NERC GEOPHYSICAL EQUIPMENT FACILITY LOAN 835 SCIENTIFIC REPORT

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Integrated geophysical studies of a hydrothermal system: Nisyros Island, Greece

Abstract

A microgravity and GPS monitoring network established at the Nisyros caldera volcano (Greece) in 2003 enables the quantification of subsurface processes over time at this restless volcano. Data indicate that the current activity is dominated by mass and density changes at depth, most likely due to dynamic changes in a shallow hydrothermal system. The purpose of the fieldwork in 2007, supported by loan 835, was to survey a network of 20 joint GPS/gravity benchmarks and to obtain continuous multiparametric geophysical data near the hydrothermally active areas of the caldera floor in order to shed light onto sub-surface dynamics. The latter investigations revealed non-steady short-term oscillatory signals, recorded by both geodetic as well as seismic and electromagnetic instrumentation. The combined records indicate that the oscillations are associated with thermohydromechanical disturbances of the hydrothermal system. The dominant period of oscillation (>60 min) reflects short-term processes most likely associated with instabilities in the degassing process. Re-occupation of the network in 2007 enabled tracking of island-wide changes in the subsurface structure and ectend the observation period to more than 4 years Some of the obtained data in 2007 is also used to construct a Bouguer anomaly map of the island and will provide a crucial starting point for the modelling of gravity/height change and other geophysical data in the future.

Background

Magma intrusion or changes within the hydrothermal system? - The island of Nisyros, at the eastern end of the Aegean Arc, is dominated by a restless caldera (Figure 1). A series of large eruptions led to the development of a 4 km wide summit caldera. In the last decade the island has witnessed increased seismicity and inflation of more than 10 cm (Sachpazi et al., 2002), possibly related to intrusion of fresh magma. There is also a risk of hydrothermal eruptions within the caldera (Marini et al., 1993), similar to the event of 1888.

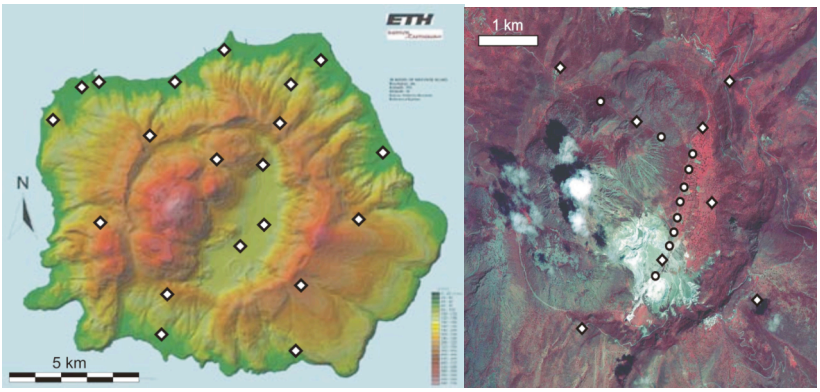

Figure 1. Topographic map of Nisyros Island (left), showing GPS and microgravity stations. ASTER image of caldera

(right) shows concentrated GPS network in hydrothermally active area.

Surface deformation and gravity changes are measured by the PI and coworkers periodically and these studies are augmented by electromagnetic and seismic investigations at the volcano in order to shed light on mass/density changes at depth and their causative processes. In these investigations, the possibility of magmatic intrusion (and potential volcanic activity) is appraised and compared with shallower hydrothermal system activity. Both sources represent risk to the local and regional population as well as to visitors, as the island is a tourist centre in the summer months and large groups visit the active crater area during this time. Our work, thus, not only contributes to our understanding of caldera unrest and the processes responsible for long-term instability of these systems but also contributes to hazard assessment on the island.

GPS survey and data processing

Suitable ground control did not exist in the working area. Therefore, an important part of this project was the survey of ground control points, using the Leica System 530 GPS sets requested from NERC GEP.

Static GPS measurements were carried out on the flank, summit, and off-volcano reference stations. The network (Figure 1) is designed to identify sub-surface mass and volume changes related to both the shallow hydrothermal system and the deeper-seated magmatic system. The GPS network consists of 23 benchmarks, which are positioned to provide coverage of the entire island. Sixteen of these benchmarks are located on the coast and middle flanks of the island outside the caldera walls. The remaining points are concentrated within the caldera along two perpendicular traverses. Static GPS observation methods were used. Datums consisted of either a concrete pillar with a screwmount or a re-locatable datum placed on a fixed outcrop of bedrock above which a tripod was placed. Each benchmark was occupied at least twice for periods ranging from 20 to 45 minutes. Leica System 530 receivers and AT502 antennas were used, with a sampling rate of 1 Hz. Baseline lengths were between 1 km and 8 km. The microgravity network is co-located with GPS benchmarks for elevation control, meaning that it is reliant upon simultaneous observation. Daily processing was completed whilst at the volcano using Leica GeoOffice software to check for errors in the dataset.

Time series GPS data has been recorded simultaneously with gravimetric, electromagnetic (very low frequency, magnetotelluric, self-potential), and seismic data. The joint setup was installed five times at different sites within the caldera and recorded a total of 150 hours worth of multi-parametric data. The kinematic GPS data was collected with a sampling rate of 0.2 Hz. Two GPS reference stations were installed at the caldera wall at a distance of about 3 km.

Subsequent to the field-program, post-processing was carried out at the University of Bristol using Leica GeoOffice software. Precise Ephemerides were used, together with automatic ionospheric and Hopfield tropospheric models. The standard deviation for most of the stations is better than 1 cm in the vertical. The results will be numerically modelled using both Finite Element modelling software and custom numerical modelling.

Preliminary findings

Static GPS

Results for the static GPS measurements are given in Table 1. Comparing this data with GPS records obtained during earlier surveys shows a slight deformation of up to 2 cm per year in both the horizontal and the vertical component. Deformation mainly occured on the northeastern part of the island within the caldera and at the outer caldera flank. Vertical deformation is also typically reflected in the gravity records (free air effect), however, the simultaneously collected gravity data did not reveal any significant residual changes in the annual records.

For an interpretation of these findings we are currently modelling the results using (i) a Finite Element approach for modelling changes in deformation (forward approach) and (ii) the genetic algorithm GRAVW1-4 (Tiampo et al., 2004) for a joint analysis of displacement and gravity data (using both forward and inverse modelling).

Results 2007 (UTM)						
Point Id	**Easting**	**Northing**	**Ellip. Hgt.**	**Sd. Easting**	**Sd. Northing**	**Sd. Hgt.**
Base 1	516053.9913	4050638.5059	352.6033	0.0100	0.0065	0.0300
Base 2	515587.8133	4048541.5392	147.1310	0.0004	0.0004	0.0011
Base 3	512475.9845	4051960.5671	35.0844	0.0004	0.0005	0.0012
Rover 1	514067.3301	4047625.7627	299.7797	0.0005	0.0006	0.0014
Rover 2	515761.8440	4049103.4130	141.6364	0.0006	0.0007	0.0016
Rover 3	512475.9753	4051960.5656	35.0814	0.0007	0.0007	0.0019
Rover 4	515819.3397	4050254.8173	169.9542	0.0007	0.0008	0.0020
Rover 5	515125.3789	4047929.7827	156.2756	0.0008	0.0010	0.0023
Rover 6	515019.2255	4048306.7862	141.4997	0.0008	0.0011	0.0023
Rover 7	513984.4663	4047621.4481	306.7833	0.0010	0.0012	0.0026
Rover 8	516914.1420	4052286.9308	76.9382	0.0009	0.0010	0.0027
Rover 9	517461.4903	4048772.8572	353.6465	0.0011	0.0011	0.0030
Rover 10	516103.8501	4050589.3147	349.4095	0.0011	0.0012	0.0030
Rover 11	513575.7557	4050735.6967	290.2184	0.0012	0.0012	0.0032
Rover 12	516024.9965	4051542.6717	201.4751	0.0014	0.0021	0.0033
Rover 13	515554.1560	4048487.1545	144.6374	0.0014	0.0018	0.0035
Rover 14	511773.7025	4051171.5638	130.5933	0.0012	0.0014	0.0037
Rover 15	512360.1738	4051960.5605	74.1319	0.0014	0.0016	0.0038
Rover 16	514848.2202	4048646.8829	182.4071	0.0016	0.0022	0.0041
Rover 17	518311.0769	4050088.2200	33.3802	0.0015	0.0016	0.0059
Rover 18	514217.0798	4051939.2987	59.5206	0.0022	0.0030	0.0055
Rover 19	516179.6400	4047580.3861	420.4531	0.0032	0.0033	0.0072
Rover 20	518219.0588	4050259.8084	33.0138	0.0047	0.0056	0.0113

Table 1. Sample Leica GeoOffice software output for base stations and control points surveyed during the field campaign on Nisyros in May 2007 (coordinates in UTM). Standard deviation of each position is given in meters.

Kinematic GPS as part of the joint multiparametric geophysical setup for cont. monitoring

Earlier multiparametric field campaigns were performed at Nisyros caldera in October 2004 and June 2006. During the occupation in October 2004 short-term variations in residual gravity data were documented and we speculated on hydrothermal processes as the causative source for the observed variations (Gottsmann et al., 2005). Therefore, the focus of the occupation in 2006 and 2007, was to obtain joint continuous time series (Figure 2), using

(1) one automated continuously recording (1 Hz) gravimeter (Lacoste&Romberg model D-41),

(2) two gravimeters (Lacoste&Romberg model G-403 and G-513) manually read at 0.003 Hz for a total of about 30 hours,

(3) 4 Leica GPS 500 receivers (loaned from NERC's GEF (OU loan 2006, UoB loan 835 in 2007; 1 Hz),

(4) one Lennartz LE-3D/5s seismometer (125 Hz), and

(5) one very low frequency (VLF; 15–250 kHz; sampling frequency of 4 Hz) electromagnetic receiver.

The instrumentation was deployed jointly in areas previously identified as being affected by short-term changes (Gottsmann et al., 2005). The records confirmed the earlier assumption of the existence of short-term variations on a time scale of 40 to 60 min. We where howver surprised to find astrong correlation between the individual geophysical signals. In particular, an increase in seismic energy is directly correlated with ground deformation and residual graviety changes indiacting fundamental mass and density changes at depth. We found that the recorded signals are best explained by short-term changes in a complex hydrothermal system in the form of instabilities in the degassing process at depth and resultant upward movement of fluids. Results from the 2006 experiment were published in Gottsmann et al. 2007 (AGU Editors' Highlight paper).

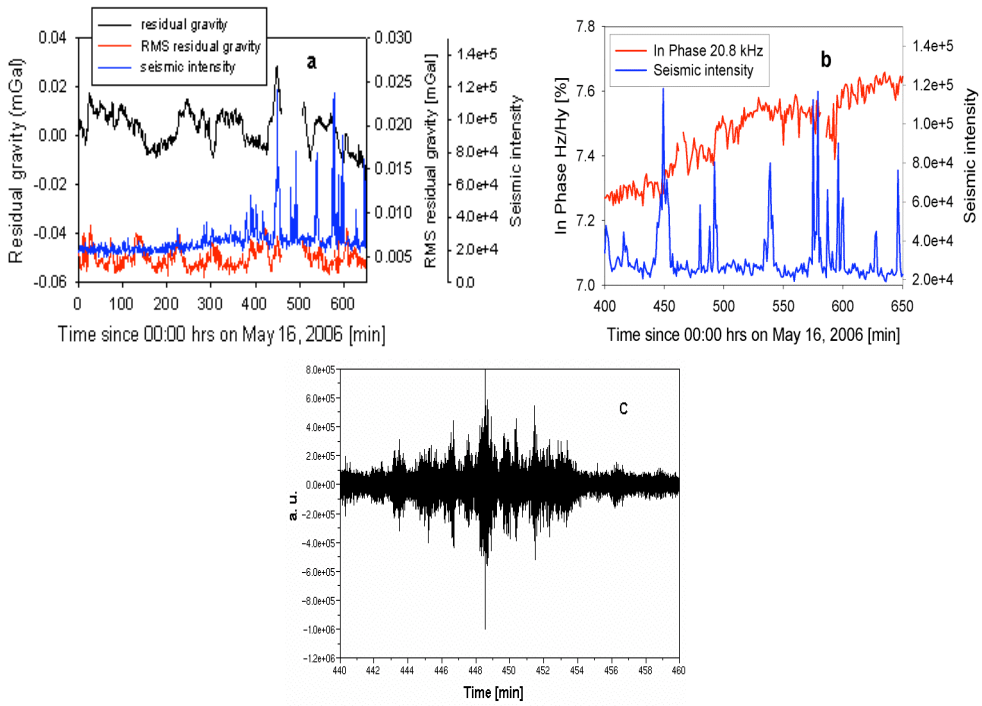

Figure 2. (a) Residual gravity data and RMS gravity errors and seismic intensity recorded in May 2006. Gravity data is reduced for the effect of ground deformation resulting in a periodic oscillation with average amplitudes of 0.02 mGal and a peak of 0.03 mGal, coinciding with the burst in seismic intensity. (b) The 20.8 kHz In Phase VLF and seismic intensity records. The 445 min seismic burst is matched by a break in slope in the VLF record (black broken line. (c) Example of seismic tremor signal recorded between 440 and 460 min ("the 450 min event"). The waveform is interpreted to represent the superposition of a series of discrete bursts in the hydrothermal system.

In order to obtain a more detailed insight into the short-term subsurface dynamics at the caldera, we devised another 14-day multi-parameter geophysical experiment in May 2007. The GEF GPS loan in 2007 enabled the installation of 2 references and 2 rovers and the collection of more than 150 hrs of joint multiparameteric data. In addition to the geophysical instruments, which were already used during the occupation in 2006 and are listed above, continuous electric self-potential data and magnetotelluric data were recorded.

A preliminary analysis of the kinematic GPS data of May 2007 indicates elastic deformation of the caldera occurring over short-time scales (see Figure 3). The plots show prominent peaks in deformation (min 2285 and min 3570, Figure 3), which are indicating a horizontal displacement of about 3 cm and a vertical displacement of up to 10 cm (1σ errors are ca. 3 cm). These deformation cycles typically last about 35 to 55 min, consistent with observations in 2005 and 2006. In addition, the GPS records show several smaller spikes (e.g. min 2826 - 2829, Figure 3) and troughs indicating a mean relative ground motion of up to 2 cm, which occurred within only a few minutes and are hence a considered as noise. In previous surveys the correlation of gravimetric, seismic and electromagnetic signals indicated joint source processes, which were also reflected by pressure transients resulting in ground deformation.

The 2007 electromagnetic and seismic data are currently post-processed and analyzed by R. Carniel (University of Udine, Italy) and N. Coppo (University of Neuchâtel, Switzerland). We are going to compare the joint gravity and GPS data with these other geophysical records in order to look for correlations in the signals and to thus shed light on the nature of these processes. The data is then used for modelling of subsurface processes. Colleages at Bristol and Moscow are currently devising numerical models of multiphase flow and the idea is to simulate degassing processes numerically to investigate and model processes behind the observed multiparametric signals. We expect to get essential insights into the sub-surface dynamics and the processes that cause periodic unrest at the caldera.

We anticipate writing a combined paper on the time-lapse gravity and ground deformation observations as well as the continuous observations after a renewed campaign in 2008 and report new findings during the IAVCEI general Assembly in Iceland in August 2008.

Figure 3. Time series GPS data recorded at the Nisyros caldera in May 2007. GPS data is reported relative to reference stations outside the caldera. Data were recorded at 0.2 Hz and averaged to 0.016Hz. Time [min] since 00:00 hrs on 16 May 2007. Simultaneously, electromagnetic and seismic time series were obtained at the same site. Comparison and analysis of covariance between all signals is expected to help identifying amplitudes and wavelengths of ground deformation time series caused by subsurface processes rather than multipath, tropospheric or simiar effects and will enable characterisation of the causative subsurface reservoir.

Conclusions and recommendations

Our analysis presents one of the first quantitative studies of the background dynamic processes at a restless caldera via the analysis of simultaneously recorded gravimetric, geodetic, seismic and electromagnetic signals. The correlation between the individual time series enables the identification of a joint source processes. The dominant period of oscillation (40–60 min) indicates short-term processes most likely associated with instabilities in the degassing process, whereby bubbles coalesce and rise through a complex hydrothermal system. These processes constitute the majority of geophysical signals recorded at the ground surface and hence dominate activity at the Nisyros caldera. Given the number of phreatic craters formed in the caldera in historic times, hydrothermal explosions pose a serious hazard on the island. With several hundreds of day visitors to the hydrothermal area during the summer months, a significant number of people are at direct risk from sudden catastrophic discharges. The trigger mechanisms of such instabilities in the hydrostatic liquid column are still poorly understood, and forecasting of phreatic activity is intrinsically difficult and associated with a high degree of uncertainty. Integrated data sets such as those collected in 2006 and 2007 may help identify key parameters and their dynamic range during background mode, which may enable forecasting when this system develops from background activity to a state where catastrophic discharge is to be expected. Aqueous fluid migration must be regarded as an important causative mechanism for periodic unrest at the Nisyros caldera and most most likely also at other hydrothermally active collapse calderas.

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