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A Combined Regional Conceptual and Supercritical Numerical Model of the Reykjanes Peninsula

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ABSTRACT

Conceptual and numerical modelling of geothermal systems has become an invaluable tool in the successful exploration, utilisation and long term management of geothermal resources. These tools provide valuable input into informed decisions to sustainably utilise these resources. With increased interest and subsequent exploration of the roots of high-temperature geothermal systems, new modelling approaches and techniques need to be explored and developed.

One such high temperature geothermal system is the Reykjanes peninsula which is located in South-West Iceland and is the landward extension of the divergent plate boundary of the mid-Atlantic ridge. It is home to three geothermal systems namely Reykjanes, Eldvörp and Svartsengi, two of which are being utilised for electricity and heat production.

This study aims to further explore new modelling techniques by creating a new regional conceptual and supercritical model of the Reykjanes peninsula. It encompasses multiple geothermal reservoirs and simulates the hot supercritical deeper roots of these systems. Several unique approaches are developed for this study to successfully model the complexity of the total system.

Utilising a well-defined set of modelling goals a novel approach is developed to create a conceptual model of the Reykjanes Peninsula in LeapFrog. This approach is rooted in the current knowledge about divergent plates boundaries and then expanded on by taking the stratified volcanology and seismicity of the peninsula into account. This resulted in a conceptual model with an appropriately simplified lithology while at the same time providing the complexity required to calibrate an accurate numerical model.

This conceptual model was then directly used to create a new regional AUTOUGH2 supercritical numerical model to a maximum depth of 7km. To simulate the hot conductive roots of these geothermal systems a new technique was developed where the bottom boundary of the model was set as a constant temperature iso-surface. This iso-surface was initially set to the same surface as the basement lithology and was then contoured as part of the calibration process to match temperatures in multiple geothermal reservoirs.

This study successfully created a new large scale conceptual and supercritical numerical model encompassing multiple geothermal systems at great depths utilising the novel modelling techniques developed specifically for this study. It has created a strong platform for further investigation into the Reykjanes peninsula into such areas such as the interaction between neighbouring geothermal systems or the long term impacts of production or injection into the supercritical roots of these geothermal reservoirs. The techniques developed and used in these models are not unique to this region and can be used as a framework for modelling other similar scale geothermal areas.

1. INTRODUCTION

Conceptual and numerical modelling of geothermal systems has become an invaluable tool in the successful exploration, utilisation and long term management of high temperature geothermal resources. These tools provide valuable input into informed decisions for sustainably utilising these resources. As an output such models also provide an effective way to visually present and communicate a geothermal resource to a diverse audience. As a process, modelling provides a vehicle to bring different disciplines together to form an improved and consistent conceptual understanding of a geothermal system.

One such geothermal system is the Reykjanes Peninsula which is located in the south-west of Iceland and is an on-land extension of the mid-Atlantic ridge; a divergent plate boundary. Its surface geology is characterised by extensive sub-aerial lava flows with hyaloclastite formations as key surface features. It is home to two geothermal power plants known as Reykjanes and Svartsengi which have over 50 years of exploration and utilisation history. It is also the location of an exploratory deep drilling well known as IDPP2, which forms part of a project aimed at testing the economic feasibility of extracting energy and chemicals out of hydrothermal systems at supercritical conditions. To better understand these resources, conceptual and numerical modelling techniques must evolve to capture the complexity of these resources.

This paper presents a new regional conceptual and supercritical model of the Reykjanes Peninsula. The models developed as part of this study encapsulate multiple geothermal systems over a large area and includes the supercritical and conductive roots of the reservoirs. To create these models this study developed novel techniques to tackle the size and complexity of the Reykjanes Peninsula guided by overarching modelling objectives.

2. REYKJANES PENINSULA

The Reykjanes peninsula is located in south-west Iceland and spreads from the Reykjanes volcanic system through to the Hengill volcanic system. This study will be focusing on the western side of the peninsula which encompasses the geothermal systems known as Reykjanes, Svartsengi and Eldvörp shown in the aerial satellite image in Figure 1. The Svartsengi field was the first developed and with a power plant commissioned in 1976. More recently the Reykjanes field was developed and a power plant began operation in 2012. These three fields can be considered as a set of offset parallel fissure swarms which generally follow the SW-NE plate boundary that runs across Iceland as a sub-aerial extension of the mid-Atlantic ridge. Arnórsson, S (1995)

Figure 1: The Reykjanes peninsula located in south-west Iceland. There are three known geothermal systems in this area which include Reykjanes, Eldvörp and Svartsengi. Satellite image provided by Bing Maps (2019).

2.1 Tectonic Setting

In a global tectonic setting Iceland is located on the diverging plate boundary between the North American and Eurasian plates. It sits at the junction of the Mid-Atlantic ridge and the Greenland-Iceland-Faeroe ridge and is considered as a northern extension of the Mid-Atlantic Ridge. Iceland itself is a basalt plateau and rises more than 3000m above the surrounding sea floor. (Thordarson & Larsen, 2007)

There has been active spreading at the Reykjanes Peninsula for the last six to seven million years after the spreading plate boundary shifted eastwards from Snæfellsness in the east of Iceland. Spreading rates on the peninsula are highly oblique at approximately 19 mm per year. Weir et al. (2001). Fissure swarms release stress during volcanic-tectonic activity which occur every several hundreds of years and on a more frequent basis the strike-slip faults release stress by micro-earthquakes swarms at intervals of decades. Sæmundsson et al (2018).

2.2 Geology

Volcanic eruptions on the Reykjanes peninsula are fed directly from magma reservoirs below the mantle as opposed to a shallow magma chamber found at other high temperature systems. As a result no major volcanoes have developed in the region. The Reykjanes volcanic system has well defined parallel sets of fissure swarms extending to the NE and SW along the peninsula. Sæmundsson et al. (2018)

An onset of major glaciations approximately 3 million years ago has had a large influence on the volcanism in Reykjanes and across Iceland itself. This can be seen in the resultant landforms and the properties of the erupted material. Extensive hyaloclastites formed during these glaciations in the form of pillow basalts, breccia and tuffs as subglacial eruptions which dot an otherwise flat landscape. Franzson et al. (2011) In general the surface geology can be characterised by post-glacial lava flows and early post-glacial picritic lava shields with hyaloclastite ridges emerging through the Holocene age lava which have enveloped most of this low terrain region. S. Björnsson et al. (1970)

The sub-surface geology is characterised by a steady build-up of volcanic strata in a submarine and sub-glacial environment before emerging above sea-level. The stratigraphy can be broadly characterised as pillow basalt formations at a depth of 3000 m up to approximately 1400m which were the result of eruptions in deep water. This is followed by pleistocene sub-aerial lava flows located around 1100m depth. Up to about 400 m the stratigraphy is mainly shallow-water eruptions consisting of phreatic tuffs interbedded with marine sediments. Closer to the surface, the geology consists of sub-glacial and sub-marine hyaloclastite formations. The youngest of these formations form low profile hyaloclastite. G. Friðleifsson et al. (2014).

2.3 Geothermal Reservoirs

There are three known geothermal reservoirs in the west of the Reykjanes peninsula, two of which are being utilised for electricity and hot water production known as Reykjanes and Svartsengi. Drilling in the Reykjanes peninsula began in 1956 with the first high temperature well drilled to a depth of 162m. Since then the number of wells of rapidly expanded with over 60 wells drilled in the area (Orkustofnun, 2017).

The geothermal reservoirs in Reykjanes, Svartsengi and Eldvörp follow the boiling point curve with depth in the uppermost 400m to 1000m. Beyond these depths the temperatures are fairly constant which indicates a high vertical permeability and the presence of hydrothermal circulation. Arnórsson (1995). Beyond a depth of approximately 2500 m temperatures begin to increase again in the roots of the geothermal system. From the well temperature logs of the Reykjanes geothermal system the average well reservoir temperature can be estimated at approximately 280°C. The cap rock can be found from a depth of 100 m to 500 m. There is no evidence of a steam cap however there are fumaroles at the surface of the geothermal field (Friðleifsson et al., 2018). In Svartsengi average reservoir temperatures are even more consistent than the Reykjanes reservoir and a little cooler at approximately 240°C. The cap rock can be found from a depth of 250 m to 450 m and there is evidence of a steam cap in in the east of the reservoir field with temperatures of 100°C at the surface (G. Björnsson & Steingrímsson , 1991 and De Freitas et al., 2018a). Only one well exploration well has been drilled in the Eldvörp system. There is insufficient data to draw strong conclusions about the reservoir average conditions however as this system is hydraulically connected to Svartsengi some comparisons can be made. The well indicates a convectional temperature of 260°C, 20°C hotter than the Svartsengi reservoir. This can be accounted for due to different sources of heat upflow as Eldvörp lies on a fissure. The cap rock is roughly 250 m thick and on average thinner than the Svarstengi reservoir (De Freitas et al., 2018a).

Active tectonics and volcanology on the Reykjanes peninsula has created a highly fractured area which is kept active by continued seismicity along the rift zone. The general trend of faults in the lava piles of Iceland are steeply dipping and are perpendicular to the lavas that are intersected. These vertical faults provide highly permeable pathways within the reservoirs which allow effective ground- water convection and uniform temperatures within the reservoirs (Sæmundsson & Einarsson, 2014).

The coastal locations of the Reykjanes and Svartsengi reservoirs means that reservoir recharge is mostly or completely consists of seawater. These systems have a high dissolved solids content and at shallow depths in the reservoirs the chloride concentration can be up to 25% higher than what is found in seawater due to in-situ boiling (Sigurdsson, 2010).

The most scientifically significant well drilled in recent years is the extension of well RN-15 located at the Reykjanes reservoir. This well was extended and then deviated to a depth of 4659 m as part of the Iceland Deep Drilling Project (IDDP). This well became known as IDDP-2 and had the purpose of exploring the deep geothermal roots of the field in search of supercritical conditions and ultimately the source of energy for this geothermal system (G. Ó. Friðleifsson et al., 2017). This well successfully encountered supercritical hydrothermal conditions and will be a key source of data in this project including temperature profiles, permeability and lithology at depth.

2.4 Conceptual Model

Figure 2 shows a schematic lithological model representing the crust beneath the Reykjanes peninsula. It provides a simplified conceptual model of the region and was a key influence on developing a regional conceptual model in this study. It shows a layered lithological structure where beneath a thin layer of post-glacial lavas, a cap rock has formed in the hyaloclastite formations which encloses a high temperature geothermal convectional cell below.

RN-15/IDDP2 well has validated the presence of a sheeted dyke complex in an ophiolite conceptual model. This model most importantly demonstrates the source of intrusions from the lower Gabbroic crust which intrudes as dykes into the extrusive formations above which over time has formed the hot sheeted dyke complex (G. Ó. Friðleifsson et al., 2017). These intrusions and occasional eruptions have provided the heat source and vertical fractures to form the geothermal systems over time (Sigurdsson, 2010).

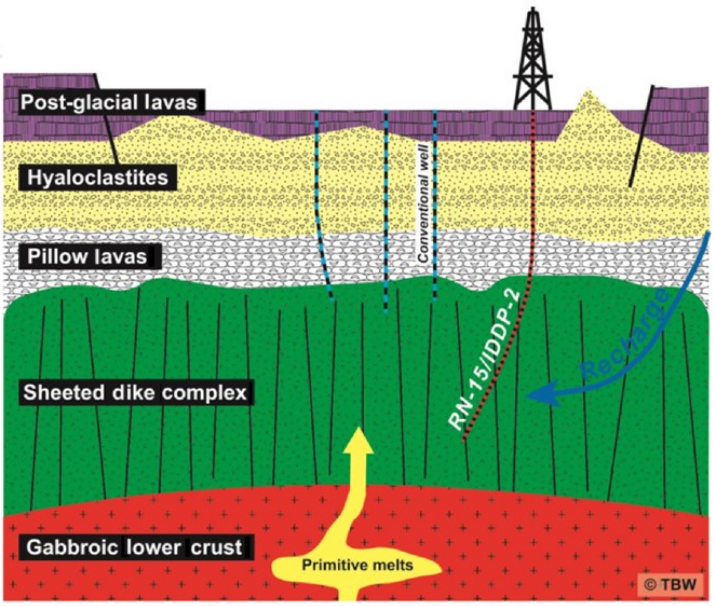

Figure 2: Schematic lithological model of the crust beneath the Reykjanes peninsula . Friðleifsson et al (2017).

3. MODELLING APPROACH

This ambitious modelling study was both large and complex and required several innovations to successfully develop and complete both the conceptual and numerical model. The problem was initially approached as a traditional single reservoir modelling project but it was soon found that this approach was not possible given the lack of availability of information and the complexity of the model. To proceed with the project an over-arching framework was required to guide the project which also set clear modelling objectives and ensured unity between the conceptual and numerical model.

The workflow designed for this modelling project is shown in Figure 3 and takes inspiration from a continuous improvement cycle. Using this workflow a clear set of modelling objectives were defined which led to the innovative development of the techniques used in this modelling study. The workflow also ensured that there was a consistent link between the conceptual and numerical model. This ensured that as the models were developed and improved that there was consistency between the models and the known geological data about the region and reservoirs.

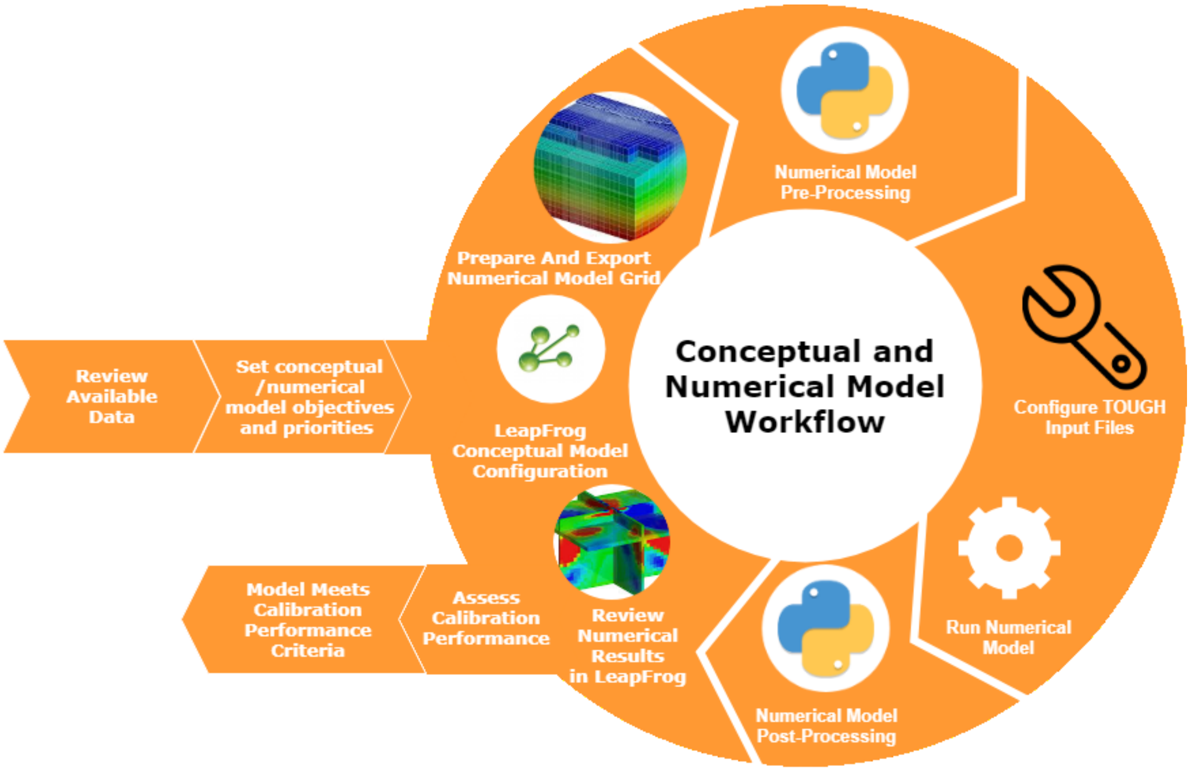

Figure 3: A circular workflow was developed to guide the modelling process used in this study. This workflow ensures that a set of clear modelling objectives are developed before entering a continuous improvement cycle of calibration. Once the calibration targets have been met the m

3.1 Conceptual Model

A set of clear modelling objectives were developed to guide the regional conceptual model. These objectives can be summarised as follows,

1. To provide a combined profile of the topography and bathymetry of the region to capture the top boundary effects of meteoric and seawater ingress.
2. Develop an appropriately simplified lithology of the Reykjanes peninsula which encapsulates the Reykjanes, Eldvörp and Svartsengi geothermal fields which sit along a divergent plate boundary utilising as much direct geological information as possible.
3. To map trends and zones of highly permeable structures across the region based on the location of faults, fissures and areas of high seismic activity.
4. To map out the clay caps of the known geothermal resources.
5. To create a central repository of geological and geophysical information in graphic format including geological maps and cross sections, resistivity surveys and well logs which will be continually referred to as the conceptual and numerical models are developed and calibrated.

LeapFrog software was used to develop the 3D regional conceptual model and also acted as the main repository of graphical geological information on the region. The conceptual model was developed in three steps. Firstly the stratified lithological layers were created utilising a simplified lithology. Secondly permeable structures were identified in the region. Finally the clay caps were developed over the known geothermal resources.

Usually the lithology within a conceptual model is developed by interpolating across the available geological information normally in the form of geological maps, cross sections and well logs. The size of the conceptual model, the known layered volcano-stratigraphy of the region and the lack of sub-surface geological data outside the known explored reservoirs meant that an alternative approach was required. This alternative approach is rooted in divergent plate boundary theorem and the findings of the IDDP-2 well.

At a divergent plate boundary, as the adjacent plates move apart, long and narrow fractures form creating a pathway for hot molten rock from the mantle to escape towards the sea floor. As this molten material cools new sea floor is generated. This molten material slowly cools top downwards, thickens and is pushed away from the spreading centre due to continuous upwelling from the mantle. (Tarbuck et al., 2005). Friðleifsson et al (2018) reports on the drilling of IDDP-2 at the Reykjanes geothermal field, who draw comparisons between in-situ oceanic crust at a divergent plate boundary and the lithology of the IDDP-2 well which is illustrated in figure 4. The summarised lithology shows the similarities between all three wells. Each well consists of an extrusive basalt and pillows layer, followed by what is known as an extrusive-intrusive transition zone as evident by increasing frequency of dikes within an extrusive body, which finally culminates in a hot sheeted dike complex, a source of heat and energy in hydrothermal systems. The clear difference between IDDP-2 and the other two wells is that the extrusive-intrusive transition zone extends to a much lower depth. It is this similarity that will be used as the basis to form the lithological structure for the conceptual model. To summarise Iceland can be considered as over thickened oceanic crust with the addition of shallow sub-surface eruptions and sub-aerial lava flows.

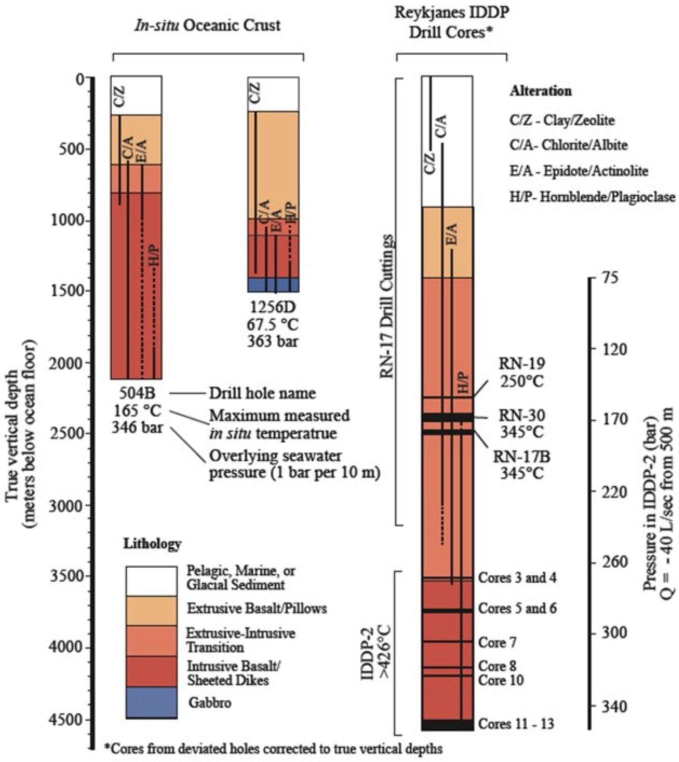

Figure 4: Comparison of alteration and rock types observed in IDDP-2 cores from the Reykjanes geothermal system to the two deepest holes drilled into in situ oceanic crust G. Ó. Friðleifsson et al (2018).

Five main lithological units were chosen to represent the stratigraphy of the region. In the context of this model they are known as post-glacial lava (L), hyaloclastite (H), pillow lava (P), extrusive-intrusive transition zone (T) and the sheeted dike complex (D). These are names used in this study to summarise a range of formations and are representative of the volcanic history over time. These lithological categories can be summarised as follows,

1. Post-Glacial Lava - represent any formations that have formed in the Holocene epoch less than 12.000 years ago. This mainly represents sub-aerial lava flows from eruptive fissures and shield volcanoes in the region.
2. Hyaloclastite - represents formations that formed during the late Pleistocene epoch during a glaciation and so is characterised by sub-glacial eruptions and low-depth sub-marine eruptive formations forming tuff. These formations are visible today as mountains and large ills along the current plate boundary.
3. Pillow Lava - represents the formations that formed before Iceland had risen above sea level, was in contact with vert thick layers of glacial ice or formed during the earlier Pleistocene epoch. These formations formed at depth beneath the sea with pillow lavas representing one of the extrusive formations that can be found at a divergent plate boundary. It must be recognised that pillow lava can also form at the base of a hyaloclastite formation in more recent sub-glacial eruption.
4. Extrusive-intrusive transition - This category represents formations where the frequency of intrusive dykes and sills begins to rapidly increase. This is typical of the subsurface geology of the region as more recent volcanic activity along the rift zone results in intrusives travelling from depth through existing formations to form new formations above.
5. Sheeted Dike Complex-This represents the formations at depth where the formation has been intruded with a very high frequency of dykes (normally dolerites) and act as feeders for overlaying extrusive formations above. This category also represents the bottom of the hydrothermal cells as the brittle-ductile boundary is approached and is characterised by rapid increases in temperatures and reduced permeability. This lithological category will be used to set the initial bottom boundary isotherm as further explained in the numerical model setup.

Using the IDDP-2 well as a benchmark for the relative locations of the main lithological units, a five layered stratigraphy was created across the region where the hot and more active lower lithological units such as the sheeted dike complex were found at deeper depths further from the active reservoirs as well as the active plate boundary.

The peninsula contains a large number of visible fault and fractures with some of these structures providing vertical permeability for known geothermal systems. The conceptual model is too large to capture all of the structures. A novel approach was developed inspired by Khodayar et al (2018). Rather than tracing out individual structures, structural trends were identified across the region by tracing out apparent trends in faults and fissures in the region. These trends had a NE-SW strike and in general were at an oblique angle to the plate boundary consistent with tectonics of the area. An emphasis was placed on creating trends along or over existing visible hyaloclastite formations. Subsequently seismic maps were used to map out the extents of the rift zone on the north and south of the model and to identify those sections of the structural trends which were most active as result of seismic activity.

Clay caps were developed from a combination of hydrothermal alteration lithology profiles and TEM and MT resistivity surveys. The surveys in cross-section and aerial map form were used to develop the shape of the clay caps in LeapFrog. The TEM and MT resistivity surveys were taken from a an article published by De Freitas who used a similar methodology to identify the location of the cap rock while creating a numerical simulation of the Svartsengi geothermal reservoir (De Freitas et al., 2018b)

3.2 Numerical Model

The design and calibration of a successful numerical model is determined by the quality of the conceptual model that it is based on as well as the calibration steps taken which should be based on sound geological principles. The supercritical numerical model developed in this study provided some interesting challenges. There are several aspects which make this model very unique which required careful planning and configuration. The model is unique in that it is simulating supercritical conditions at great depths across multiple geothermal systems and relies on the careful adjustment of both rock permeability and a high temperature conductive isosurface in the base of the model.

A gridded cubic structure was generated directly from the conceptual model. The model was orientated approximately at the same angle as the known active rift zone and was sized to capture all three geothermal systems. The grid also encompassed a significant amount of offshore blocks as well as some of the more mountainous regions in the east of the Reykjanes peninsula. This was done to ensure that the ingress of seawater and rainfall could be sufficiently captured within the numerical model.

The resolution of the grid was increased significantly in and around the reservoirs along the x and y directions and with depth the resolution was slowly decreased with the thickest blocks at the bottom of the known reservoirs. Thinner layers were used closer to the surface to provide sufficient detail to the post-glacial lava and hyaloclastite lithological categories which were less thick relative to the deeper formations in the conceptual model. The final grid consisted of 39 layers, 37 rows and 51 columns. This resulted in a finite volume model consisting of 55.468 blocks and 158249 connections which was then further expanded and changed as the model was calibrated. The numerical model has a thickness of 7 km and covers a surface area of 567 km^2.

Several boundary conditions were configured in the numerical model. An atmospheric boundary with constant thermodynamic conditions was assigned to all sub-aerial blocks. These sub-aerial blocks were then assigned an average rainfall for the region to simulate rainfall as a mass generator. Sub-sea blocks were connected to water blocks which were assigned a constant hydrostatic pressure based on depth as well as a constant temperature to simulate the influx of seawater into the geothermal systems. And lastly a temperature isosurface was a configured in the base of the model to simulate the hot conductive roots of the plate boundary. This isosurface is more clearly explained in section 3.3.

3.3 Temperature Iso-surface and Model Calibration

What makes this study significantly more interesting is that it is modelling the roots of the geothermal systems. Generally geothermal reservoir numerical models do not encompass the full length of a hydrothermal cell. This means that a geothermal upflow must be included into the base of the model which is set as boundary condition by setting a constant mass and enthalpy influx. The influx of mass energy into the system can then be adjusted to calibrate the model.

In the physical world heat is transferred by conductive and convective mechanisms from hot intrusive rocks to the surrounding fluid. With depth and temperature rocks become less permeable and so conductive heat transfer begins to dominate. This region is also known as the ductile-brittle boundary where temperatures in the rock quickly elevate and rocks begin to show evidence of plastic deformation.

Conceptually the Reykjanes plate boundary is underlain by a sheeted dyke complex which hosts a multitude of hot intrusive bodies as opposed to isolated chambers of magma. This can be approximated to a constant temperature conductive body which would have its own topography defined by the history of volcanic activity in the region. The sheeted dike complex was used to initially set the topography of the isosurface. This isosurface is shown in figure 6 as the orange layer. This is a novel approach and the whole isosurface can be contoured to form and temperature match the geothermal systems.

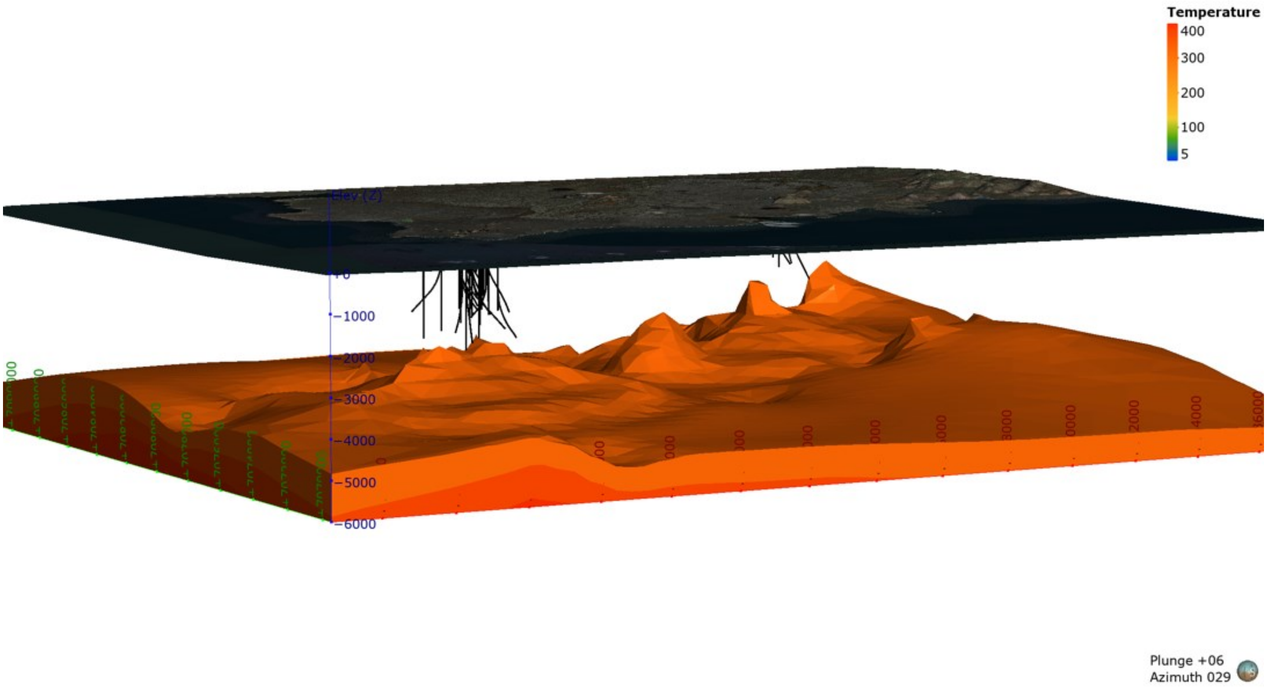

Figure 5: 450°C Temperature isosurface in the base of the model during calibration. The topography of this surface was initially defined by the lithological layer known as the sheeted dike complex. Over time this surface was contoured to calibrate the model and it can be seen that along the plate boundary this surface extends towards the surface beneath the known geothermal reservoirs.

The two main levers used to calibrate the numerical model are rock permeability and the contour of the temperature isosurface. This creates a very challenging calibration process as it requires careful contouring of the basement boundary isotherm along with permeability to develop the geothermal systems in the first place before these systems can be temperature matched against well logs.

To focus the intricate calibration process a tiered list of calibration objectives was developed. The objectives can be summarised as follows,

1. Model is numerically and thermodynamically stable with initial low permeabilities.
2. Geothermal plumes are forming under the clay caps.
3. Geothermal reservoirs are at the correct average temperatures within the convection cell.
4. Suppress unwanted geothermal plumes forming away from the geothermal reservoirs.
5. Begin temperature and pressure matching well by well.

In this study where possible formation temperature profiles were used for temperature matching. Otherwise temperature logs were used to for calibration purposes. Formation temperatures provide better evidence at the temperature conditions at which the hydrothermal systems reached equilibrium however it is under the assumption that the system was at steady state before production began. Additionally, comparisons were made to historical pressure trends to sense check the pressures simulated within the numerical model.

4. RESULTS

The unique regional approach developed for this study was used to successfully create a large scale conceptual model stretching from the mid-Atlantic ridge in the south-west to the north-east beyond the Svartsengi geothermal field which met all the modelling objectives.

Using the conceptual model a new supercritical numerical model was created which was calibrated using the unique method of adjusting a temperature isosurface set at 450°C in the base of the model. A careful coordination of adjusting the rock permeability and the isosurface resulted in a successful temperature matching calibration across multiple geothermal systems.

4.1 Regional Conceptual Model

Figure 5 presents the completed regional conceptual model developed for the Reykjanes peninsula utilising the regional conceptual model approach. This conceptual model presents a layered volcanic stratigraphy hosting a set of parallel structural trends along the plate boundary and shows how the hyaloclastite and pillow lava formations host the clay caps which overlay the geothermal reservoirs.

The lower formations known as the sheeted dike complex and the extrusive-intrusive transition zone slope away from the known geothermal reservoirs and the active plate boundary simulating the thinning of the crust around active areas along a divergent plate boundary. Two separate clay cap structures were developed. In the south-west a domed clay cap was formed around the Reykjanes reservoir and in the north-east model and long elongated clay cap was formed to enclose the Svartsengi and Eldvörp reservoirs.

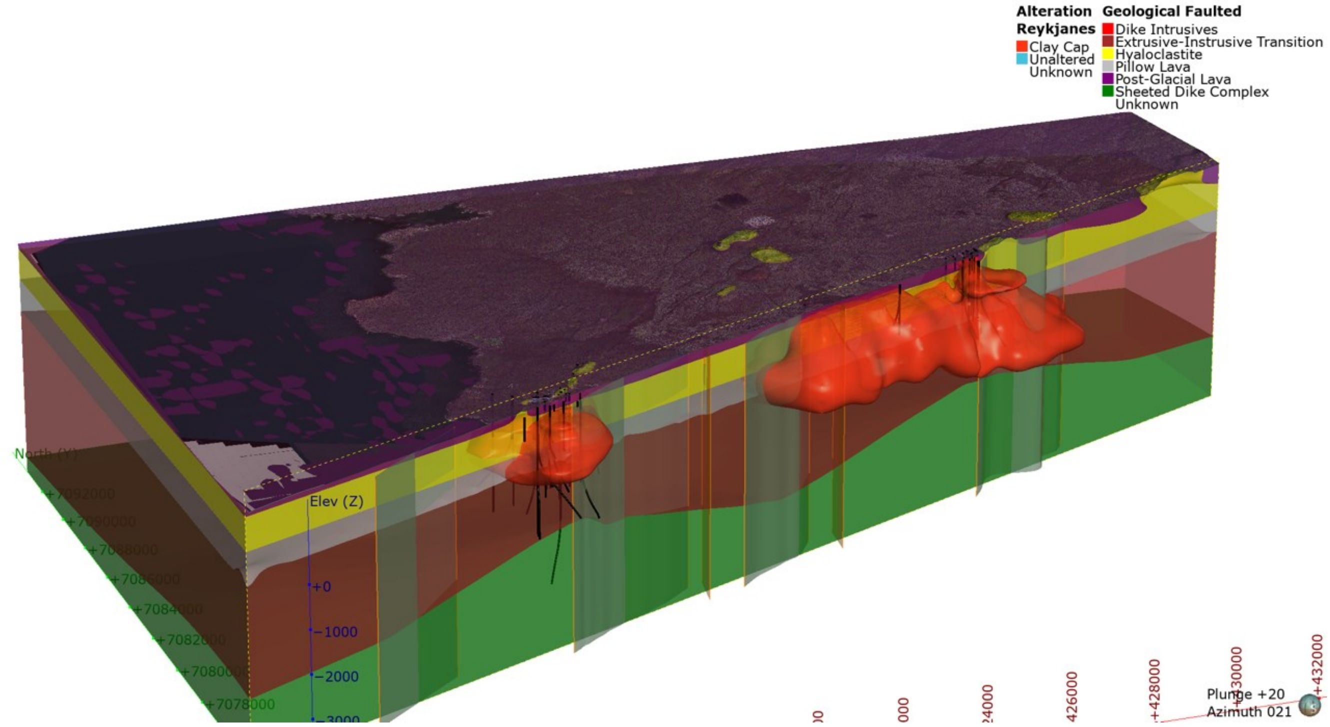

Figure 6: Regional conceptual model of the Reykjanes Peninsula before numerical calibration. This conceptual model features the clay caps in red, transparent vertical planes indicating trends of permeable structures and a layered lithological model representative of the sub-surface geology.

Figure 7 shows the cubic finite volume grid generated directly from the conceptual model. This grid demonstrates the complexity provided by the conceptual model in terms of lithological layers, permeable structures, the active rift zone and the inactive zones away from the rift zone to the North-East and South-West.

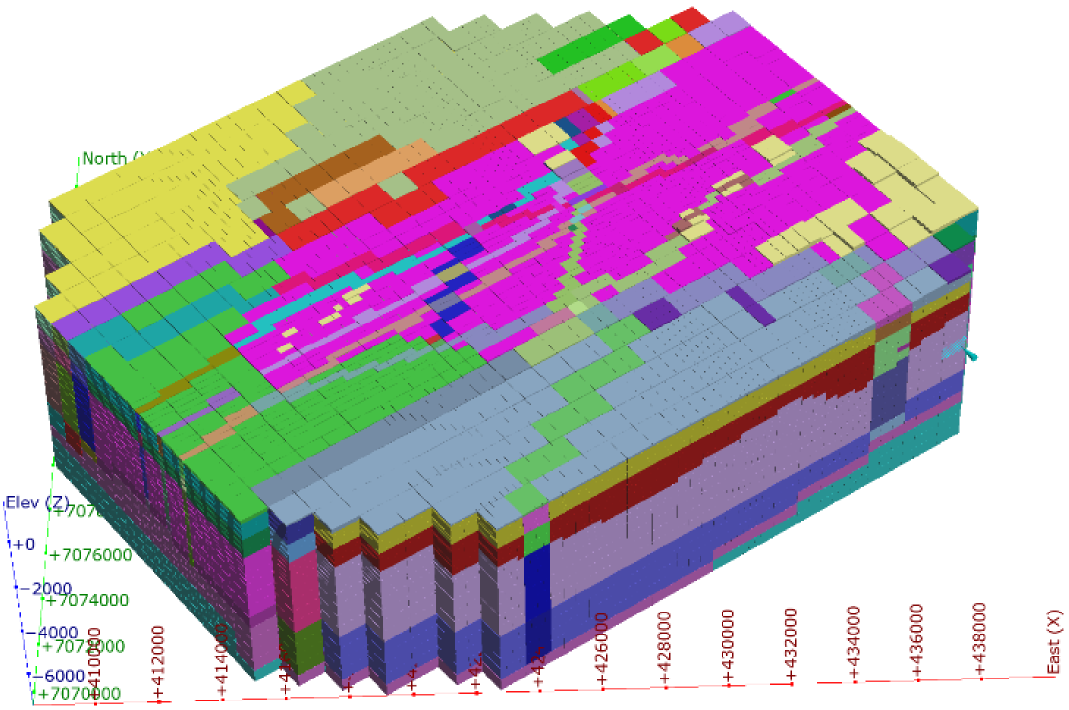

Figure 7: Cubic Grid generated for the supercritical numerical model. The grid shows the resultant complexity from the conceptual model with more than 330 rock types used in the final iteration of the numerical model.

4.2 Supercritical Numerical Model

Figure 8 presents the temperature profile of the calibrated regional supercritical numerical model of the Reykjanes Peninsula along the plate boundary encompassing the Reykjanes, Eldvörp and Svartsengi geothermal systems. Stretching from 2 km offshore the model extends north east for almost 25 kms.

Twenty AUTOUGH stimulation iterations were required to calibrate the model. Initial calibration of the numerical model was challenging and required small changes to both permeability and the isosurface to form the initial geothermal plumes in the correct location. Once formed the geothermal systems were shaped to initially meet the required reservoir temperatures followed by well temperature matching. The numerical simulation results were continuously imported back to the conceptual model to plan out the next calibration steps.

The two step process of modelling the reservoir temperatures to measured conditions was a complete success. Firstly the average reservoir temperatures were matched for all three different reservoirs by carefully increasing the the vertical permeability and raising the isosurface beneath the known geothermal systems. This was followed by well temperature matching was carried out against 38 wells across the three reservoirs.

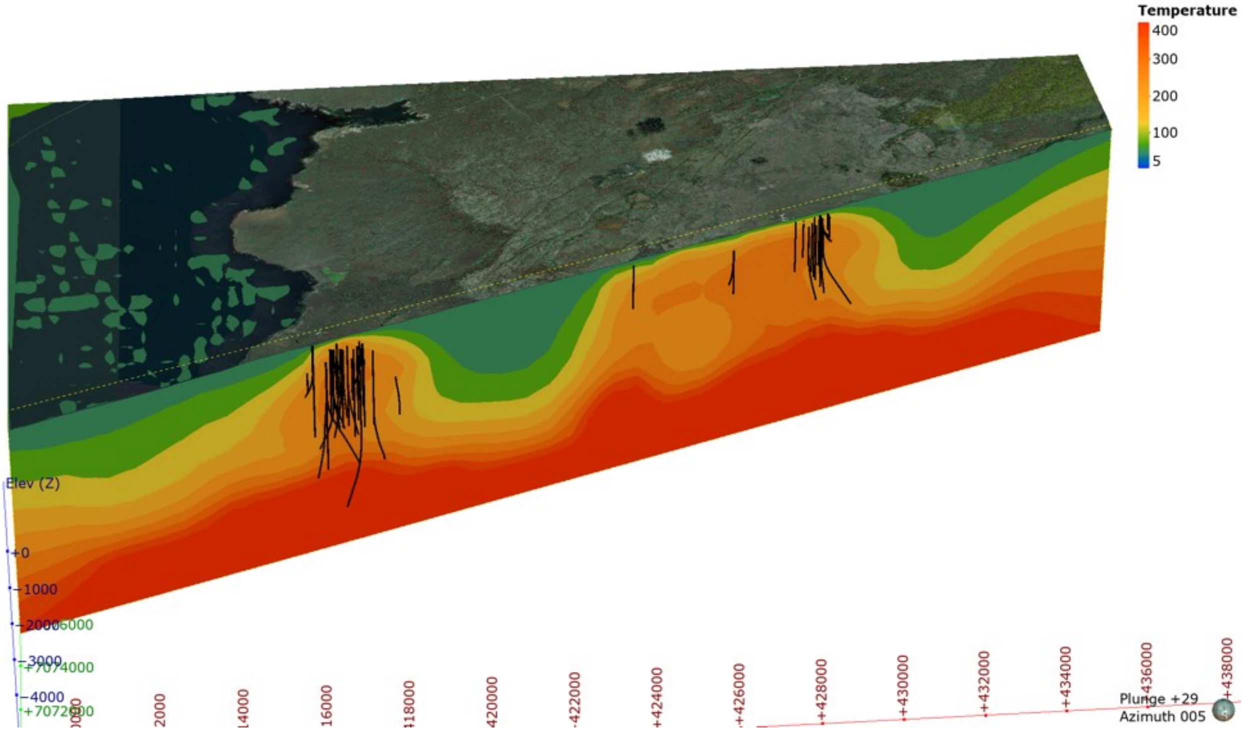

Figure 8: Temperature profile along the plate boundary in SW-NE direction (left to right).

On average the model provided excellent temperature matching results for all three geothermal systems. Figure 9 shows a temperature plot of well RN-24 in the Reykjanes Peninsula and demonstrates one of the strong correlations between well logs and simulation results. Similarly figure 10 presents the results for well SV-17, a well located in the Svartsengi field. This well demonstrates the trade off of trying to match the two separate reservoirs of Svartsengi and Eldvörp which are hydraulically connected. Despite this complication there were strong temperature matching results for the majority of the wells.

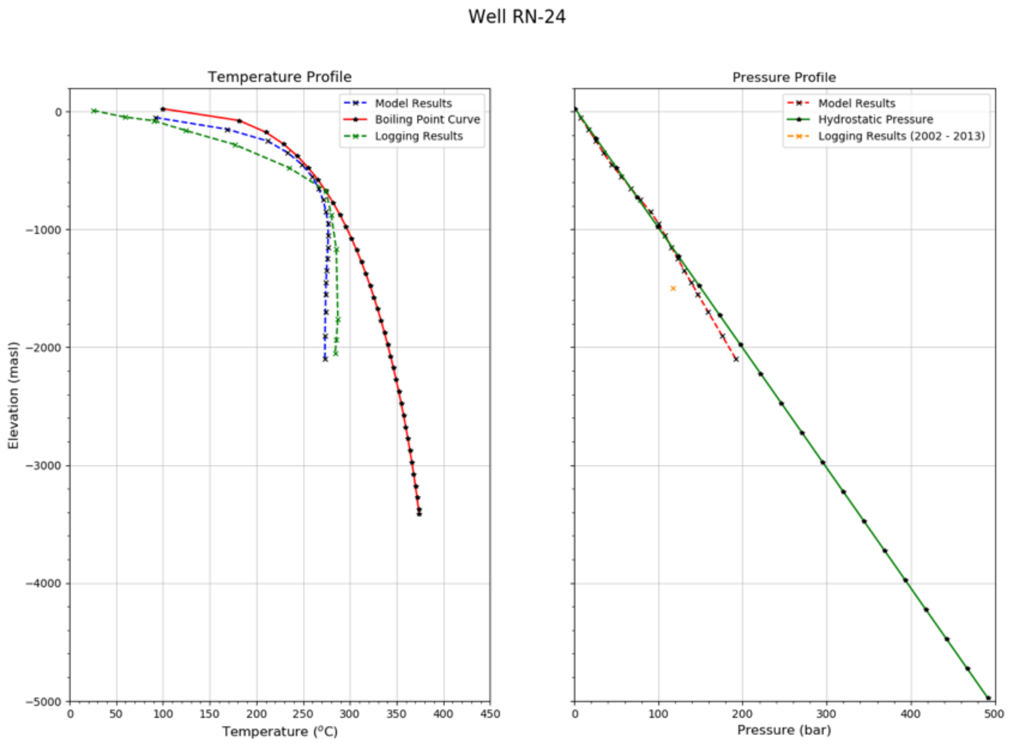

Figure 9: Temperature matching results for well RN-24 in the Reykjanes field as well as the pressure profile along the well trajectory.

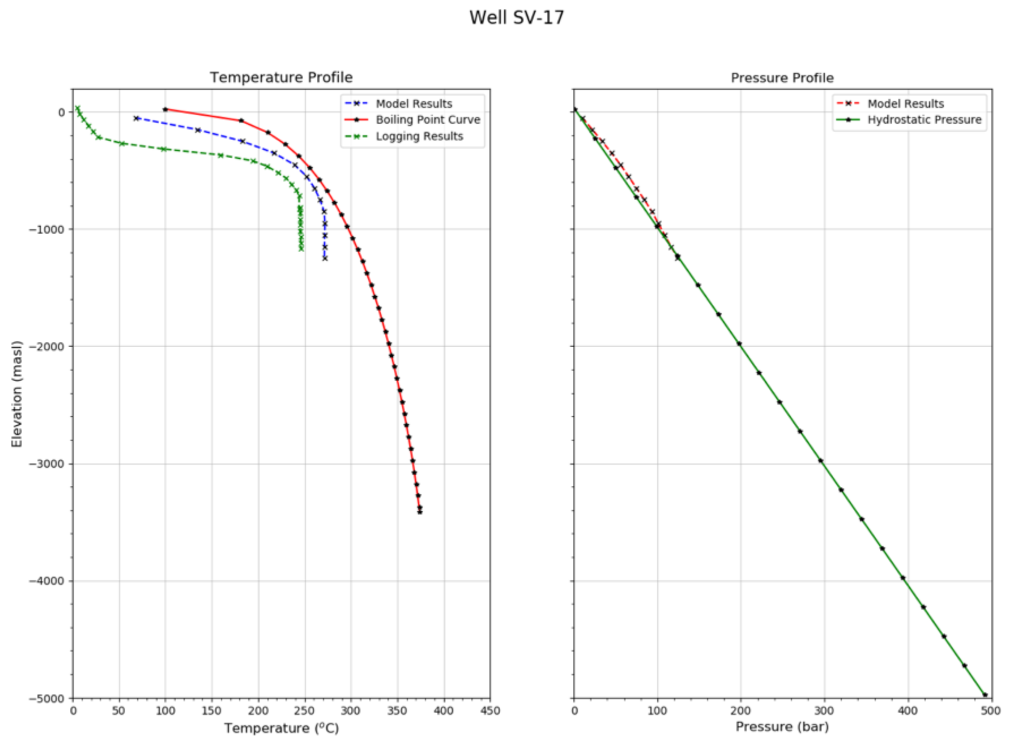

Figure 10: Temperature matching results for well SV-17 in the Svartsengi field.

4.3 Permeability Structure

The vertical permeability structure for the region along the plate boundary is presented in figure 11. The permeability distribution closely matched what was expected of these geothermal systems with a low permeability cap, a more permeable reservoir and low permeability rock matrices at depth towards the brittle-ductile boundary. Vertical reservoir permeabilities in the upper 3500 m of the reservoir ranged from 2.5 to 79 mD with highest permeability in the fractures running through the reservoirs. The fractures were one of the primary permeability controls in improving the temperature and pressure matching results in the known geothermal reservoirs.

The pillow lava and extrusive-transition zone had unexpectedly low permeabilities within this model given the conceptualisation that intrusives at these depths control vertical permeability. However this could be attributed to the low resolution of the model which cannot capture such structures in sufficient and small enough detail and so the permeability represents the average permeability of large regions of the reservoir. This may also be attributed to the general shape of the bottom boundary being too broad underneath the reservoir and so consequently requiring low permeabilities to control the heat flow into the reservoir.

In general permeability was anisotropic with depth and in a NW and SE direction away from the active rift zone. Although this is implicitly implied by the conceptual models, it was also naturally required in the numerical model to prevent the formation of rival geothermal systems away from the known reservoirs.

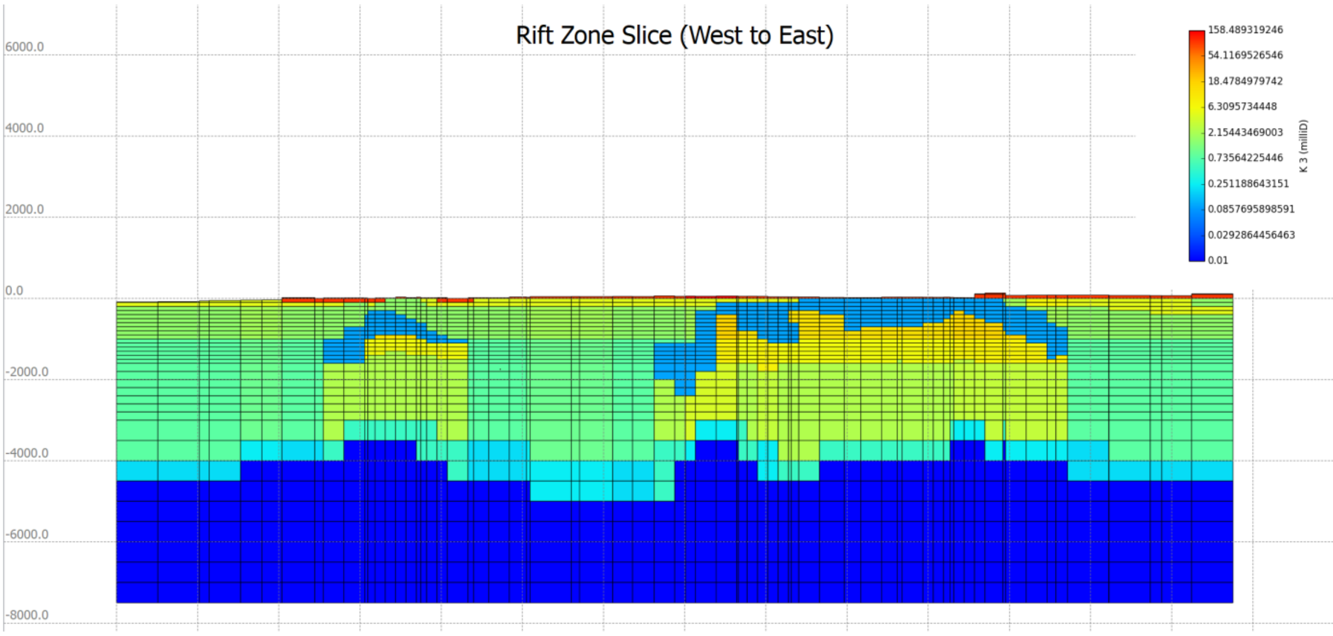

Figure 11: Vertical permeability along the plate boundary. The Reykjanes geothermal field is shown on the left and the Eldvörp and Svartsengi reservoirs are shown on the right.

5. CONCLUSION

This paper presents a large-scale modelling study which successfully simulated multiple geothermal systems in the Reykjanes peninsula across a surface area of over 567 km^2 and up to a depth of 7 km. A clear set of modelling objectives led to the development of a novel regional approach in constructing the conceptual model. This was rooted in the previous developed conceptual models, divergent plate boundary characteristics and geological information known about the region such as the general trend of permeable structures across the region. The conceptual model was carefully crafted, and a careful balance was maintained between appropriate simplification of the lithology and the necessary detail required to create a numerical model which could be successfully calibrated.

The supercritical numerical model grid was generated directly from the conceptual model creating a necessary direct link between the conceptual and numerical models. This led to a calibration process which was conceptually consistent with the primary geological data of the Reykjanes Peninsula. The supercritical numerical model was successfully calibrated utilising a new technique which adjusted the topography of a constant temperature iso-surface set at 450°C in the base of the numerical model. This iso-surface was contoured to form the geothermal plumes in the base of the model which then lead onto temperature matching multiple geothermal reservoirs.

This has culminated in the first combined regional conceptual and supercritical numerical model capable of simulating the hot conductive roots of multiple geothermal systems. This groundbreaking study has paved the way for further interesting and pertinent modelling investigations by establishing a methodology with new proven modelling techniques to model large geothermal systems to great depths.

It has also created a strong platform for further investigation into the Reykjanes peninsula into such areas such as the interaction between neighbouring geothermal systems or the long-term impacts of production or injection into the supercritical roots of these geothermal reservoirs.

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