Reservoir Assessment of the Ölfus-Bakki Low-Temperature Geothermal Area, SW Iceland

Javier Gonzalez-Garcia

Faculty of Earth Sciences
University of Iceland
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Reservoir Assessment of the Ölfus-Bakki Low-Temperature Geothermal Area, SW Iceland

Javier Gonzalez-Garcia

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Advisor(s)
Dr. Gudni Axelsson
Dr. Einar Gunnlaugsson
Dr. Gunnar Gunnarsson

Faculty Representative
Dr. Gudni Axelsson

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
Askja, Sturlugötu 7
107, Reykjavik
Iceland

Telephone: 525 4000

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Abstract

The Ölfus-Bakki geothermal area in SW Iceland is located in the S and SE margins of the high-enthalpy systems of Hveragerði and Hengill, respectively. This geothermal field contains a productive region, denominated the Bakki field, which produces fluid at temperatures in the range of 100-130 °C. Since 1979, the geothermal resource has supplied thermal energy to the town of Þorlákshöfn, mainly for space heating and aquaculture. The central objective of this study is to provide a reservoir assessment supported by the integration of the available information for this location. The methodology employed included 1) the interpretation of well logging data for pressure and temperature, 2) the interpretation of geochemical data, 3) the mapping of baric, thermal and geochemical anomalies, 4) the preparation of a volumetric assessment of the reservoir and 5) the preparation of a lumped parameter model for the Bakki field. The combination of these methods allows an improved understanding of the natural state of the reservoir as well as its response to production under different scenarios.

Data from nearly 24 wells was analyzed. Given the availability of data, the scope of the present assessment is constrained to the uppermost 1000 m of the reservoir. Analysis of the patterns of pressure and formation temperature allowed the identification of a convective system migrating southwards, very likely associated to the neighboring high-enthalpy geothermal system at Hveragerði. Chemical analyses permitted characterizing the fluids from the entire region into distinctive units. This characterization provided valuable clues to discern fluid provenance, as well as to identify possible recharge zones. Results from the volumetric assessment, based on a Monte Carlo simulation, indicated a mean reservoir capacity between 210-730 MWth for lifetimes between 30-100 years, with a 90% confidence interval of 98-1200 MWth. Lumped parameter modeling indicates that Ölfus-Bakki is an open system with unconfined aquifers. Current utilization is considered to be sustainable for the next 300 years given that production keeps growing at a similar rate compared to the past 20 years.
Dedication

To my dear family, for their support and inspiration.
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Abbreviations

a  Anno, year
bar-g  Bar gauge (pressure)
B.P.  Before present
E  East
GMT  Generic Mapping Tools
ÍSOR  Iceland GeoSurvey
m a.s.l.  Meters above sea level
m b.s.l.  Meters below sea level
MW  Megawatt
MWth  Megawatt thermal
N  North
NE  Northeast
NW  Northwest
ÖBGA  Ölfus-Bakki Geothermal Area
REYST  Reykjavik Energy Graduate School of Sustainable Systems
RP  Reykjanes Peninsula
RMS  Root mean square
S  South
SE  Southeast
SISZ  South Iceland Seismic Zone
SMOW  Standard Mean Ocean Water
SW  Southwest
WGS84 World Geodetic System 1984
WVZ West Volcanic Zone

B Boron
C Carbon
Ca Calcium
Cl Chlorine
D Deuterium
HCO₃ Bicarbonate
H₂S Hydrogen sulfide
K Potassium
Mg Magnesium
Na Sodium
O Oxygen
pH Potential of hydrogenation
SiO₂ Silica
SO₄ Sulfate
δ Isotopic deviation from standard ocean water

BA-01 Bakki 1
EB-01 Riftún 1
GH-04 Gljúfararholt 1
HJ-01  Hjalli 1
HV     Hveragerði
KS-01  Króggólfsstaðir 1
LL-01  Litlaland 1
NU-08  Núpar 8
ÞS-01  Þoróddstaðir 1
ÖL-01  Öxnalækur 1

\( A \)     Surface accessibility
\( C \)     Volumetric heat capacity
\( E \)     Heat content
\( Q \)     Production rate
\( \dot{Q} \) Thermal power
\( R \)     Recovery factor
\( T \)     Temperature
\( V \)     Volume of reservoir studied

\( res \)     In the reservoir
\( rock \)    In the rock
\( fluid \)   In the fluid

\( \beta \)    Heat capacity
\( \phi \)    Porosity
\( \kappa \)  Storage coefficient
\( \rho \)    Density
\( \sigma \)  Mass conductance coefficient
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1 Introduction

The Ölfus-Bakki geothermal area (ÖBGA) is a low-temperature geothermal resource located in SW Iceland. The study area for this project includes the west bank of the Ölfus River estuary. Its natural boundaries include the Hveragerði-Ingólfsfjall highlands to the N and NE, the Skálafell table mountain to the W, the River Ölfus to the E, and the North Atlantic Ocean to the S. This location is approximately contained between the parallels N64°02'-N63°54' and the meridians W21°27'-W21°00' (WGS84). The mentioned region lies in proximity to the towns of Hveragerði to the N, Selfoss to the E and Þorlákshöfn to the S.

Some of the wells in Ölfus-Bakki have been producing thermal fluid for the Þorlákshöfn district heating system since the late 1970s. The neighboring region around these wells is known as the Bakki Field (Figure 1-1). The resource from this field is also utilized locally for aquaculture, requiring much lower temperatures. Some shallow wells throughout the area provide fluid for this purpose. Currently, the wells servicing the Þorlákshöfn district heating system are managed by Reykjavik Energy.

Figure 1.1 Location of the ÖBGA, showing the Bakki and Hveragerði fields. Boreholes: black stars. Surface thermal manifestations: orange dots. Surface faults: red lines. Structural lineaments: green lines.
This report documents the research conducted by the author at REYST during the spring and autumn semesters of 2010. Its original intention was integrating the maximum amount of available information about the study area. This included data on the temperature and pressure conditions, production history as well as the chemistry and geology of the ÖBGA. The information was compiled and analyzed in order to conceive a consistent conceptual model that explains the nature and current state of the system. Such model must be capable of assisting in the formulation of projections for production capacity and future system behavior.

Keeping this goal in mind, the project was structured around five chapters. Chapter 2 presents a general bibliographic review of the most relevant research pertaining to the ÖBGA. This chapter contains six sections covering important aspects such as geological history and structure, mineral alteration, and hydrology. Chapter 2 aims at providing a comprehensive immersion in the principal ideas and hypotheses that have shaped the current understanding of the ÖBGA.

Chapter 3 describes the most important details regarding the different methods used in this project. The chapter is divided in five sections, each one discussing the main procedural aspects necessary to achieve the results presented in this report. Chapter 4 contains the results of the different analyses conducted. Spatial analysis and visualization was a key element in this project, and its results are discussed in this section. The interpretation of the information presented in the new maps was subsequently used in the modeling processes. As a result, the thermal capacity of the reservoir was estimated using a volumetric method (Section 4.2). Complementarily, the pressure response of the system was simulated based on assumptions inferred from the previous results (Section 4.3).

Once the main findings from the analyses, simulations and projections were presented, it was necessary concluding this paper with the integration of the new information into a final conceptual model. This model needs to be supported by the entire body of evidence available at this time. Additionally it must be able to explain the observed phenomena, and must be able to be validated by future discoveries and developments. It is expected that the model presented in this report fulfills these requirements.
2 Previous Research Summary

This section comprises an overview of the published information regarding the ÖBGA. Several authors have studied the region over the last four decades. For this reason, this section intends highlighting only the aspects that are relevant to the purpose of this project, rather than being a comprehensive bibliography review on the ÖBGA. The information presented in the following sections provides a contextual basis for the analyses conducted in further chapters.

2.1 Geological history and lithology

The ÖBGA is located at the triple junction between the West Volcanic Zone (WVZ), the Reykjanes Peninsula rift zone (RP), and the South Iceland Seismic Zone (SISZ). The lithosphere in this area has been accreted due to active rifting over the last 3 million years (Figure 2-1) (Tronnes, 2003). Over the same period of time, there is evidence for at least 20 major glaciations occurring in Iceland (Tómasson et al., 1975). As a result, the geological configuration of the area is caused by the interaction between an active spreading center and periodically-occurring glacial masses.

![Figure 2.1 Crustal propagation pattern in Iceland. The isochronous lines are labeled in Ma. (Tronnes, 2003)](image)

Volcanism in active rift zones is associated with tholeiitic basalts (Tronnes, 2003). When these basaltic lavas erupt subaerially, they flow across a topographically controlled extent. Similarly, pillow lavas are formed when the eruptions occur under deep water.
When an eruption occurs in a molten chamber under a glacial mass, a hyaloclastite unit is formed. The dynamics of these processes is described in more detail by Jakobsson and Gudmundsson (2008).

The surface geology, shown in Figure 2-2, is described by Pullinger (1991) and Sinton et al. (2005). The former author described the units outcropping around Núpafjall, while the latter studied the postglacial lava flows. A brief explanation of the units outcropping to the west of the study area is presented next in chronological order.

Figure 2.2 Geological map from Ólfus-Bakki (Friðleifsson, 2006). The surface geology and geomorphology are characteristic of a table volcano or tuya at Skálafell.

Unit 1 is composed of basaltic vitreous tuff breccia. Rocks in this unit present a glassy matrix that has undergone extensive palagonitization. The unit outcrops at the base of the cliff at Þurarhnúkur. The presence of vitreous tuff breccia suggests proximity to the surface of the glacier (Pullinger, 1991). This unit was formed during the Pleistocene epoch, product of a subglacial eruption possibly during a glacial period (Elsterian?).

Unit 2 is composed of a sequence of basaltic lavas. The rocks in this unit have been classified as aphyric olivine tholeiites. Three distinct members are described, namely olivine tholeiite lava flows, a transition zone made of subaerial lavas and tuff breccia, and a
series of olivine tholeiite pillow lavas and pillow breccias. The sequence is believed to be representative of subaerial lava flows entering the ocean, with the transitional zone being an indicator of the water level during the time of formation. The current position of the transitional zone indicates a marine transgression with a coastline standing 90-100 m above its present level (Pullinger, 1991). Given its relative position, it is likely that unit 2 was formed during the Holsteinian interglacial stage (300-250 ka).

Unit 3, also known as Kviar lavas, consists of a series of tholeiitic lava flows. The rocks show porphyritic texture with plagioclase phenocrysts. This formation overlays a series of sediments of fluvial and glacial origin. These sediments suggest the occurrence of a period with no volcanism in the area and dominated by erosion. The age of this unit is presumed to be approximately 300-250 ka (i.e. Holsteinian interglacial stage), and is related to an eruption of the Hveragerði central volcano. Unit 3 overlays a series of glacial and fluvial sediments, indicating a glacial period with no volcanism in the area. Unit 4, also referred as Þurarhnúkur hyaloclastite, corresponds to a series of tuffs, aphyric tholeiitic orthobreccias, and para-pillow lavas. This unit is product of subglacial eruptions during the Saalian glacial period (ca. 130-200 ka). The absence of a lava shield cover is an indicator that the volcanic activity was entirely subglacial (Pullinger, 1991).

Unit 5 is composed of para-pillow lavas, ortho- and para-breccias, and tuff breccias. The rocks present high vesicularity, suggesting shallow emplacement. The unit has been intruded by multiple feeder dykes, small sills and a large basaltic laccolith. This unit is thought to be product of subglacial eruptions during the Saalian glacial stage. Unit 6, Skálafell shield lava, consists of porphyritic basalts with olivine and plagioclase phenocrysts. The unit is product of subaerial volcanic activity during the Allerod interstadial (ca. 11 ka). Glacial advance during the Younger Dryas is inferred by the presence of polished surfaces, glacial striae and glacial sediments on the surface of the lava (Pullinger, 1991).

The hyaloclastites found at the peak of Mount Skálafell are not described by Pullinger (1991). However, the geomorphologic configuration of that unit suggests that it might be the product of subglacial eruptions during either the Younger or Older Dryas stadials. This unit marks the last volcanic episode in Skálafell as younger lava flows erupt from fissures located to the west of the area of interest.

The postglacial units found in the area correspond to subaerial eruptions having their origin in crater rows on the active rift zone. Pullinger (1991) refers to these lava flows as units 7, 8 and 9; whereas Sinton et al. (2005) refer to them as Hellisheiði A, Hagavíkurhraun and Nesjahraun, respectively.

Hellisheiði A is composed of plagioclase porphyritic basalts with large phenocrysts (15 mm) (Pullinger, 1991). According to $^{14}$C dating the unit was formed approximately 9240 years B.P. (Sinton et al., 2005). Hagavíkurhraun is also plagioclase porphyritic basalt, showing phenocrysts of 2-3 mm (Pullinger, 1991). The age of this unit was estimated at approximately 5000 B.P ($^{14}$C) (Sinton et al., 2005). Nesjahraun presents similar composition with sparse content of phenocrysts (1-3 m) and an age of 1865 B.P. ($^{14}$C) (Sinton et al., 2005).
The lithology of boreholes HJ-01, BA-01 and EB-01 (Figure 1-1) has been analyzed (Kristmannsdóttir et al., 1976; Tómasson et al., 1987). Appendix A shows the lithological records as well as the distribution of hydrothermal alteration minerals in these boreholes. A detailed description of the logs can be found in Kristmannsdóttir et al. (1976) and Tómasson et al. (1987). The logs mainly show a series of intercalations of sections dominated by basalts and sections dominated by hyaloclastites. Given the relatively uniform lithology observed in these well logs, comparable to the surface geology, it is likely that the deeper units originated through similar processes as the surface units. An effort to correlate the geological units from the boreholes across the Ölfus-Bakki region is presented by Sigurðsson et al. (2006). Figure 2-3 shows the geology, temperature, aquifers and mineral alteration zones as interpreted by these authors.

2.2 Tectonics and structural geology

As mentioned in Section 2.1, the Ölfus-Bakki geothermal field is located in a triple junction zone where different stress fields converge (Figure 2-4). The region is influenced by the tensional stress regime caused by active rifting in the Western Volcanic Zone and the Reykjanes Peninsula. Additionally, there is the influence of transform motion associated with the South Iceland Seismic Zone. The SISZ accommodates the left-lateral shear strain caused by two rifting zones (i.e. the Western Volcanic Zone and the Eastern Volcanic Zone) in a pattern of parallel, N-S trending, right-lateral faults known as bookshelf faulting (Sigmundsson, 2006).
Three fracture trends have been measured in the area (Pullinger, 1991). The first one is a NE-SW pattern of sub-vertical joints and normal faults parallel to the fissure swarm related to the spreading center (WVZ, RP). The second trend is a series of joints and left-lateral faults oriented N-S, and related to the SISZ. The third trend is a set of joints in a preferential E-W direction, possibly related to updoming caused by shallow intrusions (Pullinger, 1991).

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**Figure 2.4.** Regional map showing the tectonic configuration of S Iceland (Sigmundsson, 2006).

**Figure 2.5.** Subsurface structure inferred from seismicity. a) Earthquake loci distribution, b) Interpreted buried faults (green) and surface faults (blue) (Hersir et al., 2009).
Seismicity has also provided information about the subsurface structure. The frequency and loci of tremors in the area has been mapped (Figure 2-5a), revealing the location of active lineaments buried beneath the surface (Figure 2-5b) (Hersir et al., 2009).

2.3 Hydrothermal alteration

The mineral composition of the basaltic rocks in the ÖBGA consists principally of Ca-plagioclase, clinopyroxene, olivine and iron ore minerals (i.e. magnetite or ilmenite). These minerals are subjected to progressive alteration by interaction with thermal water in regions of high permeability. The secondary mineral assemblages are characteristic of the temperature conditions present in the reservoir during the time of alteration. When the reservoir temperature decreases, cooler assemblages are formed in a process denominated retrograde alteration (Winter, 2001). However, retrograde alteration exhibits extremely slow kinetics, and could be eclipsed by the presence of higher-temperature alteration (Kristmannsdóttir, 1975). This effect makes hydrothermal alteration an indicator of the maximum temperature reached by the reservoir, particularly for those cases when the temperatures encountered are lower than the mineral temperatures.

Hydrothermal alteration in Icelandic basalts was studied by Kristmannsdóttir (1975). This author identified three main alteration zones named after their characteristic minerals. These are, arranged by increasing temperature: smectite-zeolite zone, mixed-layer clay minerals-prehnite zone, and chlorite-epidote zone (Figure 2-6). A similar classification was presented by Franzson (1998), who proposed five alteration zones, namely smectite-zeolite (40-200 °C), mixed-layer clay minerals (200-230 °C), chlorite (230-240 °C), chlorite-epidote (240-350 °C) and amphibole (>350 °C). Moreover, Franzson (2003) presents the temperature of alteration for individual minerals: laumontite (120-150 °C), wairakite (>200 °C), chlorite (>230 °C), epidote (>240 °C).

The cross section in Figure 2-3 shows the vertical distribution of alteration zones. Three main zones are observed across that profile, corresponding to laumontite, chlorite-wairakite and epidote. It can be seen in this figure that the reservoir temperature is lower than the hydrothermal alteration temperature. From this observation it is inferred that the reservoir has cooled from a maximum temperature indicated by its secondary minerals. The alteration assemblages of wells LL-01, HJ-01, BA-01 and EB-01 are shown in Appendix A.
2.4 Surface manifestations

Hot springs and fumaroles are present in the Ölfus-Bakki area. Figure 1-1 shows the location of the main clusters of geothermal activity seen at the surface. A lineament of hot springs (both active and extinct) trends in a rough NE-SW direction across the Bakki area. A large cluster of fumaroles is located around the Hveragerði high-temperature geothermal field. Another set of fumaroles is located in the Hverahlíð field, just north of Mt. Skálafell. Surface manifestations are indicated by orange triangular symbols in the maps of Section 4.1 as well as in Appendices C and D.
2.5 Hydrology

In the general hydrological model presented by Tómasson et al. (1975) and Árnason (1976), thermal water in the lowlands originates as precipitation falling in the highlands, seeping down into a groundwater system, and migrating through zones of enhanced permeability driven by a hydraulic gradient. This pattern is illustrated in Figure 2-7. Differences in deuterium content in present-day precipitation are used as evidence to support this model, since precipitation falling in the interior has been depleted of the heavy isotope compared to that falling near the coast.

![Figure 2.7. Map of the concentration of deuterium in the precipitation, and the boundaries of the active volcanic zone in SW Iceland (Tómasson, 1975).](image)

Kristmannsdóttir and Sveinbjörnsdóttir (1992) show that the waters in Bakki are relatively depleted in D and enriched in both Cl and $^{18}\text{O}$. The authors interpret the low δD content as a distant water source (i.e. Langjökull), and the high Cl as a component of marine origin. The oxygen isotope shift is interpreted by Zhang (2001) to be the product of water-rock interaction at the temperature conditions in the reservoir.
However, Arnórsson and Andrésdóttir (1995) show that the low deuterium content might be caused by mixing of a relatively saline, δD-depleted component (i.e. seawater-freshwater mixture) and a Cl-deficient component with a higher δD value (i.e. local precipitation). Their interpretation involves local meteoric recharge moving down through fractures and mixing with older groundwater. The older groundwater still present today is suspected to be a mixture of seawater and freshwater entering the reservoir during the last deglaciation. This component has low mobility perhaps due to a small hydraulic gradient (Arnórsson and Andrésdóttir, 1995).

Fridleifsson (1978) characterizes the hydrologic suitability, or potential, of geothermal reservoir rocks in Iceland based on structure and primary porosity. The highest potential in quaternary rocks is seen in stratiform horizons of pyroclastics, ignimbrites and sediments; in olivine tholeiite compound lava shields; and in primary and reworked hyaloclastites. Pillow lavas are considered to have high effective permeability, serving as potential aquifers, whereas glassy hyaloclastites, doleritic intrusions and lava flows present low effective permeability, thus acting as potential aquitards. Bedding planes separating low-permeability volcanic layers can also act as conduits for groundwater flow (Fridleifsson, 1978). High permeability is also found around faults and interconnected joints.

2.6 Adjacent high-enthalpy systems

The Ölfus-Bakki geothermal field is located to the S and SE of the Hengill volcanic complex. Three distinct volcanic systems (viz. Hengill, Hrómundartindur, Grensdalur) provide heat to five geothermal systems (viz. Nesjavellir, Bitra, Hellisheiði, Hverahlíð, Hveragerði). An influx of groundwater from a distant source in the Langjökull glacier migrates in a SE direction through the fault swarm in the WVZ, mixing with local meteoric water infiltrating the system (Tómasson et al., 1975). The migrating groundwater interacts with a group of distinct heat sources throughout the volcanic system (i.e. Nesjavellir, Bitra, Hellisheiði, Hverahlíð), (Gunnarsson et al., 2010). A convective system is formed in the vicinity of these volcanoes, forming a complex upflow pattern (Figure 2-8b) (Franzson et al., 2010; Gunnarsson et al., 2010). Water-rock interaction and mixing with meteoric water from local recharge zones provide a different chemistry to the southern fields (i.e. Hellisheiði, Bitra, Hverahlíð) (Mutonga et al., 2010). Additionally, there is some older water of marine origin still present in the reservoir at Hveragerði, mixing with the water migrating to the south (Geirsson and Arnórsson, 1995). The details of the conceptual model of the Hengill geothermal area are intricate and some areas lack direct measurements. It is likely that the model will continue evolving conceptually as new data emerges.
Stratigraphic relations suggest that the Hellisheiði geothermal system is 0.7-0.8 Ma old, while the Nesjavellir system is 0.3-0.4 Ma old (Franzson et al., 2010; Helgadóttir et al., 2010). The distribution of alteration minerals and current temperatures indicate that the peak of thermal activity was achieved during the last glacial period. Thereafter, the greater system underwent an episode of gradual cooling. Thermal activity in the westernmost fields was reactivated due to two eruptive episodes occurred 2 and 5 ka ago, respectively (Franzson, 2010).
The Hveragerði geothermal field receives groundwater at 240-250°C from the north. As the water crosses this region, mixing with cold groundwater takes place. Boiling occurs in the uppermost 200 m in the upflow zones. The water produced from this field is in equilibrium with secondary minerals (Geirsson and Arnórsson, 1995). The water then flows out of the field to the south, entering the study area. This process is illustrated in figure 2-9.

Figure 2.9. Conceptual model of the Hveragerði geothermal field. (Geirsson and Arnórsson, 1995).
3 Methodology

The assessment of the ÖBGA required the implementation of different methods. First, a set of pressure and temperature data from wells across the area was interpreted. Second, a series of maps was prepared in order to visualize those interpretations. Third, data sets containing fluid chemistry information were analyzed and visualized spatially. Fourth, the maps were used to conceive a preliminary conceptual model of the system. Fifth, static modeling was applied to evaluate the dimensions and the capacity of the resource. Sixth, dynamic modeling was conducted to determine the system pressure response and to project its future behavior. Finally, the results of the modeling processes were incorporated into the final version of the conceptual model that will be discussed in Chapter 5.

3.1 Well log interpretation

Approximately 90 wells have been drilled in the Ölfus-Bakki area. From this group, the records of 24 wells have been selected on the basis of depth and number of measurements. Appendix B contains the temperature records of these wells. The objective of well log interpretation in this project consists of the identification of formation temperature and possible feed zones.

The temperature measurements were performed during and after drilling. In almost every case, cooling water was injected at irregular intervals, thus disturbing the thermal recovery of the well and preventing the use of an analytic method to estimate formation temperature (i.e. Albright or Horner methods). The results from the manual estimation of formation temperature are shown in Appendix B.

The methodology presented by Stefánsson and Steingrimsson (1990) is applied to identify possible feed zones in the well records. These feed zones of the productive wells in the Bakki field are indicated in Figure 3-1, as examples. The interpretation is based on the presence of localized thermal anomalies caused by internal flow. It must be noted that these points do not necessarily represent productive feed zones, as they are in some cases more directly related to regions of higher permeability that absorb some of the cooling water that circulates during drilling. The feed zones identified and reported during drilling are also shown in Figure 3-1 (Kristmannsdóttir et al., 1976; Tómasson et al., 1987; Zhang, 2001).
Figure 3.1. Reported and interpreted feedzones in the three major productive wells from the Bakki Field (solid arrows). Dotted arrows: suspected feedzones. Red arrows: hot aquifers. Blue arrows: cold aquifers. Horizontal axis: temperature (°C), vertical axis: depth (m b.s.l.). Large arrows: main aquifers.

Pressure logs were also analyzed for twelve available locations. Given the nearly linear trend of pressure, it was possible to extrapolate to obtain the values at greater depths for some of the shallower wells.

### 3.2 Geochemical data interpretation

Data from geochemical sampling was available at 19 locations throughout the study area. Information regarding rock forming constituents, incompatible constituents, dissolved gases, stable isotopes and pH was used in the current project. The principal objective is visualizing the distribution of the major chemical constituents in the ÖBGA.

The samples were organized by constituents, then by location. For those cases in which there exists more than one sample per constituent per location, the average of the measured concentrations was calculated. In this manner, each sampled well is left with a single value for a given constituent. These values are in form XYZ, where X and Y are the geographic coordinates of the well and Z its concentration. The resulting data sets are suitable to serve as input in a surface generation routine (Section 3.3). To improve the fit of that surface routine, a series of points were added on the southern boundary. These points simulate values in a region offshore where the reservoir is saturated with seawater. The oceanographic data was obtained from the Ocean Explorer workbook from the Classroom.

Another objective of the geochemical interpretation is the characterization of fluids. The use of Na-Mg-K (Giggenbach, 1988) and Cl-HCO\textsubscript{3}-SO\textsubscript{4} (Giggenbach, 1991) geoindicators allow determining the state of equilibrium of the fluid with the alteration minerals. Furthermore, it provides some clues about the provenance of that fluid. In this kind of analysis three selected constituents in a sample are normalized and plotted in a ternary diagram. The sample is then classified according to the region of the diagram where it is located. This analysis allows both the grouping of samples with related origin, or equilibrium state, and their differentiation from unrelated samples. The results of this classification are then visualized in a regional map.

Other methods were employed to obtain more information about the geothermal system. These included heavy isotope analysis, which compares the values of $\delta$D and $\delta^{18}$O. This permits to gain some insight regarding the origin of the water (i.e. marine versus meteoric origin, glacial versus interglacial precipitation). It must be indicated that the proportions of deuterium and 18-oxygen are directly dependent on the climate conditions acting during the time of precipitation; therefore, precipitation formed during a glacial period has a different isotopic signature than present-day precipitation. This characteristic could be used as a proxy indicator of the fluid age. However, the interpretation of these values is not straightforward, requiring the consideration of other factors affecting the origin and nature of the fluid.

In a similar manner, the molal ratio between chlorine and boron has been proven to be an effective analysis method in Icelandic groundwater systems (Arnórsson and Andrésdóttir, 1995). Provenance trends can be identified by plotting the samples in respective charts. The results are presented in Section 4.1.4.

### 3.3 Mapping

The results of the interpretation process described in sections 3.1 and 3.2 can be visualized spatially. The software program Generic Mapping Tools (GMT) (Wessel and Smith, 1998) was used to present this information. Three sets of maps were prepared for this report, based on temperature, pressure and chemical distribution.

For formation temperature, a set of maps was created by plotting the wells and their respective values within the ÖBGA. The GMT surface tool (Wessel and Smith, 1998) was invoked to create an interpolated surface between wells. In order to obtain reliable surface interpolations, boundary conditions were defined by including additional points outside the desired mapped domain. Some of these points come from the adjacent Hengill geothermal complex. Another boundary condition was defined by a line oriented NEE-SWW, passing through approximately 5 km S of Þorlákshöfn with a constant thermal gradient of 80°C/km (Foulger, 1995).
At every data point location, the temperature values for every 100 m interval from 0-1000 m b.s.l. were extracted. This generated a dataset of XYZ triplets that can be processed into a surface grid file. Each file represents the formation temperature for a slice of the reservoir cut at a given depth. If the maps are arranged successively, a thermal tomography of the mapped area can be obtained.

A similar process is adopted to map the pressure distribution in the region of interest. Two boundary conditions were defined. The first one included measured values from the Hengill area, while the second one was given by the hydrostatic pressure gradient of a water column along an imaginary line. This line has the same orientation as the one described above for the temperature boundary condition.

The results and interpretation of the mapping process are developed in Section 4.1.

### 3.4 Volumetric Resource Assessment

After gaining some insight into the nature and current state of the ÖBGA through spatial analysis (Sections 3.3, 4.1), it was convenient to estimate the production capacity of the reservoir beneath the Bakki field. The field capacity is determined by its size, heat content and production response. In order to determine the size and heat content, static modeling was employed. A probabilistic volumetric method was selected, given its relative simplicity of implementation and its widespread use in the geothermal industry.

The heat content in the reservoir, \( E_{\text{res}} \), is the sum of the heat content in the rock, \( E_{\text{rock}} \), and in the fluid, \( E_{\text{fluid}} \).

\[
E_{\text{res}} = E_{\text{rock}} + E_{\text{fluid}} \tag{3-1}
\]

The heat content in the rock is given by the expression:

\[
E_{\text{rock}} = V (1 - \phi) \rho_{\text{rock}} \beta_{\text{rock}} (T_{\text{res}} - T_{\text{reference}}) \tag{3-2}
\]

Where \( V \) is the reservoir volume studied, \( \phi \) is the porosity, \( \beta \) is the heat capacity, \( \rho \) is the density, \( T_{\text{res}} \) is the reservoir temperature and \( T_{\text{reference}} \) is the temperature at the surface. Similarly, the heat content in the fluid is given by the expression:
The heat content in the reservoir is then multiplied by the surface accessibility, $A$, (i.e. the proportion of the reservoir volume studied that can be accessed by drilling from the surface) and by the recovery factor, $R$ (i.e. the percentage of accessible energy that may be technically recovered) (Equation 3-4) (Axelsson, 2010). Since the surface of the Bakki field is crossed by roads and there are no major topographic barriers, the surface accessibility is close to one. The recovery factor is often assumed to be in the range of 5-20% (Axelsson, 2010).

$$E_{\text{reversible}} = E_{\text{res}} A R$$  \hspace{1cm} \text{Equation 3-4}

The methodology employed to determine the heat content of the reservoir is a variation of that described for a 3D model by Halldórsdóttir et al. (2010). The volume of the reservoir can be evaluated from the estimated formation temperatures (Sections 3.3, 4.1.1.). Since the principal use of this geothermal resource is space heating, the range of utilization temperature is 60-90 °C (Lindal, 1973). Furthermore, heating systems in Iceland are often designed to supply water at 80°C and eject water at 40 °C, with an outdoor temperature of −15 °C (i.e. 80/40/-15 heating system) (Ragnarsson, 2009). Consequently, the volume of the regions of the reservoir with temperatures greater than 80°C needs to be incorporated into the calculation.

The area within the 80°C contour is measured on the thermal maps at every 100 m, this step is repeated down to 1000 m b.s.l. (i.e. $M = 10$). Thus, a set of known areas, $A_{\text{measured}}$, at known intervals, $N$, is obtained. The volume contained between two of the measured areas can be approximated numerically by dividing the mentioned volume into 100 slices (i.e. $N = 100$) of 1 m height (i.e. $Z = 1$ m). The cross section area, $A_i$, of each single slice is given by Equation 3-5.

$$A_i = \begin{cases} A_{\text{measured}}, & i \in \{(N[0,M]) \times N\} \\ A_{i-1} + \frac{A_{\text{int}(\frac{i}{N}) \cdot N} - A_{\text{int}(\frac{i-1}{N}) \cdot N}}{N}, & i \not\in \{(N[0,M]) \times N\} \end{cases}$$ \hspace{1cm} \text{Equation 3-5}

This approximation ensures that the calculated areas gradate smoothly between the measured intervals. The volume of the reservoir with temperatures in excess of a target value is thus determined by the sum of the products of the height, $Z$, and cross sectional area, $A_i$, from each slice (Equation 3-6).
Since the reservoir temperature is not distributed homogeneously, the method above is used to measure the parts of the reservoir with temperatures greater than 80, 100, 120 and 150 °C, respectively. As a result, the portion of the reservoir within the intervals bounded by these temperature values is obtained by subtracting the corresponding values. By knowing the volume estimates at these intervals with different temperatures, it is possible to calculate the heat content implementing the formula from Halldórsdóttir et al. (2010) (Equations 3-7, 3-8).

Where $Q$ is the heat content of the reservoir, $N$ is the number of volume subdivisions within the reservoir, $C$ is the heat capacity per volume, $\varphi$ is the porosity, $T$ is the temperature, $\rho$ is the density, $P$ is the pressure and $\Delta V$ is the volume of the section of the reservoir under consideration. The next step is preparing a Monte Carlo simulation to solve Equations 3-4, 3-7 and 3-8. In this fashion, the variables become sets of random values bounded by an interval of confidence and given a specific type of distribution (Section 4.2). The equation is solved for each random point; its solution corresponds to the 90% interval of confidence bounded by the percentiles 5 and 95 from the set of solutions.

### 3.5 Lumped Parameter Modeling

After estimating the size and heat content of the Bakki reservoir by static modeling (i.e. volumetric assessment), dynamic modeling is used to simulate its nature and production response. A lumped parameter modeling approach was selected.

Lumped parameter models constitute a simple and effective method to simulate the pressure response to production of a reservoir. The method has been described by Axelsson (1989). The model intends to estimate the storativity and permeability parameters within the reservoir through an analogy with capacitance and resistivity of electrical systems. Lumped models contain a group of tanks (capacitors) connected through resistors. The tanks have storage coefficients, $\kappa$, responding to a load of liquid of mass $m$ by a pressure increase given by $p = m/\kappa$. The mass conductance (permeability) of a resistor, $\sigma$, transfers...
liquid mass given by \( q = \sigma \Delta p \), in response to a pressure differential \( \Delta p \) (Axelsson and Arason, 1992).

Lumped parameter models are capable of simulating both open and closed systems. Open models are connected, through a resistor, to an infinitely large imaginary reservoir with constant pressure. This configuration simulates a system where recharge equilibrates with mass extraction. In comparison, closed models are not connected to any external reservoirs (Axelsson and Arason, 1992). This simulates a system with either limited or no recharge. The configuration of a 1-tank open and a 3-tank closed lumped models can be seen in Figures 3-2a and 3-2b as examples.

![Diagram of lumped parameter models](image)

**Figure 3.2. Examples of lumped parameter models of hydrological reservoirs (Axelsson and Arason, 1992).**

The pressure response, \( p(t) \), is dependent on the type of model used. The pressure response for an open model with \( N \) tanks is given by equation 3-9, whereas that for a closed model is given by equation 3-10

\[
p(t) = - \sum_{j=1}^{N} Q \left( \frac{A_j}{L_j} \right) (1 - e^{-L_j \tau})
\]

**Equation 3-9**

\[
p(t) = - \sum_{j=1}^{N-1} Q \left( \frac{A_j}{L_j} \right) (1 - e^{-L_j \tau}) + QBt
\]

**Equation 3-10**

Where the coefficients \( A_j \), \( L_j \), and \( B \) are functions of both the tank storage coefficients, \( \kappa_j \), and of the resistor conductance coefficients, \( \sigma_j \).
The simulated parameters can be used to infer the size of the reservoir and the average permeability. The capacitance/storage in a liquid-dominated geothermal system can result from two different kinds of storage mechanisms (Axelsson, 1989). In the first case, storage is controlled by liquid/formation compressibility. The capacitance parameter, $\kappa$, is in this case related to volume $V$ by the expression:

$$\kappa = V \rho [\varphi c_w + (1 - \varphi)c_r]$$

Equation 3-11

Where $\rho$ is the liquid density and $c$ is the compressibility of water ($c_w$), and of rock matrix ($c_r$). In the second case, storage is controlled by the mobility of a free surface. In that case, the capacitance parameter is given by Equation 3-12.

$$\kappa = \frac{A\varphi}{g}$$

Equation 3-12

Where $A$ is the surface area of the modeled portion of the reservoir, $\varphi$ is its porosity and $g$ is the acceleration of gravity.

Lumped parameter models are also employed to estimate future pressure changes for scenarios with different production rates. In this case, conservative predictions are given by the best fitting closed model where limited or no recharge is assumed. In contrast, optimistic predictions are given by the best fitting open model (i.e. recharge equilibrates with mass extraction). Then, the results from both models are plotted together in a pressure vs. time graph (Axelsson and Arason, 1992). In most cases, the predicted pressure response of the reservoir is given by a semi-open model. This model is bounded by the extreme cases corresponding to the open and closed model projections, respectively (Figure 3-3).
If the predicted reservoir behavior results in considerable pressure decline, reinjection might be necessary for sustainable reservoir management. The proportion of required reinjection can be inferred from the projected pressure response trends obtained at different production rates. In this case it is necessary to determine the maximum sustainable production rate, at which pressure achieves equilibrium over a long period of time (e.g. more than 30 years). The rate of reinjection is thus given by the difference between the simulated and the maximum sustainable production rates.
4 Results

This chapter presents the relevant findings obtained after the implementation of the methods described in Chapter 3. Its content is arranged in three sections (viz. mapping, volumetric modeling and lumped-parameter modeling) organized in a sequential manner. The analysis begins with the cartography of the relevant characteristics observed in the geothermal field. Then, it takes the information inferred from the created maps to formulate and support assumptions used in the volumetric and the production-response modeling processes.

4.1 Mapping

The spatial information processed in this project falls within four categories (viz. temperature, pressure, water table and geochemistry). The following sections contain medium-resolution versions of the maps prepared for this report. Higher resolution versions for these images can be found in Appendices C and D.

4.1.1 Temperature

The thermal anomalies in the ÖBGA are mapped at 100 m intervals. The vertical extent of the mapped region ranges from sea-level down to 1000 m b.s.l.. Figure 4-1 presents the maps of formation temperature estimated at 200 m intervals.

The first map is shown in Figure 4.1a. Higher temperatures are found north of Hveragerði decreasing southwards, thus evidencing a possible heat source for the Ölfus-Bakki system. In the middle section of the map, a lobular anomaly protruding through a colder region in the lowlands is observed. This anomaly is distinctively noticeable from 0 to 600 m b.s.l. (i.e. red circle in Figures 4-1a,d). Below 700 m the formation temperature distribution roughly approaches the topography, with the hotter parts lying under the highlands and the cooler parts under the flood plain of the Ölfus River. This lobular feature can be interpreted as convective system advancing southwards.
Figure 4.1. Formation temperature in the uppermost 1000 of the ÖBGA. Red circle in 4-1 a,d represents a lobular thermal anomaly evidencing a convective system.
Another salient characteristic is the colder temperatures around well ÆS-01. This anomaly is observed from 0-600 m b.s.l., being most notorious at 400 m b.s.l. (Figure 4-1c). As it will be discussed in Section 4.1.4, this thermal disturbance evidences infiltration of meteoric water through the surface faults at Þurárhnúkur.

### 4.1.2 Pressure

The general pressure distribution for the study area was determined for the same intervals as in the temperature maps. However, the scarcity of control points within the area of interest restrains the use of these maps as only a very general indication of the orientation of the pressure gradient. This trend reflects the regional trend of groundwater flow.

In a fashion similar to formation temperature, pressure in the geothermal field is correlated with topography. The highest pressure region is located to the N of Hveragerði, while the lowest pressure region is observed beneath the floodplain of the Ölfus River.

The inferred flow pattern is aligned in a N-S direction. Groundwater appears to migrate from the high temperature region (N of Hveragerði) to the lowlands in Ölfus. Additionally, it can be stated that any recharge water entering the system through the highlands at Ingólfsfjall and the E and S flanks of Skálafell would flow in the direction of the Ölfus lowlands.

Figure 4-2 shows the pressure distribution interpolated using the boundary conditions described in Section 3.3. An interval of 200 m was selected to illustrate the temperature distribution at depth. Figures 4-2c-f show the presence of a pressure depression in the Bakki field. This phenomenon might act as a point of convergence for fluids from different sources. The presence of two of the main production wells in the region (viz. HJ-01, BA-01) suggests the possibility that this pressure anomaly could be caused by production.

Appendix C contains a series of high resolution maps incorporating both pressure and formation temperature distribution. These maps are available at 100 m intervals.
Figure 4.2. Pressure distribution (bar$_r$) in the uppermost 1000 mbsl of the Ölfus-Bakki geothermal system.
4.1.3 Water table

The water level values were plotted in the study area. This feature is indirectly related to the pressure distribution in the geothermal field, as well as to the groundwater flow patterns for the unconfined aquifers. Given the scarcity of pressure control points, the water level maps are included to support the set of pressure maps. Figures 4-3a and 4-3b illustrate the interpolated surface for the maximum and minimum measured water level values at every control point.

![Minimum measured waterlevel](image1.png)  ![Maximum measured waterlevel](image2.png)

*Figure 4.3. Minimum (a) and maximum (b) water level (in m a.s.l.) measured in the wells of the Ölfus-Bakki region.*

The pattern observed through the mapped area shows a similar trend to that observed in the previous section. As it was observed with pressure, the water table is directly correlated with topography. Moreover, a similar pressure low was observed in the proximity of the Bakki field.
4.1.4 Chemistry

The fluid chemistry data available for the study area allow the preparation of a series of maps showing the distribution of related parameters. These parameters include concentrations, isotopic relative depletion, molal ratio and pH. Furthermore, the fluid characterization obtained by the use of geoindicators (Section 3.2.3) permits visualizing the presence of regions within the mapped domain that exhibit a distinctive compositional fingerprint. This factor is used to delineate the extent of the Bakki reservoir, as well as to infer the occurrence of recharge and mixing processes within the geothermal system.

The fluid constituents that were mapped fall within five categories (viz. rock-forming constituents, incompatible elements, heavy isotopes, major gases and geoindicators). Additional maps were prepared for sulfate, pH and Cl/B molal ratio. The rock forming constituents used are Ca, K, Mg, Na, and SiO$_2$, their maps are shown in Figure 4-4a,e.

The Ca distribution (Figure 4-4a) has its highest concentration at the ocean (412 ppm). High Ca concentrations are also observed near the wells at Bakki (BA-01, HJ-01). The lowest concentrations are seen around Hveragerði and S of the Ingólfsfjall Mountain. The K concentration distribution (Figure 4-4b) also presents the highest values in proximity to the ocean (399 ppm), while relatively high concentrations are seen to the NW of Hveragerði. Low K concentrations are distributed across an elongated region extending from Íngólfsfjall to Hliðardalskóli (well HS-02). Mg is most abundant in marine water (1284 ppm) and is depleted throughout the geothermal system, with the conspicuous exception of Þóroddstaðir (well BS-01) where Mg-enriched waters were sampled (Figure 4.4c). Mg enrichment is also observed in Hliðardalskóli, although this seems to be part of the regional trend near the coast line. Na is relatively abundant across the mapped region (Figure 4.4d). Depletion of Na is mainly localized around Ingólfsfjall, in addition to relatively lower concentrations observed at Þóroddstaðir and Hliðardalskóli. The distribution of SiO$_2$ decreases more or less homogeneously from the NW to the SE (Figure 4.4e). This pattern seems to correlate with formation temperature (Section 4.1.1.), and consequently, with SiO$_2$ solubility.
Figure 4.4 Chemical distribution for rock-forming constituents in Ölfus-Bakki. a) Calcium, b) potassium, c) magnesium, d) sodium, e) silica.
The second category of constituents contains incompatible elements, mainly B and Cl. B is relatively abundant in ocean water (4.50 ppm) as well as in the high temperature area N of Hveragerði (Figure 4-5a). There is relative depletion of B in the middle section of the map, from Ingólfsfjall to Bakki and Þóroddstaðir. Cl is abundant throughout the mapped area, except for Ingólfsfjall, Þóroddstaðir, and Hliðardalskóli (Figure 4-5b). The Cl/B molal ratio has been used to determine the provenance of groundwater in geothermal systems in Iceland (Arnórsson and Andrésdóttir, 1995).

Figure 4-6 illustrates the distribution of chlorine and boron throughout the study area, showing that wells HJ-01, BA-01 and EB-01 lay close to the seawater line (constant Cl/B = 1300). The same chart shows that wells BS-01, ÖL-01, and HV-08 are located in the region between the seawater and rock-dissolution lines (i.e., Cl/B = 1300 and Cl/B = 30, respectively). Wells AR-04, SO-01, AB-04 and AB-09 are relatively depleted in both Cl and B, being closer to the rock-dissolution line.

Figure 4.5 Chemical distribution for incompatible elements in Ölfus-Bakki. a) Boron, b) chlorine, c) Cl/B molar ratio.
Figure 4.6 Relationship between chlorine and boron for different locations throughout the study area. Notice the samples from Bakki (triangular symbols) are closer to the seawater line compared to samples from other locations.

This configuration suggests mixing occurs throughout the geothermal system, with a prevalent seawater component in the wells at Bakki (triangular symbols) and a prevalent precipitation component at the wells S of Ingólfsfjall (squared symbols). The wells at Hveragerði-Núpajökull (circular and rhombic symbols) are placed between these two groups. Figure 4.5c illustrates the spatial distribution of the Cl/B ratio, where the wells at Bakki present values closer to seawater, those at Núpajökull-Hveragerði are intermediate and those adjacent to Ingólfsfjall are closer to rock-dissolution.

The third category includes heavy (stable) isotopes (i.e. $^2$H and $^{18}$O). These isotopes are measured as a deviation from the standard mean ocean water (SMOW). The distribution of $\delta^{18}$O is presented in Figure 4-8a, indicating depletion of this isotope in Bakki. The same region also undergoes depletion in deuterium, pattern that extends to Þóroddstaðir. A relative enrichment in deuterium is observed at the foothill of Ingólfsfjall. The relationship between both isotopes is plotted in Figure 4-8, where meteoric origin for some of the samples can be concluded.
As it has been suggested before, the waters from wells adjacent to Ingólfsfjall (i.e. AB, AR, LB, SO) are of meteoric origin. This is also deduced from Figure 4-8, since these samples align very closely with global meteoric water and local precipitation. Another interesting aspect from this chart is the arrangement of the samples from well HJ-01 at Bakki. There is one particular set of samples obtained in 1988 that retrieved water from the aquifers at 70, 410, 425, 480 and 583 m below the surface. The results from this group of samples were plotted in Figure 4-8 (triangular symbols). From the five aquifers, four present the oxygen shift characteristic of thermal waters; however, the deepest aquifer plots close to the meteoric line. A mixing model for this well was formulated by Zhang (2001), documenting the deep anomaly as well as the chemical changes triggered by production from this well. It is possible that the aquifer at 583 m depth is connected either to an active recharge zone or to a confined aquifer containing older meteoric water. More evidence, however, is necessary to support any of these hypotheses.

The fourth category of mapped constituents includes major gases such as H₂S and CO₂. The occurrence of H₂S is restricted to the Hveragerði high temperature system, while it is relatively depleted in the rest of the mapped area (Figure 4-9a). The distribution of CO₂ shows depletion throughout most of the mapped area, being accentuated at Bakki. Additionally, there is a prominent enrichment anomaly concentrated around wells ÖL-01, ASÍ-01 and SO-01. This anomaly correlates with the pH distribution across the geothermal field (Figures 4-9b-c).

Although it does not belong to any of the mentioned categories, the distribution of SO₄ was also mapped (Figure 4-9d). The general trend observed has an enriched area close to the ocean, with depleted areas near Ingólfsfjall and Þóroddstaðir. This trend is in agreement with the occurrence of mixing with meteoric water entering by recharge in these zones.

![d18O distribution](image1.png) ![dD distribution](image2.png)

*Figure 4.7* Distribution of stable isotopes throughout the ÖBGS. a) Deviation of $^{18}\text{O}$, b) deviation of deuterium. Expressed as per mil deviation from the SMOW composition.
Figure 4.8 Relationship between δD and δ18O for different locations throughout the study area. Notice the samples from well HJ-01, at Bakki (triangular symbols). The sample from its deepest aquifer is closer to the meteoric line than the samples from other aquifers in the same well.
Finally, the fifth category includes the results of fluid characterization by geoindicators. Figure 4-10a presents a Na-K-Mg ternary diagram evaluating the equilibrium between the fluid and the alteration minerals in the geothermal system. If the points in the diagram are grouped geographically, five distinct zones can be identified. These groups are delimited by the colored ovals in the diagram. The wells at Bakki, Hveragerði, Hliðardalskóli, Núpafjall, and Ingólfsfjall are represented by the black, orange, brown, green and blue ovals, respectively. The waters from Bakki, Hveragerði and Hliðardalskóli are equilibrated if the Na/K geothermometer equation by Árnasson et al. (1998) is chosen, or are partially equilibrated if the equation by Giggenbach (1988) is selected. Additionally, the samples from Núpafjall and S of Ingólfsfjall are below equilibrium according to Giggenbach (1988) and are partially equilibrated according to Árnasson et al. (1998).

Another geoindicator used was Cl-SO₄-HCO₃. The samples are evaluated and classified spatially, then presented in Figure 4-10b. The waters from Bakki (black), Hveragerði (orange), and Núpafjall—except for HS-02—are chlorinated waters from volcanic origin. The samples from Hliðardalskóli are sulphated waters of volcanic origin. The partially equilibrated to sub-equilibrated samples are of peripheral origin, and are mostly bicarbonate waters with either a chlorinated (i.e. ÞS-01, LB-02) or a sulphate (i.e. ABs) component.

The zones identified in the ternary diagrams are plotted in a map (Figure 4-11). One salient feature that is immediately evident is the physical boundary between wells EB-01 and ÞS-01, delineated by a nearly vertical tectonic lineament trending in a NEE-SWW direction. For quick reference, this lineament will be referred as the Bakki lineament henceforth. Similarly, the N-S lineament serving as W boundary for the mapped region will be referred as the Bitra lineament, and the two smaller parallel lineaments to the E will be referred as the Þurarhnukur and Núpar lineaments respectively. The location of the lineaments is labeled in Figure 4-11.

Figure 4.9 Spatial distribution of a) hydrogen sulfide, b) carbon dioxide, c) pH and d) sulfate.
Figure 4.10  Fluid characterization using geoindicators. a) Na-K-Mg, b) Cl-HCO$_3$-SO$_4$. Related samples are grouped together: in black—Bakki, in orange—Hveragerði, in green—Núpafjall and surroundings, in brown—Hliðardalskóli, in blue—Ingólfsfjall.
Figure 4.11 Spatial distribution of the distinctive zones identified through geoindicators (Color code indicated in Figure 4-10).

The information inferred from the geothermal cartographic analysis in this section allows the proposal of a conceptual model for the ÖBGA. In the temperature maps it is observed that the heat source in the system is located in the Hveragerði area. Furthermore, the pressure distribution shows that fluid is likely to flow southwards and from the highlands to the lowlands. Finally, geochemical evidence indicates that the fluids from Bakki are unrelated to those from Þóroddstaðir, indicating the possibility of mixing with meteoric water in the latter region. All this evidence favors the interpretation of the ÖBGA as a convective system with deep water circulation. The convective system is manifested as a plume, located between 0 and 600 m b.s.l. in the Hveragerði area, migrating southwards following the regional hydraulic gradient. The movement of fluid is constrained by the presence of buried tectonic lineaments. These lineaments bound some regions, catching some fluid and allowing mixing with meteoric water that infiltrates through surface faults and fractures. The details of this hypothesis are developed in Chapter 5.
4.2 Volumetric model

The limits of the Bakki geothermal field can be determined from map interpretation. From this interpretation, it is proposed that the field is bounded to the N by the Bakki lineament. The existence of this boundary is supported by the chemical difference between the fluids from wells EB-01 and ÞS-01, separated by this feature (Section 4.1). To the E, there is a gradational boundary separating the wells at Bakki from those S of Ingólfsfjall by means of a pressure gradient depression (Section 4.1.2.). This is inferred from the different chemistry between these two regions, the absence of faults, and the pressure distribution maps. The Núpar lineament, to the NE, restrains the flow from Þóroddstaðir to the E. To the S, there is a relatively flat pressure gradient that serves as a gradational boundary, separating seawater-saturated rock and the mixed fluids at Bakki. To the W, there is a boundary separating the waters from Hliðardalskóli.

The exact location of the eastern, western and southern boundaries is uncertain. Therefore, it is necessary to constrain the extent of the geothermal field by defining conservative and optimistic boundaries (Figure 4-13). The actual extent of the Bakki geothermal field is expected to fall somewhere between these two boundaries.

Figure 4.12 Cross section diagram dissecting the study area. It has been modified to include the Bakki lineament, whose location is consistent with discontinuities in temperature, lithology and mineral alteration. Modified after Sigurdsson et al. (2006).
Once the confidence interval for the surface extent of the reservoir is defined, it is possible to estimate the reservoir volume with temperatures greater than the threshold of exploitation. The principal use of this geothermal resource is space heating and aquaculture, the former requiring temperatures greater than 80°C. For this reason, it is necessary to estimate the volume of rock above that temperature down to 1000 m b.s.l.

The temperature maps (Section 4.1.1) were used to measure the cross sectional area of the reservoir at the given temperature and depth intervals. These discrete areas can be used to compute the volume of that part of the reservoir. The method was described in Section 3.4. The approximated volume is illustrated in Figure 4-14a. The same approach is taken to calculate the part of the reservoir with temperatures greater than 120 (Figure 4-14b) and 150 °C. Table 4.1 presents the results of the area measurements at different depths, while Table 4.2 shows the volume of the reservoir approximated numerically (Section 3.4). These values are later used to account for the differential formation temperature distribution throughout the reservoir.

Figure 4.13 Estimated surface extent of the Bakki geothermal field. A conservative estimate is bounded by the red dotted line, while an optimistic estimate is bounded by the blue dotted line.
Figure 4.14 Projected volume of the reservoir underlying the surface extent indicated in Figure 4-13. a) Volume of rock hotter than 80°C, b) Volume of rock hotter than 120°C. The blue-delineated volume represents the optimistic estimate, while the conservative estimate is in red. The Bakki and Núpar lineaments are highlighted in yellow. Wells BA-01, HJ-01 and EB-01 are shown by green triangles (well heads) with white vertical lines (drilling paths). Modified with added content after Google™ (2010)
Table 4.1 Measured cross sectional surface areas at given temperature ranges for different depths within the reservoir. These values are used to calculate volumes of rock at different temperature intervals.

<table>
<thead>
<tr>
<th>Elev. (m.b.s.l.)</th>
<th>Surface of reservoir, T &gt; 80°C</th>
<th>Surface of reservoir, T &gt; 100°C</th>
<th>Surface of reservoir, T &gt; 120°C</th>
<th>Surface of reservoir, T &gt; 150°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conservative (m²)</td>
<td>Optimistic (m²)</td>
<td>Conservative (m²)</td>
<td>Optimistic (m²)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>1.90E+06</td>
<td>5.95E+06</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>1.19E+07</td>
<td>2.54E+07</td>
<td>1.52E+05</td>
<td>6.13E+05</td>
</tr>
<tr>
<td>400</td>
<td>1.51E+07</td>
<td>3.53E+07</td>
<td>9.06E+06</td>
<td>1.92E+07</td>
</tr>
<tr>
<td>500</td>
<td>1.60E+07</td>
<td>3.84E+07</td>
<td>1.12E+07</td>
<td>2.67E+07</td>
</tr>
<tr>
<td>600</td>
<td>1.62E+07</td>
<td>3.98E+07</td>
<td>1.03E+07</td>
<td>2.64E+07</td>
</tr>
<tr>
<td>700</td>
<td>1.64E+07</td>
<td>4.50E+07</td>
<td>1.49E+07</td>
<td>3.43E+07</td>
</tr>
<tr>
<td>800</td>
<td>1.64E+07</td>
<td>4.54E+07</td>
<td>1.53E+07</td>
<td>4.01E+07</td>
</tr>
<tr>
<td>900</td>
<td>1.64E+07</td>
<td>4.54E+07</td>
<td>1.64E+07</td>
<td>4.54E+07</td>
</tr>
<tr>
<td>1000</td>
<td>1.64E+07</td>
<td>4.54E+07</td>
<td>1.64E+07</td>
<td>4.54E+07</td>
</tr>
<tr>
<td>Total</td>
<td>1.27E+08</td>
<td>3.26E+08</td>
<td>9.46E+07</td>
<td>2.38E+08</td>
</tr>
</tbody>
</table>

Table 4.2 Volume calculated numerically using the surfaces shown in Table 4-1.

<table>
<thead>
<tr>
<th>Volume of reservoir at T &gt; 80°C</th>
<th>Volume of reservoir at T &gt; 100°C</th>
<th>Volume of reservoir at T &gt; 120°C</th>
<th>Volume of reservoir at T &gt; 150°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conservative (m³)</td>
<td>Optimistic (m³)</td>
<td>Conservative (m³)</td>
<td>Optimistic (m³)</td>
</tr>
<tr>
<td>1.18E+10</td>
<td>3.02E+10</td>
<td>8.64E+09</td>
<td>2.15E+10</td>
</tr>
</tbody>
</table>

After estimating an approximate volume of the reservoir, the following step is estimating its capacity. The formulas for the Monte Carlo simulation are discussed in Section 3.4. Three parts of the reservoir are considered in this method. The first one presents temperatures from 80-100°C while the other two contain temperatures in the ranges of 100-120°C and 120-150°C, respectively. The volume of each part is obtained by subtracting consecutive values in Table 4.2.

The formulas will be implemented using the parameters summarized in Table 4.3. The random porosity values are assumed to be triangularly distributed, in an interval consistent with typical porosity values for Icelandic basalts (Sigurdsson and Stefansson, 2002). The assumed value for reference temperature is 4.75 °C, the annual average temperature around Hveragerði (www.vedur.is). The density and heat capacity of basalt was taken from published standard values (Turcotte and Schubert, 2002). A high value of utilization efficiency is assumed for direct use (i.e. \( \eta \approx 1 \)).
In order to run the Monte Carlo simulation, a population of 10,000 random values was generated for porosity, temperature and volume. These random values are arranged in triangular, uniform and normal distributions, respectively. In the case of volume, the 90% interval of confidence is bounded by the minimum and maximum values from Table 4.3. The fluid properties (i.e. density and heat capacity) are dependent on temperature; therefore, these values were calculated from steam tables for each random temperature point.

The results were computed for three time frame scenarios. The first one assumes complete heat mining in a 30-year time frame, while the other two assume 50 and 100 years respectively. The probability distributions of these calculations are plotted in Figures 4-15, 4-16 and 4-17. The statistical parameters are summarized in Table 4.4.
Figure 4.15 Histogram for the probability distribution of the maximum capacity of the system within a time frame of 30 years.

Figure 4.16 Histogram for the probability distribution of the maximum capacity of the system within a time frame of 50 years.
Figure 4.17  Histogram for the probability distribution of the maximum capacity of the system within a time frame of 100 years.

Table 4.4  Statistical parameters of the volumetric reservoir capacity estimation. The Monte Carlo simulation produced a set of solutions for thermal power (in MW) at different time frames. The thermal capacity is given by the 90% interval of confidence.

<table>
<thead>
<tr>
<th>Thermal Power [MW]</th>
<th>30 years</th>
<th>50 years</th>
<th>100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>734.24</td>
<td>440.55</td>
<td>209.63</td>
</tr>
<tr>
<td>Percentile 5</td>
<td>346.05</td>
<td>207.63</td>
<td>98.26</td>
</tr>
<tr>
<td>Percentile 95</td>
<td>1226.90</td>
<td>736.14</td>
<td>351.55</td>
</tr>
<tr>
<td>Median</td>
<td>702.78</td>
<td>421.67</td>
<td>200.49</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>270.98</td>
<td>162.59</td>
<td>77.95</td>
</tr>
</tbody>
</table>

The calculated capacity of the reservoir corresponds to the 90% interval of confidence at each time scenario (Table 4.4). Therefore, the maximum capacity of the reservoir ranges from 98 to 1,200 MW, considering all the time frames involved and the uncertainty in the outcome of the volumetric method. This range reflects the uncertainty of the parameters used in the model calculations.
The average production rate ($\bar{m}$) between 1999 and 2009 for the wells HJ-01, BA-01 and EB-01 combined was 37.25 kg/s (Aradóttir, 2010a, 2010b). From Table 4-5 it was estimated that the average fluid temperature ($T_{\text{fluid}}$) from these wells was 110.3 °C. Assuming that the specific heat of water ($\beta$) at that temperature is 4204 J kg$^{-1}$ K$^{-1}$, and that the reference temperature ($T_{\text{reference}}$) is 4.75 °C (Table 4-3), Equation 4-1 is used to estimate the thermal power extracted from the reservoir ($\dot{Q}$).

$$\dot{Q} = \dot{m} \beta_{\text{fluid}} (T_{\text{fluid}} - T_{\text{reference}})$$

Equation 4-1

Thus, the average extracted thermal power over the last decade was 16.5 MW$_{\text{th}}$. Therefore, the thermal capacity of the reservoir, according to the volumetric estimate, is much larger than its current load. Furthermore, the thermal capacity of the reservoir could be expressed as a production rate of water at 110.3 °C, if Equation 4-1 is solved for production rate ($\dot{m}$) (Equation 4-2).

$$\dot{m} = \frac{\dot{Q}}{\beta_{\text{fluid}} (T_{\text{fluid}} - T_{\text{reference}})}$$

Equation 4-2

The maximum capacity intervals (i.e. percentiles 5 and 95 in Table 4-4) were used in equation 4-2. It was determined that the reservoir would reach thermal breakthrough after 30 years by sustaining a maximum production of 1,090-3,880 kg/s. In a similar fashion, breakthrough would be achieved after 50 years with a maximum production of 656-2,330 kg/s, and after 100 years with 310-1,110 kg/s. If sustained, the current production rate (i.e. 37.25 kg/s) would produce that state after 580 years approximately.

It must be noticed that the volumetric assessment does not take into account the effect of permeability and recharge. Consequently, the system response is neglected using this method alone. This situation requires the implementation of a dynamic modeling method, such as lumped-parameter modeling. In the following section, production data from the Bakki field will be used to analyze the system response and to make projections into the future behavior of the system under different production scenarios.
4.3 Lumped-Parameter Model

Currently, there exist three production wells at Bakki, namely BA-01, HJ-01 and EB-01. Well BA-01 was drilled in 1977, reaching a depth of 866 m and producing 115 °C fluid at a rate of 25 l/s (Aradóttir, 2010a). Well HJ-01 was drilled in 1984; it has a depth of 605 m and was connected to the district heating system of Þorlákshöfn in 1987. Well EB-01, 1733 m deep, was drilled from 1986 to 1987 (Aradóttir, 2010b). This well was mostly unused until 2004, being regularly monitored ever since. Wells BA-01 and HJ-01 are separated by a distance of 160 m, while the distance between wells BA-01 and EB-01 is 1250 m. Table 4.5 presents a technical summary of these three wells.

Table 4.5 Technical summary of wells at Bakki (Aradóttir, 2010a; 2010b).

<table>
<thead>
<tr>
<th>Well</th>
<th>BA-01</th>
<th>HJ-01</th>
<th>EB-01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of drilling</td>
<td>1978</td>
<td>1984</td>
<td>1987</td>
</tr>
<tr>
<td>Depth</td>
<td>m</td>
<td>885</td>
<td>500</td>
</tr>
<tr>
<td>Depth to pump</td>
<td>m</td>
<td>39.5</td>
<td>49.1</td>
</tr>
<tr>
<td>Water level</td>
<td>m a.s.l.</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>115</td>
<td>102</td>
</tr>
<tr>
<td>Casing depth</td>
<td>m</td>
<td>204</td>
<td>570</td>
</tr>
<tr>
<td>Casing diameter</td>
<td>in</td>
<td>10¾</td>
<td>11¼</td>
</tr>
<tr>
<td>Pump Type</td>
<td>8JKH</td>
<td>6JKH</td>
<td></td>
</tr>
<tr>
<td>Pump Level</td>
<td>2</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Pump tubing Diameter</td>
<td>6&quot;</td>
<td>5&quot;</td>
<td></td>
</tr>
<tr>
<td>Pump tubing Number</td>
<td>13</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Motor hp</td>
<td>40</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Motor rpm</td>
<td>3000</td>
<td>3000</td>
<td></td>
</tr>
</tbody>
</table>

The production history of these wells is shown in Figure 4-18. Data previous to 1989 was inferred from published values for total extracted fluid (Aradóttir, 2010a). The individual record for well BA-01 starts in 1992, while that for well EB-01 begins in 2004.
Figure 4.18 Production histories of the three active wells at Bakki. The values prior to January 1989 are annual averages calculated from published records of total mass extracted from BA-01 and HJ-01 (Aradóttir, 2010a).

Water level measurements were available since 2002 and 2009 for wells HJ-01 and EB-01, respectively. Meanwhile, well BA-01 has been artesian throughout its operation. Consequently, the record for HJ-01 was selected to represent the reservoir pressure response in a lumped parameter model. The application Lumpfit was used to simulate pressure changes generated in response to production (Axelsson and Arason, 1992).

The input for Lumpfit included both the known values for total production since December 1979, and water level values since January 2002. These values are specified at time intervals of one month. Because the average fluid temperature for this field is close to 110 °C, the water density value used was 950 kg/m³. The initial parameters used are displayed in Table 4.6.

The modeling process was executed several times, each time with different initial water level values. Meaningful results were achieved only for initial water level values above 12 m a.s.l. It was observed that values greater than 12 m a.s.l. produced small increments in the coefficient of determination, $R^2$, when fitting a 2-tank open model; however, they also produced larger decrements in $R^2$ when fitting a 2-tank closed model. The result presented in Table 4.6 corresponds to the value that produces an optimal fit for the two largest models (i.e. 2-tank closed, 2-tank open).
Table 4.6 Initial parameters used with Lumpfit

<table>
<thead>
<tr>
<th>Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time unit</td>
<td>Months (2.63e6 s)</td>
</tr>
<tr>
<td>Water density</td>
<td>950 kg/m³</td>
</tr>
<tr>
<td>Initial water level</td>
<td>12 m a.s.l.</td>
</tr>
<tr>
<td>Average past production</td>
<td>0 kg/s</td>
</tr>
<tr>
<td>Coefficient of turbulence</td>
<td>0 m/(l/s)²</td>
</tr>
</tbody>
</table>

The modeling process begins with the simplest configuration, a one-tank-closed model. Once a stable solution was found for each configuration, the model was allowed to grow in complexity. Lumpfit was able to find stable solutions for 1-tank closed, 1-tank open, 2-tank closed and 2-tank open configurations. The results of the simulations are presented in table 4.7 and Figure 4-19.

Table 4.7 Summary of results obtained from lumped-parameter modeling.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tanks</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Model type</td>
<td>Closed</td>
<td>Open</td>
<td>Closed</td>
<td>Open</td>
</tr>
<tr>
<td>A1</td>
<td></td>
<td>6.472E-2</td>
<td>0.240</td>
<td>0.241</td>
</tr>
<tr>
<td>L1</td>
<td>0.162</td>
<td>1.698</td>
<td>1.714</td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td>1.197E-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L2</td>
<td></td>
<td>2.310E-4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1.808E-3</td>
<td>1.160E-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>κ (ms²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>κ1</td>
<td>156246</td>
<td>4365</td>
<td>1173</td>
<td>1167</td>
</tr>
<tr>
<td>κ2</td>
<td>242395</td>
<td>234923</td>
<td></td>
<td></td>
</tr>
<tr>
<td>σ (1e-6 ms)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>σ1</td>
<td>2.688E-4</td>
<td>7.540E-4</td>
<td>7.567E-4</td>
<td></td>
</tr>
<tr>
<td>σ2</td>
<td></td>
<td></td>
<td></td>
<td>2.074E-05</td>
</tr>
<tr>
<td>Coefficient of determination (%)</td>
<td>53.35</td>
<td>60.998</td>
<td>82.993</td>
<td>83.005</td>
</tr>
<tr>
<td>RMS misfit</td>
<td>1.440</td>
<td>1.317</td>
<td>0.869</td>
<td>0.869</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.448</td>
<td>1.332</td>
<td>0.885</td>
<td>0.890</td>
</tr>
</tbody>
</table>

As it was indicated in Section 3.5, the simulated parameters can be used to infer the size of the reservoir. The modeled storage coefficients (κ) are substituted in Equations 3-11, 3-12. The calculation assumes compressibility values of 5.0E-10 Pa⁻¹ for water (cₗ) and 2.0E-11 Pa⁻¹ for basalt (cᵣ) (Grant et al., 1982), and average porosity of 10% (Section 4.2).
For the case of compressibility-controlled capacitance, the volume estimate using 2-tank closed and open models was 4200 and 3683 km$^3$, respectively. Considering the space constraints of the ÖBGA, this result is unacceptable. Conversely, in the case of a free-surface-mobility-controlled storage, the estimated surface area ranges between 23.9 and 23.1 km$^2$ (i.e. using 2-tank closed and 2-tank open models, respectively). These values are comparable to the surface area estimation shown in Figure 4-13 (i.e. 16.4 km$^2$ for a conservative estimate, 45.4 km$^2$ for an optimistic estimate). These results are summarized in Table 4-8. From these estimates, it can be deduced that storage in the reservoir corresponds to an open system that is predominantly controlled by the mobility of a free surface (i.e. an unconfined reservoir).

Table 4.8 Comparison between reservoir size estimations derived from lumped-parameter and volumetric modeling.

<table>
<thead>
<tr>
<th>Storage Mechanism</th>
<th>Number of Tanks</th>
<th>2 Tank Model Type</th>
<th>Volumetric Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Closed</td>
<td>Open</td>
</tr>
<tr>
<td>Compressibility</td>
<td>Volume (km$^3$)</td>
<td>4200</td>
<td>3683</td>
</tr>
<tr>
<td>Free-surface mobility</td>
<td>Surface Area (km$^2$)</td>
<td>23.9</td>
<td>23.1</td>
</tr>
</tbody>
</table>

The future response of the reservoir can be projected using different production scenarios. This requires the use of both open and closed tank models. In this manner, additional points representing future production rates are added to the existing 2-tank closed and 2-tanks open models. Figure 4-19 shows the way these two models fit the observed data.

Figure 4.19 Modeled water level in well HJ-01 reflecting pressure response in the Ölfus-Bakki reservoir. a) Using a 2-tank closed model, b) 2-tank open model.
For the purposes of this report, three predictive scenarios are formulated for the next 20 years. In the first case, the average production rate from the last 5 years is kept constant. The second scenario considers an increment of 50% over that same rate, while the third scenario extrapolates the growth rate trend observed over the last 20 years to the future production. The results are presented in Figures 4-20 a, b and c.

Figure 4.20  Projected water level response for the next 20 years under different production scenarios.

a) Past 5-year average production rate is kept constant.

b) That rate is increased by 50%.

c) Growth rate from the last 20 years is sustained.
In all three scenarios the difference between the optimistic and conservative projections is relatively small, while the water level decrease is relatively significant. In the first scenario, a water level drop between 9.5-10.0 m is observed over the next 20 years. This is equivalent to a water level drop rate of 47-50 cm/a. In the second scenario, the observed water level drop ranges between 17.8-18.4 m (i.e. 89-92 cm/a). Similarly, the third scenario predicts a water level drop of 14.2-14.8 m (i.e. 71-74 cm/a).

The modeled behavior suggests that the pressure response of the system is highly sensitive to production. The effects of production can be mitigated, at least, by two different methods—viz. reinjection, or readjustment of pumping equipment. The former method, in the Bakki field, implies pumping the effluent from the Þorlákshöfn district heating system back to the location of reinjection. In Section 4.1.1, it was mentioned that the heat source in the system lies outside the boundaries of the production field. Therefore, it would be necessary to implement peripheral reinjection in the vicinity of Hveragerði to avoid compromising the thermal integrity of the resource. The second method simply requires lowering the position of the pumps at the wells HJ-01 and EB-01, as well as adding a pump at well BA-01 by the time artesian flow ceases.

The sustainability of the second method depends on the considered time frame. If the water level drop rates calculated above are applicable, then the water level would drop 47-92 m after 100 years. Similarly, after 300 years the water level would be 140-275 m lower. In Iceland, several cases have been reported where the pumps have been adjusted up to 250 m in response to production-induced drawdown (G. Axelsson, pers. comm., January 2011).

Consequently, reinjection in the Bakki field would be advisable only in the case that the average production rate surpassed the limit of 60 kg/s (i.e. 50% increment over the current average rate). The economic analysis of reinjection escapes the scope of this report, given the necessity of laying several kilometers of pipeline, transporting the effluent upstream, and possibly drilling new reinjection wells. However, the results of the modeling process suggest that the reservoir would be capable of supporting, without reinjection, the current level of production and the current production rate of growth.
5 Concluding remarks

The abundance of physical, chemical, and geological data in the Ölfus-Bakki area, gathered over the years, allowed the implementation of the analyses conducted in this report. The well-log records available provided enough information on the thermal and baric configuration throughout the study area. Manual interpretation of the temperature records was necessary to extract this information (Appendix B). The results from the interpretative process were used to generate the maps of pressure and temperature from Sections 4.1.1 and 4.1.2. These maps revealed a pattern where hot fluid appears to migrate to the south from Hveragerði to the estuary of the Ölfus River. Similarly, the pressure gradient allows a possible flow pattern from the highlands (Ingólfsfjall, Skálafell) to the lowlands (Ölfus flood plain).

The results from multiple chemical analyses conducted in the area constituted an additional source of data. The average concentration values at each location were used to generate concentration maps for the main chemical constituents identified in the fluids. The maps show a regional trend, suggesting the extent of influence of marine water, as well as a marked difference between two adjacent wells (i.e. EB-01 and ÞS-01). Furthermore, evidence from heavy isotopes and geoindicators seem to corroborate that compositional difference. The geoindicator characterization allows categorizing the study area within distinctive units. In this manner, the fluids from Hveragerði and Bakki appear closely related to one another, and appear relatively close to those from Núpar, Öxnalekur and Kröggölfsstaðir. These fluids are, however, unrelated to those from Þóroddstaðir, Hliðardalskóli and the foothills of Ingólfsfjall. By superimposing the tectonic lineaments inferred from seismic data, the distinction between the fluids from Bakki and Þóroddstaðir seems to be explained by the presence of a physical barrier. A lithological discontinuity is also observed in this region being a clear indication of a fault, known in this report as the Bakki lineament. Similar structures are oriented perpendicularly, the most notorious being the Bitra lineament that separates the neighboring Hengill geothermal complex.

When this information is combined, it appears that the regional flow pattern takes fluid from Hengill—of volcanic origin, chlorinated, and at equilibrium with local alteration minerals—and transports it to the south. This fluid spreads across the lowlands where the hydraulic gradient is lower. In the lowlands, mixing with fresh meteoric water takes place in the vicinity of the Ingólfsfjall foothill. The volcanic fluid that remains unmixed continues its south-bound migration. Then, the N-S trending Núpar lineament creates a divergence in the flow pattern, sending one part to Þóroddstaðir and the other to Bakki. At Þóroddstaðir, there is both infiltration by recharge of meteoric water through multiple local fractures/faults and subsequent mixing with the volcanic fluid in a fault-bounded confined space. This seems to account for the observed chemical and thermal differences between the two localities. At Bakki, the fluid continues its path; however, differences in pressure gradient create a boundary between this system and the adjacent Hliðardalskóli. The origin
of that fluid is probably meteoric, migrating from the west by a topography-controlled hydraulic gradient. These processes are illustrated and summarized in Figure 5.1.

Figure 5.1 Conceptual model of the ÖBGS. Hot volcanic waters flow to the south from Hveragerði (red). Meteoric waters enter the groundwater system through the faults manifested at the surface (blue), mixing with the volcanic waters (purple). Buried faults (yellow, white) restrain groundwater flow. Marine water (cyan) is present to the south of the region, reaching the reservoir (red- and blue- delineated blocks) and mixing with volcanic water. The fluids from Hliðardalskóli come from a different source, possibly meteoric (orange). Small confined packages of old glacial water might be present throughout the area. Well heads and drilling paths are shown (green triangles, white lines). Modified with added content after Google™ (2010)

One of the implications of this conceptual model is that the extent of the Bakki geothermal field is relatively well-known. This allows the implementation a volumetric model that uses numerical volume approximation in order to reduce the uncertainty of this parameter. This method estimates that the volume of the uppermost 1000 m of reservoir with temperatures exceeding 80 °C falls within 11.8-30.2 km³. Through a Monte Carlo simulation, it was possible to evaluate the thermal capacity of the reservoir. It is estimated that the Bakki field is capable of sustaining the current production rate for 580 years before reaching thermal breakthrough.

The volumetric model does not account for either recharge or system pressure response. For this reason, lumped parameter modeling was required to complement those results. It was estimated that the ÖBGA better fits an open, unconfined system. This assertion is consistent with the conceptual model deduced from the mapping process. The lumped
parameter model indicates that the surface area of the Bakki field extends across 23.1 km$^2$. These results are consistent with the surface area deduced from the conceptual model (i.e. 16.4-45.5 km$^2$).

The lumped parameter model also suggests that the Bakki field is capable to support the current production rate sustained for 300 years. This would require readjustment of the pumping equipment in the long term. It also appears that the geothermal field is capable of sustaining for the next 300 years the growth rate observed over the past 30 years. Therefore, reinjection might not be a priority for the management of this resource at this time, unless the average production rate increases more than 50% from its current level.
6 Works Cited


APPENDIX A: Lithological record and hydrothermal alteration for wells HJ-01, BA-01 and EB-01. Bakki.
Figure A-1. Lithologic record and alteration minerals from well HJ-01 (Zhang, 2001)
Figure A-2. Lithologic record and alteration minerals from well BA-01 (Zhang, 2001).
Figure A-3. Lithologic record and altered zones from well EB-01. Modified from (Tómasson et al., 1987)
APPENDIX B:
Well log interpretation for temperature records.
APPENDIX C:
Ölfus-Bakki: Formation temperature
(0-1000 m b.s.l.).
Fm T (°C) and P (bar-g) at 0 m.b.s.l.
Fm T (°C) and P (bar-g) at 100 m.b.s.l.
Fm T (°C) and P (bar-g) at 200 m.b.s.l.
Fm T (°C) and P (bar-g) at 300 m.b.s.l.
Fm T (°C) and P (bar-g) at 400 m.b.s.l.
Fm T (°C) and P (bar-g) at 500 m.b.s.l.
Fm T(C) and P(barg) at 600 m.b.s.l.
Fm T (°C) and P (bar-g) at 700 m.b.s.l.
Fm T (°C) and P (bar-g) at 800 m.b.s.l.
Fm T (°C) and P (bar-g) at 900 m.b.s.l.
Fm T (°C) and P (bar-g) at 1000 m.b.s.l.
APPENDIX D:
Ölfus-Bakki: Fluid Chemistry Distribution (Liquid phase).
Ca distribution
K distribution
Mg distribution
Na distribution
B distribution
Cl distribution
CI/B distribution
dD distribution
$d^{18}O$ distribution
$SO_4$ distribution
H$_2$S distribution
$\text{CO}_2$ distribution
pH distribution