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, Barcelona, Spain

H. Rymer and L. K. Wooler
Department of Earth Sciences, Open University, Milton Keynes, UK

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[1] 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 microgravity surveys for hazard assessment in volcanic areas in the light of these findings and propose protocols of microgravity surveys for hazard assessment in volcanic areas.

2. Microgravity Surveys

[4] 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 microgravity 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.

[5] After correction for Earth and Ocean Tides, the difference in gravity observed between a benchmark and the reference station, the observed gravity change (Δgobs), 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 (Δgr) is obtained via

\[ Δg = Δg_{obs} - Δg_{FA} + U_z - Δg_{def} - Δg_{gwt} \]  

where \( Δg_{FA} \) is the free-air gravity gradient (−308.6 μGal/m; 1 μGal = 10^{-8} m s^{-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 \( Δg_{gwt} \) is the ground water table effect. In this discussion, we are particularly concerned with \( Δg_{obs} \).

3. Observations and Results From Nisyros Caldera

[6] 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 km² hydrothermal area with fumaroles and mudpools is located in the central southern part of the caldera (known as the Lakki Plain; Figure 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 µGal) 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 (Figure 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 µGal. 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 (Figure 1). This procedure involved a set of 10 gravity readings taken every 4–5 min over a period of 30–60 min. Two gravity change time series obtained this way (after correcting for tidal effects) giving the mean of each set of readings at benchmarks located close to Stefanos crater (Figure 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 µGal. Data obtained at most other benchmarks within the Lakki Plain show similar wavelengths and amplitudes. Maximum amplitudes detected during the 2004 campaign were 25 µGal.

4. Discussion and Implications

[9] 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 (±3 cm), at neither benchmark were the gravity changes accompanied by resolvable ground height changes (Figure 2).

[10] Traditional inversion techniques employing homogeneous, 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 hydro-

Figure 1. Shaded relief image of Nisyros (36°35.25′N, 27°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 were obtained at benchmarks marked by black circles (close to Stefanos crater). See color version of this figure in the HTML.

Figure 2. (left) Observed gravity change time series recorded on Nisyros at two benchmarks (close to Stefanos crater) on 14.10.2004 (top) and 17.10.2004 (bottom). 2σ errors on gravity measurements are ±3 µGal. (right) Elevation changes derived from 1 Hz GPS measurements at the same benchmarks. The waveforms of the gravity and elevation changes do not correlate in time nor in amplitude. Within error the observed gravity changes appear not to be accompanied by ground deformation and are hence not affected by Free-Air or Bouguer effects.
permeable caldera–fill deposits, a residual gravity change from the gravity variations observed along the caldera rim. Faults. Steam propagation along the latter could explain the NE-SW striking faults as well as the caldera boundary degassing and steam propagation on Nisyros are large scale interface propagation. A key candidate to foster effective as well as transient pressure variations during steam/liquid interactions would deviate significantly from an interpretation 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. It is worth stressing that a sampling interval equal to or less than a few tens of minutes is needed to properly study anomalies like the ones shown in Figure 2, and thus an array of continuously recording gravimeters should be employed.

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 degassing 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 $\phi$ of 0.4 in permeable caldera–fill deposits, a residual gravity change ($\Delta g_r$) of 20 $\mu$Gal could be induced for example by a ca. 1.2 m change, $\delta q$, in the level of an unconfined aquifer, if a water density $\rho_w$ of 1000 kg/m$^3$ is assumed.

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

After the dissipation of the pocket the resultant fall of the aquifer to its “background level” could account for the subsequent gravity decrease (Figure 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, when performing conventional surveys with benchmark occupation typically ranging from between a few months to a few years, a strong noise, with amplitude greater than the precision of the instrument and possibly also greater than the “useful” signal, could appear over the frequency corresponding to the sampling interval. As a consequence, the real period of such a signal (and thus any hypothesis about its source) remains ambiguous. This ambiguity cannot be solved in the time domain (Nyquist limit). However, if the general rule of quicker-evolving sources being shallower is assumed to hold true, this ambiguity could be tentatively solved in the space domain, provided that the available network of stations is dense enough to allow effects linked to sources at different depths to be distinguished from each other.

An example of what is stated before is presented 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 residual gravity changes with periods corresponding to the sampling interval, possibly due to background hydrothermal activity are up to 40 $\mu$Gal. 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. It is worth stressing that a sampling interval equal to or less than a few tens of minutes is needed to properly study anomalies like the ones shown in Figure 2, and thus an array of continuously recording gravimeters should be employed.

One question remaining, however, is whether the observed short-term gravity changes are fully induced by sub-surface mass/density fluctuations in the hydrothermal system(s) or whether perhaps 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, there may be mechanical coupling effects in readings using gravimeters such as employed during our surveys [Davies, 1999]. 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 microgravity 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 microgravity 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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References


J. Gottsmann, Institute of Earth Sciences Jaume Almera, CSIC, Lluis Solé Sabaris s/n, Barcelona 08028, Spain. (jgottsmann@ija.csic.es)

H. Rymer and L. K. Wooller, Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, UK. (h.rymer@open.ac.uk; l.k.wooller@open.ac.uk)