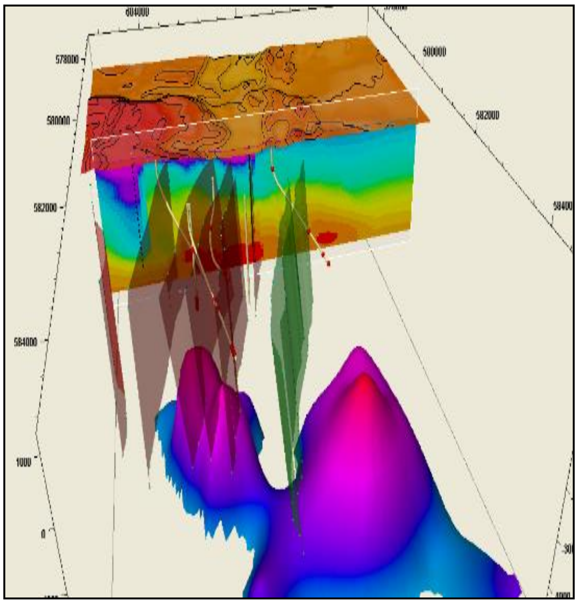

**Figure 5: Combination of aspects in Krafla geothermal system. Faults (green planes), volcanic fissures (red planes), resistivity, temperature cross section and feed points (red points) are visualized. Well paths cut through faults and fractures and feed points are often related to these permeable features. (based on Weisenberger et al., 2015).**

Lithological logs and correlations between them result in a lithological model. It provides information about the stratigraphy in the area. The model is based on cutting analysis, published in reports for each of the wells. The lithological model will be updated with some additional data, such as VSP and wireline logging, which will result in a geological facies model.

Gravity data have not been translated into a 3D model but results have been presented as a Bouguer gravity map that shows anomalies that can be interpreted in conjunction with the abovementioned models.

Other data that have been described in this paper, that have not been translated into 3D models, such as aeromagnetic surveys, seismic and geochemical data, are also an essential part of the conceptual model.

## 5. PICO ALTO GEOTHERMAL SYSTEM

Terceira is one of nine inhabited islands that belongs to the Azores. They are located along the Terceira Rift, which marks the boundary between the Eurasian and African plates. The Terceira Rift is a major tectonic feature of the Azores Triple Junction and causes the stress distribution to form a system of fractures, one trending WNW-ESE and the other NW-SE. Pico Alto is one of five volcanic complexes in Terceira. It is mainly composed of trachyte, an evolved volcanic rock, but rhyolites, trachydacites and trachybasalts are also abundant. Primary permeability seems to be insignificant despite moderate alteration (Henneberger et al., 2004).

Geological and geophysical explorations in Terceira indicate that there is an active and exploitable high temperature geothermal system beneath Pico Alto volcano. AMT resistivity measurements have been conducted and based on low resistivity anomaly temperature gradient wells were drilled to image the thermal conditions of the system (Henneberger et al., 2004).

## 6. DISCUSSION

Conceptual models are a useful tool to estimate the behavior and development of geothermal systems. They describe concepts and ideas that are based on available data. They predict the location of physical features and how they affect the behavior of the system. E.g. the location of outflow and upflow zones are very important and they are controlled by the most important parameters; temperature distribution and permeability. When data have been collected, datasets are integrated for all disciplines. If anomalies are seen in the data, they are interpreted from different perspectives and correlated between datasets. Different aspects are compared and estimated how they affect each other.

The data for the Krafla conceptual model are mainly classified into two categories; surface data and subsurface data (Fig 6). These categories have subdivisions based on the origin of data. Conceptual models are developed for a specific purpose and conditions are different between systems. Therefore, different assumptions are made when they are built. Priorities of data are also different in every case and understanding the constraints of the data is important. Geothermal systems are dynamic, data have to be monitored and updated consistently and thereby also the 3D models that visualize the data. Time factor is an important parameter when pressure, temperature and chemical content of fluid are recorded, because they are time dependent and show different responses as a result of utilization.

Workflow is a way of combining all available data and describes how to bring together multidisciplinary results based on characterization, exploration results and physical properties (Fig 3). It is supposed to screen possible risks and different scenarios. This results in improvements in well targeting and highlighting uncertainties. It is essential to list carefully the origin of data and location in file systems to be able to track the work step by step from the exploration phase to the comprehensive 3D model. Using workflows allows documentation of the work during the modelling process that can be repeated if parameters change.

To be able to apply the Krafla workflow to the Pico Alto geothermal area, using limited data from the Pico Alto geothermal area, basic information, such as tectonic setting, recent volcanism, lithology and depth to heat sources, are really important. What they have in common and what is different is an important base for further work. Instead of collecting more data from Pico Alto, existing data and improved understanding from Krafla geothermal area are used to make predictions in Pico Alto geothermal area.

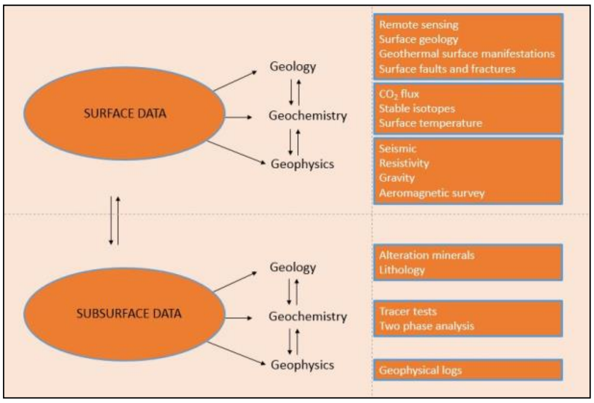


**Figure 6: Relationship between available data for the Krafla conceptual model. Parameters have to be linked with each other and repeated interactions between disciplines are essential.**

## 7. CONCLUSIONS

The workflow from Krafla conceptual model describes how the data are divided into categories and how they interact with each other. These interconnections and data constrains will be used for building the Pico Alto conceptual model. Petrel 3D software allows better understanding of the systems and is helpful to decide the location and direction of the wells.

Data acquisition in Krafla has to be listed carefully as well as solution of various problems that have come up during the drilling history. This is important for future work, both in Krafla and Pico Alto. With improved understanding and learning from mistakes, risk, cost and uncertainities of siting wells can be reduced.

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