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Analysis and Modelling of Gravity Changes in the Reykjanes Geothermal System in Iceland, During 2004-2010

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ABSTRACT

Reykjanes is the southwest tip of the Reykjanes Peninsula in Iceland, precisely where the Mid-Atlantic Ridge comes onshore. The Reykjanes geothermal system is in the center of Reykjanes and has been utilized for power production by HS Orka since 2006 with a power production of 100 MW_e at present.

An analysis of gravity changes observed in the Reykjanes geothermal system during the last decade is presented, with the principal purpose of estimating the mass changes in the geothermal system during the period 2006–2010 and hence the renewal of the fluid reserves in the system. The gravity surveys this work was based on were conducted by Iceland GeoSurvey during the summers of 2004 (prior to start-up of the Reykjanes 100 MW_e power plant), 2008 and 2010. 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 a simple mass change model. 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 set up by Vatnaskil Engineers for HS Orka.

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 is in the range of 30–50%. The renewal for the period 2004–2008 was probably somewhat less, but can't be estimated because of the loss of a measuring point in the center of the Reykjanes well-field 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 1400–1700 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 and SW as the observed one and the calculated maximum anomaly is a little smaller. A smaller and lower calculated gravity-change anomaly for the 2008–2010 period indicates that the numerical model allows slightly more recharge to the geothermal system than is the case in reality.

1. INTRODUCTION

The Mid-Atlantic Ridge comes onshore at the southwestern tip of Iceland, on the Reykjanes Peninsula (Figure 1). The peninsula marks the southwestern most part of the active volcanic and rift zones of Iceland, and forms the transition from the Reykjanes Ridge in the west to the South Iceland Seismic Zone in the east, southeast of the Hengill high-temperature area (Einarsson, 1991). Reykjanes is the southwest tip of the Reykjanes Peninsula, with the Reykjanes geothermal system in its center.

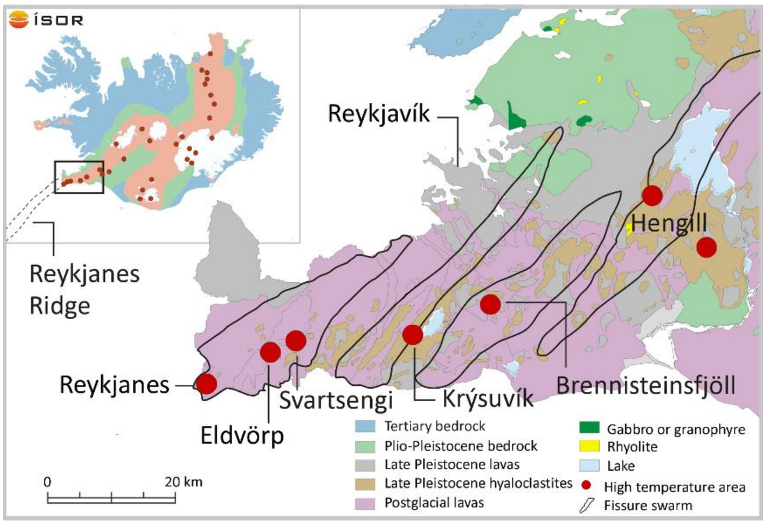

Figure 1: A geological map of the Reykjanes Peninsula, showing the fissure swarms and high-temperature areas along with the Reykjanes Ridge on the inset (based on a geological map of Iceland by Jóhannesson and Sæmundsson, 1999, modified from Harðardóttir et al., 2009).

The geology of the Reykjanes Peninsula is characterized by Pleistocene basaltic lavas, hyaloclastite ridges and postglacial lava flows (Sæmundsson and Einarsson, 1980). At Reykjanes, only tholeiitic basalts have been erupted. Eruptions have occurred on a series of NE-SW trending eruptive fissures which can be grouped into four en echelon volcanic fissure swarms (Sæmundsson, 1978). The fissure swarms consist of normal faults and extensional tension fractures in addition to the eruptive fissures, and they are intersected at an oblique angle by a series of near vertical N-S right-lateral strike-slip faults (Keiding et al., 2009).

Five high-temperature geothermal systems are present on the Reykjanes Peninsula (Figure 1). They are located on the obliquely rifting plate boundaries of the American and Eurasian plates, primarily at the intersection of the fissure swarms and the strike-slip faults. The geothermal systems are, from west to east, the Reykjanes, Eldvörp, Svartsengi, Krýsuvík and Brennisteinsfjöll systems, with two of the seven installed geothermal power plants in Iceland located in Reykjanes and Svartsengi. The Reykjanes geothermal system has been utilized for electrical power production by HS Orka since 2006 with a power production of 100 MW_e at present. The nearby geothermal system in Svartsengi, about 13 km to the ENE of Reykjanes, has been utilized by HS Orka since 1976 to provide hot water for domestic heating (150 MW_{th}) and production of electricity (75 MW_e). Together, the two geothermal power plants in Reykjanes and Svartsengi produce about 30% (175 MW_e in total) of all electricity production from geothermal energy in Iceland.

Inevitably, the extraction and exploitation of geothermal fluids can have several side effects. Pressure drawdown and contraction of the rock matrix are two effects causing subsidence above the reservoir. In Reykjanes, subsidence and pressure drawdown have been documented by geodetic- and gravity surveys throughout the years (Magnússon, 2009 and 2013). Results showed no sign of subsidence in Reykjanes before the start of production in May 2006, but then subsidence abruptly started, and average subsidence rates of around 14-16 mm/year in 2004-2008 were measured, with the highest rates of more than 30 mm/year during the first years of production (Keiding et al., 2010). Recent InSAR results indicate subsidence rates over 40 mm/year from September 2009 to October 2013 (Michalczewska, K., personal communication, 2014). The shape of subsidence in Reykjanes is elliptical and elongated in the NE-SW direction, thus aligning with the trend of the volcanic fractures in the area.

The effect of production on geothermal systems can be estimated with the use of repeated gravity- and geodetic surveys. The production of hot water and steam from geothermal systems, and re-injection of geothermal fluid, causes changes in the gravitational field of the Earth, as well as elevation changes. Using Gauss's potential theorem, elevation corrected gravity variations can be used to estimate the mass changes in the geothermal system. This method has been used in various geothermal areas worldwide, for example in Wairakei in New Zealand (Allis & Hunt, 1986; Hunt, 1995), Hatchobaru in Japan (Nishijima et al., 2005; Ehara & Nishijima, 2008) and Svartsengi in Iceland (Eysteinsson, 2000; Guðnason, 2010).

Presented here are the results of an analysis of gravity changes observed in the Reykjanes geothermal system during the last decade, with the principal purpose of estimating the mass changes in the geothermal system from the time of start-up of the Reykjanes 100 MW_e geothermal power plant, i.e. during the period 2006-2010, and hence the renewal of fluid reserves in the geothermal system. The gravity surveys this work was based on were conducted by Iceland GeoSurvey during the summers of 2004, 2008 and 2010. Magnússon (2009 and 2013) describes the survey in 2008 and 2010 as well as previous surveys.

The analysis involved three main steps:

1) Estimation of the mass changes in the Reykjanes geothermal system through a Gauss-integral of the observed gravity changes during the two periods, 2004-2008 and 2008-2010.
2) Simulation of the gravity-change anomaly for 2008-2010 by a simple mass change model of a spherically shaped mass change at variable depth, intended at helping estimate at what depth the main mass changes occur.
3) Calculation of gravity changes at the observation points of the gravity grid, on basis of mass changes in the numerical TOUGH2 reservoir model of the Reykjanes geothermal system set up by Vatnaskil Engineers for HS Orka. This is done by adding up the gravitational effects of the mass changes in each of the numerous blocks of the reservoir model, for the two periods under study, i.e. 2004-2008 and 2008-2010.

2. DATA ON GRAVITY CHANGES

The gravity data were acquired in local gravity surveys, using a Scintrex CG3M gravimeter. The gravity surveys were performed in a base network of 57 gravity stations, with repeat occupations, that covers both the Reykjanes and Svartsengi geothermal systems on the western part of the Reykjanes Peninsula (Magnússon, 2009 and 2013). Only the southwestern most part of the base network is shown on the figures in this paper. Datum was established by tying the data sets to a reference station in Reykjavik, located at a distance of roughly 60 km distance. The gravity data collected during the gravity surveys in 2004, 2008 and 2010 has been corrected for elevation changes, which are measured simultaneously with precision GPS-measurements, as well as for the effect of the tidal forces of the Sun and Moon.

Observed gravity changes in Reykjanes from 2004 to 2008 are shown in Figure 2. It should be pointed out that a measuring point in the center of the well-field was destroyed during construction of the Reykjanes geothermal power plant in 2006, and hence the gravity-change anomaly is poorly defined during this period, because data on the gravity change in the center of the field is missing. A much deeper gravity low would have been expected in view of the net mass extracted during this period. As a consequence, the mass change in the Reykjanes geothermal system, estimated through a Gauss-integral, will be underestimated and the fluid renewal overestimated, for this period.

Observed gravity changes in Reykjanes from 2008 to 2010 are shown in Figure 3. During this period, the gravity changes are much better defined and a clear anomaly is seen, centered in the center of the Reykjanes well-field.

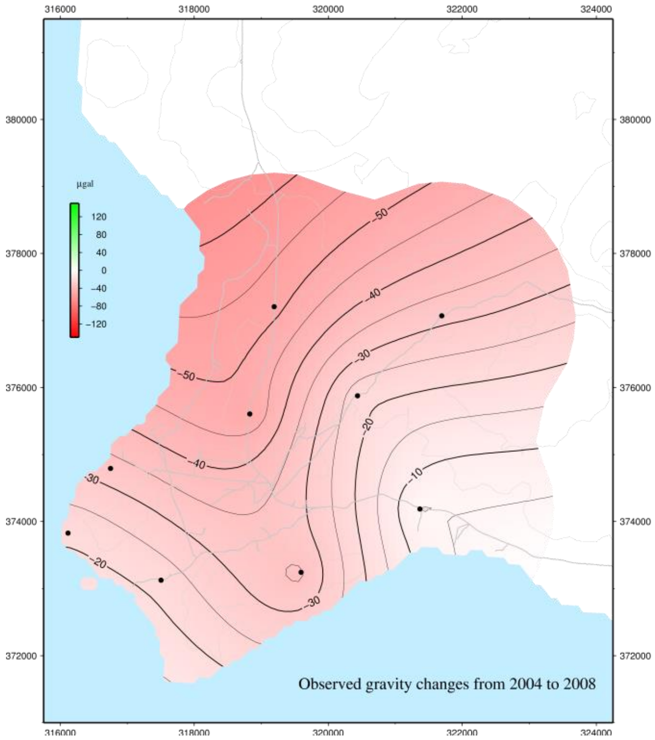

Figure 2: Observed gravity changes in Reykjanes from 2004 to 2008. Black points denote the measured points of the gravity surveys. Note that a measuring point in the center of the well-field was destroyed in 2006 and hence the gravity-change anomaly is poorly defined during this period (see Figure 3). A much deeper gravity low would have been expected.

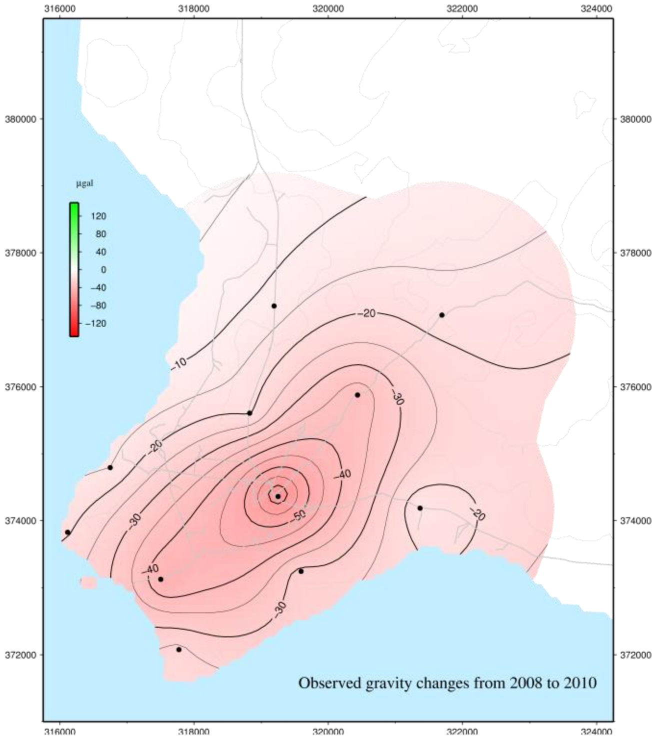

Figure 3: Observed gravity changes in Reykjanes from 2008 to 2010. Black points denote the measured points of the gravity surveys.

3. MASS CHANGES ESTIMATED BY GAUSS-INTEGRAL

As a result of Gauss´s flux theorem in potential theory, gravity measurements provide a unique estimate of the total anomalous mass (Parasnis, 1986). The mass changes in the geothermal system (geothermal reservoir) are estimated with the following surface integral, or the so-called Gauss-integral:

$$\Delta M = \frac{1}{2\pi G} \iint\limits_{0<r<R} \Delta g dx dy \tag{1}$$

where ΔM denotes the estimated mass change, G the gravitational constant ($G = 6{,}67 \times 10^{-11}$ m^3 kg^{-1} s^{-2}) and Δg (x, y) the change in gravity at a measuring point (x, y) on the surface, obtained after the removal of any regional trends. The symbol R indicates the radius of the area included in the Gauss-integral, while $r = \sqrt{(x^2 + y^2)}$. The center of the coordinate system is set in the center of the gravity anomaly (see Figure 3), which coincides approximately with the center of the Reykjanes well-field. The integral is integrated numerically by dividing the area involved into a cylindrical grid, and extrapolating and digitizing the gravity-anomaly data.

The results of this analysis are presented in Table 1 for two area radiuses R, i.e. 3 and 4 km. In the case of the 4 km radius the gravity data needs to be extrapolated into the ocean. In addition, the gravity decline data for the area between 3 and 4 km radius is somewhat uncertain, but has a large effect on the results because of much greater area involved. This reduces the accuracy of the 4 km results. In contrast, the results for a 3 km radius most likely underestimate the mass changes to some extent, because they neglect changes outside that radius (see Figures 4 and 5).

Table 1: Estimates of mass changes and natural mass recharge in the Reykjanes geothermal system during two periods, 2004-2008 and 2008-2010, based on Gauss integration (eq. (1)), with numbers in Mton (10^9 kg). Note that results for the 2004-2008 period are uncertain, as discussed in Chapter 2.

	2004–2008		2008–2010	
	3 km radius$^{1)}$	4 km radius	3 km radius	4 km radius
Estimated mass change$^{2)}$	>19.6	>32.4	18.0	26.2
Mass extracted	48.4		37.7	
Mass re-injected	0		1.7	
Net mass extracted	48.4		36.0	
Natural mass recharge$^{3)}$	<28.8	<16.0	18.0	9.8
Ratio between recharge and net extraction	<60%	<33%	50%	30%

1) Radius of integration area, relative to center of well-field
2) According to measured gravity changes
3) Natural mass recharge = Net mass extracted – Estimated mass change

It should be emphasized that the gravity-change anomaly for the 2004-2008 period is poorly defined, because data on the gravity change in the center of the well-field is missing. As a consequence, the mass change in the Reykjanes geothermal system during this period, estimated through a Gauss-integral, will be underestimated and the fluid renewal conversely overestimated, for this period.

The results in Table 1 for the 2004-2008 period indicate fluid renewal ratios in the range of 33 – 60%. However, the estimate is uncertain and less fluid renewal during the first years of operation of the Reykjanes 100 MW$_e$ geothermal power plant would actually be expected. The results indicate that the fluid renewal for the 2008-2010 period is in the range of 30 - 50%. This can e.g. be compared with comparable estimates for the Svartsengi geothermal system for the periods 1975-1999 and 1999-2004, which indicate fluid renewal ratios of about 60 and 70%, respectively (Guðnason, 2010).

4. GRAVITY CHANGES SIMULATED BY A SIMPLE, ANALYTICAL MODEL

A simple, analytical model used to simulate the gravity decline anomaly observed for the 2008-2010 period is a model of a subsurface sphere wherein the mass declines by ΔM. The gravity change, Δg, in a model involving such a body is given by:

$$\Delta g = G \frac{\Delta M d}{r^3} \tag{2}$$

where ΔM denotes the estimated mass change, G the gravitational constant, d the depth to the center of the sphere and $r = \sqrt{(x^2 + y^2 + d^2)}$, the distance from the center of the sphere to an observation point on the surface. The sphere is located at the center of the coordinate system used, or at (0, 0, d).

The results are shown in Figures 4 and 5. Figure 4 shows the results for a mass change based on an integration radius of 3 km, while Figure 5 shows the results for a mass change based on an integration radius of 4 km (see Table 1). The observed gravity anomaly data are plotted along two cross-sections in both figures, one NE-SW and the other NW-SE, with the observed data being plotted with small open circles. The calculated gravity anomalies are plotted as solid lines for three different depths of the sphere; i.e. in Figure 4 for 1300, 1400 and 1500 m depth, respectively, and in Figure 5 for 1600, 1700 and 1800 m depth, respectively.

The results show that a simple model of a subsurface sphere simulates the observed gravity anomaly data fairly well. However, the calculated anomalies are too sharp, indicating that the actual mass change in the Reykjanes geothermal system is probably confined to a volume which is more elongated than a sphere, e.g. shaped like a cylinder with a diameter somewhat longer than its thickness.

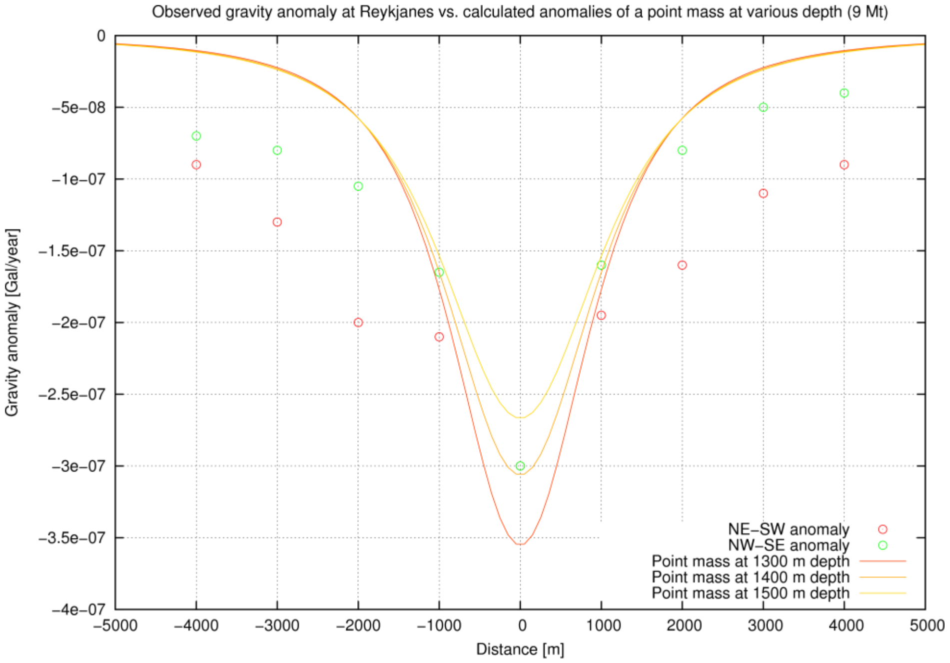

Figure 4: Comparison of observed gravity changes in Reykjanes (open circles in two cross-sections, NE-SW and NW-SE) and gravity changes calculated by a model of a sphere at three different depths, experiencing mass changes (ΔM) based on an estimation with a radius of integration of 3 km.

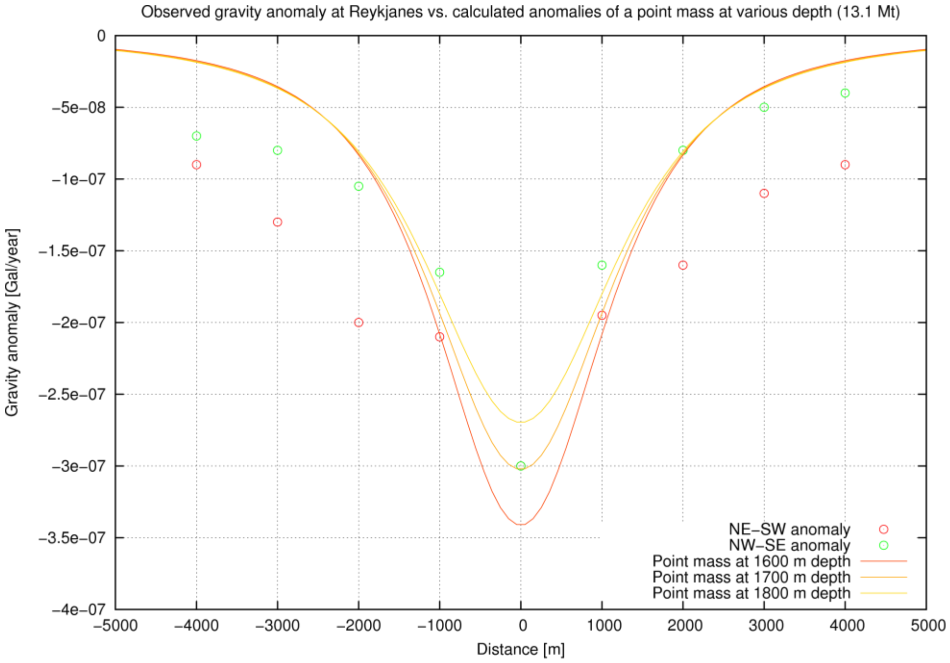

Figure 5: Comparison of observed gravity changes in Reykjanes (open circles in two cross-sections, NE-SW and NW-SE) and gravity changes calculated by a model of a sphere at three different depths, experiencing mass changes (ΔM) based on an estimation with a radius of integration of 4 km.

Based on the best fit of the lowest point of the observed gravity anomaly and the calculated anomalies, a model of a point mass change centered at 1400 m depth best fits the observed gravity anomaly for the mass change estimate based on a radius of integration of 3 km, while a model of a point mass change centered at 1700 m depth best fits the observed gravity anomaly for the mass change estimate based on a radius of integration of 4 km. Both estimates are realistic, with the shallower estimate (1400 m) indicating that a part of the mass change has occurred in the steam-cap zone of the geothermal reservoir at Reykjanes, while the deeper estimate (1700 m) indicates that most of the mass change has occurred in its deeper, liquid dominated part.

5. GRAVITY CHANGES CALCULATED ON BASIS OF MASS CHANGES IN THE TOUGH2 MODEL

The third step in the analysis of the gravity changes observed in, and around, the Reykjanes geothermal system involves using the TOUGH2 reservoir model of the Reykjanes geothermal system, developed by Vatnaskil Engineers for HS Orka. The analysis is done by calculating the mass changes in each of the numerous blocks of the model in the Reykjanes area, for the part of the model within a 6 km radius (R = 6 km) from the center of the well-field, for the two periods under study (i.e. 2004-2008 and 2008-2010). Consequently, the gravity change at each measuring point of the gravity grid is calculated for each block of the reservoir model, and the total gravity changes calculated by summing up the changes for each and every block. The following equation is therefore used for each measuring point of the gravity grid on Reykjanes, and for each of the two time periods:

$$\Delta g = \sum_i G \frac{\Delta m_i d_i}{r_i^3} \tag{3}$$

where Δm_i denotes the mass change in each block of the reservoir model (block number i), G the gravitational constant, d_i the depth of the block and r_i the distance from a measuring point to the center of each block.

The calculated mass changes in each layer of the numerical reservoir model are presented in Table 2, out to a radius of 6 km from the center of the well-field, for the two periods under study. According to the results, the greatest mass change occurs in layers E-H (800-1750 m depth) during the 2004-2008 period and also in layers E-H (800-1750 m depth) during the 2008-2010 period. These depth ranges can also be compared with the depth range estimate of 1400-1700 m based on the results for the spherical model presented in Figures 4 and 5. In general, these are significant mass changes down to the bottom of the reservoir model (Table 2).

Table 2: Calculated mass changes in each layer of the TOUGH2 reservoir model of the Reykjanes geothermal system (layer depths in meters), calculated out to a radius of 6 km from the center of the well-field with numbers in Mton (10^9 kg).

Layer (depth-interval)	2004–2008	2008–2010
A (0 – 250)	0.009	0.135
B (250 – 350)	0.844	-0.058
C (350 – 650)	-1.245	-0.351
D (650 – 800)	-1.712	-1.239
E (800 – 1050)	-6.553	-4.455
F (1050 – 1100)	-7.381	-4.053
G (1100 – 1500)	-10.591	-5.923
H (1500 – 1750)	-5.725	-5.958
I (1750 – 2200)	-2.523	-1.272
J (2200 – 2450)	-2.381	-1.327
K (2450 – 2850)	-1.934	-1.170
L (2850 – 3050)	-1.918	-1.236
M (3050 – 3400)	-1.676	-1.136
Total	-42.79	-28.04

According to Table 2, the reservoir model experiences -43 and -28 Mton mass change during the two periods, respectively, up to a radius of 6 km from the center of Reykjanes. The calculated mass change for the 2008-2010 period is somewhat greater than the mass change estimate in Table 1, which is logical because of a greater radius of calculation. The total calculated mass change in the reservoir model for the 2004-2008 period is more than 50% greater than for the later period, which is not surprising because of the start-up of the Reykjanes 100 MW_e power plant in May 2006. The calculated mass change for the 2004-2008 period is also much greater than the mass change estimate in Table 1, which supports the contention that the mass change estimate in Table 1 for this period is an underestimate.

Figures 6 and 7 show contour maps of the observed gravity changes and the gravity changes calculated on basis of mass changes in the TOUGH2 reservoir model in the Reykjanes geothermal system, for the two periods under study. For the 2004-2008 period, the calculated gravity changes show a very drastic gravity decline anomaly, which can’t be compared with the observed gravity changes because data on the gravity change in the center of the well-field is missing, as already mentioned (Figure 6).

For the period 2008-2010, the observed and calculated gravity changes actually show quite comparable results (Figure 7). The observed and calculated anomalies are comparable in shape, even though the calculated one doesn’t extend as much to the NE and SW as the observed one.

The maximum calculated gravity change is slightly smaller than the observed one for the 2008-2010 period. In general, the calculated gravity change for this period is slightly less than the observed one, which can be interpreted as indicating that the numerical reservoir model allows slightly more recharge to the geothermal system than is the case in reality. Another interpretation is also possible, which is that the mass changes in the reservoir model, after the start-up of the Reykjanes 100 MW$_e$ power plant, occur a little faster than happens in reality.

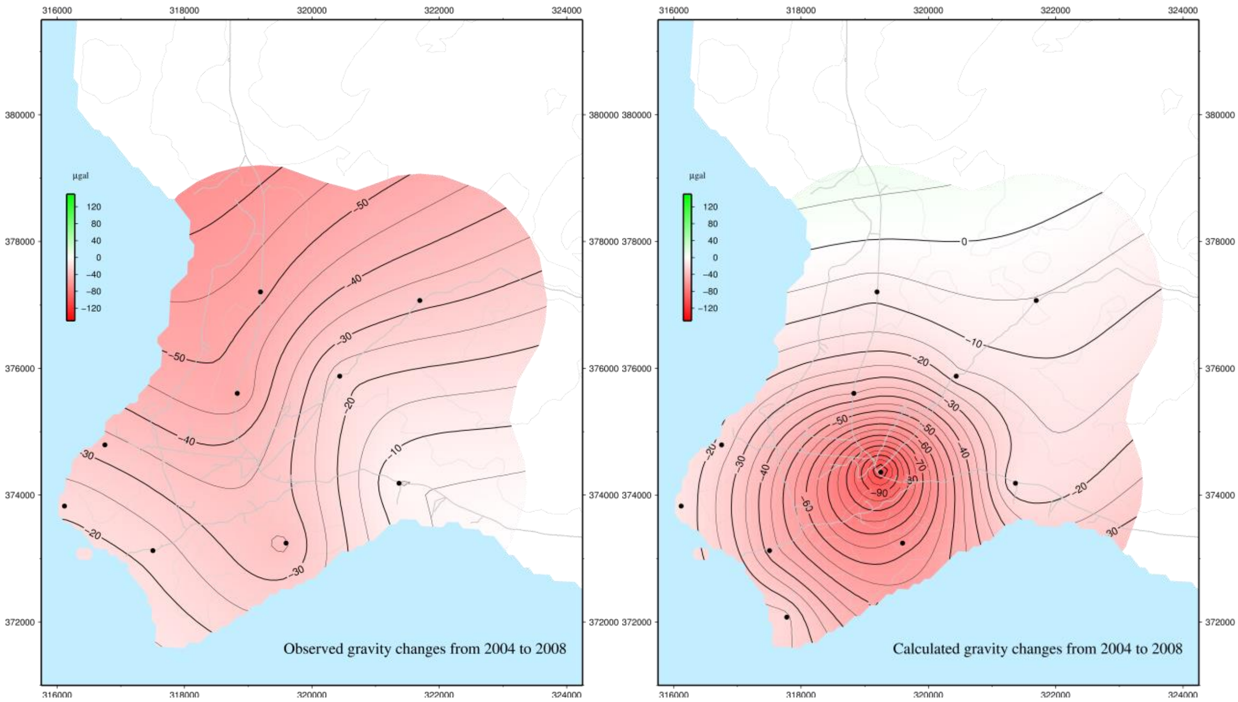

Figure 6: Comparison of observed gravity changes (left) and gravity changes calculated on basis of mass changes in the TOUGH2 reservoir model of the Reykjanes geothermal system (right) for the period 2004-2008. Note that a measuring point in the center of the Reykjanes well-field was destroyed in 2006 and hence the observed gravity-change anomaly is poorly defined during this period.

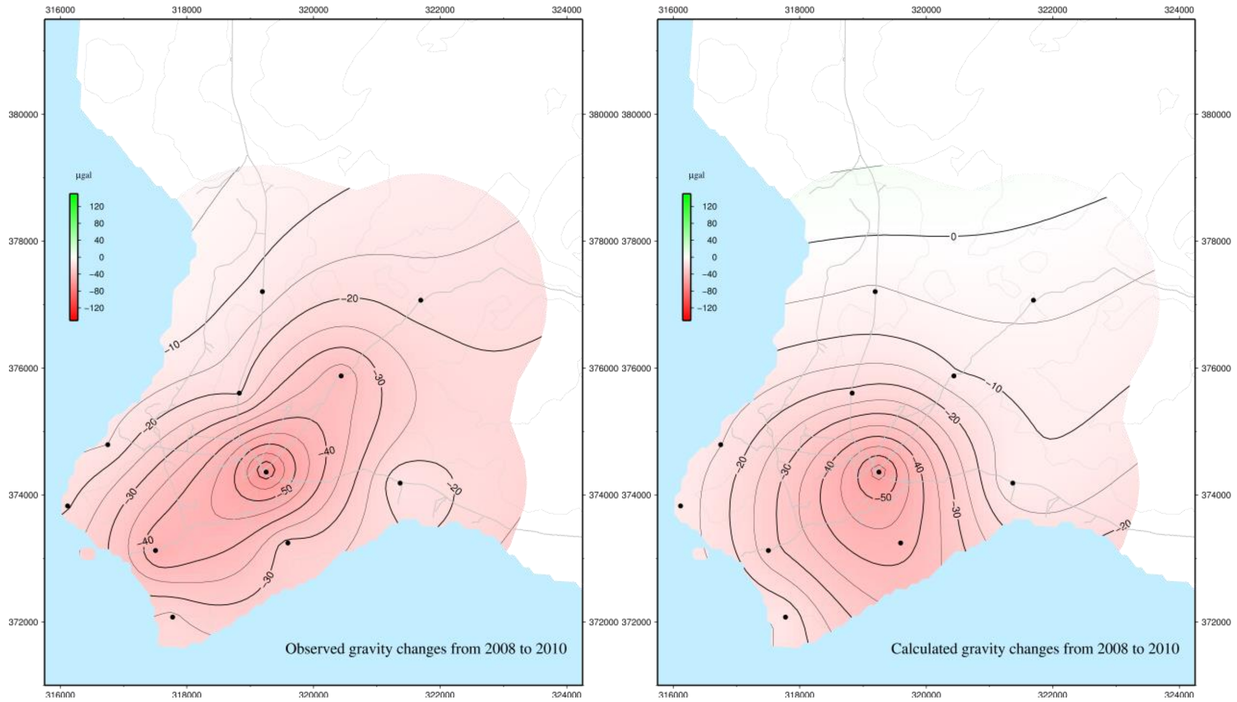

Figure 7: Comparison of observed gravity changes (left) and gravity changes calculated on basis of mass changes in the TOUGH2 reservoir model of the Reykjanes geothermal system (right) for the period 2008-2010.

7. CONCLUSIONS

Exploitation of geothermal fluids in Reykjanes since the start-up of the 100 MW$_e$ power plant in 2006 has caused both pressure drawdown and a cumulative surface subsidence within the well-field. In Reykjanes, subsidence and pressure drawdown have been documented by geodetic- and gravity surveys throughout the years (Magnússon, 2009 and 2013). Results showed no sign of subsidence before the start of production in May 2006, but then subsidence abruptly started and the highest rates of subsidence were measured during the first years of production, of more than 30 mm/year (Keiding et al., 2010). To reduce this drawdown, re-injection of geothermal water has been carried out in Reykjanes since 2009.

The effect of production on geothermal systems can be estimated with the use of repeated gravity- and geodetic surveys. The gravity- and geodetic surveys this work was based on were conducted during the summers of 2004, 2008 and 2010. Using Gauss's potential theorem, the estimated renewal of the reservoir mass in Reykjanes during 2008-2010 is in the range of 30-50%. The renewal for the period 2004–2008 was probably somewhat less, but can't be estimated because of the loss of a measuring point in the center of the Reykjanes well-field in 2006. Using a simple, analytical model of a subsurface spherical mass-change volume to simulate the gravity decline anomaly observed for the period 2008-2010 indicates that the center of the volume is at a depth of 1400–1700 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 and SW as the observed one and the calculated maximum anomaly is a little smaller. A smaller and lower calculated gravity-change anomaly for the 2008–2010 period indicates that the numerical model allows slightly more recharge to the geothermal system than is the case in reality. The overall results demonstrate how numerical modelling can be enhanced through incorporation of gravity monitoring data. The discrepancy between the observed and calculated anomalies for the 2008–2010 period, furthermore, indicates that the calibration of the Reykjanes numerical model can be improved further.

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