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New results on the gravity monitoring (2014–2017) of Soultz-sous-Forêts and Rittershoffen geothermal sites (France)

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Abstract

This article presents the study of the mass redistribution associated with the geothermal energy exploitation of the Soultz-sous-Forêts and Rittershoffen plants by microgravity monitoring in the period 2014–2017. The two plants are located in the eastern part of France in the Rhine Graben. This rift is characterized by thermal anomalies. The Soultz-sous-Forêts enhanced geothermal system is a demonstration site producing 1.7 MWe thanks to three wells 5 km deep. The Rittershoffen geothermal plant is used to produce heat (24 MWth) with two wells of 2 km depth. The most recent production episodes at Soultz-sous-Forets and Rittershoffen began on 24 June 2016 and 19 May 2016, respectively. Each summer, since 2014 for the Soultz-sous-Forêts network and since 2015 for the Rittershoffen network, gravity measurements have been taken with a Scintrex CG5 gravimeter in order to calculate the gravity variation compared to a reference station and a reference time. The stability of the reference station at the Soultz-sous-Forêts plant was investigated by repeated absolute gravity measurements from the FG5#206. Gravity ties with the gravity observatory of Strasbourg were also performed to compensate for the absence of superconducting gravimeter at the in situ reference station. Precise leveling was undertaken simultaneously to each gravity survey showing that vertical ground displacement is lower than 1 cm; hence, this leads us to consider that the detected gravity changes are only due to Newtonian attraction. We do not detect any signal at the Rittershoffen network in the investigated period. After the beginning of production, we noticed a small differential signal at the Soultz-sous-Forêts network, which is spatially associated with the injection and production wells' positions. Furthermore, the maximum gravity value appears in the same area as the induced seismicity related to the preferential paths of the geothermal fluid. However, a simple model based on a geothermal reservoir of cylindrical shape cannot explain the observations in terms of amplitude.

Keywords: Gravity changes, Monitoring, Geothermal energy, Soultz-sous-Forêts, Rittershoffen

Background

The Soultz-sous-Forêts and Rittershoffen geothermal sites are located in the eastern part of France in the Upper Rhine Graben (Meyer and Foulger 2007). At these geothermal plants, temperature anomalies at the top of the basement (see Fig. 1) reach around 85 °C (Baillieux et al. 2014).

The Soultz-sous-Forêts research project started in 1987 to extract geothermal energy from Hot Dry Rocks (HDR). Nevertheless, a large volume of brine was discovered and the Soultz-sous-Forêts geothermal site became the first Enhanced Geothermal System (EGS) demonstration site producing electricity in France (Dezayes et al. 2005). The boost concept of EGS (Lu 2018) consists of extracting heat from HDR volumes even where the permeability is naturally low but improvable by means of hydraulic and/or chemical stimulations. Two or more wells are drilled into the HDR and operate as production and injection wells. Heat is exploited using water as working fluid as follows: the HDR is stimulated to produce fractures by the injected fluids, which run through the permeable pathways made in the rock, collecting heat which is then extracted via production wells.

The wells (see Fig. 2) are aligned in the direction of regional maximum horizontal stress N170°E (Valley and Evans 2007). GPK2 is the injection well and GPK3 is the production well. Note that GPK4 was also used as injection well from the 24th of January to the 30th of June 2017. The well depths are almost 5 km with 500 m long open holes (Genter et al. 2010). A temperature of 165 °C allows producing 1.7 megawatts of electrical output (MWe). The most recent geothermal production began on the 23rd of June 2016 after a period of maintenance.

The ECOGI project takes place in Rittershoffen, 6 km east of Soultz-sous-Forêts (Baujard et al. 2017). This EGS geothermal project was initiated in 2004 with the plant dedicated to an industrial use for heat application. It produces 170 °C hot water and delivers 24 megawatts thermal (MWth) heat power to the “Roquette Frères” bio-refinery, 15 km

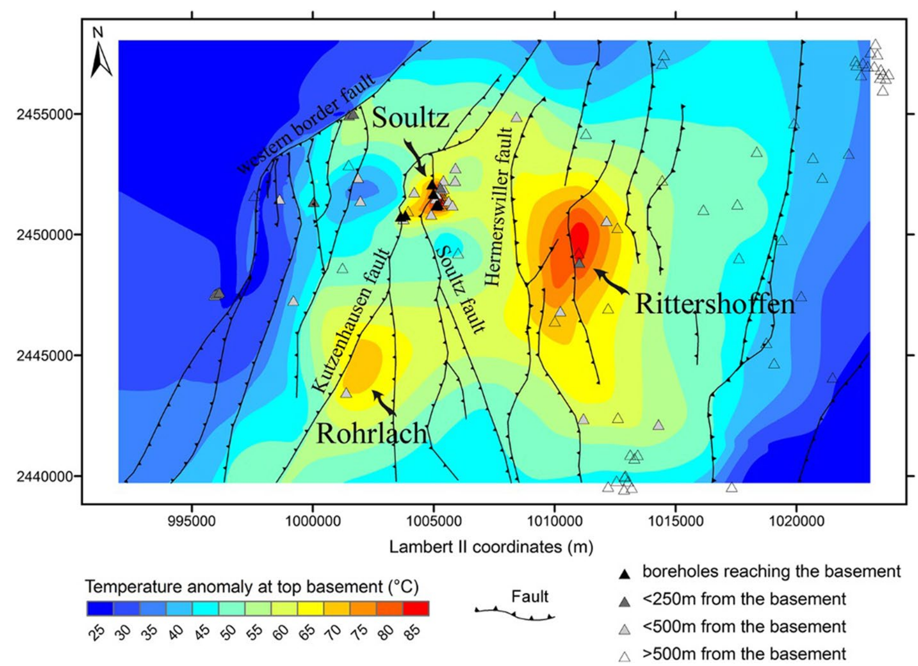


Fig. 1 Temperature anomaly in °C at top basement which is around 1400 m MD (Measured Depth) in Soultz-sous-Forêts and around 2200 m MD in Rittershoffen (Aichholzer et al. 2015). Fault traces with their dip directions and boreholes represented by triangles are also shown (From Baillieux et al. 2014)

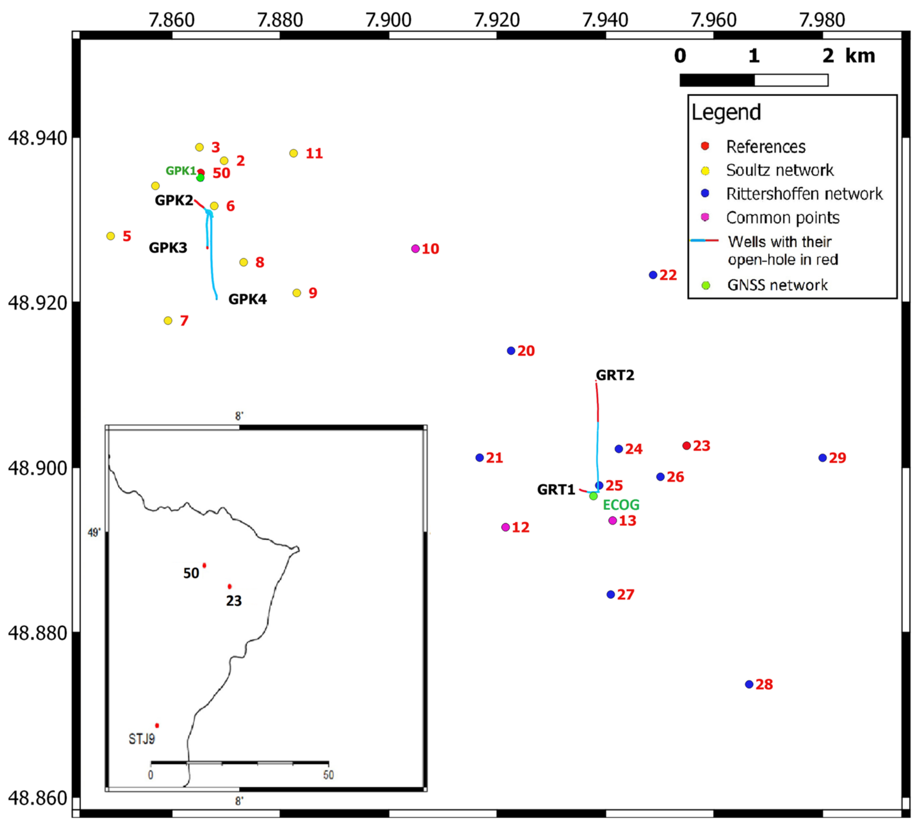


Fig. 2 The Soultz-sous-Forêts (yellow circles) and Rittershoffen (blue circles) gravity networks. The station codes are written in red. In particular, the stations 50 and 23 (red circles) are, respectively, the reference station of the Soultz-sous-Forêts and Rittershoffen networks. The two continuous GNSS stations are indicated in green. The projection of GRT1, GPK3, GPK4 injection wells and GRT2 and GPK2 production wells on the surface is represented by a blue line. The red lines are their open-hole trajectories. STJ9 in the inset indicates the position of the gravity observatory of Strasbourg J9

from the drill site. Around 25% of the industrial heat need is covered. GRT-1 injection well was drilled vertically in December 2012. GRT-2 production well was drilled in July 2014 and is deviated to the North, 1 km away from the first well. The wells (see Fig. 2) are at nearly 2.5 km in depth and cross a regional fault. This N355°E normal fault dips 45° to the west and shows an apparent vertical offset of 200 m. The beginning of the production was the 19th of May 2016.

Long-term microgravity monitoring has demonstrated to be a powerful tool to characterize the geothermal reservoir evolution and evaluate flow redistribution during geothermal energy exploitation (Crossley et al. 2013). To report on some successful applications of such methods, we can mention Allis and Hunt (1986) at Wairakei geothermal field in New Zealand, De Zeeuw-van Dalfsen et al. (2006) at Krafla geothermal plant in Iceland, Sugihara and Ishido (2008) at Okuaizu and Ogiri geothermal plants in Japan, Nishijima et al. (2010) at the Takigami geothermal field in Japan. In France, Hinderer et al. (2015) initiated microgravity monitoring at the Soultz-sous-Forêts geothermal plant in summer 2013 with two additional stations near Rittershoffen. In Hinderer et al. (2015), only the 2014 gravity double differences were computed because of a faulty gravimeter used in 2013. We continue here this previous work which described only the natural state of the geothermal reservoirs without any activity. We developed the network at Rittershoffen geothermal plant by adding eleven stations. Then, yearly repetitions have been performed since 2014 for Soultz-sous-Forêts area and since 2015 for Rittershoffen area including the start of geothermal production in 2016 at both plants. Initial results were shown by Portier et al. (2018) focusing on the stability of the reference station and the estimate of vertical deformation with continuous GNSS. We extend here this study by presenting the full gravity monitoring from 2014 to 2017 for the Soultz-sous-Forêts and Rittershoffen geothermal sites taking into account the vertical deformation by repeated geodetic leveling. We also show that our maps of surface gravity change seem to be related to the induced seismicity. Finally, we make an attempt at modeling to explain the positive change in gravity close to the injection zone by a cylindrical body with a width small compared to depth.

Microgravity monitoring

Time-lapse microgravity method investigates the underground mass redistribution; it can gain insight into the geothermal fluid path and help to evaluate the water storage changes.

Methodology

To cover an approximately 4 km^2 area around the geothermal plants, thirteen gravity stations (see Fig. 2) have been measured each summer since 2014 for the Soultz-sous-Forêts network and since 2015 for the Rittershoffen network (Hinderer et al. 2015). Stations 10, 12 and 13 are common to both networks. Scintrex CG5 gravimeters are used in the surveys; this spring relative gravimeter (RG) has a 5 μGal precision (1 μGal $= 10^{-8}$ m s^{-2}) and a large drift which can reach tens or hundreds of μGal day^{-1}. To correct this instrumental drift, short loops of five stations are operated with measurements beginning and ending at a reference station. The Soultz-sous-Forêts and Rittershoffen reference stations are, respectively, stations 50 and 23. To study the stability of the station 50, absolute measurements are done with an FG5 gravimeter (AG) at least once per year. The precision of this instrument is between one and two μGal. Finally, gravity variations at the reference stations are also assessed through tie measurements with the gravity observatory of Strasbourg J9, where several superconducting gravimeters (SG) operate permanently. The relative SG has a precision better than 0.1 μGal and a small drift of 1 or 2 μGal $year^{-1}$. By combining these three different types of gravimeter (RG, AG and SG), we apply the hybrid gravity concept introduced by Okubo et al. (2002) to our geothermal object (see also Hinderer et al. 2016).

Data processing

Gravity measurements have been done with different Scintrex CG5 gravimeters (#40691, #41224, #41317). These instruments were calibrated using an absolute gravity calibration line and a correction coefficient was applied to the associated data for each instrument.

The impact of ambient temperature was also evaluated. Special attention was given to the loop ranging between the reference stations and the gravity observatory of Strasbourg J9 (see Fig. 2) which is inside a bunker. Fores et al. (2017) have demonstrated that ambient temperature can modify Scintrex CG5 measurements by a factor close to -0.5 μGal/ °C. Indeed, closing a 5 station loop lasts around 2 h. The Scintrex CG5 gravimeter records the relative atmospheric temperature simultaneously to the gravity measurement. The difference of temperature between the measurement at a station and the first measurement at the reference station in a same loop leads to gravity changes ranging between -2 and 2 μGal. Since the accuracy of Scintrex CG5 gravimeter is 5 μGal, we did not take into account the induced variation.

Gravity data are selected and processed with PyGrav Python software (Hector and Hinderer 2016). The instrumental drift is removed and simple differences $dg^{t}_{x-x_0}$ are calculated for each station x (Hinderer et al. 2015) with respect to a reference station x_0 at a time t, which has hence a gravity value set to zero.

$$dg^{t}_{x-x_0} = \left(g_x - g_{x_0}\right)_t \tag{1}$$

Finally, double differences (Hinderer et al. 2015) are obtained by subtracting the simple differences at time t_0 from the one at time t. It represents the gravity variation at station x with respect to a reference station x_0 and a reference time t_0.

$$Dg^{t-t_0}_{x-x_0} = dg^{t}_{x-x_0} - dg^{t_0}_{x-x_0} \tag{2}$$

The error is calculated by taking the square root of the variance sum of each involved measurement.

The observed gravity changes are possibly due to two causes: the Newtonian attraction of the redistributed masses and the vertical deformation in the existing gravity field. Hence, precise leveling surveys were performed to monitor ground displacement.

Vertical deformation control

In principle, vertical ground movements can induce a change of about 2 μGal cm^{-1} in the Bouguer approximation or nearly 3 μGal cm^{-1} using the Free-air gradient. This deformation should be accounted for to understand the mass balance of the geothermal reservoir under production (Hunt et al. 2002). Both leveling and GNSS monitoring show negligible vertical ground deformation. We are unable to discriminate among the possible processes of mass redistribution (with variable mass and/or density) working at depth. Hence, we are forced to assume the most likely process, namely the one working at constant density. As a matter of fact, there is a volume change leading to a vertical deformation produced by any mass variation which keeps constant the density at depth. In view of this process, we consider that the most suitable way to account for the vertical ground deformation is through the Bouguer gradient.

Methodology

Geometric leveling surveys have been performed on the Soultz-sous-Forêts and Rittershoffen gravity stations since 2014 (Ferhat et al. 2017). Five loops were used (see Fig. 3). Each gravimetric site is collocated with a leveling benchmark. In addition to the gravity stations, some benchmarks are included in the national leveling benchmarks installed by the French Mapping Agency (IGN, *Institut National de l'Information Géographique et Forestière*); so the altitudes are defined with respect to the national vertical reference system (NGF-IGN69). To avoid seasonal displacements linked to hydrological loading,

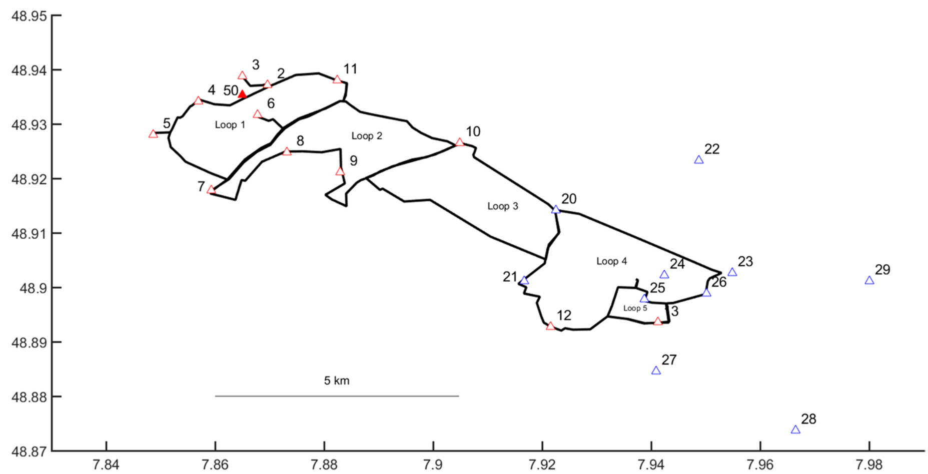


Fig. 3 The five loop map of the Soultz-sous-Forêts leveling network connecting gravity stations (red triangles). In addition, Rittershoffen gravity stations are represented with blue triangles; the elevation of stations which are not included in loops has been monitored by GNSS measurement. The leveling and gravity reference is the station 50 (bold red triangle)

Table 1 Height differences (h) and their errors (σ_h) in mm at gravity stations of Soultz-sous-Forêts network compared to 2014 survey

Station	2015–2014				2017–2014			
	h (mm)	g_h (μGal)	σ_h (mm)	$g_{\sigma h}$ (μGal)	h (mm)	g_h (μGal)	σ_h (mm)	$g_{\sigma h}$ (μGal)
50	0	0	0	0	0	0	0	0
2	1	0	4	− 1	− 1	0	4	− 1
3	NC	NC	NC	NC	− 1	0	6	− 1
4	6	− 1	5	− 1	7	− 1	6	− 1
5	2	0	7	− 1	− 6	1	7	− 1
6	7	− 1	9	− 2	8	− 2	9	− 2
7	− 6	1	8	− 1	− 1	0	8	− 2
8	− 2	0	7	− 1	6	− 1	9	− 2
9	0	0	8	− 2	11	− 2	9	− 2
10	NC	NC	NC	NC	15	− 3	10	− 2
11	1	0	5	− 1	6	− 1	6	− 1

The reference station for each epoch is the station 50. The associated gravity changes (g_h) and ($g_{\sigma h}$) in μGal are also indicated using the 2 μGal cm^{-1} coefficient. Leveling measurement at stations 10 and 3 was not conducted (NC) in 2015

vertical control was done at the same period, i.e., end of May. The reference station is the same as the one of Soultz-sous-Forêts gravity monitoring (station 50). In 2014, double leveling was performed involving two foresights and two backsights measurements but it was time-consuming. Since 2015, surveyors have applied only single-leveling. The LEICA DNA03 digital level and a leveling rod were used to obtain a precision of a few millimeters. Some sections were also observed using invar staff and Trimble DiNi 02 digital level. The mean range of the measurements is about 30 m.

Soultz-sous-Forêts elevation changes

The maximum vertical deformation in 2015 compared to 2014 survey at station 50 is equal to 7 mm which leads to a gravity change of − 1.4 μGal (see Table 1). This

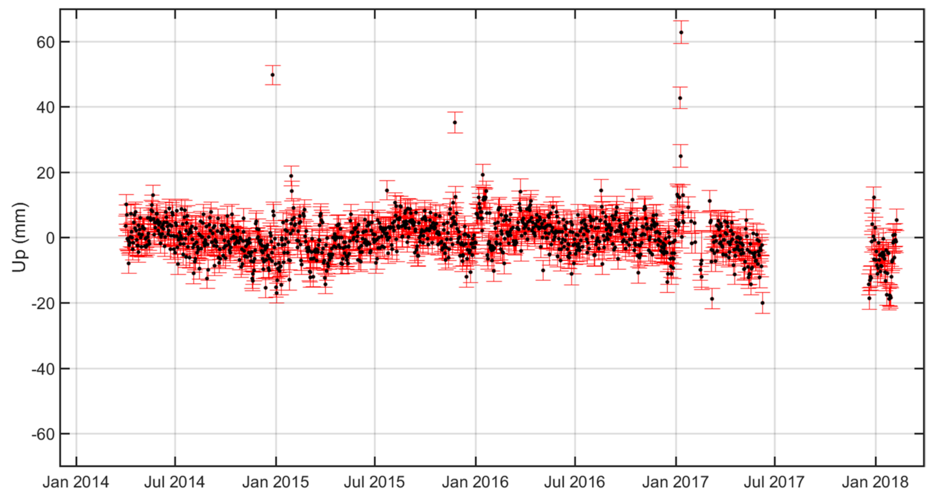


Fig. 4 Time series of GPK1 permanent GNSS vertical positions. Standard deviations vary between 5 and 10 mm (From RéNaSS 2018)

height-induced gravity change is negligible as the Scintrex CG5 precision is around 5 μGal. In the same way, the ground displacement in 2017 compared to 2014 ranges between −5 and 15 mm which represent, respectively, 1 and −3 μGal. We notice that the largest deformation of 15 mm measured at the station 10 is associated with the largest error of 10 mm: this station is the farthest away from the reference station.

The stability of the leveling reference station 50 is monitored with a permanent GNSS station called GPK1 (RéNaSS 2018). This station is equipped with a TRIMBLE NETR9 receiver and TRIMBLE Zephyr antenna. GNSS data were processed using SCRS-PPP software. Figure 4 shows the vertical displacement in mm at the leveling reference station 50 from 2014 to the beginning of 2018. The mean vertical precision is 7 mm. The observed seasonal effect is minimized by performing leveling campaign at the same period of the year. We notice that the calculated positions in 2015 and 2017 compared to 2014 during the leveling survey are, respectively, equal to −5 and 0 mm with an error ranging between 5 and 10 mm. Hence, we consider the reference leveling station as stable.

Is there any link between the observed gravity and height changes? We argue that there is none since the leveling measurements are not correlated to the gravity measurements (see Fig. 5). Indeed, if we consider gravity changes at the closest date of the leveling survey, we find a coefficient of determination $R^2 = 0.01$ indicating no correlation. Its value is the same if we distinguish between data obtained in 2015 and those in 2017 (values measured at the stations 12 and 13 are not presented in this study because they are closer to the Rittershoffen network and hence too far away from the reference).

Rittershoffen elevation changes

As quoted before, Rittershoffen stations are quite far away from the leveling reference station. This leads to high errors around 1 cm in height. We do not show the results of leveling for the Rittershoffen network but rather exclusively use the continuous GNSS data collected at ECOG (RéNaSS 2018). As for the GPK1 station, measurements are

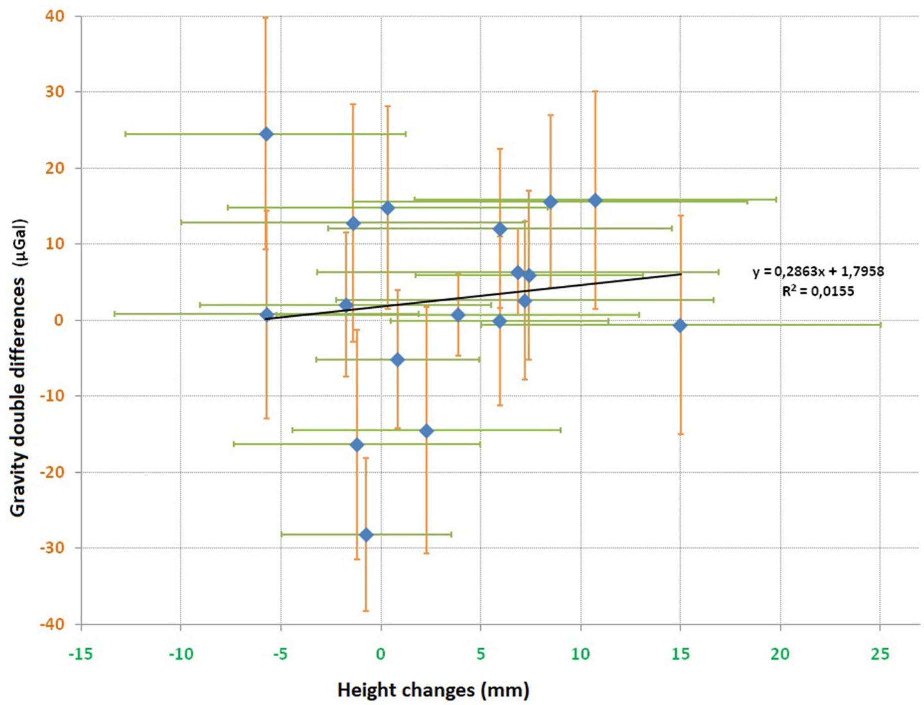


Fig. 5 Gravity double differences (in µGal) as a function of height changes (in mm) in 2015 and 2017 compared to 2014 with their errors. The coefficient of determination is equal to 0.0155

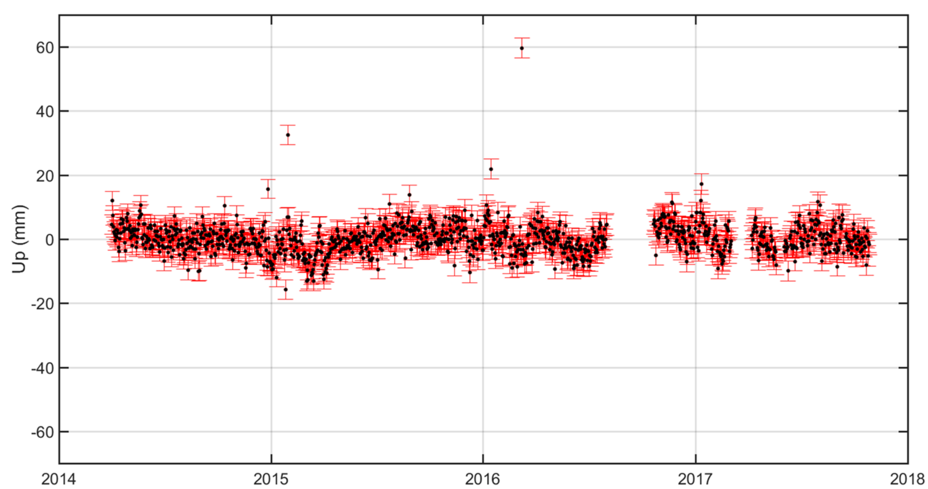


Fig. 6 Time series of ECOG permanent GNSS vertical positions. Standard deviations vary between 5 and 10 mm (From RéNaSS 2018)

collected on the Rittershoffen geothermal plant with a TRIMBLE NETR9 receiver and TRIMBLE Zephyr antenna. GNSS data are processed with SCRS-PPP. The accuracy of the height changes retrieved from the GPS data varies between 5 and 10 mm. The GPS height changes (see Fig. 6) measured on the 15th of July 2015, 2016 and 2017 compared

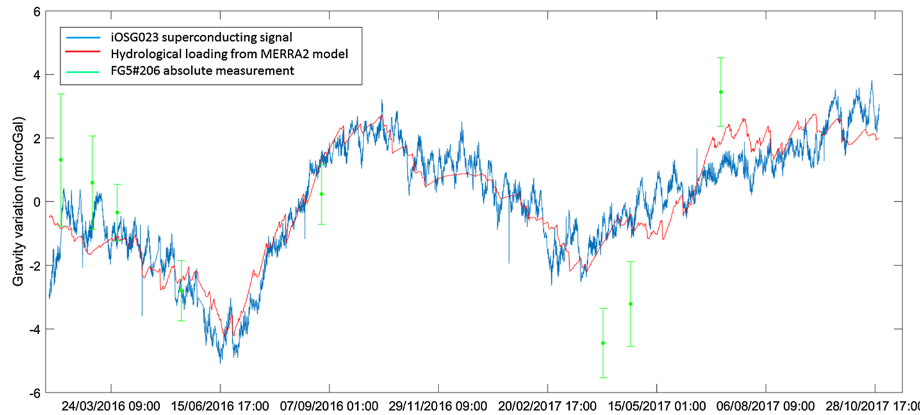


Fig. 7 Gravity variation measured at the observatory of Strasbourg J9 in μGal by iOSG023 superconducting gravimeter (blue curve). This signal is corrected for the effect of solid Earth and ocean loading tide, atmospheric pressure, polar motion and instrumental drift. It is linked to the hydrological loading (red curve) obtained with MERRA2 model (Boy 2018). FG5#206 absolute measurements and their errors corrected for the effect of solid Earth and ocean loading tide, atmospheric pressure, polar motion are represented in green

to the 15th July of 2014 are, respectively, 0, −5 and −2 mm, which correspond to equivalent gravity changes lower than 1 μGal.

Thus, leveling monitoring at the Soultz-sous-Forêts network shows vertical deformation lower than 1 cm. We observe a higher value at the station 10; nevertheless, the associated error is the highest measured value which could be explained by the long distance to the reference station. Continuous GNSS measurements have proven the stability of the reference station 50 and the ECOG Rittershoffen station. So, we conclude that the observed double differences in gravity must be mostly caused by mass changes (i.e., effect of Newtonian attraction).

Results

Reference station stability

Before the beginning of the production, FG5#206 absolute measurements at the reference station 50 revealed gravity variations ranging between −2 and 2 μGal. After the beginning of the production, in parallel to absolute measurements, we have studied the gravity variation of the reference stations 23 and 50 with respect to the gravity observatory of Strasbourg J9. Several superconducting gravimeters operate permanently there, especially the new-generation iOSG23, installed in January 2016.

Superconducting gravity data are processed with T-Soft software (Van Camp and Vauterin 2005). The effects of solid Earth and ocean loading tides, atmospheric pressure and polar motion are removed from the gravity signal; spikes are also deleted before modeling the instrumental drift. To better separate instrumental drift from real gravity changes, we superimpose eight absolute measurements to the obtained signal (see Fig. 7). These FG5 data are corrected for the effect of earth and ocean tides, air pressure and polar motion similarly to the SG data. We suppose that data do not superimpose perfectly because the investigated superconducting gravimeter time series is too short to evaluate correctly the instrumental drift. Furthermore, we think that the absolute measurement error is underestimated. We notice that the residual superconducting signal

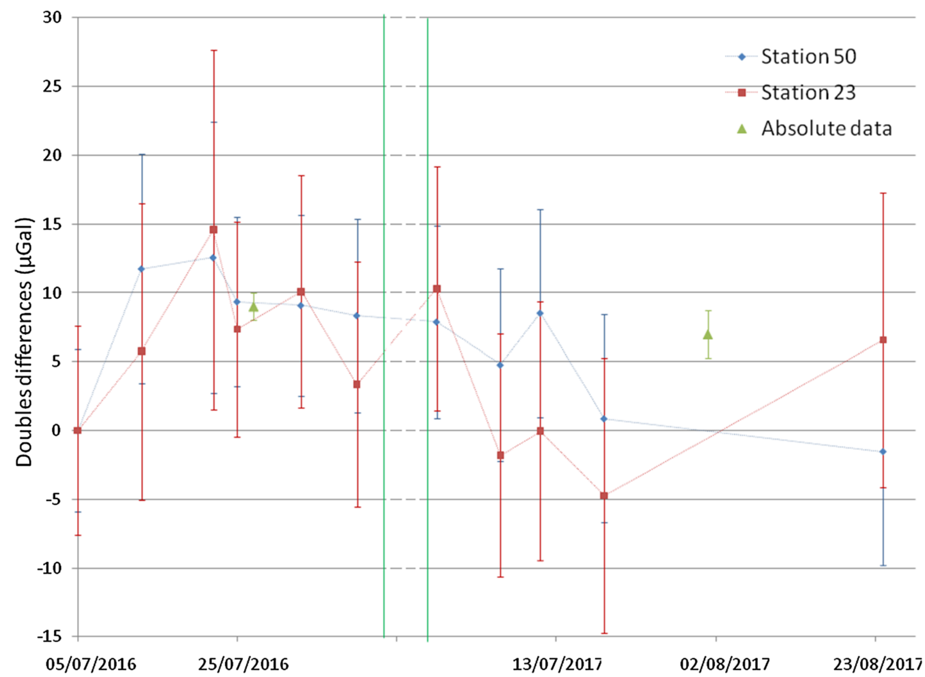


Fig. 8 Gravity double differences and their errors at the reference stations 23 and 50 compared to the observatory of Strasbourg (STJ9) taking the 5th of July 2016 as temporal reference. Two absolute measurements are also displayed with their errors; absolute measurements are corrected for the effect of solid Earth and ocean loading tide, atmospheric pressure, polar motion

coincides well with the effect of the hydrological loading calculated by MERRA2 global hydrology model (Boy 2018). This model has a spatial and temporal resolution of 0.625° in latitude and longitude and 1 h, respectively.

Finally, by taking into account the gravity variation at the STJ9 reference station (see Fig. 2), we obtain the double differences shown in the Fig. 8. We notice a gravity increase in 2016 of around 15 µGal and then, in 2017, a decrease which leads to null gravity change for the station 50 and −5 µGal for the station 23 before an increase of 10 µGal. The mean error is 7 µGal for the station 50 and 9 µGal for the station 23.

Double differences

Rittershoffen network

The Rittershoffen interference tests were performed in May 2016 between GRT1 and GRT2 wells. Then, the production began on the 20th of May 2016. A geothermal fluid of around 80 °C was injected in GRT1 injection well to produce around 170 °C water in GRT2 well. The mean flow rate for the two wells was approximately 110 $m^3 h^{-1}$.

The reference station is here station 23. We choose the third survey of 2015 as temporal reference because of its low error. The Rittershoffen double differences are presented on Fig. 9. In 2015, some double differences (see Eq. 2) exceed the 95% confidence interval: nevertheless, these changes are not linked to the geothermal energy exploitation. After the beginning of the production, we notice a negative change of 20 ± 4 µGal at the station 26 and a positive change of 21 ± 11 µGal at the station 29 in 2016. In 2017, no

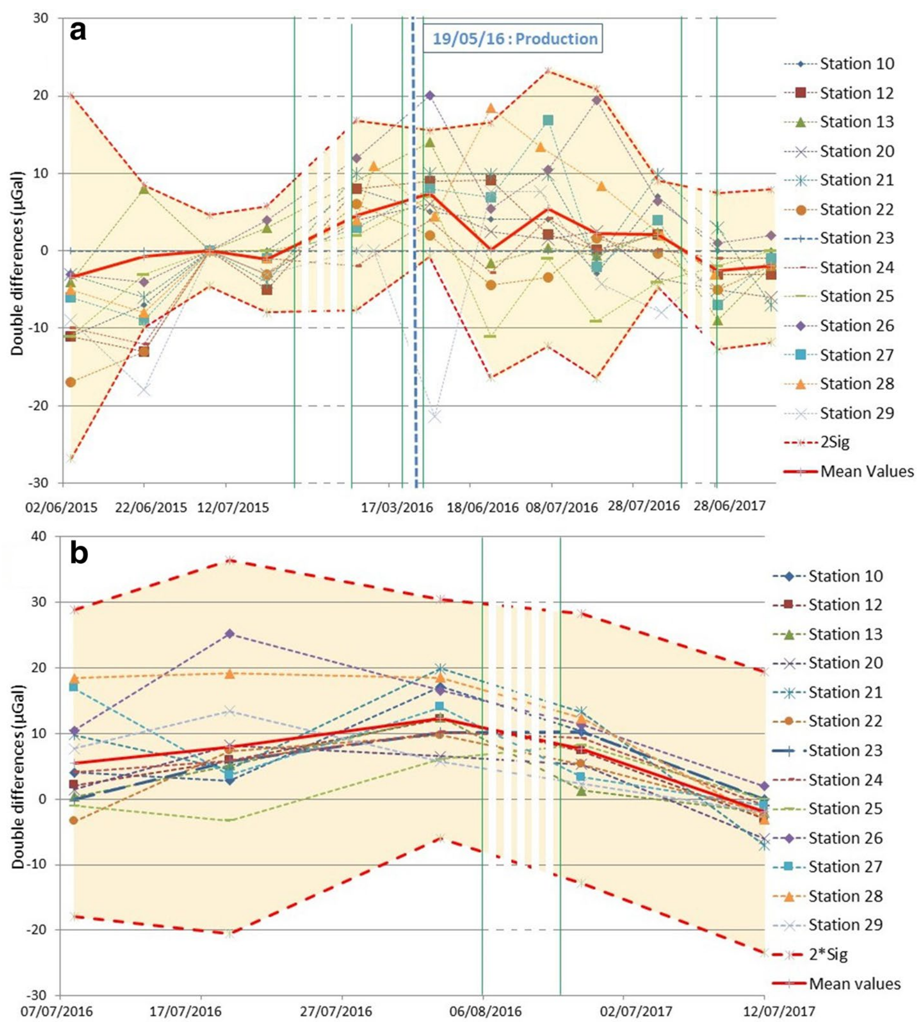


Fig. 9 Rittershoffen gravity double differences in µGal. 95% confidence interval is highlighted in yellow and is centered on the mean survey value (red line). **a** We do not consider the gravity changes at the reference station 23 (blue dotted line); **b** accounting for it

double differences exceed the 95% confidence interval. If we consider the gravity variation of the reference station 23, no signal is detected.

Soultz-sous-Forêts network

The Soultz-sous-Forêts interference tests were carried out in May 2016 between the GPK2 injection well and the GPK3 and GPK4 production wells. The production began on the 24th of June 2016. So, GPK2 is the injection well and GPK3 the production well. From the 24th of January to the 30th of June 2017, injection was also done into GPK4 well. The injected flow rate was equal to the produced flow rate which is around 100 $m^3\ h^{-1}$. The injected and produced geothermal fluids have, respectively, a temperature of around 80 °C and 165 °C. When two production wells have been used, the GPK4 flow rate was ranging between 29 and 43 $m^3\ h^{-1}$ and the GPK3 one was ranging between 57 and 73 $m^3\ h^{-1}$.

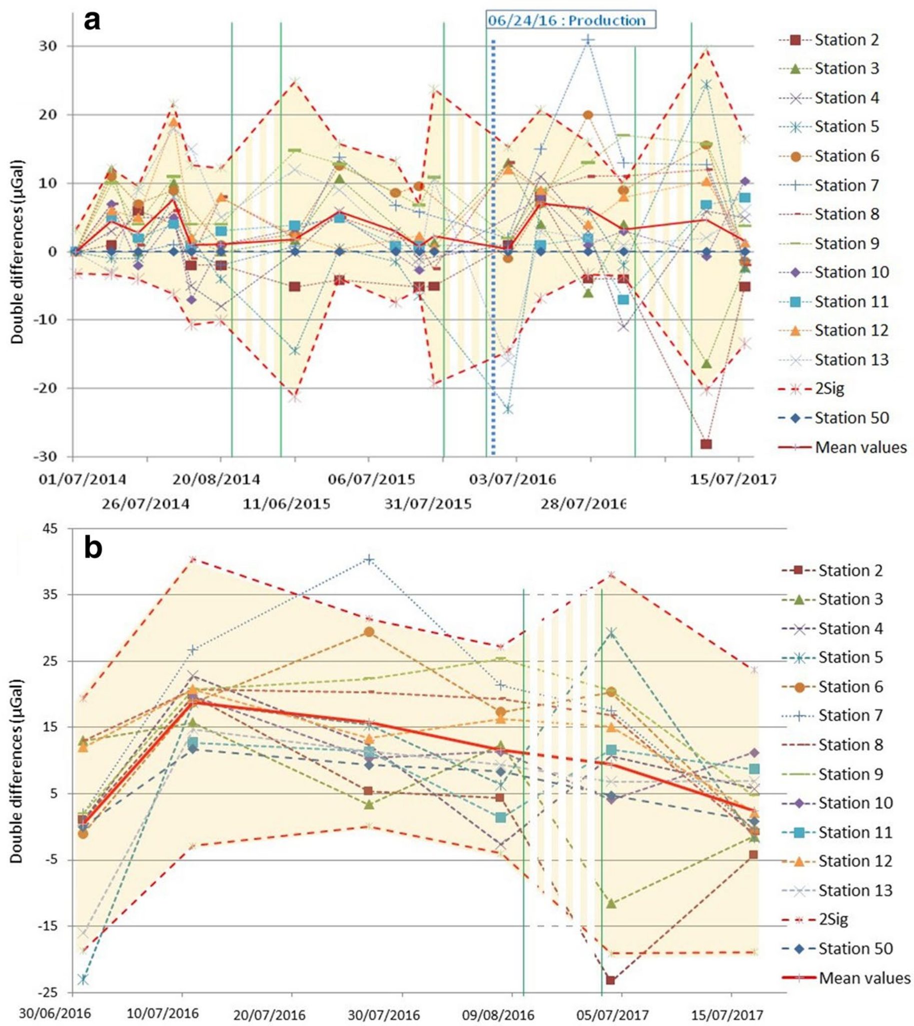


Fig. 10 Soultz-sous-Forêts gravity double differences in µGal. 95% confidence interval is highlighted in yellow and is centered on the mean survey value (red line). **a** We do not consider the gravity changes at the reference station 50 (blue dotted line); **b** accounting for it

The gravity reference station is the station 50 and the temporal reference is the first survey in 2014. The Soultz-sous-Forêts double differences (see Eq. 2) are presented in Fig. 10. We do not notice any significant value before the production starts; no double differences exceed the 95% confidence interval. After the beginning of the production, if we do not consider the gravity variation measured at the reference station, positive changes are observed at the stations 7, 6 and 9 near the injection area. The maximum value of 31 ± 6 µGal is recorded at the station 7. Negative changes are obtained at the stations 5, 3, 4 and 11 in 2016 and at the station 2 in 2017 in the north part of the studied area. The minimal value of -28 ± 10 µGal is measured at the station 2. When we take into account the stability of the reference station, the survey errors increase. Nevertheless, the maximum values recorded at the station 7 and 2 are still significant.

Discussion

Spatial distribution of the gravity changes

We study the spatial distribution of the gravity double differences before and after the start of the production. For a better understanding of the interplaying processes, gravity measurements have been interpolated by a kriging method and superimposed to the recorded induced seismicity cumulated over 2017 (see Fig. 11b). The induced seismicity informs us about the opening of new cracks and fractures as well as on the preferential pathway of the geothermal fluids. The 2017 interpolated gravity value does not take into account the gravity variation of the reference stations since it would only lead to an offset.

For the Rittershoffen network, we do not notice any coherent signal. The seismicity is mainly concentrated around the GRT1 injection well (Maurer et al. 2017) but it is not associated with any significant positive gravity changes after the beginning of the production.

In Soultz-sous-Forêts, a spatial coherence appears after the beginning of the production (see Fig. 12): the injection area around GPK3 and GPK4 wells is associated with the highest gravity value and the production area near GPK2 well is linked to lower gravity values compared to the reference station 50. Despite stations 7, 8 and 9 are equidistant from the injection wells open holes, the gravity value at the station 7 is higher. This is in agreement with the location of the seismicity epicenters (Maurer et al. 2017) leading us to hypothesize a possible influence from the fracking on the fluid circulation. It seems that after injection geothermal fluids circulate preferentially westwards.

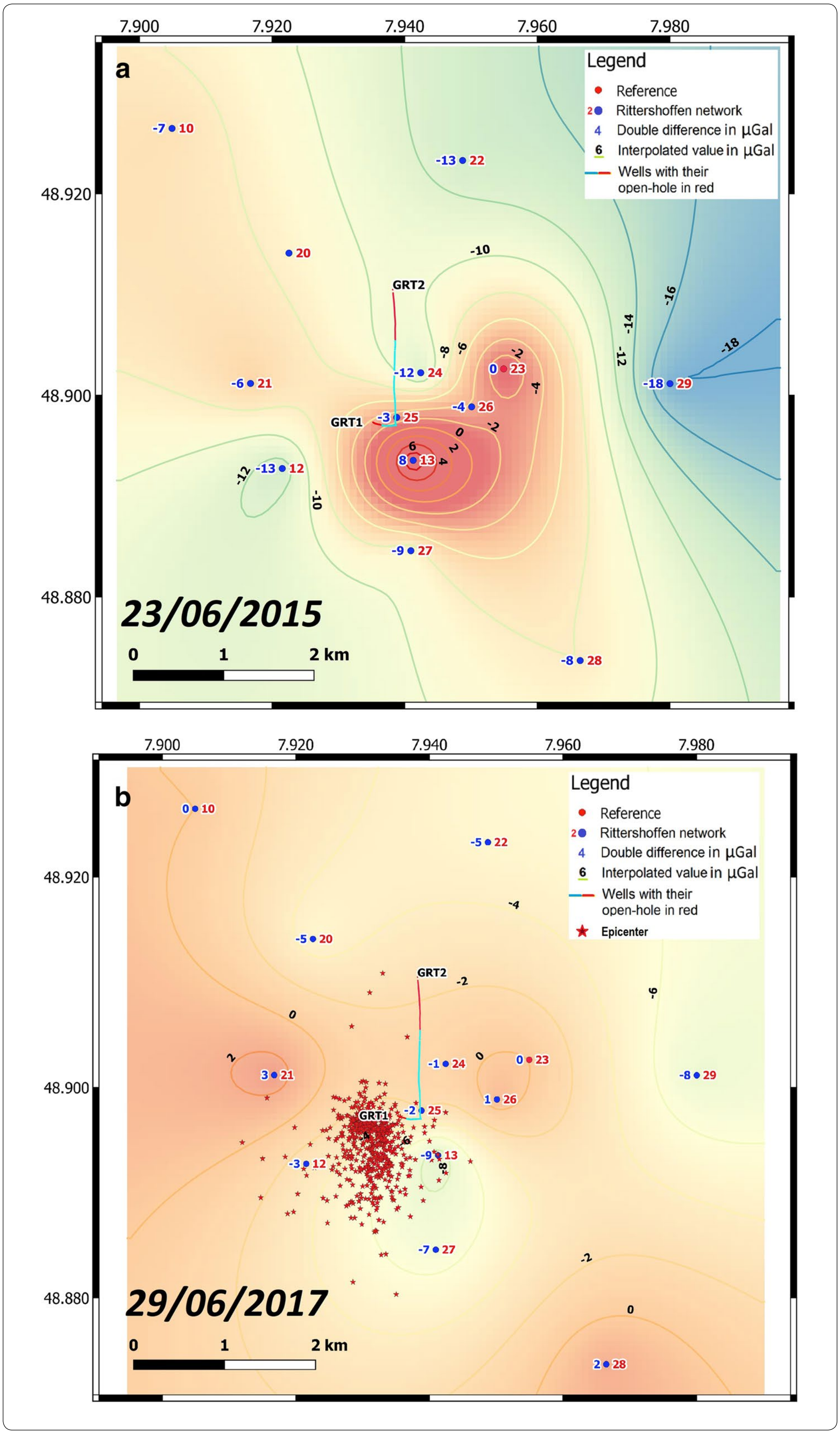
A tentative simplistic model

We do not have any realistic model of mass flow changes available for our study so far. This is why we propose here a rather simple model of Newtonian attraction to explain the largest surface gravity change observed on July 27th, 2016 at the station 7 belonging to Soultz-sous-Forêts network (see Fig. 10). Rather than considering a simple Mogi spherical source, we model a cylindrical body with a radius r and a height h with the top face located at a depth z under the observation point (station 7). Indeed, a cylindrical source could be a more realistic geometry for an open-hole injected fluid into a fractured volume. In this case, the resulting gravity variation g_{cyl} (Kara and Kanli 2005) induced by a cylinder of density ρ at ground level above the centre of cylinder is

$$g_{cyl} = \pi r^2 G \rho \left[\frac{1}{z} - \frac{1}{z+h} \right] \quad (3)$$

(See figure on next page.)

Fig. 11 Rittershoffen maps of interpolated gravity double differences in µGal measured on the 23rd of June 2015 (**a**) and on the 29th of June 2017 (**b**) before and after the beginning of the production, respectively. The geothermal energy exploitation has begun on the 19th of May 2016. The same interpolation color scale is used for the two maps. The station codes are indicated in red and the double differences in blue. On the 23rd of June 2015, no observation was done at station 20. The isolines values are written in black. Well trajectories are represented in blue with their open-hole in red: GRT1 well is the injection well and GRT2 well is used for the production. We superimposed also the cumulated induced seismicity epicenters from January to July 2017 on the second map. They are concentrated near the injection well


a
23/06/2015
Legend
Reference
Rittershoffen network
Double difference in µGal
Interpolated value in µGal
Wells with their open-hole in red
GRT1
GRT2
0 1 2 km
b
29/06/2017
Epicenter

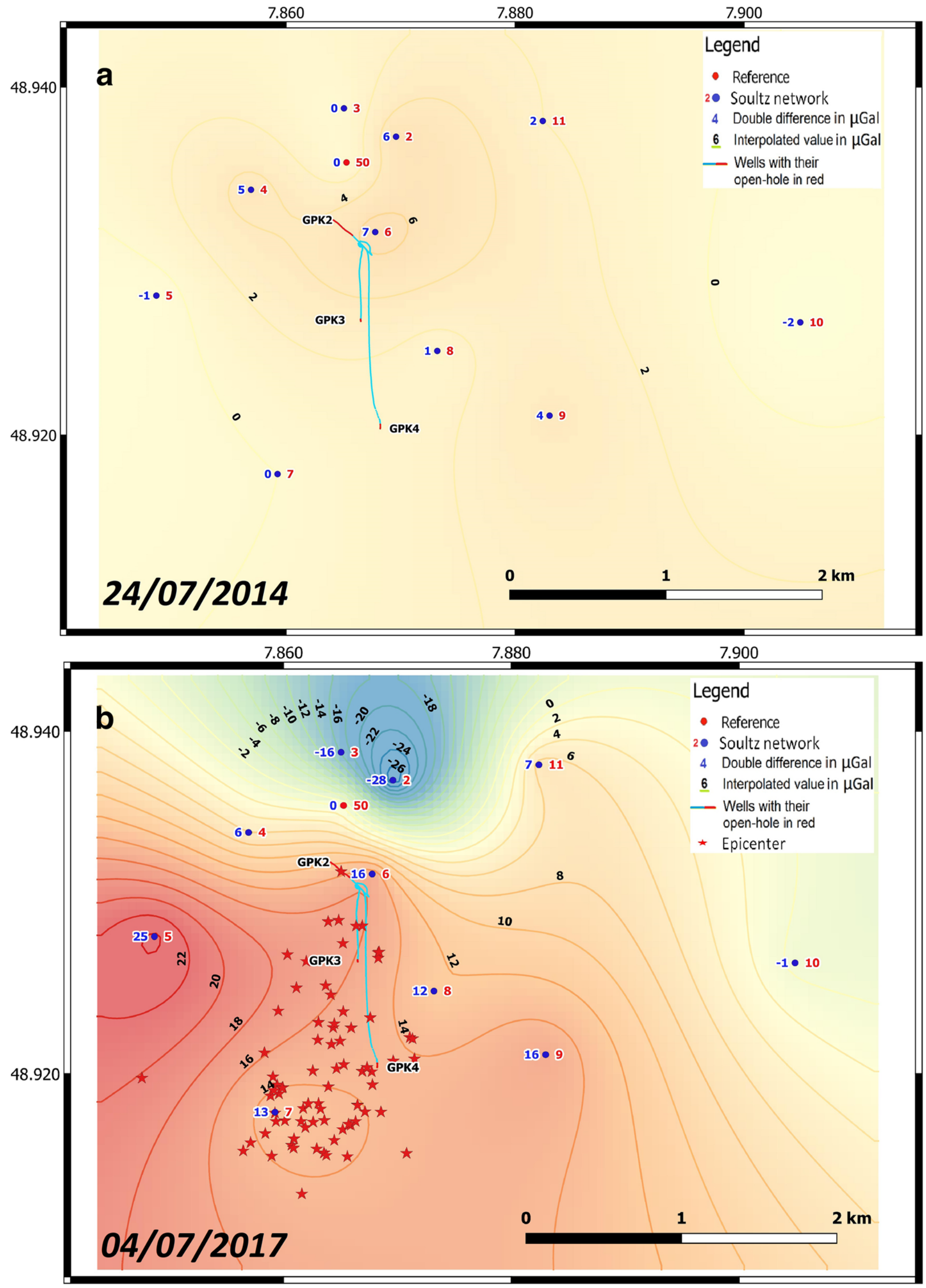


Fig. 12 Soultz-sous-Forêts maps of interpolated gravity double difference in µGal measured the 24th of July 2014 (**a**) and the 4th of July 2017 (**b**) before and after the beginning of the production, respectively. The geothermal energy exploitation began on the 24th of June 2016. The same interpolation color scale is used for the two maps. The station codes are indicated in red and the double differences in blue. The isolines values are written in black. The wells are represented in blue with their open-hole in red: GPK3 and GPK4 wells are the injection wells and GPK2 well is used for the production. We superimposed also the 2017 cumulated induced seismicity epicenters on the second map

assuming that $h \ll z$ and where G is the gravitational constant equal to 6.67×10^{-11} m^3 kg^{-1} s^{-2}. Taking into account a geothermal fluid density of 1060 kg m^{-3} (Baujard and Bruel 2006), to induce a gravity effect measurable of 30 μGal (like the one of the 27th of July 2016 at the station 7), we would need to inject:

- A mass of 112.5 MT at 5 km depth. This mass corresponds to a geothermal fluid included in a cylinder with 10 m height and 1838 m radius. If we consider an injection flow rate of 100 m^3 h^{-1}, this volume would be reached after 121 years.
- A mass of 84 kT at 137 meters depth in a cylinder of 50 m radius and 10 m height. It corresponds to 33 injection days with a 100 m^3 h^{-1} flow rate.

In the first case, we respect the injection depth (5 km) considering tube wells. It leads to an unreasonably long period of injection. In the second case (137 m), we respect the injected volume as the production has begun on the 24th of June 2016 and the gravity change was measured on the 27th of July 2016, but the cylinder depth linked to geothermal activity is unrealistic because the rather superficial depth is impossible in the context of the tube well. Furthermore, the lowest depth of the Soultz-sous-Forêts induced seismicity is around 3 km and it is reached by only a few events.

Moreover, four points have to be considered in addition:

1. The open-hole part of the injection wells is not under the station 7 (about 1 km to the north-east). Since the surface gravity due to a buried cylinder decreases away from its centre, we would even need a larger injected volume than computed previously at 5 km depth to explain the 30 μGal changes. The second option where we locate the real injected volume at 137 m would lead to a negligible gravity change at station 7.
2. We extract the same volume than the injected volume once the geothermal loop is established. Our model explaining the increase of 30 μGal at station 7 by a single cylinder does not take into account the effect of a second cylinder with a mass deficit linked to the extraction close to station 2 (see Fig. 12). This would also lead to smaller changes at station 7 when adding the effects of both cylinders.
3. If the water volume is located in a porous medium, the size of the cylinder radius would be larger and be able to modify the shape of the surface gravity anomaly but not its maximum amplitude at the center.

Indeed, we have studied the influence of the cylinder radius on gravity double differences above the cylinder centre in the two mentioned cases, i.e., the first one considering the real injection depth of Soultz-sous-Forêts geothermal plant and the second one considering the cumulated injected volume on the 27th of July 2016. Hence, we defined two models which lead to a 30 μGal gravity change like the one measured at the station 7. We considered the density fixed (1060 kg/m^3).

In the case of a 5000 m depth of the cylinder, the model requires an injected mass of 112.5 MT which leads to a volume of 1.06×10^8 m^3. We have studied the impact of the radius length r. Assuming that $h \ll z$, we choose to work with a maximum height of 50 m ($=z/100$) obtained for a radius of 822 m. As shown by Fig. 13, the height of the cylinder h decreases in conjunction with the increase of the radius when considering a

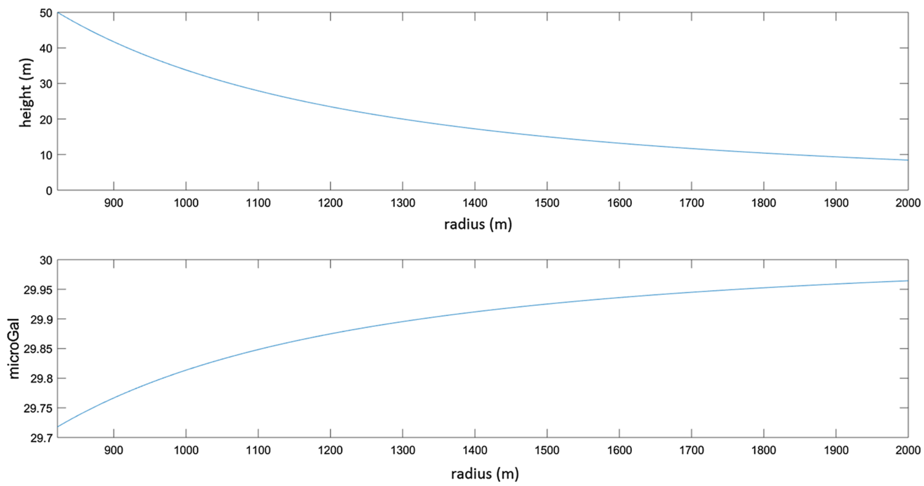


Fig. 13 Height of the cylinder (top) and gravity value at the ground level above the centre of the cylinder (bottom) compared to the radius of the cylinder. A mass of 112.5 MT with a density of 1060 kg m^{-3} is injected at 5 km in depth

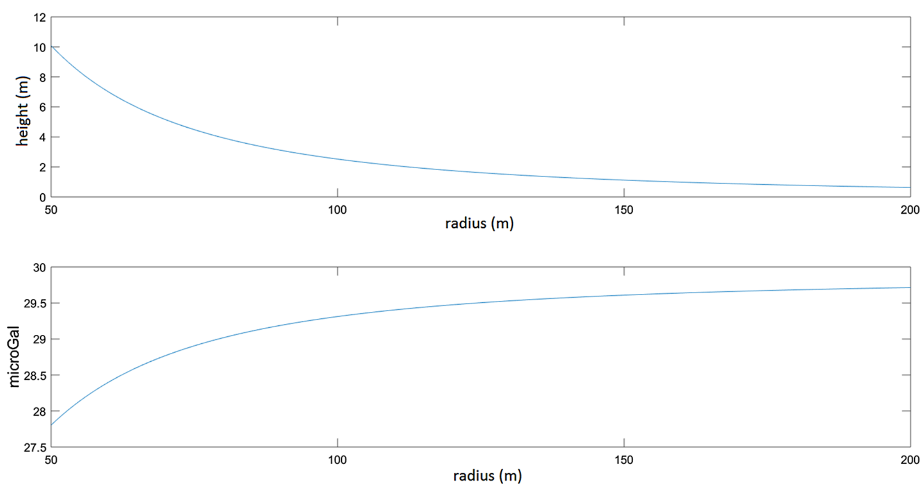


Fig. 14 Height of the cylinder (top) and gravity value at the ground level above the centre of the cylinder (bottom) compared to the cylinder radius. A mass of 84 kT with a density of 1060 kg m^{-3} is injected at 137 m in depth

fixed volume. Moreover, the radius does not impact significantly the gravity above the cylinder centre.

The real injected mass is 84 kT which corresponds to a volume of 7.9×10^4 m^3 and the model requires to locate this mass at 137 m. We choose to work with a radius of 50 m and a height of 10 m. As shown by Fig. 14, the height of the cylinder decreases with increasing radius and the gravity only slightly increases. Once again, the radius does not impact significantly the gravity above the cylinder centre.

Table 2 Values of the radius (in m), the volume (in m^3) and the mass (in MT) of the cylinder for a geothermal fluid of 80 °C (sub-case 1) and 160 °C (sub-case 2)

	Sub-case 1: geothermal fluid of 80 °C	Sub-case 2: geothermal fluid of 160 °C
Density	1033 kg/m^3	969 kg/m^3
Radius of the cylinder	1863.27 m	1923.82 m
Volume of the cylinder	1.09069×10^8 m^3	1.16273×10^8 m^3
Depth of the cylinder	5000 m	5000 m
Mass	112.6 MT	

We consider the real injection depth of 5000 m

Table 3 Values of the radius (in m), the volume (in m^3) and the mass (in kT) of the cylinder for a geothermal fluid of 80 °C (sub-case 1) and 160 °C (sub-case 2)

	Sub-case 1: fluid keeps its initial temperature of 80 °C	Sub-case 2: fluid warms up until the produced temperature of 160 °C
Density	1033 kg/m^3	969 kg/m^3
Radius of the cylinder	50.2 m	51.8 m
Volume of the cylinder	79,200 m^3	84,431 m^3
Depth of the cylinder	135 m	135 m
Mass	82 kT	

We consider the real injected mass

4. We do not consider the density variation with the temperature. While a density of 1060 kg m^{-3} is measured at 20 °C (Baujard and Bruel 2006), the injected and produced fluids have a temperature of 80 °C and 165 °C, respectively.

We define the boundary limits of our models taking into account the density changes. We have studied two sub-cases for the two previous cases considering the real injection depth and the real injected volume. We impose in one sub-case a density value of 969 kg m^{-3} (160 °C) and in the second one a density value of 1033 kg m^{-3} (80 °C). We assume that the mass is conserved leading to a change in volume (elastic medium). However, we do not consider the effect of the pressure. We fix the height of the cylinder at 10 m. The volume changes of the cylinder due to the temperature-induced density changes are shown in Table 2 for the real depth case and in Table 3 for the real injected mass case.

The discussion of the four points above shows that it is not possible with our simple cylindrical model to explain a 30 μGal gravity change close to the injection zone in Soultz-sous-Forêts. Other prismatic bodies with possible large dip angles (faults, fractures) would be more realistic but are beyond the scope of our study.

Conclusion

Microgravity monitoring has been performed at the Soultz-sous-Forêts and Rittershoffen geothermal sites. Two relative gravity network of thirteen gravity stations each have been established and repeatedly measured each summer since 2014 for the Soultz-sous-Forêts network and since 2015 for the Rittershoffen network. The networks have been measured with a Scintrex CG5 gravimeter. The stability of the reference stations of both networks was studied thanks to FG5#206 absolute measurements but also thanks to tie measurements with respect to the gravity observatory of Strasbourg J9, where gravity variations are continuously recorded by a new-generation iOSG023 superconducting gravimeter. Precise leveling monitoring showed that vertical deformation is negligible (lower than 1 cm). Furthermore, we checked that the vertical deformation appears to be unrelated to gravity changes recorded at the Soultz-sous-Forêts network. This means that gravity double differences are only caused by the Newtonian attraction due to the geothermal fluid redistribution at depth. On the Rittershoffen network, we do not detect any signal after the beginning of the production of the plant. On the contrary, a differential signal appears on the Soultz-sous-Forêts network with higher double differences gravity values measured near the injection area and lower values near the production area. Moreover, this observation is coherent with the location of induced seismicity epicenters, which should be related to the preferential path of the geothermal fluids. Nevertheless, a simple model using a cylindrical shape for the geothermal reservoir cannot explain this result. Despite the small signals (or lack of signals) we observed here in this study, we still believe that gravity monitoring is a powerful method to estimate the mass balance during long-term geothermal energy exploitation, especially for large production geothermal plants like the ones in Iceland or Indonesia.

Authors' contributions

JH, UR, MC, YA and NP have acquired, processed and interpreted gravity data. GF has acquired, processed and interpreted precise leveling data. J-DB has acquired and processed FG5#206 absolute measurements. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The datasets supporting the conclusions of this article are available on:
http://cdg.u-strasbg.fr/PortailEOST/Gravi/v1/ (superconducting data).
https://eost.unistra.fr/observatoires/geodesie-et-gravimetrie/renag-eost/gotherm/ (GNSS data).
http://loading.u-strasbg.fr/surface_gravity.php (hydrological loading).

We do not share gravity measurements, leveling data and induced seismicity epicenters; the authors signed a confidentiality agreement with ES-G (Electricité de Strasbourg-Géothermie).

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