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Thirty years of precise gravity measurements at Mt. Vesuvius: an approach to detect underground mass movements

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ABSTRACT

Since 1982, high precision gravity measurements have been routinely carried out on Mt. Vesuvius. The gravity network consists of selected sites most of them coinciding with, or very close to, leveling benchmarks to remove the effect of the elevation changes from gravity variations. The reference station is located in Napoli, outside the volcanic area. Since 1986, absolute gravity measurements have been periodically made on a station on Mt. Vesuvius, close to a permanent gravity station established in 1987, and at the reference in Napoli. The results of the gravity measurements since 1982 are presented and discussed. Moderate gravity changes on short-time were generally observed. On long-term significant gravity changes occurred and the overall fields displayed well defined patterns. Several periods of evolution may be recognized. Gravity changes revealed by the relative surveys have been confirmed by repeated absolute measurements, which also confirmed the long-term stability of the reference site. The gravity changes over the recognized periods appear correlated with the seismic crises and with changes of the tidal parameters obtained by continuous measurements. The absence of significant ground deformation implies masses redistribution, essentially density changes without significant volume changes, such as fluids migration at the depth of the seismic foci, i.e. at a few kilometers. The fluid migration may occur through pre-existing geological structures, as also suggested by hydrological studies, and/or through new fractures generated by seismic activity. This interpretation is supported by the analyses of the spatial gravity changes overlapping the most significant and recent seismic crises.

1. Introduction

As is well known, internal geodynamic processes (i.e., seismicity, volcanic activity) can produce time/space gravity changes containing information about terrestrial mass displacements. In the case of volcanoes, for example, gravity changes, particularly if observed before and after an active phase, contribute to model underground magma migration and density variations. This is of particular importance as precursor phenomena and makes gravimetry a powerful investigative tool able to detect the ascent of magma.

Gravity changes associated to volcanic activity are defined as "local" (1-100 km wave-length) and lead to abrupt and short-term (few days to few years) changes. Their amplitude is expected of the order of few to hundreds microGal, but often is quite small, on the order of 10^{-9}-10^{-8} g (10-10^2 nm/s^2; 1-10 μGal), where *g* is the mean value of normal gravity (9.806 199 203 m/s^2).

High precision gravity measurements are carried out to monitor the volcanic activity of Mt. Vesuvius (southern Italy) since 1982. Repeated relative measurements are routinely collected on a network covering the whole volcanic area. Since 1986 the measurements of the absolute value of g at two stations have been carried out on long-time intervals (from 2 to 10 years); in 1987, a permanent gravity station was also installed.

In this paper, the main results obtained by the repeated relative gravity surveys at Mt. Vesuvius over 30 years (from 1982 to March 2012) are presented and discussed.

2. Structural setting and present dynamics of Mt. Vesuvius

Mt. Vesuvius is a strato-volcano, about 15 km southeast of Naples (Figure 1), composed of an older structure (Mt. Somma) and a nested younger one (Mt. Vesuvius). It is structurally located on a principal NE-SW trending fault system [Marzocchi et al. 1993] and lies on a sedimentary basement.

Information on shallow structures comes from a deep borehole drilled down to a depth of 2200 m below sea level (b.s.l). [Principe et al. 1987] and several geophysical studies [e.g., Finetti and Morelli 1974, Cassano and La Torre 1987, Zollo et al. 1996, Berrino et al. 1998, Bruno et al. 1998, Di Maio et al. 1998, Fedi et al. 1998, Auger et al. 2001, Tondi and De Franco 2003, Tondi and De Franco 2006, Berrino and Camacho 2008]. In particular, a 2.5D inversion of a more complete Bouguer

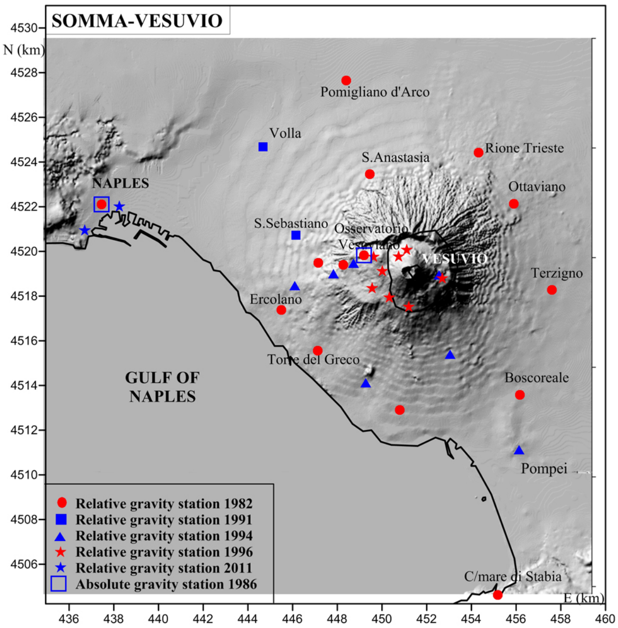

Figure 1. Gravity network at Mt. Vesuvius. Relative benchmarks are represented with several different symbols according to their establishment date. The open blue squares show the location of the two absolute stations. The absolute and relative station at Osservatorio Vesuviano (on the top of the volcano) also guests the permanent recording gravity station (see text).

anomaly map, obtained by the integration of the existing terrestrial gravity data with those collected off-shore during five cruises carried out by Osservatorio Vesuviano from 1986 to 1994 [Berrino et al. 1991, Berrino 1998], suggested that the sedimentary basement is 11 km thick, with the top at a depth of 2 km [Berrino et al. 1998]. This was confirmed by a joint tomographic inversion of first P wave arrivals recorded along five profiles intersecting the crater, and gravity data that also provided an image of a conduit structure 5 km wide that extends from the surface to the maximum depth of the model (6 km) [Tondi and De Franco 2003, 2006]. Seismic tomography has shown no significant evidence [Auger et al. 2001, Tondi and De Franco 2003] for the existence of a shallow magma chamber within the sedimentary basement [Cortini and Scandone 1982, Rosi et al. 1987].

Moreover, a joint inversion of P and S-wave arrival times from both local earthquakes and shots data collected during the TOMOVES 1994 and 1996 experiments show the presence of a high Vp and Vp/Vs anomaly located around the crater axis, between 0 and 5 km depth, involving the volcano edifice and the carbonate basement; this anomaly has been interpreted in terms of magma quenching along the main conduit, because of the exsolution of magmatic volatiles [De Natale et al. 2004].

A recent 3D inversion of the complete, on-land and off-shore, Bouguer gravity map [Berrino and Camacho 2008] has generally confirmed the global setting of the area as outlined by the previous 2.5D investigation [Berrino et al. 1998], and also confirmed the presence of lateral density contrasts inside the volcano edifice only hypothesized in the 2.5-dimensional inversion. The models indicate a high density body that rises from the top of the carbonate basement and extends above sea level. This probably represents an uprising of the same basement, which is just below the volcano and which coincides with the V_P and V_P/V_S anomalies detected under the crater. Taking into account the density of these modelled bodies, Berrino and Camacho [2008] suggested that they represent solidified magma bodies as previously suggested by Berrino et al. [1998] and De Natale et al. [2004].

Vesuvius is a quiescent volcano whose last eruption occurred in March 1944. Currently, the volcano shows a low level of infrequent increasing seismicity, small ground deformation consisting mainly at continuous slight subsidence localized on the cone (probably due to compacting processes), gravity changes and moderate gas emission discharged by the fumaroles widespread in the crater area [e.g., Berrino et al. 1993, Berrino 1998, Bianco et al. 1999, Pingue et al. 2000, Chiodini et al. 2001, Iannaccone et al. 2001, Lanari et al. 2002, Del Pezzo et al. 2004]. In particular, seismicity is shallow, occurring at depth that does not exceed 6 km b.s.l. and concentrated along the crater axis. A complete catalogue of the seismic data collected by Osservatorio Vesuviano is available for seismicity from 1972 to present [Berrino et al. 1993, Vilardo et al. 1996, Iannaccone et al. 2001, INGV-Osservatorio Vesuviano website: www.ov.ingv.it]. Several periods of increasing seismicity have been recognized: 1978, 1989-1990, 1995-1996, and 1999-2000. Moreover, an increase in seismicity is also well documented in 1963-1964 [Imbò et al. 1965b]. The strongest seismic events in recent years occurred on March 19, 1989, with local magnitude of M_L=3.2 [Berrino et al. 1993] and on October 9, 1999 (M_L= 3.6) [Del Pezzo et al. 2004]; both occurred about 3 km beneath the central cone of Mt. Vesuvius.

Del Pezzo et al. [2004] hypothesized that shallowest seismic events may be triggered by the increase in fluid pore pressure generated by the changes in the level of aquifers, while for deepest events (located inside the carbonate basement, > 2.5 km) they suggested the hypothesis that the pre-fractured carbonate basement may be the site of tectonic stress release.

The fumarolic fluids have typically hydrothermal compositions, with H_2O as major constituent, and are fed by a hydrothermal system located underneath the crater. Also a CO_2 component is present probably produced through metamorphic reactions which take place in response to a thermal anomaly locally present in the carbonate sequence, at depths > 2.5 km underneath the volcano [Chiodini et al. 2001]. The arising of deep fluids (also with high contents of CO_2) through tectonic displacement from the carbonate basement is also hypothesized by hydrological studies [Celico et al. 1998], which also defined a shallow (thick about 600-700 m) and a deep (inside the carbonate basement) separate aquifers, mainly from the fact that the outflow amount from the shallow aquifer is higher than the direct recharge. A conceptual geochemical model suggest that the hydrothermal reservoirs connected to the fumarolic vents are located at depths of 2.6 to 4.8 km and 1.3 to 2.2 km. Geochemical evidence also suggests that no input of fresh magma at shallow depth took place after the last eruptive period [Chiodini et al. 2001].

Ground deformation over the last 30 years has been characterized by subsidence in the upper part of the volcanic edifice occurring with an average rate of few mm/years. Data continuously collected until 1999 by a tide-gauge established on June 1985 in the harbour of Torre del Greco confirmed a very slow subsidence of about 5 cm during the period 1985-1993 but also showed an inversion of the trend from 1993 to 1995 [Berrino et al. 1993, Berrino 1998, Pingue et al. 2000] resulting in a small uplift of about 3 cm. Later (from 1995 to the end of 1999) no significant vertical ground movements were observed [e.g. Berrino et al. 2006]. In addition, 2 tilt stations, operating from 1987 to 1991, respectively at Vesuvius (Osservatorio Vesuviano) and at Leopardi (a suburban district of Torre del Greco), also showed a slow long-term southeast tilt [Berrino et al. 1993]. Tide-gauge and tilt data were coherent with levelling data.

Moreover, results obtained by spaceborne SAR interferometry from 1992 to 2000 also show a narrow annular area that, although not continuous, extends around the base of the Somma edifice. The total subsidence from 1992 to 2000 was 5-7 cm with an average rate of 0.3-0.8 cm/year [Lanari et al. 2002]. The subsidence pattern is unusual and difficult to interpret in terms of a volcanic source. Lanari et al. [2002] propose gravitational sliding and extensional tectonic stress at the contact between different lithological units as the cause of deformation.

Continuous GPS data collected from 2005 up till now show a slow subsidence in the upper part of the volcano with a reduced rate of −1.4 mm/yr [INGV-Osservatorio Vesuviano website].

Nevertheless, geodetic data indicate the absence of significant ground movements linked to the internal dynamical processes [Berrino et al. 1993, Pingue et al. 2000, Lanari et al. 2002].

3. Gravity data collecting procedures

Relative gravity measurements have been routinely carried out since 1982. The first network comprised 11 stations linked to a reference in Naples (Figure 1) outside the active volcanic area; it was built on the basic stations of a gravity survey carried out in 1960 for prospecting purposes [Tribalto and Maino 1962]. The stations were located all around the base of the volcanic structure and along a profile running from Ercolano to the Old Building of the Osservatorio Vesuviano, on the volcanic edifice at an elevation of about 600 m a.s.l. (Figure 1) [Berrino et al. 1985]. The network has been progressively expanded to reach a configuration of 34 stations in 2011, covering the whole base of the volcanic structure and the volcanic edifice till the base of the Gran Cono at about 1000 m a.s.l. Figure 1 shows the present day gravity network with different symbols for stations according to their establishment date. Most of the stations coincide with or are very close to altimetric benchmarks to remove the effect of the vertical ground movements from gravity changes.

Since 1986, the network has been linked to an absolute gravity station established in Naples, in the same building as the previous reference [Berrino 1995]. This absolute station also belongs to the "Zero Order Reference Italian Gravity network" [Berrino et al. 1995]. It was surveyed again in 1994, 2003 and 2009 [Berrino 2000, D'Agostino et al. 2008] to check and confirm its long-term stability. Particularly during the 1986-2003 gap, it was also checked and confirmed taking into account data from the absolute station on Mt. Vesuvius (Osservatorio Vesuviano), which was also established in 1986 and re-measured in 1994, 1996, 1998, 2003, 2009 and 2010 [Berrino 1995, Berrino et al. 1999, D'Agostino et al. 2008].

In fact, the comparison between gravity changes independently obtained by relative and absolute measurements shows a very good agreement (Figure 2, open blue squares). Because relative measurements are referred to Naples, this proves the stability of the reference at least over the 1986-2010 time interval. The absolute measurements have been carried out in co-operation with the Istituto Nazionale di Ricerca Metrologica – INRiM in Turin, using the IMGC absolute gravimeter [e.g. D'Agostino et al. 2008]. At the absolute stations, the free-air gradient (FAG) is measured, to reduce the measured value to the ground level [Berrino 1995]. At the same time, in 1987, a permanent gravity station was established in the same place as the absolute and relative gravity stations at Mt. Vesuvius [Berrino et al. 1993, Berrino et al. 1997, Berrino 2000, Berrino et al. 2000, Berrino et al. 2006] and in the same place where a first experiment of continuous gravity measurements were performed during the 1960s [Imbò et al. 1964, 1965a]. The recording station is installed on a concrete pillar located in an artificial cave, 20 m deep (φ: 40.828N, λ: 14.408E; h: 608 m) [Berrino et al. 1997]. The gravity

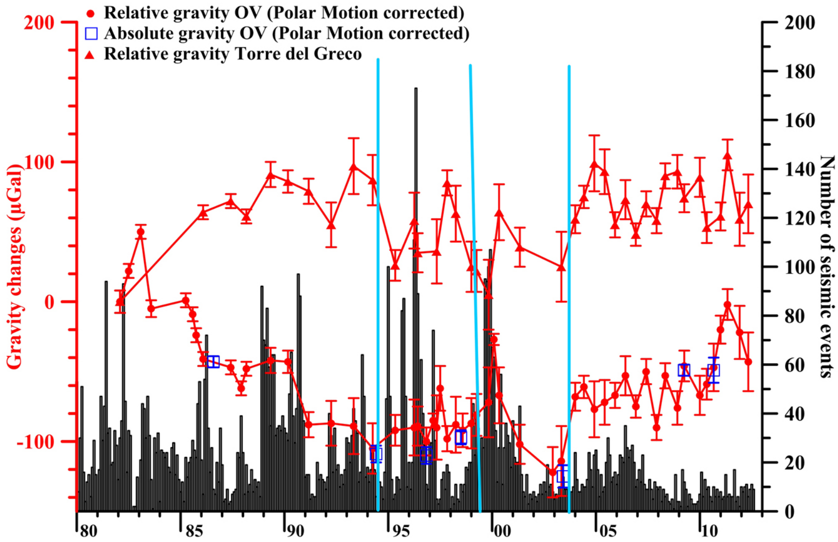

Figure 2. Gravity changes over the 1982-2012 period at two selected stations and comparison with the occurrence of the seismic activity (black bars) recorded at the station located at the Osservatorio Vesuviano, on the volcanic structure. The two selected stations are respectively located on the top (Osservatorio Vesuviano, OV – red full circles) and at the base (Torre del Greco – red full triangles) of the volcano. The blue open squares overlapping the curve referred to the Osservatorio Vesuviano station indicate the gravity changes there measured by absolute gravimetry. The cyan vertical lines delimitate the main recognized time intervals discussed in the text.

sensor is the LaCoste and Romberg model D, number 126 (LR-D126), equipped with an MVR electrostatic feedback system [van Ruymbeke 1991], implemented at the Royal Observatory of Belgium in Brussels (ROB) and upgraded in 1994 and 2005. Therefore, three data sets are available: 1987-1990; 1994-2001 and 2006 to present. The first two series provided the main tidal parameters and their variation in time but no additional information were inferred by the gravity residuals because no sufficiently clear gravity signals were detected probably due to a poorly constrained removed pressure effect [e.g., Berrino et al. 2000, Berrino et al. 2006]. No significant information has been obtained during the last period because of frequent failures of the new acquisition system and because we suspect a problem in the air-tight sealing system. Therefore, last data set requires more careful analyses.

Relative gravity measurements have been collected using several LaCoste and Romberg models D meters (no. 62, 136 and 85).

D-62 and 136 worked together for long time (till 1996), D-136 was used alone until 2003 when the D-85, presently used, was introduced. All meters have been calibrated against during several joint field surveys carried out in several volcanic and non-volcanic areas. Particularly, D62 and D136 were also calibrated on Italian calibration lines [e.g. Berrino 1995] and during several "International Comparison of Absolute and Relative Gravimeters" carried out at the Bureau International des Poids et Mesures (BIPM) at Sevres-Paris [Becker et al. 1990, 1995, 2000].

Field measurements are collected following appropriate procedures to obtain high quality data. Each gravity difference between pairs of stations is independently measured and each station is occupied several times, at least twice, at different times to better detect and remove the instrumental drift and not recoverable tares (steps on the drift curve) due to shocks during the transportation. At each occupation, several readings at several time intervals are done to be sure of the reached stability of the meter on the site. Each reading is cleaned by earth-tide and pressure changes effects.

In the past, the Earth-tide effect was removed according to the Longman's formula [1959] and using a mean gravity amplification factor of 1.16. From some years, we removed the luni-solar effect according to Tamura's gravity potential catalogue [Tamura 1987]; in the case of Vesuvius, the synthetic tide is calculated using tidal parameter computed from the local gravity records over the 1994-2001 period [Berrino et al. 2006].

The mean coefficient of −0.35 μGal/hPa is adopted to remove the atmospheric effect from gravity readings [Warburton and Goodkind 1977, Spratt 1982]. Atmospheric pressure is simultaneously measured at each occupation of each gravity station through portable barometers. Currently we are using a Delta Ohm, mod HD 2114B.0, portable barometer with a resolution of 0.1 hPa and accuracy of 0.3 hPa. Only the cleaned readings recurring with the same value or at least with a difference of few microGal (3-4 μGal) are accepted and their average value is used to detect and remove the instrumental drift and, finally, to compute the gravity difference between a couple of stations.

In this way we obtain gravity differences with an error no greater than ±5-6 μGal, and we also have a redundancy of repeated observations under different conditions on a gravity base net formed by several loops which misclosures are adjusted by means of least-square method. Of course, these procedures require long time surveys, of the order of 20-25 days, due to the number of points, the their long distances, and large gravity differences.

Finally, the adjusted gravity differences are used to compute for each station its gravity difference with respect to the reference station and afterward to compute gravity changes over time. Although the error on a single gravity difference between any pair of stations is generally a few μGal, we consider for any field survey the average error resulting by adjustments and thus an overestimated error in the computation of gravity changes over different time intervals. Furthermore, gravity changes observed at the absolute stations are also corrected for the effect of the Polar Motion (available at the International Earth Rotation and Reference System Service – IERS) in order to compare with those obtained by absolute measurements.

In most cases for Vesuvius, the adjustment error is within ±10 μGal except for data from 1993 to 2004 when in most surveys results between ±10 and ±25 μGal. We observed that the time interval of increasing error overlaps a period of increasing seismicity, so we can likely affirm that most of the increasing error is associated with the increasing seismic noise. This affirmation was confirmed by some adjustments carried out splitting the network in two parts: the first consisting of the benchmarks located at the base of the volcanic edifice, the second formed by all the stations on the volcano. The first area always showed a smaller error, generally within ±10 μGal. The correlation between increasing error and seismicity can be observed in Figure 2 where the temporal gravity changes at two stations are shown together with the seismic activity (monthly number of seismic events) over the same period (1980-2012). The stations Osservatorio Vesuviano and Torre del Greco, respectively on the top and at the base of the volcano, have been selected because they have the greatest number of observations and are considered the most representative of the observed gravity changes.

Of course, also the different sensitivity of the instruments, the longer time required for field survey due to the increased number of stations, the sometimes unfavorable weather conditions can contribute to increase the error. We obviously prefer to use a global adjustment to avoid the introduction of discontinuities in the gravity changes field easily obtainable through separated adjustments.

Gravity surveys were annually repeated until 1995, and from 1996 twice per year generally in spring and autumn, apart from the period from 2000 to 2003 when only three field surveys were carried out (i.e. April 2000, February 2001 and April 2003; see Figure 2 also).

4. Main results and discussion

We focus on the results of repeated gravity measurements carried out from 1982 to March 2012 and analyze a data set longer than those analyzed in previous works [e.g. Berrino and Riccardi 2000, Berrino et al. 2006].

The main results obtained over 30 years generally indicate that on the short-term, moderate gravity changes occur, mostly within the statistical error and without defined spatial patterns. Statistically significant changes are sometimes observed on isolated stations showing very local effects not due to volcanic activity. Significant gravity changes showing defined field geometries have been observed only on a few short time intervals, particularly from middle ’90s to beginning of 2000s. Moreover since 2005, as well as from 1996 to 1999, when measurements have been carried out twice per year, significant periodic fluctuations likely of seasonal origin, of the order of some tens of μGal, are detected. The amplitude of these changes are in agreement with the computation made by Berrino [2000] who estimated a contribution of the seasonal water level changes of the order of 10-15 μGal, taking into account the highest piezometric seasonal fluctuation measured in some wells SE the Mt. Vesuvius [Celico et al. 1998] and considering a realistic porosity of the surface rocks of about 10%. During this period, most of these changes occurred all around the base of the crater. The short wavelength of the gravity change fields suggests the effect of a much localized source at a very shallow depth respect to the ground surface. This could be related to the shallow hydrothermal circulation (about 250-500 m below the ground surface) beneath the caldera singled out by a combined magnetotelluric and electomagnetic investigation [Manzella et al. 2004].

On the contrary, over the long-term, the overall fields display well defined patterns. From 1982 to present several main periods of evolution in the gravity field can be recognized; they can also be observed on the temporal trends at the two selected stations shown in Figure 2, marked with cyan vertical lines. In order to easily compare the following spatial gravity changes, and taking into account the errors in the analyzed periods, we have drawn all discussed fields with a contour interval of 20 μGal and compare data collected during the same seasons to avoid seasonal effect.

1) **1982-1994** (Figure 3a): Two distinct areas are progressively formed. The first characterized by a gravity decrease located in the north-western and central

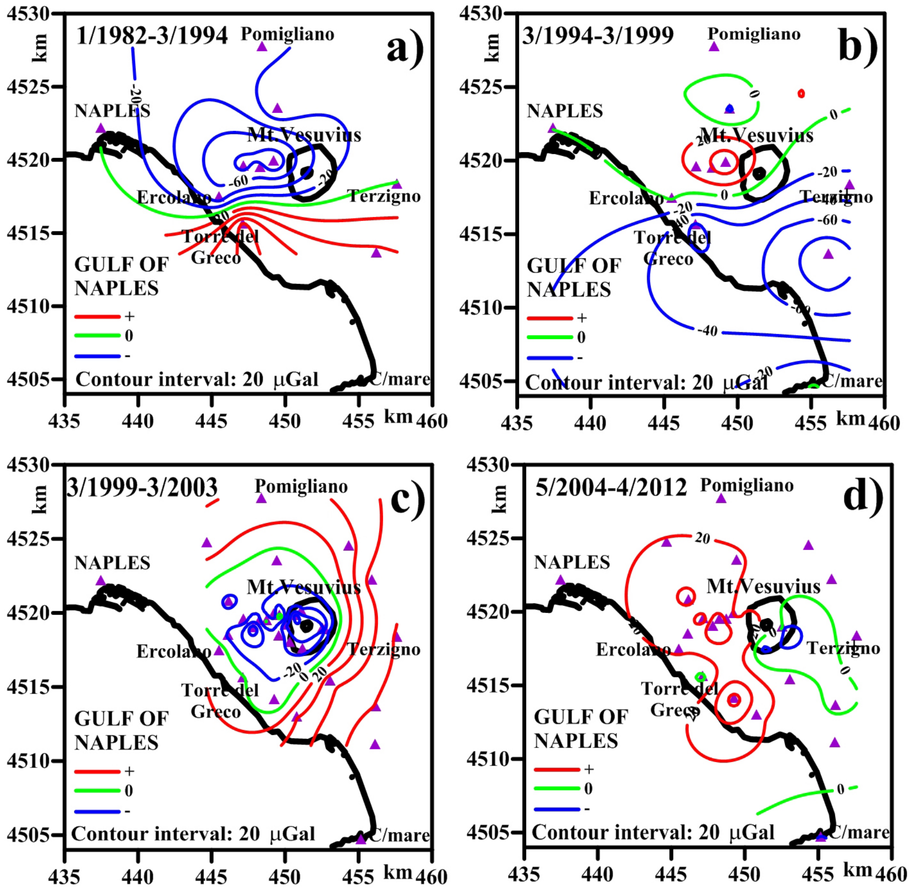

Figure 3. Gravity change fields over the recognized long-term periods characterized by significant gravity changes: a) 1/1982-3/1994; b) 3/1994 – 3/1999; c) 3/1999 – 3/2003; d) 5/2004 to present days. Red contour lines indicate gravity increase, blue lines gravity decrease and green lines the areas of null gravity changes.

part of the area and particularly on the higher part of the network, the second one showing an increasing gravity at the base of the volcanic edifice, mainly in the south-eastern sector. The greatest values are, respectively, centered at the Osservatorio Vesuviano (globally about −100 μGal) and Torre del Greco (about +90 μGal) stations (Ref. Figure 1 for stations positioning). The gravity decrease detected at the Osservatorio Vesuviano station results also by the repeated absolute measurements, showing a 60 μGal decrease from 1986 to 1994 (Figure 2, blue open squares). This change probably started in 1983-1984, as suggested by the numerous repeated measurements carried out at the station Osservatorio Vesuviano (Figure 2, red full points) where a continuous gravity increase until 1983 was observed. The 1982-1983 trend followed the gravity increase noted since 1959 and estimated with an average rate of more than 20 μGal/year, [Berrino and Riccardi 2000]. The temporal gravity change in 1959-83 time interval was obtained by reviewing data collected during 1959-60 [Tribalto and Maino 1962] and 1965 (Bonasia, unpublished data) gravity surveys in the Vesuvian area. Moreover, as also discussed by Berrino [2000], all the stations at the base of the volcano indicate a general increase growing almost constantly in time until 1990, when a slow inversion occurred (Figure 2, red full triangles). By contrast, the area of decreasing gravity (Figure 2, red full points) formed step-like and, starting from the top, involved different areas at different times. Also, a trend inversion is observed from 1994. The overall 1982-1994 gravity change field (Figure 3a) shows that in the area of transition from the negative to the positive area, a strong gradient almost NNE-SSW appears crossing one of the most important NE-SW structure there located by geological and geophysical evidence [e.g. Finetti and Morelli 1974, Cassano and La Torre 1987, Berrino et al. 1998]; the zero line (area of null changes – green line in Figure 3a) runs from Torre del Greco to Terzigno. An evaluation of the mass change amount computed by means of Gauss' theorem separately for the two characteristic areas and over the time interval 1982-1991, was made by Berrino et al. [1993]. They estimated the total amount of the mass increase/decrease in $9{\cdot}10^{10}$ kg e $-5.5{\cdot}10^{10}$ kg respectively. The computation of the mass change amount extended over the whole 1982-1994 interval gives values of $5.2{\cdot}10^{10}$ kg and $-7.7{\cdot}10^{10}$ kg respectively for the increasing/decreasing area. Berrino et al. [1993] also suggested a mass migration (e.g. fluids) from one area to another one through pre-existing lineations at the depth of the seismic foci (at a few kilometers), taking also into account the absence of significant ground deformation. Moreover, considering that the long-term gravity variation field is progressively built up over time, they suggested that it could not reflect any influence of the perched water tables because there was no correlation between the shape of the gravity changes and the known hydrological situation (i.e., orientation of the surface and deep watersheds, shape of the piezometric field, etc. [Celico 1982]). In addition, if we consider the underground overflow rate, estimated in about $7 \cdot 10^7$ kg/month on the base of data collected during piezometric surveys carried out in 1994 [Celico et al. 1998], it is not in agreement with the average rate of mass changes (about $-5.3 \cdot 10^8$ and $+ 3.6 \cdot 10^8$ kg/month) over the whole 1982-1994 period. However, the hypothesis made by Berrino et al. [1993] is consistent with the hydrological studies [Celico et al. 1998] which suggest an arising of fluids, mainly in the southern part of the volcano, from the deep carbonate through pre-existing tectonic structures, such as the previously mentioned NE-SW one. Furthermore, the gravity decrease detected at the Osservatorio Vesuviano station results from repeated absolute measurements, showing a 60 μGal decrease from 1986 to 1994 (Figure 2). This time interval overlaps the 1989-1990 seismic crises (Figure 2).

2) **1994-1999** (Figure 3b): In this period, we observe some of the largest gravity changes with several fluctuations, most disturbed fields (sometimes with defined field geometry) and, as already mentioned, an inversion of the general trend. Of course, the overall comparison does not take into account the intermediate changes. Gravity returned to increase on the top of the volcano – reducing the previous decrease – and a faster gravity decrease at the base of the volcanic structure occurred. The greatest values are always observed respectively at the stations Osservatorio Vesuviano (on the top, +59 μGal) and Torre del Greco and Boscoreale (at the base, −66 and −98 μGal respectively). An evaluation of the total amount of the mass increase/decrease in $1.6 \cdot 10^{10}$ kg e $-1.0 \cdot 10^{10}$ kg respectively. Again the two areas are separated with strong gradient in Torre del Greco crossing the NE-SW structure. The reliability of the gravity inversion can be strongly constrained by taking into account the temporal gravity changes at the Osservatorio Vesuviano and Torre del Greco stations shown in Figure 2. A high degree of similarity in the changes depicted at both stations is very evident. An inversion of the trend is also evident in the ground movement during 1993-1994 as obtained by tide-gauge data [e.g. Berrino 1998, Berrino et al. 2006]. The results obtained by relative gravimetry are also confirmed by the repeated absolute measurements in 1996 and 1998 (Figure 2). This 1994-1999 time interval overlaps the 1995-1996 seismic crisis (Figure 2).

3) **1999-2003** (Figure 3c): Once again an inversion in the global gravity field is observed. Also during this time interval we observe some large and almost steady changes. A gravity decrease (maximum −91 μGal) occurs at the top of the volcano, mainly in the area at the base of the volcanic cone, while a significant gravity increase (maximum 81 μGal) involves the whole base area and partly nulls the gravity decrease previously occurred in the south-eastern area. The total amount of the mass increase/decrease have been respectively evaluated in $1.0 \cdot 10^{11}$ kg e $-3.5 \cdot 10^{10}$ kg. A strong gradient crossing the NE-SW structure in Torre del Greco is again evident. This time interval overlaps the 1999-2000 seismic crisis (Figure 2).

4) **2004 to present** (Figure 3d): The most significant changes occurring during this time interval show a clear seasonal effect with amplitude generally of the order of some tens of μGal. Over the whole period, no statistically significant gravity changes occurred and no important seismic activity was detected. A weak and insignificant seismic activity occurred during this time interval (Figure 2).

It is noteworthy that the main gravity changes are well correlated with the occurrence of seismic activity. This correlation was also noted in the changes of the tidal gravity factor, namely for the M_2 tidal wave, obtained by the analyses performed on the gravity records during the 1960s, 1987-1991 and 1994-2000 [e.g. Berrino et al. 2006, Riccardi et al. 2008].

5. Conclusions

We analyzed 30 years of gravity data collected at Mt. Vesuvius and show several long-term periods during which interesting gravity changes occurred. Only a few short periods showed significant changes.

The absence of ground deformation during the whole analyzed period led us to conclude that gravity changes indicate underground mass redistribution, essentially density changes at constant volume. We can confirm (as in past [e.g. Berrino et al. 1993, Berrino and Riccardi 2000]), taking also into account the correlation with the seismic activity, that density changes may be due to fluid migration (e.g., water) in an undersaturated porous medium, through pre-existing lineations and/or new fractures generated by seismic activity.

This interpretation is supported by the analysis of the short time intervals, which shows well defined patterns of the spatial gravity changes, overlapping the most significant and recent seismic crises (i.e., the 1995-1996 and 1999-2000). The gravity field changes over the selected time intervals are displayed in Figure 4 (left and center) where, on the right, a zoom of the recorded seismicity over the same period is shown. The periods of increasing (in red) and decreasing (in blue) gravity are also shown. We can observe that a gravity increase anticipates and overlaps the seismic crises, while a period of gravity decrease soon follows. Of course, the different time scale response of the gravity decrease over the two considered time intervals, as evident in Figure 4 (graphics on the right), is due to the time interval between the considered field surveys, for most the cases carried out once per year. This does not permit to detect the exact time when the decreasing gravity really start. But, if we consider, for the 1999-2000 time interval, an additional campaign carried out in October 1999 (Figure 4, intermediate red line in the red part of the bottom graphic on the right), during the seismic crisis, we observe that the increasing gravity field is progressively built in time, starting from the volcanic structure (March 1999-October 1999) and later (October 1999-April 2000) expanding over the remnant area till few months later the end of the seismic crisis. Of course also in this case we cannot fix the exact time when the gravity increase starts, but this behavior may suggest that gravity increase starts before the beginning of the seismicity and persists some months later its end, therefore gravity decrease may occur some months later the end of the seismic crisis.

Although these observations are only a remark, if we assume that gravity changes are due to fluid migration they suggest that the arrival of fluids (gravity increase) can trigger seismicity which creates new fractures. The more fractured medium filled by new fluids (e.g., water) may be responsible for the observed gravity decrease. Taking into account the areal distribution of the gravity changes, we estimate a maximum depth of about 1000 m b.s.l. at which such a process occurs. This is the depth where Celico et al. [1998] indicate the presence of a semipermeable zone just below the bottom of the shallow aquifer.

Our interpretation of gravity changes seems in agreement with the hypothesis made by Del Pezzo et al. [2004] suggesting that shallowest seismic events may be triggered by the increase in fluid pore pressure. In

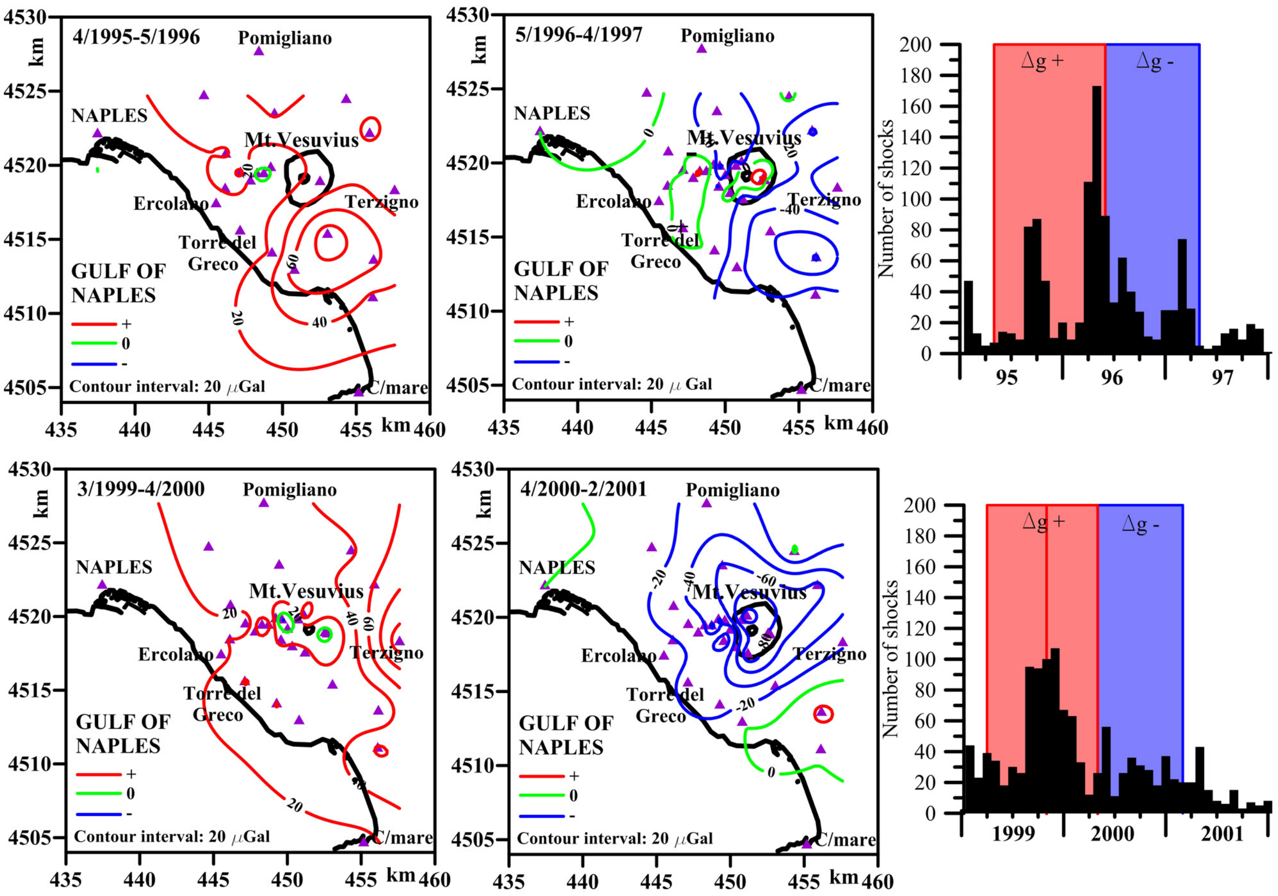

Figure 4. The few significant gravity changes fields over short time intervals overlapping the most recent seismic crises: 1995-1996 (up) and 1999-2000 (down). In both cases a gravity increase anticipates and overlaps the seismic crisis (see graphics on the right) and is soon after followed by a gravity decrease. Graphics on the right show the number of earthquakes during the analyzed time interval; on them the length of both increasing and decreasing periods are respectively highlighted in red and in blue. The intermediate red line, in the red part of the graphic on the right related to 1999-2000 interval, indicates the date of an additional field survey (October 1999).

addition, also a conceptual geochemical model suggests that the pressurization in some parts of the hydrothermal system, and its subsequent discharge through hydrofracturing, could explain the seismic crises recorded after the last eruption [Chiodini et al. 2001].

The gravity changes observed during the last 30 years suggest that no volcanic sources are involved and then Mt. Vesuvius may be considered in a quiescent stage, with a very low level of activity.

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