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A 3D Geological Static Field Model of the Krafla Geothermal Area, NE-Iceland

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ABSTRACT

3D geological static field modelling is a useful tool to compile and summarize surface and subsurface data and their interpretations. The modelling purpose is to gain a better understanding of the nature and characteristics of the geothermal system and minimize risks for future drilling targets. Geothermal systems behave differently, and priorities of data vary in every case. The workflow approach allows documentation of each step during the modelling process that can be revised if parameters change with new data acquired. The Krafla geothermal field in NE-Iceland has been explored since 1969. A large variety of datasets have been collected from 47 boreholes. Six comprehensive conceptual models have been put forward throughout the field's history. The various datasets provide the basis for a geological static model, primarily sub-divided into two groups: (1) geophysical surface data, and (2) subsurface borehole data. By recording the work already performed and the evolution of existing knowledge, the resulting workflow describes in general how to bring together multidisciplinary interpretation results, which in turn highlight areas of uncertainty and the future work required. The different datasets from Krafla have been tied together in order to do a joint-interpretation of the structural pattern in Krafla and the link to production patterns across the field.

1.INTRODUCTION

Challenges in geothermal research are faced with and solved by a variety of methods, which have been used through the years to reduce risks in well targeting. Different disciplines within the geothermal branch are used to construct geological static models and ensure their reliability. The purpose of such models is to come up with some answers to geological questions that involve risk assessment, as every model is sensitive to its input data and the assumptions made. Gathering data across all disciplines and their visualization is crucial in assigning constraints to these models. Observed anomalies have to be supported by the different datasets. In order to understand the framework and behavior of a geothermal system, *geothermal field models* integrate datasets together allowing joint interpretation of data. Here, the revision of the Krafla geological static model will be presented, as well as the workflow that was developed during the revision (Thorsteinsdóttir, U., 2017).

2. KRAFLA GEOTHERMAL FIELD

Krafla is located in the northern volcanic zone (NVZ). It consists of an active central volcano with its NNE-SSW striking fissure swarm. The Krafla fissure swarm is 100 km long and 4–19 km wide (Sæmundsson, 1978; Hjartardóttir et al., 2012). The volcano features an 8 x 10 km wide caldera which is elongated due to the expansion of the Krafla rift segment within the NVZ. It is believed to have been formed during a postglacial period about 100.000 years ago in an eruption producing semi-acidic welded tuff, also referred to as the "Halarauður". The caldera is not visible on the surface because it has been filled with volcanic material (Sæmundsson, 1978; 1991). An inferred inner caldera has been proposed considerably younger and probably formed after the area was covered with ice (Árnason et al., 2011).). An expression of a magma chamber has been located based on S-wave shadows. The top of the magma chamber has been located at 3 km depth (Einarsson, 1978). The geothermal field is located in the eastern part of the caldera. The main production area is aligned in a WNW-ESE direction, along an elongated intrusive complex (Einarsson, 1978; Sæmundsson, 1991) (Figure 1). A total of 47 wells have now been drilled and the plant produces 62 MWe from 20 production (Weisenberger et al., 2015; Hauksson, 2017).

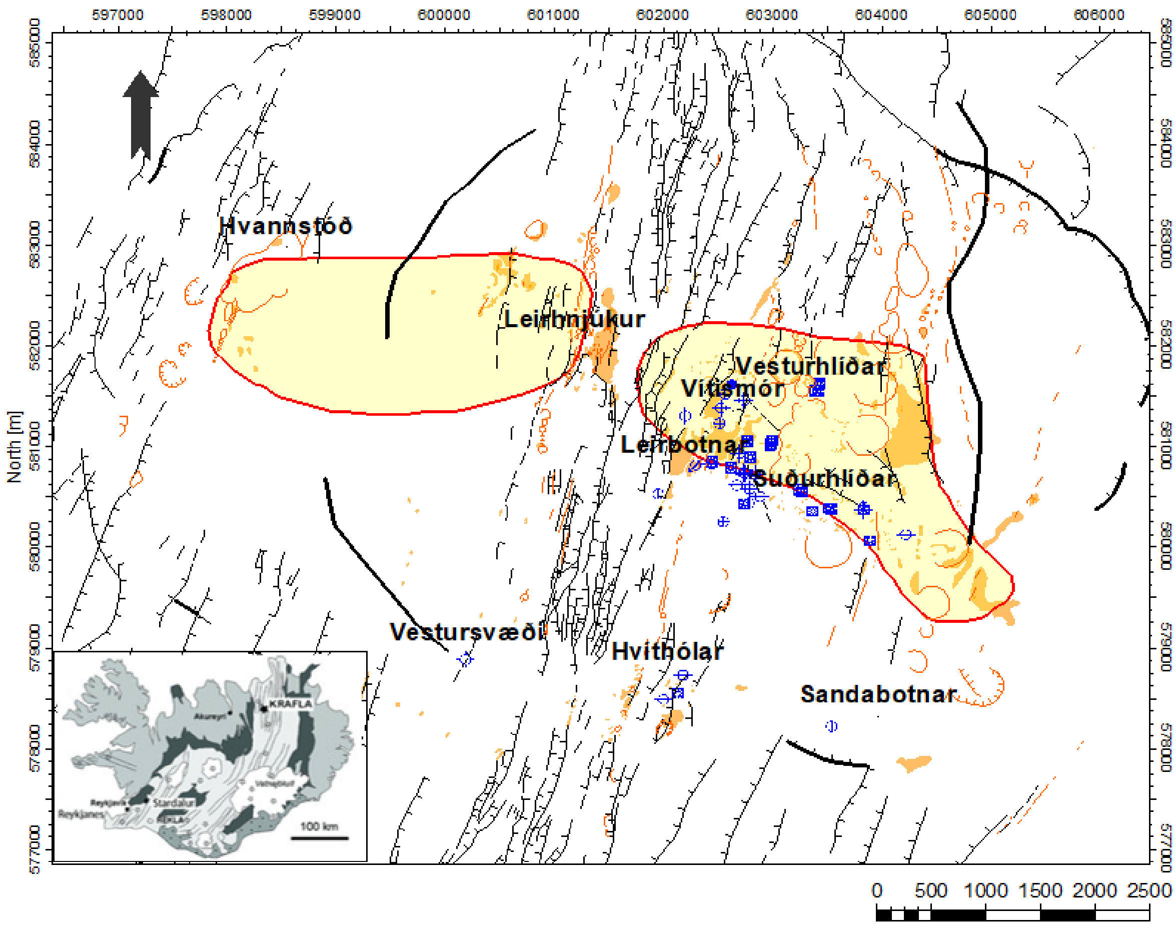

Figure 1: The Krafla geothermal field and its location on the NVZ. The map shows the outer and inferred inner caldera, drilled wells (in blue), different sub-areas of the geothermal field, and the S-wave shadows, mapped by Einarsson (1978).

The drilling and production history in Krafla spans 45 years. The main challenges that have been faced are related to the complexity of the geothermal system, in particular with respect to the geochemistry and geological sub-surface structure (Stefánsson, 1980). Of the 47 drilled deep wells, only 20 are currently used as production wells (Hauksson, 2017), which represents a low success rate in comparison to other high temperature geothermal fields in Iceland (Sveinbjörnsson, 2014). Volcanic activity in the area and shallow magma have led two wells to be drilled into magma at shallow depth (Friðleifsson et al., 2014). Problems related to acidic geothermal fluids have also been a challenge (Ármannsson et al., 2015). These issues and related questions have resulted in the development of technical solutions and methods to enable the mapping of possible risks and challenges, e.g. the location of magma pockets and well design under acidic conditions.

Several comprehensive conceptual models of the Krafla geothermal area have been made throughout its drilling history (from 1977-2017). The last two revisions of the conceptual model (published in 2009 and 2015) were partially based on 3D modelling techniques and thus, serve as a basis for the newly updated geological static field model (Mortensen et al., 2009; Weisenberger et al., 2015).

3. METHODS AND DATA

A well-organized workflow and data preparations are crucial when constructing or revising a data model. Following is a listing of model types, workflow, documentation of the work during the modelling process that can be repeated if parameters change. Building a workflow requires an estimation of data collection and processing.

3.1 Building a 3D geological static model

The resulting workflow depends on the scale and state of development of the geothermal area and advancement of the geological static model. A geological static model is evidently driven model, based on data rather than ideas. Minimizing data extrapolation avoids data to be over-estimated.

Building a geological static model involves several stages (Figure 2):

a. Structural modelling, describing the tectonic framework, including faults and geological formation zones that are tied to surface and sub-surface data information.

b. Geo-property modelling showing detailed interpretation of borehole data and surface geology to predict subsurface properties and characteristics of different geological facies. This involves thin sections and laboratory analyses from wells, well log measurements and well testing.

c. Petro-physical modelling representing reservoir properties such as formation temperature, hydrostatic and lithostatic pressure, feed zones, focal point areas, porosity and permeability.

d. Hydrological modelling describing the hydrological cycle in a specific area. Used for understanding hydrologic processes e.g. the origin of recharge and fluid flow. It is based on isotope analyses and major elements analyses of both spring water and borehole fluid.

Interpolating field data can cause errors due to discontinuity of structures and lithological boundaries in the subsurface which are difficult to predict in a complex system. Therefore, the construction requires pre-processing, integration and quality check of the data. Models' reliability depends on the input data; accuracy of the measurements, interpretation of individual data and the modelling process. Geological static field models from active geothermal areas are constantly under progress. Hence, there is no such thing as a final geological static field model. It should be updated continuously as new information becomes available, e.g. information on additionally drilled wells, new measurements or new technology implementations.

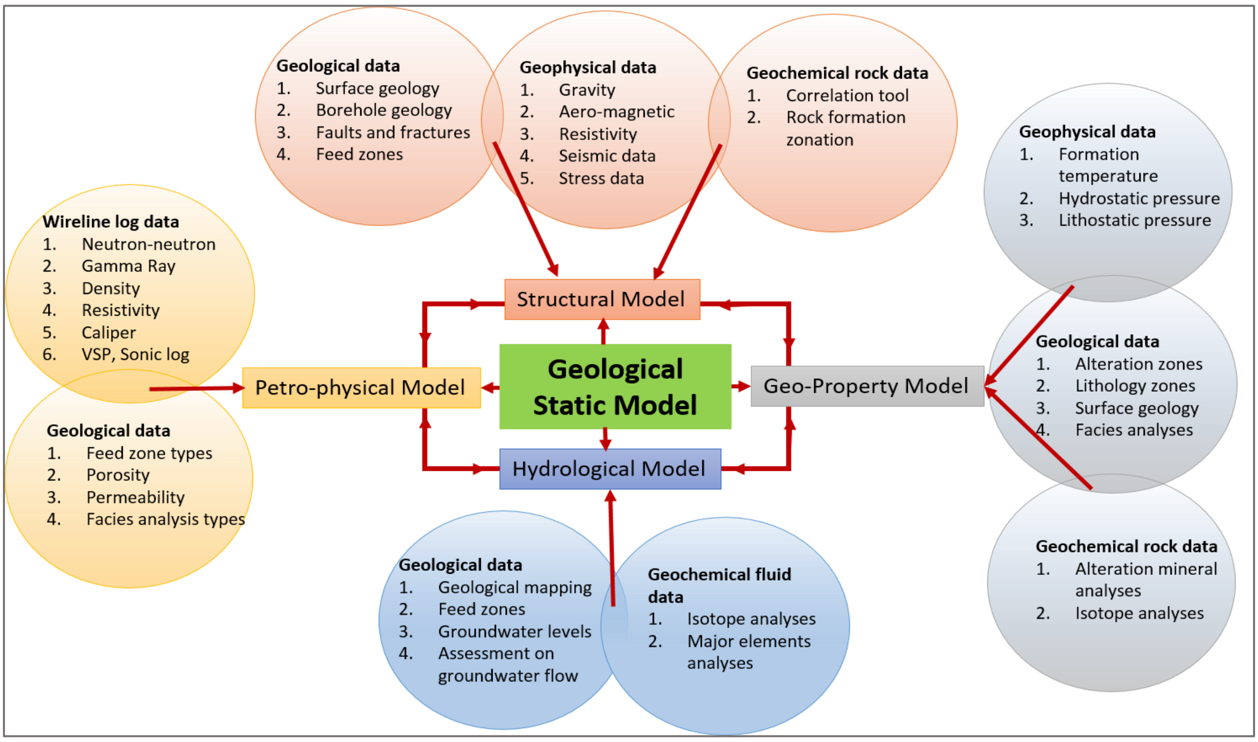

Figure 2: Subdivision of main datasets used for the construction of 3D geological static models. These lists are not a final product and could have additional items that are relevant for other areas. Overlapped areas and red arrows represent integration between datasets and models. Taken from Thorsteinsdóttir, 2017.

The Krafla geological static model does not describe changes in the physical conditions or energy transfers in the geothermal system. Rather, the model emphasizes the existing and present state conditions, e.g. geological and geophysical database that build on the geological framework. The goal is to constrain the modelling parameters and develop a model with enough details to represent the tectonic framework and stratigraphic heterogeneity of the system. Interpolation over long distances, where there is lack of data is minimized to optimize accuracy and reduce uncertainty in the model.

3.2 Workflow

The workflow that was developed through the revision of the Krafla geological static model is comprised of five principal steps (Figure 3);

1) Data acquisition and preparing
2) Data importing
3) Data correlation
4) 3D modelling
5) Combined results

Following each step in a model construction, quality control should be checked including listing of source, references, data manipulation, constraints, uncertainties and advantages/disadvantages. The priority of datasets is dependent on the state of development of the geothermal system (Cumming, 2009). Having datasets across all disciplines from different scientists requires close integration and information sharing during the process. During the modelling process, simplification of the data is unavoidable, as data gaps force general interpolations. Smoothing of data can remove relevant information and it is, therefore, essential to keep track of such changes.

3.4 Input data

Since the publication of the latest Krafla conceptual model in 2015 (Weisenberger et al., 2015), additional measurements and re-interpretations of available datasets have resulted in an update of various geophysical and geological parameters. During the acquisition of available and recently acquired data and in the making of a preliminary version of a workflow, it was decided to divide the data into two groups; surface geophysical data, and subsurface borehole data. The added geophysical surface data are:

- Location of seismic events from October 2013–November 2016 (Blanck et al., 2014, 2016, 2017);
- Focal mechanism analyses from eight selected earthquakes in 2016 (Blanck et al., 2017);
- Seismic refraction profile data from 1971-1973 (Ágústsson et al., 2011);
- Seismic tomography presenting V_p and V_p/V_s ratio models (Schuler et al., 2015);
- 3D inversion of resistivity (Rosenkjaer et al., 2015);
- Aero – magnetic map (Karlsdóttir et al., 1978);
- Bouguer and Free air gravity maps (Magnússon, 2016).

The borehole data include collected data during and after drilling for all boreholes:

- Drill cutting analyses for lithology and alteration
- Geophysical log data (drilling and wireline)
- Feed zone interpretations for their locations and size estimation
- Grouping of well quality based on enthalpy and energy production

New geophysical log data presented in the revised model are Televiewer logging results of well K-18 (Árnadóttir 2014; Blischke et al. 2016) and VSP (Vertical Seismic Profile) profile from well K-18 and K-26 (Kästner; F., 2015). Lithology interpretation based on drill cuttings has been included in digital format for all the wells, and additional data from well K-41 that was drilled in 2016. The revision of the geological static model was developed in Petrel, a software for 3D mapping, modelling and visualization. The datasets have provided information for the updated sub-models in the Krafla geological static model; geological model, alteration model, formation temperature model, resistivity model (1D and 3D) and tomographic model.

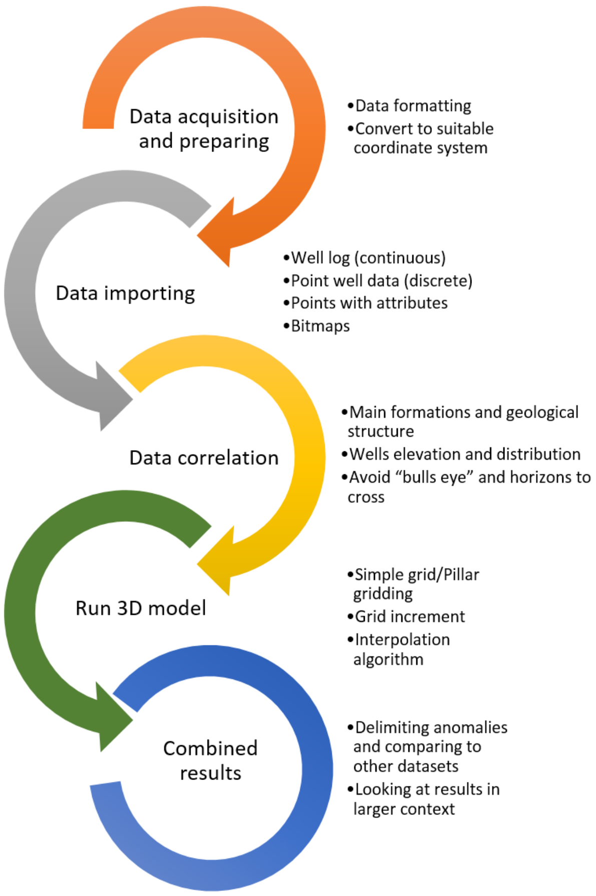

Figure 3. The principal workflow steps diagram to visualize the complexity of geological field modeling tasks. Taken from Thorsteinsdóttir, 2017.

3.3 Data acquisition and preparing

Data acquisition and preparing creates the basis for the work that follows. It depends on the modelling software, how much the data have to be processed in regard to data quality, interpretation certainty and formatting issues (depth determination, coordinate system, points and commas etc.). If additional information exists, should they be imported as well. For *data import*, continuous or discrete data are either linked to wells or coordination’s in a vertical plane.

Data correlations are performed prior to the construction of the 3D grid. This is an iterative process and requires several rounds of correlations and a quality control. Detailed lithological logs can be simplified to indicate the main units that are correlated and form the basis of the static model zonation. Wells have to be lined up in reference to sea level and in logical order, such as closest offset wells, or wells along a geological trend. Correlations should then be compared with earlier work if available and geological history should be kept in mind during the correlation process. “Well tops” datasets are created in the process, including a top of each formation in each well or selected surface location. For better consistency assessment of a first path well correlation data set, a horizon is created for each well top. A review of these control horizons in a 3D or an intersection window, allows a quick detection of anomalous data points or “bull’s eyes” that are not related to zone thickness changes or cross fault intersection trends. The data correlation set is then revised and edited until the best fit of points to horizons has been reached and bull’s eyes and horizons crossing have been eliminated.

In the *3D modelling process*, each 3D grid is built from an evenly or unevenly distributed x, y, z and property data point, line, or 2D grid data set. The 3D grid construction is composed of several steps. It can be created using “simple grid” or complex “pillar gridding”. The simple grid method is used for most data types, except for fault modelling or segmented field model areas. Pillar gridding requires faults or segment separators for generating a 3D grid that is tied to a fault block or complex structure, e.g. distinct permeability or facies segment subdivisions. In both cases, x and y increment and model boundaries are defined, as close to the data distribution as possible. For the model´s lateral extent, an outline polygon is created. For the vertical distribution limits, top and base limit are defined by constant depth values or known 2D horizon grid data, e.g. topography as the top horizon. Relevant interpolation algorithms depend on data density and size of input data. Several model interpolation algorithms should be run for every dataset and they compared with the original data. Simple gridding is used when faults are not implemented and fault or field segmentation of a model does not apply for a selected data set. Simple grid geological model was created from lithological correlations in Krafla before implementing the faults, in order to make sure correlations succeed. Simple grid models can either be made using horizons/well tops created by points, or layers created to achieve the final cell thickness in the model (scaling up well logs). When a simple grid is built from upscaled logs, layering is set based on thickness and variety within every formation. Models quality is again based on data coverage and it should be kept in mind that each cell only includes one value. Upscaling averages the values within the cell which means a decrease in data resolution. Different average methods are defined, based on data distribution. Pillar gridding is the process of generating the grid from given horizons and faults or segments. Fault geometry and distance from the fault is also set, which means extrapolation of that distance back into the fault plane. Pillar gridding was used for the construction of the geological model in Krafla. Zone and layer modelling, facies modelling, and upscaling method function similar to the process described for the simple grid modelling process.

In general data compilation and *combining results* are important for the modelling process. For a better understanding and quality control, datasets should be viewed together and possible causes for anomalies considered. By delimiting anomalies in one dataset, comparison with other datasets becomes easier. This is crucial when surface and subsurface data are combined.

4. RESULTS

The geological model was compiled and investigated for structural trends that fit the analyzed geothermal system, using the model workflow approach and data processing described above. During the construction of the Krafla geological static model, resistivity structural trend picking allowed easier comparison with other models. The same applies to other geophysical data sets, e.g. magnetic- or gravity Bouguer anomalies data maps.

4.1 Geological model

The geological model is composed of *a lithological* and a *structural* model. The *lithological* model gives an idea about the lateral and vertical heterogeneity of formations. Hyaloclastite units and basaltic lavas are the most common lithologies in Krafla. Hyaloclastites form irregular ridges or mountains, whereas basaltic lavas spread more laterally. Infill sections are also found between those formations, composed of thin layers of basaltic lavas, breccia, pillow lavas and tuff. Below 1000 m depth (b. sl.), intrusions become dominant. A distinct shift in neutron-neutron, resistivity and seismic data is recognized below 1800 m depth (b. sl.). As this reflects different reflector in the strata, this is implemented in the model as a “possible basement” most likely including gabbro or dolerite intrusions, as well as younger intrusions. The different formations reflect their depositional environment and represent relative temperature conditions. The geological model was put into context with the geological history of Krafla as published by Sæmundsson (1991) (Figure 4). The *structural* model represents tectonic features within the geothermal area. Already interpreted faults, as a part of the previous conceptual models were ranked based on their influence on other datasets. The 11 best ranked structural lineaments and fault zones were used for the structural model. Using them, as well as additional borehole data and revised correlation between wells, resulted in an updated geological model.

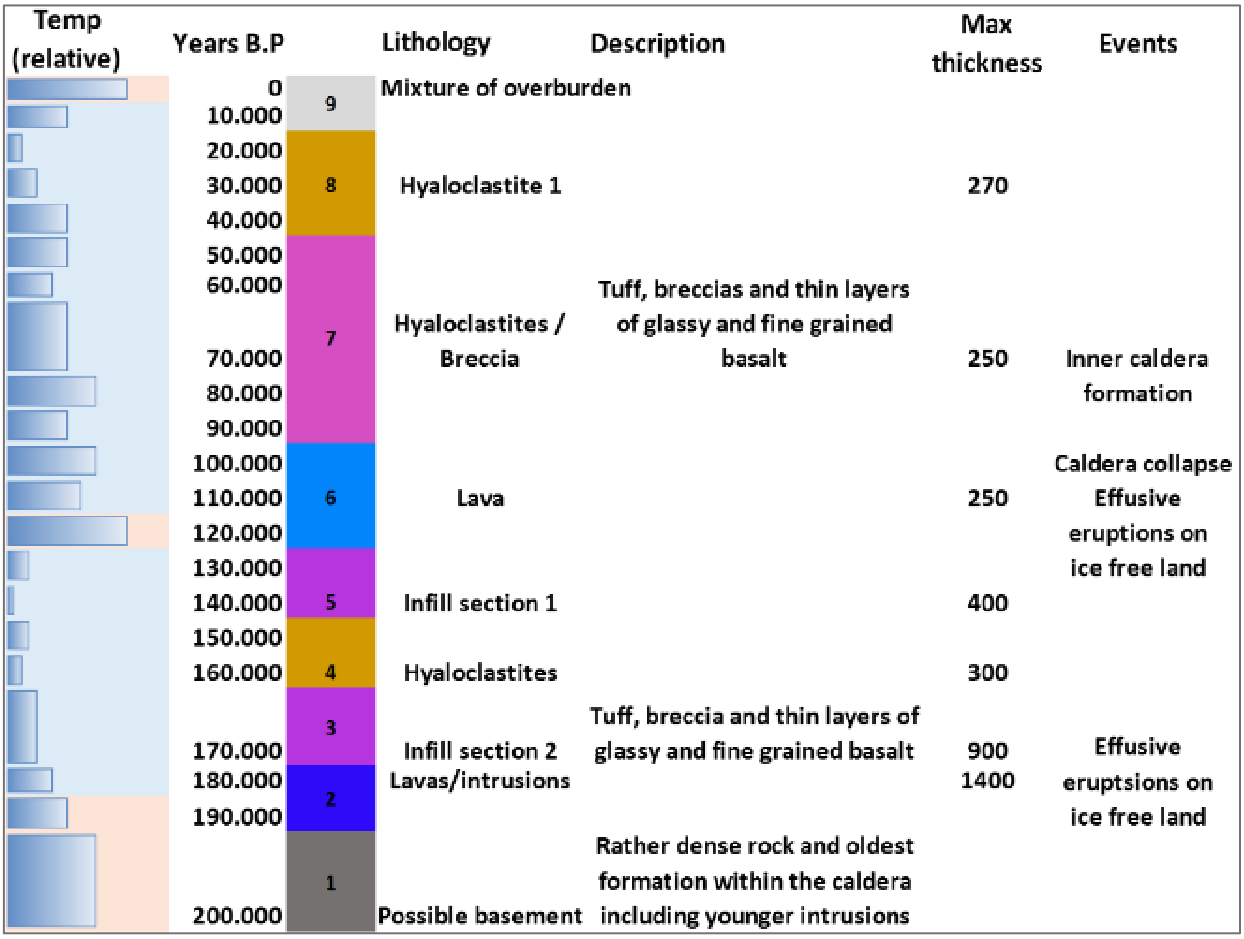

Figure 4: A possible scenario of a generalized lithological section for the Krafla area correlated to the geological history of Krafla by Sæmundsson (1991).

4.2 Structural lineaments

The most recent 3D resistivity inversion (Rosenkjaer et al., 2015) was used to compare multi-disciplinary results and for joint interpretation. A comparison was made between the resistivity models based on 1D inversion (Árnason et al., 2011) and 3D inversion of MT data (Rosenkjaer et al., 2015). The relationship between seismicity and resistivity originally put forward by Árnason et al. (2011) was included and revised using newly acquired seismic dataset and another recently made resistivity model. Distribution of earthquakes within the calderas was added as well to a gravity Bouguer anomaly dataset.

A WNW-ESE lineament has been observed in Bouguer gravity (Figure 5), aero-magnetics (Figure 6), resistivity (Figure 7), seismicity, lithology and geothermal manifestations. This also coincides well with the extent of the S-wave shadows, which are elongated in a WNW-ESE direction due to the extension along the fissure swarm (Sæmundsson, 1991). A parallel gravity low coincides with breccia dominant graben and deep intrusions. However, as only well K-06 provides information about the lithology in the graben it is not ambiguous and uncertain to draw an extensive conclusion based on that observation. NNW-SSE to WNW-ESE trending faults and fractures nevertheless indicate that the tectonics are not only controlled by simple orthogonal rifting. A NE-SW lineament has been observed in the resistivity, Bouguer gravity, aero-magnetics, seismicity and mapped surface tectonic features. The temperature anomaly domes up below the lineament (Figure 8). The NE-SW lineament is parallel to the rift and is most likely caused by the opening component of the NVZ.

A discontinuity of the NE-SW lineaments across the WNW-ESE lineament were observed in the resistivity, Bouguer gravity, aero-magnetics and seismicity. This discontinuity showed a segmentation and a left stepping fault system. As Krafla is located near the junction of the Tjörnes fracture zone (showing dextral strike-slip component) intersecting the rift zone, the lineaments could be a consequence of those two different movements.

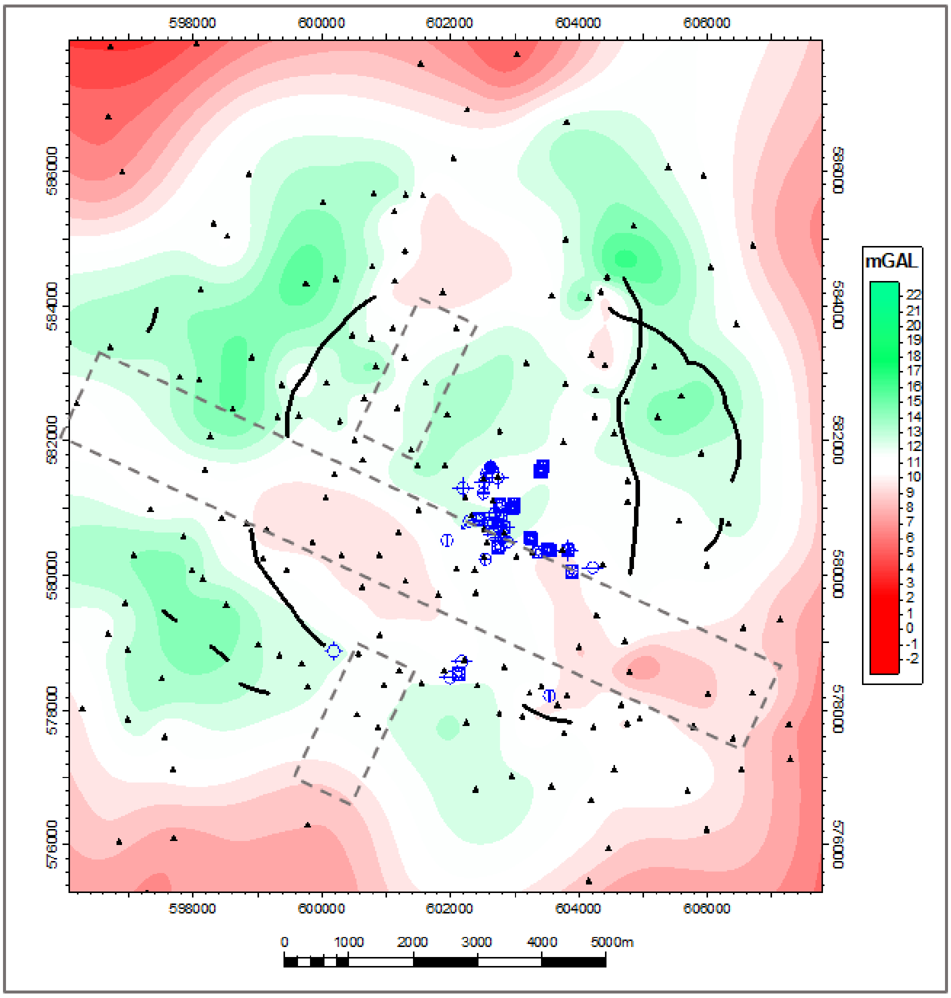

Figure 5: Bouguer gravity map of Krafla caldera and its surroundings. Inner and outer caldera rims are visualized and black triangles mark measurement sites. Gray lines show the NNW-SSE trend of low gravity. The main production area is located north of the WNW-ESE gravity low (Magnússon, 2016).

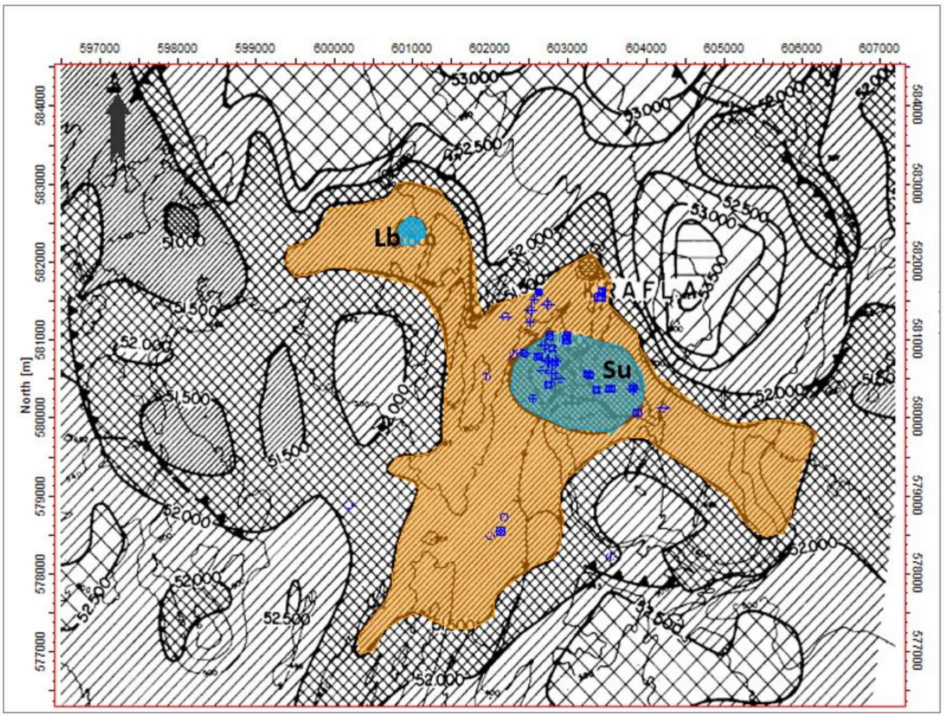

Figure 6: Aero-magnetic map of Krafla caldera showing the most distinct magnetic low below Suðurhlíðar (Su) and Leirbotnar (Lb) (Karlsdóttir et al., 1978). Orange polygon represents magnetic low and blue polygon shows a significant magnetic low, coinciding with production area.

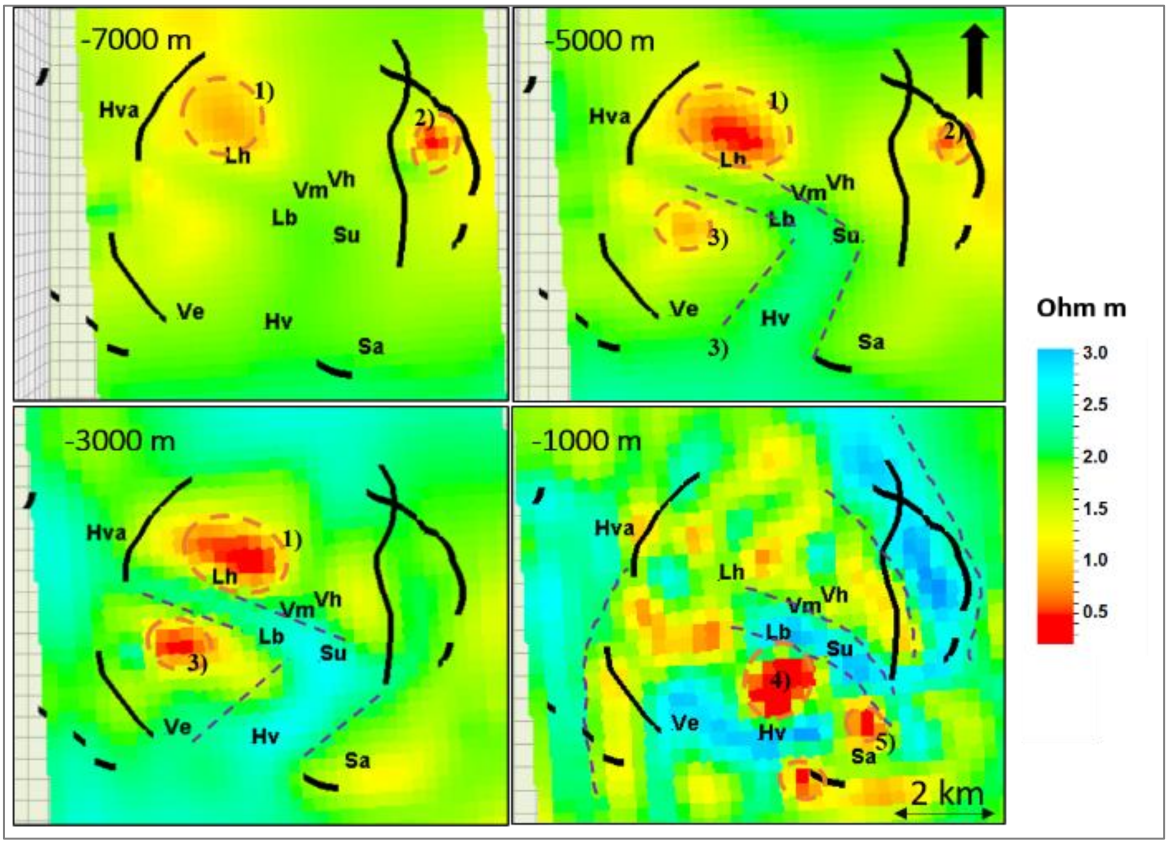

Figure 7: The subsurface resistivity structure of Krafla based on 3D inversion of MT data. Blue dashed lines delimit high resistive areas and red circles outline conductive areas. Sub-areas are labeled as abbreviations on the map: Hvannstóð (Hva), Leirhnjúkur (Lh), Vesturhlíðar (Vh), Vítismór (Vm), Leirbotnar (Lb), Suðurhlíðar (Su), Vestursvæði (Ve), Hvíthólar (Hv), Sandabotnar (Sa). Black lines mark outer and inner calderas.

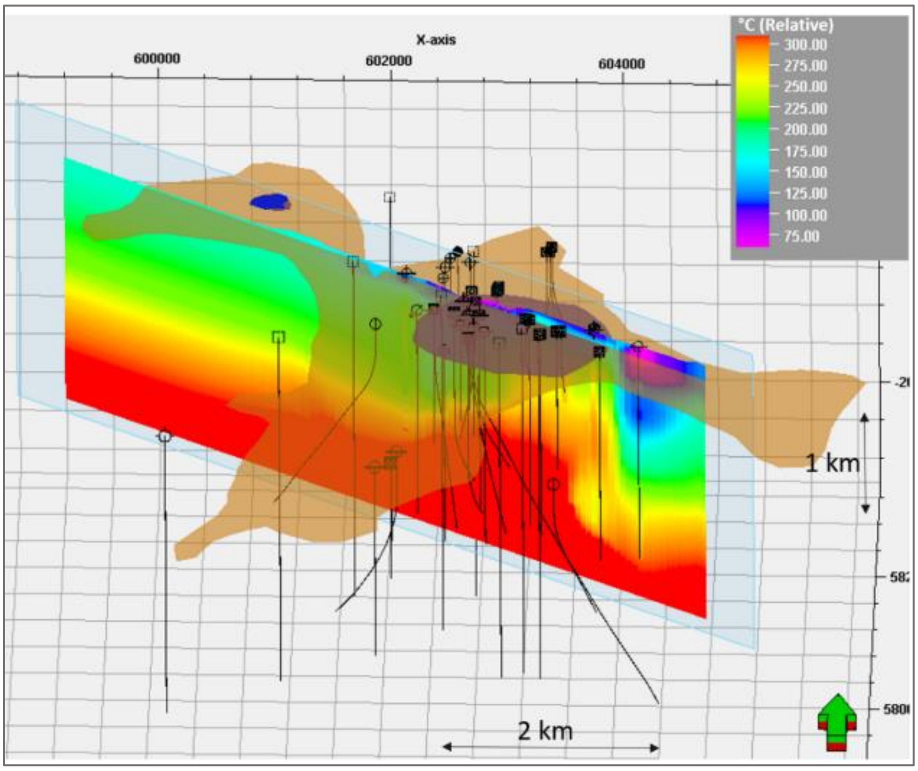

Figure 8: A 3D scene showing the magnetic low and a cross section of formation temperature. High temperature is located below the magnetic low. Taken from Thorsteinsdóttir, 2017.

5.DISCUSSSION

For the overall interpretation it is important to keep in mind that even though the modelling area is small, it is only one piece of the information of a larger system. Therefore, studies from other nearby areas and large-scale studies should always be considered with the small-scale studies. Scale and spatial resolution are also important to consider, when interpreting and comparing datasets. Resolution of large-scale magneto-telluric data is not enough to distinguish single fault features in any detail, except large scale structural lineaments. Smaller-scale data sets, e.g. such as local seismic reflection surveys, or borehole televiewer data are essential and important to increase the understanding of the structural and sub-surface geometry of a field area.

GPS data have revealed an asymmetrical rifting across the Northern Volcanic Zone (LMÍ, 2017; Metzger and Jónsson, 2014). Near the Krafla Fissure Swarm, the total GPS movement is almost zero, which could indicate that different segments are possibly pushing against the rift motion, causing the total movement to be cancelled out. Accordingly, the lineaments could be a consequence of the interplay between the dextral moment along the Tjörnes fracture zone, the opening component of the rift and volcanic deformation in the area. Different spreading and volcanic deformation causes local stress field changes that affect the neighboring systems.

Other factors than structural deformation play a role in the formation of these sub-surface lineaments. Rifting events cause horizontal and vertical displacements of magma and rock and affect the stress field, both on a small and large timescale. Emplacement of magma builds up stress by local area uplift, and cooling and contraction of magma decreases the stress. This can be seen on a very small timescale, just as rifting events of the Krafla fires showed (Hjartardóttir et al., 2012). Changes on a large scale have also been discussed by Sæmundsson et al. (1991), where different parts of the fissure swarm were active at different periods. Therefore, the stress field in Krafla is presumably caused by the interplay between the large-scale oblique rifting, as well as changes in the stress field due to emplacement of magma and deflation and inflation of the shallow magma chamber.

6. CONCLUSION

One of the main objectives of this project was to generate and test a workflow approach for constructing a geological static field model. Throughout the modelling process for the Krafla geothermal field, data comparison and compilation revealed where gaps of data or understanding need to be filled, which would result in a more coherent and reliable field model and research. Thus, using a structured modelling approach enables to better plan for future data acquisition, well planning and risking, which includes:

- Various datasets have been compiled and visualized for better representation and understanding, providing the basis of interdisciplinary working approaches.
- Minimise the gap between regional and field-scale interpretations'
- Build up the basis for spatial structural interpretation within a 3-dimensional space, enabling accurate geometrical projections and data comparisons between structural interpretations, geo-property-, petro-physical- or hydrological models.

Based on these observations, the deep structure recognized from subsurface data, can only be seen on surface to a certain extent. Combining different datasets together and viewing them in a 3D environment, sheds light on the consistency between datasets. Observations of a rotation and en-echelon fault arrays can most likely be explained by oblique rifting around Krafla. Oblique rifting can cause transform wrench fault structures that consist of a combination of localized strike-slip faults and normal faults (McClay and White, 1995). These "damage zones" can create permeable fracture networks that weaken the rock and allow geothermal fluids or intrusions to rise and travel along fault and fracture zones, representing one possible explanation to the temperature and magnetic anomaly across the Krafla field area. The junction of these two different lineaments (WNW-ESE and NE-SW) is, therefore, a pre-requisite for an efficient geothermal system.

Although a large amount of data has been implemented for the Krafla geological static model, much work remains to be done in understanding its geothermal system for future development activities, prompting several follow-up studies such as, e.g.

1) Combined structural and lithological properties borehole analysis would result in a better understanding of potential flow path correlations and reservoir connectivity;
2) implement geochemistry and production data, such as production logging including spinner logging and analysis or tracer testing into the newly updated structural model;
3) detailed interpretation of field scaled gravity and magnetic datasets analysis, constrained by borehole data and existing MT-TEM datasets;
4) or, support structural interpretations with future high-resolution earthquake location and focal mechanism analysis, and seismic refraction data surveying.

7. ACKNOWLEDGEMENTS

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