Continuous record of the gravity changes at Mt. Vesuvius

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Abstract

High precision relative and absolute gravity measurements are periodically carried out at Mt. Vesuvius (Southern Italy) to monitor the changes in the gravity field caused by the internal dynamics of the volcano. Moreover, a recording gravity station is also operating at the Osservatorio Vesuviano (Old Building) aimed at measuring in continuous mode the time variations of the gravity and the tidal parameters, possibly due to changes in the physical state of the volcano. The analysis carried out on an hourly data set spanning the 1994-1996 time interval and a comparison of the results with those previously obtained, exhibit a change in the tidal parameters which occurred between 1991 and 1994. A gravity decrease of about 60 μGal was observed during the same time interval in the same area. Consistent with relative and absolute gravity observations, no significant variations have been detected since 1994 in the tidal parameters and gravity residuals.

Key words *Earth tide – amplification factor – gravity residuals – volcanic activity*

1. Introduction

Pre-eruptive conditions in active volcanic areas are determined by the ascent of magmatic masses producing changes in density distribution at depth. Ground deformations and changes in the gravity field are then induced (*e.g.*, Berrino *et al.*, 1984; Eggers, 1987; Yokoyama, 1989; Arnet *et al.*, 1991; Brown *et al.*, 1991; Berrino *et al.*, 1992; Rymer *et al.*, 1993; Rymer and Triggvason, 1993; Berrino, 1994; Rymer, 1994; Jahr *et al.*, 1995; Lagios, 1995).

Gravity residuals of volcanic origin are obtained after removal of the effects due to «non-volcanic» sources from the measured gravity changes, mainly:

1) External sources (luni-solar gravitational effect, ocean load and barometric effects).

2) Changes in the water table level.

Changes in gravity over time are generally ascertained by repeated gravity measurements with reference to «base stations» in which gravity is assumed as zero level. A combination of absolute and relative gravimetry is necessary (Berrino, 1995). Absolute measurements verify the base stations and may reveal long-term variations or confirm stable zones. Moreover, they permit a check of the calibration and a comparison of the relative gravimeters.

Gravity changes may be also obtained in continuous mode by means of gravity records (*e.g.*, Imbò *et al.*, 1965; Davis, 1981; Berrino *et al.*, 1988; De Freitas *et al.*, 1991; Vieira *et al.*, 1991; Berrino *et al.*, 1993b; Berrino *et al.*, 1994; Goodkind and Young, 1991).

Two different approaches may be used to extract the anomalous signals from the gravity

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records due to changes in physical properties at depth, *i.e.*, the analysis of the time changes of the tidal gravimetric factor δ and/or of the gravity residuals. According to the recommendations of the WG on Theoretical Tidal Model (SSG of the Earth Tide Commission, Sec. V of IAG) the tidal gravimetric factor δ may be defined as the Earth's transfer function between the body tide signal measured at the station by a gravimeter and the amplitude of the vertical component of the gradient of the external tidal potential at the station position.

In the computation of the residuals of volcanic origin a recording reference station located outside the investigated area is useful. It may be also useful to remove the long-term and uneven regional effects.

The present paper focusses on the results of the analysis of the gravity records, spanning the 1994-1996 time interval, obtained at the station located on Mt. Vesuvius, a currently quiescent volcano located in Southern Italy.

2. Geological setting of the Somma-Vesuvius

Somma-Vesuvius is a currently quiescent strato-volcano, located about 15 km southeast of Naples (Southern Italy), consisting of an older structure (Mt. Somma) and a nested younger one (Mt. Vesuvius). It is set in the Campanian plain, a graben bordered by Mesozoic carbonate platforms downfaulted during the Pliocene and perhaps Pleistocene as a consequence of the stretching and thinning of the continental crust related to the opening of the Tyrrhenian basin (Ippolito *et al.*, 1973; Ortolani and Aprile, 1978; Ortolani and Pagliuca, 1987; Scandone, 1979; Patacca *et al.*, 1990) and characterized by main NW-SE and NE-SW-trending faults system. Mt. Vesuvius is located on a NE-SW-trending regional fault. The tectonic setting and the geometry of the carbonate basement beneath Mt. Vesuvius was delineated by gravity and seismic data (Oliveri Del Castillo, 1966; Carrara *et al.*, 1973; Cameli *et al.*, 1975; Finetti and Morelli, 1974; Finetti and Del Ben, 1986; Luongo *et al.*, 1988; Ferri *et al.*, 1990; Cubellis *et al.*, 1995; Berrino *et al.*, 1997; Fusi, 1996; Zollo *et al.*, 1996a,b). The limestone basement may have played a crucial role in the magma ascent (Scandone *et al.*, 1991; Fusi, 1996). The feeding system of Mt. Vesuvius probably consists of a shallow magma chamber embedded in the Mesozoic limestone basement (Rosi *et al.*, 1987) connected to deeper magma chambers (Cortini and Scandone, 1982) and feeding sources.

The volcanic activity of Somma-Vesuvius extended over the last 25 000 years, alternating long periods of quiescence with plinian eruptions and relatively minor effusive-explosive events (Delibrias *et al.*, 1979; Carta *et al.*, 1981; Santacroce, 1987). The last eruption occurred in 1944. Currently, Mt. Vesuvius is characterized by a low-energy seismicity (Berrino *et al.*, 1993a; Vilardo *et al.*, 1996; Bianco *et al.*, 1997) and by a moderate fumarolic emission inside the crater (Russo M., personal communication). Gravity changes in the absence of significant ground deformations, have also been detected since 1982 (Berrino *et al.*, 1993a; Pingue *et al.*, 1997).

3. The recording gravity station at Mt. Vesuvius

The gravity record at Vesuvius began in the sixties (Imbò *et al.*, 1965). This allowed the first determination of the local values of amplitude and phase of the main diurnal and semidiurnal waves of the tidal field. After a break of more than 20 years, a new recording gravity station was been set up in 1988 at the Osservatorio Vesuviano (Old Building) (Berrino *et al.*, 1988, 1994): Latitude = 40°49′N; Longitude = 14°24′E; height = 610 m msl.

The station belongs to the gravity network covering the whole Vesuvian area which is periodically surveyed by means of high-precision relative measurements (fig. 1). The recording equipment was installed on a concrete pillar, in an artificial cave 20 m deep where the daily temperature excursion is about 10^{-1} °C and the annual one is about 2°C. The station is also equipped with temperature, pressure and tilt sensors. It is close to the absolute gravity station on Vesuvius (Berrino, 1995) where the value of the gravity acceleration was measured

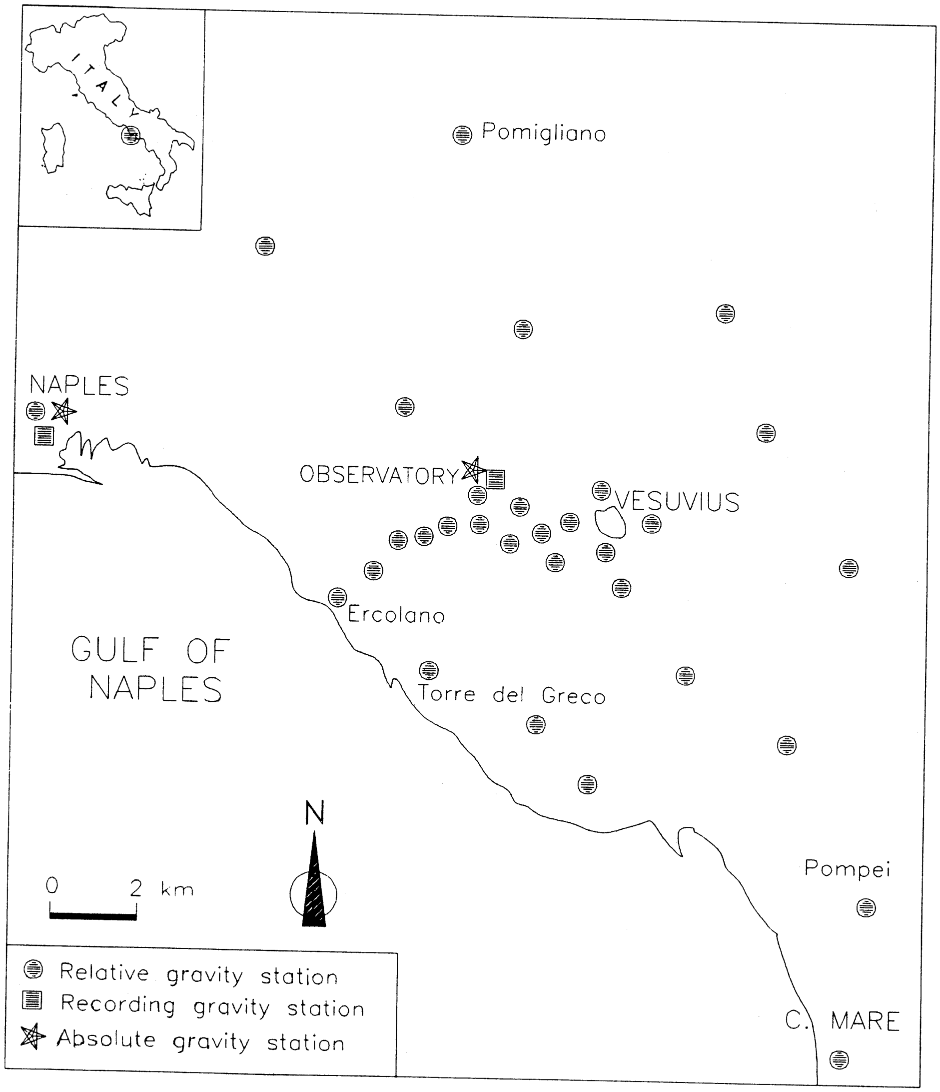

Fig. 1. Gravity network operating on Mt. Vesuvius.

in July 1986, May 1994 and October 1996. A gravity link between the absolute and recording sites provided the value of g in the cave; *i.e.*, $g = 9.80138794 \pm 4 \cdot 10^{-8}$ ms^{-2}. The value of the free-air vertical gradient was also experimentally determined on the same site, *i.e.*, $\delta g/\delta h = -(353 \pm 3) \times 10^{-8}$ s^{-2} (Berrino *et al.*, 1994).

The gravity sensor is the LaCoste & Romberg model D-126 meter, equipped with an electrostatic feedback system built at the Observatoire Royal de Belgique (van Ruymbeke, 1989, 1991). The instrumental chain was calibrated several times on site (fig. 2). An additional calibration of the feedback was carried out in June 1994 in Sèvres, at the Bureau Inter-

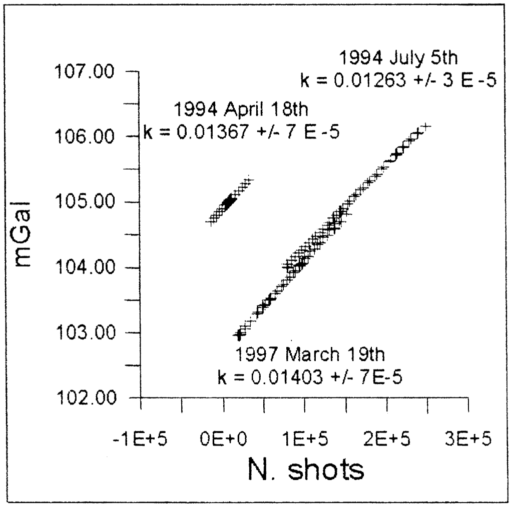

Fig. 2. Results of the calibration of the instrumental chain.

national des Poids et Mesures (BIPM) under the auspices of the International Absolute Intercomparison and Relative Gravimeter Feedback Calibration (Becker *et al.*, 1995; van Ruymbeke *et al.*, 1995). The gravity signal is sampled at a frequency of 0.0167 Hz and stored on site.

4. Analysis of the gravity records and results

The present paper considers data spanning the 1994-1996 time interval. This data set was chosen because it was obtained after an upgrade of the feed-back system performed in 1991-1994 (van Ruymbeke, 1991).

The hourly gravity values from 1994 to 1996 are shown in fig. 3, where the driftless and the theoretical gravity tides are also represented. Breaks in the data set are mainly

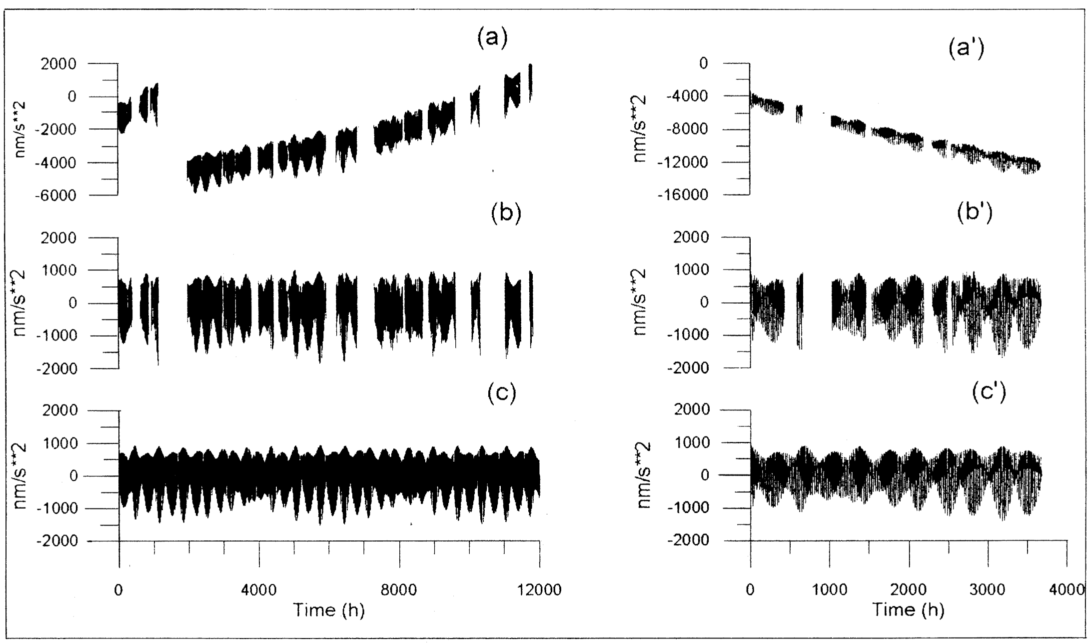

Fig. 3. Gravity records from 1994 April 7th 1:00 p.m. to 1995 August 13th 8:00 a.m. (left side) and from 1996 July 31th 11:00 a.m. to 1996 December 31th 11:00 p.m. (UT) (right side). a-a′) observed gravity tide; b-b′) observed driftless gravity tide; c-c′) theoretical gravity tide.

Table I. Tidal parameters.

GRAVIMETRIC EARTH TIDE STATION VESUVIO ITALY
40.827N 14.396E H610M P20M D1250KM VERTICAL COMPONENT
GRAVIMETER LACOSTE-ROMBERG MOD. D NR. 126
ZERO METHOD INSTRUMENT WITH ELECTROMAGNETIC FEEDBACK
TAMURA 1987 tidal potential used
WAHR-DEHANT-ZSCHAU inelastic Earth model used
Numerical filter is PERTZEV 1959 with 51 coefficients
UNITY window used for least squares adjustment

wave	ampl. nm/s**2	signal/ noise	ampl. fac.	stdv.	phase lead [deg]	stdv. [deg]
			ADJUSTED TIDAL PARAMETERS:			
			1994.04.07-1995.08.13 Number of recorded days in total: 324.79			
Q1	66.647	37.7	1.13278	0.03008	−3.0808	1.5217
O1	345.003	194.9	1.12273	0.00576	−0.1587	0.2940
M1	26.606	15.0	1.10091	0.07324	−1.7562	3.8117
P1	160.922	90.9	1.12547	0.01238	0.2335	0.6302
S1K1	483.171	273.0	1.11802	0.00410	0.2163	0.2099
J1	26.754	15.1	1.10707	0.07324	−0.7217	3.7906
N2	94.067	79.8	1.14237	0.01432	−0.2214	0.7181
M2	494.197	419.2	1.14908	0.00274	0.7238	0.1367
L2	14.063	11.9	1.15681	0.09698	−5.8150	4.8033
S2	232.687	197.4	1.16288	0.00589	1.1768	0.2903
K2	62.087	52.7	1.14135	0.02167	−1.0007	1.0879
			1996.07.31-1996.12.31 Number of recorded days in total: 122.29			
Q1	62.793	26.3	1.06728	0.04060	2.8745	2.1798
O1	343.340	143.7	1.11732	0.00777	−0.3862	0.3987
M1	27.912	11.7	1.15497	0.09885	−1.1781	4.9038
P1S1	476.321	199.4	1.10217	0.00553	0.1877	0.2874
J1	27.419	11.5	1.13458	0.09885	2.8096	4.9921
N2	92.544	50.9	1.12388	0.02207	0.7239	1.1250
M2	488.992	269.1	1.13698	0.00423	0.5468	0.2129
L2	12.960	7.1	1.06607	0.14948	−1.6086	8.0338
S2K2	225.438	124.1	1.12665	0.00908	−0.1781	0.4618
			1994.04.07-1996.12.31 Number of recorded days in total: 447.08			
Q1	65.631	44.8	1.11552	0.02488	−2.0352	1.2781
O1	345.291	235.8	1.12367	0.00476	−0.1843	0.2429
M1	26.804	18.3	1.10911	0.06058	−0.6217	3.1295
P1	161.389	110.2	1.12875	0.01024	0.0212	0.5198
K1	481.973	329.2	1.11525	0.00339	0.2056	0.1740
J1	27.487	18.8	1.13741	0.06058	−0.8732	3.0518
N2	93.658	91.5	1.13741	0.01244	−0.0476	0.6265
M2	492.720	481.1	1.14565	0.00238	0.6950	0.1191
L2	13.842	13.5	1.13863	0.08424	−5.6592	4.2391
S2	229.836	224.4	1.14863	0.00512	0.6972	0.2553
K2	62.925	61.4	1.15677	0.01883	−1.6242	0.9325

Table II. Tidal gravimetric factor in several times.

Main tidal components *	1965 (Imbò, 1965)	1987-1991 (Berrino *et al.*, 1993b, 1994)	1994-1996
K_1	1.08 (S_1K_1)	1.05 ± 0.01	1.115 ± 0.003
O_1	1.04	1.08 ± 0.02	1.124 ± 0.005
S_2	1.11	1.03 ± 0.02	1.148 ± 0.005
M_2	1.07	1.11 ± 0.01	1.146 ± 0.002

* Darwin's symbols (Melchior, 1983).

caused by power failures at the station, earthquakes or teleseisms.

The luni-solar gravitational effect (theoretical gravity tide) was computed according to Tamura's catalogue (Tamura, 1987) and the Wahr-Dehant-Zschau Earth model (Wahr, 1981; Dehant, 1987; Zschau and Wang, 1987). The oceanic loading effect is taken into account according the Schwiderski's cotidal maps (Schwiderski, 1980). The loading effect, associated to the M_2 component, is about 12 nms^{-2}. This value agrees with the mean value computed by Ducarme and Melchior (1983) at the latitude of the Campania area and that estimated by Baldi *et al.* (1995) for the Brasimone (Northern Italy) gravity station. The load effect of the Mediterranean tides is negligible (Chiaruttini, 1976).

Amplitude, phase and the δ factor of the main diurnal and semidiurnal lunar and solar waves have been computed by means of the software package «ETERNA 3.0» (Wenzel, 1994). Two separate analyses for the 1994-1995 and 1996 periods respectively were made. The results are shown in table I, compared with the results of the global analysis.

The present-day values of the gravity amplification factor, for some diurnal and semi-diurnal waves, have been compared with those obtained by previous gravity records (table II). An increase in amplitude occurred between 1988-1991 and 1994-1996 time windows. The average monthly values of the amplification factor, computed in the time domain, are shown in fig. 4. They range from 1.10 to 1.16 yelding an average value of 1.132 ± 0.003.

The gravity residuals were obtained after removal from the gravity records, correction of the instrumental drift and theoretical gravity tide.

It is well known that gravity records are affected by perturbations produced by the combined effects of the gravitational attraction of the atmosphere and the distortion of the Earth's surface resulting from barometric changes.

The atmospheric effect was computed using both the Spratt (1982) and the Warburton-Goodkind (1977) statistical approaches. The former computes the barometric effect through a linear correlation between the observed gravity changes and pressure records. The latter computes the correction coefficient as a ratio between the power spectrum of the cross correlation function between the gravity and the pressure records and the power spectrum of the pressure variation. Both methods yielded a value of about 3-4 nms^{-2}/hPa (0.3-0.4 μGal/mbar), in good agreement with that obtained

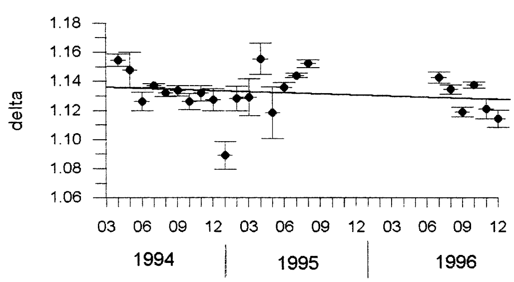

Fig. 4. Monthly values of the amplification factor.

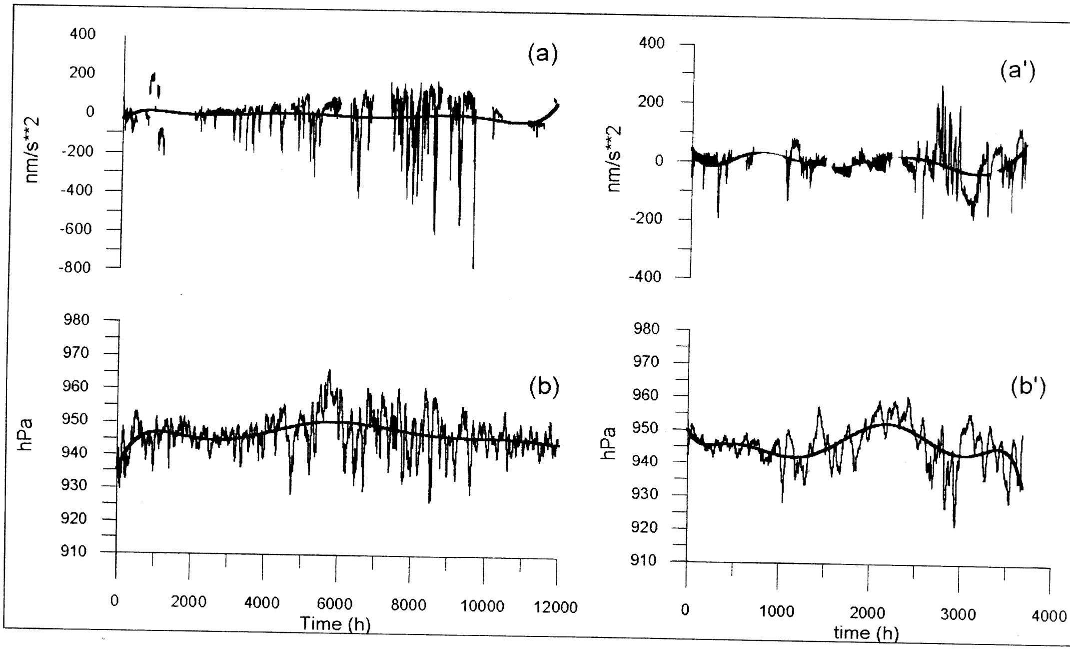

Fig. 5. Gravity residuals (a-a′) and atmospheric pressure (b-b′) from 1994 April 7th 1:00 p.m. to 1995 August 13th 8:00 a.m. (left side) and from 1996 July 31th 11:00 a.m. to 1996 December 31th 11:00 p.m. (UT) (right side).

by others (Niebauer, 1988; Merriam, 1992; Elstener *et al.*, 1995; Sun *et al.*, 1995) .

The pressure-corrected gravity residuals are shown in fig. 5.

The gravity residuals show a long-term quasi-periodic trend, also present in the atmospheric pressure record (fig. 5). This could indicate a residual effect of the «regional» barometric field not completely removed from the gravity records.

No significant gravity changes were observed in the temporal trend of the gravity residuals.

5. Conclusions

The main result from the analysis of the gravity record spanning 1994-1996 is an increase in the amplitude factor with respect to those computed in the 1988-1991 period.

This observed increase also applies to a gravity decrease of about 60 μGal which occurred in the area and revealed by both relative and absolute gravity measurements and to an increase in seismic activity. These results are represented in fig. 6, which depicts the gravity changes at the Osservatorio Vesuviano (Old Building) and seismic activity from 1982 to 1996. It also shows that no significant gravity changes have occurred since 1994. Figure 6 shows the results both from relative and absolute measurements. Because no vertical deformations were observed in the same time interval, the gravity changes can be attributed to changes in the distribution of masses at depth (Berrino *et al.*, 1993a; Pingue *et al.*, 1997). Alternatively, the increase in the gravimetric factor may be indicative of a larger deformation behaviour and then could suggest a reduced rigidity of the medium.

The current results also suggest that in order to emphasize the mass redistribution effect it is

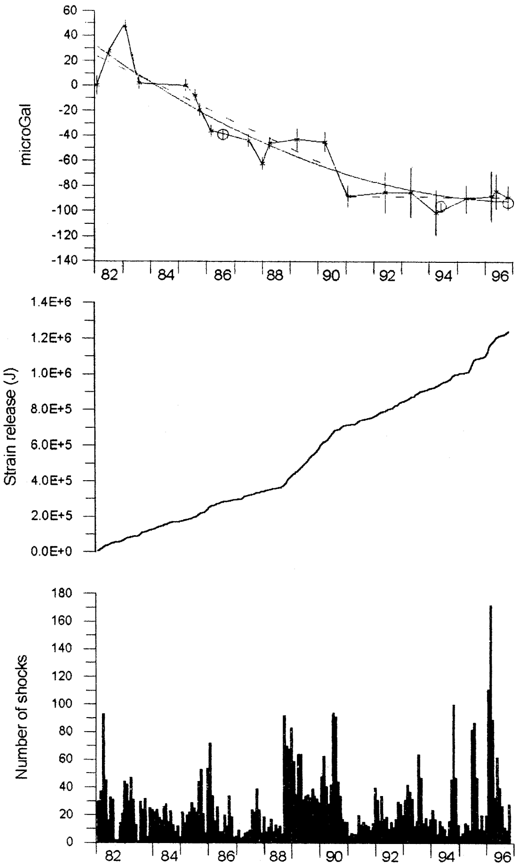

Fig. 6. Gravity changes and seismic activity since 1982 at the Osservatorio Vesuviano Old Building. The open circles represent the gravity changes at the same station by absolute measurements.

necessary to apply more refined models to remove the atmospheric effect, *i.e.*, to consider its effect not as punctual but on a more extended area, the hydrological effect and mainly the «regional» gravity changes. The latter contribution can be removed only by means of a reference gravity station outside the volcanic area.

Acknowledgements

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