Precursory signal of the last eruption of Mount Etna detected by continuous gravity observations

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Abstract

Mount Etna volcano is characterized by a fractured edifice so that the seismic activity and the ground deformation are often minimal and even insignificant during the pre-eruption phase. In this case, the microgravity represents a good alternative volcano monitoring technique to detect the mass changes in relation with the movement of fresh magma to shallower levels. In 1992, the LaCoste & Romberg gravimeter LCR8 was installed in Serra La Nave station on the Southern flank of the Etna edifice. As the spring gravimeters are strongly influenced by the Earth tides and the meteorological parameters, it was necessary to remove their effects in order to obtain reliable gravity residuals which could be related to the volcanic activity. Before the beginning of the 1995-2001 eruption, the LCR8 recorded gravity variations of about 350 µgal (1µgal = 10nm.s^{-2}), which are clearly correlated with seismic activity and other precursors of the paroxismal activity. These observations are not incompatible with the moderate 40µgal gravity increase at the Etna summit between the September 1994 and October 1995 discrete gravity measurements, due to the epoch of these campaigns.

Introduction

Most emphasis has been put in recent years on the development of volcano monitoring, based on the integration of different geophysical and geochemical techniques. This multidisciplinary approach is largely improving the monitoring reliability.

The 500.000 year-old Mount Etna is the most active volcano in Europe. Its last eruption, which began in 1995, is considered to be the most important one during the last three centuries. It involved the four craters with lateral fractures long of some 6 km on the NE and SE flanks. This eruption was explosive, characterized by many violent episodes with strong gas emissions, lava fontaining, big ash panaches, etc. It appears that Mount Etna is becoming more and more explosive indicating a change in its behaviour. According to Schiano et al. (2001), the volcanism of Mount Etna is now in a transition phase from a mantle plume source to an island arc source.

It has already been stressed that Mount Etna eruptions occur without significant precursory signals as the seismic activity and the ground deformation remain often minimal (McGuire et al., 1995; Rymer et al., 1993). In these conditions, only the microgravimetry is able to detect the mass changes associated with the emplacement of fresh magma at shallower depth. However, if microgravimetry survey is an usual tool, few examples of continuous gravity observations on volcanoes exist and none lead to any conclusive results.

Taking these facts into account, our gravimetric investigations were oriented in 1992 to the monitoring of the Mount Etna in Sicily, one of the selected European laboratory volcanoes. The LaCoste & Romberg gravimeter LCR8 was installed in Serra La Nave Observatory, situated on the South flank of the volcanic edifice near the SE crater (see figure 1), and continuously recorded gravity variations from 1992 till 1995. As the gravity changes due to volcanic activity are very small compared to other geophysical or instrumental effects, several corrections are needed to get reliable gravity residuals susceptible to reflect the volcanic effect. For this purpose we developed correction algorithms for different perturbing signals like Earth tides, atmospheric pressure and ambient temperature and humidity.

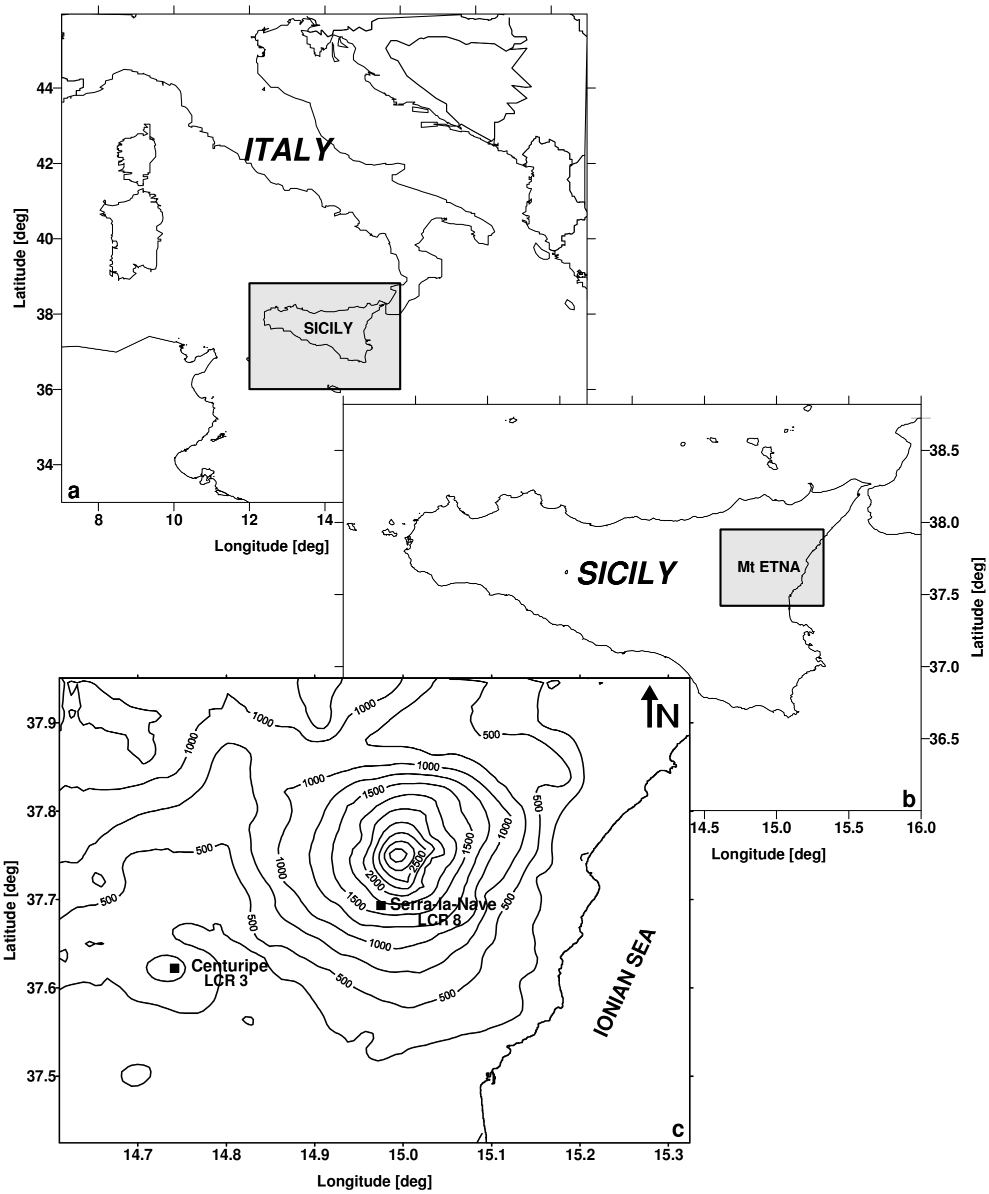

Fig. 1 – (a) = map showing the Sicily localisation in the South of Italy, **(b)** = map showing the Etna volcano position in the NE of Sicily, **(c)** = Topographic map of Mount Etna showing the position of Serra La Nave (SLN) station where the gravimeter LCR8 was installed.

Data processing

We first analyse the Earth tides effect (Eterna, Wenzel 1996) which can be thus modelled with high accuracy and removed efficiently from the raw gravity measurements (TET in figure 2 a and b) (El Wahabi et al., 1997). The residues are often called "drift".

Considering the fact that, for the final residuals, we are looking for a precision of about 1 µgal for a period of one day, a simple linear regression using the local pressure is sufficient to correct the air pressure effect. It was found that we can correct the atmospheric pressure influence on the LCR8 gravity readings by two different regression coefficients close to –1.2 µgal/mbar for the short period and –1.9 µgal/mbar for long period variations (P in figure 2 d, e and f). These coefficients are very high and indicating that this gravimeter is not well compensated any more for air pressure variations and this probably because the pressure seals are not more airtight (El Wahabi et al., 1997).

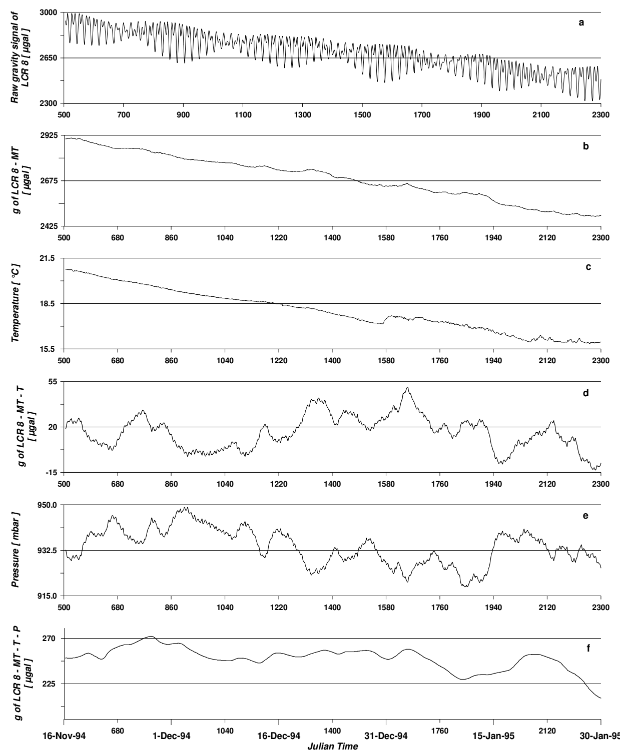

Fig. 2 – Data recorded at Serra La Nave station from 16/11/1994 to 30/01/1995. (a) = raw gravity data of LCR8, (b) = gravity residuals after removing Theoretical Earth Tides (TET), (c) = temperature records, (d) = gravity residuals after removing TET and Temperature Tendancy (TT), (e) = pressure records, (f) = final gravity residuals after removing TET, TT and Pressure effect (P).

Generally, continuous gravity recordings show a large annual variation of the drift as a common feature, with a magnitude ranging from hundreds of microgals to a few mgals. This drift usually presents for the LCR gravimeters an obvious correlation with temperature variations (TT in figure 2 b, c, d and figure 3). It is not astonishing as variations of the ambient temperature affect directly the operation of the thermostat of the gravimeter. However, in some stations (Pecny, Potsdam), where the temperature is controlled with an accuracy of ± 0.1°C, tidal gravimeters still show large annual variations in their drift. As a matter of fact, the experiment of Bastien and Goodacre (1990) has shown that, in a controlled environment, the air humidity may be directly responsible for the gravimeters drift as well. Finally, our experiment in the thermostatized fundamental station of the Royal Observatory of Belgium (ROB) (El Wahabi et al., 2000, 2001) led us to consider that the humidity was the responsible parameter for the annual oscillations present in the LCR8 drift and, more generally, that LCR gravimeters react as humidity integrators. The sensitivity of these instruments to humidity variations is thus inversely proportional to the associated frequency. The annual wave is thus largely dominating the spectrum of the instrumental response to humidity variations.

In Serra la Nave we had temperature measurements but no sensor for humidity. However our experiments at ROB have shown that natural humidity variations in the vault followed external humidity variations, which in turn are anticorrelated with temperature. External temperature represents thus a good proxy of humidity. This fact is confirmed at Serra la Nave where a cross-correlation shows a phase lag of about 70 days of the gravity signal with respect to the temperature variations outside the station (in the open air). Bastien and Goodacre (1990) obtained a similar result in Ottawa between ET-12 gravimeter and outdoor absolute humidity which was leading the gravity residuals drift by some 60 days.

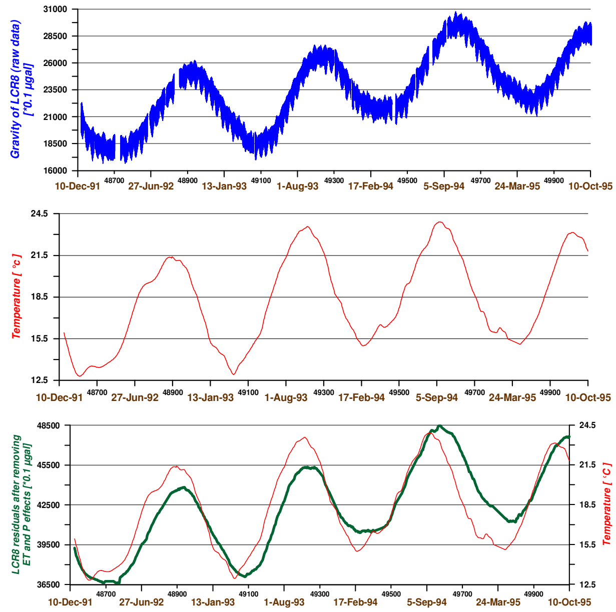

Fig. 3 – Top : raw gravity signal of LCR8 gravimeter recorded in Serra La Nave station for the period 1992-1995 ; middle : temperature variations ; bottom : gravity residuals (Earth tides and pressure effects removed) compared with temperature variations.

To account for the large frequency spectrum of the perturbing temperature and humidity signals, we determined the impulse response of the system (De Meyer, 1982) with respect to external temperature used as a proxy of the perturbing signals. We were thus able to remove the annual wave and its harmonics and obtained the final gravity residuals illustrated in figure 4.

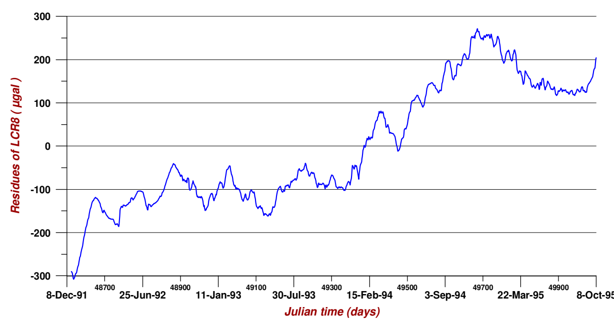

Fig. 4 – Final gravity residuals of LCR8 gravimeter (SLN) for the period 1992-1995.

These final residuals present now the raw material to be correlated with geophysical parameters. Comparing these residuals to the raw data, we notice a significant attenuation of the signal. The Fast Fourier Transfer (FFT) analysis in amplitude shows only red noise (Figure 5),

indicating an efficient correction of the periodic signals. It is therefore clear that the slower the gravity variations the higher the detection threshold. If we consider that an event must be 3 times bigger than the noise level, the one week detection threshold is about 9 µgal for LCR 8.

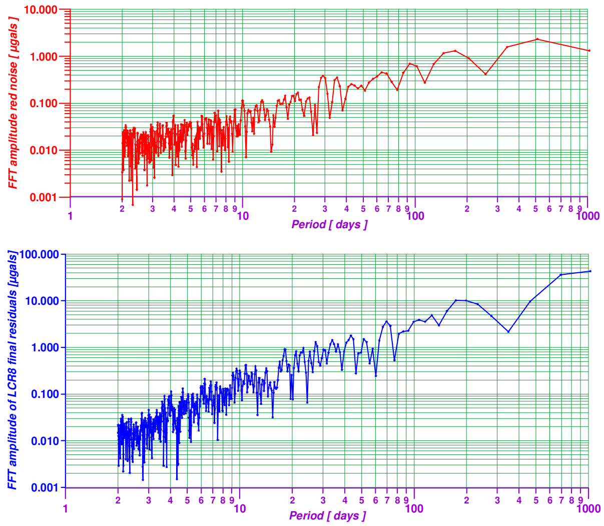

Fig. 5 – Top : FFT analysis for a red noise generated with a standard deviation equal to 1. Bottom : FFT analysis for LCR 8 final gravity residuals.

Correlation between gravity residuals and volcanic activity

Microgravity studies over some 20 volcanoes in the world showed that volcanic activity produce gravity changes of some tens to hundreds of microgals (Rymer, 1996). These gravity variations could be related to the ground deformation (inflation and deflation edifice) and/or the density changes. Basaltic shields and rifts like Krafla (Iceland), Kilauea (Hawaii) and Etna (Sicily) showed large gravity variations (over hundred of microgals) and small elevation changes. The Etna eruption of December 1991 was indeed preceded by negligible ground deformation (Rymer, 1996).

The curve of these residuals show a gravity increase of about 350 µgal, between January 1994 and January 1995, before the first activity observed at the summit craters of Mount Etna materialised by some ash emissions (Armienti et al., 1996) (see figure 7). The beginning of this gravity increase coincides with a slight increase of the seismic activity (La Volpe et al., 1999) (see figure 6). As the GPS technique did not record any inflation between 1993 and 1995 on the southern part of Etna edifice (La Volpe et al, 1999) where the LCR8 gravimeter was installed, the 350 µgal gravity residual changes of LCR8 could be considered as related to the magma rising before the 1995 Etna eruption.

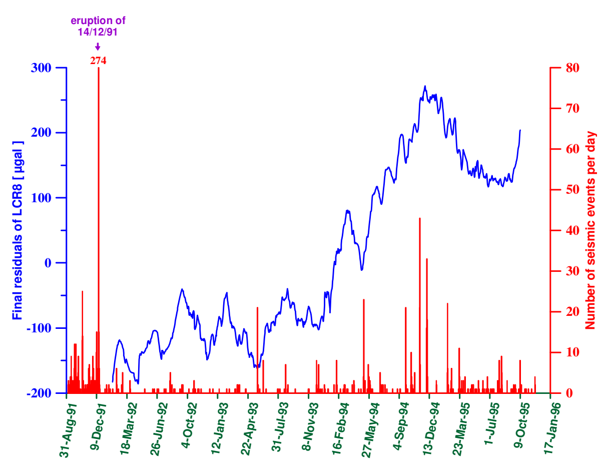

Fig. 6 – Correlation between the final residuals of LCR8 and the daily seismic activity at Serra La Nave station (from "Stato del Vulcan Etna" reports of the International institute of volcanology of Catane).

Once reaching a maximum, the gravity variations started decreasing before changing their trend with a new increase while it was occurring strong Strombolian activity at the summit craters (see figure 7).
We propose a mechanism to explain the beginning of the 1995-2001 eruption of Mount Etna in agreement with our gravity observations. In this mechanism, the magma, moved by virtue of its gravitational buoyancy, rises from its source (probably located at the crust-mantle boundary, at about 27 km depth) and fills a shallow reservoir (Wadge, 1982; Armienti et al., 1984) (plexus of dykes) within or just bellow the volcanic edifice. This first step occurred some months before the beginning of the 1995-2001 eruption and corresponds to the observed increase in gravity. During the second step, corresponding to the period of repose prior the eruption, the temperature and the lithospheric pressure of the magma decrease at this level of depth so that the processes of crystallisation and
vesiculation may start, leading to a vertical segregation of the magma. Therefore, a vertical density gradient would be expected to appear in the reservoir as a result of an upward accumulation of volatiles and other light components to the top and a downward accumulation of heavy components to the bottom. The consequence of these processes is a downward displacement of the centre of mass of the magma corresponding to the decrease of the

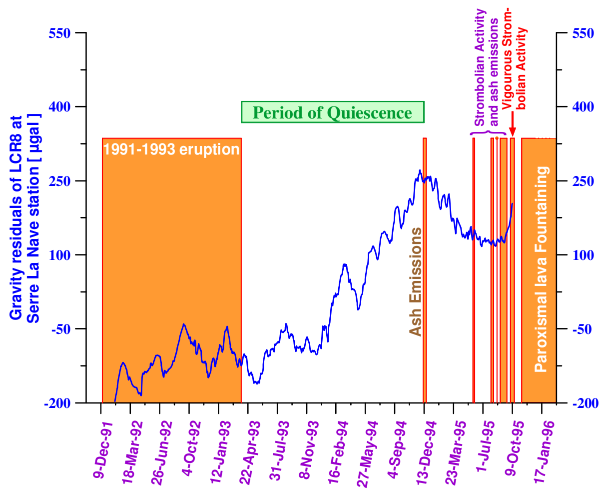

Fig. 7 – Correlation between the gravity residuals of the gravimeter LCR8 and the observed volcanic activity (Armienti et al, 1996) of Mount Etna for the period 1992-1995.

observed gravity. The over-saturation of the magma in volatiles would then trigger the eruption which would lead to the second increase in the gravity variations.

Comparison with discrete gravity measurements

Carbone and Greco (2007) propose an interpretation of discrete gravity measurements at Mt. Etna from 1994 to 1996. They use the quasi NS summit profile, which does not include SLN station. They observe a 40µgal gravity increase around the summit between September 1994 and October 1995 and propose a spherical source beneath the central craters, 2000m below the surface. It is roughly 500m below SLN but quite excentered. It is followed, between October 1995 and July 1996, by a withdrawal of mass from the central zone and the injection of a dyke to the SSE. These observations are not necessarily incompatible with Fig. 7, as the gravity at Serra la Nave had already increased of 200 µgal in September 1994 and the maximum of gravity was already overstepped in October 1995. This campaign corresponds to the final increase of gravity observed in September 1995 at SLN. Our opinion is that the summit observations reported by Carbone and Greco reflect only local gravity changes associated with shallow mass transfer, while continuous gravity changes recorded at SLN recorded deep phenomena with a large spatial extension.

Conclusions

The correction algorithms of all the known perturbations (earth tides, air pressure, temperature and humidity) have been improved to obtain the best final gravity residuals which can be correlated with other geophysical signals of volcanic origin. This correlation leads to the conclusion that continuous microgravity monitoring proves to be an efficient technique for the prevision of volcanic eruptions. So, it is very important to combine the continuous and discrete microgravity observations with the other geophysical and geochemical techniques in order to improve volcanoes monitoring.
Continuous gravity monitoring will only provide significant results after correction of all the geophysical and instrumental perturbing effects i.e. tides, pressure, temperature and humidity. The tidal gravity station at Serra La Nave is well located to detect possible gravity changes associated to the deep volcanic activity of Mount Etna.
The results of simultaneous discrete gravity campaigns depended strongly of their timing as they can only provide snapshots of the mass transfer. Due to the limited extension of the network and the lack of absolute gravity reference they were not able to detect deep mass transfers producing large scale gravity variations.

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