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Editorial Special Issue JVGR – revised version

Reykjanes, Iceland: Structure and dynamics of mid-oceanic ridge geo/hydrothermal systems

Philippe Jousset[1], Anette Mortensen[2], Gudmundur Omar Fridleifsson[3], Kristjan Agustsson[4] and Magnus T. Gudmundsson[5]

1. GFZ, German Research Center for Geosciences, Potsdam, Germany.
2. Landsvirkjun, National Power Company of Iceland, Reykjavik, Iceland.
3. HS Orka hf, Svartsengi, Grindavik, Iceland
4. Iceland GeoSurvey, Reykjavik, Iceland
5. University of Iceland, Reykjavik, Iceland

Introduction

Our understanding of volcanic processes is hampered by our limited knowledge of sources processes generating signals observed at the surface. Much has been learned about subsurface structures of volcanoes from disciplines such as volcanology, geology, petrology, geophysics, and studies of ore deposits in the mining sector. Moreover, fluid extraction and injection in exploited geothermal areas are analysed and measured, providing good proxies for the estimate of parameter ranges (density, seismic velocities, rock permeability, fluid composition, etc.) applicable to active undrilled volcanoes.

However, detailed information on structures at depth beneath active volcanoes is usually poor (only a few volcanic areas have been drilled) and not sufficient for a clear understanding of magmatic processes leading to eruption, hampering acute hazard assessment. The temporal evolution in terms of magma accumulation, storage or solidification at depth is mostly unknown. As a result, studies in areas where parameters defining those processes are better known due to in-situ observations brought by drilling and exploitation are of considerable importance. In volcanic exploited geothermal systems, many wells provide detailed structural control.

Iceland is the ideal place for this type of research. Iceland has for a long time been a natural laboratory for the study of geological processes associated with rifting and hot spots. Volcanic eruptions are frequent; volcanic activity mainly occurs within volcanic systems comprising a central volcano and an associated fissure swarm. Reykjanes is somewhat of an anomaly, as the volcanic systems have only fissure swarms but no central volcanoes.

A by-product of the intense volcanic activity is major geothermal activity. There is intensive use of geothermal energy for heating and electricity production. Active search for energy resources beyond conventional volcanic geothermal systems also occurs. Specifically, conditions where super-critical fluids are anticipated to occur at several locations in Iceland. Harnessing such reservoirs are estimated to produce fluids with about 10 times more energy than found in conventional systems. Their use is considered to provide an important future energy resource, e.g. for large industries.

The IDDP-1 drilling in Krafla was designed to find such conditions at depth, but the drill entered magma at an unexpectedly shallow depth and the geothermal objective could not be reached. The IDDP-1 work is noteworthy for the fact that there was no geophysical indication of such a magma pocket at shallow depth; the geophysical methods used were basically “blind” to relatively small bodies of magma.

The development of new technologies and approaches for imaging magma and supercritical conditions are therefore required. The integration of several methods is also a key to understand better both structures and mechanisms in geothermal systems (e.g., Jousset et al., 2011).

This special issue of JVGR has been dedicated to provide a case study for such a complementary, integrated approach. It is mainly based of the results of IMAGE (Integrated Methods for Advanced Geothermal Exploration), a FP7 EU funded project, but also includes results and data obtained after the completion of the project. The idea was to gather in one place several publications on studies from one the best places in the world to perform this kind of approach, the Reykjanes thermal area on the southwestern margin of the Reykjanes Peninsula, Iceland. Conventional exploration approaches were applied, and complemented by cutting edge methods used for imaging at depth, prior to drilling the deepest well found in volcanic and geothermal environment in Iceland, the IDDP-2 (Fridleifsson et al., 2019).

The IMAGE FP7 EU project focused on improving and integrating existing exploration methods, and implementing new ones such as ambient noise tomography or Distributed Acoustic Sensing (Jousset et al., 2018). The final achievements of the IMAGE project are illustrated by many contributions in this special issue. The main results exposed here lead to more robust predictive models of the critical exploration parameters on local scales. They comprise:

1) The identification of the key situations where favourable reservoir parameters (temperature, permeability, resource extent) can be expected, which includes the relationships between geological structures and geothermal resources, defining the exploration methods to be applied.
2) A better understanding of the processes that control permeability.

3) The determination of the fundamental properties of supercritical geothermal reservoirs and the respective technologies to measure and define them, a major step forward in making this so far untapped resource available.

Advanced exploration techniques developed and tested in IMAGE present a significant step forward towards the goal of imaging geothermal systems with a higher degree of accuracy and resolution, thus making geothermal targets for industrial exploitation more accessible. Those results lead to new ways for studying active volcanoes where supercritical conditions occur.

Structure of the special issue.

The special issue has 27 original papers, mostly about the topics and results from IMAGE, but it also includes papers on related subjects. We ordered and group them by geographic location, starting from the Reykjanes Peninsula and then taking a way to the North of Iceland until Krafla.

An initial paper by Voight et al. (2019) is a tribute to Kristjan Saemundson who has made major contributions to unravelling the nature and workings of geothermal activity, as well as the volcanic and regional geology of Iceland, through his almost six decades of work on geology and tectonics of Iceland.

Reykjanes Peninsula

A review paper (Sigmundsson et al., 2019) explores the link between the geodynamics of Iceland, the volcanic and tectonic activity and the geothermal exploitation. Reykjanes Peninsula extends from south-west Iceland up to the triple junction expressed in Hengill. A review of the geology of Reykjanes is given by Saemundsson et al. (2019). Reykjanes has been seismically very active Bjornson et al. (2019). An important paper addresses the underestimated seismic hazard in Reykjanes (Einarsson et al., 2019).

Reykjanes geothermal reservoir

Reykjanes as such is defined as being the geothermal reservoir at the tip of the Peninsula

Imaging of Reykjanes has been performed by many geophysical techniques, including conventional and recent ones. Blanck et al. (2019) analyse the seismicity during the deployment of a dense seismic network. Martins et al. (2019) perform 3D imaging of the Reykjanes peninsula high-enthalpy geothermal field with ambient-noise tomography. Toledo et al. (2019) developed an optimization technique and applied it at the Reykjanes network, demonstrating that the network was adequate for imaging properly the Reykjanes reservoir. The resistivity structure is presented by Karlsdottir et al. (2019).

The results obtained are validated by the drilling results of IDDP-2 (Fridleifson et al., 2019), and were actually used to guide the latest steps of the IDDP-2 drilling (Jousset et al., 2016). Nono et al. (2019) analysed samples of the IDDP-2 measuring in the laboratory the electrical conductivity of samples from the deep supercritical geothermal reservoirs. Kummerow et al. (2019) conducted non-reactive and reactive experiments to determine the electrical conductivities of aqueous geothermal solutions up to supercritical conditions.

Exploitation generates mass and energy transfer and produces deformation. Parks et al. (2019) found the source of the exploitation-induced deformation at Reykjanes, while Darnet et al. (2019), focussed on monitoring the geothermal reservoir using the Controlled-Source Electro-Magnetic method.

Krýsuvík geothermal area

The geothermal site Krýsuvík is also a potential target for exploitation. Hersir et al. (2019) discussed the structure of the geothermal reservoir using results from inversion of magnetotelluric (MT) resistivity data. Gudjonsdottir et al. (2019), explores the link between deformation and gas emissions.

Hengill geothermal reservoir

In the eastern termination of Reykjanes Peninsula, the complex triple junction volcano Hengill, which is also since long time an exploited geothermal site is addressed in two papers: Steigerwald et al. (2019) analyses the fracture patterns at the surface, while Juncu et al. (2019) interprets induced seismicity and deformation associated to geothermal exploitation

Krafla

In the North of Iceland, another transform fault system is present and is introduced by Young et al. (2019). In the north, structural knowledge of one of the most productive geothermal area in Iceland is improved with the results presented in three papers using conventional VSP techniques (Kästner et al., 2019; Millett et al, 2019; Reiser et al., 2019).

The exploitation of a geothermal reservoir sometimes requires stimulation to prompt efficient extraction of fluids, as illustrated in Krafla by Eggertsson et al. (2019). The exploitation of geothermal systems produces induced seismicity (due to the stimulation) and this induced and natural seismic activity can be used to image structures at depth, as is done by Doyeon et al. (2019).

Iceland past and present volcanic and geyser activity.

As for completeness of the processes with time associated to geothermal activity in Iceland, two papers addresses seismic activity at active volcanoes (Greenfield et al., 2019) and at natural unexploited hydrothermal systems, Geysir (Walter et al., 2019).

Finally, in order to understand the structure of present geothermal systems and possibly the reservoirs associated with active volcanoes, it is also useful to study old inactive systems that allows discovery of features inaccessible in active reservoirs (Liotta et al., 2019).

Concluding remarks.

This special issue does not solve all questions regarding the Reykjanes geothermal system or other related sites. Many more studies involving the integration of different methods at several different sites are required to address those issues more fully.

However, it provides an interesting update on the state of the art in the research on the interaction between volcanoes, hydrothermal systems and earthquakes at different spatial and temporal time scales, with a focus on Iceland and Reykjanes. It demonstrates that the combination of knowledge from volcanoes and exploited geothermal systems is beneficial for a better understanding for both volcanic hazard and exploited geothermal reservoirs. This applies in particular to the case where super-critical fluids are encountered. Those places at depth are close to magma chambers in the crust: this region may hold great potential for harnessing of thermal energy from the Earth´s crust. Specifically, an approach combining conventional and new methods surface geological, structural, geochemical and geophysical monitoring and deep drilling in those regions where supercritical fluids are sought (for both harnessing more geothermal energy and searching for volcanic hazard mechanisms) is certainly of great benefit for ensuring sustainable and resilient future of human societies.

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