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On the interpretation of gravity variations in the presence of active hydrothermal systems: Insights from the Nisyros Caldera, Greece

J. Gottsmann

Institute of Earth Sciences Jaume Almera, CSIC, Lluís Solé Sabarís s/n,
Barcelona 08028, Spain

H. Rymer

Department of Earth Sciences, The Open University, Milton Keynes, MK7
6AA, United Kingdom.

L. K. Wooller

Department of Earth Sciences, The Open University, Milton Keynes, MK7
6AA, United Kingdom.

J. Gottsmann, Institute of Earth Sciences Jaume Almera, CSIC, Lluís Solé Sabarís s/n,
Barcelona 08028, Spain.

jgottsmann@ija.csic.es

H. Rymer, Department of Earth Sciences, The Open University, Milton Keynes, MK7 6AA,
United Kingdom.

h.rymer@open.ac.uk

L. K. Wooller, Department of Earth Sciences, The Open University, Milton Keynes, MK7 6AA,
United Kingdom.

l.k.wooller@open.ac.uk

Abstract. We report on short-term (over tens of minutes) residual gravity changes recorded at the restless Nisyros caldera in Greece via a series of discrete measurements at benchmarks within or in proximity to a hydrothermal area located along the caldera floor. The obtained time series reveal sinusoidal gravity variations with amplitudes of up to **25** μGal and wavelengths of 40-50 min. Degassing of a magmatic source coupling into (shallow) hydrothermal systems including the ascent of steam pockets and transient pressure variations during steam/liquid interface propagation appear to be the most likely causative process for the observed short-term variations. We **assess** standard protocols of micro-gravity surveys for **hazard assessment in volcanic areas** in the light of these findings and propose **additional** techniques, **such as continuous gravimetry**, for the discrimination of hydrothermal signals from deeper-seated, **i.e.** magmatic, signals during gravity monitoring of restless **volcanoes** hosting active hydrothermal systems.

1. Introduction

Gravity change and deformation time series data are employed both to quantify the long-term subsurface dynamics (mass/volume/density changes) at restless calderas [*Rymer and Tryggvason, 1993; Berrino, 1994; Battaglia et al., 2003; Gottsmann et al., 2003*] and for forecasting volcanic activity as a volcano develops from a state of unrest to a state where a volcanic eruption has to be anticipated [*Rymer and Williams-Jones, 2000; Gottsmann and Rymer, 2002*]. Critical to the interpretation of residual gravity variations, i.e. data corrected for the effect of vertical ground deformation on gravity, is the correction for additional phenomena such as, for instance, secular variations **in the level of** the ground water table. Failure to account for such contributions results in attributing the entire gravitational signal to deeper, usually magmatic, processes. Conclusions drawn may then be unrealistic and may contribute little to the assessment of hazards associated with volcanic unrest. The presence of active hydrothermal systems at many restless calderas (e.g., Yellowstone, Long Valley, Campi Flegrei) expressed at the surface by fumaroles, mudpools or geysers has often prompted controversial debates on the causative processes of unrest: magma or hydrothermal fluid migration. One controversial recent example is the case of ground inflation at Campi Flegrei between 1982 and 1984 [*Berrino, 1994; Bonafede and Mazzanti, 1998; Gottsmann et al., 2003, 2005*].

Based on a detailed evaluation of short-term residual gravity variations recorded at the restless caldera of Nisyros (Greece), this paper highlights a **previously unrecognised** effect of hydrothermal activity on gravity changes measured at volcanic areas.

2. Micro-gravity surveys

A widely applied technique to quantify sub-surface mass/volume/density changes at active volcanic areas is the inversion of gravity-height time series. These data are traditionally obtained by joint deformation and micro-gravity surveys, whereby individual relative gravity readings are obtained at benchmarks (with a simultaneous control of

benchmark elevation) which are part of a larger network. Repeated occupation of the network leads to gravity-height time series, which are evaluated with respect to base line data obtained at a reference usually located outside the area of interest.

After correction for Earth and Ocean Tides, the difference in gravity observed between a benchmark and the reference station, the observed gravity change (Δg_{obs}), comprises an array of signals. In order to extract the gravity signal produced by a sub-surface mass and/or density change, gravity residuals need to be quantified. The residual gravity change at each benchmark (Δg_r) is obtained via

$$\Delta g_r = \Delta g_{obs} - \Delta g_{FA} * U_z - \Delta g_{def} - \Delta g_{wt} \quad (1)$$

where Δg_{FA} is the free-air gravity gradient ($-308.6 \mu\text{Gal}/\text{m}$; $1 \mu\text{Gal} = 10^{-8} \text{ms}^{-2}$), U_z is the vertical displacement, Δg_{def} is the Bouguer effect of deformation, and the resulting propagation of density boundaries, on gravity [Walsh and Rice, 1979] and Δg_{wt} is the ground water table effect. In this discussion, we are particularly concerned with Δg_{obs} .

3. Observations and results from Nisyros caldera

Nisyros, an 8 km-wide island located at the eastern end of the Hellenic island arc, hosts a 3.8 km-wide caldera. An approx. 0.9 km^2 hydrothermal area with fumaroles and mudpools is located in the central southern part of the caldera (known as the Lakki Plain; Fig. 1) and has been the locus of at least 13 phreatic eruptions in historical times [Caliro *et al.*, 2005; Hardiman, 1996], the most recent in 1888. A volcano-seismic crisis on Nisyros between 1995 and 1998 was accompanied by 14 cm of ground uplift on the island [Sachpazi *et al.*, 2002]. This episode has not (yet) culminated in an eruption.

A joint gravity-deformation network installed in 2003 [Gottsmann *et al.*, 2004] was re-occupied in 2004, using Lacoste and Romberg gravimeter G-403. The network runs around the outside of the caldera and along a line roughly N–S through the caldera with a total of 23 benchmarks. During both campaigns, we noticed significant (up to $25 \mu\text{Gal}$) gravity

changes over a time scale of hours at six benchmarks located within the caldera floor as well as at two benchmarks along the caldera rim (Fig. 1). These benchmarks lie within or proximal to (1.5 km or less) the exposed hydrothermal area. The observed gravity variations on the order of tens of μGal could be explained by neither tidal, atmospheric, instrumental (drift or tare) nor by deformation effects (see below). The precision of each meter reading was to within better than $3 \mu\text{Gal}$. It is important to note that we have not noticed such variations distal to the hydrothermal system or the caldera rim, i.e., along the flanks of the volcano.

The repetitive nature of these variations prompted us to conduct repeated readings at a number of benchmarks located within the caldera (Fig. 1). This procedure involved a set of 10 gravity readings taken every 4-5 min over a period of 30-60 min. A gravity change time series obtained this way (after correcting for tidal effects) giving the mean of each set of readings at a benchmark located close to Stefanos crater (Fig. 1) within the hydrothermal area is shown in Figure 2. The data show a distinct pattern of gravity changes which can be approximated by a sinusoidal variation with a wavelength of ca. 45 minutes and with a maximum amplitude of ca. $13 \mu\text{Gal}$. Data obtained at most other benchmarks within the Lakki Plain show similar wavelengths and amplitudes. Maximum amplitudes detected during the 2004 campaign were $25 \mu\text{Gal}$.

4. Discussion and Implications

In order to attribute the **observed amplitude of gravity changes of 12–25 μGal** to a free-air effect due to vertical ground deformation, elevation changes of ca. 4-8 cm are required. Such changes are clearly measurable with our GPS set-up using 2 Leica SR530 receivers (rover and a reference station) and AT502 antennas at a 1 Hz sample rate during both campaigns. However, within the precision of the measurements ($\pm 3 \text{ cm}$), at neither benchmark were the gravity changes accompanied by resolvable ground height changes (Fig. 2).

Traditional inversion techniques employing homogenous, isotropic, elastic half-space models require gravity changes to be associated with ground deformation in order to be able to infer on the nature of the causative source by deducing the source density from constraints on volume and mass variations at depth. In the absence of resolvable ground deformation, such “simple” models fail to provide answers as to the nature of the causative process of these short-term gravity variations on Nisyros and alternative models need to be employed. In a recent paper, *Caliro et al.* [2005] provided a comprehensive study of the hydrothermal system at Nisyros based on structural, geochemical and seismological investigations. A number of arguments point towards the hydrothermal system as the causative source for the observed short-term gravity variations. The gravity variations were recorded so far in areas:

1. of intensive hydrothermal surface alteration,
2. bounded and dissected by faults,
3. of increased CO₂ flux [*Caliro et al.*, 2005] ≥ 5 times the background level of $8 \text{ g m}^{-2} \text{ d}^{-1}$ [*Cardellini et al.*, 2003],
4. of low-frequency, harmonic signals which are interpreted by *Caliro et al.* [2005] to be likely associated to the dynamics of fluid-filled buried cavities ca. 1–2 km beneath the central part of the Lakki Plain ,
5. at the eastern-most zone of diffuse degassing of the Lakki plain where the occurrence of harmonic tremors indicates instabilities in the degassing process [*Caliro et al.*, 2005].

A complex interplay between a magmatic source and the overlying hydrothermal systems with contributions from meteoric water and seawater appears to presently orchestrate the degassing process on Nisyros [*Chiodini et al.*, 2002; *Brombach et al.*, 2003]. Magma degassing is buffered by a deep hydrothermal system at boiling temperatures coupling into a shallower hydrothermal system [*Caliro et al.*, 2005]. The dominant causative process for the observed short-term gravity variations could be the hydrothermal/magmatic de-

gassing process itself, for instance, the generation, ascent and dissipation of steam pockets from the boiling hydrothermal reservoir along fracture zone or faults as well as transient pressure variations during steam/liquid interface propagation. A key candidate to foster effective degassing and steam propagation on Nisyros are large scale NE-SW striking faults as well as the caldera boundary faults. Steam propagation along the latter could explain the gravity variations observed along the caldera rim.

A short-term gravity increase could be triggered, for example, by rising steam pockets resulting in underplating and uplift of an hydrothermal aquifer.

Assuming an effective void fraction ϕ of 0.4 in permeable caldera-fill deposits, a residual gravity change (Δg_r) of 20 μGal could be induced for example by a ca. 1.2 m change, δq , in the level of an unconfined aquifer, if a water density ρ_w of 1000 kg/m^3 is assumed.

$$\Delta g_r = 2\pi G \rho_w \phi \delta q \quad (2)$$

After the dissipation of the pocket the resultant fall of the aquifer to its 'background level' could account for the subsequent gravity decrease (Fig. 2). Based on the obtained data we would argue that such processes (at least on Nisyros) occur on the timescales of tens of minutes, which is also supported by seismic data [*Caliro et al.*, 2005].

Assuming that the observed gravity changes are predominantly associated with the current "background" phase of degassing on Nisyros, it appears obvious that results obtained via traditional, periodic gravity surveys are very much biased on the timing of benchmark occupation. Conventional surveys only record instantaneous states of the mass distribution at continuously active systems. If one happens to measure at a time where the hydrothermal system is at approximately the same "state" as during the previous measurement, the resulting residual change is likely to be close to zero. If however one happens to relate a measurement corresponding to the "peak" of a gravity signal similar to that shown in Fig. 2 to one corresponding to a "trough", one could infer on a significant sub-

surface mass change inducing the observed gravity change. As a consequence the time scale associated with this process could be deduced to occur over several months or even years if a “peak” measurement is compared with a “trough” measurement (or vice versa) during a subsequent occupation (months or years later).

The straightforward method during traditional surveys is to incorporate short-term gravity variations by employing the mean of the meter readings and associated errors. In the case of Nisyros after a series of annual surveys, residual gravity changes would be associated with a significant level of noise. This data set would provide little information for the precise quantification of associated sub-surface mass/density changes at the caldera.

A potential example of this dilemma is given in Figure 3, which shows residual gravity data recorded during ground subsidence at the Campi Flegrei caldera [*Berrino, 1994; Gottsmann et al., 2003*]. Data are shown for benchmarks Solfatara, located in an active hydrothermal area of the Campi Flegrei caldera and at Serapeo, located in the area of maximum ground deformation. Note, that some residual gravity changes between two occupations are up to $40 \mu\text{Gal}$. One could speculate that some “spikes” in the shown gravity data derive from relating “peak” and “trough” readings triggered by background hydrothermal activity during two successive field campaigns. An interpretation of results obtained for example by the inversion of such time series accounting for potential hydrothermally-induced short-term gravity variations would deviate significantly from an interpretation based on the assumption that the recorded gravity variation represent long-term mass/density variations beneath the caldera.

One question remaining, however, is whether the observed residual gravity changes are simply induced by sub-surface mass/density fluctuations in the hydrothermal system(s) or whether perhaps at least part of the signal corresponds to the gravimeter’s mechanical response to, for example, microseisms induced by harmonic seismicity (tremors). Although the gravimeter manufacturer claims that measurements are generally unaffected by horizontal ground acceleration, limited studies indicate mechanical coupling effects

in readings using gravimeters such as employed during our surveys. In order to better quantify potential artifacts as well as fundamental sub-surface processes and their associated timescales, we deem it paramount to obtain long-term gravity change time series at restless calderas, for instance, via the installation of continuously recording gravimeters. Another solution could be employing two gravimeters operating simultaneously, one in continuous mode, a second employed following the routine of conventional micro-gravity survey. The continuous time series would give critical baseline data via the statistical analysis of the data including spectral analysis. This approach could provide an important tool for the discrimination of hydrothermal signals occurring over minutes from magmatic signals occurring over months or years. This technique is certainly not yet standard for volcano monitoring, although long-term continuous gravity observations on Etna have provided important constraints on time scales of magma replenishment [*Carbone et al.*, 2003]. It is hence perhaps worth reappraising standard protocols of micro-gravity surveys for volcano monitoring [*Rymer*, 1989] by fine-tuning the method for investigations at hydrothermally-active volcanoes. Future continuous gravimetric investigations will have to show whether the phenomenon reported here is also common at other volcanic systems hosting hydrothermal areas.

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Figure 1. Shaded relief image of Nisyros ($36^{\circ}35.25'$ N, $27^{\circ}10.0'$ E) based on 90 m SRTM image showing areas of hydrothermally altered deposits and areas of anomalously high CO₂ flux (after *Caliro et al.* [2005]) along the caldera floor (Lakki Plain). Short-term residual gravity changes were recorded at locations indicated by circles. Time series shown in Figure 2 was obtained at benchmark marked by black circle (close to Stefanos crater.)

Figure 2. Left: Observed gravity change time series recorded on Nisyros (close to Stefanos crater) on 14.10.2004. 2σ errors on gravity measurements are $\pm 3 \mu\text{Gal}$. Right: Elevation variation derived from 1Hz GPS measurements close to Stefanos crater. The similar form of variations in the two timesets do not correlate in time. If we were to correct for vertical deformation, it would in fact amplify the residual gravity signal since positive height change results in a decrease in gravity.

Figure 3. Residual gravity change time series recorded at Solfatara (left) and Serapeo (right), Campi Flegrei, Italy, from June 1987 to March 2001 during ground subsidence. Data from *Berrino* [1994] and *Gottsmann et al.* [2003].