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Renewability Assessment of the Reykjanes Geothermal System, SW-Iceland

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ABSTRACT

Geothermal resources are generally classified as renewable energy sources, but this may be an oversimplification. They are in essence of a double nature, i.e. a combination of an energy current (through heat convection and conduction) and vast stored energy. The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly, in particular the part renewed by heat conduction. In addition the relative importance of the two components depends on both the geological nature of a system and the rate of energy extraction during utilization. A research project, supported by the GEORG research fund in Iceland, was recently completed in the Reykjanes high-temperature geothermal system, which is located on the very tip of SW-Iceland, where the Mid-Atlantic ridge comes ashore. The Reykjanes system has been utilized on a small scale for decades, but in 2006 a 100 MW_e power plant started operation in the field. The associated greatly increased production has caused drastic changes in reservoir conditions, in particular a considerable drop in reservoir pressure. The purpose of the project was to evaluate the relative importance of the two renewability aspects (energy current vs. stored energy) for the Reykjanes geothermal system under the current state of utilization. This was done through compilation of available data, such as reservoir monitoring data, and collection of new data, mainly micro-gravity and geodetic data. Consequently these data were jointly interpreted, partly by simulating data (e.g. gravity-change data) by an up-to-date numerical reservoir model of the geothermal system. In addition repeated TEM-resistivity surveying was used to try to follow the growth of a steam-zone in the shallower parts of the geothermal system. The results of the project do e.g. indicate that during the period 2008 – 2010 the renewal of reservoir fluid through recharge was of the order of 30 – 50%.

1. INTRODUCTION

Utilization of geothermal resources plays a fundamental role in the energy economy of Iceland (Ragnarsson, 2013). High-temperature (> 200°C) volcanic resources found throughout the volcanic zone of the island are used for electricity generation while lower temperature (< 150°C) resources found outside the volcanic zone are used in direct applications, mainly for space heating (satisfying 90% of the current need). About 2/3 of the primary energy used in Iceland comes from geothermal resources. The combined installed capacity of geothermal power plants is 665 MW_e, which is about 24% of the installed capacity in the country, the rest being hydropower. Because of this key role of geothermal resources, their sustainable utilization and renewability have been receiving ever increasing attention.

Geothermal resources are generally classified as renewable energy sources, but this may be an oversimplification. They are in essence of a double nature, i.e. a combination of an energy current (through heat convection and conduction) and vast stored energy (Axelsson, 2011). The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly, in particular the part renewed by heat conduction. In addition the relative importance of the two components depends on both the geological nature of a system and the rate of energy extraction during utilization.

A number of long and well documented utilization and response case histories of hydrothermal systems are available worldwide, many spanning more than 30 years. These are extremely valuable for studying the long-term response and hence production capacity of geothermal resources, as well as their renewability and possible sustainable utilization. Simple evaluations, and associated calculations presented by Axelsson (2011), for a few low-temperature (< 150°C) case histories, demonstrate this. The cases histories presented reveal that the associated geothermal systems can often be classified as either open or closed as regards production induced recharge. Fluid volumes extracted over several decades range from being much less to being approximately equal to the estimated pore volumes of the reservoirs of these case histories. O'Sullivan *et al.* (2010) provide another example of a renewability assessment, based on numerical modelling of the Wairakei geothermal system on the North Island of New Zealand.

A research project, supported by the GEORG research fund in Iceland (georg.hi.is), was recently completed in the Reykjanes high-temperature geothermal system, which is located on the very tip of SW-Iceland, where the Mid-Atlantic ridge comes ashore (see Fig. 1). The Reykjanes system has been utilized on a small scale for decades, but in 2006 a 100 MWe power plant started operation in the field. The associated greatly increased production has caused drastic changes in reservoir conditions, in particular a considerable drop in reservoir pressure.

This GEORG research project is the subject of this paper. The main objective of the project was to add significantly to the understanding of the nature of geothermal resources, in particular their recharge and mass balance under production, through unifying analysis and modelling of data from different sources, pertaining to the Reykjanes-Svartsengi geothermal region in SW-Iceland, with particular emphasis on the Reykjanes geothermal system. Thus the hope was to improve the understanding of the renewability of geothermal resources and evaluate the relative importance of the two renewability aspects (energy current vs. stored energy) for the Reykjanes system, in particular, under the current state of utilization. This was done through compilation of available data, such as reservoir monitoring data, and collection of new data, mainly micro-gravity and geodetic data. Consequently these data were jointly interpreted, partly by simulating data (e.g. gravity-change data) by an up-to-date numerical reservoir model of the geothermal system. In addition repeated TEM-resistivity surveying was used to try to follow the growth of a steam-zone in the shallower parts of the geothermal system.

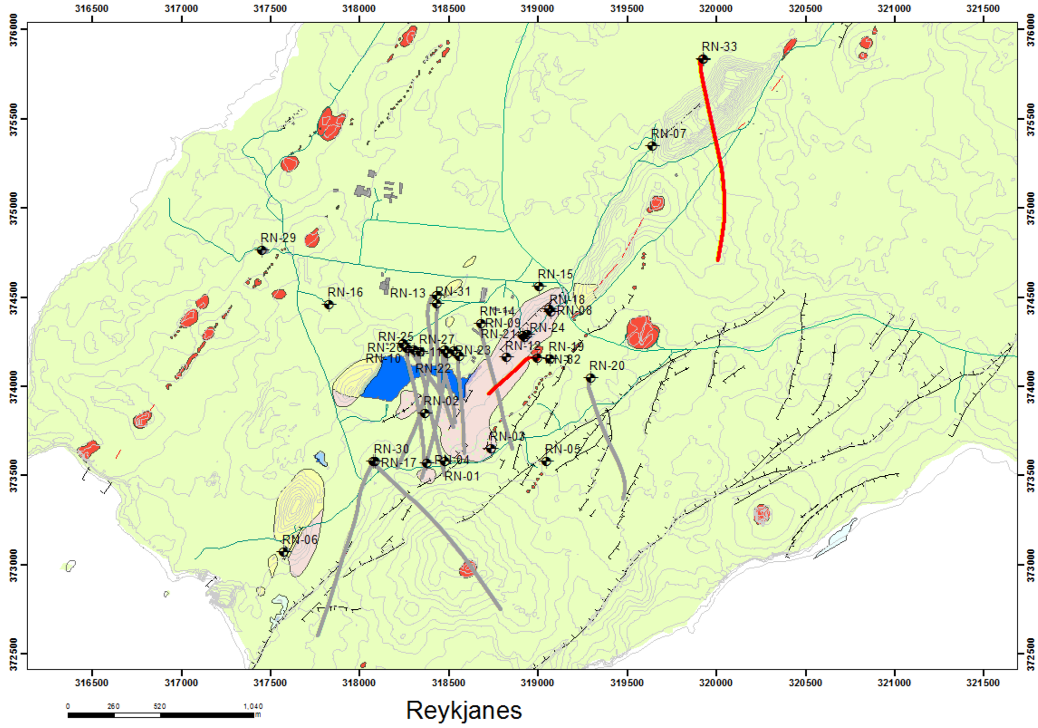

Figure 1: A simplified map of the Reykjanes geothermal area, located on the very southwest tip of Iceland, showing wells, tectonic faults and fractures as well as recent volcanism.

This paper is organized as follows. This introduction is followed by a discussion of the renewability of geothermal resources. Subsequently the Reykjanes geothermal system is briefly introduced along with its utilization. Following that the GEORG project is described and its main results presented through four subchapters.

2. RENEWABILITY OF GEOTHERMAL RESOURCES

Geothermal resources are distributed throughout the Earth's crust with the greatest energy concentration associated with hydrothermal systems in volcanic regions at crustal plate boundaries. Yet exploitable geothermal resources may be found in most countries, either as warm ground-water in sedimentary formations or in deep circulation systems in crystalline rocks. Shallow thermal energy suitable for ground-source heat-pump utilization is available world-wide and attempts are underway at developing enhanced geothermal systems (EGS) in places where limited permeability precludes natural hydrothermal activity. Saemundsson *et al.* (2009) discuss the classification and geological setting of geothermal systems in considerable detail.

The renewability of geothermal resources is an issue that has received considerable attention lately, as well as the question whether to classify them amongst the renewable energy resources or the non-renewable ones. They are generally classified as renewable because they are maintained by a continuous energy current. Geothermal energy has for example been classified as renewable by the European Parliament and the Council of the European Union (2009). This has been disputed by some scientists, for example in Iceland, on the grounds that geothermal energy utilization actually involves heat-mining.

The key to understanding the nature of geothermal resources, including their renewability, as well as estimating their long-term response to utilization, production capacity and possible contribution to sustainable energy development, is comprehensive and focussed research, often based on extensive exploration and monitoring data. Axelsson (2011) e.g. points out the extremely valuable information contained in well documented and monitored utilization case histories. A number of such case histories for hydrothermal systems are available, many spanning more than 30 years. These are also particularly valuable for studying the renewability and possible sustainable utilization of geothermal resources. The Reykjanes geothermal system, which is the subject of this paper, is an example of a system having a highly informative response case history.

Geothermal resources are normally classified as renewable energy sources, because they are maintained by a continuous energy current and how enormous the energy content of the Earth's crust is compared to the energy needs of mankind. This is in accordance with the definition that the energy extracted from a renewable energy source is always replaced in a natural way by an additional amount of energy with the replacement taking place on a time-scale comparable to that of the extraction time-scale (Stefánsson, 2000). In addition they simply don't fit well with non-renewable energy sources like coal and oil, for example because of much more limited greenhouse gas emissions.

But this classification has been disputed, as mentioned above. In addition to the discussions in Iceland mentioned above various authors have referred to geothermal energy utilization as “heat mining”, for example Sanyal (2010). Axelsson (2011) claims that this dispute simply arises from a need to force a complex natural phenomenon into an inadequate classification scheme. The claim that geothermal resources are non-renewable has, moreover, been used as an argument against increased geothermal development. The foundation for increased geothermal utilization worldwide is, however, improved understanding through amplified research.

Classifying geothermal resources as renewable may also be an oversimplification. This is because geothermal resources are in essence of a double nature, i.e. a combination of an energy current (through heat convection and conduction) and stored energy (Axelsson, 2011). The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly, in particular the part renewed by heat conduction. During production the renewable component (the energy current) is greater than the recharge to the systems in the natural state, however, because production induces in most cases an additional inflow of mass and energy into the systems (Stefánsson, 2000).

The double nature of geothermal resources is strikingly apparent through different assessments of the geothermal resources of Iceland carried out in the 1980’s by different investigators. Bödvarsson (1982) estimated the size of the total heat flow through the crust while Pálmason *et al.* (1985) estimated the amount of thermal energy stored in the crust. Stefánsson (2000) combined the results of the two studies in a unified presentation, however, 15 years later.

The renewability of different types of geothermal systems (see classification by Saemundsson *et al.*, 2009) is quite diverse. This is because the relative importance of the energy current compared with the stored energy is highly variable for the different types. In volcanic systems the energy current is usually quite powerful, comprising both magmatic and hot fluid inflow. In convective systems of the open type, i.e. systems with strong recharge, the energy current (hot fluid inflow) is also highly significant. But the inflow can either originate as hot inflow from depth or as shallower inflow, colder in origin. In shallow inflow situations the inflow is heated up by heat extraction from hot rocks at the outskirts of the system in question. The renewability of such systems is then supported by the usually immense energy content of the hot rocks of the systems. In convective systems of the closed type, i.e. with limited or no recharge, the renewability is more questionable. The energy extracted from the reservoir rocks through reinjection in such situations is only slowly renewed through heat conduction, but again the energy content of the systems is usually enormous. They can, therefore, be considered slowly renewable in nature.

Sedimentary systems, which are mostly utilized through doublet operations, are comparable to the closed convective systems as the energy current is usually relatively insignificant compared to the stored energy. Their renewability is, therefore, mainly supported by heat conduction and hence is relatively slow. The same applies to EGS- or hot dry rock systems. Both these types can thus also be considered slowly renewable. In most such cases the stored energy component is extremely large because of the large extent and volume of the systems.

Sustainable development involves meeting the needs of the present without compromising the ability of future generations to meet their needs. Geothermal resources have the potential to con-tribute significantly to sustainable energy use worldwide in coming decades as well as to help mitigate climate change. Sustainable geothermal utilization has received ever increasing attention over the last decade (see e.g. Axelsson, 2010). The discussion has nevertheless suffered from a lack of a clear definition of what it involves and from a lack of relevant policies as well as a lack of research on the subject. The word “sustainable” has in addition become quite fashionable and different authors have used it at will. The terms renewable and sustainable are moreover often confused. The former simply refers to the nature of a resource, while the latter should refer to how it is used.

3. UTILIZATION OF THE REYKJANES GEOTHERMAL SYSTEM

The Reykjanes geothermal system is located on the southwest tip of the Reykjanes peninsula in SW-Iceland, where the Mid-Atlantic spreading ridge comes ashore. It is characterized by tectonic and volcanic activity with NE-SW striking faults and fissures. The nature and utilization of the system is e.g. described by Sigurdsson (2010) and Fridriksson *et al.* (2010). Below 1 km depth the reservoir temperature is in the range of 280 – 310°C, while temperatures as high as 350°C have been measured in deep wells. The reservoir fluid is hydrothermally modified sea-water. Surface manifestations are prominent in the area, including steam-vents, mud-pools and warm ground. They cover an area of approximately 2 km^2 and extensive drilling (see below) appears to indicate that the productive part of the geothermal system is of approximately the same size.

Development of the Reykjanes geothermal system started as early as 1956 with the drilling of a shallow (~160 m) well. Drilling continued during 1968 – 1970, when 7 wells were drilled, with the deepest one drilled to a little more than 1750 m depth. One more well was added in 1983 and during this period some intermittent, small-scale industrial utilization was active at Reykjanes. This included salt and sea-mineral production along with fish drying. In 1998 exploration and development of the geothermal resources at Reykjanes picked up again due to plans for large scale electrical generation. This involved comprehensive geological and geophysical exploration as well as the drilling of 14 deep production wells, later followed by the construction of a 100 MW_e capacity geothermal power plant.

The power plant was commissioned in May 2006, which was manifested in a drastic increase in mass extraction, from about 50 to 800 kg/s (see Fig.2). The production increase has caused a great drop in deep reservoir pressure (see Fig. 3), which amounted to about 35 bar in the main production sector after 3 years, and about 40 bar after 7 years of production. The pressure draw-down is considerably less at the margin of the present production sector (see e.g. well RN-16 in Fig. 3), yet still considerable. To counteract the pressure draw-down reinjection of separated brine was initiated in 2009, as can be seen in Fig. 2 (difference in total and net production). Other changes in the geothermal system have ensued as a consequence of the pressure drop (Fridriksson *et al.*, 2010). These include the development of a steam cap above about 1000 m depth in the main production sector, which has also resulted in increased discharge enthalpy of many production wells.

The increased enthalpy as well as the drilling of a few shallow wells, aimed at extracting saturated steam from the steam cap, has resulted in continuously decreasing production (see Fig. 2). In 2013 the total production was only about 70% of what it was in

2007, the first full year of production. The formation of the steam cap has also resulted in greatly increased surface activity. Yet the increase is comparable to natural surges in activity due to periodic earthquake activity. The great pressure draw-down is, in addition, reflected in gravity changes and surface deformation, both of which will be discussed in detail below. Finally it should be mentioned that no clear indications of major changes in chemical content of produced fluid have been observed to date in Reykjanes.

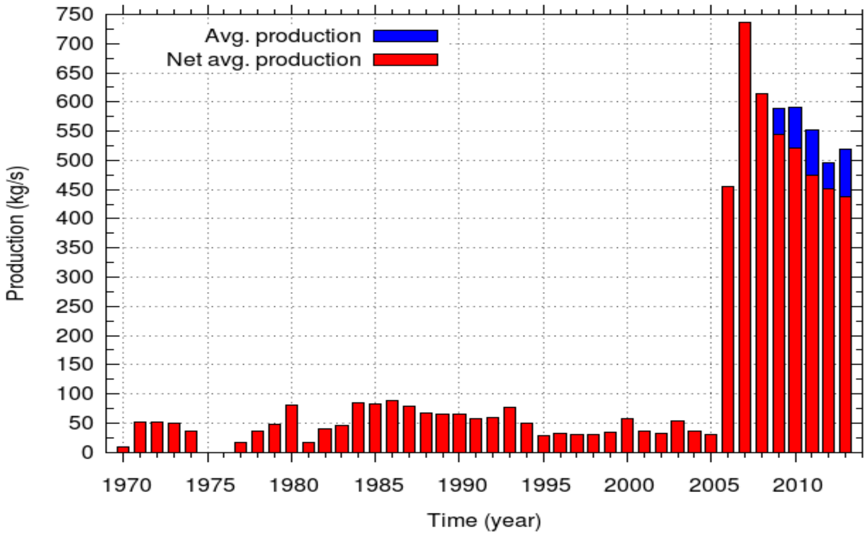

Figure 2: Average yearly mass production from the Reykjanes geothermal system from 1970 up to 2012 (Gylfadóttir, 2014). The operation of the 100 MW_e power-plant started in 2006, while significant reinjection started in 2009.

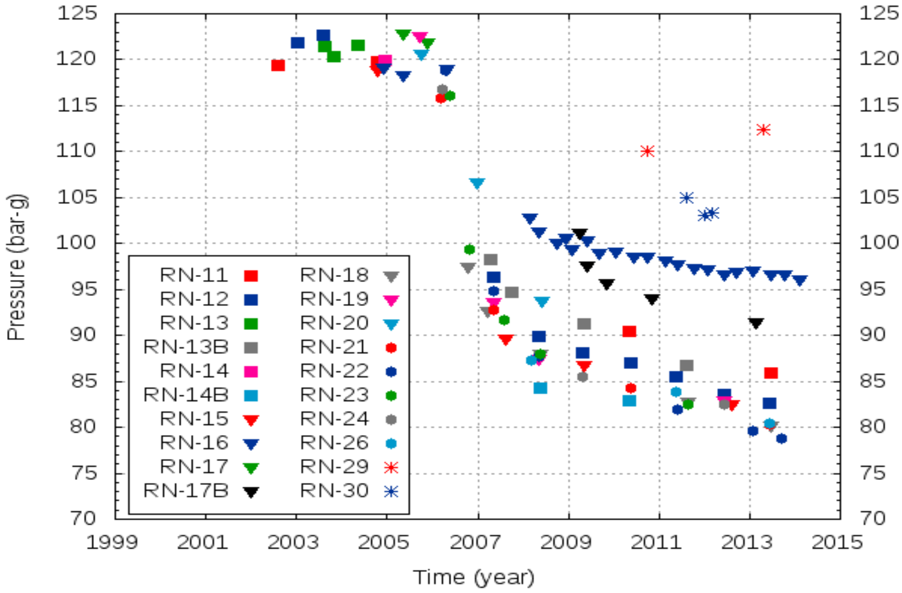

Figure 3: Pressure monitoring data from a number of wells drilled into the Reykjanes geothermal system, measured at a depth of 1500 m b.s.l. (Gylfadóttir, 2014). Most of the data-points are measured in production wells during breaks in production while some are measured in observation wells, e.g. in well RN-16, which lies at the margins of the main production field.

The great pressure draw-down in the Reykjanes geothermal system is noteworthy, it being considerably greater if represented as draw-down production unit (i.e. bar/(kg/s)) than in many other geothermal systems. This can result from the relatively small size of the geothermal system and relatively low permeability, but the question is also whether it also results from limited recharge? The objective of the GEORGE project, the subject of this paper, is to try and answer this question. It should, furthermore, be noted that the pressure draw-down continues with time in spite of the somewhat declining production. This clearly indicates that recharge to the geothermal system is considerably less than the production and that the system is partly closed. The reader is referred to the discussion on open vs. closed systems by Axelsson (2011). The project under discussion tries to estimate to what degree the system is closed.

4. RENEWABILITY ASSESSMENT OF THE REYKJANES SYSTEM

4.1 Project Description

The renewability of geothermal resources hasn't been systematically addressed and the issue is not yet fully understood. It is highly dependent on the boundary conditions of geothermal systems, and in particular on their inflow, or recharge, in both the natural state and during production. The inflow is believed to be a combination of shallow inflow, which is colder than the average reservoir fluid, and deep hot recharge. The recharge is reflected in the mass balance of geothermal reservoirs during long-term utilization, which in turn is reflected in e.g. pressure changes, gravity changes and surface deformation. Another side of the mass balance is the development, or growth, of steam-zones in high-temperature geothermal systems during utilization. The purpose of the GEORG project discussed here was to develop methods to study the recharge and mass balance and apply them to the Reykjanes-Svartsengi geothermal region in Iceland, with particular emphasis on Reykjanes.

The project involved the following participants:

- Iceland GeoSurvey (ÍSOR), the main geothermal research institute in Iceland, provided expertise on geophysical methods, geothermal reservoir physics and reservoir modelling.
- The Institute of Earth Sciences at the University of Iceland (IES-UI), which has long-standing experience in volcanological research, provided expertise in geophysical and geodetical methods.
- GNS Science of New Zealand, which has long-standing experience in volcanological, geothermal and environment research, provided support and advice.
- HS Orka is the power company utilizing Svartsengi and Reykjanes; it has extensive experience in geothermal exploration and geothermal resource management.
- Vatnaskil Consulting Engineers, which is an engineering firm specializing in water resource and environmental modelling (geothermal reservoirs, groundwater, surface runoff and river hydraulics as well as pollution and environment), is responsible for the numerical modelling of the geothermal systems involved.

The project has aspired to join together the results of several different scientific methods or disciplines to address the issue in question, in particular the following methods:

(a) high-resolution 3-D surface deformation monitoring (InSAR and GPS monitoring),
(b) micro-gravity monitoring,
(c) repeated TEM (transient electromagnetic) resistivity surveying,
(d) reservoir pressure- and temperature monitoring,
(e) chemical content monitoring and
(f) dynamic geothermal reservoir modelling.

Combining surface elevation and gravity data has been used to estimate the mass balance of geothermal systems during production, resistivity surveying has been used for exploration and chemical data has been used to study processes in geothermal systems and their recharge. Detailed numerical modelling of geothermal systems has also been used extensively to simulate the response of geothermal reservoirs to production. The innovative aspect of this project involves joining together the results of the different methods through unified modelling of aspects (a) through (e).

Extensive repeated geodetic measurements have been collected in the study areas for decades. These include conventional optical levelling, precise GPS geodetic measurements, satellite radar interferometric observations utilizing InSAR satellite data, and electronic distance measurements prior to advent of GPS. The project aimed at combining all available data to infer 3D-deformation fields. This includes geodetic data that ÍSOR has collected in the geothermal region as well as data on deformation over broader area collected by IES-UI and collaborators. Derivation of a precise 3D-deformation field was based on joint interpretation of InSAR images together with GPS derived 3D displacement vectors at the surveyed sites. The Reykjanes region is affected by plate movements and is volcanically and tectonically active. Therefore the data analysis included the separation of deformation due to these causes from the deformation caused by geothermal energy production.

High resolution micro-gravity surveying has been conducted in the region by ÍSOR and its predecessors at regular intervals during the last three decades. The project aimed at interpreting such data jointly with the surface deformation data. The project also applied repeated TEM resistivity surveying at a few selected locations in Reykjanes, surveyed before large-scale production started, with the intention of monitoring the growth of a steam zone in the region.

The data analysis and interpretation of the project involved different kinds of modelling. This included simple modelling of the gravity changes observed on basis of the mass changes in the reservoir (see below), simple modelling of the surface deformation observed and one-dimensional inversion of TEM resistivity survey data. In addition a numerical reservoir model developed by Vatnaskil for the geothermal systems involved, already available, was employed for forward modelling.

The numerical reservoir model is regional and covers the three geothermal fields of the Reykjanes peninsula: Svartsengi, Eldvörp and Reykjanes. It covers a total area of about 1102 km^2 and is three-dimensional, divided vertically into 15 horizontal layers of varying thickness. The model and contains 2025 elements per layer and within an area of approximately 4 km^2 centered in the Reykjanes field, the numerical mesh consists of a relatively dense network of regular elements. The *TOUGH2/iTOUGH2* modelling framework is used for calculating conditions in the model. The present model, which is based on older models dating back to as early as 1982, has been under development since 2009; it's constantly being updated as new data become available. The model extends vertically from +50 m a.s.l. down to -3450 m a.s.l., with its bottom being well below the deepest wells in Reykjanes. The model models the initial temperature and pressure conditions in the Reykjanes system (Svartsengi as well) by simulating estimated initial temperature and pressure profiles for all deep wells within the model area as well as simulating the pressure decline observed in the reservoirs since production from them started (see e.g. Fig. 3 for Reykjanes).

The results of the items discussed above will be presented and reviewed briefly below. It should be emphasized that the project has intended to address specifically, and add to the understanding of, boundary conditions and their role in the long-term production response of geothermal systems. Up to now more emphasis has generally been put on detailed information on the production parts of the systems, which has been made available through the drilling and testing of numerous wells.

The approach and methods applied in the project are, to a variable degree, comparable to that employed to studies of geothermal resources in other geothermal countries, most notably New Zealand, where scientists have taken a pioneering role in the development of appropriate methods. As recent examples the work of Hunt *et al*. (2003) involving analysis and modelling of gravity changes associated with geothermal utilization and that of Brockbank *et al*. (2011) involving comparable deformation modelling may be noted. Some related work has also been carried out in Japan with Nishijima *et al*. (2005) providing an example of gravity change data interpretation. In addition Bromley (2014) discusses the connection between production-induced subsidence and induced seismicity. It should, therefore, be noted that an important part of the project focuses on applying methods comparable to those developed for geothermal fields in New Zealand to the Reykjanes-Svartsengi fields and on comparing the results with results obtained in New Zealand.

4.2 Deformation

To monitor crustal deformation, in particular the subsidence, around the Reykjanes geothermal power plant, annual and biannual GPS measurements have been performed by IES-UI on a regular basis during the last decade and InSAR images from the German TerraSAR-X and TanDEM-X satellites have been collected and analyzed (Michalczewska et al., 2014). In addition ÍSOR has conducted GPS measurements in the measurement grid used for gravity monitoring (see below) every few years. These data have been merged and jointly analyzed to provide a spatial and temporal model of surface deformation in the area. The main results are presented in figures 4 and 5.

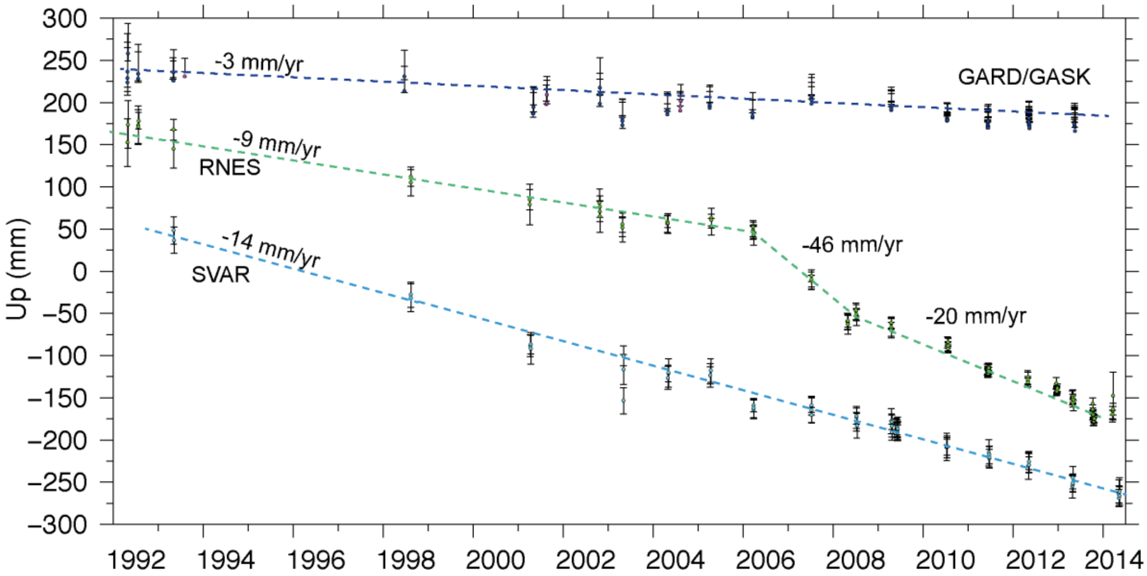

Figure 4: Subsidence in Reykjanes (RNES) and Svartsengi (SVAR) estimated from GPS measurements spanning 1992 to 2014. The site Gardskagi (GARD/GASK), outside the affected area, is shown here for reference.

Figure 4 shows the changes in elevation (subsidence) in the Reykjanes and Svartsengi fields during the last two decades while Fig. 5 shows a map of the subsidence in the area, along with the estimated horizontal displacement-field. The rate of subsidence in Reykjanes appears to have been fastest in the two years after the power plant started production but has relatively been steady since then. This corresponds well with the observed pressure changes in the geothermal reservoir (see Fig. 3).

The InSAR data from January 2009 to July 2013 show a 4 km x 3 km subsidence bowl with over 40 mm/yr subsidence rate in the center, which also corresponds well with observed spatial variations in reservoir pressure draw-down. The subsidence is elongated in the NE-SW direction following the direction of the main fissure swarm of the region, as does the pressure draw-down bowl.

At the time of writing of this paper the surface deformation above the Reykjanes geothermal system hasn't been modelled. The aim is, however, to model it with a simple point and ellipsoidal source models and interpret the results jointly with the results of the gravity modelling presented below and the numerical reservoir model of the geothermal system.

4.3 Gravity Changes

An analysis of gravity changes observed in the Reykjanes geothermal field during the last decade was at the core of the project, with the principal purpose of estimating the mass changes in the geothermal system during the period 2006–2010 and hence the renewal (recharge) of the fluid reserves in the geothermal system. This work is described in more detail by Gudnason (2015). The gravity surveys this work was based on were conducted by ÍSOR during the summers of 2004 (prior to start-up of the Reykjanes power plant), 2008 and 2010. Figure 6 shows a contour-map of the measure gravity changes in Reykjanes between the middle of 2008 and the middle of 2010, as an example. The analysis involved three main steps. First, an estimation of the mass changes in the geothermal system through a Gauss-integral of the observed gravity changes during two periods, 2004–2008 and 2008–2010. Secondly, a simulation of the gravity-change anomaly for 2008–2010 by two simple mass change models. Thirdly, a calculation of gravity changes at the observation points of the gravity grid on basis of mass changes in the numerical *TOUGH2*-model of the geothermal system discussed above. It should be mentioned here that Eysteinsson (2000) presents the results of gravity monitoring in the Svartsengi field up to the end of last century, including a Gauss-integral analysis.

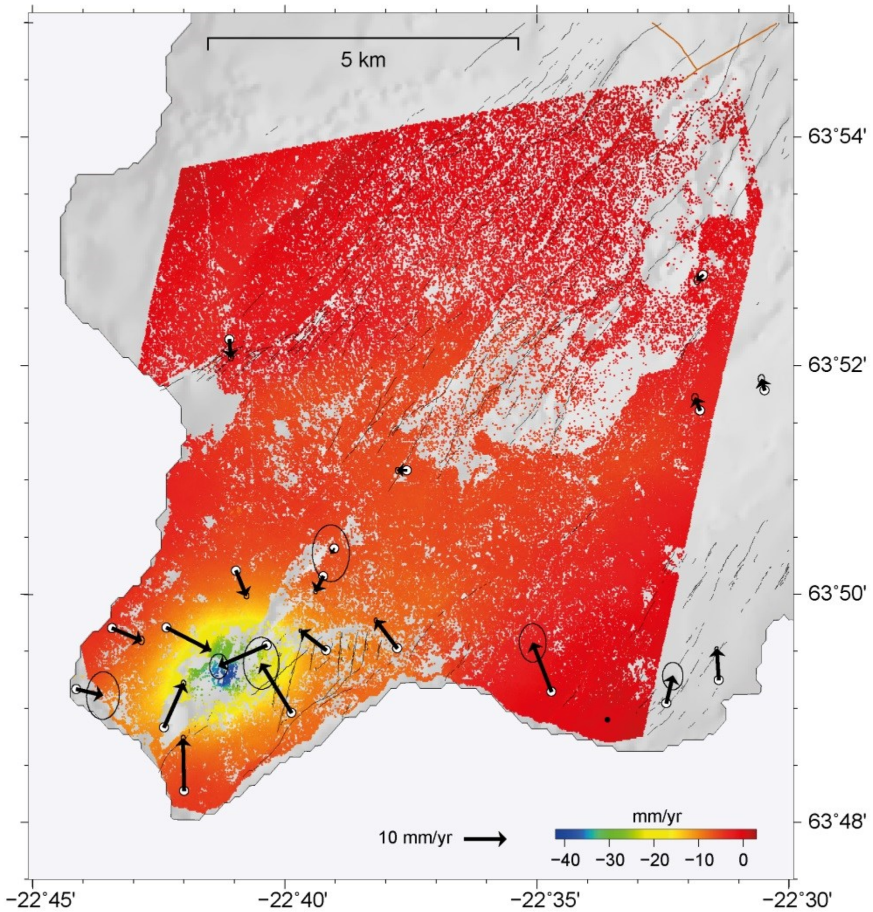

Figure 5: Average subsidence rate from January 2009 to July 2013 in Reykjanes estimated from the combination of sets of ascending and descending TerraSAR-X InSAR interferograms (Michalczewska et al., 2014). Horizontal velocities are estimated from GPS data spanning 2008 to 2013.7.

The results of a Gauss-integration of the gravity-change anomaly for the period 2008–2010 indicates that renewal of the reservoir mass during that period was likely in the range of 30–50%. The renewal for the period 2006–2008 was probably somewhat less, but can't be estimated because of the loss of a centrally located measuring point in 2006. A simulation of the 2008–2010 anomaly by a spherical mass-change volume indicates that the center of the volume is at a depth of 1300–1700 m. Modelling of the gravity changes on basis of the mass changes in the *TOUGH2* numerical reservoir model of the Reykjanes geothermal system result in quite comparable results for the 2008–2010 period. The observed and calculated anomalies are comparable in shape, even though the calculated one doesn't extend as much to the NE as the observed one and the calculated maximum anomaly is a little smaller. A smaller and lower gravity-change anomaly for the 2008–2010 period indicates that the numerical model allows somewhat more recharge than is the case in reality. These results show that the gravity data can now be used to support the calibration of the reservoir model.

4.4 Other Aspects

TEM-resistivity surveying was conducted in the Reykjanes field in both 1996 and 2004. In association with the project described here soundings were repeated in 6 stations in 2009, 2011 and 2012. The purpose was to attempt to monitor the growth of the steam cap of the geothermal system. Interpretation of the repeated TEM resistivity soundings indicates some shallow changes, particularly an increase, in resistivity at some of the stations, changes which may likely be attributed to the growth of steam cap of the system. The interpreted changes don't yield quantitative results, however, but the results supporting the contention that resistivity methods may be a useful monitoring tool.

No clear indications of major changes in chemical content of produced fluid have been observed to date in Reykjanes, as already mentioned. Such monitoring data can be used as the basis of simple modelling of the contribution, or balance, of fluid of different origin in the reservoir, i.e. colder recharge vs. hot reservoir fluid. If it is assumed that the fluid recharging the system has a chemical composition different from that of the reservoir, the fact that no changes have been observed contains information on the minimum volume of the Reykjanes reservoir. On basis of the fluid volume extracted during the first 8 years of operation of the Reykjanes power plant a volume of about 1.2 km^3 is estimated (assuming a porosity of 10%), which is considerably less than the minimum estimated volume of the system, which is of the order of 3 km^3. This result, along with the limited recharge, likely explains why no chemical changes have been observed so far.

Based on the production and reinjection history of the Reykjanes geothermal system, along with the results of the modelling of the observed gravity changes, some simple mass and energy balance modelling can be performed. This hasn't been completed at the writing of this paper, but rough estimates show that due to the limited recharge and small reservoir volume the reservoir fluid content may be depleted in some decades, unless reinjection is increased. Plans in that direction are already underway. In contrast, the energy in-place in the system is enormous and it is estimated that only a small fraction (2%) of that will have been extracted after 100 years under current extraction and recharge conditions, in spite of the limited size and recharge of the system.

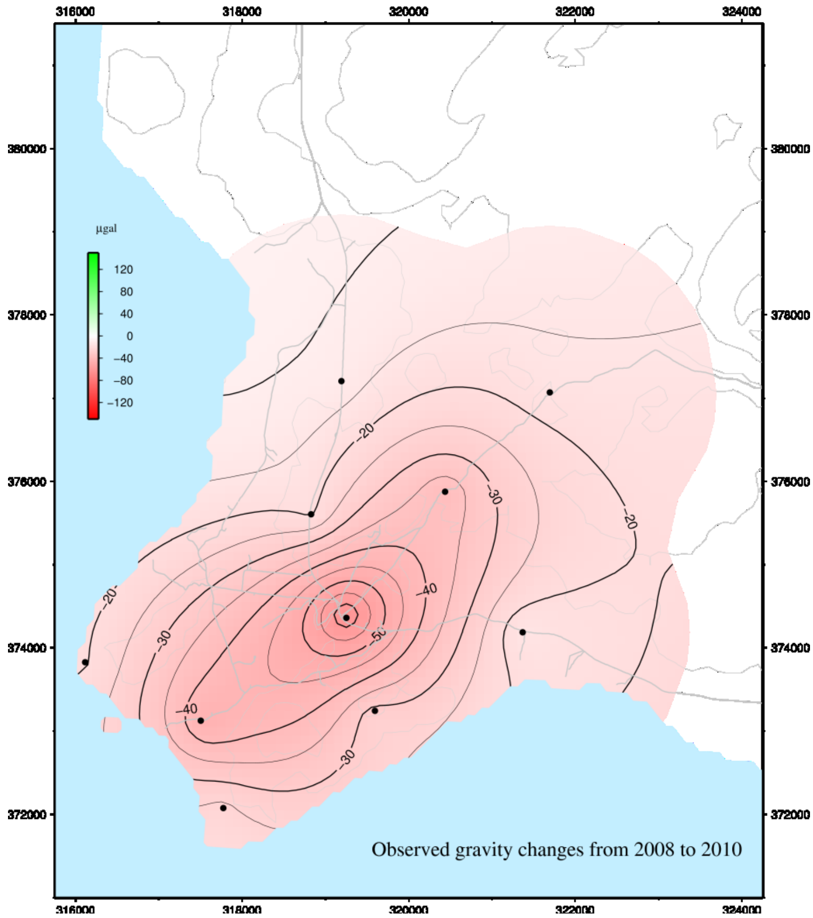

Figure 6: Observed gravity changes in Reykjanes from 2008 to 2010 (from Gudnason *et al.*, 2015). The black dots denote fixed gravity monitoring stations.

5. CONCLUSIONS

This paper has reviewed and presented the results of a research project involving the Reykjanes high-temperature geothermal system, which is located on the very southwest tip of Iceland, supported by the Icelandic GEORG research fund and carried out during 2009 – 2014. The purpose of the project was to assess the renewability of this particular geothermal resource, specifically to evaluate the relative importance of the two components of its renewability, i.e. the steady energy current (through heat convection and conduction) and the vast stored energy, which is renewed quite slowly, under the current state of utilization. This was done through compilation of available data, such as reservoir monitoring data, and collection of new data, mainly micro-gravity and geodetic data. Consequently these data were jointly interpreted, partly by simulating data (e.g. gravity-change data) by an up-to-date numerical reservoir model of the geothermal system. In addition repeated TEM-resistivity surveying was used to try to follow the growth of a steam-zone in the shallower parts of the geothermal system.

The principal results are the following:

- During the period 2008 – 2010 the renewal of reservoir fluid through recharge is estimated to have been of the order of 30 – 50%. This corresponds to about 250 ± 60 kg/s on the average. The renewal can't be estimated for the period 2006 – 2008 due to lacking data, but is expected to have been less.
- This renewal is less than the 60 – 70% renewal which has been estimated for the nearby Svartsengi system (Eysteinsson, 2000), indicating that the Reykjanes system is more closed, i.e. with less natural recharge, despite a quite comparable geological setting.
- The limited fluid renewal in the Reykjanes geothermal system during the current large-scale utilization along with the small size of the geothermal system identifies the need for greatly increased reinjection. This is already being planned and associated research is ongoing, e.g. comprehensive tracer testing.

- In spite of the limited size and recharge the energy in-place in the system is enormous. It is estimated that only a small fraction of that will have been extracted after 100 years under current extraction and recharge conditions.
- Deformation modelling has not been completed at the time of writing of this paper, but it can further constrain the renewability of the Reykjanes resource as well as the likely shape and volume of maximum mass change due to utilization.
- Interpretation of the repeated TEM resistivity soundings indicates some shallow changes due to the growth of steam cap of the Reykjanes system, supporting the contention that resistivity methods may be a useful monitoring tool. In this case it doesn't yield quantitative results, however.

Some further evaluation of the data from Reykjanes is recommended as well as further development of the methods employed. This includes:

- Gravity monitoring should be made more comprehensive by both increasing the number of stations and increasing its frequency (from once every few years to once every one or two years). Steps in that direction are already underway. Some technical improvements in the methodology are also being planned.
- Deformation monitoring can also be improved, both by making it more comprehensive and by following advances in GPS and InSAR monitoring technologies.
- Gravity change data should be used as a direct calibration parameter in the numerical reservoir modelling, instead of using it only together with forward modelling as done here.
- The simple deformation modelling still to be completed is expected to provide additional constraints on the nature of the Reykjanes geothermal system. More complex finite element modelling should also be attempted.
- Monitoring of pressure changes in marginal wells of the geothermal field should be enhanced (frequency and accuracy) to better determine the extent and shape of the pressure draw-down in the Reykjanes geothermal system, and hence help delineate the systems boundaries and its boundary conditions.
- Chemical monitoring data can be used as the basis of simple modelling of the contribution, or balance, of fluid of different origin in the reservoir (see previous section), i.e. colder recharge vs. hot reservoir fluid, both data on changes in chemical content and data indicating no changes.
- The ultimate goal would, consequently, to set up one all-embracing model to simulate gravity change, deformation and chemical data along with all reservoir data in a fully coupled manner.

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