UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

Orkustofnun, Grensasvegi 9,
IS-108 Reykjavik, Iceland

40th Anniversary Workshop
April 26 2018

NUMERICAL SIMULATION OF THE SVARTSENGI GEOTHERMAL FIELD, SW-ICELAND

Melissa Anne De Freitas
Energy Unit
Ministry of National Security, Air and Sea Port Development
Kingstown
SAINT VINCENT & THE GRENADINES
melissa.defreitas@gov.vc ; m.defreitas89@gmail.com

ABSTRACT

Ground subsidence has been observed due to over 40 years of geothermal production in the Svartsengi geothermal field. A numerical model is being developed for the geothermal system to simulate the subsidence along with data reflecting reservoir changes due to the production as well as to predict its future behaviour by incorporating it into a geothermal production model of the area. The model parameters were determined using an assorted source of data and when the model is completed, it will be a valuable tool for predicting subsidence due to geothermal exploitation in Svartsengi.

1. INTRODUCTION

Iceland is situated astride the Mid-Atlantic Ridge whose boundary consists of rifting and transform segments separating the North-American and Eurasian tectonic plates. In the southwest, the Reykjanes segment of the Mid-Atlantic Ridge comes onshore at the Reykjanes Peninsula, extending from there with an azimuth trend of 70° along the entire peninsula (Einarsson, 2008). Iceland's geographical location has made it a very tectonically and volcanically active area with a vast geothermal potential, subject to a range of crustal deformation processes.

The Svartsengi-Eldvörp high-temperature system lies within the active volcanic zone of the outer Reykjanes Peninsula shown in Figure 1. The Svartsengi field lies within a basaltic lava field at low elevations between 20-30 m a.s.l. surrounded by low hyaloclastite mountains. Eldvörp is located approximately six kilometres WSW from the Svartsengi field. Though previously treated as separate systems, numerous studies have proven a clear connection between Svartsengi and Eldvörp.

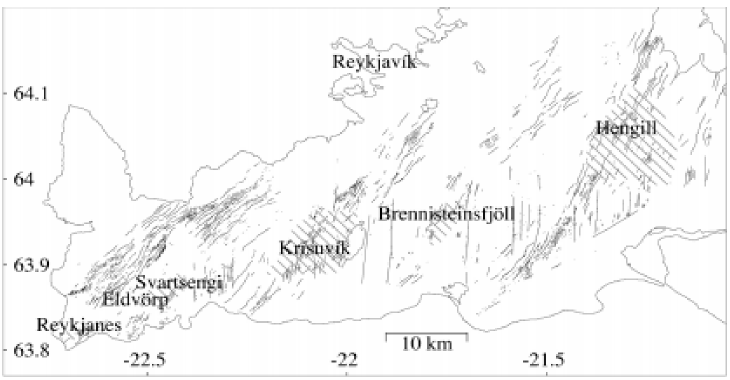

FIGURE 1: Tectonic map of the Reykjanes Peninsula, modified from Clifton and Kattenhorn (2006)

The Svartsengi reservoir is characterised by uniformed pressure conditions and reservoir temperatures of 240°C below 900 m depth within the main production zone (Björnsson and Steingrímsson, 1991). Temperatures have been observed to increase to the southwest, with higher temperatures of 268°C at Eldvörp. A subsidence bowl has formed over the Svartsengi field after the first few years of production, with over 0.36 m of subsidence occurring between 1975 to 2014 (Magnússon, 2015). The subsidence at Svartsengi is rather complex, due to effects of vertical deformation and nearby glacial isostatic adjustment. Numerous production models have been developed during the last 40 years of production but these have neglected to include the effects of subsidence. This project however attempts to create a numerical model, while incorporating the subsidence within the Svartsengi geothermal field.

2. SVARTSENGI GEOTHERMAL FIELD

2.1 Subsurface geology of the Svartsengi geothermal field

At present, there are 25 wells drilled in the main Svartsengi field, and one in Eldvörp, attaining depths from a few hundred metres to just over 2000 m b.s.l. The main alteration features obtained have been identified (Franzson 1983, 1987) as illustrated in Figure 2. Figure 2 summarises the main alteration features, as well as the relationship between the alteration mineralogy found in wells 2-10 and their formation temperatures. The elevation of the mixed-layer clay and chlorite zones observed in the east corresponds to the reservoir's expanding steam zone. Further correlation between the resistivity, temperature and alteration mineralogy is discussed in Section 2.2.

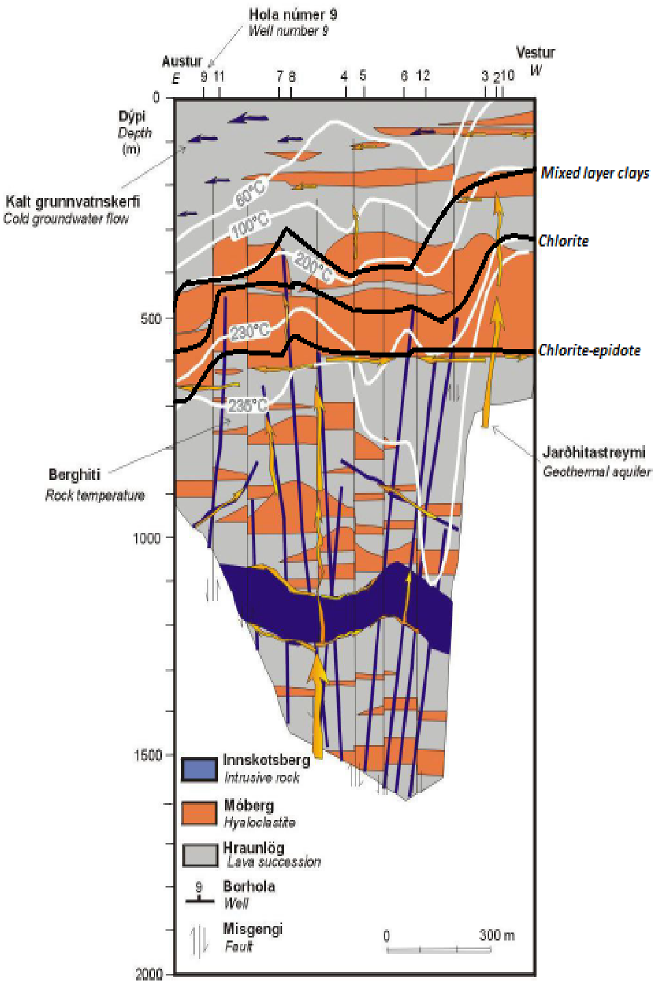

FIGURE 2: Geological cross-section modified from Franzson (1990)

Hyaloclastite layers of thickness 100 m are scattered throughout the profile, with an exception of the layer located between 300-600 m which is observed in most of the deeper wells, acting as a caprock to the hydrothermal system. Dislocations of hyaloclastite boundaries observed in Figure 2 indicates faults dissecting the strata. Intrusives, which are anticipated to range from dykes to sills (Franzson, 2017) are observed below 800 m depth. The location of aquifers shown in Figure 2 were assessed on the basis of circulation losses that occurred during drilling. A notable absence of feed points between 400 and 600 m is attributed to the presence of the system's hydrothermal caprock. Franzson (2017) further concluded that aquifers above 500 m are connected to stratigraphic boundaries, while those in the reservoir (below 800 m) relate generally to intrusive boundaries.

Geothermal reservoirs are characterised by extensive fracturing and high permeability (Gudmundsson and Thórhallsson, 1986). High permeabilities within the reservoir are thought to result from near vertical intrusives and fractures, resulting in a high vertical permeability. A hydrological model of the Svartsengi area presented by Kjaran et al. (1979 and 1980) found the average permeability of the reservoir to be in the range of 100-150 millidarcy.

2.2 Resistivity structure of the Svartsengi geothermal field

An early DC resistivity survey conducted along the western Reykjanes Peninsula revealed a shallow, continuous, east-west striking low-resistivity zone along the Reykjanes plate boundary (Georgsson, 1981). Figure 3 reveals a common reservoir extending from Eldvörp to the north of Svartsengi, with clearly defined boundaries, spanning an area of 30 km^2 at 1000 m b.s.l. (Karlsdóttir, 1998).

The results presented in Figure 3 reveal a resistivity profile synonymous with that of a high temperature geothermal field. The surface resistivity surveys of the high-temperature geothermal systems in the volcanic zones of Iceland have uncovered similar resistivity structures, correlating to the distribution of alteration mineralogy within the reservoir (Árnason et al. 2000). In these systems, the resistivity is relatively high in cold unaltered rocks outside the reservoir. A low-resistivity cap is observed on the outer, upper margins of the reservoirs, underlain by a highly resistive core.

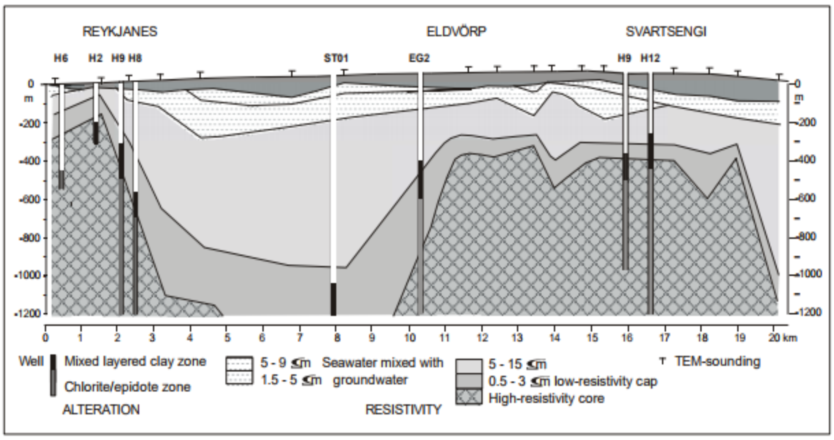

FIGURE 3: ESE-WNW trending TEM resistivity cross-section along the outer Reykjanes Peninsula (Karlsdóttir, 1998)

The resistivity structure obtained from a later magnetotelluric (MT) survey (Figure 4) confirms the earlier models by Georgsson (1981) and Karlsdóttir (1998). The cross-section in Figure 4 traverses west to east across Eldvörp and Svartsengi. It reveals three up flow zones from the core into the overlying low-resistivity cap. A clear reservoir boundary, consistent with Karlsdóttir (1998) is observed west of Eldvörp, where the cap rock dips vertically below depths of 3000 m b.s.l. A comparison between the resistivity profile and thermal alteration derived from well data shows that resistivity measurements reflect the alteration in the geothermal field.

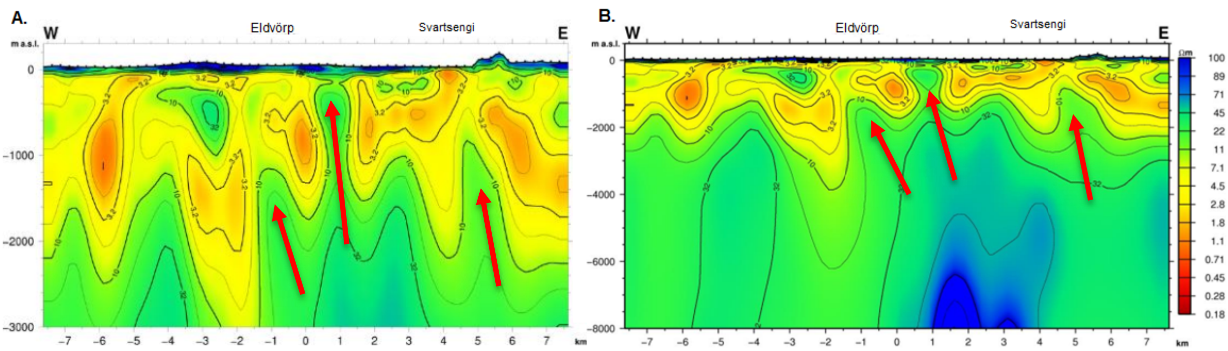

FIGURE 4: Resistivity cross- section through Svartsengi down to 3000 (A) and 8000 (m B) depth b.s.l,. modified from Karlsdóttir and Vilhjálmsson (2015), with arrows pointing towards up-flow areas

2.3 Production history

Figure 5 summarises the production history at the Svartsengi power plant. In 2015, the total production was 488 kg/s, with over half of this being reinjected into the reservoir. The pressure history during 1980-2016 at 900 m depth is depicted in figure 6. The pressure drawdown in Eldvörp follows the same trend as the decline in Svartsengi, with pressure in both fields reacting strongly to reinjection in Svartsengi

(Gudmundsdóttir, 2016). This pressure connection between Eldvörp and Svartsengi further confirms the previous theories that Eldvörp is a part of the Svartsengi geothermal field. In 2000, when there was no reinjection, there was a sudden decrease in pressure, however as reinjection steadily increased during the following years, there was little pressure decline between 2004 and 2008, followed by pressure recovery during 2008-2010 which was attributed to downflow in a newly drilled reinjection well (Gudmundsdóttir, 2016). This pressure connection between Eldvörp and Svartsengi further confirms the previous theories that Eldvörp is a part of the Svartsengi geothermal field.

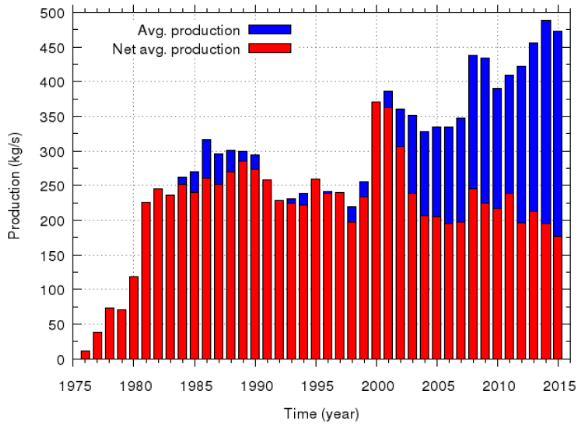

FIGURE 5: Production history at Svartsengi for the period 1975-2015 (Gudmundsdóttir, 2016)

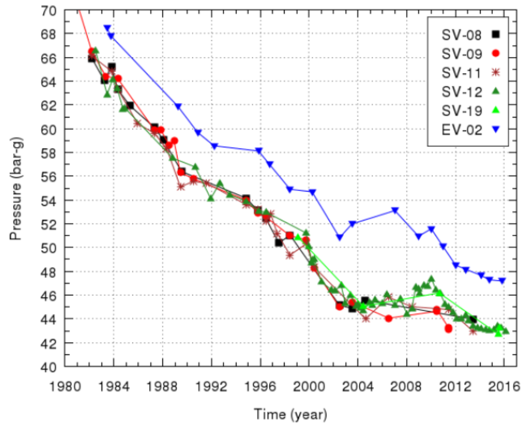

FIGURE 6: Pressure history at Svartsengi and Eldvörp for the period 1980-2016 (Gudmundsdóttir, 2016)

2.4 Subsidence

The extraction of fluid during geothermal exploitation creates a pressure reduction within the reservoir, thereby resulting in compression of the rock matrix. Subsidence in Svartsengi has been extensively monitored since the onset of production, initially by levelling and gravity measurements, and later on additionally by GPS and Satellite Radar Interferometry (InSAR). Extensive geodetic levelling conducted between 1975 to 1992 (Eysteinsson 1993), revealed a vast, elongated subsidence bowl spanning an area of over 100 km^2, with maximum subsidence centred on the Svartsengi well-field. He found that the average rate of subsidence rate following the first 7 years of production was 14 mm/year, with the maximum located directly at the centre of the wellfield. Between 1982 and 1987, an E-W elongated subsidence ellipse was formed. The mean subsidence rate reduced to 7-8 mm/year from 1982-1992, however, during the time interval 1985-1992, the centre of subsidence shifted slightly to the west. The average subsidence increased during 1992-1999 to 14 mm/yr, with the a further west-ward displacement of the point of maximum subsidence. The mean subsidence rate from 2004-2014 decreased to 11 mm/year (Magnússon 2009, 2013, 2015). This decrease in the rate may be attributed to the increase in reinjection during this period (Figure 6).

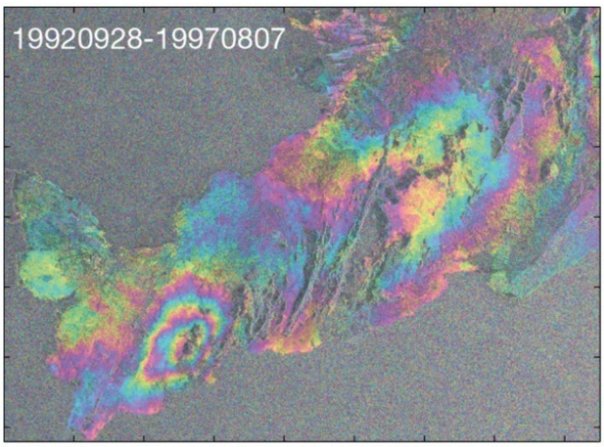

FIGURE 7: A wrapped interferogram of the Reykjanes Peninsula (1992-1997) showing subsidence around the Svartsengi power plant (Keiding, 2009)

InSAR imaging has confirmed the presence of a subsidence bowl by a series of concentric fringes over the Reykjanes central volcano (Figure 7), with the centre of subsidence located between Svartsengi and Eldvörp (Vadon and Sigmundsson, 1997). The average rate of subsidence reported varied from 25 mm/year in 1992 to 9 mm/year in 1993, which is analogue to further ground levelling surveys conducted between 1992 and 1999 (Eysteinsson 2000). Overall, from 1975 to

2014, geodetic surveys have revealed approximately 0.36 m of subsidence in the Svartsengi geothermal area (Magnússon, 2015).

2.5 Previous reservoir models

The Svartsengi geothermal area is a large unconfined liquid-dominated reservoir of hot water-filled rock, surrounded by warm and cold aquifers (Gudmundsson and Thórhallsson, 1986). Steam leaks observed near shallow wells SV-2, SV-03 and SV-10 provided evidence of the development of a steam zone in the north-east portion of the field after a few years of fluid production. This was made evident by borehole data, which revealed temperatures profiles on or near the boiling point curve. They constructed a simple model that assumes a liquid-dominated reservoir with temperatures between 235 and 240°C extending from below 500 m b.s.l. to at least 2 km depth. It is furthermore assumed to be completely isolated from the warm surface groundwater system between 0 and 300 m depth.

Björnsson and Steingrímsson (1991), calculated the formation temperatures of the reservoir and proposed a conceptual model (Figure 8) which depicts the liquid dominated reservoir at depths exceeding 600 m; and a two-phase chimney in the north-east part of the field. Further analysis of the temperature profiles reveals a temperature anomaly close to well 4, which Björnsson and Steingrímsson (1991) interpret as the main upflow of the geothermal system, that feeds permeable horizontal intrusive layers as well as the steam chimney of the two-phase system. This, in addition a hydrothermal upflow along the Eldvörp fissure (Franzson, 1987) was incorporated by Björnsson and Steingrímsson (1991).

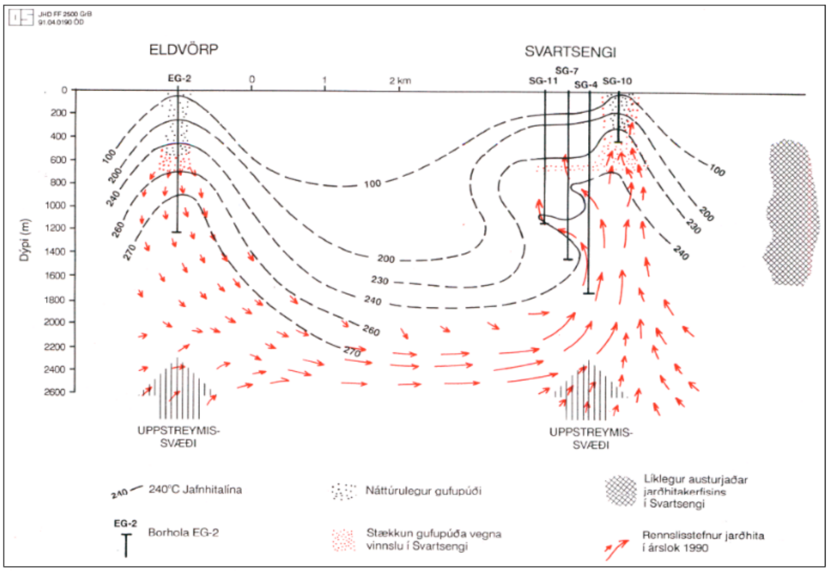

FIGURE 8: Temperature model of the Svartsengi reservoir (Björnsson & Steingrímsson, 1991)

The production model by Ketilsson (2007) in Figure 9 reproduces the conditions of the main production area within the Svartsengi reservoir. This model takes into account more physical conditions and properties that have been observed in the Svartsengi geothermal field, and an excellent fit was found to observed data series for pressure history, temperature and production enthalpy.

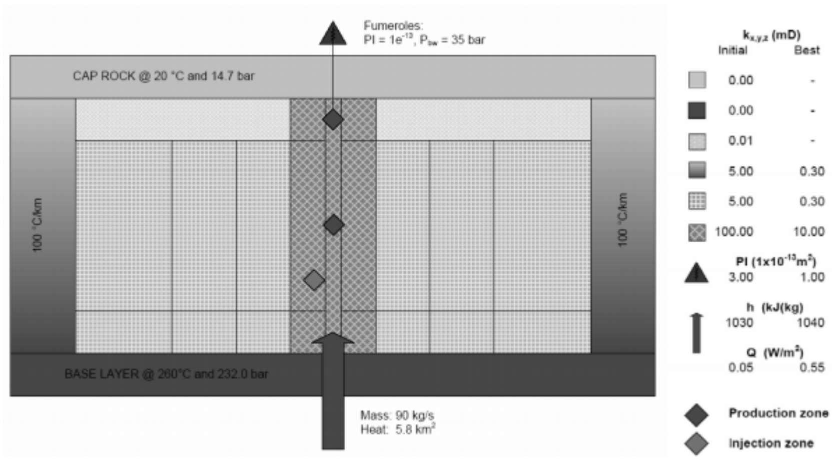

FIGURE 9: Production model of the Svartsengi reservoir (Ketilsson, 2007)

3. CURRENT NUMERICAL MODEL

3.1 Natural state model

Numerical simulations have been increasingly utilised to estimate the outcome of different geothermal management actions, such as changes in exploitation and reinjection, by predicting the response of reservoir to future production. Conceptual models are the first steps to creating a numerical model, since they provide information on the geological structure and reservoir boundaries, as well as the temperature, pressure and fluid interactions within the system. A thorough analysis of all geological, geophysical, borehole and production data was therefore completed before the commencement of the first model.

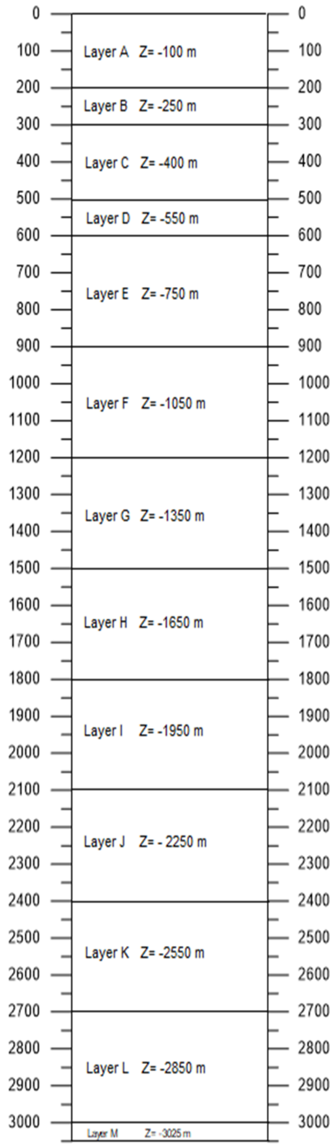

FIGURE 10: Vertical layers in the Svartsengi model

A simple numerical model for the entire Svartsengi geothermal field is being developed for this project. A TOUGH2 grid file was created using the Steinar software package which uses the Amesh program (Haukwa, 1999) that generates discrete grids for numerical modelling of flow and transport problems, formulated on the integral finite difference method (Pruess et al., 1999). This model covers an area of 468 km^2, extending from sea level to 3050 m b.s.l. (Figure 10). It is divided vertically into 13 layers (Layers A to M) of varying thickness. Thinner layers are defined close to the surface, while thicker layers are modelled deeper into the liquid dominated reservoir. The model is discretized horizontally with rather course elements outside of the wellfield, and finer elements within the well field, where more precision is required. A geothermal gradient of 100 °C/km was applied to the entire model.

Dirichelet boundary conditions were applied to the top and bottom layers to control the initial conditions of the reservoir as well as around the lateral edges of the model to restrict the flow of reservoir fluids. A low-permeability caprock was modelled in Layers B and C. In addition to having an 'inactive' high-temperature bedrock of 307°C in Layer M which incorporates the background heat flux, Neumann boundary conditions were applied by adding mass flow sources to Layer L of the model (Figure 11). This simulates the deep up-flow from the geothermal plume (O'Sulluvan and O'Sullivan, 2016). Three upflow zones are included and their locations are illustrated in Figure 11. Source A represents the upflow along the Eldvörp fissure (Franzson, 1987), while source B represents the upflow to the main production area modelled by Björnsson and Steingrímsson (1991). The third source (C), between Eldvörp and Svartsengi was interpreted from the MT profile in Figure 4. Since Eldvörp is a part of the Svartsengi field, it is assumed that they are therefore being fed by the same source. An initial enthalpy of 1300 kJ/kg was applied to each source. Initially, flow rates of 10 kg/s was set at each source. These upflow areas are modelled as vertical fractures, i.e. high z permeabilities are assumed and

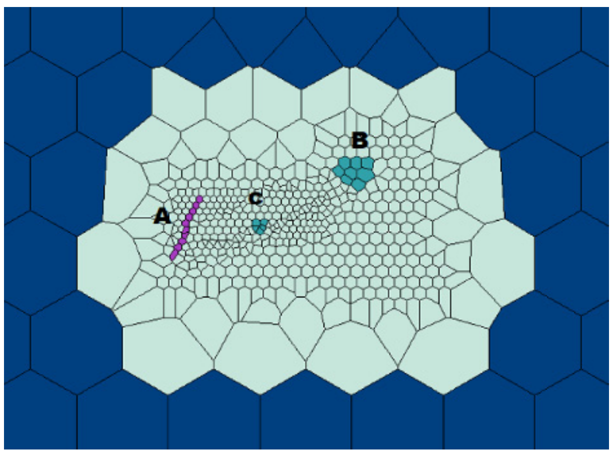

FIGURE 11: Up-flow zones A, B and C, modelled as mass heat sources

reservoir rock parameters were borrowed from Ketilson (2007). These parameters were imported into TOUGH2, and the conditions were simulated for 1,000,000 years in an attempt to achieve steady state and mimic the natural state conditions of the reservoir.

3.2 Next model development steps

The temperature and pressure tend to show little variation throughout the Svartsengi field, although temperatures have been observed to increase towards the south-west. Temperatures in Svartsengi appear to be primarily permeability controlled. This model is currently being calibrated to imitate the natural state conditions of the field, mainly the temperature conditions. After successful completion of this, further calibration would be done to model the effect of production and mass changes. Finally, an attempt will be made to calibrate for subsidence by modelling the compression of rocks within the subsidence bowl over the Svartsengi geothermal area.

5. CONCLUSIONS

The Svartsengi geothermal field lies within a tectonically interesting area that is characterised by unusually high permeabilities, with uniformed temperature and pressure conditions. Previous models have attempted to model the conditions of the Svartsengi reservoir, and have accurately predicted many different scenarios, however separate models have shown large scale subsidence that have occurred due to mass extraction which have not been included in these models. This model when completed, will add to the existing knowledge of the Svartsengi geothermal area by incorporating the subsidence due to over 40 years of geothermal exploitation.

ACKNOWLEDGEMENTS

I would like to acknowledge and extend my gratitude to the UNU-GTP for granting me the opportunity to pursue studies at the University of Iceland. Special thanks to my supervisors Dr. Gudni Axelsson and Dr. Páll Einarsson for their continued support and guidance.

REFERENCES

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G., and Gudlaugsson, S.Þ., 2000: The Resistivity structure of high-temperature geothermal systems in Iceland. *Proceedings of the World Geothermal Congress 2000, Tohoku and Kyushu, Japan*, 923-928.

Björnsson, G., and Steingrímsson, B., 1991: *Temperature and pressure in the geothermal system in Svartsengi. Original status and changes due to production.* Orkustofnun, Reykjavík, report OS-91016/JHD-04 (in Icelandic with English summary), 69 pp.

Clifton, A.E., and Kattenhorn, S.A., 2006: Structural architecture of a highly oblique divergent plate boundary segment. *Tectonophysics, 419,* 27-40.

Einarsson, P., 2008: Plate boundaries, rifts and transforms in Iceland. *Jökull, 58*, 35-58.

Eysteinsson, H., 1993: *Elevation and gravity measurements on the Outer Reykjanes Peninsula 1992.* Orkustofnun, Reykjavík, report OS-93029 / JHS-08 (in Icelandic), 53 pp.

Eysteinsson, H., 2000: Elevation and Gravitational changes at geothermal fields on the Reykjanes Peninsula, SW Iceland. *Proceedings of the World Geothermal Congress 2000, Tohoku and Kyushu, Japan*, 559-564.

Franzson, H., 1983: The Svartsengi high-temperature field subsurface geology and alteration. *Geothermal Resources Council, Trans., 7*, 141-145.

Franzson, H., 1987: The Eldvörp high-temperature area, SW-Iceland. Geothermal geology of the first exploration well. *Proceedings of the 9th New Zealand Workshop*, *NZ*, 179-185.

Franzson, H., 1990: *Svartsengi: Geological model of a high-temperature system and its surroundings.* Orkustofnun, Reykjavík, report OS-90050 / JHS-08 (in Icelandic), 42 pp.

Franzson, H., 2017: *Svartsengi-Eldvörp. A conceptual geological model of the geothermal reservoir.* ÍSOR - Iceland GeoSurvey, Reykjavík, report ÍSOR-2017/017, 69 pp.

Georgsson, L.S., 1981: A resistivity survey on the plate boundaries in the Western Reykjanes Peninsula, Iceland. *Geothemal Resources Council, Trans., 5,* 75-78.

Gudmundsdóttir, V., 2016: *Svartsengi-Reykjanes reservoir temperature and pressure monitoring report 2015.* ÍSOR - Iceland GeoSurvey, Reykjavík, report ÍSOR-2016/032, 85 pp.

Gudmundsson, J.S., and Thórhallsson, S., 1986: The Svartsengi Reservoir in Iceland. *Geothermics, 15-1,* 3-15.

Haukwa, C.B., 1999: *AMESH, A mesh creating program for the integral finite different method, a user's guide version 1.0.* Lawrence Berkeley National Laboratory.

Karlsdóttir, R., 1998: *TEM-measurements in Svartsengi 1997.* Orkustofnun, Reykjavík, report OS-98025, 46 pp.

Karlsdóttir, R., and Vilhjálmsson, A.M., 2015: Svartsengi – Eldvörp – Sandvík. 3D inversion of MT Data. ÍSOR – Iceland GeoSurvey, Reykjavík, report ÍSOR-2015/001, 166 pp.

Keiding, M., 2009: *Stress and strain of a plate boundary - the Reykjanes Peninsula, SW Iceland.* University of Iceland, Reykjavík, PhD thesis, 122 pp.

Ketilsson, J., 2007: *Production capacity assessment of geothermal resources by numerical modelling.* Reykjavík: University of Iceland, MSc thesis.

Kjaran, S.P., Elíasson, J., and Halldórsson, G.K., 1980: *Svartsengi – investigation into geothermal production.* Orkustofnun, Reykjavík, report OS-80021 / ROD10 – JHD17, 98 pp.

Kjaran, S.P., Halldórsson, G.K., Þórhallsson, S., and Elíasson, J., 1979: Reservoir engineering aspects of Svartsengi geothermal area. *Geothermal Resources Council, Trans., 3*, 337-339.

Magnússon, I. Th., 2009: *GNSS- and gravity measurements on the Outer Reykjanes Peninsula 2008.* ÍSOR – Iceland Geosurvey, Reykjavík report ÍSOR-2009/029, 60 pp.

Magnússon, I.Th., 2013: *GNSS- and gravity measurements on the Outer Reykjanes Peninsula 2010.* ÍSOR – Iceland Geosurvey, Reykjavík report ÍSOR-2013/066.

Magnússon, I.Th., 2015: *GNSS- and gravity measurements on the Outer Reykjanes Peninsula, 2014.* ÍSOR – Iceland Geosurvey, Reykjavík, report ÍSOR-2015/053., 82 pp.

O'Sullivan, J., and O'Sullivan, M., 2016: The effect of bottom boundary conditions on predictions of steam production from geothermal reservoir models. *Proceedings of the 41st Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, CA.*

Pruess, K., Oldenburg, C., and Moridis, G., 1999: *TOUGH2, user's guide version 2.0.* Lawrence Berkeley National Laboratory.

Vadon, H., and Sigmundsson, F., 1997: Crustal deformation from 1992 to 1995 at the Mid-Atlantic Ridge, Southwest Iceland, mapped by Satellite Radar Interferometry. *Science, 275*, 193-197.