FINAL REPORT: GEF LOAN 778

INTEGRATED MONITORING AT NISYROS ISLAND, GREECE

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Abstract
The field campaign conducted on the volcanic island of Nisyros in 2006 provided an opportunity to conduct a diverse research program targeted at better understanding the volcanic system and structural setting of the volcano. An integrated monitoring campaign used GPS together with seismic, gravity and electro-magnetic measurements over sustained periods to give insight into the temporal variations in the hydrothermal system. Continued monitoring of the micro-gravity network was complemented by Rapid Static GPS measurements. Finally, kinematic GPS methods were used to support a static gravity survey of the caldera region to provide further information on the structural setting.

INTRODUCTION

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 large caldera some 22,000 years BP. In the last decade the island has witnessed increased seismicity and inflation of more than 10 cm, possibly related to intrusion of fresh magma. There is also a risk of hydrothermal eruptions within the caldera, similar to the devastating events which occurred there in 1888. The aim of the field campaign was to monitor surface deformation and gravity changes at the volcano in order to quantify mass movements at depth. The study also contributes to increasing our understanding of caldera unrest and the processes responsible for long-term instability of these systems.

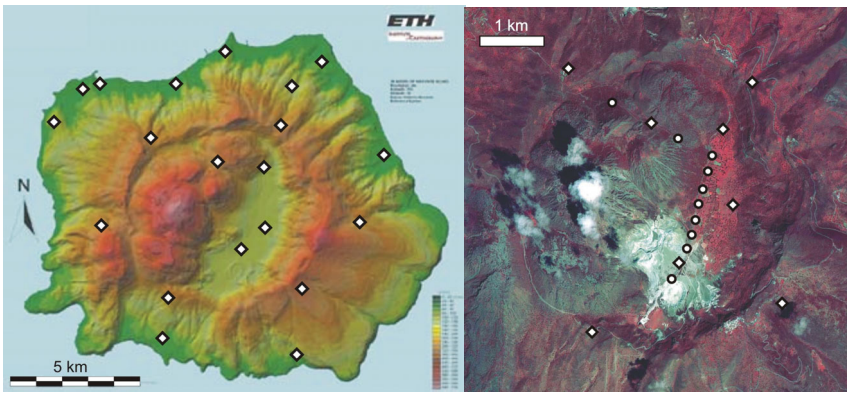
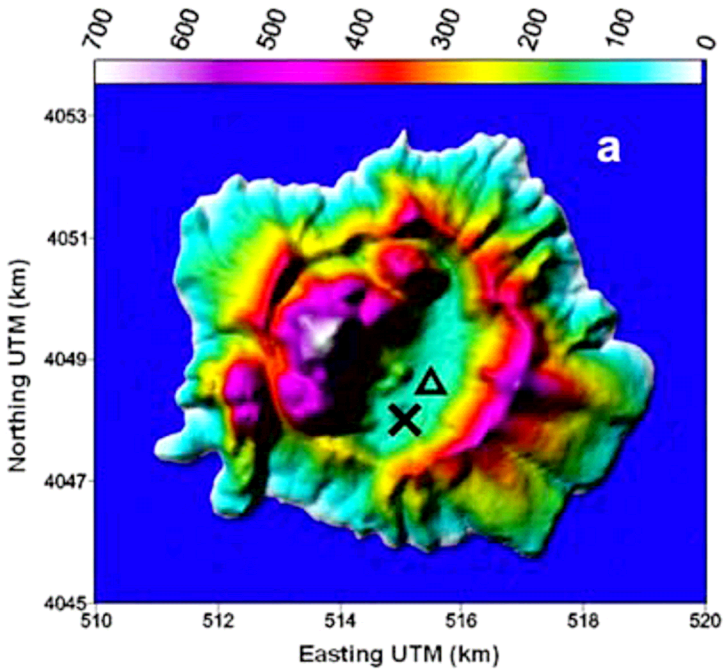


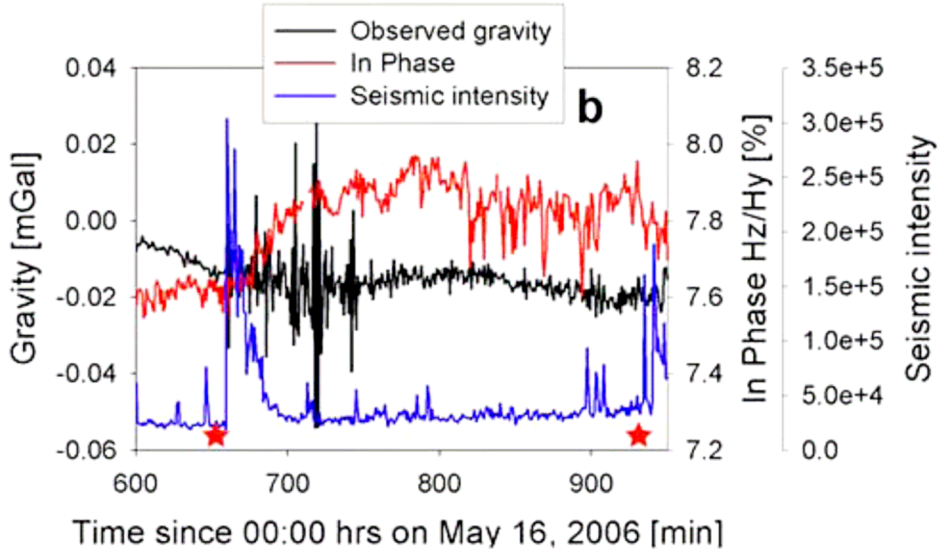
Figure 1. Topographic map of Nisyros Island (left), showing GPS and microgravity stations. Aerial image of caldera (right) shows concentrated GPS network.

FIELDWORK SUMMARY

The field campaign gave the opportunity for a variety of applications of the GPS loan equipment over the 2-week period. This included a brief survey of the pre-existing monitoring network, locational support for static gravity mapping, kinematic mapping of topographic features and, most importantly, semi-permanent recording at sites used for integrated monitoring of the hydrothermal system. In order to obtain a more detailed insight into the short-term subsurface dynamics at the caldera, we devised a 10-day multi-parameter geophysical experiment in May 2006 including the following instrumentation and observation frequencies: (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 (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) and more than 120 h of simultaneous records were collected. For clarity, we have low-pass (1 min) filtered all records. In the preliminary paper published on this work, we focused on 2 data sets: a 24 hr record on May 16, 2006 and a 4 hr record on May 19, 2006. These were selected for the following reasons: (1) on May 16, ground deformation (recorded using the NERC GPS receivers), gravity changes and seismicity were recorded at the same location while the VLF record was obtained ca. 600 m to the south-west, inside a phreatic crater hosting boiling mudpools and fumaroles, enabling a spatial separation of the origins of signals observed by the different instruments (Figure 2b); (2) we recorded two teleseismic events that day which allow us to assess the caldera system's response to external triggers (Figure 2b); (3) we can employ the data set to monitor an instability in the subsurface dynamics which we interpret to be a key phenomena for the understanding of processes at restless calderas with hydrothermal activity (Figure 3); and (4) using both May 16 and 19 records, the data enable a direct quantification of the timescale of short-term cyclic oscillations at the caldera (Figure 3). Figures 1b and 1c present joint records (continuous gravity, GPS, VLF, seismicity) of May 16, 2006, including signals caused by 2 teleseismic events. Note, that all gravimetric data shown are corrected for the effect of Earth and Ocean tides. Focusing on the record preceding the teleseismic events, the continuous gravimetric signal shows a roughly periodic oscillation with maximum amplitudes of 0.015 mGal (Figure 1c). The GPS data correlates with the gravimetric record (e.g., min 100–250), whereby ground subsidence is matched by gravity decrease. This is the opposite behaviour one would expect if the gravimeter is responding solely to ground deformation (a free air effect results in a gravity increase with ground subsidence). Interestingly though, the GPS record displays several spikes (at t = 30 min, 300 min, 450 min and 520 min) indicating relative ground motion of up to 0.15 m whereas the GPS RMS (root mean square error) rarely exceeds 0.04 m. Particularly, the min 445 event is associated with a RMS of less than 0.02 m. We can exclude poor satellite coverage or multipath as sources for the observed ground deformation as well as sidereal effects. Similar short-term ground deformation was recently also observed at the Yellowstone caldera (Tikku et al., 2006).


700
600
500
400
300
200
100
0
a
Northing UTM (km)
4053
4051
4049
4047
4045
510
512
514
516
518
520
Easting UTM (km)


Observed gravity
In Phase
Seismic intensity
b
Gravity [mGal]
0.04
0.02
0.00
-0.02
-0.04
-0.06
8.2
8.0
7.8
7.6
7.4
7.2
In Phase Hz/Hy [%]
3.5e+5
3.0e+5
2.5e+5
2.0e+5
1.5e+5
1.0e+5
5.0e+4
0.0
Seismic intensity
600
700
800
900
Time since 00:00 hrs on May 16, 2006 [min]

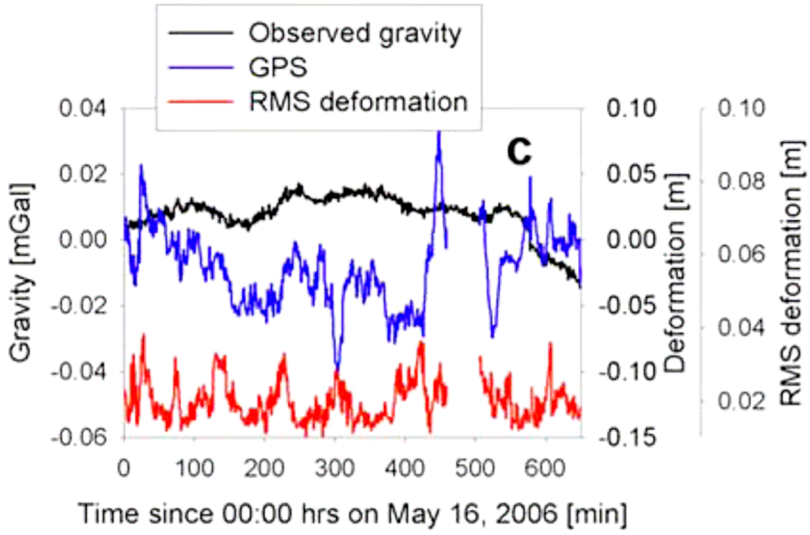

Observed gravity
GPS
RMS deformation
c
Gravity [mGal]
0.04
0.02
0.00
-0.02
-0.04
-0.06
0.10
0.05
0.00
-0.05
-0.10
-0.15
Deformation [m]
0.10
0.08
0.06
0.04
0.02
RMS deformation [m]
0
100
200
300
400
500
600
Time since 00:00 hrs on May 16, 2006 [min]

Figure 2. (a) Colour-coded digital elevation model (in m) of Nisyros Island, Greece, located at 36.57_N and 27.18_E in the Aegean Sea. Cross and triangle indicate approximate locations of instrumentation on May 16 and 19, 2006, respectively. (b, c) Joint records (continuous gravity, GPS, VLF, seismicity) of May 16, 2006. Figure 1b includes signals caused by the arrival of surface waves at min 659 from a Mw = 7.4 seismic event (10:39 UTC) at the Kermadec Islands (U.S. Geological Survey Earthquake Hazards Program, 2006, available at http://earthquake.usgs. gov/, hereinafter referred to as USGS, 2006) and a Mw = 6.8 earthquake in the Nias region of Indonesia about 5 hours later (USGS, 2006, time of teleseismic events are marked by red stars). The energy of the first event dissipates quicker in the seismic record than in the gravimetric record due to the excitation of the gravimeter by the Earth's eigenmodes. The VLF In Phase (20.8 kHz) record displays a break in slope about 15–20 min later indicating a change in the electrical properties of the subsurface. Figure 1c shows periodic oscillations in observed gravity and GPS data over approximately 10 h including several spikes and troughs in the GPS record, which cannot be explained by artefacts or poor satellite coverage. GPS data is reported relative to a reference located outside the caldera. The GPS RMS (root mean square) error is below 0.03 m for these events. [Reproduced from Gottsman et al., 2007]

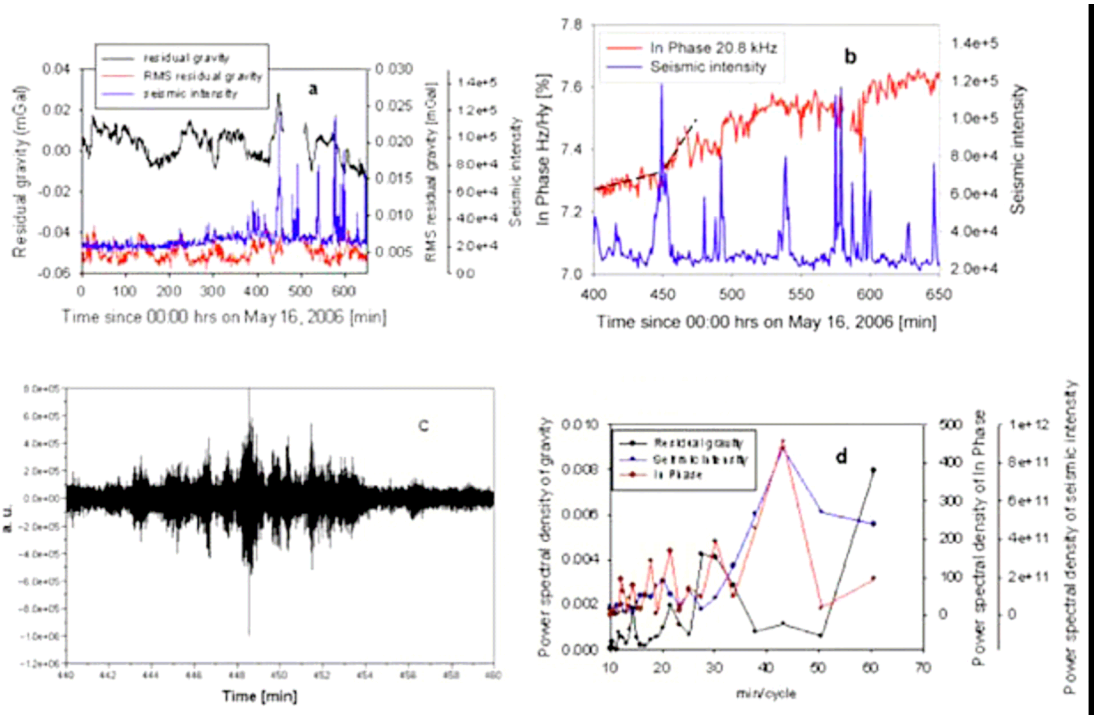


Figure 3. (a) Residual gravity data and RMS gravity errors and seismic intensity. Gravity data is reduced for the effect of ground deformation assuming a Bouguer density of 2100 kg/m3 for caldera fill rocks, resulting in a periodic oscillation with average amplitudes of 0.02 mGal and a peak of 0.03 mGal, coinciding with the burst in seismic intensity at 445 min. (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) followed by a peak amplitude after a delay time of 18 min. A similar delay is seen after the 490 min event and subsequent to the Mw = 7.4 teleseism a few hours later (Figure 1b). (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. (d) Fast-Fourier-Transform (FFT) power spectrum of gravity, seismic and VLF In Phase records of the first 10 hours of May 16, 2006. The VLF and seismic time series indicate cyclic oscillatory behavior with a peak power at 43 min also seen, though to a lesser power, in the gravimetric record with a peak at 60 min. Since the gravimeter and GPS receiver were not co-located with the VLF receiver during the experiment, we attribute the differences in the periods to differences in the sub-surface dynamics at the two locations. The seismic record is more global and identifies cycles at either location. [Reproduced from Gottsman et al., 2007]

DEM Generation

Kinematic GPS methods were used to generate an XYZ-dataset covering a small hydrothermal crater system within the main caldera. This location was the site of several integrated studies, and as such a 3-dimensional representation was requested to provide a convenient data presentation base.

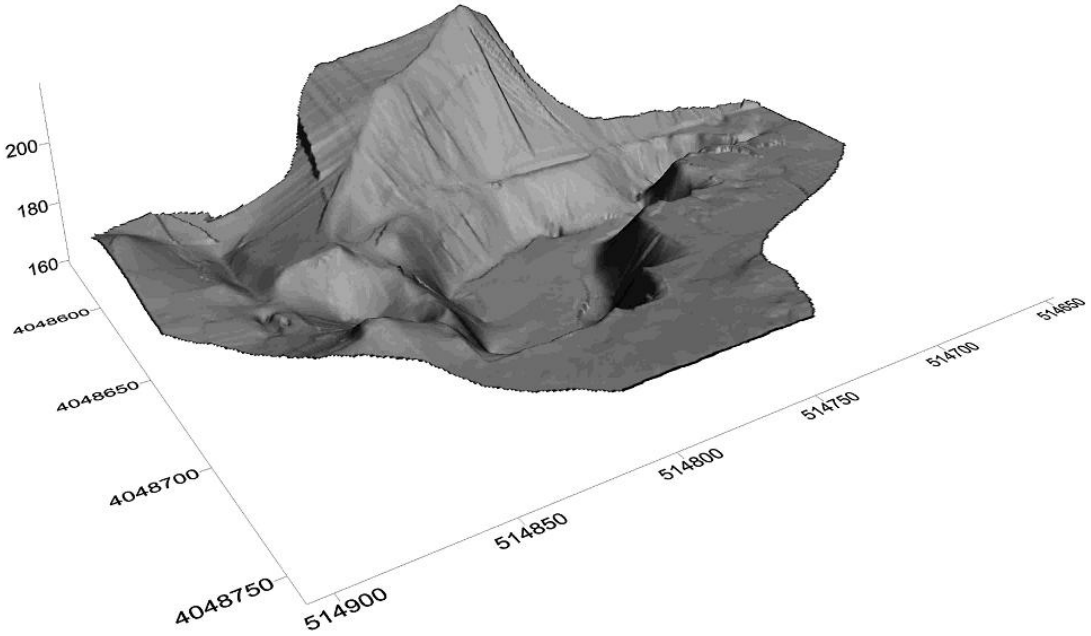


Figure 4. Three-dimensional representation of upper crater system, as generated using kinematic GPS during the field campaign. Axes are UTM.

STATIC GRAVITY

During the campaign, attention was also given to the structural setting of the caldera system. To this end, a static gravity campaign was carried out covering the main caldera and the caldera edge. This involved a brief simultaneous gravity and GPS measurement, together with a brief record of the surrounding topography. Several hundred measurements were made, covering a significant part of the caldera region, and it is hoped that this dataset will contribute to a better understanding of the fault systems related to the caldera-forming event and also to the wider regional tectonic faults. Final analysis of this dataset will be attempted later this year.

The Bouguer map produced using these data is reproduced in Figure 5.

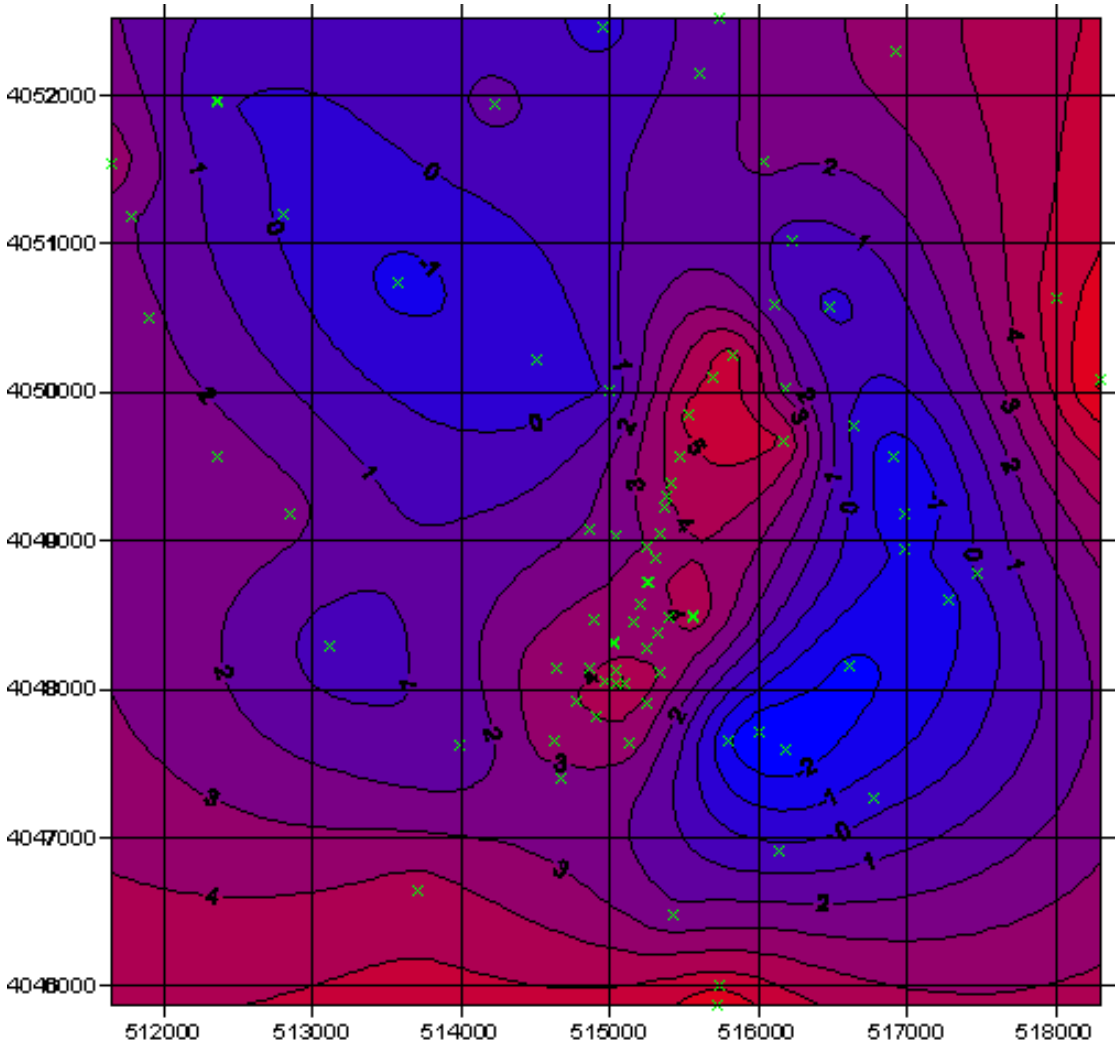


Figure 5. Preliminary Bouguer anomaly map for Nisyros using the GPS and gravity data collected during this campaign. Warm colours are positive gravity and the units are mGal. The reference is near the main town of Mandraki. The density used for data reduction is 2.6 Mg m^{-3} and terrain corrections have only been made on land at this stage.

CONCLUSIONS AND FUTURE WORK

This field campaign provided an opportunity to examine temporal changes in gravity detected in previous campaigns in more detail, and was successful in showing that these variations are not limited to the gravity signal. While GPS-derived variations were relatively small, the lack of significant variations showed that the gravity signal can not be solely due to deformation but that a secondary process must be involved. This was also reinforced by the detection of seismic and electro-magnetic signals.

A presentation of the initial results of the campaign was given at the American Geophysical Union's December 2006 meeting. Taking this further, a paper was published in Geophysical Research Letters this year (Gottsmann et al., 2007). This manuscript, which documents the temporal changes in the hydrothermal system at Nisyros, was attributed by AGU as a journal highlight because of its importance to the interpretation of gravity variations at restless calderas.

Following on from this successful campaign, a further campaign was conducted integrating additional instruments and extending the spatial and temporal coverage of the survey. This campaign, in May 2007, was again supported by NERC GPS equipment (this loan in the name of Joachim Gottsmann, University of Bristol).

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Tikku, A. A., D. C. McAdoo, M. S. Schenewerk, and E. C. Willoughby (2006), Temporal fluctuations of microseismic noise in Yellowstone's Upper Geyser Basin from a continuous gravity observation, Geophys. Res. Lett., 33, L11306, doi:10.1029/2006GL026113.