Insights into the internal dynamics of Etna volcano through discrete and continuous microgravity observations

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Abstract

Discrete and continuous microgravity observations have been routinely performed at Mt. Etna since 1986 and 1998, respectively. Besides furnishing a full view of how gravity measurements from Etna are accomplished and reduced, this paper is a collection of case studies aimed at demonstrating the potential of microgravity studies to investigate the plumbing system of an active volcano and detect forerunners to paroxysmal volcanic events.

As for discrete measurements, case studies relative to the 1994-96 and 2001 periods are reported. During the first period, the observed gravity changes are interpreted within the framework of the strombolian activity which occurred from the summit craters. Gravity changes observed during the first 9 months of 2001 are directly related to the underground mass redistributions who preceded, accompanied and followed the July-August 2001 flank eruption of Etna.

As for continuous measurements, a three-year (1998-2000) sequence and a 48-hour (26-28 October 2002) sequence, both from PDN station, are presented and discussed. The first one is maybe the longest continuous gravity sequence ever acquired at a station very close to the summit zone of an active volcano. It allows to discover the cyclic character of a source whose geometrical characteristics are retrieved through data from discrete measurements.

The second sequence is also likely to represent an unique item: a gravity sequence encompassing the onset of an eruption and coming from a station only 1.5 km from the eruptive fissures. It allows some constraints to be set on the characteristics of the intrusive mechanism leading to the eruption.

Key words: Mt Etna, microgravity, magma sources, modeling

1. - Introduction

The study of time variations of the Earth gravity field can provide fundamental pieces of information about the internal dynamic of the globe at different time and space scales. On the field, because of the instrument limitations and of a greater exposure to external perturbations than in laboratory-like conditions (meteorological effects, micro-seismic activity, etc.), only temporal gravity changes whose amplitude is at least a few tens of μGal can be studied. Changes of such a relatively large amplitude can be easily reached in tectonically active or volcanic zones (Torge, 1989).

Temporal gravity changes in volcanic zones are related to sub-surface mass-redistrubutions or to elevation changes in response to magmatic activity and vary according to the size, depth and rate of evolution of the magma bodies involved. The associated gravity anomalies can thus change significantly in both space (wavelengths ranging from hundreds of meters to tens of kilometers) and time (periods ranging from minutes to years). The choice of monitoring strategy is therefore crucial for correctly assessing the anomalies of interest.

Usually, microgravity measurements are accomplished in a “discrete” fashion: a single instrument is used to make a series of measurements at several places, referring each gravity value to the value from a non-active site, i.e. where changes of the gravity field due to underground mass redistributions are not expected (reference point). The whole survey is then repeated and any time-change in the gravity difference between the reference point and the places of interest is noted. After removing the effect of Earth Tides, the observed time variations of the gravity field, are interpreted in terms of sub-surface mass-redistributions.

One of the main drawbacks of repeated network monitoring is the lack of information on the rate at which the volcanic processes occur, since only the change of the subsurface mass distribution between the times when two successive surveys have been performed (usually ranging between a week and a year) can be assessed and therefore there remains some ambiguity as to the nature of the processes themselves. Also, a common problem on active volcanoes is snow coverage which prevents discrete gravity surveys on the summit zone from being accomplished during the winter time and thus makes gravity changes not identifiable on a timescale of less than about 6 months. Coupled with the desire to reduce the exposure of personnel in active areas, there is a need to integrate the repeated surveys with continuous observations at key sites. However, given the high cost of a gravity meter, only a few instruments can be used at a time in a single area. Consequently, if the time resolution of discrete measurements is restricted by the frequency of the repeated surveys that can be made, the space resolution that can be achieved through continuous measurements is usually poor, due to the limited number of available stations.

Discrete microgravity surveys have been carried out at Mt. Etna since 1986, using a network of stations that, in its current configuration, comprises 70 benchmarks. Microgravity studies involving repeated measurements have allowed mass redistributions occurring at depths ranging between about 6 km b.s.l. and a few hundred meters below the surface to be detected and correlated with the ensuing activity (Budetta *et al.*, 2004).

Since 1998 the Etna network for discrete measurement has been integrated with three continuously running gravity stations which have worked intermittently since then. Continuous microgravity observations at Etna, extending the period of observable changes down to a few minutes, have allowed important fast variation to be observed and interpreted as due to shallow intrusive processes or changes in the gas content within the upper levels of the plumbing system.

In the following, some representative case studies from Etna are presented to show how discrete and continuous gravity studies can be used separately or, better, in conjunction to gather a more complete picture of those volcanic phenomena which can produce underground mass redistributions, and thus variation of the gravity field, at volcanic zones.

2. - Discrete gravity measurements at Mt. Etna

2.1 - The gravity network for discrete measurements.

The first 20 Etna microgravity stations for discrete measurements were installed in 1986 and located 3-4 km apart (Budetta *et al.*, 1989; Budetta and Carbone, 1998). Up to date, the network (Fig. 1) is composed of 70 stations 0.5 to 4 km apart, covers an area of about 400 km^2 and consists of four integrated subarrays (dates of installation in brackets): (a) the Main Network (1986); (b) the Summit Profile (1992); (c) the East-West (E-W) Profile (1994) and (d) a four-station Base Reference Network (1994). The subarrays have different characteristics regarding the density of the traverse, access to stations (determined by snow coverage), and the time required to take measurements. Each subarray can be occupied independently, optimizing the flexibility in taking measurements to accommodate the changeable activity and accessibility of the volcano.

A calibration line was also established in February 1995 to investigate systematic variations in instrumental calibration factor with time. The line runs 80 Km along the motorway from Catania to Enna (Fig. 1) and consists of six stations (Budetta and Carbone, 1997).

2.2 - Data acquisition

Measurements over the whole Etna microgravity array are usually conducted every six months by the "step method", in which adjacent stations are connected at least three times. Some parts of the array are reoccupied more frequently (approximately monthly measurements along the E-W and Summit Profiles, although snow coverage restricts measurements along the Summit Profile to summer months). Stations along the calibration line and Summit Profile are occupied in sequence, the arrays being traversed at least two (Summit Profile) or three (calibration line) times for each survey ("profile method").

Since 1994 discrete gravity measurements at Mt. Etna have been performed using a Scintrex CG3-M gravimeter (serial num. 9310234). A real-time compensator fitted to the instrument allows the instrumental drift to be corrected to a few tens of μGal/day (Budetta and Carbone, 1997). Variations of the CG-3M calibration factor with time are evaluated to a precision of about 30 ppm (Budetta and Carbone, 1997) by repeatedly occupying the Catania - Enna calibration line (Fig 1).

Under the unfavorable conditions encountered at Mt. Etna (dirt tracks, strong height differences, etc.), the Scintrex CG-3M gravimeter yields a high precision thanks to its low sensitivity to shocks and changes in external temperature. Budetta and Carbone (1997) and Carbone *et al*. (2003a) evaluated the uncertainties affecting measurements taken by the Scintrex CG3-M gravimeter on Etna to be ± 7 μGal (± 11 μGal at stations along the Summit Profile, connected by very dirt tracks and measured through the profile method) at the 95% confidence interval. According to Rymer (1989), the error on temporal gravity differences is given by $\sqrt{2}$ x *e* (*e* is the error on a single survey). Thus, at the 95% confidence interval, the error on temporal gravity differences on Etna is 10 μGal (15 μGal along the Summit Profile).

2.3 - Case studies

2.3.1 - The 1994-96 summit anomalies

Between September 1994 and October 1995, a positive gravity change of about 40 μGal was recorded along the Etna Summit Profile (Fig 2b), in correspondence of the summit craters. This anomaly reversed between October 1995 and July 1996, while a new positive anomaly, also of about 40 μGal, appeared further south (Fig 2c), centered upon CS and CZ, the stations closest to the fracture system which opened in 1989 and was reactivated during the 1991-93 eruption (Fig. 2a). Through a 3D modeling, Budetta *et al.* (1999) showed that the September 94-October 95 gravity variation can best be related to a spherical source beneath the Central Craters at an elevation of about 1000 m a.s.l. (Source 1 – Figs 2a and 3). The same source is also consistent with the central part of the October 1995-July 1996 gravity change (Fig 2c). Conversely, an elongate source (Source 2 - Figs 2a and 3) can be used to explain the eccentric positive change centered on stations CS and CZ (Budetta *et al.*, 1999). Assuming a prismatic geometry and an orientation following the trend of the 1989 surface fracture, 3D modeling yields a good fit with observation for a source 2.5 km long, 0.5 km in vertical extent and with a top about 0.8-1 km above sea level (Source 2 – Figs 2a and 3).

None of the summit gravity changes observed between 1994 and 1996 was accompanied by significant variations in elevation (Puglisi and Bonforte, 1999). Thus, they are only due to underground mass changes. Accordingly, the central increase (1994-95)/ decrease (1995-96) cycle reflects either voids around the central conduit being filled and drained, or changes in magmatic vesicularity (Dzurisin *et al.*, 1980). The occurrence of the eccentric 1995 – 1996 gravity increase, close to the 1989 fracture system, suggests a passive mode of intrusion, perhaps with magma filling voids in the fracture system, a view also confirmed by the absence of significant accompanying seismicity at shallow depth (Spampinato *et al*., 1998).

The magnitudes of the mass changes indicated by 3D modelling for the central changes are an increase of $2x10^{10}$ kg (corresponding to a volume of about 10^7 m^3, assuming a density of the vesiculated magma of 2000 kg/m^3) between September 1994 and October 1995, and a comparable decrease between October 1995 and July 1996. For example, a 10 vol.% of melt in the source zone, implies that the volume inferred would correspond to a sphere with a radius of about 300 m.

A mass increase of about the same magnitude result to have occurred within Source 2 ($2x10^{10}$ kg, equivalent to about 10^7 m^3 of magma), suggesting a mean width of 8 m for the intrusion. Such a width is greater than that for classical Etnean dykes, whose mean thickness is about 2 m (Ferrari, 1991). Possibly, therefore, the intrusion should more properly be considered as a collection of parallel dykes.

Between November 1995 and February 1996 at least ten episodes of paroxysmal strombolian activity occurred from the summit craters (Armienti *et al.,* 1996), their explosive nature indicating the eruption of fresh, gas-rich magma. The largest eruptive episode occurred on 23 December 1995 and expelled about $3x10^6$ m^3 of scoria and lapilli (Armienti *et al.* 1996). It is feasible, therefore, that the total mass ejected by the entire sequence of eruptions was similar to that of the shallow intrusion detected in 1994-95 by summit gravity changes (Fig 2b).

The gravity data are compatible with both (a) the lateral injection of the first shallow intrusion (1994-1995) into the 1989 fracture (Fig 3b1), a process allowing the ascent and eruption of new magma and (b) the summit activity having been fed by the first shallow intrusion, while new magma entered the 1989 fracture system (Fig 3b2).

2.3.1 – Gravity changes related to the 2001 eruption

Activity at Mt. Etna during late 2000 and the first months of 2001 consisted of episodic Strombolian and ash explosions and lava emission from the summit craters. Since late January, lava emission concentrated at the Southeast Crater (Lautze *et al.*, 2004). Effusive activity escalated during the following months, with many paroxysmal episodes of fire fountaining accompanied by lava effusion. The 2001 flank eruption started on 17 July, when an new eruptive fissure opened at the base of the Southeast Crater, producing a lava flow that spread into the Valle del Bove. Until late July, the new fissure system propagated, along a North-South direction. On the 19th a vent opened at 2570 m, on the upper southern flank, and gave rise to violent phreatomagmatic explosions. From the end of July the lava effusion rate rapidly diminished and, by 9 August, the eruption ended, after having produced an estimated volume of ca. 48 million m^3 (INGV-CT, 2001).

Following a 8-month period (June 2000 – January 2001), during which a weak gravity increase (within about 20 μGal; Carbone *et al.*, 2003b) was observed, a progressive gravity decrease (Fig 4b), starting between February and May 2001 and continuing until July 2001 (5 surveys, the last one performed on 19 July, two days after the start of the eruption), was measured along the E-W Profile (Fig. 1). The maximum amplitude of the decrease is about 80 μGal, while the wavelength of the anomaly is of the order of 15 km (Fig. 4b). Between the 19th of July and the 2nd of August 2001, a period encompassing the early stage of the eruption, a gravity increase was observed along the East-West Profile (Fig. 4c), which partially compensates the previous gravity decrease. No further significant gravity changes were observed until September 2001 (2 more gravity surveys performed on 16 August and 26 September). GPS measurements, taken between 2000 and 2001, evidenced elevation changes always less than 5 cm in the zone covered by the E-W Profile (Bonforte et al., submitted). Thus, it is feasible to assume that the major part of the 2000-2001 gravity changes are due to underground mass redistributions.

Carbone *et al.* (2003b) assumed the source-volume of the January-July 2001 gravity decrease to have the same geometrical characteristics as that responsible for previous gravity changes observed at Etna, i.e. to be elongated and oriented NNW-SSE (Budetta and Carbone, 1998; Budetta *et al.*, 1999; Carbone *et al.*, 2003a). This source-volume is thought to play a key role in regulating the flux of magma from the deeper mantle source to the upper plumbing system of Etna (Carbone *et al.*, 2003a). It also coincides with a high-V_p body, inferred through the study of arrival times of seismic waves (Patanè *et al.*, 2002), which is homogeneous in V_p, but quite heterogeneous in V_p/V_s, thus revealing the presence of a molten fraction and/or unfilled fractures (Laigle *et al.*, 2000).

A 3D calculation shows that a good fit with observed data (Fig.4d) is obtained for a length of the body of about 3 km, a depth of the mass center of about 2.5 km b.s.l. and a mass change of about $2.5*10^{11}$ kg (the projection of the source onto the surface is shown in Fig. 4a).

Slow mass changes, with periods of about 3 years, which took place approximately within the same volume between 1994 and 1999, were interpreted as fluctuations in the magma/host-rock ratio (Budetta *et al.*, 1999; Carbone *et al.*, 2003a). Conversely, the relatively fast (4-5 months) pre-eruptive gravity decrease and the even faster (14 days) increase in late July, after the start of the 2001 eruption are thought to represent a rather quick process, leaving open voids in the source region, followed by collapse and/or refilling of the open spaces by new magma coming from depth (Carbone *et al.*, 2003b). Seismic data highlight a progressive renewal of tensile stresses during the first months of 2001 with hundreds of events clustering on the southeastern sector of the volcano, mainly along a NNW-SSE alignment, at a depth of 1-5 km, which coincides with the inferred source of the January-July 2001 gravity decrease (Bonaccorso *et al.*, 2004). In this way, the observed initial variation could be the effect of a mere opening of new voids by tectonic stresses.

Petrological and volcanological evidences (INGV-CT, 2001; Pompilio *et al.*, 2001) highlight that, during the 2001 eruption, the vents below an elevation of 2750 m were fed by a magma that, given the abundance of amphibole crystals, evolved under high pressure and possibly experienced a quick rise to the surface. The gravity increase observed during the 19 July – 2 August period along the East-West Profile could mainly be the effect of the emplacement of the magma flow coming from the deep storage system into the new path opened by tectonic stresses. This process is likely to have started before the 19^{th} of July, its positive gravity effect being overwhelmed by the effective decrease in density of the host rock by the tectonic tensile stresses which were still active. This model, involving a relatively rapid magma ascent, is in agreement with the petrological and vulcanological features of the products emitted.

Using continuous tilt and GPS measurements Bonaccorso *et al.* (2002) detected the emplacement of a N-S trending dyke whose inferred volume is about one third the erupted volume and, since no other intrusion was inferred to form inside the volcano edifice during the months preceding the eruption, they concluded that the 2001 eruption must have been fed by material coming directly from a deeper region. This conclusion is also in agreement with the assumption of a rapid magma flow from a deep storage system to the surface, mainly occurring while the eruption was in progress.

3. - Continuous gravity measurements at Mt. Etna

The three continuous Etna gravity stations (Fig. 1) are equipped with LaCoste and Romberg (L&R) spring gravimeters, each featuring an electronic feedback system. The stations are located: ca. 10 km south of the active craters, outside the Serra la Nave Astrophysical Observatory (SLN; 1740 m a.s.l.), 2 km NE of the summit North-East Crater at the Pizzi Deneri Volcanological Observatory (PDN; 2920 m a.s.l.) and just 600 m S of the summit South-East Crater (BVD; 2920 m a.s.l.). At SLN and BVD the sensors are installed into semi-underground concrete boxes (Fig 5a), while at PDN the gravity station is inside the observatory building.

3.1 - Setup of the continuous gravity stations

The conditions at a site close to an active crater are far from the clean, ideal laboratory and so it is quite difficult to attain the required precision in the gravity data. At Etna we have developed a 3-component setup (Fig. 5d) for field stations in the active volcanic environment which is robust, easy to remove and re-establish and cheap (the gravity meter being by far the most expensive item).

The power system employs solar panels connected to trickle-charged batteries (Fig 5b). To provide a constant power supply (within a few hundredth of a Volt) to the feedback systems of the recording L&R meters a dc-dc converter coupled with a low-dropout tension stabilizer is used.

The acquisition system comprises the gravity meter itself, which outputs analogue signals representing the gravity field and tilt changes along two perpendicular axes X and Y. Sensors for the atmospheric temperature and pressure are also installed at each station. The whole acquisition system is placed inside a thermally insulating polystyrene container (Fig. 5b and c). Data are acquired every second. The average over 60 measurements is then calculated and stored in the solid-state memory of the data logger (at 1 datum/min).

After being temporally stored in the solid-state memory of the data logger, data are dumped to the INGV - Sezione di Catania (Catania, Italy) automatically every 24 hours by the transmission system which employs a cellular or wireless connection. Using a suitable software on a computer in Catania it is also possible (a) to remotely activate the stepper motor, fitted to each meter, which turns the meter dial, allowing the meter to be reset (Fig. 5c) and (b) to monitor in real time all the parameters recorded.

3.2 - Data reduction

Once the gravity data are transmitted to the INGV in Catania, they are real-time pre-analyzed through a software called GraVisual, suitably designed under the LabView® environment. Besides permitting the compensation of instrumental resets and the interpolation of gaps in the data sequences, this software allows the data to be reduced for the effect of:

1. Eart Tide;
2. instrumental drift;
3. ground tilt;
4. atmospheric pressure

The tidal gravity effect on Etna is modeled through the Eterna 3.30 data processing package (Wenzel, 1996), which allows the parameters of the main tidal components to be calculated on the grounds of the available recorded data.

The instrumental drift is modeled as a first or higher degree curve, depending on the length of the sequence under study.

Ground tilt changes are measured through the electronic levels fitted to L&R gravimeters (resolution = 2.5 μrad; LaCoste and Romberg, 1997). The gravity effect of the tilt changes is calculated using the formula (Scintrex Limited, 1992):

$$\delta g = g(1-\cos X \cos Y) \tag{1}$$

where g is an average gravity value (980.6 Gal).

The correction for the effect of atmospheric pressure is performed through the value of the theoretical local admittance (-0.365 μGal/mbar), a combination of (i) the gravitational attraction of the air column and (ii) the distortion of the Earth's surface resulting from barometric changes (Spratt, 1982; Niebauer, 1988; Merriam, 1992).

Changes in the atmospheric temperature were shown to affect the signal from continuously recording gravimeters (Andò and Carbone, 2001; 2004). It is now well established that apparent gravity changes depend on the temporal development and magnitude of the temperature change that caused them as well as on the insulation and compensation of the spring gravimeter utilized (Carbone *et al*., 2003c). Thus, the correction formulas are instrument-specific and often frequency-dependent. Accordingly, case-by-case nonlinear approaches must be followed in order to reduce the signal from continuously running gravity meters for the effect of temperature. Because of that reason, the reduction for the temperature effect is not accomplished as a standardized procedure through the GraVisual software. It is to be noted that important temperature effect occur over periods greater than about 1 month (Carbone *et al*., 2003c). Thus, if sequences lasting less than 1 month are taken into account, the instrumental effect of atmospheric temperature changes can be neglected.

3.3 - Case studies

3.3.1 - The October 1998 – February 2000 gravity sequence

Between October 1998 and February 2000, an almost continuous sequence was acquired at PDN station. Only 8 interruptions of the continuous record, with length ranging between 5 and 90 hours, occurred because of various shortcomings (temporary failures of the power system, seismic shocks sending the proof mass outside the measurement range of the feedback system, etc.). The first degree instrumental drift rate of the data sequence is about 285 μGal/month, while the mean background noise is less than 1 μGal.

Raw gravity data are presented in Fig. 6a. The same sequence, reduced for the effect of (i) Earth Tide, (ii) instrumental drift, (iii) ground tilt, (iv) atmospheric pressure and (v) atmospheric temperature, is shown in Fig. 6b. The first four corrections were accomplished as noted in the previous section, while, as for temperature, the procedure outlined by Andò and

Carbone (2001) was followed (Carbone *et al.*, 2003c), which leads to a reduction in the amplitude of the signal of about 90 %.

The main features of the reduced gravity sequence (Fig 6b) are the cycles with period of about 6 months and amplitude of about 100 μGal peak-to-peak.

In Fig. 6b data acquired through discrete measurements at station CO (about 500 m far away from PDN; Fig. 7) in June 99, July 99, September 99 and October 99 are also reported (black dots). The good fit between continuous and discrete data would indicate that both were caused by the same source. Also, given the similarity of the cycles evidenced in the reduced continuous sequence from PDN (Fig. 6b), as for period and amplitude, it is likely to assume that this source worked throughout the entire 1998-2000 period.

The geometrical characteristics of this source are assessed through a 3D inversion on the discrete measurements along the Summit Profile between June and September 1999 (Fig. 7c). Assuming a prismatic shape and an orientation following the trend of Etna's Northeast rift (Garduño *et al.*, 1997; Fig 7a), a good fit with observation is achieved for a source 1.5 km long, 0.5 km in vertical extent, with its top about 1.8-2 km above sea level (the projection onto the surface of this source is shown in Fig. 7a) and within which a mass decrease of about $2x10^{10}$ kg took place.

Carbone *et al*. (2003c) assumed the cyclic mass variations affecting the magma within the inferred dike to be due to fluctuations of the degassing processes. This view is supported by the negative correlation, over the 6-month-period component, between the gravity sequence acquired at PDN and the volcanic tremor observed at both PDN and ESP stations (placed respectively within a few meter from the homonymous gravity station and in the southeastern sector of the volcano). Given that the volcanic tremor is generated by non-stationary fluid flows due to gases escaping through open magma-filled conduits (Seidl *et al.*, 1981; Schick, 1988) and its amplitude is related to the intensity of turbulent motions (Leonardi *et al.*, 1999), it is likely that the increasing of the degassing processes in the inferred source leads to both a gravity (mass) decrease and an increase in the spectral amplitude of the volcanic tremor, and thus to the observed negative correlation.

3.3.2 - The gravity sequence encompassing the start of the 2002 NE-Rift eruption

The 2002-03 Etna eruption began on the night of October 26-27, 2002 with lava flows issued from fissure systems on both the southern and northeastern flanks of the volcano (Andronico *et al.*, 2005). The activity on the southern flank lasted 93 days with a variable eruptive style. It concentrated mostly at a vent located at 2750 m a.s.l., with intense fire fountains, strombolian activity and lava flows from different vents at its base.

On the northern flank, the activity occurred along the eastern border of Etna's Northeast Rift (Garduño *et al.*, 1997; Fig. 7a). It lasted 9 days and was characterized by fire fountaining, strombolian and effusive activity. The explosive activity was less intense than that occurring on the southern flank.

A gravity sequence, encompassing the start of the eruption on the northeastern flank (2002 NE-Rift eruption) was acquired at PDN station (Fig. 1). Before the start of the eruption, the mean background noise of the gravity signal was less than 1 μGal (1 μGal = 10 nm s^{-2}). It increased progressively from 21:36 GMT on 26 October. Successively, from 00:07 of the 27th, a very strong and rapid gravity decrease took place (Fig 8): in less than one hour, the amplitude of the change reached about 400 μGal. Afterwards, the mean value of the gravity signal started rising again at a high rate (roughly 100 μGal/hour). In Fig 8, the complete decrease/increase anomaly is evidenced against the strong background noise through a low-pass filter with cut-off frequency of 24 cycles/day.

Unfortunately, it is not possible to evaluate the influence of elevation changes on the gravity signal under study since, during the period of interest, due to power-saving reasons, the continuous GPS station working at PDN recorded on a daily basis. As for ground tilt, peak-to-peak fluctuations up to 120 (long) and 350 (cross) μrad occurred during the 26-27

October anomaly, whose calculated gravity effect is within 30 μGal (Branca *et al*., 2003). Obviously, tilt changes that move the meter away from the horizontal position (where it measures the full force of gravity) produce a negative effect. As for other possible perturbations to the gravity anomalies under study here, it is noteworthy that instrumental effects linked to atmospheric parameters are expected to be very small over periods of the order of a few hours (Andò and Carbone, 2001). In particular, temperature, pressure and relative humidity changes contemporaneous to the 26-27 October gravity anomaly were surely too weak (within 0.1 °C, 2 % RH and 4 mbar respectively) to produce any significant effect.

As stated before, a part of the 400 μGal gravity decrease observed during the onset of the 2002 NE-Rift eruption is due to ground tilt and, possibly, to height changes. Anyway, it cannot be ruled out that most of the 26-27 October gravity anomaly is linked to subsurface mass redistributions. The likeliest mechanism able to cause a quick and strong density decrease is opening of new voids. Accordingly, the negative (first) part of the anomaly could have been caused by the opening of a dry fracture system on the northeastern slope of the volcano, within 1 km from the station, during the early stage of the 2002 NE-Rift eruption (Branca *et al*., 2003). By assuming the new forming fractures to be dry, the magma overpressure is ruled out as a cause of their opening, and thus it is suggested that they are rather the effect of external forces. Accordingly, the right *en-echelon* arrangement of the new fracture system, observed in the field, reflects the eastward gravitational sliding of the mega-block delimited by the Provenzana-Pernicana fault system (Borgia *et al*., 1992; Lo Giudice and Rasà, 1992; Froger *et al*., 2001). Magma from the central conduit would have used the new fracture system as a path to the eruptive vents downslope, and, filling the newly formed voids, provoked the observed gravity increase which roughly compensated the previous decrease. It is noteworthy that some characteristics of the 2002 NE-Rift eruption, namely (i) its short duration (9 days) and (ii) the effusion rate decreasing rapidly with time are in keeping with the inferred intrusive mechanism.

4. – Conclusive remarks

Many years of gravity studies based on discrete measurements from Mt. Etna have proved the potential of this technique to investigate the plumbing system of an active volcano and detect the occurrence of processes that can forerun paroxysmal events. In particular, the development of certain processes, such as passive intrusions (i.e. into pre-existing voids and fractures) and/or density changes of static magma bodies (due to crystallization, degassing, etc.), leading to variations of the gravity field not accompanied by deformations and/or seismic activity, can be detected exclusively through microgravity studies.

Example of meaningful mass-redistributions which occurred below Mt. Etna, at various depths, within both the volcanic pile and the underlying sedimentary basement, are presented in the previous sections. Their interpretation, in conjunction with pieces of information from other data sets, has allowed steps forward to be taken towards understanding how Etna works.

To overcame the shortcoming, typical of any discrete measurement, of the time resolution being limited by the repeat time of the measurements campaigns, experiments of continuous gravity observations were started at Etna in 1998. A special station setup was designed aimed at running delicate and sensitive instruments such as gravimeters against the harsh environment usually encountered on the summit zone of an active volcano. This setup, in conjunction with suitable procedures aimed at reducing the instrumental effect of atmospheric parameters, has allowed a good signal-to-noise ratio to be achieved. The complementary pieces of information coming from (i) the extension of the period of the observable changes down to a few minutes and (ii) the possibility to continue the measurements even when the sites of interest are not physically accessible (snow cover, adverse weather conditions, paroxysmal activity, etc.) allow both to discover anomalies over period which could not be investigated through discrete measurements (a few minutes to a few days), and thus to study alternative sources of gravity changes, and to better constrain any hypothesis on possible source mechanisms, if long continuous sequences can be used in conjunction with data from discrete measurements.

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Figure 1 - Sketch map of Mt. Etna showing the position of both the benchmarks for discrete microgravity measurements and the continuously running microgravity stations. The position of the Catania - Enna calibration line is also reported in the bottom left inset.

Figure 2 - Gravity changes along the Summit Profile between 1994 and 1996. The September 1994 - October 1995 variations (b) are attributed to the arrival of new magma in a source zone modeled as a sphere whose projection onto the surface (Source 1) is shown in (a). The October 1995 - July 96 variations (c) are associated with a withdrawal of magma from the source zone responsible for the previous change and the contemporary arrival of new magma in a source zone, modeled as a prism-shaped body, whose projection onto the surface (Source 2) is also shown in (a).

Figure 3 - Schematic representation showing mass redistributions detected by gravity changes during the September 1994 - July 1996 interval. (a) During the September 94 – October 95 period, a mass increase occurs 2000 m beneath the summit (Source 1). (b) Two possible sequences of events for the October 95 – July 96 time interval: (b1) shallow-level magma is intruded laterally (towards Source 2) to allow the summit eruption of deeper magma; (b2) magma from depth feeds the lateral intrusion (Source 2) directly, as well as replacing the shallow-level magma which is erupted at the summit.

Figure 4 - Gravity changes observed along the E-W profile between (b) January and 19 July 2001 and (c) 19 July 2001 and 26 September 2001. In (d) the gravity effect of the best-fit model source [whose projections onto the surface in shown in (a)], discussed in the text, is reported.

Figure 5 - Continuously running gravity station at Mt. Etna. (a) Panoramic view showing the relative position of BVD station and the Southeast Crater (one of the summit craters of Etna), 600 m away from the station. The sensor is placed inside a semi-underground concrete box. (b) An inner view of the concrete box: it is possible to recognize (i) the gravimeter inside the polystyrene thermo-insulating box; (ii) the trickle-charged batteries; (iii) plastic white boxes (IP65) hosting the electronics. (c) Particular of the gravimeter. The stepper motor to remotely reset the meter is mounted on its black lead. (d) Schematic of the three-component setup of Etna's continuous gravity stations.

Figure 6 - (a) Raw gravity data recorded at PDN stations during the October 1998 – February 2000 time interval. (b) The same sequence as in (a), reduced for the effects of: (i) Earth Tide, (ii) instrumental drift, (iii) ground tilt, (iv) atmospheric pressure and (v) atmospheric temperature. Filled circles in (b) are gravity changes assessed by discrete relative observations at CO, a site very close to the continuous station (see Fig. 7).

Figure 7 – Gravity changes along the Summit Profile during the June-July 1999 (b) and June-September 1999 (c) periods. They are attributed to a mass decrease in a source zone, modeled as a prism-shaped body, whose projection onto the surface is shown in (a).

Figure 8 - Reduced gravity, after removal of the best linear fit and the theoretical Earth Tide effects, observed at PDN station during a 48-hour period encompassing the start of the 2002-03 eruption. The solid curve is a low-pass filter (see text for details).

Dashed lines mark (left) the start of the seismic swarm heralding the eruption and (right) the first opening of the eruptive fissures on the northeastern slope of the volcano.