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3-D Modelling of Campi Flegrei Ground Deformations: Role of Caldera Boundary Discontinuities

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and Folco Pingue[2]

Abstract—Campi Flegrei is a caldera complex located west of Naples, Italy. The last eruption occurred in 1538, although the volcano has produced unrest episodes since then, involving rapid and large ground movements (up to 2 m vertical in two years), accompanied by intense seismic activity. Surface ground displacements detected by various techniques (mainly InSAR and levelling) for the 1983 to 1996 period can be modelled by a shallow point source in an elastic half-space, however the source depth is not compatible with seismic and drill hole observations, which suggest a magma chamber just below 4 km depth. This apparent paradox has been explained by the presence of boundary fractures marking the caldera collapse. We present here the first full 3-D modelling for the unrest of 1982–1985 including the effect of caldera bordering fractures and the topography. To model the presence of topography and of the complex caldera rim discontinuities, we used a mixed boundary elements method. The *a priori* caldera geometry is determined initially from gravimetric modelling results and refined by inversion. The presence of the caldera discontinuities allows a fit to the 1982–1985 levelling data as good as, or better than, in the continuous half-space case, with quite a different source depth which fits the actual magma chamber position as seen from seismic waves. These results show the importance of volcanic structures, and mainly of caldera collapses, in ground deformation episodes.

Key words: Campi Flegrei, deformations, caldera, 3-D, boundary elements, levelling.

Introduction

Campi Flegrei is a trachytic caldera located close to Naples (Southern Italy), formed by several episodes of caldera collapses. The first series of collapses, forming the outer caldera rim, probably started about 35000 years B.P. and are called Grey Tuff eruptions from the typically erupted products. The most recent collapse, dated 12000 years B.P., produced the Yellow Tuff, whose deposits cover entirely the caldera and the province of Naples, constituting the main ancient building material for the towns. Ground movements at Campi Flegrei caldera had been recognised since Roman times. The time evolution of slow ground movements (called "bradisisma"

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from a Greek term for "slow seism") has been reconstructed from traces of marine deposits on the ancient monuments. The most recent and complete reconstruction was made by DVORAK and MASTROLORENZO (1991), and is summarised in Figure 1. The secular trend of ground movement is subsidence of the caldera, at a rate of about 1 to 1.4 cm/year. Superimposed on this long-term trend, some fast and intense episodes of ground uplift occurred, culminating in eruption in the case of the 1538 episode (Monte Nuovo). The most recent unrest episodes started in 1968 with a fast uplift of 1.5 m and, after a slight decrease from 1972 to 1982, produced a maximum uplift of about 1.8 m in two years (see detail in Fig. 1). From late 1984 onwards, the caldera underwent a slower subsidence, with an average rate of about 5 cm/year. The intense ground uplift episode 1982–1984 also involved considerable seismicity (more than 15,000 recorded earthquakes, located in the first 3 km of the crust), with maximum magnitude slightly larger than 4 (DE NATALE and ZOLLO, 1986; DE NATALE *et al.*, 1995). Modern research on Campi Flegrei ground movements began after the episode of 1982–1984. The long-term deformation processes have been interpreted within the framework of regional structures and geodynamics (LUONGO *et al.*, 1991; CUBELLIS *et al.*, 1995).

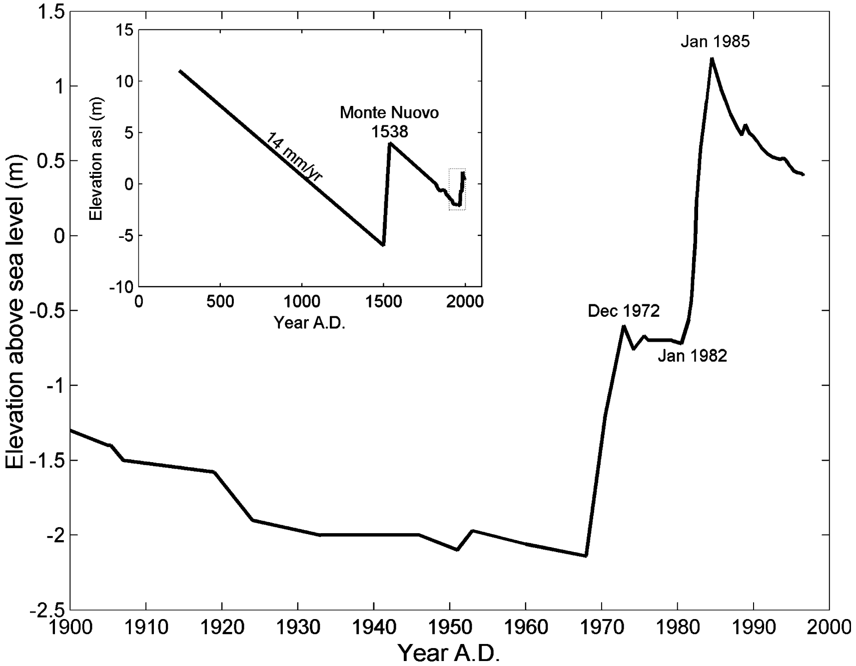


Figure 1
Elevation of the ground at Pozzuoli over the last 2,000 years, observed at the Serapeo Roman market. Vertical movements vary over 13 m and reach velocities up to 2.5 mm/day (modified after DVORAK and MASTROLORENZO, 1991).

The difficulties of applying simple mechanical models to explain Campi Flegrei deformation, similar to those hypothesised for basaltic volcanoes such as Kilauea (Hawaii), have been recognised since the mid 1970s (OLIVERI and QUAGLIARIELLO, 1969), and were summarised more recently by DE NATALE *et al.* (1991). They are mainly concerned with the low depth required for the source of overpressure to produce the observed, very localised ground deformation pattern. Furthermore, very large overpressures (on the order of several hundreds of MPa) are required to justify 1.8 m of uplift in two years. The very shallow depth required for the source (less than 2.5 km) is not compatible with realistic depths for the magma chamber. In fact, FERRUCCI *et al.* (1992) found evidence for a solid-plastic interface at about 4 km depth, interpreted as the top of the magma chamber (Figure 2b).

DE NATALE and PINGUE (1993), DE NATALE *et al.* (1997) and TROISE *et al.* (1997), demonstrated that, considering the effect of the caldera boundaries, modelled as ring faults almost free to shear under the effect of a deep source of overpressure, both the shape of ground deformation and the seismicity during unrest episodes could be interpreted in terms of a source of overpressure below 4-km depth. Such a model seems to explain most of the observations of Campi Flegrei unrests.

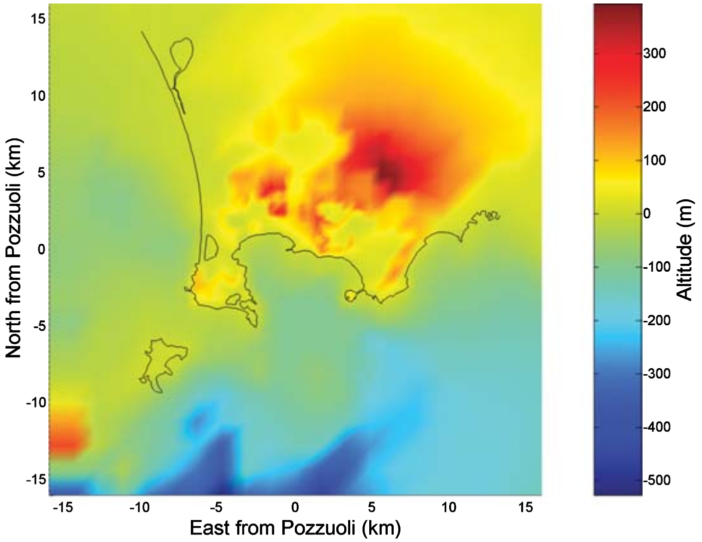
This paper represents the first attempt at detailed, three-dimensional modelling of the ground deformation pattern observed during uplift episodes at Campi Flegrei, using these caldera-bounding discontinuities. The boundary element method is used to simulate the ground deformation field. The vertical displacement data of the 1982–1984 unrest, measured by levelling (DVORAK and BERRINO, 1991), have been inverted for location and overpressure of the magma chamber, and for detailed geometry of collapse structures (ring fault dip, fault depth and width).

Forward Problem: Observations and Model Used

For modelling we use the Mixed Boundary Elements Method (MBEM) (CAYOL and CORNET, 1997), which allows the solving of 3-D problems taking into account topography, free surface and medium discontinuities (fractures) structures, without the problems of complex meshing of the finite-element methods. The MBEM approach optimises time computation, combining two different boundary element methods: (1) the direct method (RIZZO, 1967; LACHAT and WATSON, 1976), based on Betti's reciprocal theorem and the solution of Kevin's problem of a point force in an infinite body, and well suited for modelling topography and cavities; (2) the Displacements Discontinuity method (CROUCH, 1976), based on the analytical solution of a single displacement discontinuity in an infinite space, and well suited for modelling fractures.

The mesh used to describe the surface topography, made by Delaunay triangles, is shown in Figure 4. The elastic parameters of the area, taken by DE NATALE and PINGUE (1990) and DE NATALE *et al.* (1991), have been assumed to be constant

COLOUR FIG.


North from Pozzuoli (km)
East from Pozzuoli (km)
Altitude (m)
15
10
5
0
-5
-10
-15
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0
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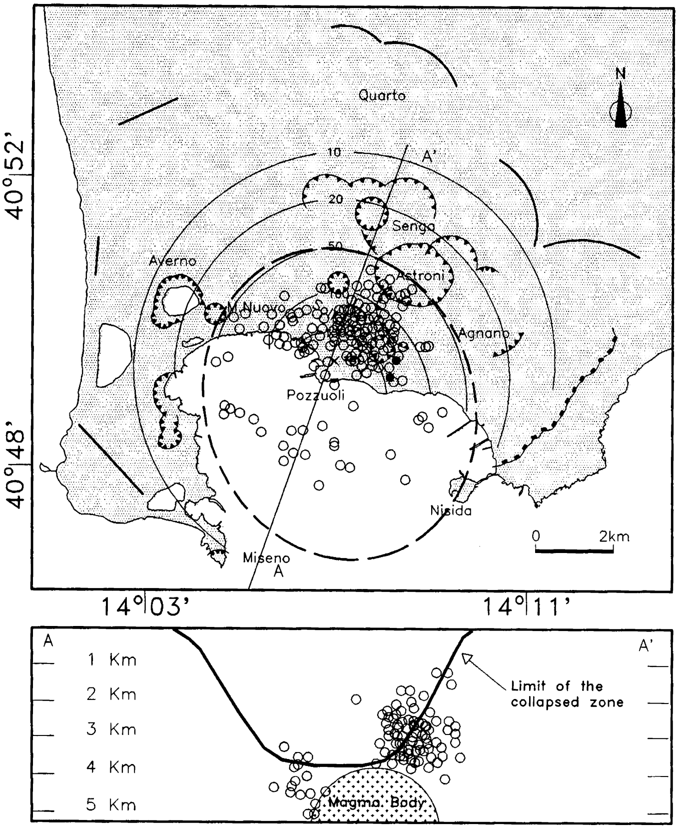
300
200
100
0
-100
-200
-300
-400
-500


Quarto
N
10
A'
20
Senga
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Averno
Astroni
M.Nuovo
100
Agnano
Pozzuoli
Nisida
Miseno
A
0
2km
40°52'
40°48'
14°03'
14°11'
A
A'
1 Km
2 Km
3 Km
4 Km
5 Km
Limit of the collapsed zone
Magma Body

spatially, namely rigidity $\mu = 5$ GPa and Poisson's coefficient $v = 0.3$. The depth of the magma chamber has been constrained to the range 3.5–4.0 km on the basis of the results of FERRUCCI *et al.* (1992), who found the depth of a reverse rigidity contrasts from the observations of *P*- to -*S* wave conversions on the seismograms of regional earthquakes and local man-made shots. In this study, the magma source is represented as a sphere undergoing isotropic pressure (volume) increase. Based on previous studies of ground deformation modelling, we fixed the magma source depth and size, assumed spherical, of radius $r = 1$ km, with the centre at 4.5 km of depth. The geometry of caldera discontinuities has been taken from the gravity model as follows: the surface trace of the high hydrothermalised zone has been digitised and extended in depth to form a 3–D ring fracture. Due to the high uncertainty of shape and location of this ring, parameters such as size, depth of top and bottom limits, and dip angle have been set to *a priori* values but will be free to vary into the inversion process. Boundary conditions on these discontinuities are free to shear (no friction), forbidden to interpenetrate. These simple conditions have been used in this study to simplify the modelling and focus the inversion on the geometry of discontinuities and location of magma source. We are aware that they are not realistic and it would be illogical, for instance, to look at the stress field in this model.

Inverse Problem: Monte Carlo Serial Sampling

All the previous data on magma chamber, surface topography and collapse structures have been incorporated into a highly flexible inversion scheme, able to invert various parameters within given limiting ranges, describing the intrinsic uncertainty of each parameter. The method used is a Monte Carlo serial sampling (MOSEGAARD and TARANTOLA, 1995), using random parameters chosen, at each iteration, near the previous best solution. The method aims to minimise, iteratively, the least-squares misfit function of theoretical versus observed vertical displacement data. The iteration stops when a significantly small value for the misfit function is reached, in this case, the equivalent misfit is obtained with the best Mogi source model (MOGI, 1958) of 60 mm, corresponding to a point source located at 2.8 km of depth just under the maximum displacement point (Pozzuoli Porto).

The horizontal position and pressure change at the source are considered unknown, and inverted for. Other parameters considered unknown are the dip angle,

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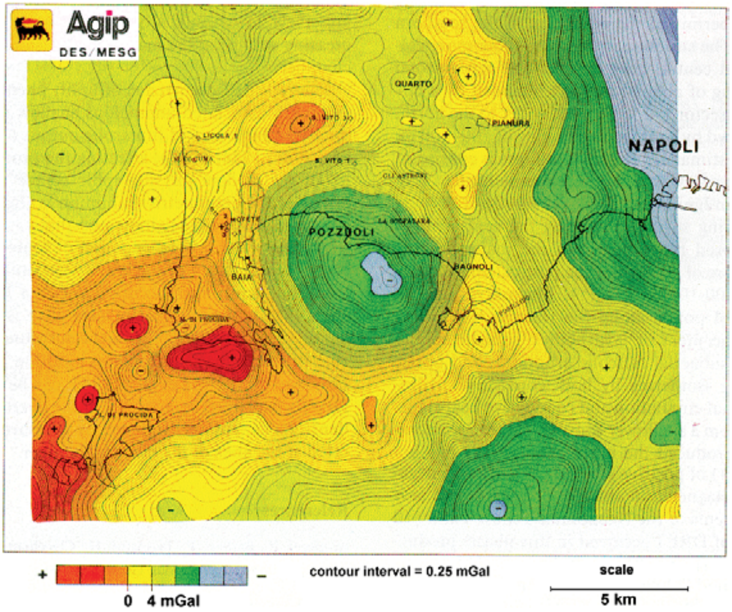
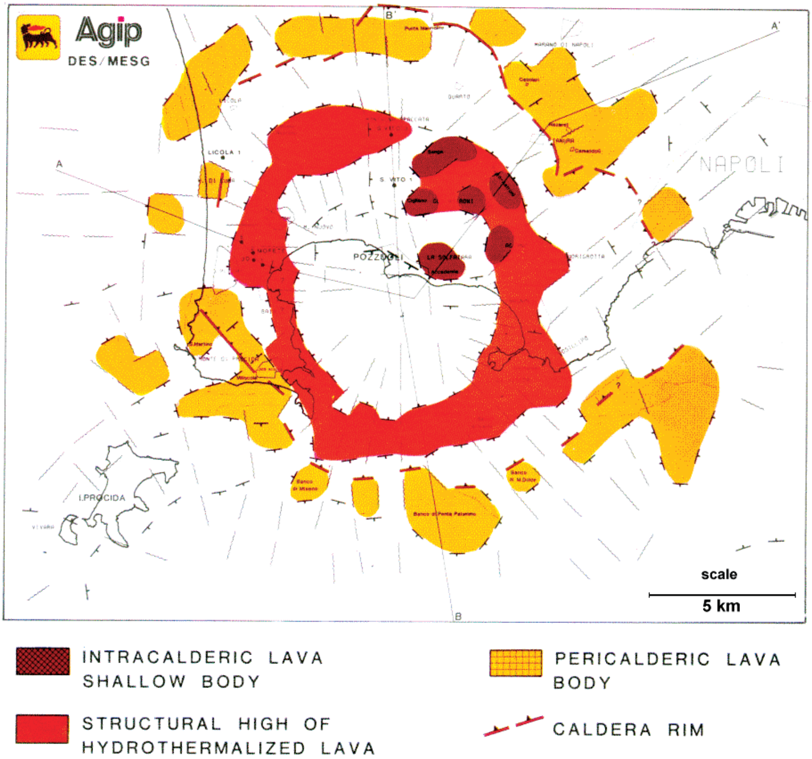
Figure 2

a) Digital elevation model of the Pozzuoli Bay compiled from topographic and bathymetric data. Elevation varies from −550 to +400 m, showing that topographic effects on deformation may be significant. b) Map with earthquake locations and vertical displacements (black curves); in the depth section A-A' the collapsed zone and earthquake are shown (from DE NATALE *et al.*, 1995).


Agip
DES/MESG
QUARTO
PIANURA
NAPOLI
LICOLA 1
S. VITO 1
POZZUOLI
BAIA
LA SOLFATARA
BAGNOLI
I. DI PROCIDA
+
−
contour interval = 0.25 mGal
0 4 mGal
scale
5 km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S. VITO 1
POZZUOLI
LA SOLFATARA
NAPOLI
I.PROCIDA
scale
5 km
INTRACALDERIC LAVA SHALLOW BODY
STRUCTURAL HIGH OF HYDROTHERMALIZED LAVA
PERICALDERIC LAVA BODY
CALDERA RIM

maximum depth and total height of the collapse discontinuities. Also the size of the ring discontinuities has been allowed to vary, within ±1/3 of the *a priori* size taken from gravity modelling (preserving the shape but allowing the scale to vary), taking into account the uncertainty in the gravity modelling. The total number of unknown model parameters is then 7, including source and collapse structures, while the observations (vertical displacement values on the levelling network) have about 80 independent values.

The iterative inversion of vertical displacement data of the 1982–1984 period required approximately 4000 iterations, i.e., about one month of computing on the Sparc Ultra 20 workstation. Figure 5 shows the evolution of the RMS residual during the iterations. Figure 6 shows the fit of the obtained 3-D model compared to the observed displacements, and the best fitting Mogi model. The final RMS residual obtained was 54 mm, with parameters indicated in Table 1. Overpressure is found equal to 35 MPa, a value three times smaller than those required by a homogeneous Mogi model. The mesh used to describe the collapse structures and magma chamber as resulting from the final model are shown in 3-D in Figure 7 and they are also shown in plane view in Figure 4. The location of the center of the spherical magma chamber is some kilometers south of Pozzuoli, beneath the sea. The dip of the ring discontinuities is steep, about 70°.

On the basis of the obtained model, it is possible to reconstruct a 3-D field of model vertical displacements (Fig. 8). This figure is remarkable, because it shows a displacement pattern in the most deformed area rather far from the circular geometry previously hypothezised (Corrado *et al.*, 1976; Berrino *et al.*, 1984; Bonafede *et al.*, 1986; Bianchi *et al.*, 1987). The maximum deformation appears shifted into the Gulf of Pozzuoli, where most of the deformed area is contained. The vertical deformation pattern on land appears to be markedly elliptical, with the major axis oriented about N50°W. Such a trend is very similar to the elliptical trend of earthquake epicentres (see Fig. 2b). We stress here that the asymmetry of the vertical displacement pattern obtained is due to the dominant effect of ring discontinuities marking the caldera collapse structure.

Discussion

The 3-D displacement model obtained in this study opens new interesting perspectives for the study of Campi Flegrei unrest, as well as for other similar calderas. The first new insight concerns the non-symmetric pattern of expected

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Figure 3
Gravity observation and modelling (from *AGIP*, 1987). a) Bouguer anomaly map. b) 3-D structure modelling constrained by geological observations and geothermal drill data. The high hydrothermalized zone is used in this work to define the global geometry of caldera discontinuities.

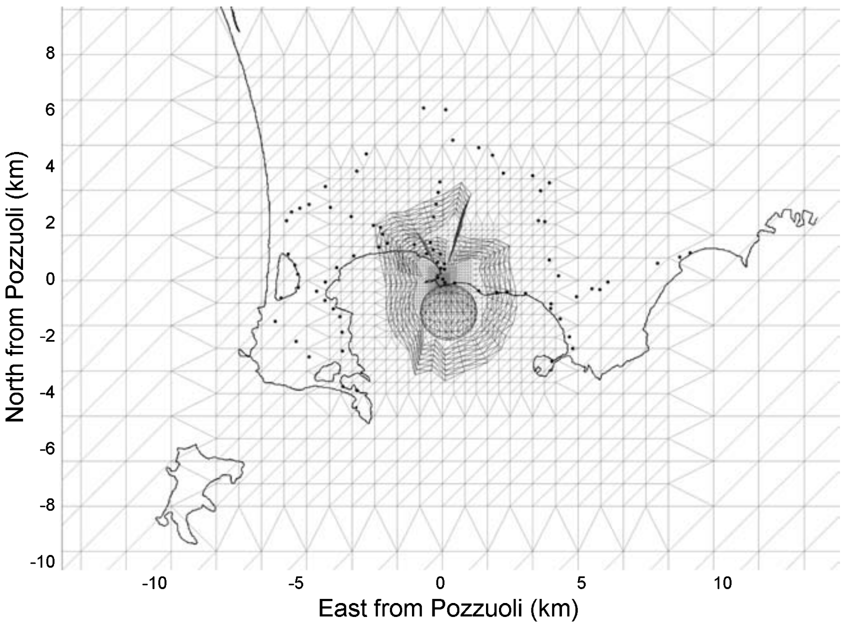

Figure 4
Mesh of free surface topography, caldera rim discontinuity and magmatic source structure, as in the best fit model (Delaunay triangles). Black dots stand for levelling benchmarks.

deformation. The maximum displacement and most of the deformed area is expected to be in the Gulf of Pozzuoli. Also, the elliptical orientation of the displacement pattern on land is very similar to the elliptical geometry of epicentres of local earthquakes that occurred in the same period (1982–1984). In view of current models for local seismicity (TROISE *et al.*, 1997, 2002) this correspondence is expected, due to the earthquakes which occur on the collapse discontinuities. It is remarkable here, that this correspondence derives naturally from the inversion of solely static displacement data, without any input information regarding seismicity. Moreover, the elliptical symmetry on-land and the maximum deformation at sea both occur from the inversion of sparse levelling data only collected on-land. The sparse nature of data from levelling lines obviously disallows interpolation of the original data to define a slightly elliptical pattern, nor is it possible to give any information about displacement offshore. The essential element dominating the character of the model displacement pattern is the presence of ring discontinuities marking the inner caldera.

Two different lines of discussion, however, can be taken to demonstrate the effectiveness of the obtained solution, and, finally, of the hypothesis of dominant control by the collapse discontinuities. The first one, already stated, is that half-space solutions like the Mogi model provide results for the source depth that are

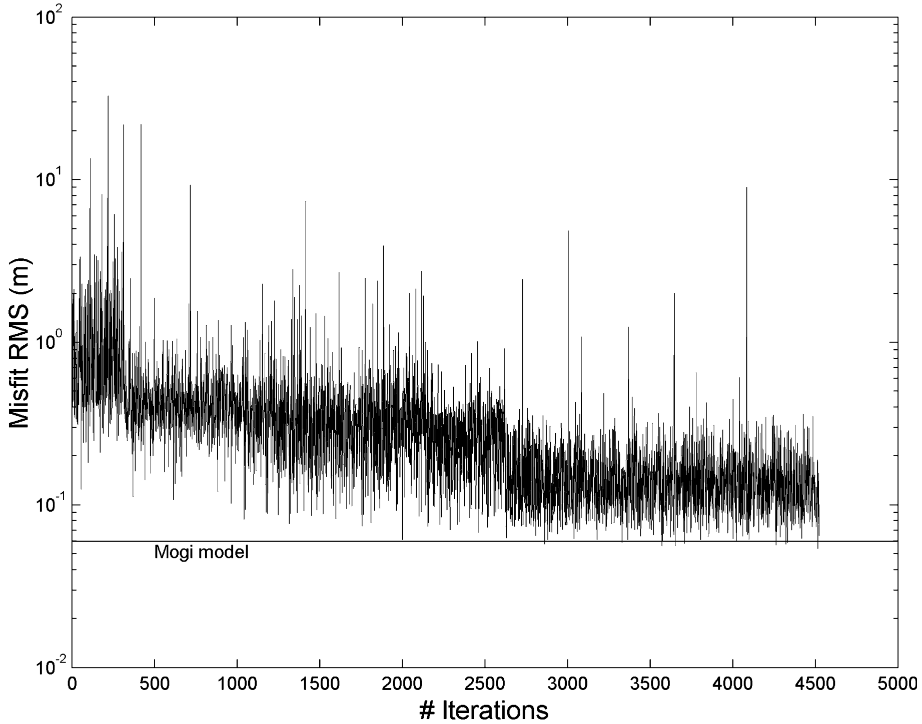

Figure 5
Misfit evolution versus number of iterations for the model inversion using a Monte Carlo serial sampling method, which slowly converged to more probable solutions. Horizontal line stands for Mogi model misfit (60 mm).

incompatible with physical constraints. This argument was made first by CASERTANO *et al.* (1976). Secondly, we discuss the effectiveness of modelled displacement patterns in the light of the actual data set. The best comparison for the modelled pattern would be with a dense displacement data set, making it possible to reconstruct detailed 2-D displacement maps. InSAR data (MASSONNET and FEIGL, 1998) would meet this need, especially for a better constraint on ground displacements next to the caldera discontinuities themselves, however, unfortunately they were not available during the 1982–1984 unrest. The observed subsidence trend at Campi Flegrei follows the same pattern as the uplift phase and, since 1992, it has been recorded by InSAR images. AVALLONE *et al.* (1999) computed the first model of subsidence based on InSAR data from the 1993–1996 period (Fig. 9), and this can be compared to the modelled pattern obtained in this study. A reconstruction of ground displacements over the period 1992–2000 from InSAR data has been obtained by LUNDGREN *et al.* (2001). Apart from the amount and sign of displacement, the patterns on land are very similar. They both show an elliptical trend oriented N50°W. Also the InSAR maximum displacement zones at Pozzuoli do not close on land. The maxima are

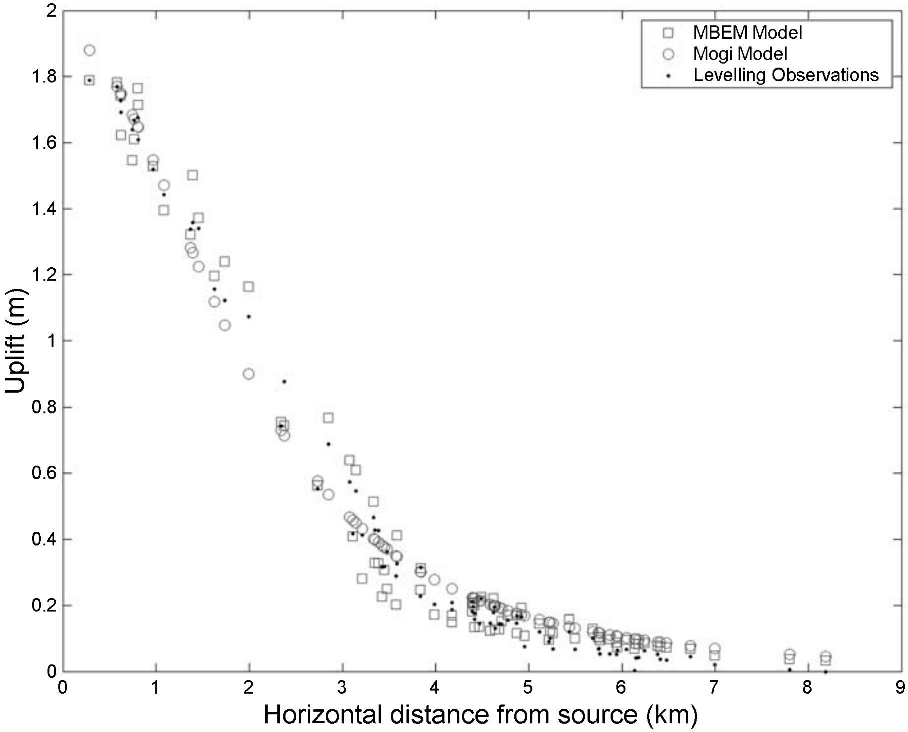

Figure 6
Comparison of levelling observations (black dots), Mogi model (circles) and MBEM model (squares) versus horizontal distance from the source. Minimum misfit is given by the 3-D model, i.e., 54 mm.

Table 1

Final parameters of best model of caldera and source

Parameters	Values
Inner caldera upper border depth[1]	1.16 km
Inner caldera lower border depth[1]	3.1 km
Inner caldera border dip angle	75°
Spherical source radius (fixed)	1 km
Spherical source depth (fixed)	4.5 km
Spherical source position West from Pozzuoli[2]	0.19 km
Spherical source position South from Pozzuoli[2]	1.33 km
Source pressure variation	+35 MPa
Best misfit	54 mm RMS

[1] Depth relative to mean sea level.

[2] Pozzuoli city coordinates = 40°49’15” N, 14°07’27” E.

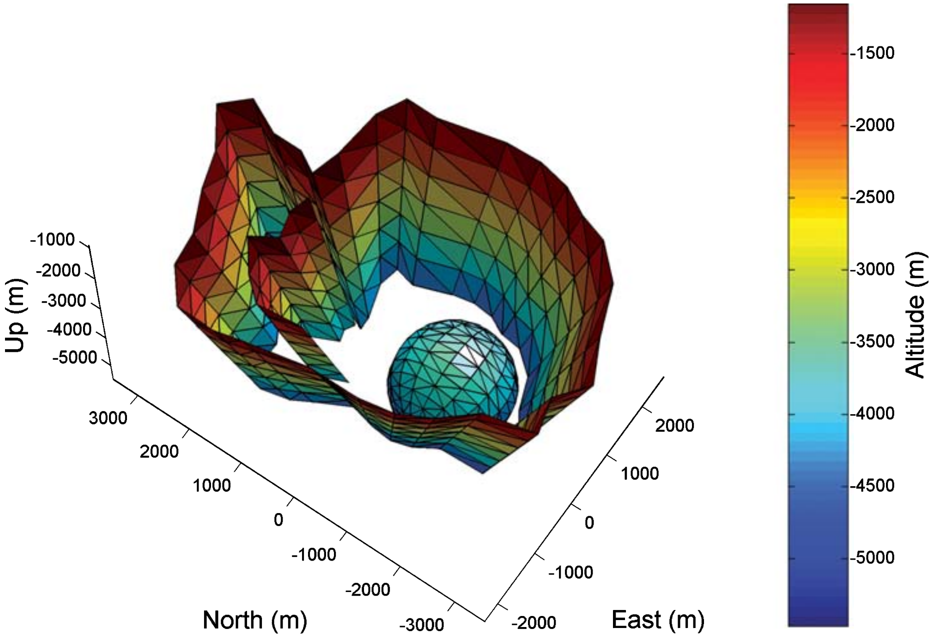

Figure 7
Three-dimensional view of caldera rim and magmatic spherical source mesh used in the modelling. Colour scale corresponds to depth below surface (all units in metre).

located at sea. The InSAR uplift data reinforce the ring discontinuity model proposed here.

The dominant role of these structural features on static deformations, was previously recognised starting from De Natale and Pingue (1993), thereafter in the papers by De Natale *et al.* (1997), Petrazzuoli *et al.* (1999), and Troise *et al.* (this issue). This is the first time, however, that a detailed quantitative 3-D model taking accurately into account the caldera structure as modelled by gravity data has been created. The agreement with all the available data strongly supports the important role of the collapse structures in the model.

The dip of the system of inward discontinuities around the caldera is steep (around 70°) in agreement with the dip of corresponding fault planes of local earthquakes (De Natale *et al.*, 1995; Troise *et al.*, 2002). The shape of the Bouguer anomaly, with the most negative area in the Gulf of Pozzuoli, may result from a rather asymmetric pattern of cumulative vertical displacements, with the area of greatest subsidence in the Gulf of Pozzuoli. The modelled location of the magma chamber is about 1 km offshore, south of Pozzuoli town. In the future, sea-floor measurements of displacement in the Gulf could improve our understanding of the deformed area and consequent models for unrest.

COLOUR FIG.

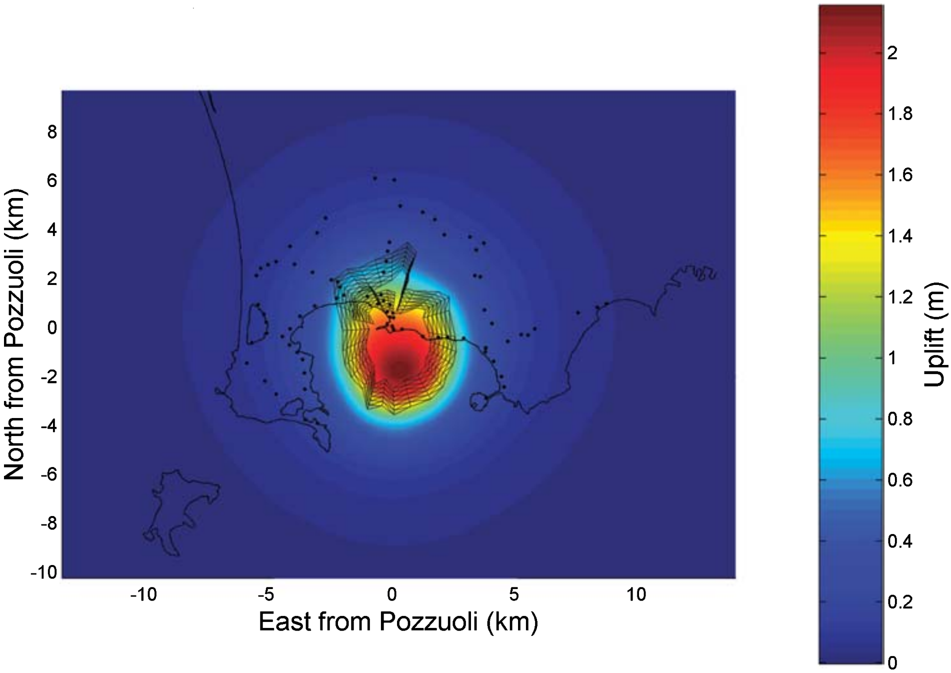

Figure 8
Vertical displacement field produced by the best fit model, caldera discontinuities (black mesh), and levelling benchmarks (black dots). Spatial displacement pattern is clearly influenced by the caldera geometry. Maximum uplift occurs about 2 km south of Pozzuoli City.

The magma chamber is only schematically described in our model with a simple spherical shape. Actually, the shape and volume of the chamber are not constrained by geophysical data. Only the depth of the top part has been well constrained by seismic evidence of *P*- to -*S* wave conversions by FERRUCCI *et al.* (1992) and DE NATALE *et al.* (2001). The extension of the chamber, however, is a matter of speculation. Petrological estimates of the volume of the residual chamber (after the caldera formation) are highly variable, from a few to some hundreds of cubic kilometres of magma (ARMIENTI *et al.*, 1983; ORSI *et al.*, 1996). Modelling and observations of about 30 years of recent unrest suggests that at least the shallowest part of the magma chamber is spatially limited, with an area less than that of the inner caldera. It would be difficult to explain the localised nature of both ground deformation and seismicity otherwise. If the source of the huge caldera-forming ignimbrites (ROSI and Sbrana, 1987) was a magma chamber of large extent, recent observations would imply that the only active part is a shallower pluton a few cubic kilometres in volume.

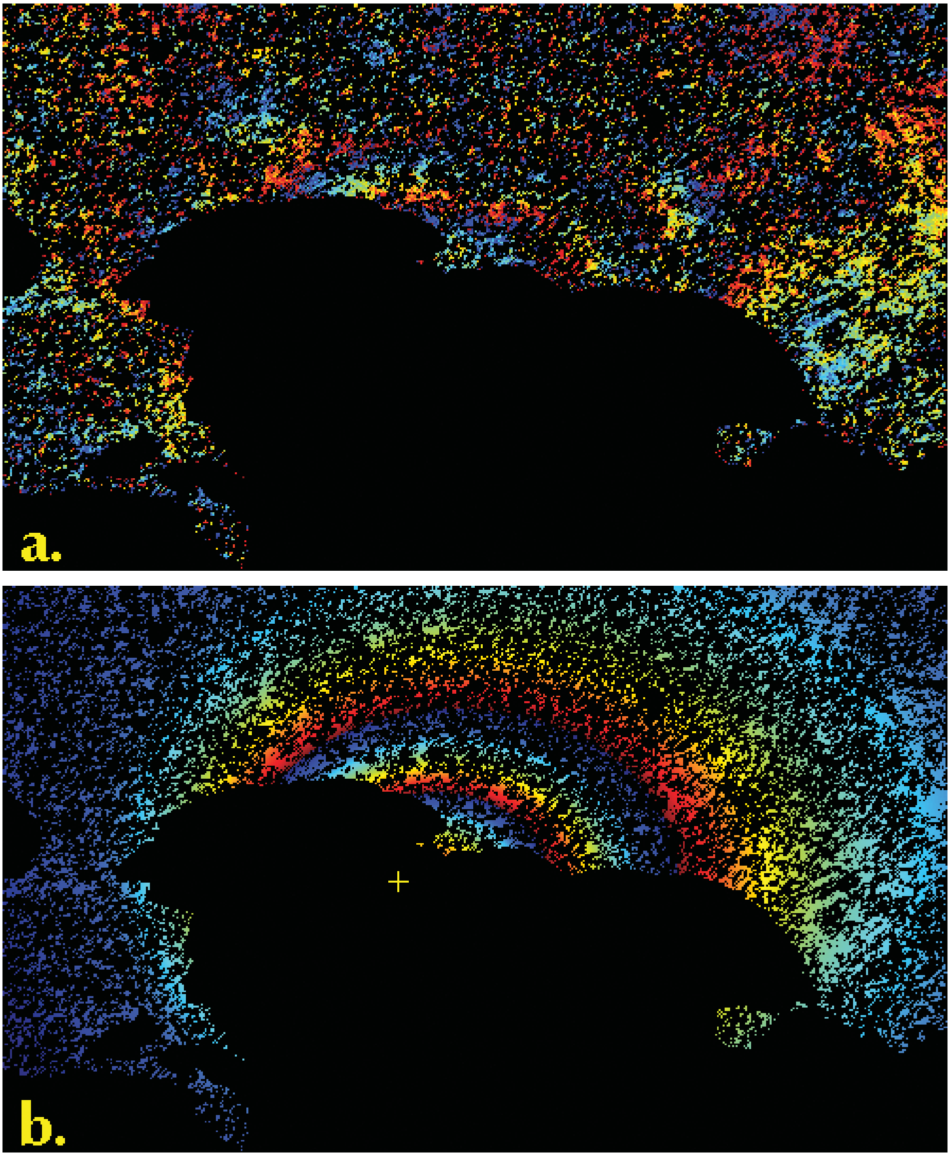

Figure 9
ERS InSAR data from the 1993–1996 period (Avallone *et al.*, 1999). (a) About 10 cm of subsidence are observed (3.5 fringes), and (b) Mogi model with 2.7-km source depth and horizontal location near Pozzuoli city (cross) fits the observations satisfactorily. The spatial pattern is very similar to previous uplift and subsidence episodes.

Conclusions

Some of the results obtained in this work can be generalised to other similar areas. They imply that, when interpreting ground deformations at calderas, the structural features of the area must be carefully considered. In particular, the collapse structures play a fundamental role during unrest episodes, affecting both static deformation and seismicity. The presence of faults and fractures at volcanoes may strongly affect the ground deformation field, and must be taken into account when modelling unrest episodes. The use of extremely simple deformation models in homogeneous elastic media may be misleading, even if the apparent fit to the data is very good.

Regarding the Campi Flegrei area, most of the observations during unrest episodes can be modelled in terms of elastic deformation resulting from magma chamber overpressure in the presence of boundary caldera collapse structures. The deformation mechanism and temporal evolution, however, are likely to involve the further contributions of pressure/temperature changes in the geothermal system, as pointed out by several authors (De Natale *et al.*, 1991, 2001; Bonafede, 1991; Gaeta *et al.*, 1998).

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