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ERiS Project: Enhancing Geothermal Reservoirs – Modelling and Analysis of Hydraulic and Thermal Stimulation

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ABSTRACT

Improved engineering decisions in stimulation and operation of geothermal reservoirs are closely related to understanding of subsurface dynamics when different physical processes and the underlying fractured structure of the reservoir strongly interact. Integrated numerical modelling and data interpretation tools that can identify governing mechanisms and forecast reservoir response to hydraulic stimulation are in their infancy but are crucial in developing sustainable and commercially competitive solutions for exploitation of deep geothermal energy. Through an interdisciplinary effort, combining recent developments in monitoring, data processing and modelling efforts, the ERiS project (2017-2020) targets knowledge building for the development of improved stimulation strategies and for achieving sustainable operation for geothermal reservoirs. The project's primary objective is to complement the expertise of the geothermal energy sector in exploitation of unconventional geothermal resources by developing new numerical models and data interpretation workflows that can identify governing mechanisms and forecast reservoir response to stimulation. In the project, different mechanisms for reactivation and propagation of fractures in the subsurface because of changes in fluid pressure, temperature and stress are investigated. Particular attention is given to a case study, where integration of mathematical modelling, numerical simulations and analysis of seismic data related to periods of fluid injection at the Reykjanes Peninsula in Iceland are key components.

1. INTRODUCTION

Utilization of deep geothermal energy spans a range of resource types and production systems, contributing to environment-friendly heating and electricity generation worldwide. Geothermal energy resources can provide dispatchable and base-load production with a small aerial footprint. These features, together with its inherent potential as an energy storage mechanism, gives the energy resource a significant potential in the transition to a low-carbon, low-emission energy system with a high share of fluctuating renewables.

Internationally, the vast majority of geothermal power and direct heating is produced from conventional hydrothermal resources, where high-temperature fluids are produced from wells at high flow rates based on favorable natural reservoir conditions, possibly enhanced by re-injection of wastewater during production. At the same time, significant geothermal resources are typically situated in igneous rocks, where the permeability of the reservoir mainly is due to discrete fractures, but where the reservoir conditions do not readily allow for commercial production. Hydraulic and thermal stimulation of such a reservoir can enhance permeability by opening and extension of naturally existing fractures, to achieve sufficient flow rates for commercial production, creating an Enhanced Geothermal System (EGS). During hydraulic stimulation, fluid is injected with elevated pressure to induce slip along existing fractures, thereby enhancing the fractures' permeability. The fluid injection is commonly performed at a slow rate to achieve slip and opening of pre-existing fractures under shear stress that are distributed in the formation and also to stay below the tensile threshold of the rock.

Induced and triggered seismicity is associated with geothermal exploitation (Cuenot et al., 2008) and can generally be recorded during injection and often decays after injection is stopped (Bachmann et al., 2011). Usually, the stimulation is designed to keep the related seismicity below a certain magnitude threshold, which depends on regulations and often deviates from case to case. Although geothermal reservoir stimulation has been successful in various geological settings and places around the world, there have also been cases where hydraulic stimulation triggered seismic events too large to be acceptable. A recent investigation of the 2017 Pohang earthquake in South Korea concludes that hydraulic stimulation of the geothermal reservoir produced seismicity that activated a critically stressed fault and ultimately resulted in the M_w 5.5 earthquake two months after the injection (Geological Society of Korea, 2019; Lee et al., 2019). Other cases of induced and triggered seismicity large enough to be felt have occurred and are related to hydraulic stimulation in several EGS projects, including in Basel, Switzerland (e.g., Häring et al., 2008), Soultz, France (e.g., Cuenot et al., 2008), and Cooper Basin, Australia (e.g., Baisch et al. 2009).

Felt seismicity has also occurred for conventional hydrothermal developments related to waste water injection or injection for pressure support, for example at the Geysers, USA, (e.g., Majer and Peterson, 2007), Husmuli, Icleand (e.g., Sveinbjornsson and Thorhallsson, 2013; Ágústsson et al., 2015) and at Yanaizu-Nishiyama, Japan (e.g., Asanuma et al., 2011). The same causes of induced seismicity are apparent related to the petroleum industry (Ellsworth, 2013; Rubinstein and Mahani, 2015).

The current dilemma for EGS is that hydraulic and/or thermal stimulation are necessary to create sufficient flow rates, while at the same time the risk related to unacceptable levels of induced and triggered seismicity must be minimized. Similarly, pressure support and waste-water injection are necessary in sustainable hydrothermal developments, while seismicity should be held within acceptable levels.

Research focused on induced seismicity shows that the relation between injection rates, injection pressure and total volumes injected and the occurrence of seismicity, moreover the magnitude of the observed seismicity, does not stand in a relation to allow for forecasting of large magnitude events to occur (Galis et al. 2017, Keranen et al. 2014, McGarr 2014, Yeck et al. 2017, Zang et al., 2014). Assessments are predominantly made based on empirical and qualitative practice. With this current understanding, the outcome of stimulation and injection operations are still challenging to both forecast and evaluate.

To improve engineering decisions in stimulation and operation of geothermal reservoirs it is necessary to better understand subsurface dynamics when different physical processes and the underlying fractured structure of the reservoir strongly interact. While the investigation of seismic events can provide more detailed characterization of the reservoir, numerical modeling of the subsurface dynamics can provide a better understanding of why and how seismicity is induced. Integrated numerical modelling and data interpretation tools that can identify governing mechanisms and forecast reservoir response to fluid injection can thus be crucial in next generation hydraulic stimulation technology and reservoir management. To develop such tools is the core motivation of the ERiS project, which started in 2017 and will be completed by the end of 2020.

2. PROJECT OBJECTIVES AND APPROACH

Through an interdisciplinary effort, combining recent developments in monitoring, data processing and modelling efforts, the ERiS project targets knowledge building for developing next generation stimulation technology and achieving sustainable operation for geothermal reservoirs. The project's primary objective is to complement the expertise of the geothermal energy sector in exploitation of unconventional geothermal resources by developing new numerical models and data interpretation workflows that can identify governing mechanisms and forecast reservoir response to stimulation. The project targets advancing the geothermal energy research field by developing

- Improved numerical models for reactivation and propagation of fractures accounting for different and interacting fracture opening mechanisms.
- Improved numerical models for assessing thermal stimulation of fractured geothermal reservoirs.
- New monitoring data interpretation workflows integrated with numerical modelling for identification and characterization of active fracture clusters based on case studies.
- A new framework for data-driven numerical modelling of geothermal reservoir stimulation.

The approach taken in the ERiS project is to combine the observation and characterization of microseismic events with mathematical modelling and simulation of the stimulation process. Modelling of the stimulation must account for coupled physical processes that are highly influenced by pre-existing, but generally unknown, fractures. By an observation-based description of the microseismicity, the likelihood for the occurrence of microseismicity and characteristics of fractures in a given geological structure can be abstracted and used as a general framework in modelling of a fracture network. Observations of the microseismicity are also required to understand the source type of the pre-dominant seismicity (e.g. component of tensile opening, or pure shear failure (Zhao et al., 2014)) and under which circumstances the various types of sources are likely to occur (Albaric et al., 2014; Zang et al., 2014). Information on the regional stress field surrounding the EGS site play an important role in the characteristics of the spatial pattern of the seismic events and the main orientation and opening of the fracture network (Goertz-Allmann et al., 2014). This can be studied in detail with waveform correlation methods and cluster analysis. Of critical importance, however, is the reciprocal link between interpretation of observations and the numerical modelling domain, where adequate generalizations need to be applied. Numerical modelling efforts are emerging (White et al, 2018), but they still have constraints on the ability to model governing coupled physics in the complex subsurface environment. In particular, the structural impact of fractures add complexity to the models.

In this context, the ERiS project focus on development and integration of new analysis methods on the observational microseismic data and corresponding specialized state-of-the art numerical modelling techniques (Nordbotten et al., 2018; Ucar et al. 2018; Berge et al. 2019). Important tasks are related to devising of workflows to combine operational data (injection pressure, injection volume and temperature), interpreted data, like magnitudes location and source types of microseismic events, and numerical modelling of flow in and deformation of the fractured formation. Basic research into processes that are insufficiently understood, such as fracture slip and opening due to thermal effects, supplements this activity. As the fractured structure of the formation strongly affects the processes, the modeling approach is based on explicit representation of the main fractures and an upscaled model of the formation they reside in; that is, a discrete fracture-matrix (DFM) model (Berre et al., 2018). Common for the numerical modeling approaches is high resolution of dynamics within and close to the fracture. This is achieved by application of simulation tools that explicitly represent the fracture geometry in the computational grid (Keilegavlen et al., 2017).

3. PROJECT RESEARCH AND STRUCTURE

With the aim to design tools and workflows for combining numerical modelling and interpretation of observations, the project extends along four lines corresponding to the identified objectives of the project (see Section 2). In the following, a description of the research is given.

3.1 Fracture Propagation as a Consequence of Slip

In stimulation of geothermal reservoirs, there are two main mechanisms of fracture deformation: The shear slip of fractures and tensile fracture opening. The latter is typically associated with high fluid pressures overcoming the tensile strength of the rock. However, tensile fracture can result as a consequence of fracture slip in low-pressure stimulation, creating so-called wing-cracks. The development of such wing-cracks, produced by slip of fractures due to water injection at pressure far below the minimum principal stress could play a key role in creating reservoir connectivity (Jung, 2013). While some modeling studies have recently been performed to better understand this mechanism in the context of geothermal reservoir stimulation (Kamali and Ghassemi, 2018), the developments are still at an early stage due to the complexity of modeling strongly coupled physical processes that govern the dynamics.

The ERiS project investigates how the wing cracks are emerged, propagated and connected due to slip at the interfaces of a pre-existing fracture. The modeling is currently based on a mathematical model for crack propagation that is solved using a finite element method combined with adaptive remeshing (Dang et al., 2018). A 2-dimensional simulation result of the propagation of a single fracture is shown in Fig. 1, showing how slip of a fracture results in propagation of wing-cracks that can connect with other pre-existing fractures.

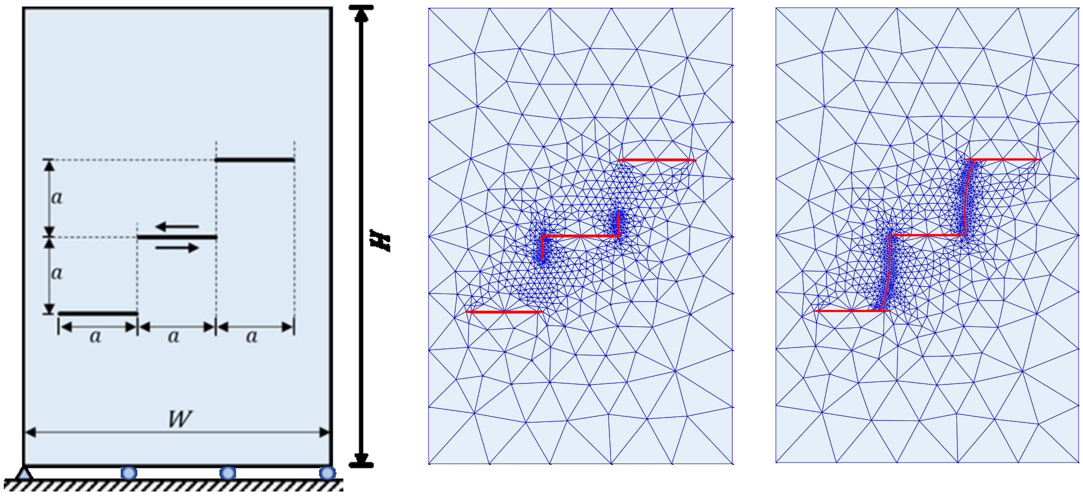

Figure 1: Model problem and numerically computed trajectories of wing cracks caused by shear slip at interfaces of a pre-existing fracture. Schematic of crack geometry and the shear slip at a preexisting fracture (left). Simulation results show how wing cracks emerge at the ends of a slipping fracture (middle) before they connect with pre-existing fractures (right).

3.2 Coupled Thermal Effects

Thermal stimulation of fractured reservoirs occurs both as a direct consequence of lower temperature drilling fluids or active thermal stimulation by injection of fluids at significantly lower temperature than the reservoir fluids and indirectly as a consequence of longer-term cooling during the operation phase of the reservoir (e.g., Friðleifsson et al., 2018; Grant et al., 2013; Luviano et al., 2015). While the direct thermal stimulation may result in tensile fracturing as a consequence of thermal shock, the long-term cooling can reduce normal loading on pre-existing fractures due to thermal compression of the reservoir and thereby induce fracture slip.

Within the ERiS project, the approach has been to start from a relatively simple physical model which has been gradually expanded. Thus, the focus was first on modeling fluid flow for fractured porous media with a one-way coupling to (temperature) transport (Stefansson et al., 2018). Then, the coupling between thermal and mechanical processes for tensile fracture nucleation and propagation was investigated in a context of rapid rock cooling. Ongoing work (Stefansson et al., 2019) examines fracture slip induced by long-term cooling of a geothermal reservoir using a model where the thermo-mechanical processes are loosely coupled to fluid flow, see Figure 2. In future work of the project, the aim is to enrich the model with a tighter coupling to the flow, enabling investigations into the full interplay of the thermo-hydro-mechanical processes and the fractures.

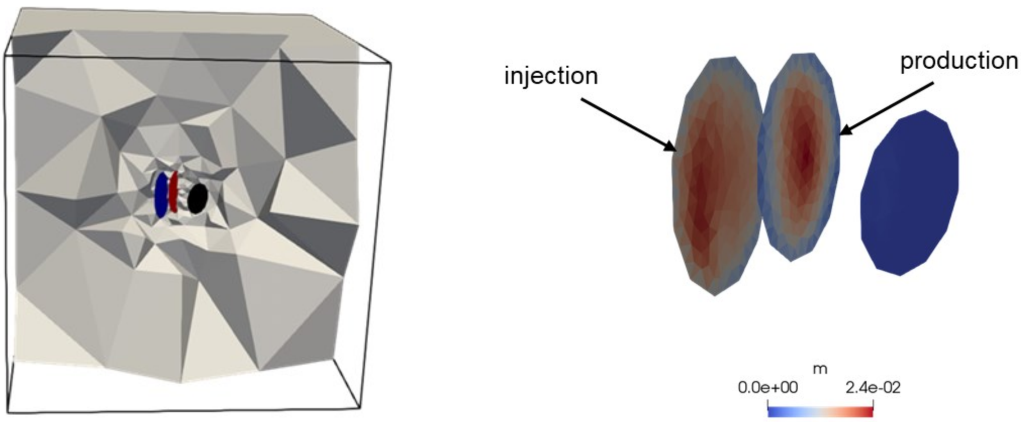

Figure 2: Simulation of thermally induced fracture slip in a geothermal reservoir. The entire simulation domain is illustrated to the left, with a zoomed in view of the fractures to the right. The colors in the right figure represent the magnitude of the induced shear displacement of the fractures due to cooling after a six-year period of production and injection in the fractured reservoir.

3.3 Integrated Data Interpretation and Modelling Driven by Case Studies

The ERiS project investigates how field observations can be coupled with numerical models to better understand seismic and hydraulic response within a geothermal reservoir. Recorded seismicity can give information on the underground geological structures like fracture locations, expected fault motions (normal, reverse, strike-slip), direction of the fracture orientation, and deviations from the local stress state, etc., that can be utilized to improve simulation models. In the project, the seismicity recorded by an EU funded research project IMAGE (FP7 grant agreement No. 608553) within the Reykjanes Geothermal Field, South-West of Iceland, during 4 months of injection in 2015 is analyzed (Fig. 3). Through an accurate absolute location, followed by a relative relocation, induced seismicity from the naturally occurring tectonically related seismicity on the Icelandic Ridge was isolated (Fig. 4). A multiplet analysis have highlighted some possible fractures, and this method might be used to distinguish different geological structures. In addition, focal mechanisms will allow to classify these earthquakes whereas the estimation of the strength of the earthquakes (moment magnitude) will be a direct link to the rupture length of the fracture. Finally, an inversion of these focal mechanisms may provide the local stress state. With this new information at hand, i.e., fracture location, fracture motion, stress state, etc., an attempt to build and calibrate numerical methods for stress evolution and fluid flow into a deep fracture network will be made.

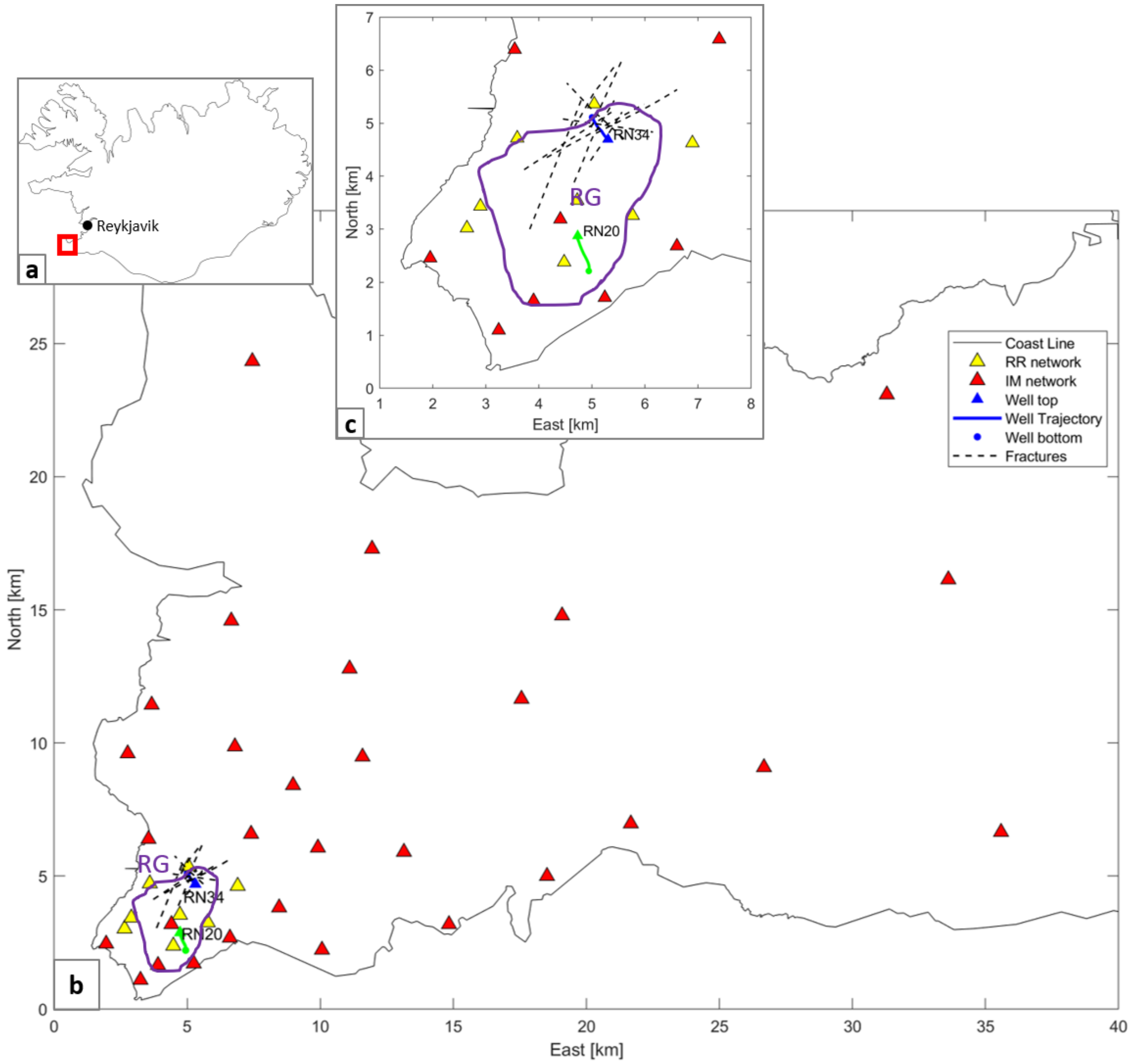

Figure 3: Study area location. (a) Global map of Iceland. The Reykjanes Peninsula, at the South-West of the island, is indicated by a red square. (b-c) Zoomed views of the Reykjanes (b) Peninsula and (c) Geothermal field. Red and yellow triangles show the location of the IM and RR sensor networks, respectively. Green and blue triangles, lines and dots indicate the top, trajectory, and bottom of the wells RN20 and RN34, respectively. The black dashed lines represent some known fractures. The approximate location of the Reykjanes (RG) geothermal field is indicated by the purple contour.

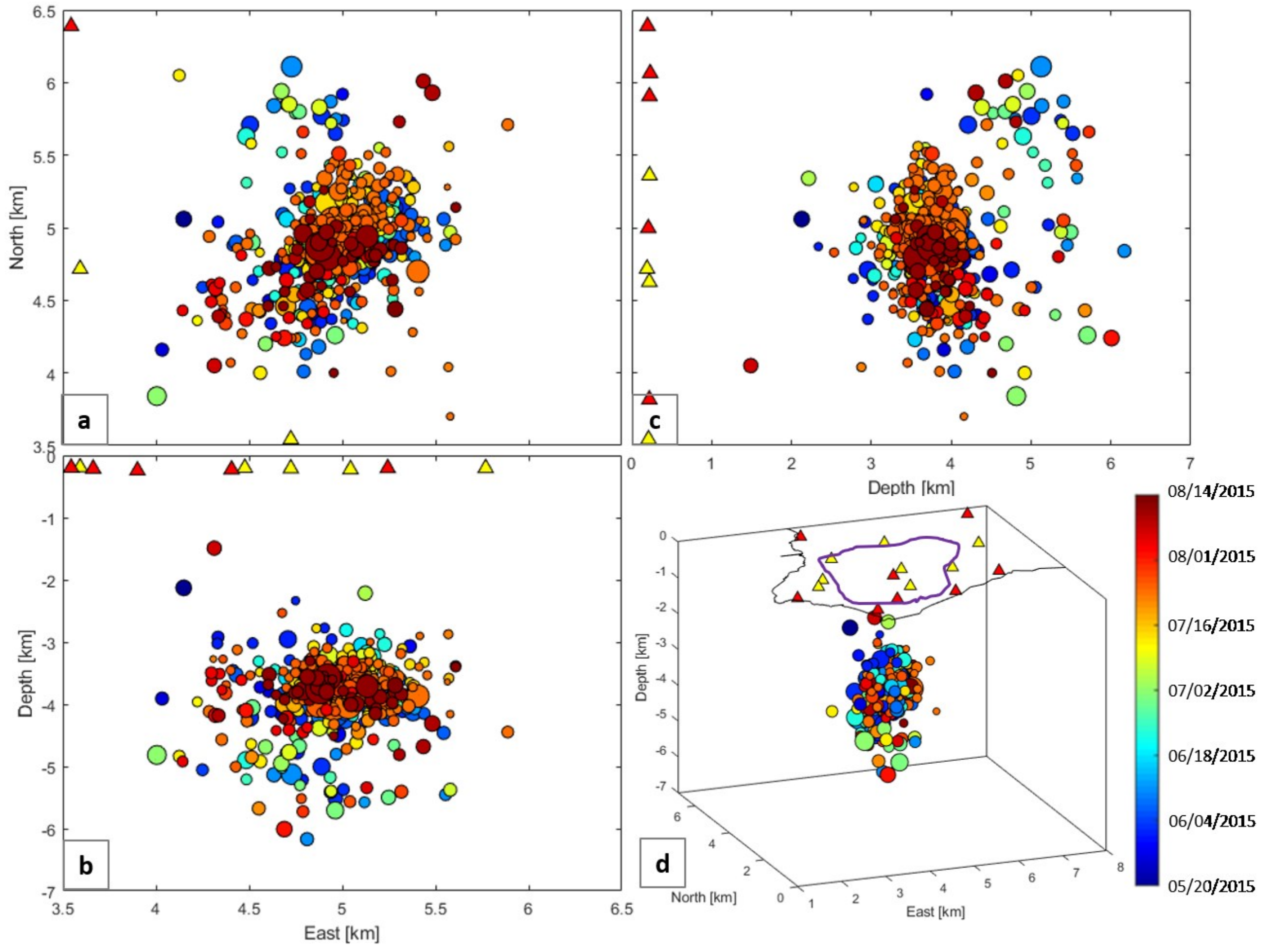

Figure 4: Induced event locations from the 20th of May 2015 to the 14th of August 2015 as a function of time within the Reykjanes geothermal field: (a) presents a 2D view collapsed in the vertical direction, (b) a 2D view collapsed in the North-South direction and (c) a 2D view collapsed in the East-West direction. Colors from blue to red is the time from the 20th of May 2015 to the 14th of August 2015 and (d) shows a full 3D view of the seismicity locations.

3.4 Tools for Data-driven Numerical Modelling of Geothermal Reservoir Stimulation

Modelling and simulation of low-pressure hydraulic stimulation is challenged by the disparate length scales in the process: The fracture width is measured in millimetres, slip surfaces are commonly in the order of square meters, individual fractures have lengths from hundreds of meters down to well below the resolution of any simulation tool, while the fracture network as a whole can have an extent of kilometres. To harness the information in the seismic signals, high simulation resolution of individual fractures is useful, but the computational cost should be kept reasonable. The ERiS project achieves this by applying simulation models based on DFM modelling principles. The simulation models combine explicit representation of main fractures that are important for flow and/or may undergo slip, with an upscaled representation of the reminder of the fracture network. The models represent flow in fractures and matrix, inelastic behaviour of the main fractures as well as elastic deformation of the host rock. The project applies an open source simulation tool, available at github.com/pmgbergen/porepy, which is purpose built for representation of coupled processes in fractured porous media (Keilegavlen et al., 2017).

A main research task within the ERiS project is to develop a protocol for construction of DFM simulations of low-pressure stimulations, that incorporates data from seismic observations. The seismic signals from fracture slip is a valuable source of information on the fracture network, including location and orientation of individual fractures as well as connectivity of the network. Key parameters that are considered are the locations of seismic events that informs on the fracture network connectivity, and local stress regimes at points of slippage, which may signify stress rotations relative to the regional conditions. As a test case, the project considers data from the Reykjanes geothermal field related to a stimulation of the well RN34, whose location is shown in Fig. 3. A model of the fractured formation is built based on a realization of the predicted fracture network near the well (Khodayar et al., 2015¸ Khodayar et al., 2018). The domain grid is shown in Fig. 5 along with results from a tentative simulation of the pressure increase in the fractured formation during stimulation of the well. The corresponding pressure distribution in the fracture network is shown in Fig. 6. For illustration purposes, event locations the 29th of March 2015 resulting from a preliminary analysis of seismic recordings during the period from the 29th of March to the 7th of April are also shown in the figure. The next steps of the numerical modelling will involve simulation of induced seismicity related to the stimulation of the well, which will be compared to the event locations obtained from the analysis of seismic data recorded during and after the stimulation.

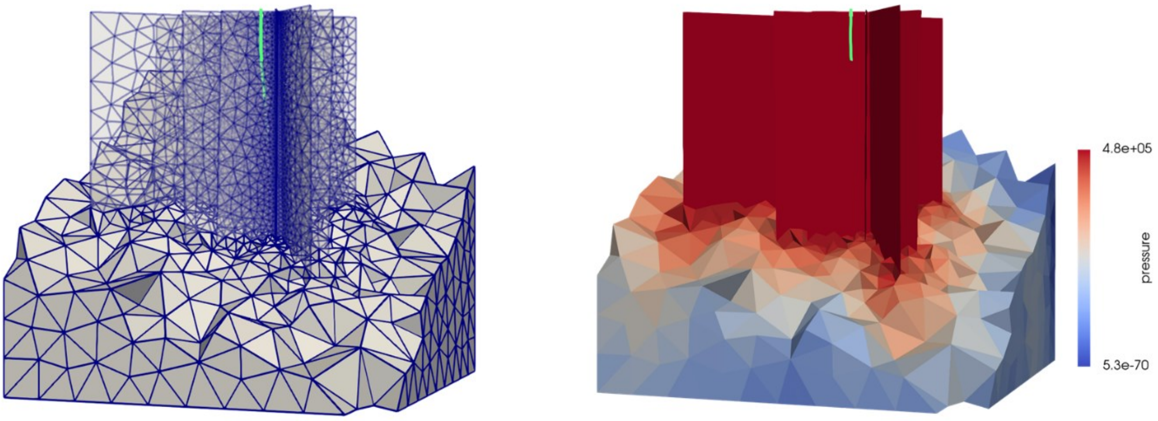

Figure 5: Fracture and matrix grid (left) and pressure profile at a specific time during stimulation from a tentative simulation of the pressure during stimulation of the well (right). The trajectory of well RN34 is shown in green (with only the uppermost part of the well being visible).

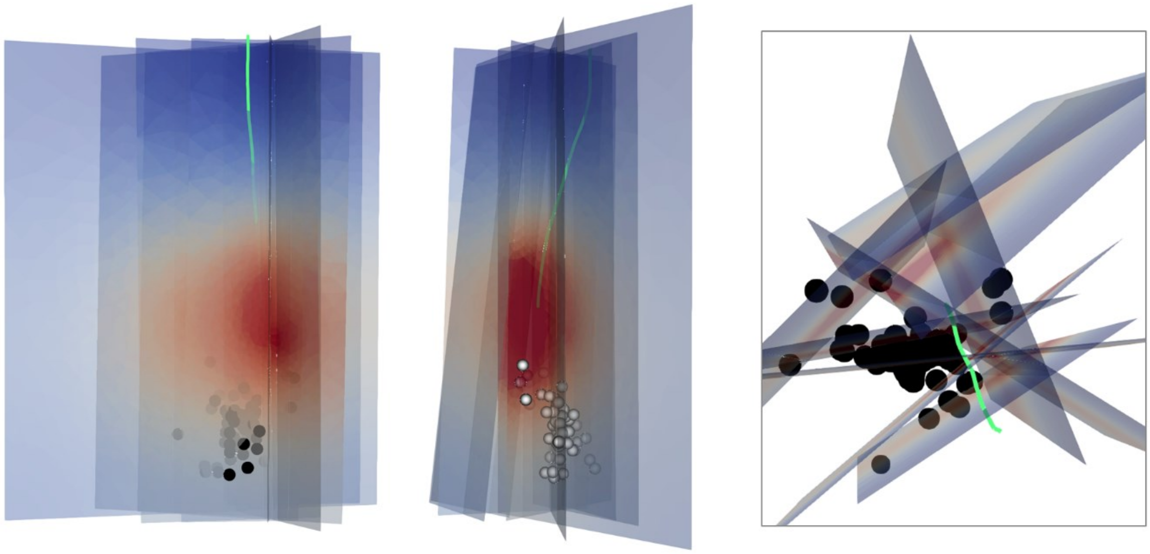

Figure 6: Pressure in fractures and preliminary location of seismic events. The view in the left figure is the same as for Fig. 3, while the middle figure shows the same results from a different horizontal angle. The right figure shows the results seen vertically from the surface. The trajectory of well RN34 is shown in green in all figures.

4. CONCLUSIONS

The ERiS project aims to increase understanding of stimulation mechanisms and induces seismicity in geothermal reservoirs. The project develops numerical models accounting for different physics resulting in reactivation as well as propagation of fractures in hydraulic and thermal stimulation. A case study from the Reykjanes geothermal field provides the basis for the development of methodology for analysis of seismic recordings as well as workflows for combining numerical modelling and interpretation of seismic observations.

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