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Non-linear effects in ground deformation at calderas due to the presence of structural discontinuities

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Abstract
The peculiar behaviour of ground deformations at calderas induced by collapse discontinuities is analysed in this paper. Firstly, we show, using a 3D finite element scheme, that the influence of collapse discontinuities on the surface deformation is dominant with respect to likely perturbations due to the heterogeneity of elastic parameters at calderas. Then, a 2D boundary element method is used to simulate the non-linear effects induced by stress-strain discontinuities on ground deformation in homogeneous elastic media. For inward-dipping discontinuities, which are common at the borders of collapsed calderas, vertical ground deformations caused by a positive increase in pressure in a shallow source are more spatially concentrated and intense than those caused by negative pressure changes. The different behaviour for different signs of pressure changes depends on the different sign of normal stress on the discontinuities, and from the non-overlapping condition for the sides of the discontinuity. The non-overlapping condition results in different stress fields at depth, for different pressure signs, which in turn cause different ground deformation. These non-linear effects only work at equal initial conditions for the stress field, for instance they do not work for fast recovery of ground level after an uplift episode produced by positive overpressure, in which the medium simply recovers the starting position before uplift. These effects have, on the contrary, important implications for long-term surface deformations at calderas. They imply for instance that, for long term subsidence, the extension of the deformed area at calderas should be much larger than for uplift episodes. This result seems in agreement with recent findings on Campi Flegrei secular subsidence, as inferred from archaeological studies.

Key words *ground deformation modeling – caldera collapse – structural discontinuities*

1. Introduction

Campi Flegrei is a caldera formed by subsequent collapses dating from 37 000 to 12 000 years ago. It is located in the Southern part of Italy, and encloses part of the metropolitan area of Naples, where more than 1.5 million people live.

Ground elevation changes at Campi Flegrei have been known since the ancient Roman age. The history of ground movements at Campi Flegrei caldera has been delineated by the integration of different data: geological, archaeological and direct measurements (Parascandola, 1947; [RS1] Dvorak and Mastrolorenzo, 1991) (fig. 1a-c). It includes episodes occurring on different time and space scales: secular subsidence at a rate of about 1 m per century and fast ground uplift at a rate up to 1 m per year. In recent times, two different episodes of fast uplift occurred, from 1969 to 1972 and from mid-1982 to December 1984. The ground uplift during the first episode was about 170 cm. The total uplift recorded between January 1982 and December 1984 amounted to 180 cm, partially

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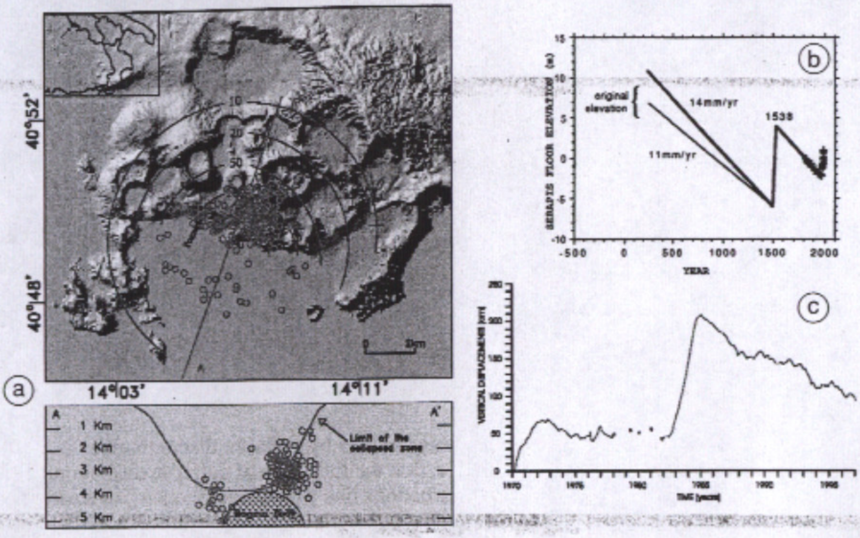

Fig. 1a-c. a) Map of various geophysical observations at Campi Flegrei. The contours of vertical elevation 1982-1984 is shown together with earthquake hypocentres; the projection of the collapsed zone as modelled from gravity anomalies is superimposed on the depth section of hypocentres. Also shown is the location of the magma chamber as inferred by Ferrucci *et al.* (1992). b) History of vertical movement at Serapis (after Dvorak and Mastrolorenzo, 1991). c) Vertical ground displacement at Pozzuoli harbour in the 1970-1996 period, as recorded by tide gauge (continuous line) and levelling data (closed circles).

recovered by a subsequent slower subsidence with an average rate of 0.1 m/yr, still ongoing. The roughly circular area raised had a radius of about 3 km centred on the town of Pozzuoli (fig. 1a-c). Periods of intense ground uplift are sometimes associated with an eruption, as occurred in 1538 (Mt. Nuovo eruption), the most recent eruptive event in the area. The two recent unrests produced a huge quantity of data and prompted new research. An overview of recent research can be found in De Natale *et al.* (2001) (see also Beauducel *et al.*, 2004). One of the most important results of the recent research (De Natale and Pingue, 1993) has been the recognition of the effect of collapse caldera borders in determining the shape of ground displacements during fast deformation episodes [RS3]. More recent studies by De Natale *et al.* (1997, 2001) and Troise *et al.* (1997) definitely demonstrated the prominent role of caldera collapse borders both on static deformations and on seismicity. In particular, these studies pointed out that the surface deformation produced by a buried pressure source is much more intense and spatially concentrated in the presence of collapse discontinuities with respect to a continuous homogeneous half-space. On the other hand, also the heterogeneity of elastic parameters at a caldera might in principle affect in a similar way the surface deformation (see *e.g.*, Bianchi *et al.*, 1987).

In this paper, we demonstrate that the role of collapse structures, described as stress strain discontinuities free to slip in response to volcanic stress changes, is much greater than of static deformation with respect to effects of the heterogeneity of elastic parameters likely to hold at calderas.

Furthermore, we show, using a plane-strain approximation and a boundary element method, that the presence of inward dipping discontinuities at calderas produces peculiar non-linear effects on the static deformation field, which should be notable during long-term deformation. As a consequence of these effects, ground displacements associated with secular subsidence phenomena should involve a larger area with respect to fast uplift episodes. Theoretical results on such non-linear effects are then discussed, also in the light of recent findings of geo-archaeology at Campi Flegrei about secular subsidence inferred from marine incrustation levels in ancient manufacts.

2. Effects of discontinuities *versus* elastic heterogeneity

The first aim [RS5] of the paper is to show the relative influence on surface deformations of heterogeneity of elastic moduli *versus* the presence of bordering fractures/lithological discontinuities, for a typical collapsed caldera. 3D finite element computation was used in this section to compute theoretical surface displacements in heterogeneous elastic media with and without bordering discontinuities. Theoretical models have been calibrated to schematically represent a system like Campi Flegrei caldera, Southern Italy. It is a chaotic collapse caldera (Scandone, 1990), with inward-dipping collapse borders. In order to exploit the roughly symmetric shape of typical calderas, an axial-symmetric approximation was used in the framework of the finite element approach. The basic model consists of a spherical pressure source, with radius $r = 1$ km, with centre located at 4.5 km of depth, embedded in a purely elastic half-space. Surface vertical and horizontal displacements computed for this simple model are shown in fig. 2. Further complexities are progressively added to such a basic model. The choices of the finite element

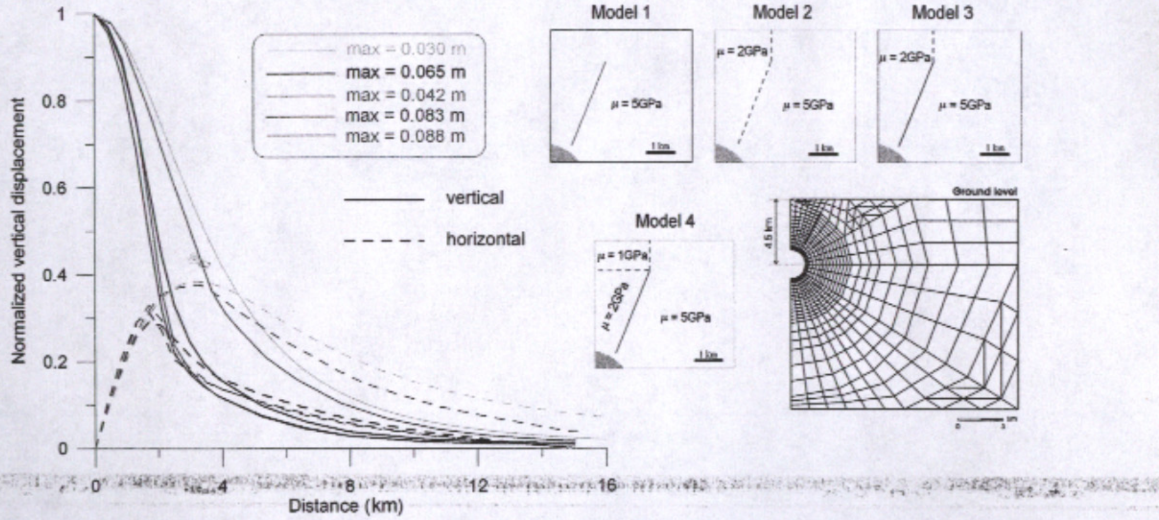

Fig. 2. Normalized vertical (continuous line) and horizontal (dashed lines) displacements computed for a spherical pressure source ($\Delta P = 5$ MPa), with radius $r = 1$ km and center located at 4.5 km of depth, in an elastic half-space. Displacements are shown for 4 models computed for different rigidity value and with an axial-symmetric finite element scheme (bottom). The green curves are for a homogeneous elastic model, without lateral discontinuities. Model 1 (black) is a homogeneous elastic model (rigidity 5 GPa), with ring discontinuities as shown in the half-section. Model 2 (violet) is a medium with lower rigidity in the inner caldera (2 GPa) with respect to the external rocks (5 GPa). Model 3 (blue) has rigidity values as model 2, and furthermore the ring discontinuities like model 1. Model 4 is like model 3, with the addition of a shallow top layer (1 km thick, covering the inner caldera) with lower rigidity (1 GPa). Note that the shapes of blue and red curves are very similar to the black ones, with also similar maximum values (within about 30%), whereas violet curves (heterogeneous model without discontinuities) are very different from the black ones and much more similar to the green ones (homogeneous, without discontinuities).

mesh and of the extension of the finite element model (see fig. 2) were tested against 3D boundary element results for the homogeneous model with discontinuities (black lines in fig. 2) using the approach described in Beauducel *et al.* (2004). Computed values for displacements and stress distributions are practically the same using the two different methods, within about 2%. As a first test, we consider the presence of bordering stress-strain discontinuities, then we consider heterogeneous elasticity, described in terms of rigidity modulus. The rigidity modulus used for the basic (homogeneous) model is $\mu = 5$ GPa used by several authors for the Campi Flegrei area (De Natale *et al.*, 1991; De Natale and Pingue, 1992; Petrazzuoli *et al.*, 1999). The inclusion of bordering discontinuities in the model, simulating the caldera collapse, is obtained adding an inward dipping, axial-symmetric truncated cone surface (shown in a half-section as a line segment, see fig. 2). The appropriate boundary conditions imposed on this surface are:

1) shear stress $\sigma = 0$, which means that lateral discontinuities are free to slip in response to the applied pressure at the buried source;

2) normal strain $\varepsilon > 0$, which means that the borders of the discontinuities can only open, not overlap.

The inclusion in the model of bordering discontinuities has a strong effect on surface displacements, producing a much sharper decay of displacement as a function of the distance from the epicentre of the source (fig. 2).

To this model with bordering discontinuities, we added heterogeneous rigidity, based on the typical structure of a collapsed caldera, in which internal rocks, mostly consisting of incoherent pyroclastic deposits, have a lower rigidity ($\mu = 2$ GPa) than external rocks ($\mu = 5$ GPa, model 2 in fig. 2). Furthermore, we added a top layer with lower rigidity ($\mu = 1$ GPa) to this model (model 3 in fig. 2). The heterogeneous rigidity model was also investigated without the addition of bordering discontinuities, to have a complete picture of the relative influence of discontinuities *versus* heterogeneous rigidity on surface displacements.

Figure 2 shows theoretical displacements, vertical and horizontal, obtained with the different models. It is clear from the figure that both collapse discontinuities and heterogeneity of elastic parameters result in amplification of maximum vertical displacements and higher spatial concentration of vertical and horizontal displacements. However, it is also clear that the largest modifications to displacement patterns are due to the inclusion in the model of bordering discontinuities, whereas only relatively small modifications are produced by the addition of heterogeneous rigidity. The displacement curves obtained with heterogeneous rigidity only are very slightly different from the ones computed in a homogeneous half-space. Furthermore, the addition of rigidity heterogeneities to the model with collapse discontinuities results in negligible changes in the displacement curves. These results, which confirm the strong influence of bordering discontinuities on surface displacement patterns, as previously evidenced by De Natale and Pingue (1993) and De Natale *et al.* (1997), also demonstrate that the effects of realistic heterogeneity of elastic parameters at typical calderas are negligible with respect to the effects of collapse discontinuities. Collapse discontinuities are then the most effective perturbation to displacements at calderas, with respect to predictions computed in homogeneous elastic half-spaces. They produce higher maximum vertical displacements and higher spatial concentration of both vertical and horizontal deformations.

Once the dominant role of bordering discontinuities at calderas with respect to other sources of medium complexity is assessed, we highlight the peculiar effects of such discontinuities on the long-term deformation.

The method used for this aim consisted of a boundary element technique called discontinuity method (Crouch, 1976) in the framework of a 2D (plane strain) approximation. In this scheme, the spherical pressure source becomes an infinite cylinder and the bordering discontinuities two infinite inwar-dipping planes. the 2D section is the same as the 3D case. Although the 2D model is only a crude approximation, it is perfectly adequate to qualitatively show the non linear effects obtained with source overpressure of different sign.

A pressure change of 5 MPa of amplitude (alternatively positive and negative) was applied at the source, starting from zero initial stress. Different dips of the ring discontinuities were considered, with positive and negative pressure changes. Positive and negative pressure changes were applied starting from the same initial conditions for stress (zero in this case).

Figure 3 shows the effect of varying the sign of pressure change at the source and the dip of discontinuities. The comparison between deformations obtained with positive and negative pressure changes for each dip of discontinuities can be made by looking at continuous and broken lines with the same model (fig. 3).

As the dip angle increases from the vertical, the shapes of ground deformations become more and more different as a function of the sign.

In the fig. 3, displacements are shown normalised and with absolute value, so that they are all positive and hence easily comparable. In general, the displacement is markedly different from positive to negative pressure values. For a dip angle of 30°, the maximum displacement obtained for negative pressure is less than half with respect to that obtained for positive overpressure. The radial extension of the deformed area, for negative pressure changes, can be much larger than for positive ones (also by a factor 2 or more).

These results imply that, for pressure changes applied to a given equal starting stress field, subsidence phenomena caused by decrease of pressure should involve a much larger area with respect to uplift phenomena due to pressure increase

This phenomenon, which corresponds to a non-linear behaviour between positive and negative pressure changes, occurs because the boundary conditions imposed on the discontinuities result in different absolute values of the stress fields. In particular, the physical constraint of non-overlapping for the discontinuity borders, makes the stress in the medium different when the borders undergo compression (as

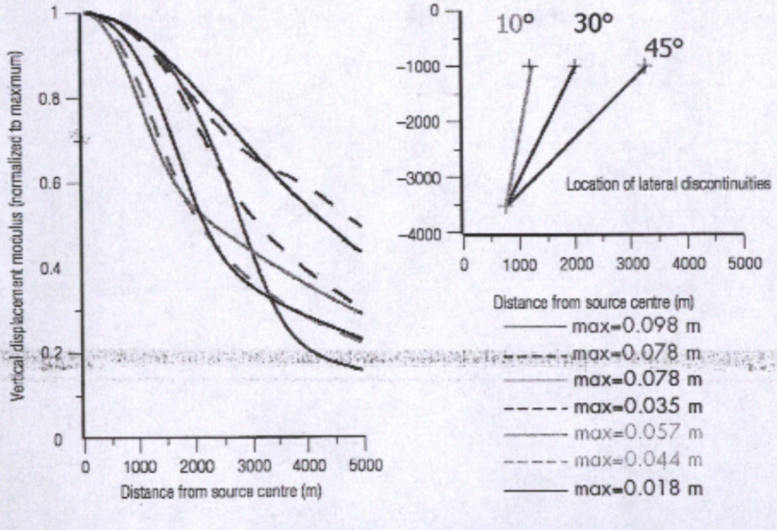

Fig. 3. Normalized vertical displacements computed in the plane strain approximation for a circular pressure source and different signs of overpressure (ΔP = 5MPa continuous line and ΔP = 5MPa dashed lines), with radius r = 1 km and centre located at 4.5 km of depth, in an elastic half-space. Displacements are computed for three different dips of the ring discontinuities and for zero initial stress. Displacements for negative pressure changes are inverted in sign, so that all displacements are shown positive. Note that for dip angle of 30° (blue curves), the maximum displacement obtained for negative pressure is less than a half with respect to that obtained for positive overpressure.

in the subsidence phase, negative pressure change) with respect to the phase of extension, corresponding to an uplift phase (positive pressure change). In other words, during the subsidence phase the stress field cannot be just symmetric with respect to the uplift phase, because the non-overlapping constraint only acts under compression, so breaking the symmetry between the two cases.

In order to better clarify this effect, we computed the stress field in the medium, both for positive and negative pressure changes. We hence computed the components of the stress tensor at several points on a grid with spacing of 250 m on both axes, over a distance of 5 km from the axis of the system and a depth of 4 km. Since the only difference for the two models is the sign of the applied pressure, in fig. 4 we show results by inverting the sign of the three stress components computed for negative pressure change. So doing, the differences in the stress state resulting from different signs of pressure changes are easily disclosed. Such marked differences, which are also the cause of the pressure sign dependence of surface deformation, are obviously due to the imposed asymmetric boundary condition $\varepsilon > 0$, which results in different stress changes in the whole volume for different signs of the applied pressure changes.

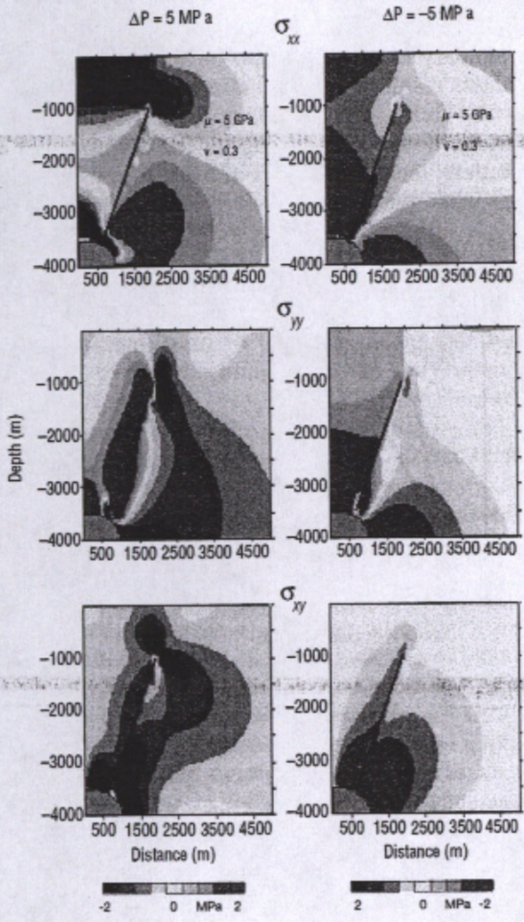

Fig. 4. Stress tensor computed, in the plane strain approximation, for the pressure source as in fig. 3. The black line indicate lateral discontinuities. The sign of stresses for negative ΔP is reversed.

3. Discussion and conclusions

The first key result of this paper is the relative importance of bordering discontinuities *versus* heterogeneity of elastic parameters in ground deformation phenomena at typical collapsed calderas. Although the strong influence of bordering collapse discontinuities had been clearly assessed before (De Natale and Pingue, 1993; De Natale *et al.*, 1997, 2001) and recently evidenced experimentally by SAR observations (Amelung *et al.*, 2000), the relative contribution of discontinuities and elastic heterogeneities has not yet been clearly stated. Some papers, dealing in particular with Campi Flegrei caldera, had previously hypothesised that the effect of strong concentration of ground deformation in the caldera area were due to the rigidity contrast between internal and external caldera rocks (Bianchi *et al.*, 1987; Quareni, 1990). In this paper, we demonstrate that the effect of realistic heterogeneity of elastic parameters (more than double rigidity for external *versus* internal rocks) is much less important, generally negligible, with respect to the presence of lithological discontinuities at the caldera borders. This result has important general implications for the interpretation of physical models of volcanic activity as inferred from static deformation data, at calderas worldwide.

In particular, both the effect of ring discontinuities and lower rigidity in the inner caldera volume lead to an higher concentration of surface ground deformation in a smaller area, *i.e.* to a sharper decay of surface displacement as a function of distance from the point of maximum displacement. Also, both the effects tend to amplify the maximum vertical displacement. As a consequence of these effects, as already pointed out by De Natale and Pingue (1993) and De Natale *et al.* (1997), estimates of pressure source depths, not taking into account the peculiar caldera structure, tend to be considerably biased towards lower values. However, the influence of discontinuities appears much more important than any realistic heterogeneity of elastic parameters.

The presence of discontinuities at the caldera borders, besides having a large effect on the shape and intensity of ground deformations, also involves considerable non-linear effects in the long-term. In fact, as demonstrated in this paper, the nature of boundary conditions at the caldera borders, and in particular the non-overlapping condition for the borders of the discontinuities, produces different stress and strain in the volume respectively for uplift and subsidence, which can be in particular shown as different shapes and amount of surface displacements. It must be noted, however, that theoretical results showing marked differences using positive or negative pressure changes have been obtained starting with an equivalent pre-existing stress condition, *i.e.* without any stress in the volume except that induced by the source overpressure. This means that the difference in the stress and strain produced by positive and negative pressure changes only holds if starting from the same initial conditions, *i.e.* the same pre-existing stress state. It is obvious that the decrease of pressure shortly following a previous pressure increase simply resets stress and strain towards the values attained before the increase in pressure. A different consideration applies the case of long-term deformation, where long-term is meant as compared with typical stress relaxation times due to visco-elastic effects. At volcanic caldera areas where high temperatures of shallow rocks are present, the effective rheology of the shallow crust may involve considerably low viscosity values. For average rock rigidity $\mu = 5$ GPa, typical of Campi Flegrei caldera in the shallowest 2-3 km, a viscosity value $\eta = 10^{18}$ Pas implies a relaxation time lower than 10 years (see De Natale *et al.*, 1991), whereas a value $\eta = 10^{19}$ Pas implies a time of about 100 years. Secular deformation at Campi Flegrei mainly consists of continuous subsidence, at a rate of about 1-1.5 cm/yr (Dvorak and Mastrolorenzo, 1991). Except for short periods, in the order of tens of years following fast uplift episodes, such subsidence then occurs over times which are larger than relaxation times of stress generated during fast uplift episodes. As a consequence, the non-linear effect of caldera border discontinuities should cause amplitude and spreading of secular subsidence very different from episodes of uplift of fast subsidence shortly following an uplift. At Campi Flegrei, in particular, hypothesising a dip of about 60° for the inward-dipping structures, secular subsidence should involve an area which is about double the area deformed during fast unrest episodes. In the recent uplifts a circle with radius of about 3 km roughly contains the contour lines up to 20% of maximum observed deformation.

In an equivalent subsidence model with negative pressure changes and dip of about 60°, the contour line at 20% would approximately correspond to a radius of about 6 km, *i.e.* about the double.

An important question then arises regarding Campi Flegrei caldera, where secular subsidence can be reconstructed since Roman times, about 2000 years ago. The question is if it is possible to note a behaviour for the secular subsidence similar to that inferred from our theoretical calculations. Recent results inferred from the study of marine incrustation levels in ancient manufacts, both of Roman and Middle ages, point out that secular subsidence really involved a larger area with respect to that spanned by recent fast uplift and subsidence episodes (Cinque *et al.*,1991). Such researches found marine levels at Baia in some periods of the Middle age, for instance, very close to the corresponding levels at Pozzuoli (centre caldera), and submersion at Miseno of about 70% with respect to Baia. In the recent episodes of fast ground deformation, the percentage of vertical displacement at Baia (2.5 km from the centre caldera) was less than 30% of the maximum, and less than 10% at Miseno. Observed data seem then in agreement with our theoretical findings, indicating the peculiar non linear effects of inward dipping caldera border discontinuities.

Results obtained here complement and refine the recent model on Campi Flegrei short-term unrests recently presented by De Natale *et al.* (2001). In this model, both mechanical effects of magma pressure changes and thermal-fluid-dynamical effects linked to hot fluid circulation in the shallow geothermal system are considered in the framework of a unitary coherent picture in agreement with geophysical and geochemical data. In addition, this paper includes in the same coherent framework also the aspects of long-term ground movements well known since Roman times.

Future research on geo-archaeological data can shed further light on this important question related to the mechanics of caldera unrests.

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