

## Gravity studies on active Italian volcanoes: a comparison between absolute and relative gravimetry

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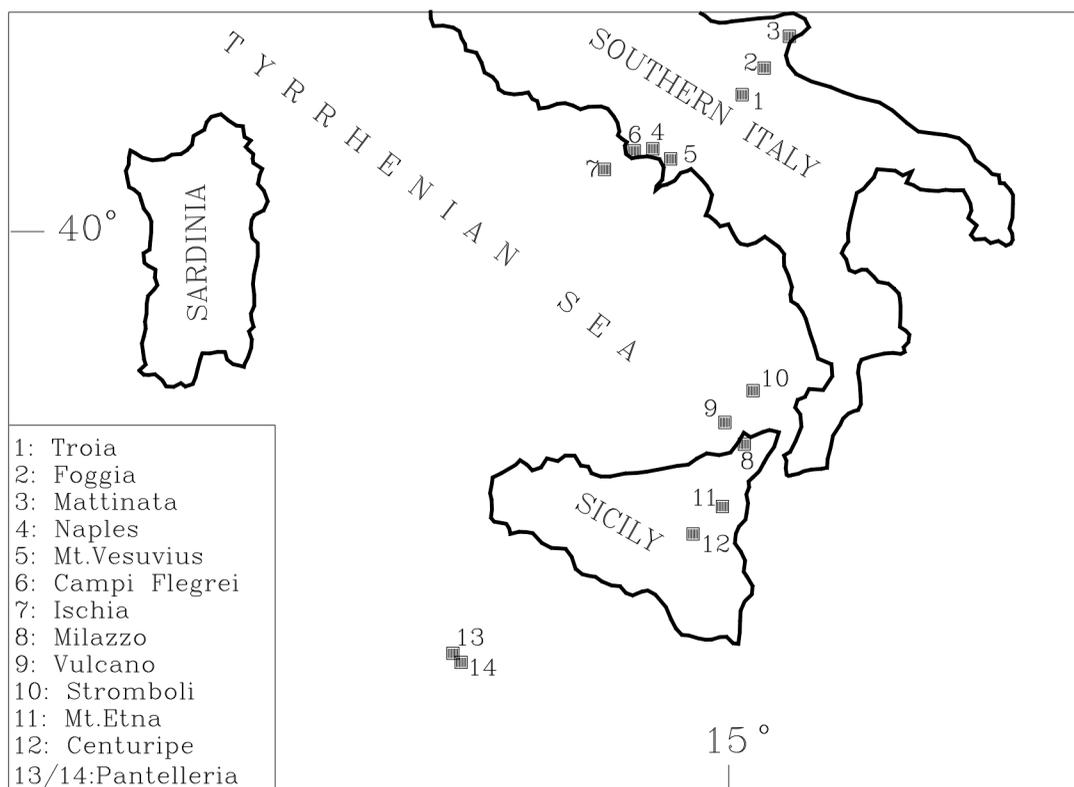
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**Abstract.** Gravity studies aimed at detecting volcanic inputs, precursors to a pre-eruptive state are in process on active Italian volcanoes. To achieve this goal high precision absolute and relative gravity measurements are carried out to identify time variations of the gravity field caused by the ascent of magmatic masses. Since 1980, gravity surveys have been carried out at Mt. Etna, the Aeolian Islands, Pantelleria, Ischia, Mt. Vesuvius and the Campi Flegrei. Absolute measurements of gravity acceleration date back to 1986 and are carried out on selected stations of the relative networks. The absolute stations work as a reference for the relative networks. Moreover, by periodically surveying them, they provide the long-term components for the temporal trend of gravity changes. Intercalibrated LaCoste & Romberg, model D, gravity meters are employed for relative gravity measurements. Absolute measurements of  $g$  are carried out by means of the ballistic Absolute Gravimeter (symmetrical rise and fall method) built at the Istituto di Metrologia "G. Colonnetti" of the Italian National Research Council. Moreover, constantly recording gravity stations are also working at Mt. Vesuvius and Mt. Etna. Their aim is to keep continuous records of the changes versus the time of the gravity field and tidal parameters, possibly consequence of the variations in the physical state of the volcanoes monitored. The absolute stations have been surveyed more than once at Mt. Vesuvius, at the Island of Vulcano and on Mt. Etna. The ensuing comparison between the gravity changes observed by relative and absolute measurements indicates that a combination of both measurements is the most complete and reliable way of defining the long- and short-term space-time evolution of the gravity field associated to volcanic dynamics. The main results concern Mt. Vesuvius and Mt. Etna, where the gravity changes obtained through absolute, relative and recording

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**Fig. 1** - Location of absolute gravity stations at Italian active volcanoes. The stations belonging to the calibration line Troia-Foggia-Mattinata are also indicated.

gravimetry have been associated, respectively, to an increase in seismic activity and to an eruptive event.

## 1. Introduction

Pre-eruptive conditions of active volcanoes are determined by the ascent of magmatic masses, producing ground deformation and changes in the sub-surface density distribution. Changes in the gravity field then occur, and the measure of such changes furnishes information about the source (movements of magma, fluids migration, etc.).

Changes, through time, in the gravity are ascertained by repeated gravity measurements which refer to “base stations” in which the gravity is assumed as being relatively stable (zero level).

A combination of relative and absolute gravimetry is strongly recommended.

Absolute measurements check the base stations and may reveal long-term variations or confirm stable zones. Moreover, they permit periodic calibration checks and comparison for relative gravimeters.

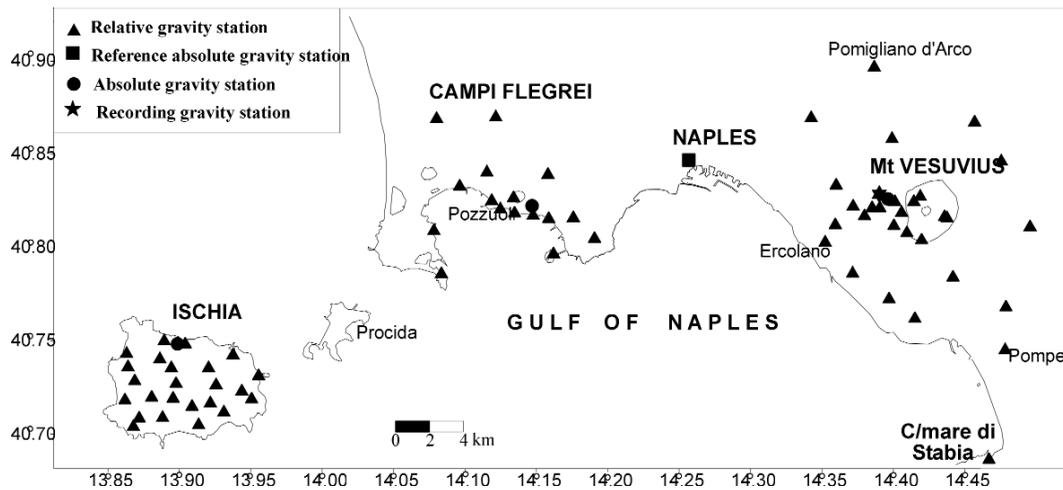


Fig. 2 - Gravity network on the Neapolitan volcanoes.

Gravity changes can also be measured in a continuous mode by means of gravity records.

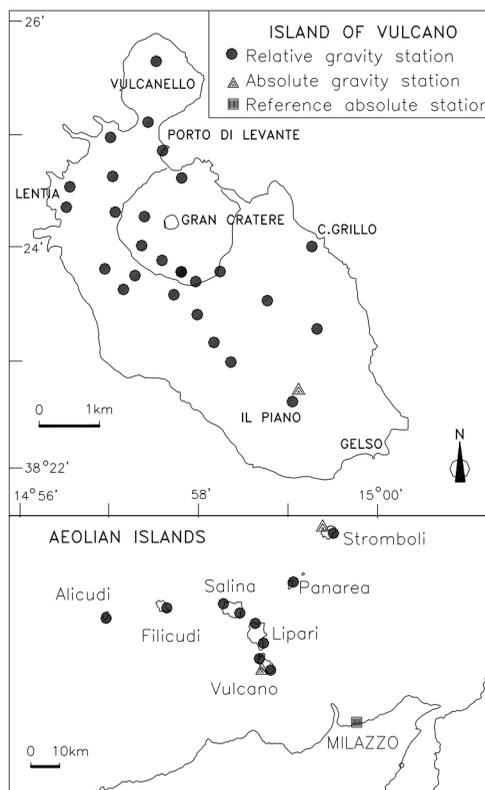
To extract the components due to sub-surface mass redistribution from the gravity records, two different paths can be explored: the time evolution of the gravimetric amplification factor  $\delta$  and/or of the gravity residuals. Gravity residuals are obtained after the effects of external sources, mainly the gravity tide and the combined action of the atmosphere and ocean, are removed from the gravity changes.

Absolute and relative measurements of the gravity are carried out at the Italian active volcanoes (Mt. Vesuvius, Campi Flegrei, Ischia, Aeolian Islands, Mt. Etna, Pantelleria) (Fig.1).

Relative measurements began in 1981 and are periodically carried out on extended networks to measure the short-term changes of the gravity. The absolute stations are established outside the volcanoes to check base stations as well as on the volcanoes to check, through their repetition, the variations observed by the relative measurements. Moreover, repeated absolute measurements of  $g$  are fully able to define the long-term trend of the temporal changes of the gravity field. On the absolute stations direct measurements of the vertical free-air gravity gradient are also carried out to transfer to the ground the absolute value. Gravimetry, in a continuous mode is also approached at Mt. Vesuvius and Mt. Etna, where recording stations work close to the absolute ones. At Mt. Vesuvius the instrumental drift of the recording gravimeter is constrained through the repeated measure of  $g$  in the site.

The location of the absolute gravity stations on active volcanoes is shown in Fig.1. The absolute measurements started in 1986 on the Neapolitan volcanoes where, presently, 4 absolute stations are operating and are located in Naples, Mt. Vesuvius, the Island of Ischia and the Campi Flegrei (Fig.1). The station in Naples works as a reference station for the relative networks realised on the volcanoes (Fig. 2). As regards the Sicilian volcanoes (Fig. 1), seven absolute stations have been established since 1990 respectively in:

- Milazzo, as reference for the relative networks on the Aeolian Islands and on the Island of



**Fig. 3** - Gravity network at the Island of Vulcano (Aeolian Islands). In the lower rectangle the gravity network on the whole Aeolian archipelagus is represented.

Vulcano (Fig. 3);

- Stromboli;
- Vulcano;
- Mt. Etna;
- Centuripe, as reference for the Aetnean relative network (Fig. 4);
- Pantelleria (Fig. 5).

On the island of Pantelleria, 2 absolute stations have been established, both working as a reference because of the difficulty of connecting the local relative network to an external reference in Sicily. Their locations were established following the results of the geophysical investigations carried out on the islands to delineate its structural pattern (Berrino and Capuano, 1995) and its dynamical behaviour (Berrino, 1997, 1998).

Finally, starting in 1988, 3 absolute stations were established in Apulia (Fig. 1) to create a new calibration line for relative gravity meters (Berrino, 1995; Berrino et al., 1988). The Apulian stations (Troia, Foggia and Mattinata) together with Naples, Milazzo and Centuripe belongs to the new “Zero Order Gravity Network” of Italy (Berrino et al., 1995).

Some absolute stations have been surveyed several times and namely:

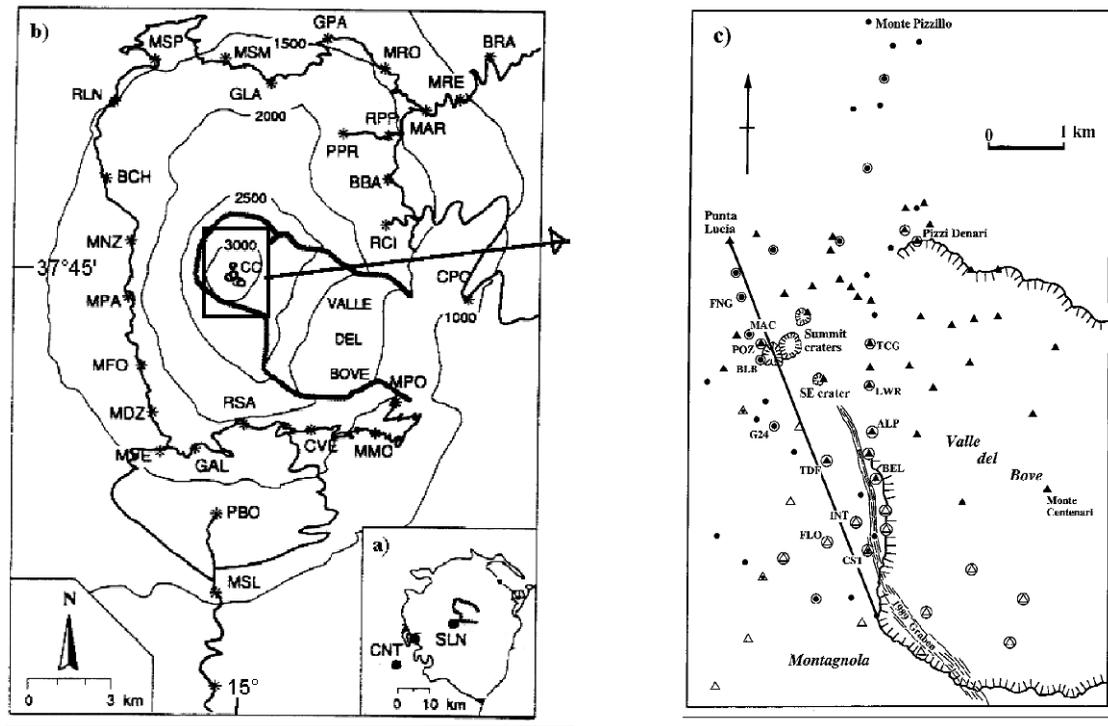


Fig. 4 - Gravity network at Mt. Etna: a) location of absolute stations; b) base network; c) summit network (After AA., 1994 modified).

- at Mt. Vesuvius in 1986, 1994, 1996 and 1998;
- at the Island of Vulcano in 1990 and 1995;
- on Mt. Etna in 1991, 1992 and 1994;
- at Centuripe in 1991 and 1994.

The results obtained by the repetition of the absolute measurements at these locations and the comparison with the results of relative measurements are presented and discussed.

## 2. Data acquisition and results

Absolute measurements are made using the absolute meter built at the Istituto di Metrologia "Gustavo Colonnetti" (IMGC), of the Italian National Research Council (CNR) (Alasia et al., 1982; Fallor and Marson, 1988). The IMGC absolute gravimeter is periodically checked at the Bureau International des Poids et Mesures (BIPM) during "International Comparisons of Absolute Gravimeters" (ICAG) (e.g. Marson et al., 1995).

As the measured value of  $g$  is not referred to the ground, the local value of the free-air gradient (FAG) is needed to obtain a more precise value of  $g$  at the ground (Berrino, 1995). Therefore, the FAG value has been experimentally measured in the absolute stations using

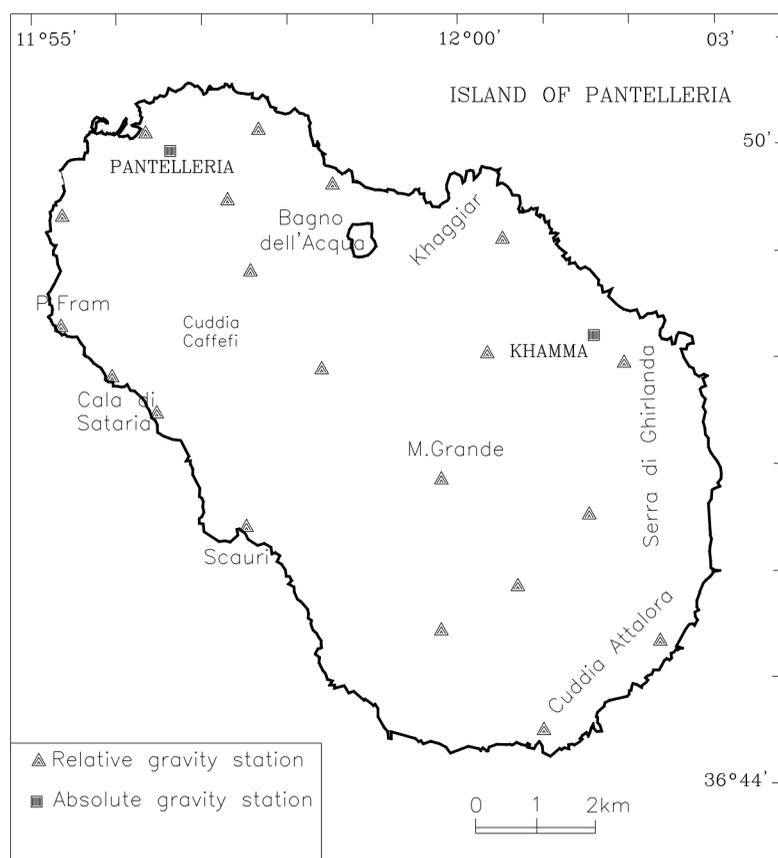


Fig. 5 - Gravity network at the Island of Pantelleria.

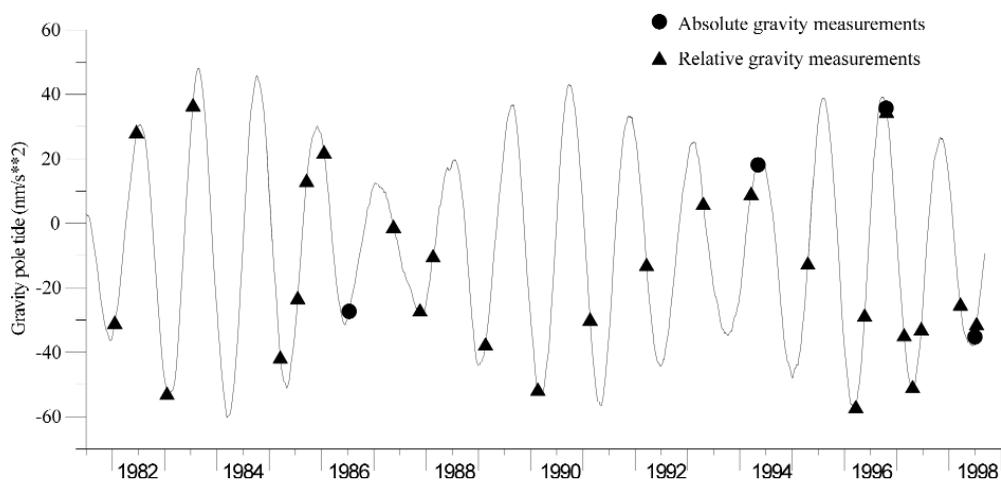


Fig. 6 - Gravity pole tide and time location of relative and absolute measurements at Mt. Vesuvius from 1981 to 1998.

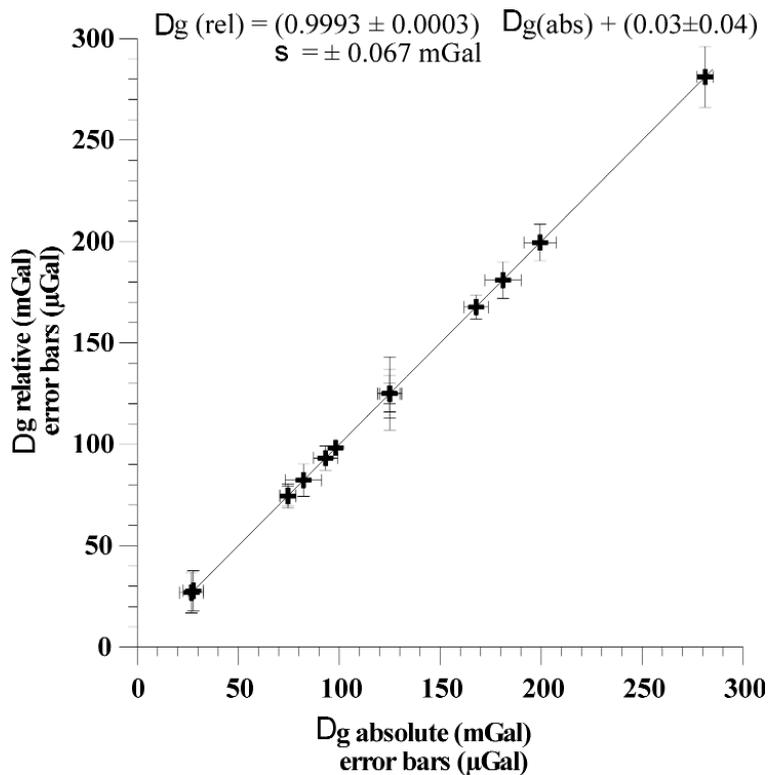


Fig. 7 - Regression of gravity differences between couples of absolute stations obtained by relative and absolute measurements.

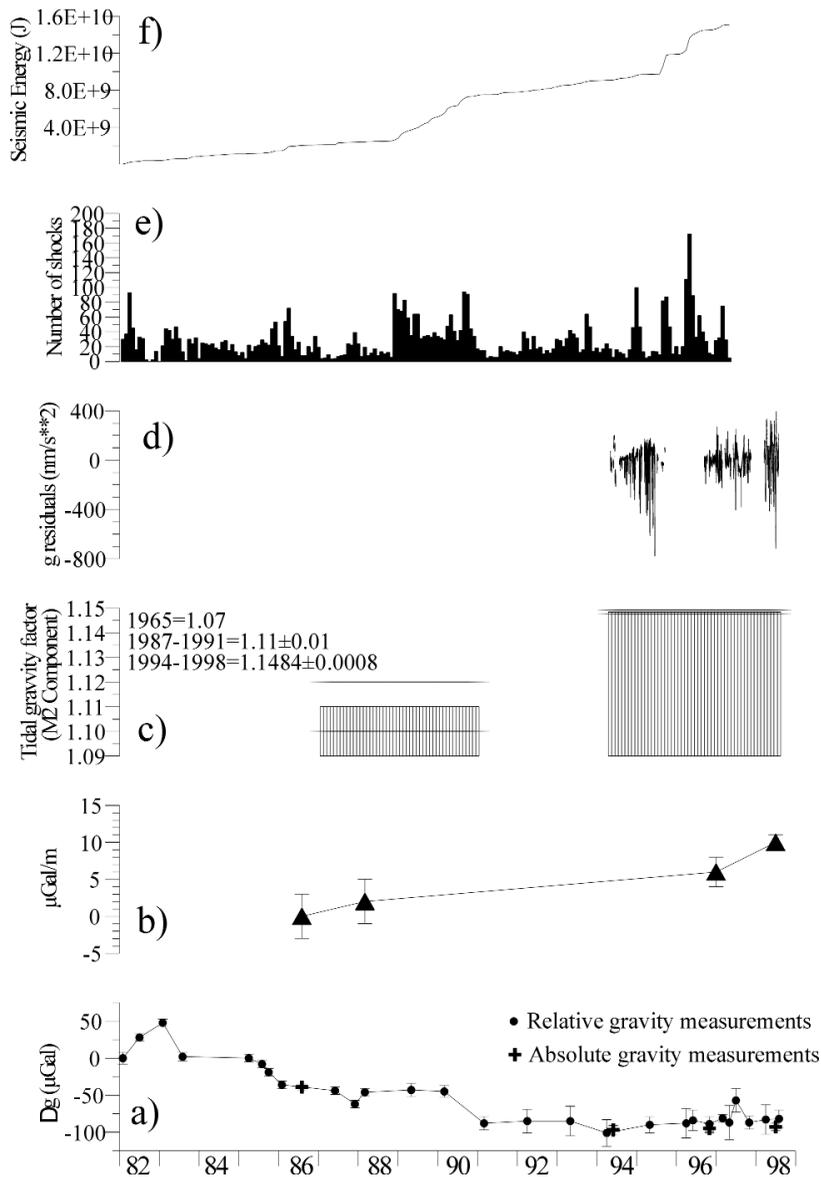
LaCoste & Romberg (LCR) models D gravity meters equipped with a feed-back system.

Relative gravity measurements are carried out using two LCR, models D, gravity meters, compared and calibrated on the Italian calibration base Troia-Mattinata (Berrino, 1995; Berrino et al., 1988) and in Sevres at the BIPM, during several ICAG meetings (Becker et al., 1990; 1995; 2000).

The earth-tide and air-pressure effects are removed from the relative measurements and the global set of gravity differences is adjusted according to the least square criterion. The uncertainty of the adjusted gravity differences is estimated less than 10  $\mu\text{Gal}$ .

The most recent recording of gravity at Mt Vesuvius began in 1987. The gravity sensor is the LaCoste & Romberg model D number 126 meter, equipped with the electrostatic feedback system built at the Observatoire Royal de Belgique (van Ruymbeke, 1989; 1991). The feed-back system is periodically calibrated. It was also calibrated on June 1994 and November 1997 in Sevres, at the BIMP, during the ICAG meetings (Becker et al., 1995; 2000); in 1994 it was also calibrated on a Calibration Platform (van Ruymbeke et al., 1995).

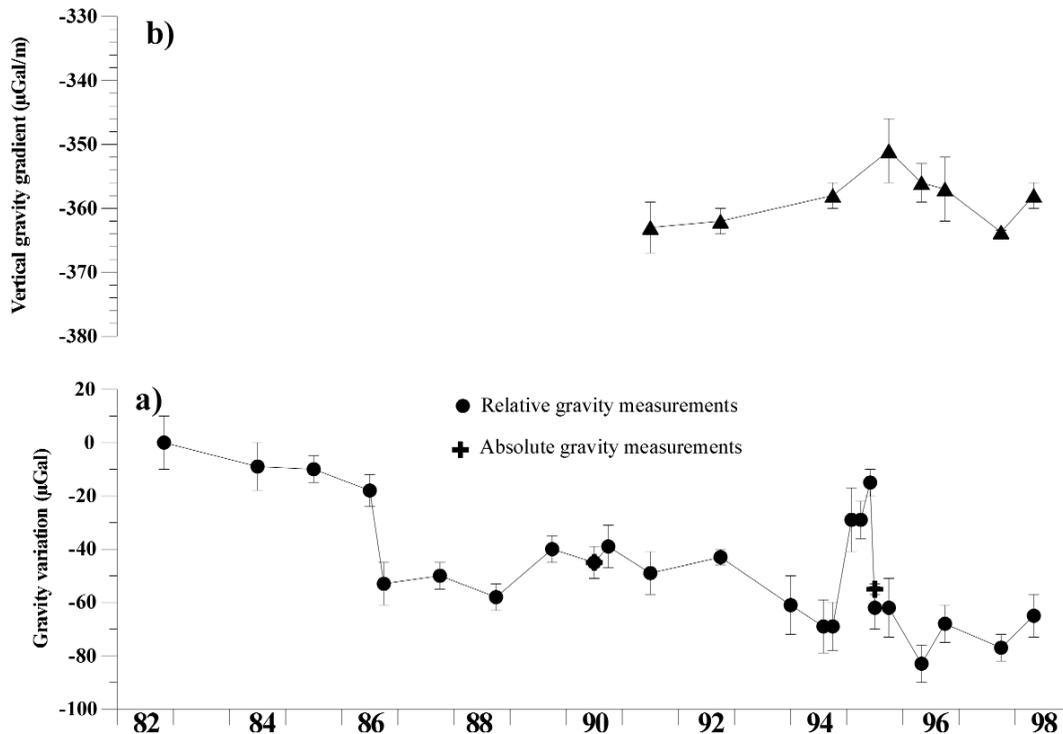
As the absolute and relative measurements are not always carried out at the same time, the effect of the polar motion must also be taken into account for a correct comparison of the gravity data. This is the case of the data collected at Mt. Vesuvius. In Fig. 6 the gravity polar tide is plotted versus time starting from 1981. In this area relative measurements began in



**Fig. 8** - Mt. Vesuvius: a) gravity variations at the Osservatorio Vesuviano Old Building station, by relative and absolute measurements; b) variation of the vertical gravity gradient; c) changes of the delta factor; d) gravity residuals; seismic activity e) number of shocks, f) cumulative seismic energy release.

January 1982 while the first measuring of  $g$  dates back to July 1986. The time of the repeated gravity surveys, both absolute and relative, are also marked on the plot. Anyhow, the contribution of the polar tide to the differences between absolute and relative data results very small, almost negligible.

Most of the absolute gravity stations have been linked by means of relative measurements too, so that a comparison of the gravity differences between couples of absolute stations,

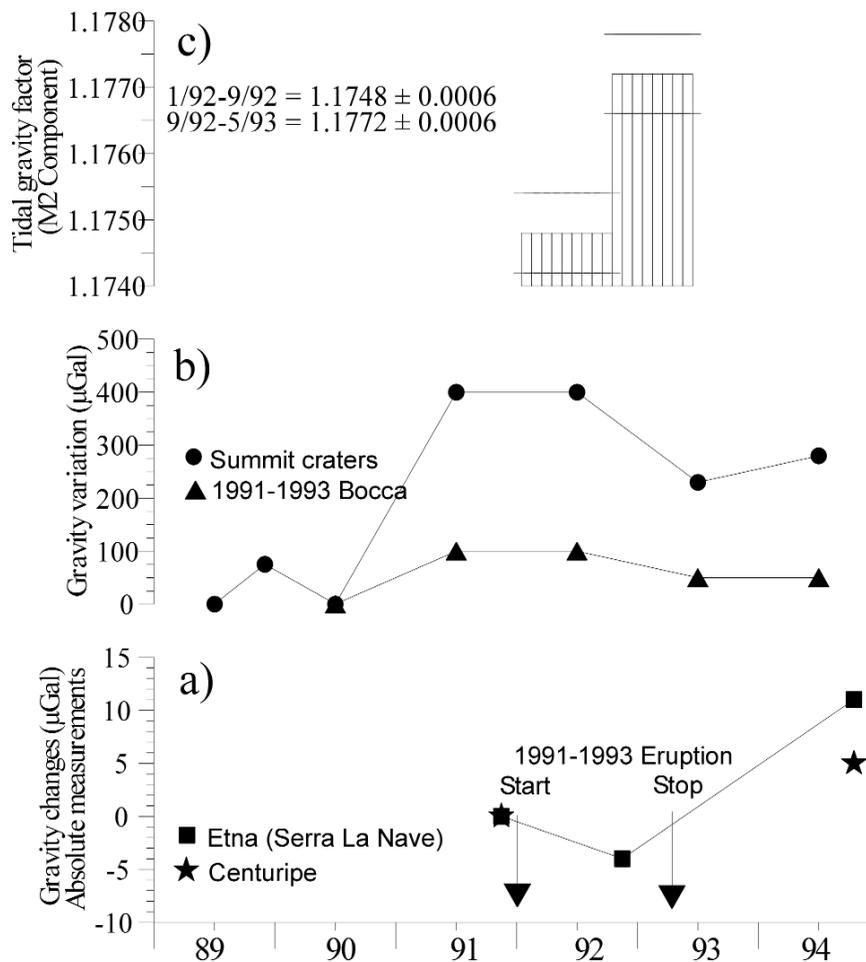


**Fig. 9** - Vulcano: a) gravity variations by relative and absolute measurements; b) variation of the vertical gravity gradient.

independently obtained by absolute and relative measurements, has been allowed. The correlation between the two different kinds of gravity differences (Fig. 7) shows a good agreement between the two data sets.

The measurement of the absolute value has been repeated more than once in 3 sites: Mt. Vesuvius, Vulcano Island and Mt. Etna.

As regards Mt. Vesuvius, absolute measurements were carried out on 1986, 1994, 1996 and 1998. Absolute measurements confirmed what was indicated by the relative ones at the same site. Namely, both data show a gravity decrease of about 60  $\mu\text{Gal}$  from 1986 to 1994, while no significant gravity changes were observed from 1994 to 1998 (Fig. 8a). This large decrease is also consistent with a small increase of the value of the vertical gravity gradient (Fig. 8b) and with the results of the recording gravimetry (Fig. 8c) indicating a significant increase of the factor  $\delta$  from 1987-1990 to 1994-1998 data sets. In the Fig. 8c the values of the  $\delta$  factor computed for the two data sets are also reported together with an old value evaluated in 1965. As already indicated (Berrino et al., 1997; Berrino and Riccardi, 1998), no significant changes in the tidal parameters occurred from 1965 to 1987/91. A change was observed from 1991 to 1994 which occurred during or soon after a significant seismic crisis whose time evolution is also represented in Figs. 8e and 8f. Focusing our attention on the 1994-1998 time interval, the absence of “long-

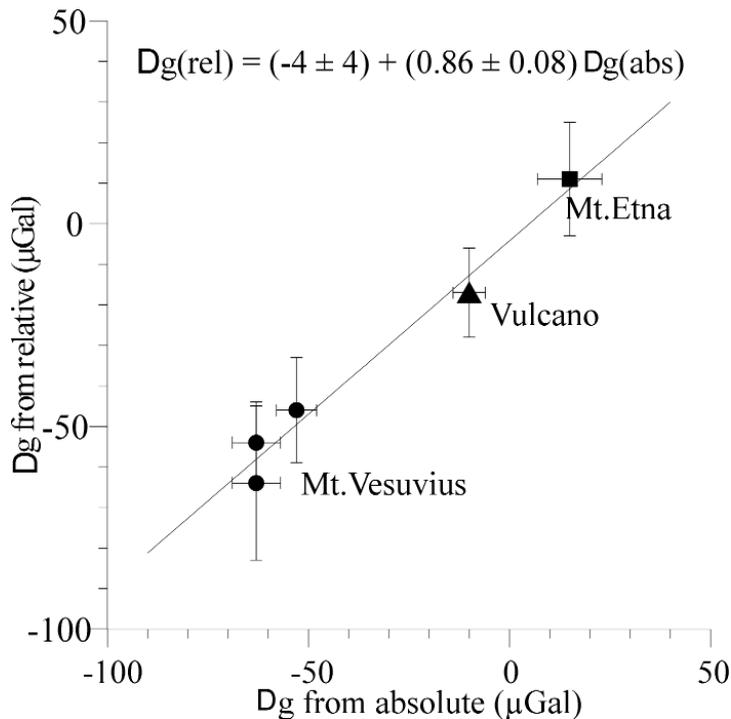


**Fig. 10** - Mt. Etna: a) gravity changes by absolute measurements at Centuripe and Serra la Nave stations; b) gravity changes by relative measurements on two selected stations of the summit network; c) variation of the gravimetric factor at the Serra La Nave station (data for b) and c) from AA., 1994).

term” gravity changes is also confirmed by residuals furnished by gravity records (Fig. 8d); in fact, the long-term trend given by the gravity residuals is not interpreted as due to volcanic sources but to residual effects of external origin, mainly barometric ones, not completely removed (Berrino and Riccardi, 1998).

The good agreement between changes obtained by absolute and relative measurements indirectly confirms a good long-term stability of the external station adopted as reference for relative measurements (Naples).

The same could be said for the station in Milazzo on the basis of results obtained at the Island of Vulcano. In this case too the repetition of the absolute measurements, carried out in 1990 and 1995, confirms the results obtained by the relative measurements that show (where the absolute station is located) no significant changes during the time interval considered (Fig. 9a). A slow, long-term gravity decrease may be observed as superimposed on steps and fluctuations



**Fig. 11** - Comparison between temporal gravity variations obtained by absolute and relative measurements at Mt. Vesuvius (circle), Vulcano Island (triangle) and Mt. Etna (square).

respectively associated to rapid changes in the local or regional dynamics (volcanic and/or seismic) as well as to seasonal effects (Berrino, 2000). The latter may also be observed in the time behaviour of the vertical gravity gradient in the same area (Fig. 9b).

Absolute stations on Mt Etna and at the external reference station in Centuripe were established at the end of October 1991 (AA, 1994; Berrino, 1995), just 1.5 months before the beginning of a big eruption that occurred from 14 December 1991 to 31 March 1993 (Calvari et al., 1994) through a fracture system that opened at the base of the SE crater (ref. Fig. 4c). On 13 December 1991 a recording gravity station was also installed on Mt Etna, a few kilometres from the eruptive vents. Absolute measurements were repeated twice on Mt Etna (October 1992 and June 1994) and once (June 1994) at Centuripe (AA, 1994; Berrino, 1995). The results obtained by repeating the absolute measurements (Fig. 10a) indicate that no significant changes occurred in that area during and after the eruption. This is also confirmed by the relative measurements carried out at stations close to the absolute one for the period October 1992-September 1994 (AA, 1994). On the contrary, relative gravity measurements carried out at the summit network showed large gravity increases, up to 400  $\mu\text{Gal}$ , close to the summit craters, just one year/six months before the eruption; no significant changes during the eruption, and a large decrease, of about 200  $\mu\text{Gal}$ , just at the end of the eruption (Rymer et al., 1993; 1994; AA, 1994). The gravity changes observed at two stations of the summit network, one close to the summit craters and the

**Table 1** - Absolute values and temporal variations of gravity at Mt. Vesuvius, Vulcano Island and Mt. Etna.

| Date  | Absolute g ( $\mu\text{Gal}$ ) | $\Delta g$ ( $\mu\text{Gal}$ )<br>(from absolute) |            | $\Delta g$ ( $\mu\text{Gal}$ )<br>(from relative) |
|---|--------------------------------|---|------------|---|
| <b>Mt. Vesuvius</b>                               |                                |   |            |   |
| 7/1986  | 980 133 127 $\pm$ 4            | 0   |            | 0   |
| 5/1994  | 980 133 064 $\pm$ 4            | -63 $\pm$ 6                                       |            | -64 $\pm$ 19                                      |
| 10/1996   | 980 133 064 $\pm$ 6            | -63 $\pm$ 6                                       |            | -54 $\pm$ 10                                      |
| 6/1998  | 980 133 074 $\pm$ 3            | -53 $\pm$ 5                                       |            | -46 $\pm$ 13                                      |
| <b>Island of Vulcano</b>                          |                                |   |            |   |
| 6/1990  | 980 029 697 $\pm$ 3            | 0   |            | 0   |
| 6/1995  | 980 029 687 $\pm$ 3            | -10 $\pm$ 4                                       |            | -17 $\pm$ 11                                      |
| <b>Mt. Etna</b>                                   |                                |   |            |   |
| 10/1991   | 979 641 965 $\pm$ 7            | 0   |            | -----   |
| 10/1992   | 979 641 962 $\pm$ 2            | -3 $\pm$ 9  | 0          | 0   |
| 9/1994  | 979 641 977 $\pm$ 6            | 12 $\pm$ 9  | 15 $\pm$ 8 | 11 $\pm$ 14                                       |
| <b>Centuripe (Reference for the Etna network)</b> |                                |   |            |   |
| 10/1991   | 979 823 094 $\pm$ 3            | 0   |            |   |
| 9/1994  | 979 823 097 $\pm$ 3            | 3 $\pm$ 4   |            |   |

other close to the 1991-1993 eruptive vents, are shown in the Fig. 10b where the results of the recording gravimetry at Mt Etna are also indicated (Fig. 10c). Recording gravity data have been analysed in two separate blocks because an increase in the  $\delta$  factor was observed during the eruption (AA, 1994; El Wahabi et al., 1998). Results of discrete gravity data are in good agreement: the small changes observed by absolute measurements may be due to the distance from the eruptive area; also confirmed by the different amplitude of changes on the two selected stations on the summit close to the eruptive zone. The small decrease obtained by absolute measurements could indicate that the gravity decrease on the summit, as obtained by relative gravimetry, probably started between the summer and autumn of 1992, before the end of the eruption.

In Table 1, the results of the absolute measurements and the temporal gravity variations furnished by both absolute and relative measurements are given for the sites considered above, while their relationship is represented in Fig. 11. Moreover, the correlation shown in Fig. 11 indicates that the gravity variations obtained using two different methodologies are quite consistent.

### 3. Conclusions

Integrated absolute and relative gravity measurements carried out on active Italian volcanoes confirms that a combination of both measurements is the most complete and reliable way of defining the long- and short-term space-time evolution of the gravity field associated to volcanic dynamics. The coupling of different methodologies and the repetition, in time, of the absolute measurements also give a check for the long-term stability of the gravity network reference station and a constraint for the long-term drift of the recording gravity meters. This means that the coupling of absolute and relative gravimetry helps to distinguish real gravity changes that occurred during volcanic activity or for apparent changes due to seasonal, hydrological and some other external sources. The main results concern Mt. Vesuvius and Mt. Etna where gravity changes obtained through absolute, relative and recording gravimetry have been associated respectively, to an increase of the seismic activity and to an eruptive event.

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