Hybrid gravimetry monitoring of the Theistareykir and Krafla geothermal reservoirs (Iceland)

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ABSTRACT

We monitor the Krafla and Theistareykir geothermal reservoirs in Northeastern Iceland using hybrid gravimetry. The two geothermal plants are located on the path of the Mid-Atlantic ridge. Power geothermal exploitation at Theistareykir began in autumn 2017, with 90 MWe installed power production capacity using a 280 to 330°C fluid. Gravity measurements were done before and after the beginning of the power production to study the related mass transfer. This method helps to quantify the recharge of the reservoir and hence, to ensure the energy sustainability. The Krafla geothermal plant is in operation since 1977 and has a power production capacity of 60 MWe since 1997.

To study the mass redistribution, we did gravity measurements with a Scintrex CG5 (#41224) gravimeter in 2017 and 2018, at 27 and 25 stations at the Theistareykir and Krafla sites, respectively. ISOR and De Zeeuw-van Dalfsen et al. (2006) had already measured the gravity at these stations. After tidal and drift corrections, double differences in gravity are calculated: they express the gravity variation at each measurement point with respect to a reference time and station. The stability of the reference stations of the two networks was investigated by performing repeated absolute measurements using FG5#206 ballistic absolute gravimeter from Micro-g Solutions. In addition, in December 2017 GFZ Potsdam deployed three superconducting gravimeters (iGrav006, iGrav15 and iGrav32) and one gPhone (#128) spring gravimeter at Theistareykir to record the continuous gravity variations in the framework of the MicroGraviMoTiS project. One gPhone gravimeter will also be installed in the near future at Krafla. The combination of results from these different instruments will be used in a fully hybrid gravimetry investigation. The vertical displacement is studied by the University of Iceland with GPS measurements.

1. INTRODUCTION

The micro-gravity method highlights subsurface mass redistribution. It is especially used to provide insight into magmatic activity in volcanic areas. For instance, continuous gravity records highlighted the dynamics of Mt Vesuvius in Italy (Berrino et al, 2006; Riccardi et al, 2008). Okubo et al (2002) introduced the hybrid gravimetry to monitor the Mt Fuji volcano in Japan. This method combines three types of gravimeters (Hinderer et al, 2016):

- A spring relative gravimeter to investigate the gravity changes at several stations with respect to a reference station;
- A permanent relative gravimeter like a superconducting one to record the continuous gravity variation at the reference station;
- An absolute gravimeter to control the long-term gravity changes and to correct for the instrumental drift of the permanent gravimeter.

Sugihara and Ishido (2008) demonstrated first the efficiency of this method to monitor a geothermal plant: they studied the Okuaizu and Ogiri fields in Japan. Indeed, the natural and anthropogenic evolution of the geothermal reservoirs is characterized by using time and space gravity changes. Their work inspired many researchers (Nishijima et al 2010; Oka et al, 2012; Sofyan et al 2015; Portier et al 2018a, 2018b). For example, Gudnason et al (2018) used the micro-gravity survey to quantify the Reykjanes reservoir recharge and hence, help to assess its sustainability.

We apply here the hybrid gravity monitoring to the Theistareykir and Krafla sites in Iceland to evaluate the impact of short and long-term geothermal production, respectively.

2. THE GEOTHERMAL PLANTS

The Krafla and Theistareykir geothermal fields are located on the boundary between the North American tectonic plate and the Eurasian plate in the northern part of Iceland. The power stations are operated by the National Power Company of Iceland, Landsvirkjun.

2.1 Krafla

The first exploration wells were drilled in 1974 at the Krafla geothermal site. One year later, a large-scale volcanic eruption occurred and threated the project. Nevertheless, the geothermal production succeeded to start in 1977. Then, the Krafla geothermal field hosted the well-known IDDP1 project; in 2009, the Iceland Deep Drilling Project reached magma at 2km depth (Friðleifsson et al., 2015). Finally, since 1997, the power plant produces 60MWe, using two steam turbines of 30 MWe. 44 wells have been drilled (Guðmundsson and Mortensen, 2015).

We measured a network of 25 gravity stations (Fig. 1) in 2017 and 2018 at the Krafla geothermal site. The same stations were used for repeated gravity measurments by De Zeeuw-van Dalfsen et al. (2006) in 2002 and 2003, and partly recorded by ISOR in 2013.

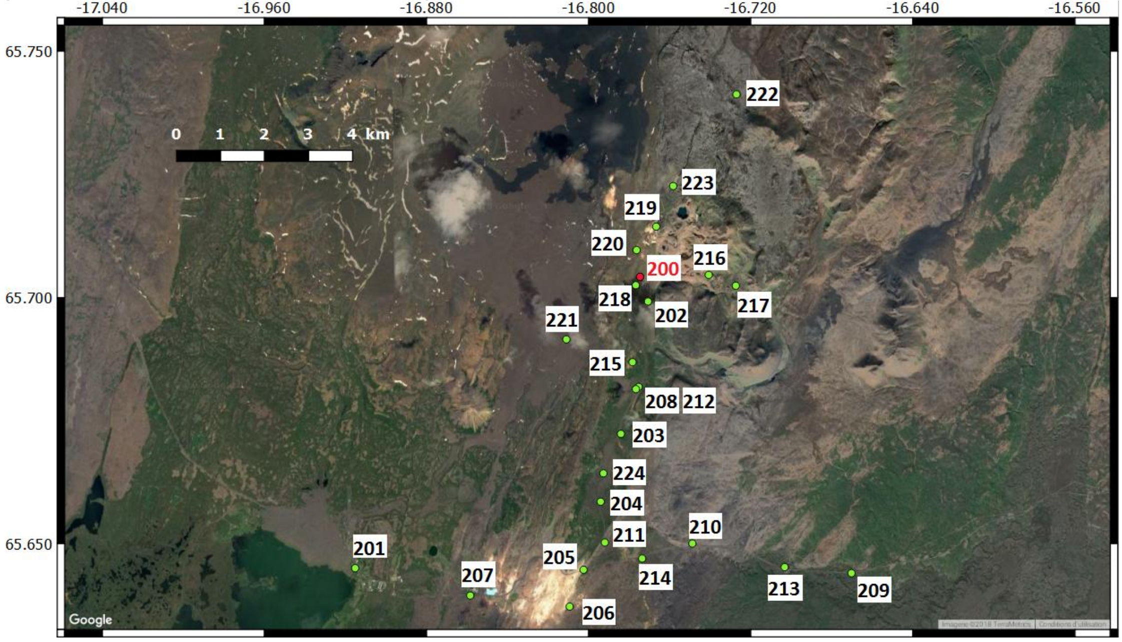

Figure 1: Map of the Krafla gravity network. The reference station is the station 200.

2.2 Theistareykir

The project of a geothermal plant construction at Theistareykir was developped in 1999, after the drilling of a first well. Consequently, exploration drillings were performed in 2002 and the building of the power station started in April 2015. The geothermal plant works with two turbine units, each with a 45MWe capacity. The first production phase began in autumn 2017 and the second one in spring 2018 to reach a total capacity of 90MWe. The power plant counts 13 production wells of 2 to 2.5km depth, which extract a 280-330°C geothermal fluid (Fig. 2). Then, the condensate steam is reinjected in the ground.

We measured a network of 27 gravity stations (Fig. 2) in 2017 and 2018 at the Theistareykir geothermal site. A part of these stations was already measured in 2011 and 2015 by ISOR (Magnússon, 2016).

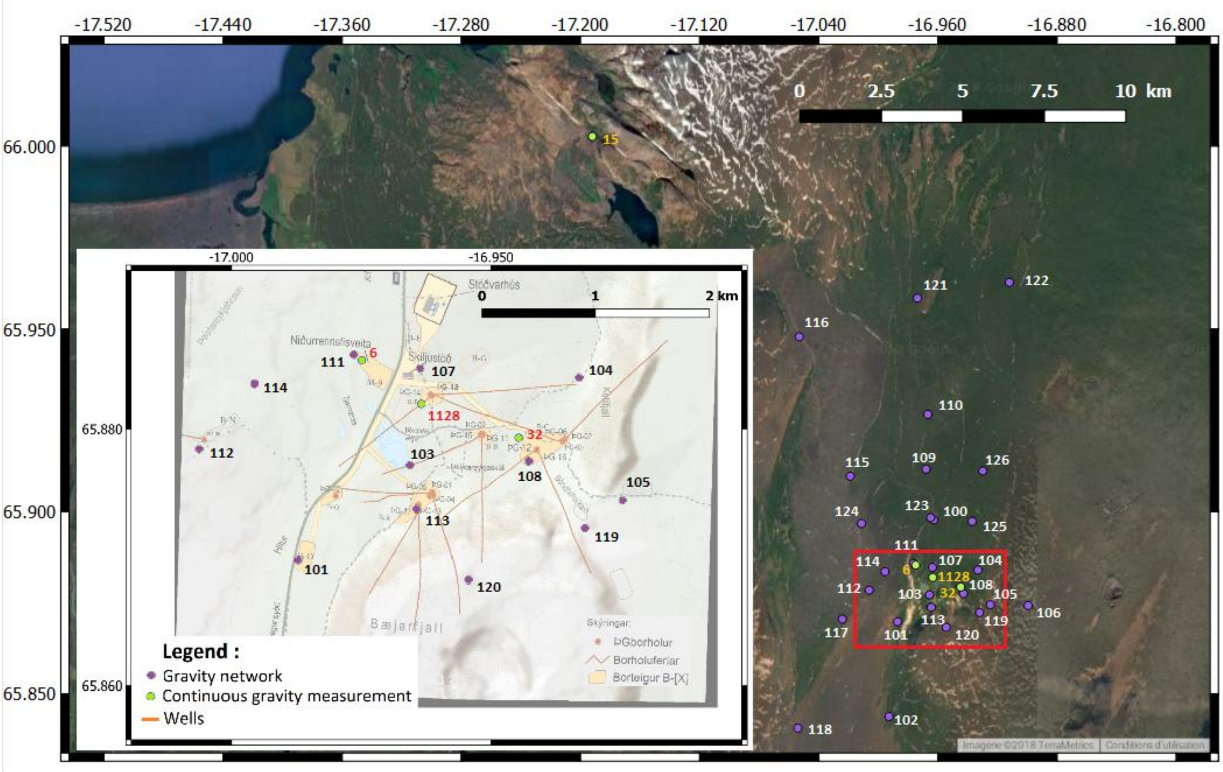

Figure 2: Map of the Theistareykir gravity network. Station 100 is used as reference station. The enlarged view shows the geothermal production area. The position of the permanent stations is also depicted in green.

3. THE MICRO-GRAVITY DATA PROCESSING

The first processing step is the calibration of the ScintrexCG5#41224 relative spring gravimeter. The correction coefficient is deduced using the gravity difference between a fixed measurement point at the gravity observatory of Strasbourg (STJ9) and another one in the Strengbach catchment in the Vosges Mountains in France as a calibration line. We use the result obtained in 2016. The tide correction is directly done with the Longman's formula (1959) during the survey. Then, the instrumental drift is corrected using the Python PyGrav software (Hector and Hinderer 2016) before that the double gravity differences $Dg_{x-x_0}^{t-t_0}$ are calculated [1]: they express the gravity variation at each measurement point x at a time t compared to a reference time t_0 and station x_0. g_x is the gravity value measured at the station x.

$$Dg_{x-x_0}^{t-t_0} = (g_x - g_{x_0})_t - (g_x - g_{x_0})_{t_0} \qquad [1]$$

The gravity variation at the reference station is investigated by performing repeated absolute measurements using FG5#206 ballistic absolute gravimeter from Micro-g Solutions in 2017 and 2018 at the both sites. The absolute data are corrected for the effect of solid earth tides and ocean loading, atmospheric pressure and polar motion.

Moreover, in December 2017, GFZ Potsdam deployed three superconducting gravimeters (iGrav006, iGrav15 and iGrav32) and one gPhone (#128) spring gravimeter at Theistareykir (Fig.2) to continuously record the gravity variations. In this abstract, we will only focus on the time-lapse micro-gravity monitoring.

To highlight the mass changes in the ground, we must correct the gravity measurements for the vertical displacement (e.g. Hunt et al 2002). Indeed, according to the Bouguer-corrected free-air gradient (BCFAG) with a density of 2670 kg.m^{-3}, vertical ground movements induce a change of about 2 µGal.cm^{-1} (1 µGal = 10^{-8} m.s^{-2}). We use GPS measurements performed by the University of Iceland. However, we do not know the vertical displacements at all the gravity stations; InSAR analysis will be done to compensate this lack.

4. RESULTS

In this abstract, we present the 2017-2018 results.

4.1 Krafla

The FG5#206 ballistic absolute gravimeter shows an increase in gravity of 8.9 +/- 2.2 µGal at the reference station 200 between summer 2017 and 2018.

GPS measurements show subsidence in the south of the studied area and uplift in the north, near the production zone, with an exception at the station 219 (-12 +/- 8 mm). Nevertheless, the errors are large. We do not observe any correlation between the vertical displacements and the gravity double differences (see Fig. 3). All gravity changes are positive independently of the sign of the vertical deformation. They are always above the free air gradient curve.

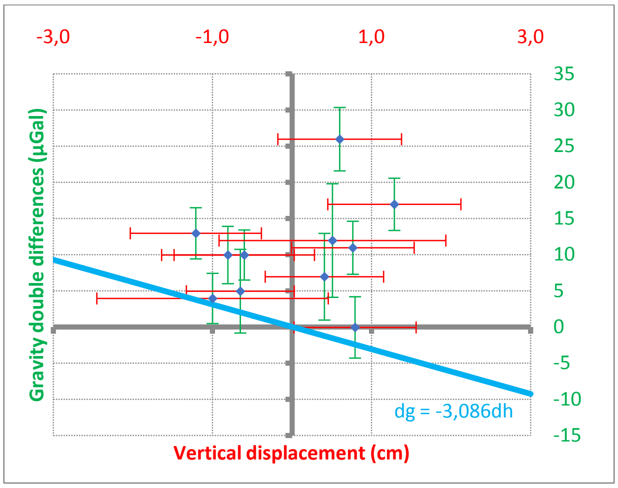

Figure 3: Gravity double differences dg (in µGal) as a function of height changes dh (in cm) in 2018 with respect to 2017 with their errors at the Krafla geothermal plant. The coefficient of determination is equal to 0.0769 (no correlation). The free air gradient theory (dg/ dh = -3.086 µGal/cm) is plotted in blue.

We calibrated and corrected the gravity double differences for the lunisolar tides and the instrumental drift. We also corrected them for the vertical displacement. Fig. 4 shows the results.

We observe a gravity increase at all the stations between 2017 and 2018 with a maximum value of 27 +/- 5 µGal at the station 220 (Fig. 4).

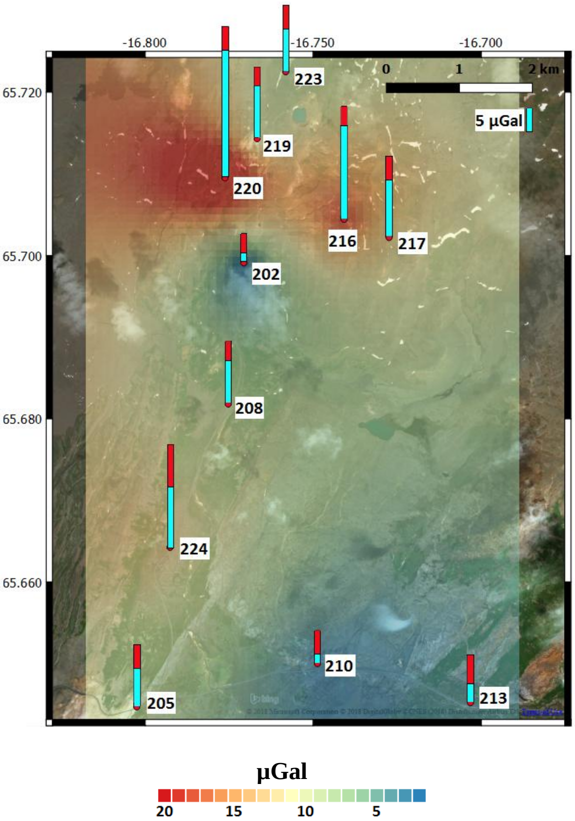

Figure 4: Map of the gravity double differences in µGal corrected for the vertical displacements with the BCFAG gradient (2 µGal.cm^{-1}) between 2017 and 2018 at the Krafla geothermal plant. Histograms show the gravity double differences (in blue) and the errors (in red) in µGal. The error bar (in red) is above the value bar (in blue) when the gravity double differences are positive. Interpolation of the gravity double differences was done, with colour coding for 0 (blue) to 20 (red) µGal. The station codes are written in black.

4.2 Theistareykir

The FG5#206 ballistic absolute gravimeter shows a decrease in gravity of 2.0 +/- 1.5 µGal at the reference station 100 between summer 2017 and 2018.

GPS measurements show general uplift on the geothermal site, up to 26 +/- 14 mm at the station 101. Only the station 103 has subsidence of -21 +/- 7 mm; however, this station is close to a lake with a variable water level that may have an additional effect on the measurement. We do not observe any correlation between the vertical displacements and the gravity double differences (see Fig. 5). Contrary to the Krafla results, we notice that almost all gravity changes are negative independently of the sign of vertical deformation.

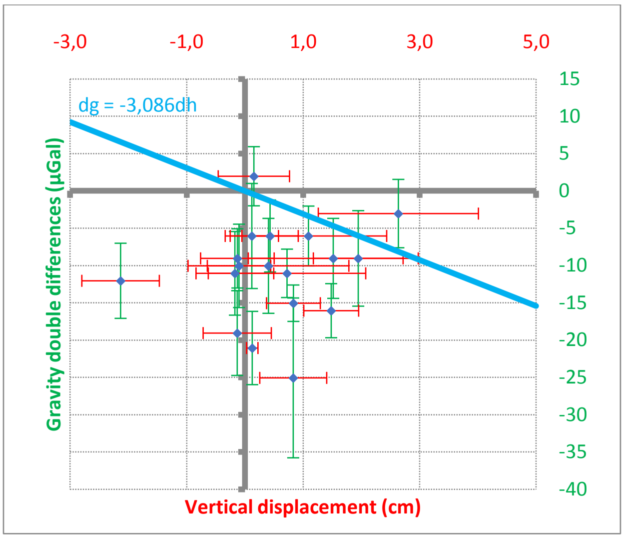

Figure 5: Gravity double differences dg (in µGal) as a function of height changes dh (in cm) in 2018 with respect to 2017 with their errors at the Theistareykir geothermal plant. The coefficient of determination is equal to 0.0213 (no correlation). The free air gradient theory (dg/ dh = -3.086 µGal/cm) is also plotted in blue.

The gravity double differences have been calibrated, corrected for the lunisolar tides and the instrumental drift. To understand the mass balance of the geothermal reservoir under production, we also corrected them for the vertical displacements. The results are presented in Fig. 6.

We observe a general gravity decrease in the geothermal area. The highest value is -23 +/- 11 µGal at the station 108 in the production zone. However, we need to keep in mind that it is also the station with the largest error.

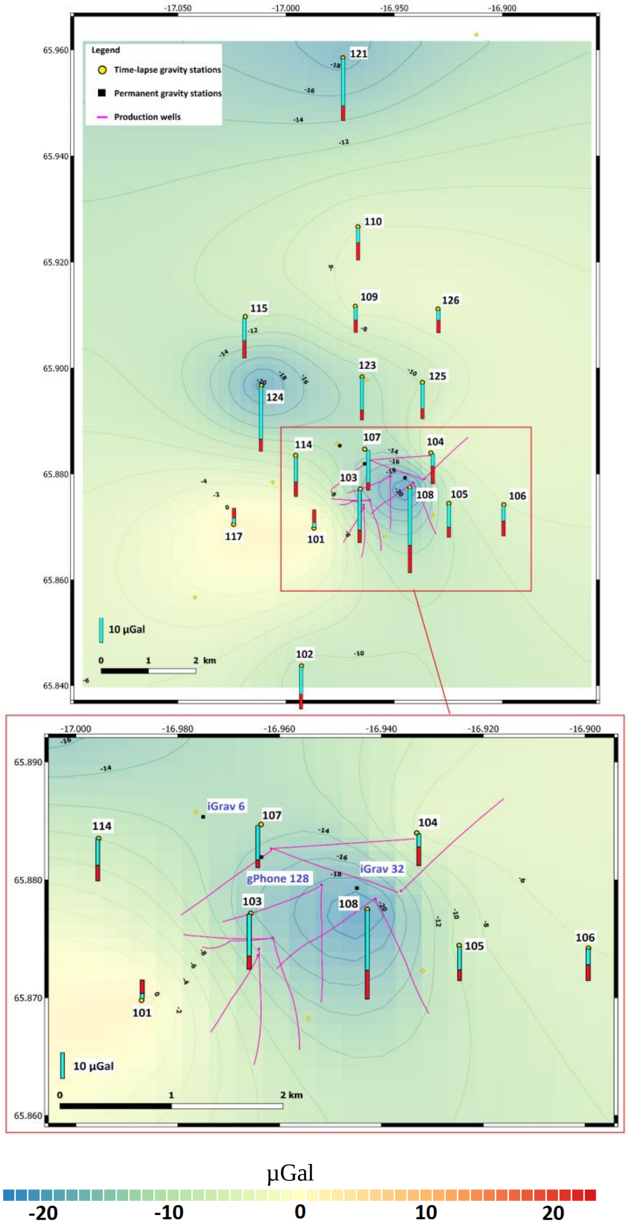

Figure 6: Map of the gravity double differences in µGal corrected for the vertical displacements with the BCFAG gradient (2 µGal.cm^{-1}) between 2017 and 2018 at the Theistareykir geothermal plant. Histograms show the gravity double differences (in blue) and the errors (in red) in µGal. The error bar (in red) is above the value bar (in blue) when the gravity double differences are positive. Interpolation of the gravity double differences was done. The station codes are written in black.

3. CONCLUSIONS

We monitored the gravity variations at the Krafla and Theistareykir geothermal plants in 2017 and 2018.

The Krafla power station is in operation since 1977. We notice a general increase in gravity with maximum values close to the production area. These higher changes are in the same area which shows uplift.

The power production started in autumn 2017 at the Theistareykir geothermal field. Hence, we collected gravity data before and after the beginning of operation. We notice a gravity decrease in the production area also associated with uplift.

To refine our observations, we will perform additional micro-gravity measurements in summer 2019. Then, we will compare them to the former gravity data. Taking into account the injected and produced masses, we expect to improve our understanding of the geothermal reservoirs and compare the results to our magnetotellurics observations that we obtained at the Theistareykir site (see abstract Time-lapse manetotellurics monitoring of Theistareykir geothermal reservoir (Iceland)).

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