Gravity “steps” at Mt. Etna volcano (Italy). Instrumental effects or evidences of earthquake-triggered magma density changes?

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Abstract

On two occasions, sudden gravity changes occurred simultaneously at two summit Etna’s stations, during local low-magnitude earthquakes. A systematic coupling between earthquakes inducing comparable maximum acceleration and displacement at the observation points and gravity steps is missing, implying (a) the non-instrumental nature of the steps and (b) the need for particular underlying conditions for the triggering mechanism(s) to activate.

We review some of the volcanological processes that could induce fast underground mass redistributions, resulting in gravity changes at the surface. These processes involve bubbles and crystals present in the magma and require particular conditions in order to be effective as mass-redistributing processes.

The gravity steps could be a geophysical evidence of the dynamical stress transfer between tectonic and magmatic systems at a local scale. Given the implications that

these transfers may have on the volcanic activity, routine volcano monitoring should include the observation of fast gravity changes.

1. Introduction

Microgravity studies through continuous measurements are not routinely carried out at most active volcanoes. Nevertheless, a few long-term experiments of continuous microgravity measurements at active volcanoes were already accomplished (e.g. Jousset et al., 2000) and allowed fast (minutes to days) mass redistribution to be detected and interpreted on the grounds of the ensuing volcanic activity (Carbone et al., 2006; Carbone et al, 2008).

At Mount Etna on a few occasions, we observed sudden changes in the mean level of the gravity signal (10 – 20 microGal in a few minutes) simultaneously at two stations and during swarms of local low-magnitude earthquakes. Gravity steps of 5-15 microGal within two minutes were also reported to occur in association with earthquakes at Merapi volcano (Java, Indonesia; Jousset et al., 2000).

These gravity steps were long assumed to be instrumental effects. Similar changes (so-called “tares”) indeed occur when a spring gravimeter is transported by car on dirt tracks. They are not supposed to occur when a gravimeter acquires continuously at a single place (Torge, 1989).

In the following we discuss arguments in favor of the possibility that, at least in some cases, gravity steps are evidences of magma reacting to local seismic solicitations.

2. Data

Since 1997, continuous gravity stations have been installed at Mt. Etna (Fig. 1; Carbone et al., 2006). The stations are equipped with LaCoste&Romberg spring gravimeters which output gravity (resolution better than 1 microGal) and tilt changes (resolution = 2.5 microrad) at a rate of 1 datum/min. Each gravity station is within a few meters from a station of the permanent seismic network which comprises more than 30 stations, mainly equipped with digital broadband three-component seismometers.

On December 24, 1997 and on October 13, 2006 gravity steps between 10 and 20 microGal were observed at the same time at two Etna stations, over periods of 1-3 minutes (Fig. 1). One of the two stations was inside the Pizzi Deneri Volcanological Observatory (EPDN) on both occasions, while the other one was inside the Torre del Filosofo hut (ETDF) in 1997 and inside a semi-underground concrete box in 2006 (EBEL). Furthermore, different couples of gravimeters were employed in each of the two occasions (Fig. 1).

The levels fitted to each gravimeter utilized did not record significant tilt changes during either couple of gravity steps. Significant ground deformation was not observed through the summit GPS continuous stations on October 13, 2006 (continuous GPS measurement have been accomplished at Etna since the end of 2000 at 1 Hz sampling rate and with a resolution of 5–10 and 20 mm for the horizontal and vertical components, respectively).

Both couples of gravity steps occurred during swarms of local low-magnitude earthquakes. The swarm on December 24, 1997 consists of 20 events with Md ranging [1.3-3.8]. The swarm on October 13, 2006 consists of 10 earthquakes with

Md ranging [1.2-2.6]. In both cases, the gravity steps are associated with the strongest earthquake of the swarm.

During the periods encompassing both couples of gravity steps, the volcanic activity interested the Summit Craters area. In particular, during the October - December 1997 period, all the four Summit Craters of Etna were active, while, during the September-December 2006 period, strombolian and effusive activity occurred from vents located at the base of the SEC cone (Fig.1a).

3. Are the gravity steps instrumental effects? A joint seismic/gravity analysis

The fact that both the Etnean gravity steps under study occur simultaneously at two stations about 3 km apart rules out local mechanical/electronic shortcomings as a triggering cause. Nevertheless, it can not be ruled out that the steps are instrumental effects induced by the ensuing seismic perturbation.

During the end of 1997, the gravity stations worked contemporaneously for a quite short time interval (only about 1 month). 5-to-6-month time-series were acquired in 2006. Furthermore, more reliable seismic data have been acquired after 2001, thanks to the improved instrumentation. Thus, the hypothesis about the simultaneous gravity steps being a mechanical instrumental effect, due to the ensuing earthquake, is tested using gravity/seismic data acquired in 2006. In particular, we calculate the maximum displacement and acceleration along the vertical direction, induced at stations EBEL and EPDN, by 400 events with Ml>1.0, during the June-December 2006 period. If the gravity steps are instrumental effects, they must occur every time the maximum displacement or acceleration induced by an earthquake approach or overcome the 13

October thresholds. Even though the thresholds are approached and crossed four times, a change in the mean level of the gravity signal does not occur in correspondence of any of the earthquakes other than the 13 October one (Fig. 2b). In particular, the earthquake on December 19 induced a vertical displacement and acceleration about 10 and 3 times larger than the October 13 earthquake, respectively.

In order to test whether the jumps are triggered by a certain frequency in the seismic signal, we compute the power spectral density (sliding 2.56 sec Hanning window with 50% overlap) of the vertical component of the ground velocity for the five selected seismic events (Fig. 2a). There are no important differences in the spectral features of the 13 October earthquake with respect to the other events under attention. In particular, a broad frequency content, with dominant spectral peaks, occurring mostly between 2 and 10 Hz, is common to all the earthquakes considered.

Note, however, that some earthquakes, even though they are not associated with permanent changes in the mean level of the gravity signal, correspond to fast gravity changes due to the shaking induced on the gravimeters (Fig. 2b).

The fact that earthquakes which induce a maximum acceleration and displacement at EPDN and EBEL, comparable to those induced by the 13 October earthquake, are not associated with gravity steps is an evidence against their instrumental nature. It also indicates that, if a volcanological process is able to trigger fast changes of the gravity field under the action of seismic waves, it requires particular underlying conditions in order to activate. Thus, the question we face is: which mechanisms could trigger sudden gravity changes at a volcano where summit activity is occurring and in concomitance with local low-magnitude seismic events?

4. Possible triggering mechanisms

An earthquake can induce fast gravity changes (i) statically, via a static stress change of the medium surrounding the seismogenetic fault and (ii) dynamically, through a change in the physical properties of the medium induced by the shaking.

Okubo (1992) derived, in analytic form, the gravity changes due to coseismic perturbations to the density field. Gravity changes, calculated through Okubo's model for both the December 24, 1997 and the October 13, 2006 earthquakes, are some orders of magnitude less than observed.

This result implies that, if the gravity steps are not instrumental effects, they must be related to a response of the medium to dynamic stresses from the seismic waves. Many authors considered the possibility that earthquakes can trigger volcanic eruptions through changes in the physical properties of a magma chamber vibrated by seismic waves (e.g. Hill et al., 2002; Manga and Brodsky, 2006). We discuss whether some of the mechanisms they proposed could induce mass/density changes of the vibrated magma body, in turn observed as gravity changes at the surface.

Etna's upper plumbing system is best envisioned as a plexus of dikes and sills, interconnecting the conduits below the four Summit Craters (e.g. De Gori et al., 2005). In order to derive to a first order the density change that the medium should experience to produce the observed gravity changes, we approximate the plumbing system of Etna to a cylinder (see Fig. 3). By taking into account the relative position of summit gravity stations and craters (Fig. 1), we calculate that the magma in the upper part of Etna storage system should undergo a density change of the order of 1-2 % to induce a gravity change of the order of 10-20 microGal at the summit Etna stations. Note that the effect on the vertical component of the gravity field at the observation points is different if density changes occur at different depths along the main axis of the source body (Fig. 3).

4.1 – Bubbles: diffusion, rectified diffusion and advection

The most simplistic way for seismic waves to change the density of a magma body is through bubble nucleation and gas diffusion. The changes in pressure induced by the contraction/rarefaction stages of the passing seismic waves can lead to diffusion of gas to/from pre-existing bubbles and/or nucleation of new bubbles. In fact, both volatile solubility and bubble nucleation rate strongly depend on pressure.

We use the simple theoretical relationships proposed by Wilson and Head (1981) to calculate which density change is induced by a given pressure change through diffusion of water, the most abundant volatile in magma. The calculation is performed assuming (i) initial water contents of 2 and 5% wt (Métrich et al., 2004) and (ii) initial pressures of 20-50 MPa (lithostatic pressure at depths between 1000 and 2000 m). A pressure change of at least 0.1 MPa is needed to induce a 1-2 % density change through diffusion of water.

Furthermore, according to Hurwitz and Navon (1994), a critical supersaturation pressure of at least 5 MPa is needed to trigger bubble nucleation. We calculate the maximum dynamic stress associated with the 13 October earthquake through the equation given in Hill et al. (1993). It relates the stress amplitude, associated with an earthquake, to $G\,(\mathring{u} * v_s^{-1})$, where G is the shear modulus ($1\text{-}2*10^4$ MPa; Trasatti et al., 2008), v_s is the shear wave velocity (3300 m/s) and $\mathring{u}$ is the peak particle velocity. A maximum dynamic stress of the order of 10^{-2} MPa results, thus one order of magnitude lower than needed to induce a 1-2 % density change through diffusion of water and also far too low to trigger bubble nucleation.

It is also to be stressed that seismic waves are merely transitory phenomena and thus the magma body would presumably recover the pre-excitation state, after the wave has passed, if there were not a mechanism able to convert the dynamic stresses into longer-lasting changes of the magma physical state.

A permanent (or lasting much longer than the duration of the shake) variation in magma properties may be induced by rectified diffusion (Ichihara and Brodsky, 2006). When subjected to seismic waves, gas bubbles expand and contract. Contraction induces oversaturation inside the bubbles and gas escapes out to the melt. The opposite happens when bubbles expand. Since the surface area is smaller for the contracting bubble, the mass flux towards the bubbles exceeds the flux towards the melt, resulting in a net flow of gas into the bubbles, and thus in a local density decrease, if bubbles are allowed to expand.

Rectified diffusion in the volcanic system is usually treated only from the point of view of its ability to rise the magma pressure, thus triggering an eruption either by stressing the chamber walls or by increasing the vigor of convection. The maximum attainable pressure increase is limited by gas resorption via ordinary diffusion and depends on bubble size, initial degree of supersaturation, duration of the shaking and amplitude of the dynamic strain wave (Ichihara and Brodsky, 2006).

A magma body undergoing convective processes over time scales much longer than the duration of the shaking, could be highly heterogeneous, with regions that are crystallizing, and tend to become supersaturated in volatiles, and other regions where mineral phases are resorbed into the melt (subsaturated). Under such conditions, the passing seismic waves would cause bubble expansion via rectified diffusion in supersaturated regions, inducing a pressure rise in the system and a rise in the saturation concentration, and thus gas resorption via ordinary diffusion, in other portions of the magma body. As a consequence, modifications in the density distribution could take place over time scales of the order of the duration of the shaking, without significant pressure changes.

Differential changes in bubble distribution in a vibrated magma body can also occur if bubbles, which are either captured at the solid surfaces of the magma container by surface tension effects (Linde et al., 1994) or accumulated in structural traps (Menand and Phillips, 2007) are shaken loose by the passing seismic waves and migrate due to buoyancy. According to Stoke's law, the possibility for this mechanism to be effective in redistributing density within an extended magma body over time intervals of the order of minutes depends upon the magma viscosity and the size of the bubbles. Large bubble sizes (> 1 cm) and viscosities of the order of 10 Pa s (the typical viscosity range of basaltic melts is 10^{-1} to $3*10^{3}$ Pa s) are required for bubbles to move fast enough and also for diffusive interactions, that would counteract the effectiveness of this mechanism, to be neglected (Pyle and Pyle, 1995).

4.2 - Crystals

Besides through redistribution of bubble size/position, changes in the density of a vibrated magma body could be induced via mechanisms involving crystals present in the melt. A mass of crystals loosely held together may accumulate below the roof or at the sides of a crystallizing magma body and could be dislodged by passing seismic waves, if the dynamic strains break the crystal-to-crystal bonds (Hill et al., 2002; Manga and Brodsky, 2006). The sinking crystal plumes could induce local gravity changes through the density contrast with the surrounding melt. A $3*10^{8}$ m^{3} crystal plume, with a density 1 % higher than that of the surrounding melt and placed below the summit crater zone, would induce a gravity change of about 10 microGal at the summit stations if it dropped about 1 km from the level of the gravity stations (about 2800 m a.s.l.). In fact, the vertical component of the gravity effect at the observation points would be almost zero at the starting position and maximum after the plume travels about 1 km downwards (Fig. 3). For that to occur over a time interval of the order of minutes, the sinking velocity must be of the order of 10 m/s, in keeping with the sinking velocity of fully formed plumes found by Manga and Brodsky (2006).

Growing crystal mushes could also act as temporary blockages, locally limiting the magma flux within the plexus of dikes and sills which forms the shallower levels of Etna storage system (De Gori et al., 2005). Removal of this blockage, once the accumulation of crystals is dislodged by the seismic waves, may lead to a sudden mass redistribution within the magma body. A similar mechanism was proposed by Brodsky et al. (2003) to explain coseismic groundwater pressure steps.

Besides breaking the grain-grain bonds in mass of crystals, seismic waves, acting on densely-packed melt-embedded crystals on the floor of a magma chamber, can cause instability on near-instantaneous timescales. Davis et al. (2007) showed that a force arising from crystal-crystal interactions (particle pressure) develops, inducing both contraction of the granular mush layer and a pressure decrease in the interstitial melt, the latter leading to generation of bubbles and changes in local crystal-melt geometry. Formation of bubbles due to the pressure decrease in the interstitial melt could result in the accumulation of a foam layer at the boundary between the crystal mush and the overlying magma; on the other hand, the overall pressurization of the system due to the generation of new bubbles at the bottom of the chamber could induce a rise in the saturation concentration, and thus a density increase in the magma above the crystal mush, if gas resorption occurs via ordinary diffusion. The amplitude and sign of the possible gravity effect measured at the surface will thus depend on the overall geometry of the system and in particular on the relative position of observation points and mush/magma interface.

5. Conclusive issues

We observed sudden gravity changes at the same time at two summit Etna’s stations, in conjunction with local low-magnitude earthquakes and during periods of activity from the Summit Craters. The lack of systematic coupling between local earthquakes inducing similar maximum displacement/acceleration at the observation points and gravity steps is a strong evidence in favor of the non-instrumental nature of the jumps and also implies that particular underlying conditions are needed for the source processes to activate. Besides, the lack of ground deformation associated with the gravity steps implies that they must result from sudden underground mass redistributions. We propose some volcanological processes that, under the action of seismic waves, could result in abrupt underground mass/density changes, observable as gravity changes at the surface. Most of these processes actually require particular underlying conditions in order to activate (a magma body with regions differently saturated in volatiles; the existence of unstable accumulations of large-sized bubbles; the presence of an unstable crystal mass in the upper part of the crystallizing magma body or of a crystal mush on the floor of the magma chamber).

The different nature of the possible triggering mechanisms, in conjunction with the geometrical relationships between source body and observation points, dictate that the characteristic of the gravity jumps (as for amplitude and sign) can be significantly different. Importantly, some of the mechanisms listed in the previous section (coupled rectified/ordinary diffusion, bubble advection channeled by sill-like structures, mass fluxes due to removal of blockages by crystal mushes) could result in lateral density redistributions and thus in changes of different magnitude, and even opposite sign (as observed in 1997; Fig. 1b, c), at the observation points.

In any case, the gravity steps discussed in the present study could be one of the rare evidences of the dynamic stress transfer between tectonic and volcanic systems at a local scale. Similar effects could be induced by distant large earthquakes which are thought to be able to trigger subsequent -or influence the course of ongoing- volcanic eruptions even over long distance (Hill et al., 2002). We thus encourage the development of a programme of continuous gravity monitoring of active volcanoes on a global scale, to be performed in conjunction with other techniques (ground deformation, gas monitoring, etc.) and to a suitable time/amplitude resolution, in order to observe rapidly-evolving, low-amplitude variations.

Figure Captions

Fig. 1 – (a) Map of Etna showing the position of the gravity/seismic stations and the epicenters of the two swarms of local low-magnitude earthquakes which took place on 1997.12.24 and on 2006.10.13 (white and black dots, respectively). The time intervals when the two swarms occurred are evidenced with gray strips superimposed on Figs. 1b-c and d-e.

Fig. 2 - Three-hour gravity data series, acquired at EBEL (b top) and EPDN (b bottom) stations and encompassing earthquakes in the Etna area. For each

earthquake are reported, over 60 sec. windows, the waveform (a top) and the spectrogram (a bottom) observed at EPDN station. The spectral amplitudes are plotted in logarithmic scale. The maximum acceleration and displacement induced by each earthquake at EBEL and EPDN stations are reported in (b).

Fig. 3 - Schematic cross section showing the relative position of the summit gravity stations and the upper plumbing system of Etna, modeled as a vertical cylinder. The inset on the right shows the normalized effect on the vertical component of the gravity field at the observation points (also shown as a grayscale across the cylinder). The same density change, occurring at different depths within the cylinder, induces different gravity effects.

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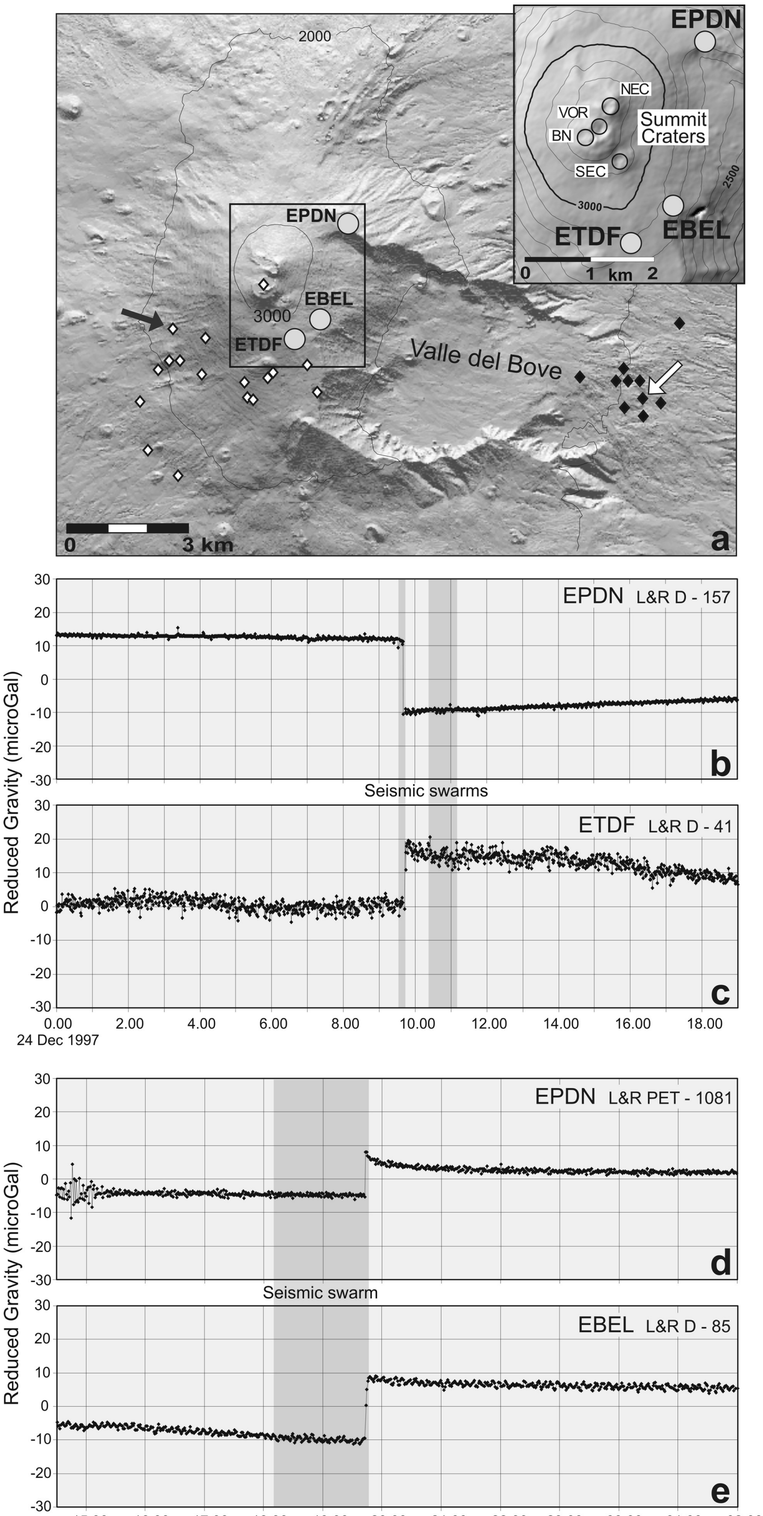
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EPDN
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a
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Summit Craters
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3000
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ETDF
EBEL
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Reduced Gravity (microGal)
EPDN L&R D - 157
b
Seismic swarms
ETDF L&R D - 41
c
30
20
10
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-10
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-30
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24 Dec 1997
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12.00
14.00
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EPDN L&R PET - 1081
d
Seismic swarm
EBEL L&R D - 85
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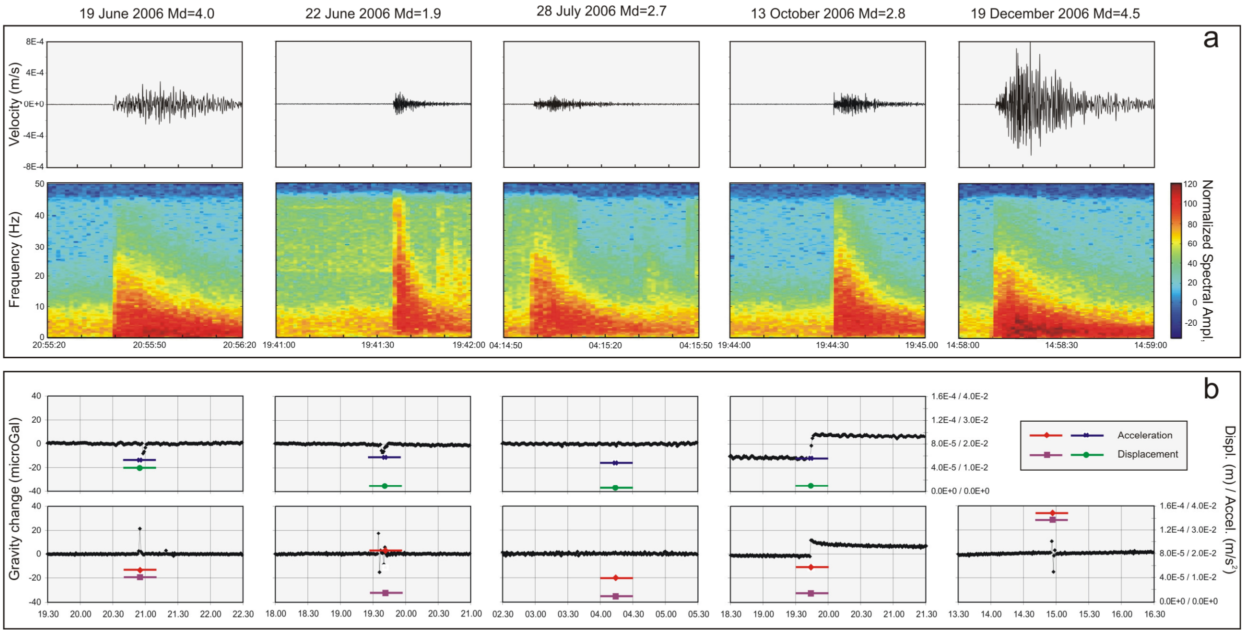
Figure 1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28 July 2006 Md=2.7
13 October 2006 Md=2.8
19 December 2006 Md=4.5
a
Velocity (m/s)
8E-4
4E-4
0E+0
-4E-4
-8E-4
Frequency (Hz)
50
40
30
20
10
0
20:55:20
20:55:50
20:56:20
19:41:00
19:41:30
19:42:00
04:14:50
04:15:20
04:15:50
19:44:00
19:44:30
19:45.00
14:58:00
14:58:30
14:59:00
Normalized Spectral Ampl,
120
100
80
60
40
20
0
-20
b
Gravity change (microGal)
40
20
0
-20
-40
Acceleration
Displacement
Displ. (m) / Accel. (m/s^2)
1.6E-4 / 4.0E-2
1.2E-4 / 3.0E-2
8.0E-5 / 2.0E-2
4.0E-5 / 1.0E-2
0.0E+0 / 0.0E+0
19.30
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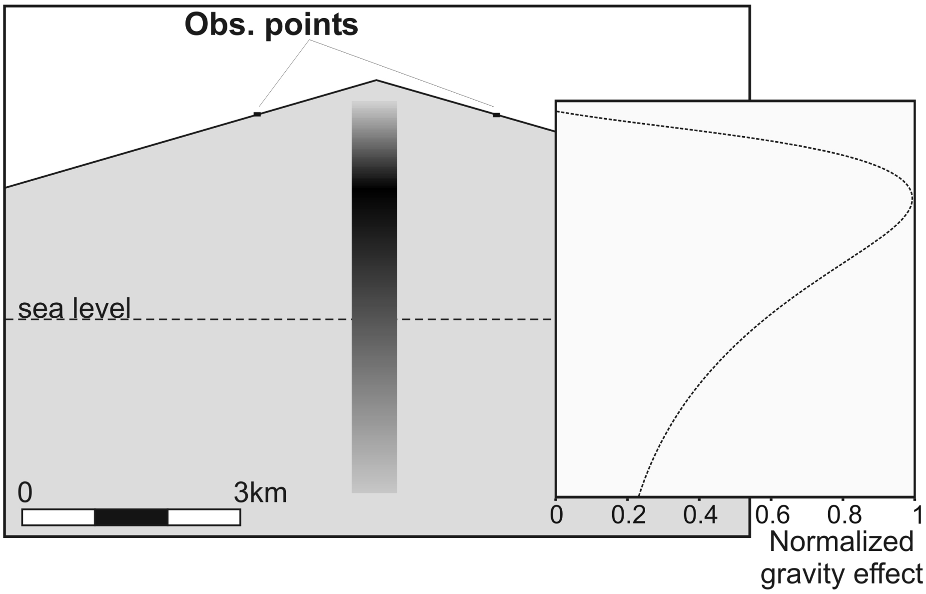
Figure 2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0.8
1
Normalized gravity effect

Figure 3