A 3D geological static field model of the Krafla geothermal area, NE-Iceland; constructing a workflow applied to the Pico Alto geothermal area, Azores

Unnur Þorsteinsdóttir

Faculty of Earth Sciences
University of Iceland
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Unnur Þorsteinsdóttir

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MS Committee
Anett Blischke
Gylfi Páll Hersir
Helga Margrét Helgadóttir
Þorvaldur Þórðarson

Master’s Examiner
Anette K. Mortensen

Faculty of Earth Sciences
School of Engineering and Natural Sciences
University of Iceland
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Faculty of Earth Sciences
School of Engineering and Natural Sciences
University of Iceland
Sturlugata 7
101, Reykjavík
Iceland

Telephone: 525 4000

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Abstract

Compiling and summarising multidisciplinary results from geothermal areas often proves to be a complicated and challenging task. In such tasks, 3D models facilitate data comparison and enable a better understanding of the systems involved, resulting in a better and risk mitigated well targeting processes. This project involves 3D modelling of a geothermal field that has been exploited for years. The Krafla geothermal field is located in NE-Iceland and has a long history of research and exploitation. Here, the Krafla geological static model has been updated using research data that have not been implemented to the model before. These include recently acquired seismic data (location of quakes and tomography), 3D resistivity model, aero-magnetic data and Bouguer and Free-air gravity maps. Borehole data (cuttings analyses and geophysical logs), which have not been available in digital format before, have been included. Furthermore, datasets were compared and cross-correlated through deep structure sub-surface analysis. Lessons learned throughout the construction of the Krafla model resulted in a proposed workflow which was then applied to the less known Pico Alto geothermal area on Terceira Island, Azores. Pico Alto is a promising geothermal field in its early stages of development. Five production wells have been drilled and exploration results presented on maps and cross sections. Here, the existing data were visualised in a 3D model, according to the workflow, in order to gain a better understanding of the Pico Alto geothermal field. The two geological static models presented here provide a useful basis for further research and model workflow applications.

Útdráttur

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Introduction

Locating heat sources and permeable zones is key to successful geothermal exploration and utilization. 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 putting constraints on these models. Observed anomalies have to be supported by the different datasets. In order to understand the framework and behaviour of a geothermal system, *geothermal field models* integrate datasets together allowing joint interpretation of data.

In order to obtain good quality results it is paramount that the modelling efforts are carried out in a systematic manner using similar procedures. This leads to the main objective of this study that concerns the development of a general workflow for constructing a 3D geological static field model, which would be the basis for dynamic reservoir field modelling. This study is conducted to develop and evaluate such a workflow.

- Update the Krafla 3D geological static model, using additional data that have not been presented before, within the proposed workflow. Compare results from variety of datasets and interpret their relationship. This is mainly done with regards to sub-surface structural interpretation.

- Propose a workflow for constructing a 3D geological static field model, which is based on lessons learned from the revision of the geological static field model of Krafla and also through literature study and other field areas.

- Apply the developed workflow to the Pico Alto Greenfield area, located on Terceira Island, Azores.

- Present the workflow’s applicability and comparison of the two geothermal field areas, and make suggestions for future work in light of insufficient data, understanding and workflow segments.

As a part of the IMAGE project (presented in section 1.1) a working tool will be developed to increase the geoscientific understanding of an area as a whole in a multidisciplinary way and decrease reservoir development risks for the geothermal field operators.
1.1 The IMAGE project

ÍSOR, Iceland GeoSurvey, is one of the 24 partners (15 science and 9 industrial partners) of the IMAGE project (Integrated Methods for Advanced Geothermal Exploration). IMAGE is an ongoing four-year research project, which began in November 2013. The project is funded by the European Union within the 7th Framework Program for Research and Technological Development. It’s aim is to develop reliable exploration and assessment methods to image geothermal reservoirs by combining interdisciplinary results. The three main aspects of the IMAGE project are described in the following three Work Packages (IMAGE, 2013):

- Advanced understanding of the processes and properties of geothermal systems that control the spatial distribution of critical exploration parameters at European to local scales and providing essential information about rock parameters of the system.
- Improve well established exploration techniques (geological, geochemical and geophysical) for imaging rock structures and detection beyond the current state of the art and testing of novel methods.
- Integrating all available data and demonstration of multidisciplinary approaches to provide predictive models for site characterization and well siting, based on conceptual advances, improved models and exploration techniques. Provide recommendation for protocol for resource assessment and supporting models.

On this basis, the project work was divided into three sub-projects, one for Management and Dissemination (SP1), one for Magmatic and Supercritical geothermal systems (SP2) and the third one for Basement and Sedimentary geothermal systems (SP3). The sites in the magmatic and supercritical contexts include Krafla (NE-Iceland), Larderello (Italy), Reykjanes (SW-Iceland), and Pico Alto (Azores). The sub-projects SP2 and SP3 were subdivided additionally into 3 Work Packages (WP) each: WP3 and WP6: Processes and Properties; WP4 and WP7: Exploration Techniques, and WP5 and WP8: Field Integration (see, Figure 1).
The Krafla geothermal field has played a crucial role in testing exploration methods and exploration techniques within the IMAGE project. Well K-18 in Krafla has been used as an exploratory well. It was not a promising production well because it did not cut workable feed zones (Friðleifsson, 1981; Guðmundsson et al., 1981). In the summer of 2014, a VSP (Vertical Seismic Profile) survey was carried out in two boreholes, K-18 and K-26 as a part of Work Package 4.2. This resulted in seismic profiles in the wells reflecting velocity contrasts below surface (Planke et al., 2016). The survey is discussed further in section 2.2. In October 2014, Televiewer data were collected in well K-18 (Árnadóttir, 2014). Televiewer aims at mapping tectonic features within the well. Sonic logging performed in K-18 was a part of the VSP experiment done earlier that year (Hersir et al., 2016). Results correspond quite well with the average VSP velocities (Planke et al., 2016).

Work Package 3.3 within IMAGE aimed at studying the impact alteration has on electrical conductivity through measuring CEC (Cation Exchange Capacity). This was done by studying core samples from well KH-1, KH-3, KH-5 and KH-6 in Krafla (Lévy et al., 2016) as well as measuring CEC from drill cuttings in well K-18 (Weisenberger et al., 2016). CEC is a good indicator of the quantity of clay, as the CEC of clay minerals, in particular of smectite, is higher than the CEC of other minerals. Indeed a semi-quantitative correlation between clay content and CEC is shown in Lévy et al. (2016). A linear correlation between smectite content and CEC is found in a study currently in progress by the same authors (Lévy, personal communication Aug, 11th 2017). A correlation between CEC and conductivity is observed with the measurements on core samples in Lévy et al. (2016). A relationship is also seen between the CEC measurements on drill-cuttings and the resistivity.
logs in borehole K-18 (Lévy et al., 2016; Weisenberger et al., 2016). Density, porosity, acoustic velocity and permeability of the cores were also measured. A linear correlation is observed between bulk density and porosity, as well as between P-wave velocity and porosity. The latter correlation was used to calculate the porosity based on sonic logs in K-18 (Lévy et al., 2016).

This MSc thesis is a part of Work Package 5 within IMAGE – Field Integration WP5.1: “Integrated application in field models”. The objectives of WP5 are the integration of data and results obtained in other WPs for developing a reliable methodology for exploration of high temperature fields in magmatic environments. This includes the following:

- Develop and test a workflow for an existing field (Krafla, NE Iceland), and apply that for the Pico Alto field on the Azores, which corresponds to an unexploited magmatic system.
- Apply integrated tectonic and analogue models for the sites, in order to increase spatial and temporal resolution of explorative concepts for the emplacement of magmatic bodies, and fluid flow pathways as a function of stress and structural evolution. This is performed in perspective of learning from fossil sites and integrates tectonic stress, temperature, rheology and tomography in explorative models (IMAGE, 2013, 21).

Task 5.1 aims at the following:

- Develop workflow for a 3D model representation and visualization to bring together multidisciplinary results based on characterization, exploration results and modelling of known physical properties like resistivity and elastic and mechanical behaviour in the temperature range 200 – 700°C. The workflow will be constructed in Krafla and Larderello, and applied in the Pico Alto field on the Azores.
- Build a-priori 3D model for 2 selected Brownfields...
- Update existing conceptual model with exploration results (IMAGE, 2013, 21).

1.2 On 3D geothermal field modelling

Modelling geothermal systems is useful to compile and summarize interpretations of available geoscientific data. Its purpose is to gain a better understanding of the nature and characteristics of the system to be able to target wells with greater success and to facilitate the geothermal exploitation. The aim of 3D modelling is to enable mapping of the available data in a three dimensional environment. By viewing more than one dataset at a time, well targeting becomes easier and more reliable, as all the data can be selectively viewed from anywhere within the model. Furthermore, filtering allows anomalies to be clearer and more visible. 3D modelling techniques have been applied in several geological areas, at various scales, for different purposes within the geothermal industry (Cumming and Mackie, 2010).
They have been developed and utilized in other industries as well, such as mining and oil and gas (Xu et al., 2014; Rivenæs et al., 2015). These modelling techniques have partially been applied to various geothermal areas in Iceland e.g. for Krafla (Mortensen et al., 2009; Weisenberger et al., 2015), Reykjanes (Khodayar et al., 2016), Hellisheiði (Gunnarsdóttir and Poux, 2016) and Þeistareykir (Mortensen, 2012).

Krafla is defined as a Brownfield area (IMAGE, 2013), referring to a well-known geothermal system, where substantial exploration experience has been gained and some geothermal development has taken place. The drilling history in Krafla spans 43 years and the main challenges that have been faced relate to the complexity of the system, with respect to geochemistry and geological structure (Stefánsson, 1980). Of the 47 drilled deep wells, only 20 are currently used as production wells (Hauksson, 2017), which is a low success rate in comparison to other high temperature geothermal fields in Iceland (Sveinbjörnsson, 2014). Volcanic activity in the area and shallow magma chamber(s) 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 (Ármansson et al., 1989). These issues and 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.

The resulting workflow of building a geological static field model of the Krafla area was then applied to an area with a known geothermal system that has promising drill sites, namely Pico Alto on Terceira Island, Azores. The area is in its early stages of geothermal development, and is referred to as a Greenfield area, with limited data availability and no long-term production history (IMAGE, 2013).

Building a workflow from a Brownfield requires an estimation of data collection and processing. The resulting workflow depends on the scale and state of development of the geothermal area, and advancement of the geological static model. The different stages of modelling depend on data availability and geoscientific knowledge of the selected area. The different main stages of a modelling progression are as follows (these terms will be used in this thesis):

1) A conceptual model is defined as “a descriptive or qualitative model of a system or section of a system that incorporates the essential physical features of the system and is capable of matching the salient behaviour or characteristics of interest to the modeller” (Grant and Bixley, 2011). They are useful to understand the large scale picture of the system and can be used when only limited data are available. A conceptual model is often summarized with a number of drawings and qualitative descriptions outlining location of heat sources, possible flow paths and main structure of the area (Figure 2). Since conceptual models are composed of concepts and ideas, it is important to be aware of the bias of conceptualisation (Rivenæs et al., 2015).
2) As more data become available, a **geological static model** can be generated. It is evidently a quantitative driven model, based on data rather than ideas. Figure 3 shows an example of this, where interpreted faults, interpreted formation temperature model and conductive areas based on low resistivity are visualized. Geological static models have a higher data resolution as well as showing small scale features and therefore, they have a higher level of confidence than conceptual models. Minimizing data extrapolation avoids data to be over-estimated (Figure 4). Dynamic data (relative permeability, pressure, fluid properties etc.) are not included.
Figure 3 An example of a 3D geological static model. The model is data tied where quantitative data is presented; interpreted formation temperature, interpreted faults, and low resistivity anomaly (Mortensen et al., 2009).
A dynamic reservoir model simulates both the natural and production response of the geothermal system (Axelsson, 2013). It is based on the conceptual and the geological static model and has the fourth dimension included; time dependent data. These are used for forecasting and include e.g. production history data and pressure changes in the system. With the development of a geothermal field, new borehole and reservoir data will be acquired. Their results are brought back into the geological static model, and the risk assessments updated, for example see the model feedback loop in Figure 5.

3) A dynamic reservoir model simulates both the natural and production response of the geothermal system (Axelsson, 2013). It is based on the conceptual and the geological static model and has the fourth dimension included; time dependent data. These are used for forecasting and include e.g. production history data and pressure changes in the system. With the development of a geothermal field, new borehole and reservoir data will be acquired. Their results are brought back into the geological static model, and the risk assessments updated, for example see the model feedback loop in Figure 5.
Building a geological static model involves several stages (Figure 6):

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.

Figure 5 Probabilistic closed-loop 3D reservoir modelling workflow example from the Petroleum industry (Singh et al., 2013).
The construction of a 3D geological static model containing complex geological structures has many challenges. 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 evolving. Hence, there is no such thing as a final geological static field model and it should be updated continuously as new information becomes available, e.g. information on additionally drilled wells, new measurements or new technology implementations.

A well-organized workflow is crucial when constructing and revising a model. A workflow allows documentation of the work during the modelling process that can be repeated if parameters change.

Since it is not a dynamic reservoir model, the geological static model built for this project in Krafla does not describe changes in the physical conditions or energy transfers in the geothermal system. Rather, the model emphasises the existing and present state conditions, referred to as a set of static data, e.g. geological and geophysical database that build on the geological framework, and would serve as a basis for a dynamic reservoir model that includes time dependent parameters. The goal is to constrain the modelling parameters and develop a model with sufficient 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.

Figure 6 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.
2 The Krafla geological static model

This chapter outlines the geological background of the Krafla geothermal field as well as researches that have been done in order to understand the nature and behaviour of the geothermal field. Relatively long drilling history, and various researches that have been performed in the area, provide large amount of data and information, from regional scale to borehole scale. Some of these data will be presented here, but they have provided a base for the construction of a geological static field model of the geothermal field.

2.1 Background

The existence of Iceland is the result of the interaction between the Northeast Atlantic ridge system, marking the boundary of the Eurasian and North American plates, and its interaction with the Icelandic mantle plume since approximately 30 Ma (Hjartarson et al., 2017). The Mid Ocean Ridge plume interaction forms a series of purely divergent or oblique rift segments, also referred to as volcanic zones (Figure 7). The associated transform zones link the different volcanic zones together (Einarsson, 1991; 2001; 2008).

In general, the volcanic zones of Iceland are regions of active extension and volcanism. The greatest volcanic activities occur along the East, West and North Volcanic Zones (EVZ, WVZ, NVZ) (Thordarson and Hoskuldsson, 2008). The Krafla volcanic system is a part of the NVZ that extends from Öxarfjörður and Skjálfandi in the north, to Vatnajökull in the south. The spreading vector of the Northern Volcanic Zone is N105°E and the total spreading is 18.3 mm/yr (DeMets et al., 1994; Metzger and Jónsson, 2010). There are five volcanic systems in the NVZ; Þeistareykir, Krafla, Fremrinámur, Hrúthálsar and Askja (Jóhannesson and Sæmundsson, 1998). Oblique spreading affects Iceland, resulting in the forming of transform systems. Normal faults and fissures are formed where the segments are nearly purely divergent, but where the rift spreads obliquely, strike-slip tectonism and structures are formed. Fissures and normal faults are grouped into fissure swarms. They are activated in rifting events, when magma either leads to an eruption or solidifies as an intrusion (Einarsson, 2008). Two major transform fault systems exist in Iceland; The Tjörnes Fracture Zone (TFZ) and South Iceland Seismic Zone (SISZ) (Figure 7). The SISZ takes up the transform motion between the Reykjanes ridge and the Western Volcanic Zone to the Eastern Volcanic Zone (Einarsson, 1991).
The Tjörnes Fracture Zone was initiated 6 – 8.5 million years ago, when volcanic activity moved from the Húnaflói rift zone to the Northern Volcanic Zone (Figure 8) (Semundsson, 1978; Homberg et al., 2010; Hjartarson et al., 2017). The transform systems are characterized by series of strike-slip fault systems that are responsible for the largest earthquakes in the latest episodes, reaching a magnitude of 6-7 (Björnsson and Einarsson, 1981). Complex en-echelon fault arrays and push up structures are common in these areas.
The Tjörnes Fracture Zone connects the offshore Kolbeinsey Ridge to the Northern Volcanic Rift Zone (Einarsson, 1991; Stefánsson et al., 2008). The TFZ is composed of the Grímsey Oblique Rift, the Húsavík-Flatey Fault and the Dalvík Lineament, which are NW orientated seismic lineaments (Figure 9) (Einarsson, 1976; Sæmundsson, 1974). The Grímsey oblique rift is the northernmost seismic zone, NW-SE oriented (Einarsson, 1976). It extends from Kolbeinsey Ridge in the NW to Krafla Fissure Swarm in the SE. The Húsavík-Flatey Fault is about 40 km south of the Grímsey Zone, terminated the Þeistareykir fissure swarm in the SE (Sæmundsson, 1974; Guðmundsson et al., 1993; Mariotto et al., 2015). The southernmost zone is the Dalvík Zone, about 30 km south of the Húsavík-Flatey Zone (Einarsson, 1976; 1991).

Figure 8 The TFZ transform zone (yellow arrow) is a consequence of the rift jump from the Húnaflói rift zone (orange arrow) to the NVZ (Hjartarson et al., 2017).
Figure 9 The fissure swarms of the Northern Volcanic Zone. Large earthquakes, occurring on the TFZ are visualized as blue, green, yellow and red points (Hjartardóttir and Einarsson, 2017).
2.1.1 Structures on the Northern Volcanic Zone

A caldera and shallow magma chambers, underlain by the rift zone, dominate the structure of the Krafla central volcano. Accumulation of magma near the base of the system and the extension across the rift zone play a major role in the stress field in the area. Examples from the Main Ethiopian rift show that zones of partial melt develop as the lithosphere is thinned during extension (Rooney et al., 2010). Thus, the brittle layer is controlled by the stress field, where stress relaxation affects the crust and causes magma to rise, as was shown in the Krafla fires. Frequency and size of rift zone eruptions influences magma supply rate and stress changes in the system.

The regional scale structure is also important for the Krafla geothermal field. It’s location in the Northern Volcanic Zone, that meets up with the Tjörnes Fracture Zone in the north, affects the structure of the system. At the junction, faults are transformed from strike-slip faults into tension faults. The Tjörnes Fracture Zone is WNW-ESE trending oceanic transform zone with a dextral component (clockwise movement) (Guðmundsson, 2000). The Northern Volcanic Zone, therefore, undergoes deformation of both types of boundaries and the stress pattern is characterized by the interplay between the two (Figure 10). Tibaldi et al. (2016) studied transform-rift junction in the Northern Volcanic Zone by mapping the geometry and nature of faults and fractures in Guðfinnugjá, where Þeistareykir Fissure Swarm intersects the Húsvík Flatey Fault (HFF). Features showed clear evidence of HFF propagating towards the fissure swarm. They concluded that the geometry of the faults and fractures are either evidence of the first stage of HFF crossing TFS or an older segment of HFF lying below the Holocene lavas, not yet propagated upward (Tibaldi et al., 2016). Magnúsdóttir and Brandsdóttir (2011) also pointed out this relationship and concluded that the Þeistareykir Fissure Swarm triggered large earthquakes in the Húsvík Flatey Fault System.

Repeated GPS measurements have revealed that the extension is not uniform across the NVZ (Árnadóttir et al., 2009; Metzger and Jónsson, 2014; LMÍ, 2017), which strongly suggests an oblique rift system with the Krafla caldera in the middle of an anomalous extension area (Figure 11). Oblique systems occur where the angle between the rift axis and the extension direction is < 90°. In these areas, offsets between fault segments, causing local deformation, occur at all scales. Therefore, displacement is both parallel and perpendicular to the fracture surface and both normal faulting and wrench faulting can be identified (Twiss and Moores, 1992; McClay and White, 1995).

Hjartardóttir et al. (2014) conclude that fractures in the Krafla fissure swarm are mainly perpendicular to the spreading direction. Deviations from this pattern occur around caldera volcanoes, where fractures and fissures radiate from the calders. East-West oriented fractures and fissures were mapped near the Vatnajökull glacier, cutting across the NVZ. Other tectonic features that are not parallel to the rift axis are WNW oriented transform zones north of Iceland that connect with the NVZ.
Figure 10 Tectonic setting of NE-Iceland. Mapped structures (faults or fissures) show interaction between both types of boundaries (Tibaldi et al., 2016).

Figure 11 The most recent GPS results from the National Land Survey of Iceland. The gray shaded areas show individual fissure swarms with associated central volcanoes (red ellipses). GPS stations are shown with blue points and the arrows represent horizontal velocities in years 2004-2016 predicted from the ITRF2014 plate motion model (LMÍ, 2017).
When a structural element dies out and extension is taken up by another structural element, a *transform zone* forms. Where strike-slip faults are associated with other structures, the stress is often taken up by extension, oblique faulting and duplex tectonic (Twiss and Moores, 1992). *Wrench faulting* is a consequence of a strike-slip fault and appears as a set of faults around the main fault (Figure 12). Changes in local stress regime can cause secondary structures such as normal faults, folds, thrust faults and joints (Lacazette, 2017). In structural analyses done by Khodayar and Björnsson (2013) results show dip-slip fractures striking NNE, ENE, E-W, WNW and NW/NW. The northerly fractures are the most common ones but E-W fractures are the least frequent ones. The NNE and WNW components show both a sinistral and a dextral component (Khodayar and Björnsson, 2013). Blocks in wrench systems sometimes rotate along with the bounding faults in vertical plane where they often rotate towards parallelism with the rift border faults (McClay and White, 1995). This is called *block rotation* (Twiss and Moores, 1992). In Khodayar et al. (2015) the relationship between resistivity bodies and structural interpretation is discussed. The resistivity bodies show clockwise and anti-clockwise rotation at different depths and are controlled by WNW to NW dextral lineaments as well as NNE to NE sinistral tectonics (Khodayar et al., 2015).

Khodayar (2014) performed a detailed structural mapping of the Þeistareykir Fissure Swarm. Mapping showed normal faults concentrated in blocks that have moved in dextral motion along a WNW trending strike-slip fault. They are interpreted as northerly pull-apart structures (Khodayar, 2014). The interplay between the northerly striking lineaments and WNW deformation is similar to pull apart structures associated with strike-slips. At greater depth, the E-W lineament appears deepest – from 4000 m to the bottom of the model (Khodayar et al., 2015).

*Pull apart* structure is a zone of extension and stepovers bounded by strike-slip resulting in topographic depressions often filled with water or sediments (Figure 13) (Twiss and Moores, 1992). They have been observed in the NVZ, Höskuldsvatn and Botnsvatn are the best known examples (Garcia and Dhont, 2005). *Horsetail splays* are generally associated with strike-slip faults and curve away from the strike of the main fault (Figure 14). They are often located at the tip of the main strike-slip fault. The fan distributes the deformation through a large area (Twiss and Moores, 1992).
Figure 13 Development of a pull-apart structure (Garcia et al., 2003, modified from Twiss and Moores, 1992).

Figure 14 Structures that occur around strike-slip faults (Kim et al., 2004).
2.1.2 Geological setting of the Krafla geothermal field

Krafla is located in the Northern Volcanic Zone. It consists of an active central volcano and a NNE-SSW trending 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 rift (Figure 15). It is believed to have been formed during a postglacial period about 100,000 years ago in an eruption producing semi-acidic welded tuff (Halarauður). The caldera is not visible on the surface because it has been filled with volcanic material (Sæmundsson, 1978; 1991). An inferred inner caldera is considerably younger and probably formed after the area was covered with ice (Árnason et al., 2011).

Figure 15 A geological map of Krafla. Holocene lavas (< 11000 years) are visualised as pink, blue and purple colours. Hyaloclastite ridges are brown and rhyolitic formations are yellow. The first Holocene eruptive stage (11000 – 8000 years) erupted in the eastern part (red stars) while dark blue lavas (8000 – 3000 years) erupted in the western part (blue stars). Lavas younger than 3000 years (yellow stars) erupted in the eastern part (Sæmundsson, 2008a). Abbreviations are explained in Appendix D.
As borehole data give only a small glimpse into the deeper layers of the caldera complex, existence of the calderas is supported by the density variations of different formations, resulting in gravity anomalies (Árnason et al., 2011).

The volcanic sequences reflect the environment at the time of volcanic activity. However, volcanic activity has both taken place during glaciation and interglacial periods. The volcanic sequences consist mainly of hyaloclastite formations and basaltic lavas, but rhyolite is also present. Hyaloclastite and rhyolite ridges formed during glacial periods, but basaltic lavas during postglacial times. The rhyolite ridges are mainly found at or outside the margins of the caldera. Extrusive lavas are dominant down to 400-1000 m below sea level but intrusions dominate at greater depths (Weisenberger et al., 2015). They are believed to have been formed mainly by a pressure drop at the end of the last glaciation period. They are primarily basaltic, but felsic or intermediate intrusions occur at variable depths. Melting of hydrothermally altered basalt is suggested to be the source of most of the silicic intrusions (Zierenberg et al., 2013) and thus, it could be suggested that this process aided the heat flow to the surface.

During the Holocene, volcanic activity has mainly been in the form of fissure eruptions. Until about 8000 years ago, it was limited to the eastern part of the fissure swarm. After this period, the spreading shifted, for about 5000 years, to the western part of the outer caldera. Around 3000 years ago, the volcanic activity shifted back to the eastern part of the fissure swarm with a frequency of 300-1000 years. This resulted in extensive faulting and increasing permeability in the shallow crust (Sæmundsson, 1991). 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. In the Mývatn fires, the activity was mainly in the southern part of the caldera, while magma injection was mainly to the north during the Krafla rifting episode. The Krafla rifting episode was characterized by long periods of inflation and short deflation periods, where magma erupted to the surface or was intruded into the fissure swarm. These periods caused stress changes in the magma chamber. Intense seismicity above the magma chamber was followed by inflation periods. Tectonic features in the area have been divided into three groups; NE-SW trending fissures and faults oblique to the plate movements, WNW-ESE fractures and faults due to shearing stress, and irregularly trending fractures and faults associated with the caldera (Sæmundsson, 1974; Björnsson, 1985; Ármannsson et al., 1987).
2.1.3 Krafla geothermal power plant

The Krafla 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). A total of 47 wells have now been drilled and currently the plant produces 62 MWe from 20 production wells using double flash system (Figure 16) (Weisenberger et al., 2015; Hauksson, 2017).

A geothermal exploration program in Krafla was initiated in 1970 and the construction of the power plant started in 1975. In the following years, exploratory wells were drilled in the area, drill cuttings analysed (lithology and alteration) and downhole logging carried out. The main geological formations were recorded as well as the location of feed zones in the wells to map permeable zones. Chemical analyses were made on steam and water to monitor the effect of magmatic gases on the chemistry of the reservoir fluids (Ármannsson and Hauksson, 1980). The geothermal field has been grouped into seven sub-areas based on geochemistry and geography. These are: Upper Leirbotnar, Lower Leirbotnar, Leirhnjúkur, Víтismór, Suðurhlíðar, Vesturhlíðar, Hvíthólar and Sandabotnar (Ármannsson et al., 1987; Mortensen et al., 2009; Ármannsson et al., 2015). Currently, production is from four sub-areas; Leirbotnar and Víтismór, Vesturhlíðar, Suðurhlíðar and Hvíthólar. Vestursvæði and Sandabotnaskarð sub-areas are both comprised of one well each, but they are not used for energy production.

Explorations soon revealed that the geothermal area in Leirbotnar consists of two distinct zones, an upper and a lower zone. The upper zone is water dominated whereas the lower zone is a two-phase system which feeds the upper zone (Ármannsson et al., 1987). Víтismór sub-area is also divided into upper and lower zones, with higher enthalpy and temperatures in the deeper zone. Permeability in Víтismór and Leirbotnar is mainly related to felsic intrusions and NNE-SSW faults and fissures. Suðurhlíðar sub-area is comprised of high enthalpy wells. High permeability in Suðurhlíðar has been explained by large amount of felsic intrusions and ESE-WNW faults. High Cl and F concentrations in some of the Suðurhlíðar wells have been explained by the presence of magma. Hveragil fault marks the boundary between Leirbotnar, Suðurhlíðar and Víтismór sub-areas.

High enthalpy is observed in the Vesturhlíðar wells and chemical analyses have revealed some mixing of fluid with condensed steam. Wells with a rather low enthalpy are present in the Hvíthólar sub-area. A reverse temperature is observed in the wells below 400-500 m depth but the access of cold fluids through active faults and fissures seems to affect both Vestursvæði and Hvíthólar sub-areas. The temperature increase in the Hvíthólar wells could be explained by remnants of hot fluid that rises from greater depth between Hvíthólar and Sandabotnaskarð sub-areas (Mortensen et al., 2009; Weisenberger et al., 2015).
Surface geological mapping

Extensive geological mapping has been carried out in the Krafla area. The first geological investigation resulted in the location of the Krafla caldera rim, main faults, fractures and the history of volcanic activity (Stefánsson, 1981). Geothermal manifestations were also mapped. CO$_2$/H$_2$ analyses indicated that the hottest fluid, 245-285°C is below the Hveragil gully (Stefánsson, 1981). Recent volcanism (during the last 3000 years) was mapped in the eighties by age determination using tephrachronological methods (Sæmundsson, 1984). Kristján Sæmundsson has studied the geological history of Krafla by mapping surface formations. He described the geometry of the lava from the last 200000 years and supports his interpretation using relative and absolute dating. Remnants from two interglacial periods and two glacial periods are found in surface outcrops. Their formation is explained in the context of climate periods and the caldera formation ~100000 years ago (Table 1) (Sæmundsson, 1991).

Figure 16 Historical overview of the exploitation of the Krafla geothermal field, representing drilled wells, published models, major events and energy production. Modified from Weisenberger et al., 2015. Previous field studies
The most recent geological map of the geothermal field was published by Sæmundsson in 2008 showing surface rock types, age and name of postglacial lavas, and tectonic and volcanic surface features. A geothermal map was also published, showing surface temperature, state of surface alteration, fumaroles, hot springs and steam emanations related to the Krafla fires (Sæmundsson, 2008a; 2008b). These maps are an important base for the geological static model of Krafla. Hjartardóttir et al. (2012) mapped in details the Krafla Fissure Swarm by using aerial photos. The pattern was compared to fractures that were active during the Mývatn fires and Krafla fires. They studied the relationship between the Krafla Fissure Swarm and the caldera as well as the impact of the Húsvík Transform Zone on the Krafla Fissure Swarm. By studying fracture density and geometry of faults and fissures they concluded that the influence was considerable. They noticed a widening of the Krafla Fissure Swarm at their intersection. Earthquakes during the Krafla rifting events (1975-1984) propagated away from the Krafla Fissure Swarm, towards the Húsvík Faults, which suggests a subsurface continuation of the Húsvík Transform Fault. The uncertainty in the location of earthquakes used in this study is about 1 km in lateral plane, it is somewhat higher for the absolute locations. Therefore, the offset observed between earthquakes and the fissure swarm could be caused by uncertainties in the earthquake location (Hjartardóttir et al., 2012).
Table 1 The geological history of the Krafla area. Pink shaded areas represent interglacial periods and blue shaded areas glacial periods. Based on Sæmundsson, 1991.

<table>
<thead>
<tr>
<th>Years (ka)</th>
<th>Relative Temp.</th>
<th>Product</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>Lava shields, acidic and basaltic tephra, scoria cones</td>
<td>Viti, Hverfell, Grænsfjörm, Hveragil, Krókkottu vötn, Graddabunga</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Tuff cones/scoria, lava shields, Andecite lavas, explosive craters, hyaloclastite ridges, hyaloclastite ridges, glacial sediments, moraines</td>
<td>Sandfell and Ellifur</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>Rhyolite</td>
<td>Rhyolite: Hrafninnuhrenggur</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>Hyaloclastite ridges</td>
<td>Sandabotnar and Halaskógafjall</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>Lava, Hyaloclastite</td>
<td>Lava: Hrafnabjorg, North of Hlíðarfjall, Hyaloclastite: Sandabotnafell</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>Hyaloclastite</td>
<td>Hrótafell</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td>Pillow lavas, Rhyolite mountains, Pillow lavas north of Gasafjöll, Rhyolite: Rani and Hlíðarfjall</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>Rhyolite</td>
<td>Jörundur</td>
</tr>
<tr>
<td>80</td>
<td></td>
<td>Breccia, pillow lavas, lavas and tuff</td>
<td>Krafla</td>
</tr>
<tr>
<td>90</td>
<td></td>
<td>Hyaloclastite</td>
<td>Viti, Inner caldera</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>Glacial sediment, porphyritic lavas</td>
<td>Langagröf, Litla Krafla</td>
</tr>
<tr>
<td>110</td>
<td></td>
<td>Hyaloclastite</td>
<td>Hyaloclastite: Grjóthals, Halarauður: caldera collapse, Lava: Vatnshlið, Múli and Syðri Bjarghóll</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td>Lava, semi acidic welded tuff (Halarauður), hyaloclastite ridges</td>
<td>Vatnshlið, Múli and Southern Bjarghóll</td>
</tr>
<tr>
<td>130</td>
<td></td>
<td>Rhyolite</td>
<td>Hágong</td>
</tr>
<tr>
<td>140</td>
<td></td>
<td>Rhyolite on top of Hágongur</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
<td>Hyaloclastite formations</td>
<td>Eirí Hágongur, Reykjahlíðarheiði</td>
</tr>
<tr>
<td>160</td>
<td></td>
<td>Hyaloclastite and lavas</td>
<td>Hyaloclastite (Ellifsvötn) and lavas (Ellifsvötn, Reykjahlíðarheiði, Grímstafáheiði)</td>
</tr>
</tbody>
</table>
Borehole data and subsurface interpolations

2D stratigraphic and alteration profiles have been interpreted several times through the drilling history of Krafla (Stefánsson, 1977; Ármannsson et al., 1987; Mortensen et al., 2009; Weisenberger et al., 2015).

Stratigraphy

As mentioned earlier, the stratigraphy in Krafla mainly consists of hyaloclastites and lava piles down to 400-1000 m b.s.l. Basaltic intrusions become dominant below. In pre-existing stratigraphic models of Krafla, the pile has been grouped into three zones of basaltic lavas and two zones of mixed hyaloclastites (tuff, breccia and pillow basalt). There is a divide concerning intrusion depth across the Hveragil fault, but felsic intrusions are not as prominent west of Hveragil as they are to the east. Shallow occurrence (~400 m) of dominant intrusions in Leirbotnar and Vítismór has been explained by their location close to recently active fissures. Lithological analyses have revealed a 200-300 m thick pile of felsic intrusions beneath Suðurhlíðar. Gabbroic intrusions are also found in that area at 1300-1900 m b.s.l (Mortensen et al., 2009; Weisenberger et al., 2015).

Alteration minerals

The type of alteration minerals formed depends on the temperature at which they become stable (Figure 17). In high temperature geothermal systems in Iceland, alteration ranges from zeolite facies to greenschist facies (Friðleifsson, 1991). Smectite and zeolites are low temperature alteration minerals formed at 100-200°C. Towards the inner part, with increasing temperature, zeolites disappear, at temperatures between 200°C and 230°C mixed layer clays (MLC) prevail and are at last transformed into chlorite at 220-240°C. At higher temperature, at around 230-250°C, epidote becomes abundant and at 280°C actinolite becomes stable (Figure 17) (Kristmannsdóttir, 1979). By recording the depth of the first appearance and extent of the minerals, former thermal condition of the system can be determined. In most cases alteration minerals are stable even though temperature in the system drops. Therefore, they record the minimum temperature the system has experienced in the past. Formation temperature (estimated temperature in the reservoir) is, therefore, important to compare to the alteration to investigate the thermal evolution of the reservoir. Parameters affecting the alteration are temperature, pressure, lithology and subsurface structure of the rocks (Flóvenz et al., 2012). The dominant alteration pattern observed in Krafla has been presented in previous conceptual models. The most prominent change in alteration is seen across the Hveragil fault. East of the fault, beneath Suðurhlíðar, high temperature alteration is found at a shallow depth. These fast changes in alteration with depth, suggest that formation temperature is close to boiling point in the Suðurhlíðar wells. However, well K-18 in Suðurhlíðar shows a less abrupt increase in alteration as the rest of the Suðurhlíðar wells. Calcite overprinting epidote is observed in the upper system in Leirbotnar and Vítismór indicating a cooling of the system after the epidote formation (Mortensen et al., 2009).

Chemical data

Chemical analyses provide information about the subdivision of the reservoir in Krafla, locations of in-flow and up-flow, origin and formation of superheated steam, thermal situation of the system, phase segregation and the existence of magmatic fluids. The origin
of recharge of the fluid was studied by Darling and Ármannsson (1989). They suggested that more than one source was present; the fluid in the sub areas to the north was derived from local precipitation and a deep inflow of possibly old fluids from far south (Darling and Ármannsson, 1989).

Throughout the drilling history in Krafla, geophysical well logs have been gathered and used for lithological correlation between wells. These data are presented in section 2.3.2.

**Geophysical and potential field data**

**Resistivity**

Resistivity models are of great value in geothermal exploration. In high temperature areas, resistivity is mainly controlled by the presence of alteration minerals – which is an indicator of former fluid paths and temperature. All high-temperature systems in Iceland show similar resistivity structure. A low resistivity cap (caused by low temperature alteration minerals) marks the outer margins of the reservoir while resistivity increases with depth and towards the interior of the reservoir (Árnason and Flóvenz, 1992).

![Resistivity models are of great value in geothermal exploration.](image)

**Figure 17** To the left: Resistivity, temperature and alteration of the basaltic crust in Iceland (Flóvenz et al., 2012). To the right: Max and min alteration temperature for different minerals (Guðmundsson, 2005).

Resistivity measurements have been conducted in Krafla using several methods. Their characteristics is presented in Table 2. From 1970 to 1984, some 120 measurements were performed, using the Schlumberger and dipole-dipole method (Karlsdóttir et al., 1978; Árnason and Karlsdóttir, 1996). Their interpretation gave a fairly detailed picture of the resistivity structure in the uppermost 1 km of the subsurface. The model showed a low resistivity anomaly inside the caldera (Karlsdóttir et al., 1978). In the eighties resistivity measurements were conducted using TEM (Transient Electro-Magnetics) (Tulinius, 1980). TEM and MT (Magnetotellurics) are the most common methods used today for resistivity prospecting in high temperature geothermal 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, several km (Hersir and Flóvenz, 2013). In 2000,
about 150 TEM measurements were made in the Krafla area. An MT resistivity program was initiated in the area in 2005. MT soundings were carried out at the same location as the TEM measurements and the two datasets were jointly inverted. Inverting TEM and MT data jointly results in a more correct resistivity model due to the inherited static shift of the MT data (Árnason et al., 2011).

TEM and MT measurements acquired during 2004-2006 in Krafla have been 1D and 3D inverted (Árnason et al., 2011; Rosenkjaer et al., 2015). The MT data reveal a conductor in the uppermost few hundred meters, and a deep lying conductor at a depth of 8-12 km. Using 1D inversion, the resistivity distribution is only allowed to vary with depth. In 3D inversion, the resistivity changes in all three directions. The 3D inversion requires good areal sounding coverage (Flóvenz et al., 2012). A comparison between 1D and 3D resistivity is discussed in section 2.4.2. The 3D inversion data show an ESE-WNW lying high resistivity structure bordered by low resistivity on each side down to ~ 4 km depth. This is probably related to a dike complex where high resistivity is thought to reflect fully crystallised rocks, while the low resistivity could reflect partially molten rocks (Weisenberger et al., 2015).

Table 2 An overview of subsurface resistivity methods. They are either passive (using natural signals) or active (source is controlled).

<table>
<thead>
<tr>
<th>METHOD</th>
<th>EXPLORATION DEPTH (KM)</th>
<th>PROCEDURE</th>
<th>ACTIVE/PASSIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC (DIRECT CURRENT) SCLUMBERGER</td>
<td>0.5 – 1</td>
<td>Current is injected into the ground through two electrodes, which produces an electrical field. The potential difference between two other electrodes is measured.</td>
<td>Active</td>
</tr>
<tr>
<td>MT (MAGNETOTELLURICS)</td>
<td>1 – 10</td>
<td>Alternating current is induced in the ground by natural oscillations of the Earth’s electromagnetic field. The electrical field is measured on the surface through electrical dipoles (x, y) and the magnetic field is measured using coils in three directions (x, y, z).</td>
<td>Passive</td>
</tr>
<tr>
<td>TEM (TRANSIENT ELECTRO-MAGNETICS)</td>
<td>0.5 – 1</td>
<td>A current is injected into a loop on the surface which creates a magnetic field. The current is turned abruptly off and creates a secondary magnetic field, which decays with time depending on the resistivity structure. The monitored signal is the decaying magnetic field at the surface caused by induced currents at depth.</td>
<td>Active</td>
</tr>
</tbody>
</table>
Seismicity

Seismic studies give information about the structural pattern of the subsurface and indications of the stress field in the area. Páll Einarsson studied the S-wave attenuation in the Krafla area to delineate a magma chamber. He located the chamber at a depth of 3-7 km and inferred it to have an irregular form (Einarsson, 1978). Einarsson and Brandsdóttir (1980) interpreted seismic events during one of the deflation periods in the Krafla fires. They concluded that areas of maximum earthquake activity and areas of maximum surface faulting usually coincided. They also studied the stress field of the area and suggested the regional stress to be stronger than the local stress (Brandsdóttir and Einarsson, 1979). Both refraction and reflection surveys have been conducted in Krafla. The earthquakes are monitored via a monitoring network on the surface and the arrival times determined from its waveform dataset.

Brandsdóttir and Menke (2008) generated a travel time diagram of seismic waves that gave some evidences about the average crustal structure. A 250 km long seismic refraction profile was acquired in NW-Iceland. Compressional velocity in the range of 2.69-6.71 km/s was found for the uppermost 17.8 km (Brandsdóttir and Menke, 2008). The profile is called FIRE (Faroes-Iceland Ridge Experiment) and is shown on Figure 18. Brandsdóttir et al. (1997) created 2D velocity models across the Krafla central volcano, interpreting a 40 km wide high velocity dome beneath the Krafla volcanic system that reaches up to a depth of 11-14 km. This high velocity structure becomes narrower towards the surface, possibly reaching the magma chamber, where P-wave velocity delays and S-wave shadows are seen (Brandsdóttir et al., 1997). P-waves are strongly attenuated in two areas in the 1D velocity model. They are at 1300 and 1700 m depth and are caused by two thin, flat low lying velocity layers (Figure 18). They do not exhibit strong S-wave attenuation. Therefore, they cannot be explained by layers of magma. Based on comparison to borehole data from Ármannsson et al. (1987), the layers are thought to be associated with high porosity, steam and water charged geothermal aquifers. Brandsdóttir et al. (1997) estimated the thickness of the magma chamber by the observed P-wave velocity delay. Its thickness is varying between 0.75 km and 1.8 km, assuming a velocity through the magma about 3 km/s and a background velocity of 5-6 km/s. Based on these interpretations, a volume range of 12 – 54 km³ is estimated by assuming a tabular shape (Brandsdóttir et al., 1997).

Another refraction survey was conducted through Krafla on a smaller scale by National Energy Authority, Geothermal division, in 1961-1963 and 1971-1973. Seismic waves were generated in five lakes in the area; Víti, Höskuldsvatn, Mývatn, Sandvatn and Eilífsvötn resulting in 13 refraction profiles. Only a preliminary interpretation of the data is available (Figure 19) (Ágústsson, 2011).

As a part of the IMAGE project, a vertical seismic profile (VSP) experiment was performed in Krafla. This was the first time this method was applied as an exploration technique in a high temperature area in Iceland. The survey was carried out in two boreholes, K-18 and K-26 in the summer of 2014. The project aimed at testing if zones of magma, supercritical fluid, superheated steam and high permeability could be detected in the geothermal field. Seismic waves were generated using an active source; air gun for the zero-offset seismic signal excitation and dynamite explosives for the far-offset shots. Receivers were placed inside the two selected VSP boreholes. Several different experiments were tested depending on the distance of the seismic source from the two wellheads. A “zero offset” (source as
close as possible to the wellhead) is the simplest and most common experiment. For K-18 and K-26, water pits were located 29 and 35m, respectively, away from the wellheads for the zero-offset experiment (Kästner, 2015; Planke et al., 2016). Processing of data resulted in reflection profiles down the wells giving inference to density contrasts below surface. Processing from both air gun and dynamite sources resulted in good quality VSP data (Planke et al., 2016). A good correlation was seen between zero-offset VSP data and borehole data. Comparatively high reflections were detected in basalt and intrusive sequences, whereas hyaloclastite and dolerite intervals were characterized by lower reflections. No major fluid zones or steam caps were observed for the zero offset experiment (Planke et al., 2016; Kästner, 2015). Interpretation of the data from the far-offset shots have not been accomplished yet.

A passive seismic monitor network has been developed for the Krafla area and maintained by the Science Institute of the University of Iceland, ISOR, Landsvirkjun and Meteorological Office (IMO). The network was initiated by the Science Institute in 1974. IMO took over as the SIL (South Iceland Lowland) network developed in the nineties (Einarsson and Björnsson, 1987). Currently the network consists of 23 stations, including Námafjall and Þeistareykir as well as six SIL stations (Blanck et al., 2017).

![Figure 18](image_url)  
*Figure 18* The W-E striking FIRE refraction profile, extending from Eyjafjörður (EY) in the W, towards Reyðarfjörður (REY) in the E, crossing the Krafla volcanic system. The magma chamber shows low P-wave velocity right within a higher P-wave velocity which is due to intrusions or rising of the mantle. Adapted from Brandsdóttir et al. (1997).
Location of earthquakes has been used to delineate the brittle-ductile boundary below Krafla. Basalts in the oceanic crust start to become ductile at 700–800°C (Violay et al., 2012). Results from Blanck et al. (2017) show that the main seismic activity occurs in six clusters above 2.3 km. Most earthquakes occur between a depth of 2.5 to 4 km and vertical distribution of events indicates location of brittle-ductile boundary at about 2.3 km depth.

Schuler et al. (2015) performed a 3D tomographic inversion of the Krafla central volcano. Models of $V_p$ and $V_p/V_s$ ratio were presented and compared to other interpretations. Low $V_p$ anomalies coincide well with the S-wave shadows from Einarsson (1978). Other $V_p$ lows do match with low density postglacial eruptive products and high $V_p$ bodies were believed to indicate high-density intrusions. The $V_p/V_s$ ratio model is useful for lithological and rheological interpretations because the ratio reflects petrophysical properties of the rock. High and low $V_p/V_s$ ratios reflect higher or lower porosity and low $V_p/V_s$ are close to the rhyolite intrusion below IDDP-1 (Figure 20) (Schuler et al., 2015).

![Figure 19 Velocity profiles from Krafla. The blue, green and red coloured profile are the interpretation from National Energy Authority and the black dotted is from Brandsdóttir et al. (1997). Taken from Ágústsson et al., 2011.](image_url)
Gravity

Gravity anomalies are caused by lateral density variations i.e. basement depth variations, rim of caldera, intrusive rock, alteration, porosity variations, faults or dikes. Gravity results have been used to map the Krafla caldera and interpret its evolution (Johnsen, 1995; Árnason et al., 2011). Bouguer and Free air gravity maps have been presented and reviewed several times in the drilling history of Krafla. In 1967-1984 an extensive gravity survey was carried out (Johnsen, 1995). The most recent Bouguer and Free air maps were published by Magnússon (2016). The maps show gravity in the Krafla and Þeistareykir areas. A striking Bouguer gravity high coincides fairly well with the caldera rims and is most likely related to intrusions that are denser than the surroundings (Árnason et al., 2011). In the Bouguer map (Figure 21), the most striking features are a NNE-SSW and ESE-WNW trending gravity lows. The NNE-SSW low is along the fissure swarm but the latter one has been interpreted as a transform graben filled with less dense rocks (Árnason et al., 2011).

Figure 20 A $V_p/V_s$ ratio model of Krafla intersecting the two wells that have been drilled into magma, IDDP-1 and K-39. The black points are hypocenter clusters, used to calculate in situ $V_p/V_s$. (Schuler et al., 2015).
Aero magnetic anomaly data

The magnetic anomaly pattern of Iceland shows broad negative anomalies over all high temperature geothermal areas, where data coverage exists (Serson et al., 1968). Negative magnetic anomalies can indicate demagnetisation of magnetic minerals caused by high temperatures and can also reflect structural changes (intrusions, younger lavas etc.). The Science Institute of the University of Iceland performed an aeromagnetic survey in 1970 across the broader Krafla region using magnetometer developed by Þorbjörn Sigurgeirsson (Einarsson and Björnsson, 1987). The map was published in 1971, revised in 1978 and has not been updated since. It shows ESE-WNW and NNE-SSW trending magnetic lows running through the production area and a significant magnetic low at Suðurhlíðar and Leirbotnar (Figure 22). This anomaly coincides with geothermal manifestations on the surface and is most likely caused by high temperature at some point and high degree of alteration (Guðmundsson et al., 1971; Karlsdóttir et al., 1978).

Figure 21 Bouguer gravity map of Krafla caldera and its surroundings. Inner and outer caldera rims are visualized and black triangles mark measurement sites. The main production area is located north of the WNW-ESE gravity low (Magnússon, 2016).
Several comprehensive conceptual models of the Krafla geothermal area have been made. The first one was presented in 1977 and was mainly based on surface exploration data and data from the first 11 wells (Stefánsson, 1977). Maps showing gravity data and the results from 1D interpretation of resistivity data were presented and lithology and flow paths as cross sections. A simplified tectonic map was presented where emphasis was put on the connection between surface geothermal activity and tectonic features. Maximum temperature was estimated using CO$_2$/H$_2$ ratio and the amount of H$_2$ in fumarole steam (Stefánsson, 1977; 1981). A report on modelling studies was presented by Guðmundur S. Böðvarsson and Karsten Pruess in the eighties (Böðvarsson and Pruess, 1982). It describes numerical modelling studies and showed a good match with field data. At that time, more detailed exploration work had been carried out regarding physical properties of the rock (permeability, transmissivity, etc.). The effect of injection was estimated, the capacity of the area was modelled and predictions made regarding power generation. The model also revealed a clearer picture on the subsurface around the Hveragil fault zone. In many respects, that model is still valid today (Weisenberger et al., 2015).
In the late eighties a simplified 2D simulation model of Hvíthólar sub-area was developed using the SHAFT-79 program. This was only based on three wells; K-21, K-22 and K-23. Distribution of temperature and pressure was simulated and the amount of up-flow and temperature was estimated 10 kg/s and ~ 300°C hot fluid. Volume calculations were done and the area estimated to last for less than 10 years (Tulinius and Sigurðsson, 1988). For a more precise modelling it was decided to add the third dimension to the model in 1991 using TOUGH. TOUGH created an opportunity to estimate the volume of the reservoir more accurately as well as the capacity and reaction of the reservoir. More precise values for out-flow and temperature were presented and the area estimated to last for at least 10-20 more years (Tulinius and Sigurðsson, 1991).

In 1996-1997, a conceptual model was presented focusing on synchronization between the conceptual and numerical model. Böðvarsson’s and Pruess conceptual model from 1982 was revised, with the emphasis on defining fluid paths of hot and cold fluids. This was mainly based on known permeable structures, barriers and surface manifestations, and temperature and pressure measurements. The main conclusions drawn from the updated conceptual model were that the Hveragil fault zone reached further to the south than in the previous model (Björnsson et al., 1997). Following the revision, a detailed 3D simulation model was constructed in TOUGH as well. Predictions were made assuming additional production in the Suðurhlíðar sub-area (Tulinius and Sigurðsson, 1991; Björnsson et al., 1997). This led to a proposed expansion of the Krafla power plant, requiring 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 emphasis was put on certain sub-areas 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 (IDDP-1 and K-40). Some re-analyses were made on alteration and re-interpretation of 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, a software for 3D mapping, modelling, and visualization.
2.2 Input data and methods

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 this project 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 (Planke et al., 2016). 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. All these datasets are used as a basis for the presently updated geological static model.

2.2.1 Petrel software

The 3D reservoir modelling software used for this study is Petrel, a Windows based software for 3D mapping, modelling and visualization (Schlumberger, 2014). Petrel is developed by Schlumberger for reservoir modelling in the Petroleum industry, but is also used broadly in the geothermal industry in Europe. The software is suitable for all reservoir modelling and its functions can also be applied in geothermal interpretations, such as seismic reflection data interpretation, geological, structural, petrophysical, and reservoir modelling. It helps to give an insight into complex reservoirs and a better understanding of the modelled system. The software provides different tools and modules for solving structural and stratigraphic features. Input data have to be prepared for suitable import formats. The software allows manual digitisation and data manipulations in 2D and 3D working environments. Therefore,
it is easy to update models dynamically, when new information becomes available. Petrel has been used for 3D modelling work by ÍSOR since 2008.

2.2.2 Input data

The subdivision of geophysical and borehole data is described in the following section, and the sources and constraints on the different datasets are also discussed.

Surface geology

Surface geological mapping in Krafla is mainly based on field observations and aerial photography. Sæmundsson (2008a, 2008b) mapped the geological and geothermal features which have been imported into the Petrel database. The surface geological map displays different rock formations, ages and names of sub- and postglacial extrusive and intrusive deposits, surface tectonic features and topography. The geothermal maps show geothermal manifestations and surface alteration features. These datasets provide key data and constraints on structure, lithology, alteration and surface manifestations. Location and geometry of tectonic features, such as faults, fractures and fissures, and variations in lithology are important because of their variance in petro-physical and transmissivity properties that control the geothermal upflow and the reservoir extent.

Surface geophysical data

Surface geophysical data include measurements made on the surface, reflecting the subsurface structure. The geophysical techniques detect changes in physical properties that might bring constraints on the thermal structure.

Location of seismic events

Micro-earthquake data of the Krafla area, spanning the period from October 2013 to November 2016, were located and analysed by Blanck et al. (2014, 2016, and 2017). Their locations have been imported into the model. These locations are based on a seismic network run by ÍSOR, Landsvirkjun and the Icelandic Meteorological Office (IMO). A total of 23 stations are included in the network, most dense at the centre of the caldera. The distribution of earthquakes shows the effects of injection and production boreholes, and is also used to estimate the location of the brittle/ductile boundary, tectonic features, seasonal variations and possible heat sources.

Focal mechanism

Focal mechanism describes the nature of a single earthquake. They were analysed for eight selected earthquakes in Krafla (Blanck et al., 2016). The eight events were chosen based on their location, from different clusters and different sub-areas inside the Krafla geothermal field. The resulting dataset, including locations, dip azimuth and slip directions, was imported into Petrel. The events were around and within the main production area spanning a depth from 1,460 m down to 2,690 m. The focal mechanism shows different results as no
obvious trend is seen in the data. The events show both normal faulting with different strike directions, as well as oblique, and strike-slip faulting mechanism (Figure 23). It is worth noting that the events are located at shallow depths, inside the caldera and above the magma chamber. These factors, as well as geothermal activity can affect the results. Therefore, no consistent regional trend can be identified from these data (Blanck et al., 2016) rather they point towards the complex fault system of the area.

Seismic tomography
Seismic tomography was performed using 1,453 earthquakes from Deistareykir and Krafla volcanic systems spanning the period from 2009 to 2012 (Schuler et al., 2015). Arrival times of P- and S-waves were used to construct a tomographic model. The model indicates slower or faster seismic velocity regions in the system. $V_p$ and $V_p/V_s$ ratio models were obtained using 3D tomographic inversion. Active and passive seismic data from Brandsdóttir et al. (1997) were used for inversion at greater depth. The tomographic inversion including P-wave velocity and $V_p/V_s$ ratio from Schuler et al. (2015) is imported to the Petrel model.
Resistivity

Two resistivity models have been imported to the Petrel model, both the 1D and 3D inversion. The 3D inversion presented here is based on 163 static shift corrected MT sounding data (TEM data used for the shift correction), acquired by ISOR, Duke University and Moscow State University in the summers of 2004–2006 (Árnason et al., 2011). The location of the MT and TEM stations is shown in Figure 24. The data were interpreted using different inversion codes published in Gasperikova et al. (2015) and Rosenkjaer et al. (2015). WSINV3DMT, a 3-D inversion program for MT data was used for the resistivity modelling presented here (Gasperikova et al., 2015). The inversion was obtained from an initial model assuming homogeneous earth of 20 Ωm. The code does not allow to include the topography. Static shift affects MT results and is caused by near surface resistivity in homogeneities and topography (Árnason, 2015). TEM data are used for these corrections.

Figure 24 Resistivity at 1000 m depth. Red triangles are MT stations and black triangles TEM stations. Sub-areas are as follows: Hvannstöð (Hva), Leirhnjúkur (Lh), Vesturhlíðar (Vh), Þítismór (Vm), Leirbotnar (Lb), Suðurhlíðar (Su), Vestursvæði (Ve), Hvíthólar (Hv), Sandabotnar (Sa). Thick black lines mark outer and inner calderas.
Aero-magnetic

The aero-magnetic map of Krafla has been imported to Petrel. Digital data behind the map were not available. For that reason, the map was imported as a jpg-file. The original map covers the area of Krafla, Námafjall and surroundings (180 km²). Only data from the area around Krafla was imported to Petrel, consistent with other datasets. The magnetic field is represented in nTesla (Karlsdóttir et al., 1978).

Gravity

Gravity data are visualized by Bouguer and Free air gravity maps. The gravity data have not been interpreted as spatial density variations. The Free air and Bouguer gravity datasets are based on measurements from 1975-2015, using a background density of 2,510 kg/m³ for Bouguer and terrain correction (Magnússon, 2016). In total 977 measurement points were used in the maps, their distribution is largely based on accessibility in the field. A topographic correction was calculated using a topographic model with a pixel size of 25 m.

Borehole data

Lithology and alteration profiles were established for the wells based on the analyses of cuttings collected at 2 m interval during drilling. Data were achieved from reports for each well. Depth correction of well logs and lithology had only been performed in some of the wells, but that is not believed to affect the lithological model.

Lithology

Most of the cutting analyses had already been imported into the Petrel database. However, no computerized data were available for the stratigraphy of 16 wells (Mortensen, 2009; Weisenberger et al., 2015). These logs were prepared in digital form and added to the model. Each lithological description has its own code, based on characteristics such as grain size, fabric and colour (Appendix D). It is important to note that the quality of the description and analyses of cuttings differs throughout the drilling history of Krafla. An example of that is what was initially interpreted simply as an intrusion, would be interpreted as a coarse grained basalt intrusion later on. Intrusions are formed at different times and cross-cut the volcanic strata. Their formation is not planar. Therefore, it was decided to exclude the interpretation of intrusions from the main lithology logs during the well correlation, but separate and visualize them as an independent column. Correlations in between the lithology logs were done with the aid of geophysical logs if available. This method has also been used consistently in geothermal investigations in order to confirm or identify different rock formations (Steingrímsson, 2011). Besides the VSP experiment resulting log data, additional wireline borehole well log data of different physical properties vs. depth were included from ÍSORs database, such as resistivity (RES), neutron-neutron (NN), gamma ray (GR), Caliper (CAL), temperature (T), pressure (P), and borehole Televiewer (BHTV) data.
Resistivity logs (RES16 and RES 64) indicate alteration state and compactness of the rock. A constant electric current is injected and the response of normal electrodes is detected. The normal electrodes, short (RES16") and long (RES64") are fixed on the logging probe. The length represents the spacing of the two potential electrodes from the electrode situated near the bottom of the probe. The response detected, varies with rock type and fluid content of the lithological unit, whereas the current tends to flow more easily through fluid fillings, pore space and altered rock. Temperature and water salinity can also affect the resistivity (Flóvenz et al., 2012).

Neutron-neutron log (NN) is sensitive to the density of hydrogen nucleus near the logging tool and reflects the rock matrix porosity. A neutron source is placed at the bottom of the probe and emits high energy neutrons. Detectors on the probe record counts per second (cps) down the well, which is later converted to API_NU (American Petroleum Institute standard neutron log units). Water absorbs the neutrons which means that if the presence of neutrons detected by the logging tool is low, the rock is most likely highly permeable or porous (Steingrímsson, 2013a).

Gamma logs (GR) are indicative of the radioactivity of the rock, here specifically the natural occurrence of radiation from potassium GR can be used as a lithology type differentiator, as the concentration of radioactive isotopes is approximately ten times greater in felsic rock than in basaltic rock (Hearst et al., 2000). Felsic formations are relatively rare in Icelandic crust and observed felsic layers on gamma ray data stand out. Gamma logs are often run together with neutron – neutron logs and are standardised as API-GU (American Petroleum Institute standard gamma ray log units) (Steingrímsson, 2013a).

Caliper logs record variations in the borehole’s diameter. Therefore, they give an inference about the formation strength. Two sets of Caliper log tool arms (X and Y) are pressed against the borehole wall to measure the width in 2 dimensions within the borehole. The motion is recorded in inches as a function of depth (Steingrímsson, 2011). A wide borehole indicates softer and washed-out, or more broken depth intervals whereas narrow borehole indicate rather stable and hard formations.

Temperature and pressure logs are fundamental in geothermal investigation. Temperature logs provide data about reservoir temperature, location of feed zones, temperature gradient and heat flow. Pressure is determined by pressure logs and is dependent on fluid circulation, injection and production during drilling. These logs are run during and after drilling with the aid of estimating formation temperature and reservoir pressure. Having pressure and temperature logging data from several wells, maps showing distribution of formation temperature and pressure can be drawn (Steingrímsson, 2013b).

Televiewer (BHTV) is a logging tool used to map permeable fractures in geothermal wells. It produces an acoustic image of the borehole wall. The image represents reflectance and roughness of the wall and the geometry in the well. Orientation, dip and strike is determined (Steingrímsson, 2013a). Comparing Televiewer data with lithology log enables separation of bedding and structural features as well as distinguishing intrusive features from the bedrock (Blischke et al., 2016).

Vertical Seismic Profiling (VSP) was recently applied in geothermal investigation in Iceland as a part of IMAGE. Its purpose is to map physical properties of the rock e.g. magma pockets,
structural features, zones of supercritical fluids and superheated steam. A seismic wavelet is detected down the well. Its propagation reflects physical properties of the rock, which then can be used to correlate with other borehole datasets, and give an idea about the structure close to the borehole (Planke et al., 2016).

**Alteration**

First detection of zeolites, smectite, mixed layer clays (interstratification of different clay minerals; illite-vermiculite, illite-smectite, chlorite-vermiculite, chlorite-smectite, and kaolinite-smectite) chlorite, epidote and actinolite were already available in the previous Petrel model. They had been arranged into zones based on different reference temperature. These zones are: Zeolite-smectite zone, mixed layer clay (MLC) zone, chlorite zone, epidote-chlorite zone and epidote-actinolite zone (Table 3). These analyses are based on XRD (X-ray diffraction), drill cuttings and petrographic analyses (Mortensen et al. 2009; Weisenberger et al., 2015). For the updated alteration model, information about quartz and disappearance of calcite have been added (Figure 25).

*Table 3 Division of alteration minerals into alteration zones, based on reference temperature. Based on Ásgrímsson (2005).*

<table>
<thead>
<tr>
<th>ZONE</th>
<th>REFERENCE TEMPERATURE (°C)</th>
<th>ALTERATION MINERALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEOLITE-SMECTITE</td>
<td>50-200</td>
<td>Low temperature zeolites, smectite</td>
</tr>
<tr>
<td>MIXED LAYER CLAY</td>
<td>200-230</td>
<td>Low temperature zeolites disappear and smectite is transformed into chlorite. quarz, wairakite, calcite, pyrite are also present</td>
</tr>
<tr>
<td>CHLORITE</td>
<td>230</td>
<td>Smectite disappears and chlorite becomes the dominant mineral</td>
</tr>
<tr>
<td>EPIDOTE CHLORITE</td>
<td>230-270</td>
<td>Prehnite, epidote, wollastonite, chlorite</td>
</tr>
<tr>
<td>EPIDOTE ACTINOLITE</td>
<td>270-350</td>
<td>Epidote, actinolite</td>
</tr>
</tbody>
</table>
Feed zones
Locations of feed zones had already been implemented to the model (Mortensen et al., 2009; Weisenberger, 2015). They are based on downhole temperature logging data, pressure logs and circulation losses. They may also be identified through drill cutting analyses. Feed zones have been grouped into 3 groups based on their size. They are located where the well crosses a fracture or permeable lithological layer, and indicate the presence of geothermal fluid entry into the well. They are of great importance when interpreting permeable structures and an important addition to the large-scale structural interpretations.

Formation temperature
Temperature logs during warm up periods are available for each well. The logs were used as a basis for a 3D formation temperature model that has been developed and imported into Petrel (Mortensen et al., 2009; Halldórsdóttir et al., 2010). The model was created in 2009 and has not been updated since. Three wells, IDDP-1, K-40 and K-41, have been drilled after that and are not incorporated into the model. The model shows variations between different sub-areas in Krafla. The main upflow is located around the Hveragil fault, between Suðurhlíðar, Vesturhlíðar and Leirbotnar sub-areas. The model shows clearly the division between the Upper and Lower Leirbotnar systems except for two wells, K-06 and K-29 in Leirbotnar. However, drawdown in well K-06 has been explained by the production in well K-28, located north of K-06 and K-29. Well K-06 was not very productive and is, therefore, only used for monitoring. A sudden temperature drop is observed west of well K-18, which is the easternmost well in Suðurhlíðar sub-area, demonstrating the location of the boundary of the geothermal system. Changes in the system such as pressure drawdown and effects from older wells have not been accounted for in the model (Mortensen et al., 2009).
3 Petrel’s output: 3D geological static model

The data listed in section 2.3 have been digitally compiled and are imported in Petrel’s 3D Krafla model. Since the data are from different dates periods in the research history of the Krafla system (from the 1970s to 2016), they required quality assessment and in many cases pre-processing. Table 4 gives an overview of the data models included. Detailed model construction constraints and settings, such as cell size, numbers of layers etc., are found in Table 1 in Appendix A.

Table 4 An overview of 3D models in the 3D Krafla geological static field model.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>BASE LIMIT</th>
<th>TOP LIMIT</th>
<th>MODEL-LING AREA (KM)</th>
<th>MODEL TYPE</th>
<th>SOURCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEOLOGICAL MODEL</td>
<td>-2000</td>
<td>Topography</td>
<td>~2.7 x 2</td>
<td>Pillar gridding</td>
<td>Mortensen et al., 2009; Weisenberger et al., 2015; well reports 1976-2016</td>
</tr>
<tr>
<td>ALTERATION MODEL</td>
<td>-3000</td>
<td>Topography</td>
<td>~5.3 x 5.3</td>
<td>Simple grid</td>
<td>Mortensen et al., 2009; Weisenberger et al., 2015; well reports 1976–2016</td>
</tr>
<tr>
<td>FORMATION TEMPERATURE MODEL</td>
<td>-2000</td>
<td>Topography</td>
<td>5.6 x 5.6</td>
<td>Simple grid</td>
<td>Mortensen et al., 2009</td>
</tr>
<tr>
<td>RESISTIVITY MODEL (1D)</td>
<td>-15.000</td>
<td>Topography</td>
<td>12.4 x 10</td>
<td>Simple grid</td>
<td>Árnason et al., 2011</td>
</tr>
<tr>
<td>RESISTIVITY MODEL (3D)</td>
<td>-11.000</td>
<td>Topography</td>
<td>11.5 x 11.5</td>
<td>Simple grid</td>
<td>Rosenkjaer et al., 2015</td>
</tr>
<tr>
<td>TOMOGRAPHIC MODEL</td>
<td>-6000</td>
<td>1000 m</td>
<td>21.6 x 26</td>
<td>Simple grid</td>
<td>Schuler et al., 2015</td>
</tr>
</tbody>
</table>

3.1 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. The Krafla geothermal area is complex both in terms of structure and lithology. Therefore, lithological correlation throughout the area is not straightforward. As mentioned earlier the dominant
formations in Krafla are basaltic lavas and hyaloclastite formations and their distribution is not easy to implement into a 3D model, especially hyaloclastite formations from different areas (Mortensen et al., 2009; Weisenberger et al., 2015). Petrographic analyses have not been performed in all of the wells, which results in rather rough grouping of the geological units. Contacts and boundaries are, therefore, not well constrained. However, the model shows key lithofacies units that represent differences in the overall lithotype and transmissibility. In areas where few wells have been drilled, the Petrel software extrapolates the horizon created by a point set from other wells.

To avoid extrapolation over long distances, the subsurface geological models were limited to the existence of the main production areas, namely the Leirbotnar, Suðurhlíðar, Vesturhlíðar, Víísmör and Leirhnjúkur area (Figure 26). High well density minimizes error and provides a better structural control for the model.

Figure 26 The extent of the geological model is demonstrated as a grey shaded area. K-26 and K-18 are wells that were used in the IMAGE project. Sub-areas are the following: Hvannstóð (Hva), Leirhnjúkur (Lh), Vesturhlíðar (Vh), Víísmör (Vm), Leirbotnar (Lb), Suðurhlíðar (Su), Vestursvæði (Ve), Hvíthólar (Hv), Sandabotnar (Sa). Thick black lines mark outer and inner calderas and orange dashed areas geothermal surface manifestations.
3.1.1 Lithological model

Construction of the lithological model was subdivided into three processes: Well correlation, simple gridding and pillar gridding. Instead of performing these steps one after the other, they were performed side-by-side, for quality control and cross checking. For well-to-well correlation, boreholes were organized in a logical order within the 2D “Well Correlation platform”. They were also divided into areas based on their elevation location. Well-to-well correlations were performed from base to top, linking the boreholes by stratigraphic horizons that subdivide the model into zones of formations with similar characteristics (Figure 27). Viewing stratigraphic horizons in 3D with the lithological logs of each well, allow an understanding of the geography and structure of each horizon.

Formations

Series of different lithological models were created, using different constraints and settings. While the model is constructed, an understanding of depositional environments and underlying structural settings is very important to assess the origin and physical behaviour of each formation unit. Hyaloclastite units form irregular ridges or mountains due to their phreatic nature during sub-glacial eruptions, whereas basaltic lavas spread more laterally filling and covering low areas during inter-glacial times. Horizon types are, therefore, divided into four categories; erosional (intra-glacial and times of no eruptions), discontinuous (e.g. hyaloclastite mounts), conformable (e.g. lava layers that follow the underlying morphology), or base (e.g. the proposed base of the Krafla volcanic system, sheeted intrusive rocks). The model in Figure 27 represents two hyaloclastite sequences, two basaltic lava layers and three zones of infill sections that are composed of thin layers of basaltic lavas, breccia, pillow lavas and tuff. As mentioned in section 2.3.2, intrusions are not included in the model as a horizon. The lowest formation above the proposed basement is, therefore, defined as lavas/intrusions unit, since it is likely that the number of intrusions that cut the lava sequence at this depth increases at a later point in time.
The VSP seismic data from well K-18 recognized a strong signal at 1,800 m depth. Slightly deeper, an increase is seen in resistivity logs and NN logs – indicating a denser or less porous formations. The shift in NN and resistivity data was also recognized in other wells. As this could indicate a different reflector in the strata, these shifts were picked and a horizon created (Figure 28). This is implemented in the lithological model as “possible basement”. This term is based on terminology from seismic surveys in sedimentary basins; “acoustic basement” which is used for the deepest seismic reflector, often a bedrock overlain by stratified sediments (Bruvoll et al., 2011). This rather dense rock formation that is most likely gabbro or dolerite intrusions, could underlie the oldest formation within the caldera, formed during interglacial periods ~200000 years ago (Figure 29) including younger intrusions.

Until the glaciation, ~180000 years ago, lavas continued to form, as well as minor amounts of hyaloclastites, forming the lower lavas in the lithological model (2). During the progression of the glacier, tuff and breccia formed as well as thin layers of glassy and finegrained basalt (3). As the glacier thickened for the next 50000 years, hyaloclastites continued to form (4). The glacier retreat before the Eem interglacial period again caused the formation of some breccias, thin tuffs and basaltic layers (5). During the Eem period (~125000 -115000 years ago), lavas flowed on the ice free land (6) (Figure 30).

Figure 27 A cross section showing the stratigraphy beneath the production area. The colour coding key for the cuttings described in the wells is in Appendix D. Red colour represents basaltic intrusions and yellow colour shows silicic intrusions. The section strikes NE-SW (green line on the map).
Figure 28 An example of a correlation panel where cutting analyses are grouped into zones of formation using correlation similarities and geophysical logs. Reflectivity analysis data and P-wave velocity (km/s) from the VSP is shown in well K-18. Strong reflection is seen at ~1,300 m depth.
Figure 29 A possible scenario of a generalized lithological section for the Krafla area correlated to the geological history of Krafla by Sæmundsson (1991).

Figure 30 Numbers are representing relative age of individual formations, described in Figure 29.
As the next glacial period arrived another set of thin basaltic layers, tuffs, breccias and pillow lavas were formed (7) followed by rather uniform tuff formations (8). The uppermost formation (9) in the lithological model is composed of “mixed overburden” formed during the Holocene. After the formation of the lava strata, basaltic, intermediate and silicic intrusions have formed at various times and cut the lava strata. Other factors have affected the structure of formations e.g. caldera collapse, subsidence due to the rifting, load of volcanic material and glacial progression. Land has also been rising due to glacial retreat and accumulation of magma below surface. Subsidence due to the rifting has been calculated ~20 m/10000 yrs. (Sæmundsson, 1991) resulting in 400 m subsidence during the geological history of Krafla.

Two main phases of rhyolite volcanism in Krafla are identified. The earlier phase is related to the caldera collapse ~100000 years ago, whereas the second phase is associated with a glacial period and has been related to the emplacement of ring-dike structures when Jörundur, Hlíðarfjall and Gæsafjallarani were formed (Sæmundsson, 1991; Jónasson, 1994). An overview of silicic/intermediate formations is given in Appendix E. They are in the form of tuff, breccia or crystallised rock and are most often in the lower part of the stratigraphy, but are occasionally found near the top. An apparent silicic section is seen below Suðurhlíðar and also in individual wells throughout the model. Felsic and intermediate tuff and breccia have been analysed in wells K-6, K-35, K-37 and K-39 at a depth range between ~400 m a.sl down to 600 mbsl.

3.1.2 Structural model

The structural model represents tectonic features within the geothermal area. Petrel offers a structural interpretation module that allows incorporation of faults in a 3D grid. A total of 31 interpreted faults and fissures had been imported into Petrel as a part of the previous conceptual models. Those were mainly based on surface mapping and borehole geological data, supported by gravity data (Mortensen et al., 2009; Weisenberger et al., 2015). Only 11 of these faults and fissures were used for the structural model in this project. They were selected based on comparison to other datasets: gravity, magnetics, seismicity, resistivity, stratigraphy, feed zones, temperature, alteration and highly productive wells. Sudden changes in these datasets across a tectonic feature might be caused by changes in fluid flow, activated fault or geometry of the strata. By viewing tectonic features with regard to each of these datasets, faults and fissures were evaluated and ranked (Table 5). The 11 faults and fissures were imported into the model using pillar gridding, with a 100 m horizontal offset limit that allows the forming of a fault escarpment within this set radius and fault trend. As most faults did not appear to show major fault throws, a maximum fault displacement was set to 40 m vertically.
Table 5 Ranking of faults within the geo-static model. N-S fault III and N-S fault VI were picked as boundary faults in the model.

<table>
<thead>
<tr>
<th>FAULT</th>
<th>BOUGUER MAP</th>
<th>MAGNETIC</th>
<th>SEISMICITY</th>
<th>STRATIGRAPHY</th>
<th>MT/TEM</th>
<th>HIGH ENTHALPY</th>
<th>TEMPERATURE</th>
<th>MAIN FEED ZONES</th>
<th>ALTERATION</th>
<th>RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVERAGIL EXPLOSION</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>7</td>
</tr>
<tr>
<td>KRÖFLUJALL</td>
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<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>HÓLSELDAR 3</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<td>4</td>
</tr>
<tr>
<td>VESTURHLÍÐAR CO2 _ W</td>
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<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>NV-SA FAULT</td>
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<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>NS FAULT V</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>HÓLSELDAR FISSURE</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
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<td>6</td>
</tr>
<tr>
<td>DAL FIRES ERUPTIVE FISSURE</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>


3.1.3 Geological facies model

Following the construction of the structural model described above, a preliminary geological facies model was created (Figure 31). It was generated using sequential indicator simulation that creates lithofacies values in all model cells. Therefore, it represents distribution of lithological units in the area. As this model was constructed to focus on the in-situ formations, intrusions were left out and the emphasis was on horizontal formations. First, all well lithology logs were scaled up to fit the structural framework model grid cell distribution for each main formation sequence. Variogram type, fraction and trends were set for each lithofacies type within every zone, based on proportion curves. The model presented here is more detailed than the pillar gridding structural model and is not as manually controlled. It is important to note, however, that no faults are present in this model and its purpose is mainly to cross check the geological model (Figure 32).

Figure 29 A Preliminary geological facies model of Krafla generated by scaling up lithology from well logs and used to compare to the geological model presented in Figure 32.
Figure 30 A comparison between the geological model, based on faults and correlations between boreholes (N-W section), and the geological facies model, generated by scaling up well logs (E-W section).
Figure 31 A comparison of lithological log based on cutting analyses, including intrusions (to the left for each well), lithological log generated from the geological facies model (in the middle) and lithological log generated from the lithological model (to the right). Generating different models using different assumptions and building process is crucial to estimate the models reliability. Legend for different lithologies is found in Appendix D.
3.2 Resistivity

The most recent 3D resistivity inversion (Rosenkjaer et al., 2015) was used to compare multi-disciplinary results and for joint interpretation. Figure 34 shows the 3D resistivity model at different depths with reference to sea level. At great depths (-7000 m) two striking conductors are seen below Leirhnjúkur (1) and east of Vesturhnjúkur (2) sub-areas. The eastern one fades out at shallower depth (-3000 m) and another conductor, north of the Vestursvæði (3), becomes more prominent (it is a bit vague at -7000 m). Conductors (1) and (3) are more apparent at an even shallower depth (-3000 m). At -1000 m depth three conductors are seen below Leirbotnar/Hvíthólar (4), and two additional conductors below Sandabotnar (5). The resistivity highs show a curving towards the south. At -5000 m depth, a WNW-ESE lying resistivity high starts to appear as well as a NE-SW lying resistivity high. These lineaments are quite clear at -3000 m depth.

![Figure 32 The subsurface resistivity structure of Krafla based on 3D inversion. Blue dashed lines delimit the resistivity highs but red circles the 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.](image)

For a better understanding and easier comparison of the resistivity structures, trends in the resistivity model were picked every 500 m using the Seismic interpretation module in Petrel. A pseudo 3D seismic reflection data volume was generated, that contains the resistivity model values instead of the seismic two-way-travel time. Structural trends were grouped and...
coloured based on their strike. Blue coloured lineaments strike WNW-ESE, while red coloured lineaments strike NE-SW. Figure 35 shows how the interpreted S-wave shadows as mapped by Einarsson (1978) are bordered by the WNW-ESE trending lineaments and low resistivity.

Árnason et al. (2011) discussed the relationship between seismicity, resistivity and location of S-wave shadows. Interpretations were based on earthquakes recorded in 2004-2005 and 1D inversion of resistivity data. Earthquakes were clustered inside in WNW-ESE direction; one cluster inside the boundaries of a resistive core in the NE and another cluster where the inferred transform graben runs through the calderas. They pointed out that most of the earthquakes were located within the inner caldera but deep earthquakes (>3 km) were mainly located outside the inner caldera. Lack of earthquakes below 3 km depth was explained by temperature transition, from brittle (>600°C) to ductile (1100 -1200°C) rocks (Árnason et al., 2011).

Figures 36 and 37 show the relationship between earthquakes recorded from 2014 to 2016 and the 3D resistivity model. Lateral distribution of earthquakes are more concentrated in certain areas than in the 2004-2005 data, showing WNW-ESE trend and NW-SE trend. The

Figure 33 Resistivity trends striking WNW-ESE (blue colored) and NE-SW (red colored). Low resistivity (<0.7 Ωm) and S-wave shadows mapped by Einarsson (1978) are also shown. The map is intersected below 600 mbsl.
reinjection wells; K-26 and K-39 are shown on the map. Comparison of injection rates and seismic activity has been done in Krafla and a clear increase of seismic activity is noticed during days of high injection rate (Blanck et al., 2014; 2016). Other factors affecting earthquake distribution is heat extraction in the geothermal system and local tectonics. Vertical distribution is consistent with Árnason et al.’s (2011) observation; showing the majority of earthquakes occurring near the top of the S-wave shadows and a sudden decrease of events below 3 km depth (Figure 37).

Figure 34 Resistivity at 2 km depth and earthquakes located above a depth of 2 km from 2014-2016. Blue dashed lines show the inferred transform graben mapped by Árnason et al. (2011) and green dashed lines represent the parallel resistivity high.
Figure 35 The cross section shows how earthquakes are distributed below the production area and above the S-wave shadows (red shaded areas). Red earthquakes: 1.1 – 2 km, blue earthquakes: 2.1-3 km and black earthquakes: > 3 km. Earthquakes are also concentrated within the high resistivity.
3.2.1 Comparison of resistivity models

After interpreting the structural lineaments in Petrel, a comparison between the two available resistivity inversion models in a horizontal plane becomes more easy. As Figure 38 shows, the main trends picked from the 3D inversion model do not match very well with the 1D inversion resistivity model. The NE-SW trend is not as distinct in the 1D inversion and instead of the two main conductors in the 1D inversion, the 3D inversion contains three main conductors. In both cases the low resistivity is well constrained inside the inner caldera and also the well-defined conductor below Leirhnjúkur. A brief summary of the results of the 1D inversion by Árnason et al. (2011) is listed in Table 6 and the results compared with the 3D inversion.

Figure 36 The 1D resistivity inversion model (at -2000 m) displayed with the trends from the 3D resistivity inversion (blue: WNW-ESE direction, red: N-S direction). The resistivity high beneath Vítismór, Leirbotnar and Suðurhlíðar observed in the 3D inversion, does not match very well with the 3D inversion.
Table 6 Results from the 3D inversion compared with the main results from the 1D inversion by Árnason et al., 2011. Earthquake distribution is also revised from Árnason et al., 2011.

<table>
<thead>
<tr>
<th>1D RESULTS</th>
<th>CONSISTENT WITH 3D RESULTS?</th>
</tr>
</thead>
<tbody>
<tr>
<td>A CONDUCTOR IN THE UPPERMOST FEW HUNDRED METERS UNDERLAIN BY HIGHER RESISTIVITY</td>
<td>Yes</td>
</tr>
<tr>
<td>DEEP CONDUCTOR DOMES UP UNDER AND NORTH AND LEIRHNJÚKUR</td>
<td>Yes</td>
</tr>
<tr>
<td>DEEP CONDUCTOR DOMES UP UNDER VÍTI AND KRAFLA</td>
<td>Not as prominent</td>
</tr>
<tr>
<td>THE TWO MAIN CHIMNEYS COINCIDE WITH THE MAGMA CHAMBERS</td>
<td>No</td>
</tr>
<tr>
<td>THE TWO UP-DOMING CONDUCTORS ARE CONFINED WITHIN THE INNER CALDERA</td>
<td>Yes</td>
</tr>
<tr>
<td>AT THE DEPTH OF ~2 KM BSL. RESISTIVITY STARTS DECREASING WITHIN THE INNER CALDERA</td>
<td>Yes</td>
</tr>
<tr>
<td>DEEP CONDUCTORS REACH CLOSEST TO THE SURFACE NW OF MOUNT KRAFLA</td>
<td>Yes</td>
</tr>
<tr>
<td>DEEP CONDUCTORS REACH CLOSEST TO THE SURFACE NORTH OF LEIRHNJÚKUR</td>
<td>Yes</td>
</tr>
<tr>
<td>DEEP CONDUCTORS REACH CLOSEST TO THE SURFACE UNDER LEIRHNJÚKSHRAUN</td>
<td>Yes</td>
</tr>
<tr>
<td>SEISMICITY IS CONFINED WITH THE INNER CALDERA</td>
<td>Yes</td>
</tr>
<tr>
<td>SEISMICITY IS LESS WITHIN THE TRANSFORM GRABEN</td>
<td>No</td>
</tr>
<tr>
<td>THE SEISMICITY IS SHALLOW AND CLUSTERS OVER THE UP DOMING CONDUCTORS</td>
<td>Yes</td>
</tr>
<tr>
<td>THE SEISMICITY EXTENDS TO GREATER DEPTH AWAY FROM THE UP DOMING CONDUCTORS</td>
<td>Yes</td>
</tr>
<tr>
<td>DEEP EARTHQUAKES ARE MAINLY OUTSIDE THE INNER CALDERA</td>
<td>Yes</td>
</tr>
</tbody>
</table>
3.3 Combined results

The first part of the thesis has described the modelling process and data compilation of the latest revision of the Krafla geological static model. The revision is based on earlier conceptual models, as well as new and old data, that had not been implemented to the model before. A comprehensive integration of multi-disciplinary results was performed to be able to estimate the applicability of the different datasets. A brief correlation between geophysical and geological datasets was conducted in order to increase the understanding of the subsurface tectonic controls in the Krafla field area. Those sub-models that were built in this project were limited to the highest data density area to minimize data extrapolation errors.

3.3.1 Krafla data summary

Since the latest publication of a conceptual model in 2015, various data have been implemented into this project that include:

- Location of seismic events from October 2013 to November 2017 and analysis of focal mechanism from 2016
- Seismic refraction profile data
- Seismic tomography
- Resistivity model based on 3D inversion of MT data
- Aero-magnetic map
- Bouguer and Free air gravity maps
- Additional results from drill cutting analysis (lithology, alteration)
- Additional geophysical log data
- Grouping of feed zones, enthalpy and energy production

These datasets have provided information for the updated sub-models in the Krafla geological static model.

- Interpreted faults and structural lineaments 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 structural model. By scaling up lithology interpretations of the wells and using sequential indicator simulation, a geological facies model was built. Although the building process and assumptions were different, the two models coincide overall quite well and were used to cross check each other. The geological model was put into context with the geological history of Krafla as published by Sæmundsson (1991).

- A comparison was made between the resistivity models based on 1D inversion (Árnason et al., 2011) and 3D inversion of MT data (Rosenkjæer et al., 2015). The most conductive areas are at similar places, except for the conductive anomaly north of Vesturhlíðar and Hvíðólar.
• 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.

Subsurface and surface lineaments from different datasets were considered. Although not apparent at the surface, the WNW-ESE lying structure seems to play a crucial role in the deformation at greater depths.

3.3.2 Structural lineaments, fault and fracture zones

Curewitz and Karson (1997) suggested in a global survey, that hot springs are generally associated with faults or fault intersections. Feed zones in wells often correspond to faults and, therefore, it is extremely important to understand the structural framework of geothermal areas.

The apparent WNW-ESE striking subsurface lineament that is seen in various datasets in Krafla has been argued for by specialists that don’t agree with this structure. In section 2.1.1, structures on the NVZ are presented, with the aim of giving an insight into the stress pattern and tectonic control of the NVZ. Documenting relationships between related tectonic features can provide important information on the stress field. In this section, possible explanations will be discussed by comparing the large scale and small scale picture and look into the link between datasets that have been presented here.

In Figure 39, the asymmetrical rifting observed in GPS data from LMÍ (2017) is visualized as blue arrows. These are preliminary results based on data measured in 2004-2016, published in a newsletter by the National Land Survey. These data have been processed further after the newsletter publication but have not been presented. The map also shows the main structural elements that form on the junction between the TFZ and NVZ. The dextral strike-slip component that has been documented and interpreted as a consequence of the TFZ is marked as red dashed lines, but other apparent structural lineaments that are not following the trend of the fissure swarm are marked as yellow dashed lines. The blue arrows represent the total movement of tectonic blocks indicating an uneven structurally segmented and oblique opening of this area. Around the KFZ and ÞFZ, the apparent total movement is nearly zero, which could indicate that different segments are possibly pushing against the rift motion, causing the total movement to be cancelled out. A complex system was noted for the Þeistareykir fissure swarm structural setting, where both components were observed, sinistral and dextral components (section 2.1.1) (Khodayar and Björnsson, 2013).

GPS data from Metzger and Jónsson (2014) (measured in NE-Iceland in 1992-2009) show consistent results. Differences in rift directions and magnitude are observed although the fixed point is different and the datasets cover different time periods and different research areas. Metzger and Jónsson (2014) also present InSAR time-series analyses of 17 years from the area. In general they revealed a deflation of the Krafla central volcano in particular the area covered by the recent lava flows. Furthermore, a broad uplift north of Krafla was detected. Subsiding areas have been related to the cooling of the lava flows from the 1975-1984 rifting events, drainage at the caldera into the lower crust, geothermal production and
local subsidence within the fissure swarm. Joint interpretation of GPS and InSAR data shows that some of the vertical movements detected by GPS measurements can be explained by volcanic deformation (Metzger and Jónsson, 2014).

Accordingly, the lineaments could be a consequence of the interplay between the dextral moment of the TFZ, the opening component of the rift and volcanic deformation in the area. Different spreading and volcanic deformation causes local stress field changes that effect the neighbouring systems. Although Krafla is not heavily vegetated or covered by sediments, young lavas cover the majority of the area, making surface–sub-surface interpolation difficult. Using the integration of all available datasets, a series of sub-surface structural lineaments can be recognized. Here, the structural lineaments are identified in 3D space and anomalies related to them.

**Surface lineaments**

Fumaroles and mud pools in Krafla are primarily associated with the WNW-ESE intrusive complex cross-cutting the caldera (Sæmundsson et al., 1991). This reflects the presently most active area. The intrusive complex is most likely related to the shallow magma chamber, based on the mapped S-wave shadows by Einarsson (1978). Craters and fissures are lined up in a NE-SW and N-S direction (Figure 40), where the red dashed lines represent the difference in strike to the south of the caldera and towards the north.

Surface mapping of faults shows mainly NE-SW lying lineaments but NNW-SSW trending faults have been mapped in the Suðurhlíðar sub-area and Leirbotnar (blue dashed lines on Figure 40) (Karlsdóttir et al., 1978). The landscape around Krafla shows an apparent WNW-ESE component that becomes more apparent towards the NNW.
Figure 38 The figure to the left shows how geothermal manifestations are aligned in the WNW-ESE direction (red shaded areas within purple dotted lines) and how surface tectonic features strike differently north of and south of the calderas (red dotted lines). On the figure to the right, light blue dashed lines show the NNW-SSW to WNW-ESE trending faults and fissures as well as the magma chamber. Dark blue dashed lines show the inferred transform graben mapped by Árnason et al. (2011) and green dashed lines represent parallel resistivity high. The sub-areas are labeled as abbreviations on the map: Hvannstöð (Hva), Leirhnjúkur (Lh), Vesturhlíðar (Vh), Vítismór (Vm), Leirbotnar (Lb), Suðurhlíðar (Su), Vestursvæði (Ve), Hvíthólar (Hv), Sandabotnar (Sa). Black lines mark outer and inner calderas and blue points mark well tops.
**Subsurface lineaments**

**Bouguer map and lithology**

The Bouguer gravity map shows an anomaly trending WNW-ESE running through the caldera south of the main production area and widens to the east. This is discussed by Weisenberger et al. (2015), where alternatively this pattern is interpreted as a graben that cuts through the calderas and a change in spreading direction around Krafla. It is pointed out that this trend is the same as in other low gravity lineaments in the Húsavík transform fault system. In addition to the WNW-ESE lineament seen on the Bouguer gravity map, another gravity low trending NNE-SSW is seen. In Weisenberger et al. (2015) it is stated that these density contrasts are at shallow depths, and are, therefore, interpreted as an inner caldera. Moreover, the trend shows a discontinuity and an offset across the WNW-ESE graben (Figure 41).

![Figure 39 A Bouguer gravity map modified from Magnússon (2016). Black triangles represent gravity stations and blue dashed lines the inferred transform graben mapped by Árnason et al.(2011). Green dashed lines represent a high resistivity area. Purple lines show the NNW-SSE trend of low gravity and the red line shows the location of the lithology cross section in Figure 42.](image-url)
A lithological cross section crossing the margins of that implied graben zone is displayed on Figure 42. The geometry of the formations shows a tilt towards the graben and a sudden drop in depth to lavas and intrusions from 500 mbsl. to 1000 mbsl. Borehole data have revealed the existence of a fault between well K-06 and K-07 with a relief change of 300 m towards the southwest (Karlsdóttir et al., 1978). This indicates that the WNW-ESE fault zone has a normal fault component.

**Figure 40** NNE-SSW cross section of the geological model, showing a sudden drop in lavas and intrusion with depth between K-06 and K-07 and a tilt towards the graben. The figure to the right shows the location of the cross section.

**Resistivity**

The two general trends seen in the resistivity model are as previously described; a NNE-SSW trend along the fissure swarm and another one trending WNW-ESE through the main production area. The most striking features are the offsets across the WNW-ESE lineaments and the curving of the resistivity high, towards the south (Figure 43 a,b).

The interpreted lineaments in the resistivity data indicate structures striking in a NE-SW direction (black) and in a WNW-ESE direction (blue) (Figure 43c) as well. This, combined with the interpreted surface faults (red) and fissures (pink), indicates an even more complex and segmented structure within the caldera than previously described (Karlsdóttir, 1978; Árnason et al., 2011, Weisenberger et al., 2015).

Figure 43c shows how deep structures based on the resistivity data (blue and black) do not reach to the surface, and the main trend of the surface faults and fissures that reach down to -2500 m line up perpendicularly to the deep structure interpretation. However, two fissures (1) and (2) show this WNW-ESE and NNW-SSE trend, indicating that this structure also affects surface deformations.
Figure 41 Figure a) shows resistivity at -2000 m depth. The purple dashed lines delimit the NW-SE trending resistivity low, that shows an offset across the WNW-ESE trending lineament. White dashed line shows the trend of the resistivity high, curving towards the south. Figure b) shows the same structure at -1000 m depth. Figure c) shows the deep structures mapped on the resistivity data. The main trends strike N-W (black) and WNW-ESE (blue). Evaluated faults (red) and fissures (pink) in the structural model are also visualized. Two of the fissures strike WNW-ESE to NW-SE, labelled 1) and 2).
The cross-section in Figure 44 displays the resistivity across the inferred buried graben. A sudden drop in resistivity is around well K-06, where the depth to intrusions increases. The high resistivity zone is, therefore, underlain by the mapped S-wave shadows and the low resistivity within the inferred buried graben. Intrusions are generally reflected by high resistivity whereas partial melting and presence of fluids decreases the resistivity.

![Figure 42](image)

*Figure 42 A resistivity cross section across the boundary of the inferred buried graben. Low resistivity is observed within the inferred graben where depth to intrusions increases. Legend for lithological logs is found in Appendix D.*

**Aero-magnetic, temperature, alteration**

The aero-magnetic map is in a general agreement with the resistivity model (Figure 45). An aero-magnetic anomaly trending WNW-ESE passes through the Leirhnjúkur, Víttismór and Suðurhlíðar sub areas. A polygon that encircles a magnetic low (<51000 nT) was created from the aero-magnetic map in order to compare this pattern with other datasets. As the figure shows, the orange shaded area (51000-51500 nT) is trending NE-SW (red dashed outline). It meets with the WNW-ESE trending magnetic low (parallel to the green dashed outline). North of this lineament, the magnetic anomaly suddenly increases (see Figure 22 in section 2.2). As magnetic anomalies either reflect structural changes or high temperature at some point, this discontinuation indicates some structural feature that changes the rock type and stage of the system north of the lineament. At the junction of the two trends, the magnetic field becomes even lower (<51000 nT), where the formation temperature model shows the highest temperature, possibly indicating the present main upflow of the geothermal area (Figure 46).
Figure 47 displays how low temperature alteration (zeolite-smectite zone) extends to a greater depth when crossing the inferred buried graben, and high temperature alteration is seen at shallower depth in Leirbotnar and Suðurhlíðar, where the high resistivity core is located. It should be noted that the data control is not as good along the inferred buried graben as in Leirbotnar and Suðurhlíðar, where the main production area is located.
Figure 44 A cross section of the formation temperature model underlain by an aero-magnetic low polygon (51000 – 51500 nT). Orange shaded area represents 51000-51500 nT and blue shaded area represents <51000 nT.

Figure 45 Formation temperature at 1000 m bsl. and alteration zones crossing the WNW lineament. The blue dashed lines represents the inferred buried inner graben mapped by Árnason et al., 2011 and the green dashed lines represent the lineament seen in resistivity and aero-magnetic data.
Seismicity

In addition to apparent earthquake clusters described by Blanck et al., (2014, 2016, and 2017) the WNW-ESE and NW-SE trend is also observed in all the earthquake datasets. Shallow lying earthquakes (0.4-1 km) from 2014, show a N-S trend in seismicity south of the WNW-ESE lineament. This trend is not continuous to the north, whereas the NNW-SSE trend appears to continue further to the west (Figure 48). The earthquake activity appears to occur beneath the main production area and the field production induced seismicity should be kept in mind. However, the north-southerly trends that reach away from the production area more likely indicate natural earthquakes that relate to fault zones that were not triggered by the geothermal production. This could not be seen as clearly in the interpreted earthquakes records from 2016 and 2015.

Figure 46 Seismicity in the uppermost 1 km from Oct 2013 – Oct 2014. The reinjection wells, K-26 and K-39 are highlighted. Yellow shaded are shows the S-wave shadows, black thick lines mark inner and outer calderas and well tops and paths are also shown (blue). Green dotted lines show N-S to NE-SW trending seismicity clusters north and south of the WNW-ESE trending lineament.
Combined interpretation

In conclusion, the discussed datasets were compared in order to increase the understanding of how known lineaments seen on surface and subsurface data from the Krafla field might fit into the large scale tectonic picture of the NVZ. The most apparent features are as follows:

- A WNW-ESE lineament that was observed in the resistivity, Bouguer gravity, aero-magnetics, seismicity, lithology, surface tectonics 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). As noted in Einarsson (1978) the S-wave shadows are related to magma, in some kind of a magma chamber. Whether it is a massive body of molten magma or a number of small chambers, pockets or sills has not been clarified so far. Therefore, the high resistivity could be related to an intrusive complex, resulting in high temperature and low magnetic anomaly. The 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 from that observation. The NNW-SSE to WNW-ESE trending faults and fractures nevertheless indicate that the tectonics are not only controlled by simple orthogonal rifting.

- The NE-SW lineament were observed in the resistivity, Bouguer gravity, aero-magnetics, seismicity and mapped surface tectonic features. This is parallel to the rift and is most likely caused by the opening component of the NVZ.

- Bending of WNW-ESE trends towards NW-SE direction was observed in the resistivity data and surface tectonic interpretations (Figure 43). Such patterns might be a consequence of the interplay between NE-SW trending shallower structures and WNW-ESE trending deep structures. Such rotations are also known in oblique rifting systems (section 2.1.1) and rotation towards parallelism with the rift border faults strengthens that analogue to a possibly right-oblique system (McClay and White, 1995).

- The discontinuities of the NE-SW lineaments across the WNW-ESE lineament were observed in the resistivity, Bouguer gravity, aero-magnetics, seismicity and surface tectonic elements, such as interpreted faults and fissures. This discontinuity showed a segmentation and a left stepping fault system. A possible explanation for this is also the consequence of an oblique rifting across the NVZ (Figure 49).
Based on these observations, the deep structure recognized from subsurface data, can only be seen on surface up to a certain extent. 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 localised strike-slip faults and normal faults, see section 2.1.1 (McClay and White, 1995). These “damage zones” can create permeable fracture networks that weaken the rock and allow geothermal fluids to rise and travel along fault and fracture zones. The junction of these two different lineaments (WNW-ESE and NE-SW) is, therefore, a pre-requisite for an efficient geothermal system.

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, like the rifting events of the Krafla fires shows. 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.

As detailed structural mapping still remains to be accomplished in Krafla, these scenarios that have been described here could provide a base for further research studies that would improve the understanding of the Krafla geothermal system, and also serve as an analogue for other high temperature field areas.
4 Workflow

The main objective in this project was updating and developing a 3D geological static field model of a Brownfield, the Krafla geothermal area, NE-Iceland and based on that experience to construct a workflow and apply to a Greenfield, the Pico Alto Geothermal Area. To avoid giving misleading information in the different models, they were tied to available datasets, both with respect to lateral and vertical extent, from a regional scale to borehole data scale.

All the data presented here have been prepared for the Petrel 3D modelling software. Therefore, the workflow is based on that process and does not necessarily apply to other modelling software. The general workflow for constructing such a geological static field model is presented in Figure 50. It is noteworthy that the process is not linear. Iterative work is essential to gain the most reliable model results.

4.1 Modelling steps – From paper to a 3D digital geological static model

The workflow is comprised of five principal steps (Figure 50) that will be described in detail in the following text. These are:

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

Following each step, quality control should be checked including listing of source, references, data manipulation before importing those into the model, 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. The model should neither be too complicated nor too simplified. 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. Detailed low scale data should always be preserved in the model even though they are not displayed in a regionally extending section.
Figure 48 The principal steps that build up the workflow.

- Data acquisition and preparing
  - Data formatting
  - Convert to suitable coordinate system
- Data importing
  - Well log (continuous)
  - Point well data (discrete)
  - Points with attributes
  - Bitmaps
- Data correlation
  - Main formations and geological structure
  - Wells elevation and distribution
  - Avoid “bulls eye” and horizons to cross
- Run 3D model
  - Simple grid/Pillar gridding
  - Grid increment
  - Interpolation algorithm
- Combined results
  - Delimiting anomalies and comparing to other datasets
  - Looking at results in larger context
4.1.1 Data acquisition and preparing

This phase is in many cases the most time consuming one, but at the same time a very important one, as the phase creates the basis for the work that follows. It depends on the modelling software, how much the data have to be processed in regards to data quality, interpretation certainty, formatting issues, such as depth determination, coordinate system, points and commas etc. In Petrel, all depth values should be listed in (-) if defined as MD (measured depth) and values below sea level should be listed in (-) if defined as Z. The input data should also be converted to a suitable coordinate system. Datasets should be prepared as ASCII files, including location (x, y, z or well name, MD) and a property value (such as temperature, resistivity etc.). If additional information exist, it should be imported as well.

4.1.2 Data import

For importing well data, either continuous well logs or discrete point well data are defined. This is dependent on the downhole data interval. For discrete data (lithology, alteration, intrusive intervals, feed-zones, etc.) “Point well data” are selected. For continuous data (temperature, caliper, gamma etc.) “Well logs” are selected. Data that are not confined to a certain well, such as seismic, MT and gravity data, are imported as “Petrel points with attributes”. Coordinate values and depth values are defined alongside the property value. For quality control of the imported data it is important to have the original displays or interpretation included for a direct comparison. Here, maps or figures can be imported selecting “Bitmap image” for all selected figures, where the files are either bmp, jpg, tiff, tif, gif or png. The positioning of these images can be selected for selected 3D location points in any horizontal or vertical position.

4.1.3 Well correlation

Well 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 within the “Well section window”, 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 using the “Make surface” tool that creates a 3D surface of the selected well top point set. 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 well formation top correlation data 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.
4.1.4 3D modelling

Each 3D model data 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 for input data – model output quality control.

Simple grid

Simple gridding is used when faults are not implemented as a first path overview model, or 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 horizons are used to build the model, they are given horizon types that are defined based on the formations’ nature and geometry. 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. The next step is “scaling up well logs”. Upscaling averages the values within the cell which means a decrease in data resolution. Different average methods are defined, based on data distribution. To assign values to all the other grid cells, Property modelling (Facies modelling/Petrophysical modelling) is used. The interpolation between cells is done using variety of methods. An overview table for the interpolation methods can be found in Appendix B.

Pillar gridding

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 Petrel extrapolates 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.
4.1.5 Combined results

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. During the construction of the Krafla geological static mode, resistivity structural trend picking allowed easier comparison with other models. The same applies to the magnetic low and the main trend of the Bouguer gravity map e.g. 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 a puzzle of a larger system. Therefore, studies from other nearby areas and large scale studies should always be considered with the small scale studies.

Smooth and “good looking” models can look convincing but they are not always the best solution, as nature is not smooth and simple. They can indicate lack of data and a high degree of extrapolations. Scale and spatial resolution is also important to consider, when interpreting and comparing data sets. Resolution of large-scale MT 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, therefore, important to support less detailed datasets.
5 A 3D modelling of the Pico Alto geothermal field on Terceira, Azores

The Pico Alto geothermal field is located on Terceira, one of the volcanic islands on the Azores archipelago. Drilling of production wells has been ongoing in Pico Alto for eleven years. The wells have revealed a maximum reservoir temperature up to $>240^\circ$C and well tests have pointed out the capacity to support a 50 MW power plant. Therefore, Pico Alto seems to be a promising area for future power generation but short drilling history and few data make interpretation and well targeting difficult. Therefore, Pico Alto serves as a Greenfield in this project. Here, the drilling history of Pico Alto is outlined and available data (shape files, bitmap images, well logs etc.) presented on a 3D scale.

5.1 Geological setting

The Azores archipelago is located east of the triple junction formed by the Eurasian, North–American and Nubia micro-plates (Figure 51). This location causes both complex tectonic framework and complicated strain distribution. Different spreading rate of the plates results in a WNW-ESE trending zone of deformation; Azores–Gibraltar Fault Zone (Luis et al., 1994). The Terceira rift runs through the archipelago striking WNW-ESE and belongs to

![Figure 49 Geological setting of the Azores archipelago. The Azores are spread along the WNW-ESE trending Terceira rift that runs through the Terceira island (orange arrow)(Montensinos et al., 2003).](image)
the western segment of the fault zone. The spreading is ultra-slow, only a half rate of 4 mm/yr (Searle, 1980).

**5.1.1 Terceira**

Terceira is one of the nine islands on the archipelago. Wide variety of rock formations and geological structures are seen on the island. Four volcanoes are present on the island; Serra do Cume, Guilherme Moniz, Pico Alto and Santa Barbara (Figure 52) (Nunes, 2000). The Basaltic Fissural Zone is located west of these volcanoes (Nunes et al., 2016). Volcanic products from this volcanic complex, mainly formed in Quaternary times, include pyroclastic deposits, evolved lava flows and basaltic lava flows (Nunes et al., 2016). Major structural lineaments have been mapped and recognized by GPS and InSAR data; trending NNW-SSE, ENE-WSW/NE-SW and WNW-ESE/NW-SE, parallel to the Terceira Rift (Marques et al., 2014; Nunes, 2015). The ENE-WSW lineament of Furnas do Enoxfre across the island runs obliquely to the Terceira Rift and has been related to a transform system of the Africa/Nubia-Eurasia plate boundary (Marques et al., 2105). Three basaltic eruptions have taken place on Terceira island since the islands settlement in the mid 1,400. The one in 1761 occurred on-land, east of Santa Bárbara Volcano and the other two in 1867 and 1998-2000 off-shore (Montensions et al., 2003). The volcanism is controlled by NW-SE to W-E fractures, and has shown both Hawaiian and Strombolian style resulting in formation of scoria cones, eruptive fissures and emission of aa and pahoehoe lava flows (Nunes et al., 2014).

**5.2 Pico Alto geothermal field**

The Pico Alto geothermal field is located on the intersection between the Pico Alto caldera, Guilherme Moniz caldera and the Basaltic Fissural Zone. At greater depth, the system interacts with the Santa Bárbara Volcano formations (Figure 53). Although a heat source cannot be confirmed directly, the young volcanic activity is thought to serve as a heat source for the geothermal system and its tectonic location (GeothermEx, 2010). The Pico Alto caldera is elongated in the direction of the Pico Alto volcanic system and has produced sheets of ignimbrite, dated 19,000 and 23,000 years BP as well as trachytic, trachydacites and rhyolite (Figure 54). Basaltic lavas have erupted from the Pico Alto plumbing system, suggesting a layered magma chamber. (Nunes, 2015). The Guilherme Moniz Volcano is mainly composed of pyroclastic deposits but also trachytes, rhyolites and trachydacites (Nunes, 2015). An interplay between evolved rock formations and a complex structure means that Pico Alto is a promising target for geothermal exploration (Sæmundsson et al., 2012).
Figure 50 A geological map of Terceira island showing main geological formations and surface tectonics. 1: Serra do Cume Volcano, 2: Guilherme Moniz Volcano, 3: Santa Bárbara Volcano, 4: Pico Alto Volcano; 5: Basaltic Fissural Zone, including the 1761 lava flow (yellow). Dotted areas include trachyte domes and coulées. a: volcanic and tectonic lineament, b: fault scarp, c: crater rim, d: caldera rim, e: basaltic eruptive centre, f: silicic eruptive centre, g: eruptive fissure, h: fumaroles, i: thermal waters spring. The red line shows the trend of the Terceira Rift, white circles indicate the geothermal wells (Nunes, 2000).
5.2.1 Previous studies

Geothermal exploration was initiated in Pico Alto by the Laboratório de Geociências e Tecnologia (LGT) in 1977-1979. A total of nine shallow (< 222 m) thermogradient (TG) wells were drilled in the area and a dipole-dipole resistivity survey was carried out (GeothermEx, 2010). An assessment of the geothermal resource potential was made in 1980 using all existing data. The electrical potential was estimated based on surface manifestations and characteristics of the volcanoes (Johnston, 1980). Geothermal Energy of New Zealand (GENZL) studied the geology and geochemistry in 1981. This resulted in a conceptual model in 1982 (GENZL, 1982).
Geological and geothermal mapping was conducted by LGT (Laboratory of Geosciences and Technology), Idrogeo slr and 3D Research snc in 1981-1998. This project was based on field work and aerial photography, interpretation of the volcanic stratigraphy, and the tectono-stratigraphic evolution of the island (Geoterceira, 2011). Geochemical samples were collected from fumaroles and steam in the Furnas do Enxofre area as well as cold water sampling throughout the island. The geological map was revised by adding tectonic elements. Radon, mercury and helium from soil samples were analysed. Fluid chemistry

Figure 52 The Pico Alto production area. The map shows the geometry of surface formations as well as tectonic features. Red lavas are from the 1761 eruption, light pink colour represents basaltic lava flows and dark pink pyroclasts. Gray coloured lavas are trachyte and pumice deposits. Green formations south of the production area belong to Guilherme Moniz Volcano. The blue line represents the cross section on Figure 53. Red square indicates the extent of the exploration area (Nunes, 2016).
data were collected in 45 springs on the island and their temperature measured. Finally, 18 MT resistivity soundings were carried out in the north-central part of the island (Idroego and 3R Research, 1994).

In 1982 they continued their work and measured gravity resulting in a Bouguer gravity map. A DC Schlumberger and a MT resistivity survey was carried out in 1982 (GENZL, 1982), and in 1999 – 2000, additional resistivity surveys were performed that included 624 AMT stations. These studies indicated the presence of a low resistivity cap in the vicinity of Furnas do Enxofre (GeothermEx, 2000a; Geosystem, 2000). Based on this survey, drill sites for thermogradient wells were located.

A conceptual model for Pico Alto was published by GeothermEx in 2000, presenting results and interpretations based on the resistivity surveys, temperature and fluid distribution as well as pressure and phase conditions (GeothermEx, 2000a). In 2003, four thermogradient wells were drilled, reaching maximum depth of 600 meters. They allowed evaluation of temperature distribution in the geothermal field. In 2006-2009, four production wells (PA) were drilled. Testing of these wells revealed high temperature in the reservoir (>240°C), two phase and steam dominated zones. An electrical potential of 50 MWe over the estimated lifetime of a typical power generation project (30 years) was suggested. Permeability of the reservoir is low, due to highly altered rocks. This means a relatively low productivity of the wells, ranging from 1 to 3 MWe for each well (Geoterceira, 2011). Results and conclusions of previous work and studies are summarised and published by Geoterceira in 2011 and followed by proposing the location of the main heat source, boiling and fluid paths distribution in the system, as well as possible locations of permeable zones. This feasibility study was reviewed by ÍSOR in 2011, and included a review of geological, geophysical, geochemical and reservoir engineering data, considering advantages and disadvantages of each dataset. Following this review, suggestions were made concerning future well sites and data acquisition.
Thus, a gravity survey was performed by Montensinos et al. (2014) using 174 stations, publishing new Bouguer and Free air gravity maps, as well as density contrast model using 3D gravity inversion of the complete Bouguer anomaly data (Montensinos et al., 2014). In 2016 another revision of the conceptual model was published by TARH and ÍSOR, and a detailed review of all results presented after 1999 was presented, including the AMT survey and flow tests from the TG and PA wells. The emphasis of this latest revision was on joint interpretation of geological, geophysical and geochemical data. This also included a study of the climate, geomorphology and soil characterization, geological conditions and groundwater hydrology (Carvalho et al., 2016).

A total of 664 earthquake events were recorded from April 2003 to March 2011 on Terceira by the Azores University. Only 6 stations, covering the whole island (~400 km²), were used for the survey. Two alignments were seen on the data; one related to the Furnas do Enoxfre lineament (ENE-WSW) and another one aligned in WNW-ESE direction (Nunes, 2014).

### 5.2.2 Input data

The following datasets are used for the construction of the 3D Pico Alto static data model and are mainly based on geological and geophysical results from the TARH and ÍSOR (2016) conceptual model. As previously – datasets are grouped into surface data and subsurface data. They are presented in Table 7.
<table>
<thead>
<tr>
<th>Dataset</th>
<th>Type</th>
<th>Source</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial image</td>
<td>Bitmap</td>
<td>USGS</td>
<td></td>
</tr>
<tr>
<td>DEM topography</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Craters, caldera, faults</td>
<td>Shape files</td>
<td>Nunes, 2015</td>
<td></td>
</tr>
<tr>
<td>Resistivity</td>
<td>Bitmap; shape files</td>
<td>GeothermEx, 2000a; Geosystem, 2000</td>
<td>Data are only available for -500 m, -250 m, 0 m, 100 m, 250 m and 500 m. No values are available between these depths.</td>
</tr>
<tr>
<td>Earthquakes</td>
<td>ASCI file - points</td>
<td>Nunes, 2014</td>
<td>Only 6 stations covering the whole Terceira</td>
</tr>
<tr>
<td>Gravity data; Free air, Bouguer, density contrast based on gravity inversion</td>
<td>Bitmap; shape files</td>
<td>Montensinos et al., 2014</td>
<td>Rugged features of the terrain made measurements difficult. Thus, the observations were complemented with previously acquired gravity data.</td>
</tr>
<tr>
<td>Well paths</td>
<td>ASCI file</td>
<td>Geotherceira, 2011</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>ASCI file-well log</td>
<td>Egilson et al., 2014</td>
<td>Only available for well PA2, PA3 and PA 4</td>
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<tr>
<td>Fluid temperature</td>
<td>ASCI file-well log</td>
<td>GeothermEx Inc., 2009; Egilson et al., 2014</td>
<td>Available as well logs and contour data (temperature distribution).</td>
</tr>
<tr>
<td>Alteration</td>
<td>ASCI file – points</td>
<td>GeothermEx Inc., 2009; Mateus et al., 2014; EDA, 2017</td>
<td>Different sources give varying results. Both were imported but kept separated in Petrel. Merged zoning is presented here, an unpublished work by EDA.</td>
</tr>
<tr>
<td>Lithology</td>
<td>ASCI file – points</td>
<td>Nunes, 2015; Geotherceira/GeothermEx, 2007</td>
<td>Lavas are highly altered that affects quality of analyses</td>
</tr>
<tr>
<td>Feed zones; large (1), small (2)</td>
<td>ASCI file - points</td>
<td>GeothermEx, 2010</td>
<td>Based on circulation losses and temperature fluctuations.</td>
</tr>
</tbody>
</table>
5.2.3 3D grid compilation

3D simple grid models were created for alteration, fluid temperature, resistivity and density (Table 8). Data, including reports, papers, shape files and figures were provided by João Carlos Carreiro Nunes (TARH) and António Luís Peixoto Franco (EDA). Although lithological logs were imported to Petrel, no lithology model could be created with a degree of certainty. Well to well correlations were not possible, due to lack of information on the formation types. They are highly altered and their lateral distribution is limited due to high viscosity. The lack of lithological wireline log data made it also unreasonable to attempt to correlate in between boreholes as well. Namely, the lithological origin have not been analysed from the well cuttings. With such a limited database, a lithology or facies model would include too many assumptions, and could introduce interpretation errors. The focus is, therefore, on the comparison with the existing 3D simple grid data sets and the wellbore locations in reference to each other.

Table 8 An overview for 3D models in the Pico Alto geological static model.

<table>
<thead>
<tr>
<th>MODEL</th>
<th>BASE LIMIT (M)</th>
<th>TOP LIMIT (M)</th>
<th>MODEL AREA (M)</th>
<th>MODEL TYPE</th>
<th>SOURCE</th>
<th>INTERPOLATION</th>
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<tr>
<td>ALTERATION MODEL</td>
<td>-1500</td>
<td>Topography</td>
<td>0.6 x 2.1</td>
<td>Simple grid</td>
<td>EDA, 2017</td>
<td>-</td>
</tr>
<tr>
<td>FLUID TEMPERATURE MODEL</td>
<td>-1500</td>
<td>600</td>
<td>0.6 x 1.1</td>
<td>Simple grid</td>
<td>Egilson et al., 2014; Geotherm Ex Inc, 2009</td>
<td>Kriging</td>
</tr>
<tr>
<td>RESISTIVITY MODEL (AMT)</td>
<td>-550</td>
<td>Topography</td>
<td>13 x 7.5</td>
<td>Simple grid</td>
<td>Geosystem, 2000</td>
<td>Kriging</td>
</tr>
<tr>
<td>DENSITY</td>
<td>-1500</td>
<td>1000 m</td>
<td>12.6 x 12.6</td>
<td>Simple grid</td>
<td>Montensions et al., 2014</td>
<td>Kriging</td>
</tr>
</tbody>
</table>
**Alteration**

The alteration model input is based on two different sources; Mateus et al. (2014) and well logs from GeothermEx (2010). No XRD analyses are available. Data from Mateus et al. (2014) are based on thin sections and binocular analyses of drill cuttings that are only present for PA wells. A first path alteration data from GeothermEx (2010) are available for the PA and TG boreholes, and are based on binocular analyses. Alteration minerals that are indicators of specific temperature ranges or permeability were imported to the model, and are grouped by their purpose within the model (Table 9). As the different input datasets were not very consistent in comparison, it is clear that the Pico Alto project would benefit from a detailed petrological analysis.

*Table 9 Alteration minerals detected in PA wells. Source 1: GeothermEx; Source 2: Mateus et al., 2014.*

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Source</th>
<th>Temperature indicator</th>
<th>Feed zone indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clays</td>
<td>1</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Oxides</td>
<td>1, 2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Silica</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quarz+Calcite</td>
<td>2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Chlorite</td>
<td>1</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Chlorite/Smectite</td>
<td>2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td>1, 2</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Pyrite</td>
<td>1, 2</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Epidote</td>
<td>1, 2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Sericite</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zeolites</td>
<td>2</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Anhydrite</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silification</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonatation</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sericitization/ilitization</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chloritization</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Alteration zoning in the model is based on information from EDA, where data from binocular analyses and thin section analyses are joined according to António Franco-EDA RENOVÁEIS, S.A. (personal communication May, 24th 2017). First appearance of epidote in PA 4 and PA 1 was first detected at 1229 m measured depth only (for PA 4) and 1673 m depth (for PA 1), respectively, causing the epidote zone to drop towards the NE and SW (Figure 55).
Fluid temperature

The fluid temperature model is based on information and data published in reports by ÍSOR and GeothermEx. Temperature logging was done by ÍSOR in 2013-2014 for four production wells; PA2, PA3, PA4 and PA8. These were continuous logs measured in static conditions (no flow). (Egilson et al., 2014). The resolution of the logs from GeothermEx, 2010 is slightly lower with a sample rate of 25 meters. These logs were used to calculate the fluid temperature model for PA1 and the four thermogradient wells (GeothermEx, 2010).

Figure 56 shows the highest temperature observed in the northern part of the exploration area, around PA 3 and PA 8, whereas the temperature is lower in the southern part. The highest temperatures have been detected in well PA 3 and PA 8 (283°C and 293°C).

Figure 57 displays comparison of alteration and fluid temperature. Epidote is formed at temperatures higher than 230°C. As noted before, the first appearance of epidote varies between wells, but alteration reference temperature and fluid temperature coincide quite well.
It is worth noting that these alteration zones are only composed of an interpretation of a few alteration minerals, resulting in a wide range of alteration reference temperatures. The fluid temperature model is based on few data and high temperature is concentrated around high temperatures in individual wells (PA 3 and PA 8). Therefore, it would be difficult to compare or explain with certainty whether or not the geothermal system is heating up or cooling down.
Feed zones were imported to the Petrel model, based on well log temperature fluctuations and circulation losses (GeothermEx, 2010). They were available for the production wells and grouped into small (1) and large feed zones (2), by GeothermEx based on their relative size (Figure 58). Small feed zones (1) are based on < 10 l/s of circulation losses during drilling whereas large feed zones are based on losses >10 l/s during drilling or that significant temperature inflections seen on the temperature logs. On Figure 58, large feed zones (orange) and small feed zones (green) are visualized with temperature. Large feed zones were dominant in wells PA 8 and PA 2.

![Temperature cross sections and feed zones in wells based on temperature fluctuations and circulation losses (green points: small, orange points: large).](image)

**Resistivity**

The pseudo 3D AMT resistivity model was constructed from shape files that contain the contour line data sets made up of a series of depth level resistivity maps (GeothermEx., 2000a; Geosystem, 2000). These maps represent resistivity distribution at -500 m, -200 m, 0 m, 200 m and 500 m a. sl. All contour lines for each map were digitised in Petrel and converted to point sets with each point´s x, y, z and resistivity value. The vertical resolution of the model was not good, since shape files were only available every 200 – 300 m. A drastic shift is seen in the model at 400 m a.sl. which is due to the high resistivity contrasts and lack of resistivity values between 500 m and 200 m a.sl (Figure 59). Each map contour set was double checked with the map image input. The resulting 3D simple grid model matches quite well with bitmap image input data (Figure 60).
Figure 57 Shape files and figures representing AMT values at certain depths.

Figure 58 Resistivity model constructed from shape files and an example of a cross check to make sure the model is consistent with cross sections. A drastic shift in resistivity between 500 m and 200 masl is due to lack of data in this depth range. Two conductive areas are seen in the data, the northern one is observed at all depth values and is located below the exploration area.
The resistivity data reveal a conductive anomaly, which is elongated in WNW-ESE direction, parallel to the Terceira rift, and close to the junction of the Terceira rift and the lineament of Furnas do Enoxfre (Figure 61). There is no apparent small scale trend connecting the surface tectonic features and the resistivity lineament. The exploration area is located at the north-eastern border of this conductive anomaly.

Figure 59 The resistivity structure of Pico Alto geothermal field at sealevel. The inferred calderas are visualized as black thick lines. The large scale tectonic lineaments; Terceira rift and the lineament of Furnas do Enoxfre are visualized as blue thick lines. Blue thin lines show volcanic tectonic lineaments, red eruptive features are domes and black eruptive features show craters.
**Gravity**

Bouguer, Free air and complete (residual) Bouguer gravity anomaly maps were obtained using gravity data distributed over two zones around the exploration area; Zone A (174 stations) and Zone B (229 stations) (Figure 62). Good data coverage within zone A increases reliability and enables a fairly good resolution of the anomalies. The complete Bouguer gravity anomaly map was used in the inversion, meaning that regional effects had been accounted for. The 3D inversion of gravity data shows spatial density variations, thus, providing information on the subsurface structure of Pico Alto (Montensinos et al., 2104).

![Figure 60 A complete Bouguer anomaly map. Measurement sites are represented as red triangles. Terceira rift and the lineament of Furnas do Enoxfre are visualized as blue thick lines. Blue thin lines show surface eruptive features, red eruptive features are domes and black eruptive features show craters. The map covers the whole Zone B, but Zone A is within the pink square. The large scale tectonic lineaments; Terceira rift and the lineament of Furnas do Enoxfre are visualized as blue thick lines. Blue thin lines show volcanic tectonic features, red eruptive features are domes and black eruptive features show craters.](image-url)
The density simple grid 3D model was also constructed from shape files that contain the contour line data sets of a series of depth level density maps. These depth level maps were at -1500 m, -1000 m, -750 m, -500 m, -250 m, 0 m, 100 m and 200 m a.s.l. They are based on a study done by Montensinos et al., 2014. The digitised contour lines were converted from lines to point data files in ArcGIS, similar to the resistivity contour line shape files. The model matched quite well with figures (Figure 63), except for gaps in the figures, representing no values that were not implemented into the model.

![Figure 61 Density model constructed from shape files and an example of a cross check to make sure the model is consistent with cross sections. The density contrast values used in the model correspond to a discrete set of values between -300 and 300 kg/m$^3$.](image)

![Figure 62 A horizontal section of temperature model visualized with the density model. Higher temperature is observed within the high density.](image)
A low density trend is observed in the south-eastern corner of the exploration area at the junction of the Terceira rift and NNE-SSW trending fault. North of the NNE-SSW trending fault higher density is seen. Low density anomalies are observed in the inferred calderas of Pico Alto and Guilherme Moniz. Figure 65 shows that the highest temperature is observed within the gravity high. In Montensinos et al. (2014) it has been suggested that this could be associated with the geothermal activity.

Figure 63 Density at sealevel. The inferred calderas are visualized as black thick lines. The large scale tectonic lineaments; Terceira rift and the lineament of Furnas do Enoxfre are visualized as blue thick lines. Blue thin lines show surface eruptive features, red eruptive features are domes and black eruptive features show craters. A low density is observed of the junction of Terceira rift and the lineament of Furnas do Enoxfre, and low density is observed within the exploration area.
Seismicity

Earthquakes recorded between April, 2003 and March 2011 were imported to Petrel. A total of 664 events were recorded in this time period and most of them occurred in the geothermal exploration area. They were grouped based on their size and depth distribution. Earthquakes from the research area are shown on Figure 66. The yellow points show earthquakes with magnitude <1, green points show earthquake with magnitude ranging from 1,1-2 and the red points show earthquakes greater than 2. Due to few seismic stations, the error of location are estimated >100 m (Nunes, 2014).

Figure 64 Earthquakes recorded from April, 2003 to March, 2011. The yellow points show earthquakes with magnitude less than one, green points show earthquake with magnitude ranging from 1,1-2 and the red points show earthquakes greater than 2.
5.3 Summary

In the third part of this thesis, the workflow presented in chapter 3 was applied to the Pico Alto geothermal field. No data existed in Petrel before this thesis work had started, except for the DEM model and the aerial GIS photo assemblage of Terceira. All accessible data were imported to the model and the first static geological model was constructed. In addition to the data compiled for the conceptual model that was published by ÍSOR and TARH in 2016, data were received from João Carlos Carreiro Nunes (TARH) and António Luís Peixoto Franco (EDA), which include:

1. Surface mapping (faults, fissures and craters)
2. AMT resistivity data
3. Location of seismic events (2003-2011)
4. Gravity data, Bouguer, Free air maps, density model
5. Geophysical logs (pressure, temperature)
6. Hydrothermal alteration zonation
7. Lithological logs
8. Grouping of feed zones

The main effort was put into generating 3D models from the available datasets. Borehole data were used for constructing an alteration model and temperature model. Resistivity model and density model were built from shape files and bitmap images. Detailed values were available on lateral scale, but the vertical resolution was not as good. However, these models give good indications for large scale structural lineaments.

Out of the four 3D models that were generated, two represented large scale variations around Pico Alto (resistivity and density). Both of them reveal an anomaly where two structural trends meet; the Terceira rift and the ENE-WEW trending lineament of Furnas do Enoxfre. The two remaining models, alteration and temperature, only show variations within the drilled area, as they were based on well data only.
6 Workflow comparison and future work

As one of the main objectives of this thesis is rather to generate an approach for constructing a geological static model, than to make an effort of solving individual problems, many questions have come up during the process that cannot be answered here. Throughout the modelling process for both Krafla and Pico Alto geothermal fields, data comparison and compilation revealed where gaps of data or understanding need to be filled, which would result in a more coherent and reliable model.

Subdivision of datasets that build up the geological static model was presented in Figure 6 in section 1.2. This was built from literature studies from other geothermal areas as well as petrological studies. As every model is dependent on its input data, the applicability of a workflow is also determined by available data for each area.

The main emphasis in the construction of the Krafla geological static model, was revising the geological model with the addition of lithological data, evaluation of faults in the model and the addition of a possible basement. As this was a revision of a conceptual model, updated data was compared to pre-existing data and interpretations. The structural framework of Krafla was also of interest in this project. Numerous datasets could be compared directly and structural similarities pointed out.

As no 3D data from Pico Alto were available in Petrel before this work started, the modelling emphasis was different. Due to limited data available for the Pico Alto geothermal field, data didn’t allow the same data comparison as for Krafla. The applicability of the workflow was mainly in the form of technical methods, namely step 1, 2 and 4 in the workflow. The main effort was generating 3D models and sorting and listing different data sources.

Much work remains to be done for both areas and suggestions for future work that came up during the model construction, is listed in the following sections. Figure 6 in section 1.2 was adjusted to each geothermal area, where the input datasets that were included in the model are labelled with a black font and datasets that could reveal more information but do not exist are labelled grey.

6.1 Krafla geological static model

In this project, various datasets have been compiled and visualized for better representation and understanding of both the large scale and small scale pictures of the Krafla geothermal area. Figure 67 gives an overview of the data that have been implemented to the Krafla geological static model. It shows how most input datasets were used for structural interpretations and a geo-property model. Most input data are lacking in the petro-physical model and the hydrological model.
6.1.1 Future work and modelling suggestions

Although a large amount of data is available for the Krafla geological static model, much work remains to be done in understanding the system and many explanations are required. Several follow-up studies become apparent such as the following:

1) For a deeper understanding of the internal structural conditions of this complex field, a study of the structural field and borehole data is necessary, which might result in a better understanding of the structural elements and stress field orientations of the Krafla area. A structural analysis would result in a more detailed geological static field model as well as a better understanding of the correlation between potential flow paths and reservoir connectivity. Lithology, BHTV (borehole-televiewer) or fault plane solution data, from the inferred transform graben, would give more information on the geological structure.

2) Furthermore, it is necessary to implement geochemistry and production data into the newly updated structural model, and run additional tracer tests. A comprehensive comparison of known production data (flow, T/P logs) to the structural and lithological model would enable a reservoir volume estimate and highlight potential exploration areas.
3) In order to construct a more detailed lithological model, an additional petrographic comparison and analyses of all borehole data would be useful. This would include using existing borehole data analyses and newly acquired borehole data. Re-analyses of felsic formations in Krafla could also support the existence of the inner caldera.

4) An improved resistivity model based on denser data coverage and 3D inversion of the static shift corrected MT data.

5) A 2D or 3D interpretation of the gravity data, constrained by borehole data and seismic studies would result in a model of subsurface density distribution. The results could be used to constrain the 3D resistivity model.

6) Petro-physical analyses data such as density, porosity and permeability, compared with pressure (hydrostatic/lithostatic), and present state formation temperature reservoir model, would reveal information of super-critical reservoir conditions in the reservoir.

7) After the successful VSP experiment in the IMAGE project, it seems to be a good idea to continue subsurface imaging of the Krafla field or any other high temperature field through borehole seismics. This includes near offset surface receiver lines for imaging structures between boreholes and near field subsurface structures that are not visible on the surface. The broad borehole and potential field data interpolation methods provide a good general understanding of the structural settings of the field. However, they cannot support the smaller and secondary structural elements. The VSP method could, therefore, prove to be a valuable and risk decreasing method for borehole targeting and understanding of the internal reservoir geological structures.
6.2 Pico Alto geological static model

Figure 68 shows the input data in the Pico Alto geological static model, listed on the flow chart. No coherent model can be built from these input data, which is no surprise, working with data from a Greenfield area.

6.2.1 Future work and modelling suggestions

For a more comprehensive geological-static model for Pico Alto geothermal field, the following suggestions are made:

1) Different qualities of lithological analyses and lack of geophysical logs made the correlation between wells difficult. A revision of the lithology in the PA wells exists. It is needed for the TG wells, specifically for a better understanding of the geological architecture and extent of the individual formation zones. Additional well data and petrographic and isotope analyses would be crucial to provide a better correlation tool.

2) As the main challenge in Pico Alto is mapping the permeability, interpretations of faults and fissures would benefit from a structural interpretation field study, seismic monitoring resulting in seismicity fault plane analysis, additional tracer tests, and
further borehole data acquisition, such as a structural log analysis of BHTV data. Having surface faults and fissures interpreted, provides information on possible fluid paths and allows more integration between datasets and consideration of Pico Alto within the large tectonic framework.

3) As a support for the structural interpretation, more precise earthquake location would be useful, including analyses of focal mechanism.

4) Although the AMT resistivity model coincides quite well with temperature distribution, its depth of penetration is very shallow. An MT survey and accompanied 3D resistivity model reaching to greater depths would be useful.

6.3 Conclusion

The main product of the revision of the Krafla geological static model was the workflow that was applied to the Pico Alto geothermal Greenfield. Although the availability of data was different for the two areas, the workflow was applied with success, and provided additional information about the two geothermal fields. The main conclusions of this study are the following:

- The resulting workflow, developed from the construction of the Krafla geological static model was applied to the geothermal field in Pico Alto. Five principal steps are presented in the workflow. Although, the same workflow was followed during the construction of the two geological static field models, the output models were different and restricted by the available data.

- An agreement is seen between the different datasets in Krafla, where the most striking features are NE-SW trending lineament and WNW-ESE trending lineament. The oblique rifting across the NVZ seems to influence the structural framework that shows an asymmetry across the WNW-ESE trending lineament. Deep structures, e.g rotation and en-echelon arrays that have been described in the Þeistareykir fissure swarm, are also observed in some subsurface datasets in Krafla.

- The exploration area in Pico Alto is also located at a junction of two different lineaments. Large scale data show a clear anomaly at the junction of the Terceira rift and the lineament of Furnas do Enoxfre.

- For both areas, the geological model gives a static overview that is essential for geo-scientists that collect and interpret data, but also for clients to see data coverage and estimate the models reliability. Having a certain approach for listing and treating data, as well as a platform where all results are brought together saves time and results in a faster way of comparing data.

For the two geological static models, there are still gaps that need to be filled with further researches and modelling work. As there is no such a thing as a final geothermal field model, the workflow could be run again with additional knowledge with the aim of improving the models.


Appendix A

Table 10 3D sub-models within the Krafla Geological static model

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Base limit (m. b. sl)/Topograpy</th>
<th>Grid cells nI x nJ x nK</th>
<th>No. of layers</th>
<th>Cell thickness</th>
<th>Interpolation method</th>
<th>Vertical direction</th>
<th>Major dir x Minor dir</th>
<th>Source</th>
<th>Comments (use, constraints)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological model</td>
<td>-2000 / Topography 2.7 x 2</td>
<td>Pillar gridding 10 horizons</td>
<td>81 x 75 x 9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Well reports uth</td>
<td>Uncertainties: Different interprets, depth corrections, model manually controlled (faults, horizons etc.). Useful for well targeting and design, what fault and geological units the well path will intersect.</td>
</tr>
<tr>
<td>Geological facies model</td>
<td>-2000 2.7 x 2</td>
<td>Simple grid, upscaling from 10 to 45, depending on variation within the layer</td>
<td>81 x 75 x 125</td>
<td>50</td>
<td>Sequential indicator simulation</td>
<td>200</td>
<td>5000</td>
<td>Well reports uth</td>
<td>Faults are excluded from the model. Mainly automatically controlled, by scaling up well logs. Useful to compare to the main geological model and allows further calculations and interpretations about physical properties of the rock (porosity etc).</td>
</tr>
<tr>
<td>Model</td>
<td>Grid Size</td>
<td>Upscaling</td>
<td>Grid Type</td>
<td>Well Reports</td>
<td>Notes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
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<td>----------------------------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intrusions facies model</td>
<td>-2000</td>
<td>2.7 x 3</td>
<td>Simple grid, upscaled</td>
<td>Well reports</td>
<td>Cells are upscaled where intrusinos cut well paths. The model could be developed further using interpolation allowing high vertical range. As intrusions are missing from the geological and facies model, upscaled intrusions are important for joint interpretation.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alteration model</td>
<td>-3000</td>
<td>5.3 x 5.3</td>
<td>Simple grid</td>
<td>Well reports</td>
<td>The model has not been updated since 2015. Since then, one well has been added additional information (quatrz and disappearance of calcite) are visualized as horizons on the model. Alteration model is crucial to compare to resistivity and temperature model.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Temperature model</td>
<td>-2000</td>
<td>5.6 x 5.6</td>
<td>Simple grid, upscaled</td>
<td>Well reports</td>
<td>The model was created in 2009 and has not been updated since. Three wells, IDDP-1, K-40 and K-41, have been drilled after the latest revision and are thus not incorporated into the model. Formation temperature model is used to estimate thermal evolution of the system.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model Type</td>
<td>Res. Range</td>
<td>Grid Size (m)</td>
<td>Upscaling Factor</td>
<td>Resolution (m)</td>
<td>Interpolation</td>
<td>Depth Increment</td>
<td>Author(s)</td>
<td>Notes</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>------------</td>
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<td>---------------</td>
<td>----------------</td>
<td>--------------------------</td>
<td>----------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Resistivity model</td>
<td>-15000</td>
<td>12.4 x 10</td>
<td>Simple grid</td>
<td>130 x 103 x 128</td>
<td>Kriging</td>
<td>100, 200, 500, 1000, 2000, 3000</td>
<td>Arnason, 2008</td>
<td>Layered earth: 30 - 40 layers, with constant thickness, increasing exponentially with depth. Absence of conductors in the transform graben. Depths to magma chamber could not be determined as there was uncertainty in how to interpret the low res</td>
<td></td>
</tr>
<tr>
<td>(3D)</td>
<td>-11000</td>
<td>11.5 x 11.5</td>
<td>Simple grid</td>
<td>245 x 245 x 109</td>
<td>-</td>
<td>100</td>
<td>Knútur Árnason/Guðn Í Karl Rosenkjaer, 2015</td>
<td>The WSINV3DMT code assumes flat surface</td>
<td></td>
</tr>
<tr>
<td>Tomography model</td>
<td>6000/10000</td>
<td>21.6 x 26</td>
<td>Simple grid</td>
<td>491 x 573 x 140</td>
<td>Closest/Function</td>
<td>-</td>
<td>Joan Shuler</td>
<td>The grid spacing in the model tested with 1, 2, and 3 km wide grid nodes, but depth spacing was denser near surface because of higher density of earthquakes in the top 3 km. The grid increment is 110 x 110 and depth spacing 500 meters. The spacing is doubled towards the edges of the model.</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Table 11 Interpolation algorithms used in the modelling work. They are all stochastic algorithms.

<table>
<thead>
<tr>
<th>Interpolation</th>
<th>Description</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kriging</td>
<td>Uses a variogram expressing the spatial variability of the input data. Error of estimation is low. Gives the user control of advanced settings.</td>
<td>Not suitable for large input data. Gives the value with the highest probability for each point (reduces high values and increases low) can cause errors. Relatively fast because transfer to external algorithms is not required.</td>
</tr>
<tr>
<td>Kriging (Gslib)</td>
<td>The same method as Kriging but using external files and the Gslib executable. Search radius in fraction of variogram. Gives the user control of advanced settings.</td>
<td>Slower than Kriging because it uses external executable</td>
</tr>
<tr>
<td>Kriging interpolation</td>
<td>Data points are smoothly connected. Considers data only within the variogram type. Works in XYZ.</td>
<td>Relatively fast because transfer to external algorithms is not required.</td>
</tr>
<tr>
<td>Closest</td>
<td>Assigns the values of the closest input point to each cell in the model. An orientation can be set so that the search around the cell is weighted in a specific direction.</td>
<td></td>
</tr>
<tr>
<td>Functional</td>
<td>Creates a 3D function. The cell values are interpolated with a weighted distance to the input data.</td>
<td>Medium fast and can fail with too few input points. The algorithm will create values higher and lower than the min/max values of the input data.</td>
</tr>
<tr>
<td>Sequential indicator simulation</td>
<td>The result is dependent on upscaled well log data, defined variogram, random seed, frequency distribution and trends in 1D, 2D and 3D.</td>
<td>Most appropriate to where either the shape of facies bodies is uncertain or where number of trends control the facies type. Local variations away from input data can cause uncertainties.</td>
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Appendix C
Legends for the geological map by Sæmundsson, 2008a.
## Appendix D

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## Appendix E

### Silicic formations in Krafla

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