Three years of monitoring using leveling and hybrid gravimetry applied to geothermal sites of Soultz-sous-Forêts and Rittershoffen, Rhine Graben, France

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Abstract

Here we report on some case histories of geodetic and gravity surveys for monitoring of geothermal sites. The monitoring of a geothermal reservoir by hybrid gravimetry combining different types of instruments (permanent superconducting gravimeter, absolute ballistic gravimeter and micro-gravimeters) is presented. A relative gravimetric network equipped with levelling benchmarks was designed and surveyed at annual frequencies (2013, 2014, 2015 and 2016 for gravity measurements, 2014, 2015 and 2016 for the leveling). Repetition of high precision relative gravity measurements on a network developed around a reference station, which is regularly measured with both relative and absolute gravimeters, leads to the knowledge of the time and space changes in surface gravity. The observed gravity changes can be linked to the natural or anthropic activities of the reservoir. A feasibility study using this methodology is applied to two geothermal sites of Soultz-sous-Forêts and Rittershoffen in the Alsace region (France) in the Rhine graben (Hinderer et al. 2015).

Key words: leveling, hybrid gravimetry, geothermy, deformation monitoring

1 INTRODUCTION

Time-lapse gravimetry can be a monitoring tool of any underground or surface mass redistribution and has many applications in volcanology (magmatic chamber evolution), hydrology (water storage changes in the critical zone), and geothermics.

The surface at a geothermal site can be monitored by different techniques, i.e. GPS/GNSS, InSAR, leveling to name only a few. To get in-deep monitoring, repetitions of gravimetric measures can be performed.

Several studies have introduced the concept of hybrid (resp. super-hybrid) gravimetry (Okubo et al. 2002; Sugihara and Ishido 2008; Hector et al. 2015) that is the optimal combination of two (resp. three) types of gravimeters (absolute AG, superconducting SG or relative gravimeters RG). By using different types of gravimeters, we take advantage of each instrument: i.e. transportable for a RG and precise and absolute measurement for an AG (see Table 1 of Hinderer et al. 2015).

This paper reports an on-going experiment of monitoring using hybrid gravimetry (SG+RG) and leveling at two geothermal sites in the Rhine graben, France.

2 DEEP GEOTHERMAL EXPLOITATION SITES IN THE NORTH EAST OF FRANCE

Deep geothermal energy exploitation was defined by the French "*Grenelle de l'Environnement*" (Large Debate on the Environnement- @Grenelle-group4) as a crucial task for the development of renewable energy in France. Geothermics are well developed in many countries such as United States, Philippines, Indonesia for the first three leaders, but also in Europe: Italy and France to name only a few of them. A thermal anomaly is present in the Rhine Graben (NE of France, Figure 1) and has been exploited.

Since more than 20 years, scientists and engineers worked at the site of Soultz-sous-Forêts, France (denoted Soultz afterwards for simplicity), in Northern Alsace (60 km of Strasbourg, Figures 1, 2 and 3) in order to improve our knowledge in deep geothermal and to develop practical experiences in exploitation of natural heat (http://labex-geothermie.unistra.fr/).
Next to the site of Soultz site, a new geothermal exploitation facility has been built in 2012 at Rittershoffen at a few kilometres of Soultz (Figures 1, 2 and 3). The site is also called ECOGI (Figure 2). The objective consist in retrieving 24 MW of thermal energy from the heat of the geothermal fluid which is freely circulating in the fractured layers of the Rhine Graben (http://labex-geothermie.unistra.fr/). At ECOGI, the first well was drilled in 2012 as a vertical well reaching the depth of 2600 m. The second well is a deviated one, drilled between March and July 2014.

Many projects associated to these two sites has been launched. In 2013, several geological and structural studies, observations of surface deformation, gravimetric and magneto-telluric surveys, installation of seismological stations has been performed (http://labex-geothermie.unistra.fr/).

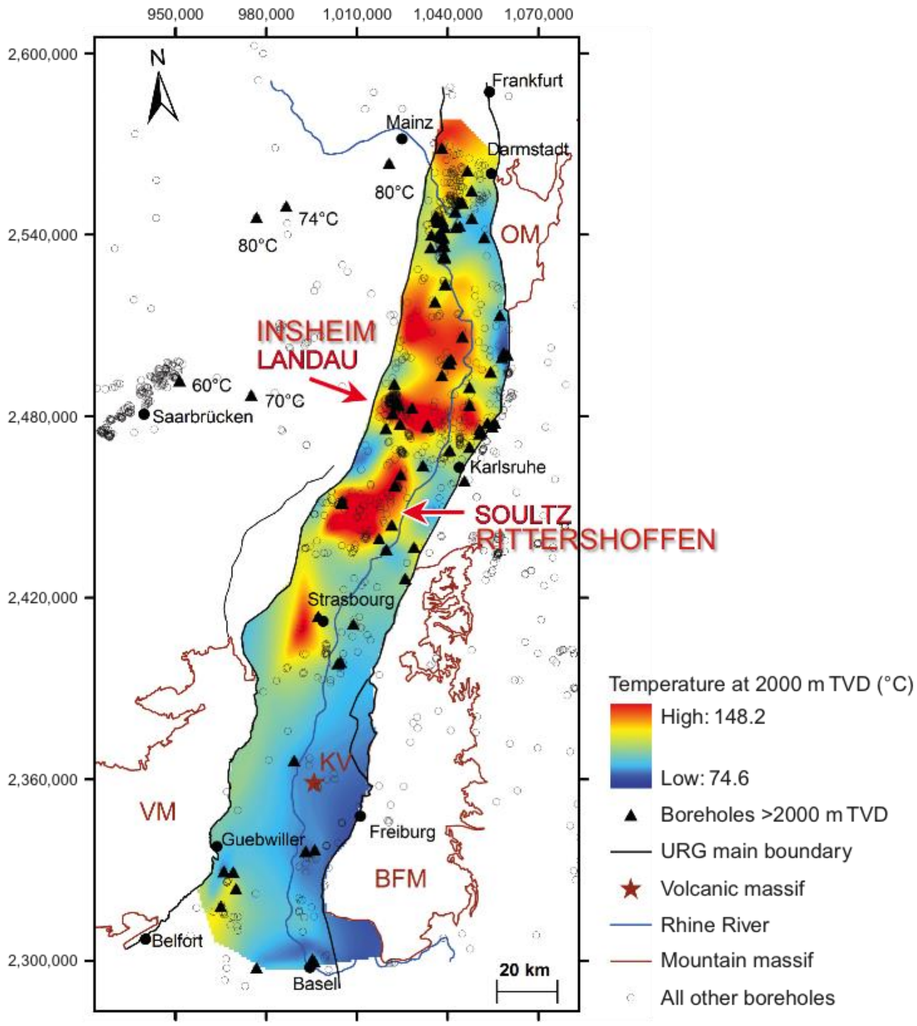

Fig. 1 Location of thermal anomalies in the Rhine Graben (NE France and Germany) and location of the deep geothermal sites of Soultz and Rittershoffen, North East of France (Albert Genter, pers. comm.).

3 THE CONCEPT OF HYBRID GRAVIMETRY

The concept of hybrid gravimetry to investigate an underground reservoir with the combination of superconducting gravimeter (SG), absolute gravimeter AG, and relative spring meter RG. The permanent gravimeter allows a precise continuous monitoring of the time-varying gravity at a reference station located on the investigated site; in order to be able to retrieve the long-term behavior, one uses generally a superconducting gravimeter (SG) rather than a spring meter because of its very small instrumental drift (a few μGal/year) and better precision (0.1–0.01 μGal). We use the site of STJ9 (10 km of Strasbourg, Figure 2) which is a super conducting gravimeter observing since 1987 and has been replaced by modern instrument in 1996 and then in 2016.

The ballistic absolute gravimeter (AG) allows to control the long-term gravity changes by repeated parallel recording over short periods of time with the SG (Sugihara and Ishido 2008), as well as to check the calibration stability of the SG. We performed episodic measurements at STJ9 site and a reference site in Soultz (GPK1 site on Figure 3) and in Rittershoffen (see Figures 2 and 3 for location).

The spring relative gravimeter (RG) is used to repeat observations on a micro-gravimetric network around the reference station by successive loops in order to gain more insight into the space-time changes in the investigated region.

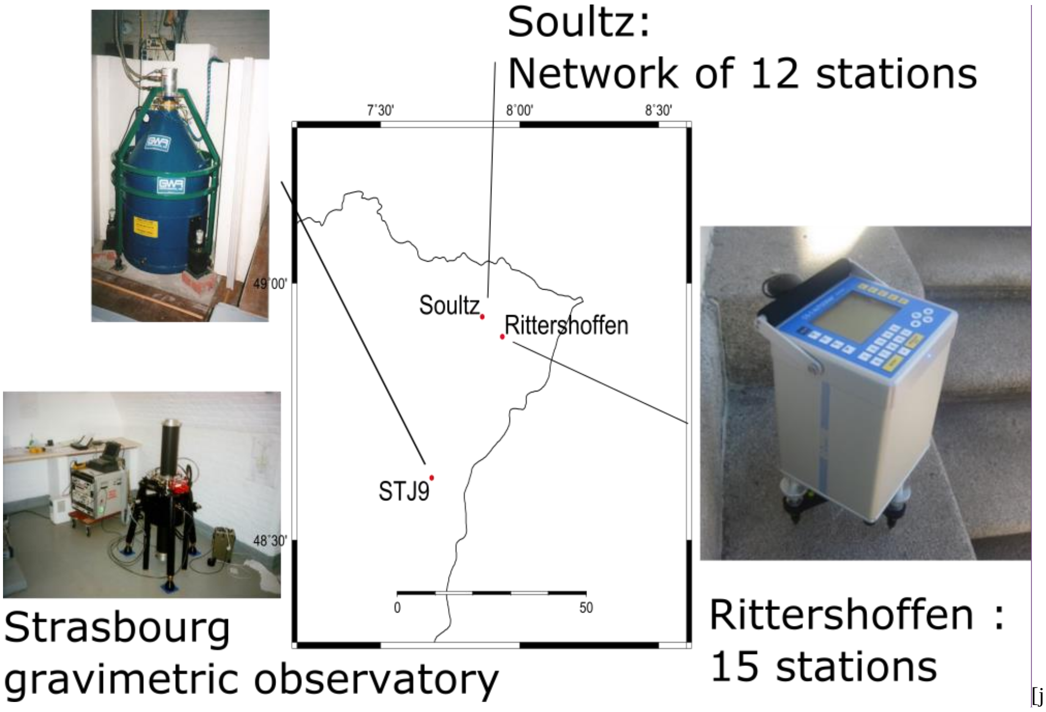

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Fig. 2 The three main locations of our hybrid gravity approach. STJ9 is the Strasbourg Gravimetry Observatory where both a superconducting gravimeter (GWR C026) and an absolute gravimeter (Micro-g Solutions FG5#206) are available. There are 12 micro-gravity stations in the Soultz network (GEIE) and 15 stations close to Rittershoffen (ECOGI) (modified from Hinderer et al 2015).

The micro-gravimetric network is divided in two networks for an easy transportation of the RG instrument, one called Soultz network and the second one called ECOGI network, close to Rittershoffen (Figure 3). The Soultz network consists of 13 sites around the geothermal exploitation sites of GPK1 and GPK2 (Figure 3). A strong effort has been done to have a dense network around GPK1 and GPK2. Concerning the ECOGI network, only two sites are very close to the ECOGI geothermal exploitation site in 2013 (2 red triangles south of ECOGI on Figure 3). In 2015, the ECOGI gravimetric network has been completed by ten new sites (Figure 3). Gravimetric surveys of Soultz network were performed in 2013, 2014, 2015, and in 2016. Next survey is programmed in summer 2018.

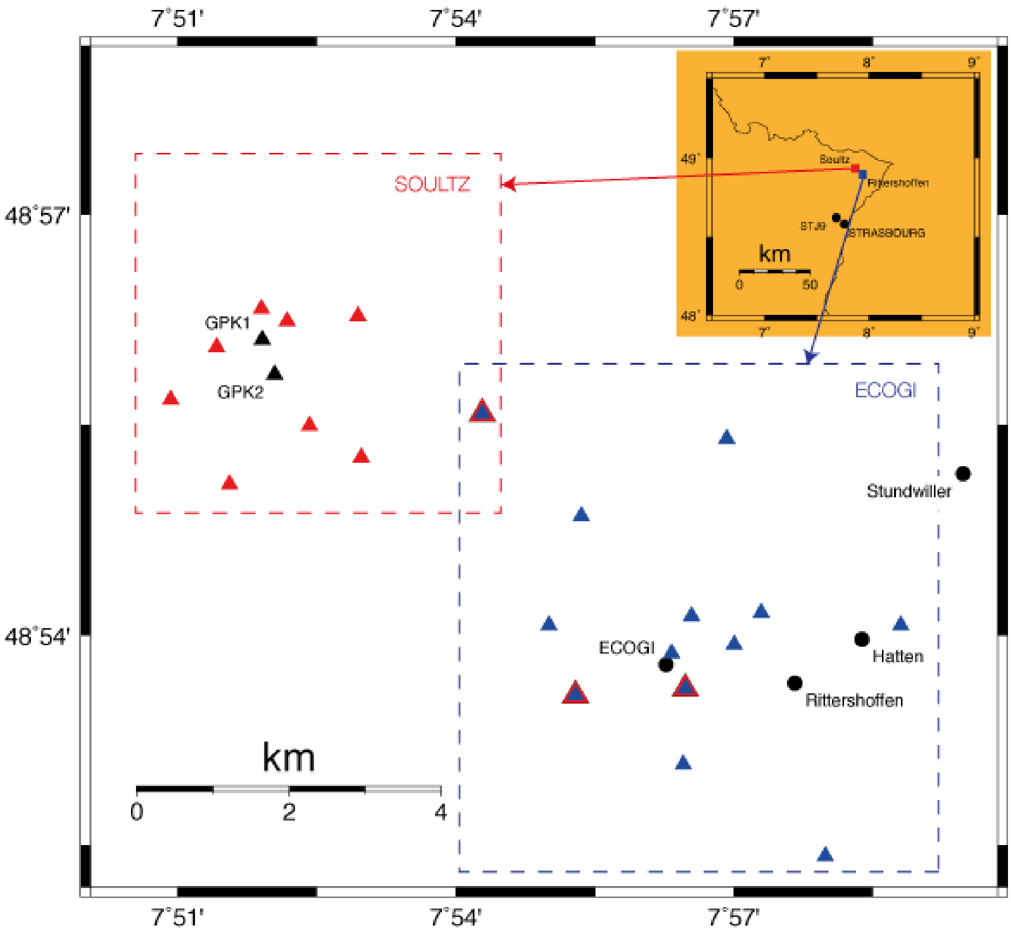

Fig. 3 Location of the relative gravimetric measurement sites (red or black triangles): 12 surrounding Soultz-sous-Forêts and 2 sites close to Rittershoffen (ECOGI site). Permanent GPS stations are indicated by black triangles or black circles. Blue triangles are the sites monumented in 2015 around ECOGI. Three sites belongs to the Soultz and ECOGI networks.

4 GRAVIMETRIC DATA PROCESSING

The repetition of a micro-gravimetric network, where x0 and t0 are the reference point and time, leads to the following formula (1) (Hinderer et al. 2015) the gravity double differences Dg at point x and time t:

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

This double gravity difference provide an interesting way of interpreting gravity changes in time and in space. Figure 4 shows no significant change in gravity double difference for Soultz network. Since any change in elevation modifies the gravity measurement, it is crucial to perform a vertical control, all gravimetric sites are equipped with a leveling benchmark, in order to measure any surface deformation at and around geothermal sites.

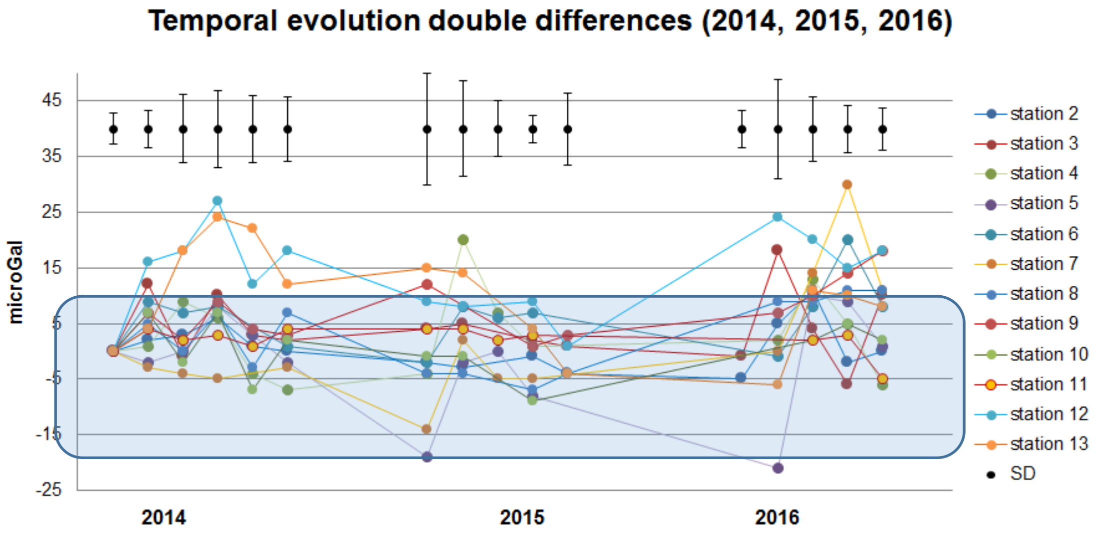

Fig. 4 Example of gravity double differences in 2014, 2015 and 2016 at the 12 sites of Soultz network (stations 2 to 13). The blue area is the ±2 σ uncertainty band computed from the uncertainties in the measurements and processing of all surveys.

5 LEVELING NETWORK CONNECTING GRAVIMETRIC SITES

In order to provide the elevations of each micro gravimetric site, a first large leveling network has been established in 2014 (Ferhat et al. 2014). This leveling network connects all of the 13 gravimetric sites of Soultz network (Figure 5). For control purposes and practical observation procedures, the leveling network is made of five loops (Figure 5). Each loop was observed using a digital level (Leica DNA03) and standard leveling staff. The leveling lines include some National leveling benchmarks installed by the French Mapping Agency (IGN, *Institut National de l'Information Géographique et Forestière*) in order to tie the altitudes to the national vertical reference system (NGF-IGN69). The loop 5 was observed several times using digital level Leica DNA02 or Trimble DiNi 0.3, but this time using invar staffs. It serves as a reference benchmark for the newly constructed geothermal exploitation site of ECOGI. By fixing the altitudes of three leveling benchmarks BM at IGN values, we computed the altitudes of all other benchmarks (Ferhat et al. 2014). Uncertainties on these altitudes are about 2 to 5 mm. This leveling network has been surveyed in May 2014, May 2015, May 2016 and May 2017 by students of the Department of Surveying Engineering at INSA, Institute for Applied Sciences, Strasbourg, France.

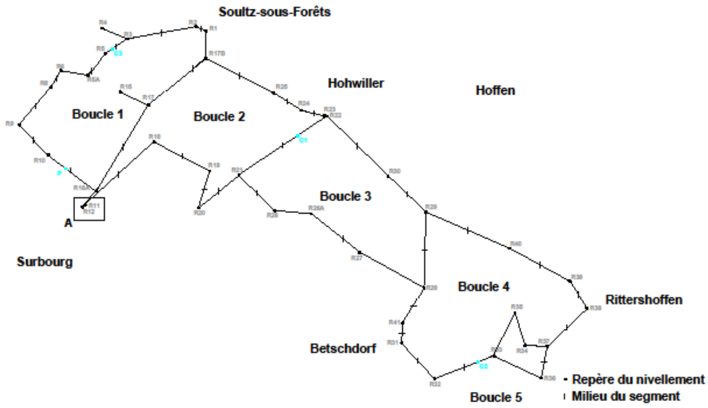

Fig. 5 The leveling network connecting the 13 gravimetric sites of Soultz network (5 loops) and comparison of height difference for consecutive section during the period 2014 – 2015 (after Ferhat et al. 2015).

Differences in elevation between consecutive leveling benchmarks have been computed for the period 2014 – 2015 and are less than few mm (Ferhat et al. 2015, Figure 5). Comparison of the elevations during the 4 years show no significant changes, uncertainties for the elevation difference are mostly about 6-7 mm. Moreover, in 2016, elevations of 10 gravimetric sites composing the ECOGI network were determined using leveling techniques for 5 sites. Due to long distance from Rittershoffen or steep topography or lack of time and operators, elevations for the 5 other sites were determined by static GPS observations associated to a local leveling tie.

6 PRELIMINARY RESULTS

Almost all observed changes in the Soultz network are within the rectangular uncertainty zone (Figure 3) and are hence not significant. In other terms, we do not observe any gravity change that exceeds our measurement precision. The lack of detectable gravity changes indicated by our results for 2014 is in agreement with the fact that during this period, the geothermal activity was completely stopped in Soultz. Analysis of selected gravimetric data acquired in 2015 and 2016 will be presented at the conference.

7 CONCLUSION

In order to monitor surface deformation and investigate geothermal fluid circulation at depth at geothermal exploitation sites of Soultz-sous-Forêts and Rittershoffen located in the Rhine Graben (NE of France), a dense leveling network and two micro gravimetric networks has been surveyed annually since 2013 (for gravity measures) and since 2014 (for leveling measures). No gravity change has been clearly observed during this period. Since no full exploitation operations are currently performed at Soultz and ECOGI sites, we do not observe clearly significant gravity changes in 2016, i.e. during the start of the exploitation. Long term leveling and gravimetric monitoring associated to repeated magneto-telluric surveys, InSAR and continuous GPS observations and seismological monitoring should provide information on surface deformation and processes at depth, i.e. in the geothermal reservoirs.

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