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On the capability of recording gravity stations to detect signals coming from volcanic activity: The case of Vesuvius

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Abstract

The goal of this paper is to describe how continuous gravity measurements can improve the geophysical monitoring of a volcano. Here the experience of 15 yr in continuous gravity on Vesuvius is presented.

A wide set of dynamic phenomena (i.e. geodynamics, seismicity, volcanic activity) can produce temporal gravity changes, with a spectrum varying from short (1–10 s) to longer (more than 1 yr) periods. An impending eruption, for instance, is generally associated with the ascent of magma producing changes in the density distribution at depth, and leading to ground deformation and gravity changes observed at surface. The amplitude of such gravity variations is often 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), so their detection requires instruments with high sensitivity and stability, providing high quality data. Natural, man-made and instrumental sources are present on the gravity records affecting the Signal to Noise Ratio. Such effects may hide the subtle volcanic signals. The main natural noise is due to ocean–atmosphere dynamics and seismic activity.

New approaches to model the instrumental response of mechanical gravity sensors (based on the inter-comparison among superconducting, mechanical and absolute gravimeters) and to investigate the temporal trends of the instrumental sensitivity are proposed. In fact, variations of the calibration factors can be considered the main cause preventing the repeatability of high-precision gravity measurements and inducing phase and amplitude perturbations in recorded gravity signals. A modelling of the background gravity noise level was performed at the Vesuvius station.

Moreover, the "far field" effects produced by large earthquakes on the gravity station have been also investigated. Finally, the time dependent behaviour of the tidal gravimetric factors, the non-stationary components of the gravity field detected at Vesuvius and the results of absolute and relative gravity measurements are interpreted in the framework of its present-day dynamics, mainly characterized by the low level of seismicity, small ground deformation, gravity changes and moderate gas emission.

Keywords: Vesuvius; gravity; record; volcanic processes

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1. Introduction

Gravimetry is a powerful investigative tool able to detect the ascent of magmatic masses. Time dependent gravity changes are generally detected by repeated relative gravity measurements of a network with reference to "base stations" (e.g. Berrino et al., 1984; Eggers, 1987; Yokoyama, 1989; Brown et al., 1991) and, more recently, also by absolute measurements (Berrino, 1995; Berrino et al., 1999; Berrino, 2000). Apart from these, there are limited data on continuous gravity at active volcanoes (e.g. Imbò et al., 1965a; Davis, 1981; Vieira et al., 1991; Goodkind and Young, 1991; Berrino et al., 1997; Budetta and Carbone, 1997; Bonvalot et al., 1998, Arnoso et al., 2001).

Two different approaches may be adopted to extract from the gravity records the signals due to changes in physical properties at depth, i.e., the analysis of the time changes of the tidal gravimetric factor (delta) and the analysis of gravity residuals.

According to the recommendations of the Working Group on the Theoretical Tidal Model (SSG of the Earth Tide Commission Sec. V of the IAG), the delta factor (δ) is defined as the Earth's transfer function between the body tide signal ($\tilde{\Delta}g_n(r)$) measured at the station by a gravimeter and the amplitude of the vertical component of the gradient of the external tidal potential (V_n) at the station.

$$-\frac{r}{n}\tilde{\Delta}g_n(r) = \tilde{\delta}_n V_n \quad \text{where} \quad \tilde{\delta}_n = 1 + \frac{2}{n}\tilde{h}_n - \frac{n+1}{n}\tilde{k}_n$$

r is the radius of the Earth and $\tilde{h}_n$, $\tilde{k}_n$ are volume Love numbers of degree n (complex value), which characterize the spherical elasticity of the Earth.

In other words, the delta factor is the ratio between the observed gravity tide and the luni-solar gravitational attraction. As it defines the Earth transfer function of the external tidal potential, the delta factor is frequency-dependent and is related to the elastic property of the Earth. Because of the viscoelastic behaviour of the Earth, its reaction to the external perturbation due to the luni-solar gravitational attraction is characterized by a certain phase shift. So the study of the time evolution of the tidal parameters (delta factor and phase) for the main tidal waves could be useful to characterize the deformational behaviour in some geodynamic context and specifically in volcanic areas. Moreover, knowledge of the specific tidal parameters for an area is required to calculate the luni-solar effect, which has to be removed from the gravity record to obtain gravity residuals. In fact, gravity residuals, due to subsurface mass redistribution, are obtained after the effects of non-volcanic sources (i.e., luni-solar gravitational effect, ocean and atmospheric contributions, instrumental drift) have been removed. Generally, gravity signals due to volcanic sources are on the order of 10^{-8}–10^{-6} g (10^2–10^4 nm/s^2; 10–10^3 μGal), where g is the mean value of normal gravity (9.806 199 203 m/s^2); thus, their detection requires instruments with high sensitivity and stability as well as a very low instrumental drift.

Besides volcanic activity, a wide set of geophysical phenomena affect the elasto-gravitational equilibrium of the Earth [e.g., Seismic Free Oscillations (SFO), luni-solar tides, Free Core Nutations (FCN), Earth's rotation changes, Plate Tectonics and seismic processes (Torge, 1989)], whose amplitude is generally on the order of 10^{-8}–10^{-9} g (10–10^2 nm/s^2; 1–10 μGal). Their spectrum varies from short periods, 1–10 s (microseismic noise), to periods longer than 1 yr (Geodynamics, Post Glacial Rebound, Polar motion) (Crossley and Hinderer, 1995; Hinderer and Crossley, 2000).

This research is intended to determine whether continuous gravity records are able to detect the gravity changes related to volcanic dynamics and thus improve the geophysical monitoring of a volcano. The experience of about 15 yr at Vesuvius (Southern Italy) is reported.

Vesuvius (Fig. 1) is a stratovolcano located in the Campania Plain (Southern Italy) at the intersection of two main fault systems oriented NNW–SSE and NNE–SSW. The Campania Plain is a graben bordered by Mesozoic carbonate platforms downfaulted during Pliocene and perhaps Pleistocene times as a consequence of the stretching and thinning of the continental crust related to the opening of the Tyrrhenian basin (Hyppolite et al., 1994). The volcanic center is formed by an ancient caldera (Mt. Somma) and by a younger cone (Mt. Vesuvius). Volcanic activity dates back to 300–500 ka (Santacroce, 1983). Information on shallow structures comes from a deep borehole drilled down to a depth of 2200 m b.s.l. (Principe et al., 1987) and several geophysical studies (e.g., Finetti and Morelli, 1974; Cassano and La Torre, 1987;

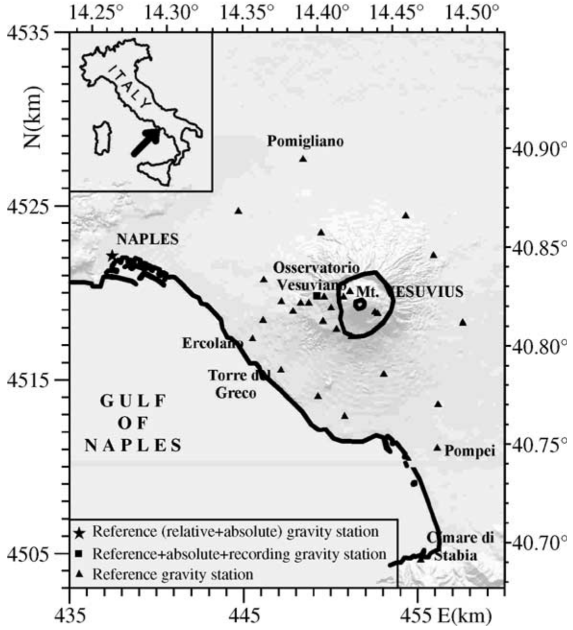

Fig. 1. Gravity network on Vesuvius.

Berrino et al., 1998; Bruno et al., 1998; Di Maio et al., 1998; Fedi et al., 1998). Zollo et al. (1996) and more recently Auger et al. (2001) suggest based on a seismic tomography the presence of a melting zone at a depth of about 8 km and a high P-wave velocity zone, with a rough cylindrical symmetry with respect to the crater axis, extending from the surface down to a depth of approximately 2 km, where it encounters the carbonate basement. Small and shallow magma chambers, suggested by some geochemical and volcanological considerations (Cortini and Scandone, 1982; Rosi et al., 1987), are undetected by seismic tomography (Auger et al., 2001). Vesuvius is a quiescent volcano whose last eruption occurred in March 1944. Currently, the volcano shows a low level of sometimes increasing seismicity, small ground deformation, gravity changes and moderate gas emission (Berrino et al., 1993a; Iannaccone et al., 2001). The strongest seismic event in recent years occurred on October 9th, 1999 ($M_L = 3.6$) which marks the beginning of the 1999–2000 seismic crisis. Results obtained both by spaceborne SAR interferometry and levelling surveys show that the Somma–Vesuvius volcanic complex is characterized by a rather continuous subsidence mainly in two zones: localized on the Vesuvius cone and in a narrow annular area that, although not continuously, 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/yr (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.

Relative gravity measurements have been routinely carried out since 1982 on a network spanning the whole Vesuvian area (Fig. 1). An absolute station was established on the volcano in 1986 and the value of g was measured repeatedly there in 1994, 1996, 1998 and 2003 (Berrino, 1995, 2000). The absolute and one of the relative gravity stations are located at the Osservatorio Vesuviano, where a recording gravity station (Fig.1) has been operating since 1987 (Berrino et al., 1993b) and where a first experiment of continuous gravity measurements was performed during the 1960s (Imbò et al., 1964, 1965a).

In this paper, the time dependent behaviour of the tidal gravimetric factors is compared with the results from relative and absolute gravity surveys, gravity records during 1960s and seismic activity from the 1970s. The results are interpreted in the framework of the present-day dynamics.

2. Data acquisition and analysis

The recording gravity station is assembled on a concrete pillar located in an artificial cave, 20 m deep (φ: 40.82°N, λ: 14.40°E; h: 608 m) (Berrino et al., 1997). The gravity sensor is the LaCoste and Romberg model D, number 126 (LR-D126), equipped with a Maximum Voltage Retroaction (MVR) feedback system (van Ruymbeke, 1991), with a range equivalent to $3 \cdot 10^4$ nm/s^2 (implemented at the ROB, Royal Observatory of Belgium in Brussels and upgraded in 1994). The data acquisition is provided by DAS or µDAS systems developed at the ROB (van Ruymbeke et al., 1995) at a sampling rate of 1 data/min (0.01667 Hz).

Here we focus on the results of gravity records since 1994 (Fig. 2a), when the instrument and logistical conditions of the station were improved. In order to check the reliability of the gravity signals, the

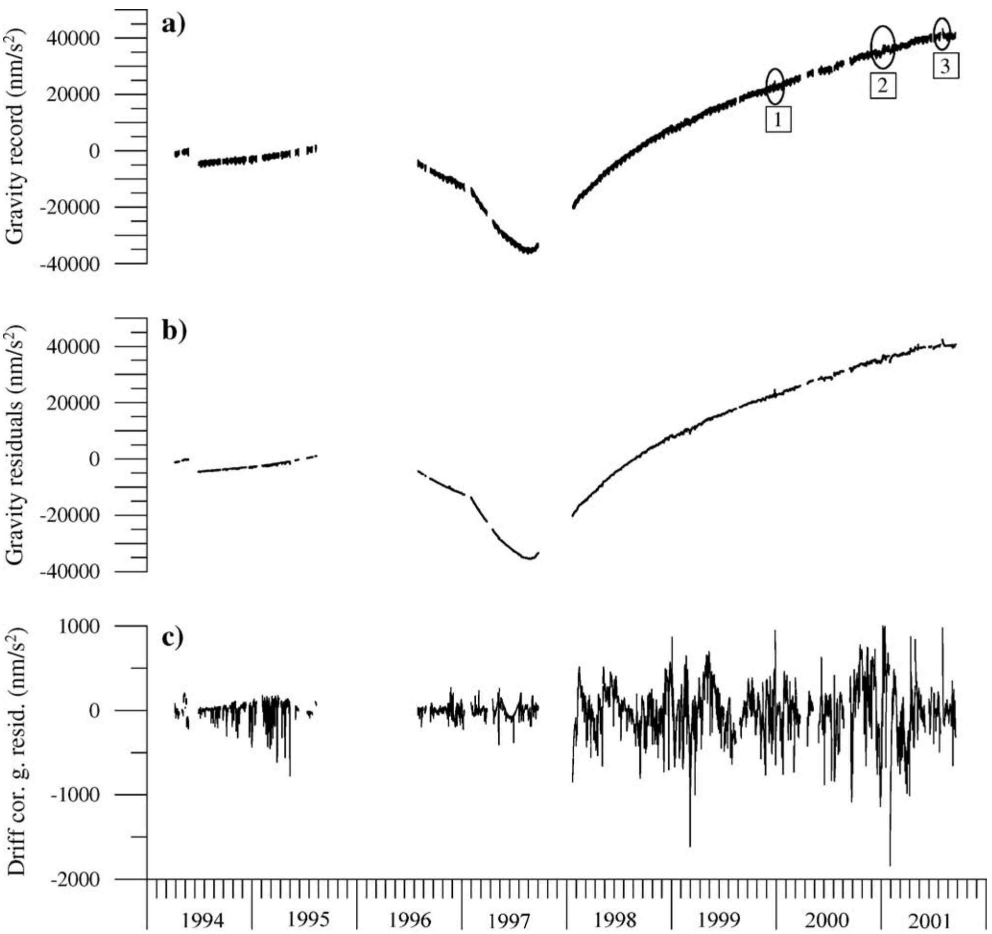

Fig. 2. Hourly values of gravity records (a), gravity residuals (b) and drift corrected gravity residuals (c). Anomalous records with abnormal drift and very large residuals are highlighted by circles.

instrumentation is periodically calibrated and an analysis of the background noise level at the station has been performed. In fact, instrumental sensitivity can change, not always linearly, as a consequence of mechanical perturbation and the noise level at the gravity station. To characterize the background noise level at the station, which could affect the instrumental response, the 1 min sampled residual gravity has been analyzed to detect any possible seasonal dependence or the presence of spectral components which could hide or mask geophysical signals. Several time windows lasting about 1 week were selected in each season (Fig. 3). The amplitude and spectral content of the noise (Berrino and Riccardi, 2004) (Fig. 3) show a flat trend in the analyzed spectral band, according to

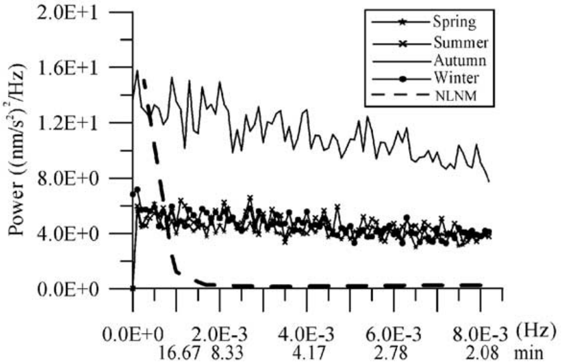

Fig. 3. Power spectra of the background noise level computed in each season at the Vesuvius gravity station, with the standard New Low Noise Model (NLNM) as a reference.

Table 1
Comparison between LR-D126 and superconducting SG-TT70-T015 meters: results (delta factor and phase) of the tidal analysis for the main tidal waves

Wave	SG-TT70-T015		D-126		SG/D
	Delta	Phase (°)	Delta	Phase (°)	Delta
O_1	1.147 ± 0.003	− 0.2 ± 0.1	1.14 ± 0.01	− 0.1 ± 0.6	1.006 ± 0.009
P_1 S_1K_1	1.137 ± 0.002	0.0 ± 0.09	1.130 ± 0.009	0.1 ± 0.6	1.006 ± 0.007
M_2	1.184 ± 0.001	1.14 ± 0.06	1.176 ± 0.003	0.9 ± 0.2	1.007 ± 0.004

In the last column the ratio (SG/D) of delta factors obtained by the records from the superconducting and D meters is listed. The tidal waves nomenclature is: O_1—diurnal lunar; P_1—diurnal lunar; K_1—diurnal luni-solar; S_1—diurnal solar; M_2—semi-diurnal lunar; S_2—semi-diurnal solar.

the standard New Low Noise Model [NLNM] (Peterson, 1993).

Changes through time of the calibration factors for different kinds of mechanical gravimeters have been detected by several authors (e.g. Bonvalot et al., 1998; Budetta and Carbone, 1997; Riccardi et al., 2002). However, a complete understanding of the physical processes affecting the instrumental sensitivity is still far from being achieved.

As changes in instrumental sensitivity can prevent the repeatability of measurements and affect the phase and amplitude of the recorded gravity signals, the accurate calibration of gravimeters plays a key role in high precision gravity measurements (Riccardi et al., 2002). The calibration of a gravimeter at an accuracy level of 10^{-8} to 10^{-9} g is difficult to attain because of the many problems in pursuing a known gravity change ("standard") at such a level of accuracy.

The stability of the calibration factors in LR-D126 has been periodically investigated on site. This kind of calibration is obtained by inducing changes in the spring length through a known "dial" turning and fitting this, by least-squares, against the instrumental output. Moreover, two additional calibrations of the feedback were carried out in June 1994 and November 1997 in Sèvres, at the Bureau International des Poids et Mesures (BIPM) during the International Comparison of Absolute Gravimeters (Becker et al., 1995, 2000). A calibration of the instrumentation was also obtained in 1997 by means of a joint intercomparison with the superconducting SG-TT70-T015 gravimeter (Table 1) and the absolute FG5-206 gravimeter (Riccardi et al., 2002). The intercomparison between spring and superconducting gravimeters is the most suitable way to determine the transfer function of spring gravimeters in the tidal band. Detailed information on the different calibra-

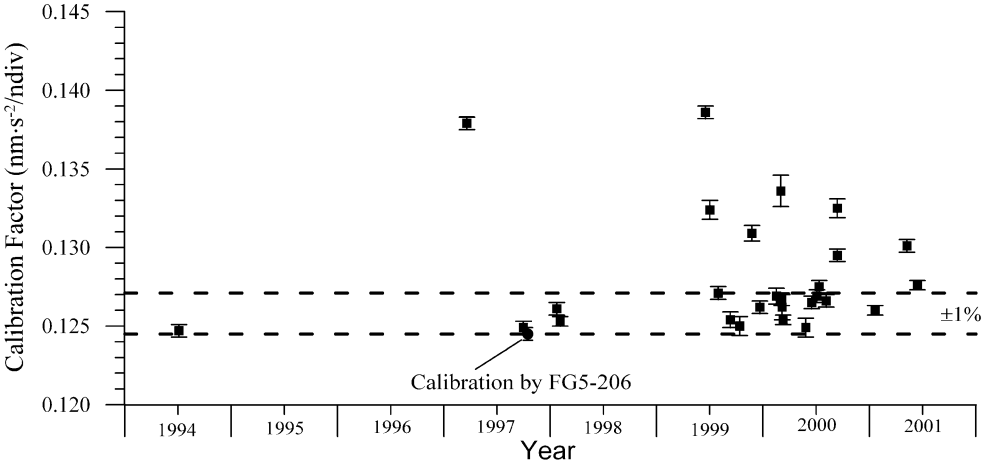

Fig. 4. Calibration factors obtained with on-site and absolute calibration for the LR-D126 gravity meter.

tions carried out at this station is given in Riccardi et al. (2002). The time distribution of the calibration factor is shown in Fig. 4. In this plot the value from the previously quoted intercomparison with the FG5-206 absolute gravimeter is shown and the suitable range of repeatability of the calibration factor at 1%

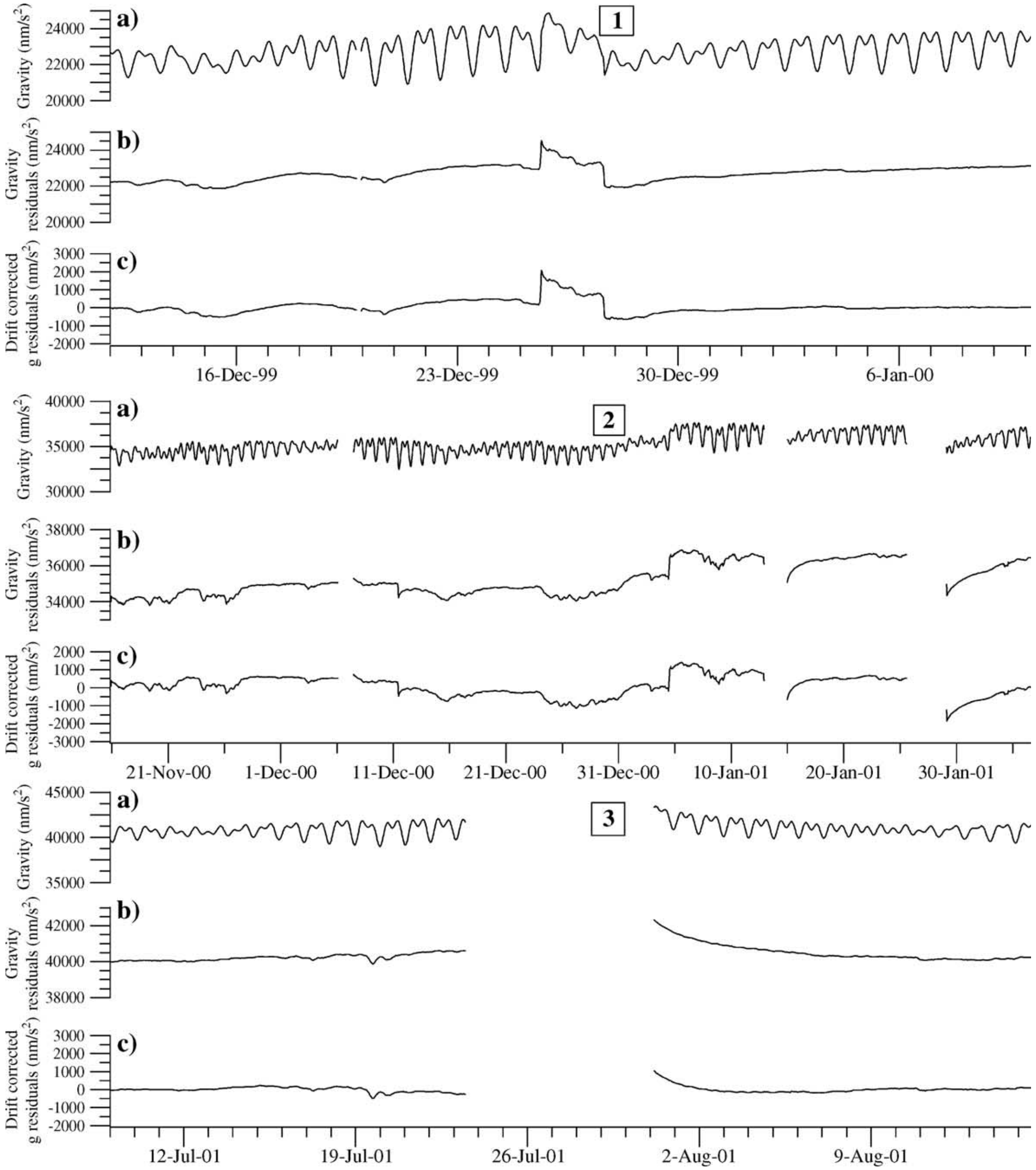

Fig. 5. Zoomed sections of the anomalous records highlighted in Fig. 2: gravity records (a), gravity residuals (b) and drift corrected gravity residuals (c).

level is also drawn. A large scattering of the calibration factor occurs from 1999 to 2001, when some anomalous signals were detected. The anomalous signals (highlighted in Fig. 2a and shown in Fig. 5) were characterized by an abnormal drift and then very large gravity residuals.

As a consequence, the tidal analysis on the 1998–2000 data shows a sharp decrease of the δ factors at the beginning of 1999 (Berrino and Riccardi, 2001). A theoretical value of the instrumental sensitivity was computed and compared with the calibration factors monitored “on site” to evaluate whether the calibration factor truly reflects changes in the instrumental response or is merely due to the adopted “on site” calibration procedures. The theoretical instrumental sensitivity was determined by a regression analysis between the meter’s output signal and the synthetic gravity tide. Thus, a set of weekly theoretical values of calibration factor was obtained and compared with the results from the repeated calibrations. A good agreement between the temporal evolution of the theoretical factors and those obtained through the “on site” calibration was detected (Riccardi et al., 2002). The set of the “on site” and theoretical calibration factors has been plotted against the time occurrence of certain large worldwide earthquakes [$M_L > 5$] (Fig. 6). A time correlation between the larger changes of instrumental sensitivity and the occurrence of seismic events can be observed. More detailed discussion concerning the instrumental sensitivity changes on the occasion of large earthquakes is given in Riccardi et al. (2002) and Berrino and Riccardi (2004); they suggest that the higher frequency of the SFO excited by large earthquakes includes the fundamental mode of oscillation (T_0: 15 to 20 s) of the LaCoste and Romberg spring gravimeters (Torge, 1989). In light of these results, a mechanical perturbation of the sensor, due to some dominant frequencies of the noise at the station on the occasion of large earthquakes, may be hypothesized. These instrumental disturbances can last several weeks.

To prevent instrumental effect on the time delta changes, a function has been computed from the calibration factors to convert the recorded signal into nm/s^2 (Fig. 7). Two calibration functions have been computed respectively by including or excluding the highest outlier in 1999. The harmonic tidal analyses were repeated on the gravity record calibrated by means of the two functions and results (δ factors and phases) compared. By using the first calibration function a good correlation between the temporal trend of the calibration factors and δ persists, indicating that the results from tidal analyses are affected by instrumental effect. Thus, taking into account these results, the first calibration function (dotted line in Fig. 7) was rejected and we adopted the second function (bold continuous line in Fig. 7) to calibrate the gravity record (ref. Fig. 2) spanning from 1999 to 2001.

All of the gravity records were analysed to obtain tidal parameters (δ factors and phases) and gravity residuals (Fig. 2). The latter have been computed by subtracting the luni-solar effect, according to Tamura’s gravity potential catalogue (Tamura, 1987) from the gravity record, as well as a first order correction for the atmospheric effect and instrumental drift.

The Wahr–Dehant–Zschau (WDZ) Earth model (Wahr, 1981; Dehant, 1987; Zschau and Wang,

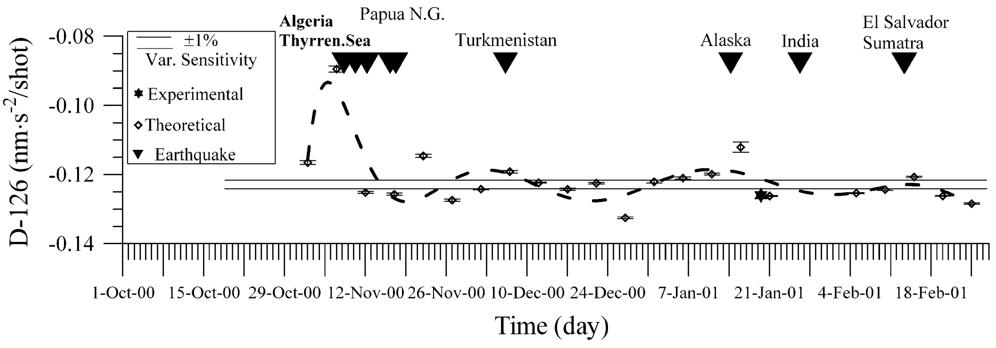

Fig. 6. On-site and theoretical calibration for LR-D126 against the occurrence of some large earthquakes ($M_L > 5$).

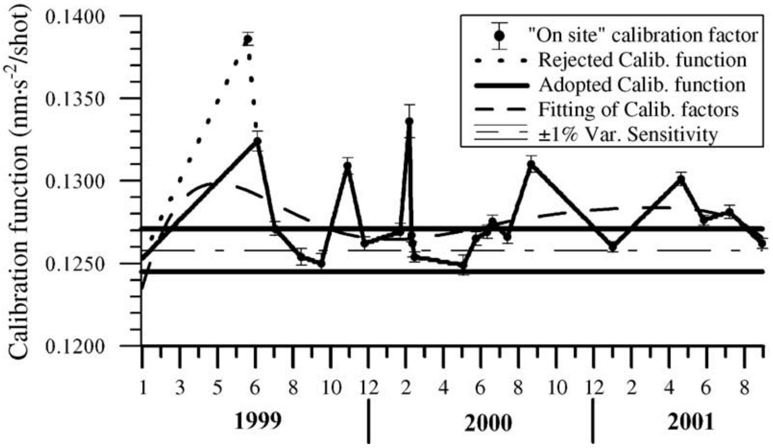

Fig. 7. Calibration functions (dotted and continuous lines) interpolating the factors obtained with the on-site calibrations (points with error bars) and polynomial fitting (dashed line). The thickest line is the calibration function adopted to convert gravity records in nm/s^2.

1987) has been adopted to compute tidal parameters, while for the computation of gravity residuals a synthetic tide was calculated using tidal parameters computed from the local gravity records since 1994.

The mean coefficient, $-3.5\ \mathrm{nm \cdot s^{-2}/hPa}$, has been adopted to correct gravity record for the atmospheric effect, in accordance with both the Warburton and Goodkind (1977) and Spratt (1982) statistical approaches (Berrino et al., 1997, 2000).

Accurate modelling is necessary to remove the instrumental drift and to distinguish it from long term gravity changes. Here, drift has been constrained by taking into account the temporal gravity changes obtained by both relative and absolute measurements. The latter show a negligible contribution on the trend observable in Fig. 2b; thus, the long term component of the gravity record can be considered instrumental drift. The drift corrected gravity residuals are shown in Fig. 2c.

The data set has been analysed by means of an algorithm for tidal analysis: "*ETERNA 3.3*" (Wenzel, 1996). The results for the main tidal waves are summarized in Table 2. The analyses have been performed on the gravity record rearranged in some temporal subsets (ref. to 1st column of Table 2) to check the time stability of the solutions and investigate the temporal changes of δ factors with a better resolution. In fact, the results of tidal analyses represent averaged values for that period; thus, performing a global analysis on the complete data set (spanning from 1994 to 2001) does not give complete information about the temporal changes of δ during such a period.

Table 2
Tidal gravimetric factors (delta) for the main tidal waves: results of analyses on several data sub-sets spanning 1994–2001 (For tidal waves nomenclature, refer to Table 1)

Time	Tidal waves			
	O_1	K_1	M_2	S_2
1994–1995 324.8 days	1.123 ± 0.006	1.118 ± 0.004	1.149 ± 0.003	1.163 ± 0.006
1996–1997 340.1 days	1.131 ± 0.005	1.115 ± 0.004	1.148 ± 0.003	1.135 ± 0.006
1996–1998 508.6 days	1.130 ± 0.004	1.114 ± 0.003	1.148 ± 0.002	1.141 ± 0.005
1994–1998 *1013.7 days*	1.126 ± 0.002	1.117 ± 0.001	1.1488 ± 0.0007	1.144 ± 0.004
1998–1999 694.6 days	1.132 ± 0.003	1.119 ± 0.002	1.152 ± 0.001	1.147 ± 0.002
1999–2000 *491.7 days*	1.143 ± 0.004	1.123 ± 0.003	1.155 ± 0.001	1.155 ± 0.003
1994–2001 *1879.3 days*	1.133 ± 0.002	1.116 ± 0.001	1.1498 ± 0.0007	1.145 ± 0.002

3. Discussion and conclusions

The results of the tidal analyses (Table 2) show an increase of the δ factor in the period 1999–2000. Moreover, the anomalies detected on records during 1999–2000 persist in gravity residuals (Fig. 2), although a calibration function, which might eliminate or at least reduce the instrumental effects, has been adopted. This appears to be well correlated with some changes in the activity of Vesuvius. Seismicity, δ factor and gravity changes have been reconstructed by the available data for the last forty years (Fig. 8).

A seismic crisis began in October 1999 (Iannaccone et al., 2001) and a significant inversion of the trend of the gravity changes occurred in 1994. In Fig. 8d the observed temporal gravity changes at the Osservatorio Vesuviano station is shown. The reliability of this gravity change may be strongly constrained by taking into account data from others stations of the Vesuvius relative gravity network. As an example, in Fig. 8d the gravity changes with time at Torre del Greco, about 5 km SW of the Vesuvius crater, and the vertical ground movement continuously obtained by tide gauge data are shown. Tide gauge data were considered because they represent the longest available dataset of continuously recorded vertical ground movement and because they were collected very close to the Torre del Greco gravity station. An inversion of the trend, detected in 1993–1994, is also evident in the ground movement. A high

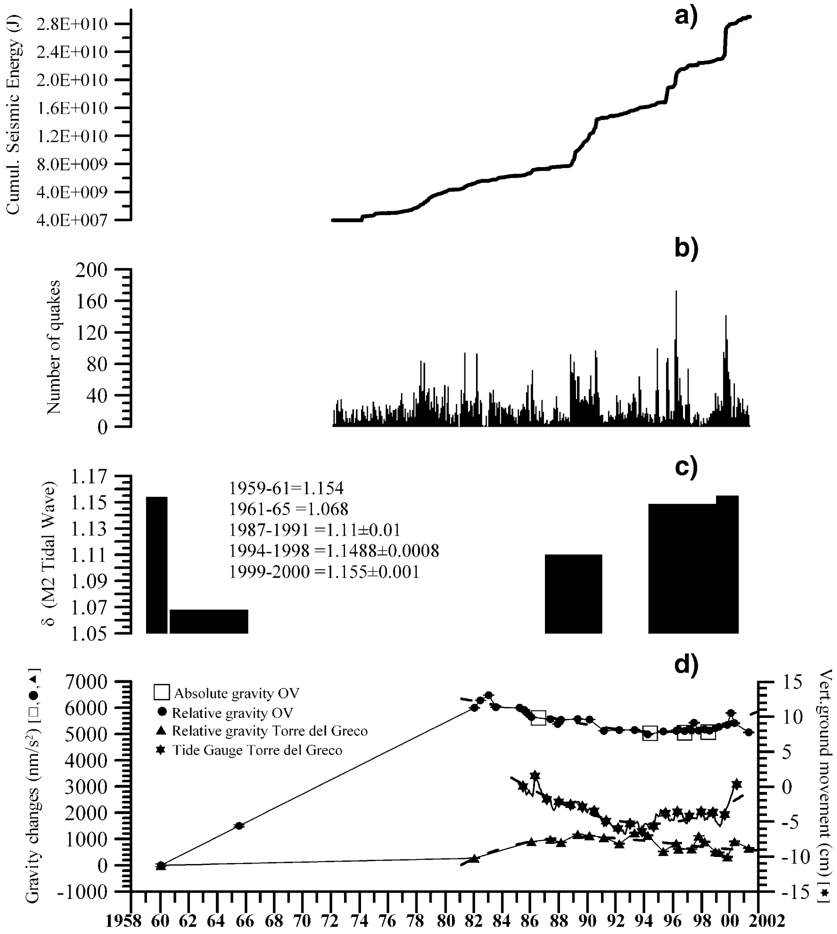

Fig. 8. Time behaviour of Vesuvius dynamics from 1959 to 2001: a–b) seismic activity; c) tidal gravity factor for M_2 tidal wave; d) gravity changes (expressed in nm/s^2 [10 nm/s^2 = 1 μGal]) at the Osservatorio Vesuviano station plus gravity and elevation changes at Torre del Greco.

degree of similarity in the changes observed at both stations is clear. This suggests that the anomalous tidal signals may be due to an "elasto-gravitational" perturbation (e.g. ground tilt changes) likely correlated with the local dynamics. The results of these tidal analyses have also been compared with the previous ones from 1987–1991 and 1960s (Table 3, Fig. 8c).

An increasing trend from the 1961 to present in the amplitude of the tidal waves is clearly detectable. Taking into account the logistic and instrumental differences between the 1959–1965 (Askania meter Gs9, Gs11) and 1987–2001 recording stations, a rough comparison among the different data can be made. From 1961–1965 to 1987–1991, changes in the tidal parameters cannot be considered significant, while an increase can be noted from 1991 to 1994 and, as previously discussed, in 1999–2000. The latter shows tidal parameters similar to the values determined in the 1959–1961 time interval.

It is noteworthy that the main changes of tidal parameters seem again well correlated with the temporal behaviour of the activity of Vesuvius.

The analyzed seismicity comes from a catalogue containing all seismic events from 1972 detected at the reference station of the Vesuvian seismic network (estimated threshold: Md = 1.9); at least three crises (1989–91, 1996, 1999–2000) (Fig. 8a–b) are reported (Berrino et al., 1993a; Vilardo et al., 1996; Iannaccone et al., 2001). Moreover, an increase in seismicity is also well documented in 1963–1964 (Imbò et al., 1965b). Concerning gravity changes, here we focus on the results of the episodic gravity measurements since 1982 collected on Vesuvius relative gravity network (Berrino, 2000; Berrino and Riccardi, 2000). The observed temporal gravity change at the Osservatorio Vesuviano station (Fig. 8d) shows an increase (more then 200 nm $\cdot$ s^{-2}/yr; 20 μGal/yr) in 1959–1983 time interval (Berrino and Riccardi, 2000, 2001), as inferred by reviewing data collected during 1959–1960 (Tribalto and Maino, 1962) and 1965 (Bonasia, unpublished data) gravity surveys. This trend fits the gravity data collected during the 1980s, when a continuous gravity increase affected the whole area (Berrino, 2000).

The 1960–1982 spatial gravity field (Fig. 9a) shows a large gravity increase characterized by null variations at the base of the volcano and by a progressive increase towards the summit, with a maximum value of about 6000 nm/s^2 (600 μGal). Accounting for the different and not inter-calibrated instruments, plus a possible height effect, an increase of no less than 3000–4000 nm/s^2 (300–400 μGal) is realistically estimated (Berrino, 2000). From 1982 to 2001 the overall field of the observed gravity changes shows several well defined patterns. Three main periods have been recognized (Berrino and Riccardi, 2000):

1) 1982–1994 (Fig. 9b): two distinct areas were progressively formed. The first on the volcano characterized by a gravity decrease, the second one at the base of the volcanic structure showing a gravity increase;
2) 1994–1999 (Fig. 9c): an inversion of the general trend occurred. An expansion of the area with decreasing values is observed;
3) 1999–2000 (Fig. 9d): a gravity increase involving the whole area starts again. It is overlapping in time with the 1999 seismic crisis.

Focusing on the most recent data (Fig. 8), it is interesting to note that the increase of the δ factor from 1991 to 1994 (Fig. 8c) occurred during or soon after the 1989–1991 seismic crisis (Fig. 8a–b). A gravity decrease of about 600 nm/s^2 (60 μGal) (Fig. 8d) (Berrino et al., 1993a) was also detected

Table 3
Comparison among tidal gravimetric factors determined during the 1960s, 1987–1991 and 1994–2000 (For tidal waves nomenclature refer to Table 1)

Wave	1959–1961	1961–1965	1987–1991	1994–1998	1999–2000
	Imbò et al., 1965a	Imbò et al., 1965a	Berrino et al., 1993b		
O_1	1.156	1.038	1.08 ± 0.02	1.126 ± 0.002	1.143 ± 0.004
K_1	P1S1K1:0.928	1.083	1.05 ± 0.01	1.117 ± 0.001	1.123 ± 0.003
M_2	1.154	1.068	1.11 ± 0.01	1.1488 ± 0.0007	1.155 ± 0.001
S_2	1.147	1.107	1.03 ± 0.02	1.144 ± 0.004	1.155 ± 0.003

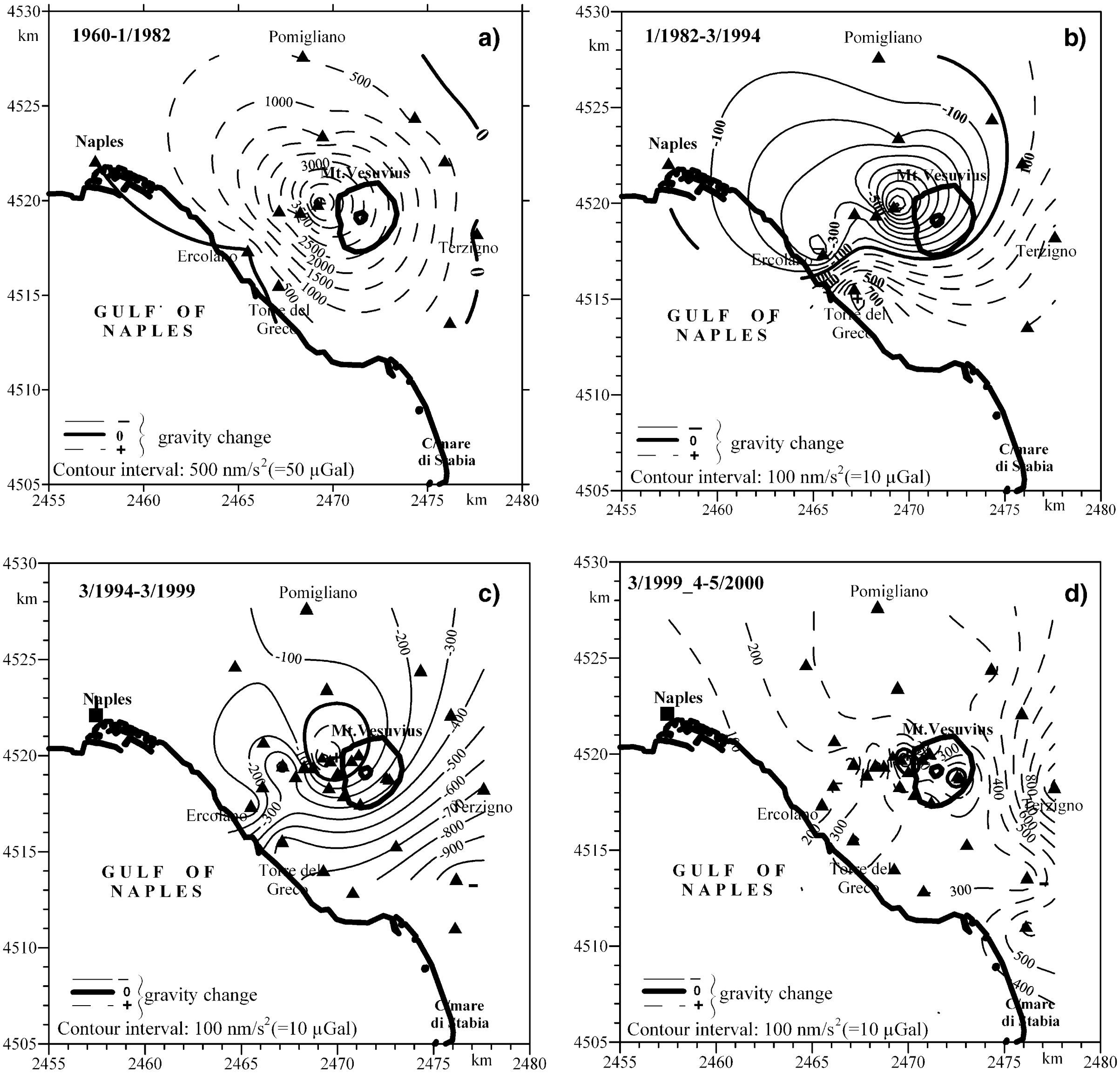

Fig. 9. Several time intervals of gravity changes from relative measurements of the Vesuvius network between 1960 and 2000. Thin lines represent negative gravity changes, thick lines indicate null gravity and dashed lines show positive gravity changes.

between 1989 and 1991 at the Osservatorio Vesuviano gravity station by both relative and absolute gravity measurements.

No additional information on volcanic sources may be inferred by the gravity residuals (Fig. 2c). Although their time distribution clearly shows an increase in amplitude and scattering during 1998–2001, coincident with the increasing seismicity, there are not enough clear gravity signals to detect or hypothesize the presence of volcanic input. In fact, the application of gravity residuals to study mass redistribution due to volcanic processes requires at least a reference station outside the volcano, which would make it possible to model and exclude long-term and non-volcanic “regional” effects (Berrino et al., 1997).

The tidal response of the investigated area could indicate a variation of the deformational behaviour probably due to the change of the mean mechanical properties of Vesuvius, as already suggested by Berrino et al. (1997).

Finally, these results suggest that continuous gravity recording on active volcanoes can be a powerful investigative method if the instrument is adequately monitored in order to detect anomalous instrumental response and/or geophysical signals due to non-volcanic sources. The state of the art demonstrates that the gravity record is able to characterize the deformational behaviour of a volcano through the time evolution of the δ factor, while the capability of gravity residuals requires a significant improvement in modelling mainly instrumental drift, atmospheric and hydrological contribution. However, the joint application of relative, absolute and continuous gravimetry is strongly recommended, also to better remove the long term instrumental drift. Thus the recognition of real gravity changes from the apparent ones, due to instrumental behaviour, becomes possible.

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