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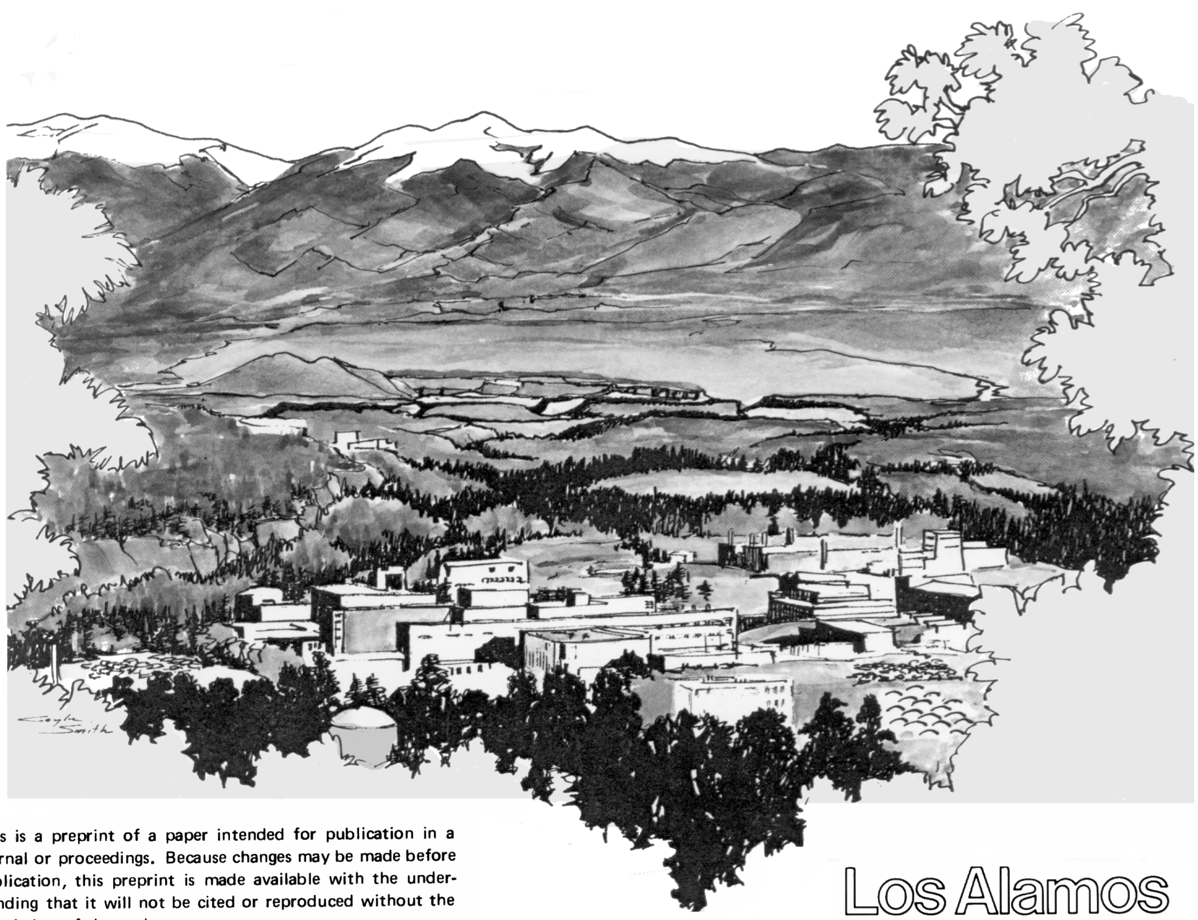

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Mechanical and thermo-fluid behaviour during unrest at the Campi Flegrei caldera (Italy)

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Abstract

The Campi Flegrei caldera (CFc) is a resurgent, nested structure resulting from the two main collapses of the Campanian Ignimbrite (37 ka) and the Neapolitan Yellow Tuff (12 ka) eruptions. While the whole structure is affected by a broad subsidence, ongoing local resurgence and unrest occur inside the young, nested caldera structure. The caldera has shown signs of unrest during the past 30 years, with two uplift events that have generated a net displacement of 3.5 m, each followed by subsidence. The time evolution of both ground deformation and seismicity recorded in Campi Flegrei in the last 30 years (since 1969 up to the present) shows aspects not completely explainable by means of mechanical models. In particular, the occurrence of an intense seismic activity during uplift and its absence during subsidence lead us to infer that these two phases might be related to two variable mechanisms. The large amount of magma and the shallow convective fluids circulation needed to explain the very high temperature gradient (100°C/km) measured also in marginal areas of the caldera, suggest the presence of a thermo-dynamical system in supercritical conditions. We have carried out an analysis of the unrest episodes by means of 3D finite-element method, simulating the mechanical and fluid-dynamical response of a two phase medium (solid–fluid) to a sudden (stepwise) pressure or volume increase at a depth of 4 km. According to geological and geophysical constraints, in our scheme we have subdivided the caldera floor into a central and a peripheral zone. The central zone represents the resurgent block and has high permeability, while the peripheral zone is less permeable. We have performed a parametric analysis assuming both Young modulus and permeability of each zone as variables. The basic test for each solution was how well it simulates the time evolution of ground deformation during the last unrest episode (1982–1984). The results obtained clearly show that fluids diffusion accounts for some peculiar features of the ground deformation such as the variable behavior between the resurgent block and the peripheral part of the caldera floor. Subsidence is explained in terms of lateral diffusion of fluids instead of a regression of source processes. Consequently, no variation of shear stress occurs during this phase, providing a physical explanation to the absence of seismicity.

Keywords: Campi Flegrei caldera, Italy; ground deformation; seismicity

1. Introduction

Detection of volume and depth of a magma chamber is a crucial parameter for the hazard assessment of any volcanic area. The inversion of ground deformation data is a very useful technique for providing a first-order evaluation of size and depth of the source (magma chamber). The simplest method to achieve such evaluation was developed by Mogi (1958) for a point-like source (finite but with small

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dimensions: depth ≫ radius) within an elastic and homogeneous half-space. Walsh and Decker (1971) and Dieterich and Decker (1975) extended this method to a source with an arbitrary shape and

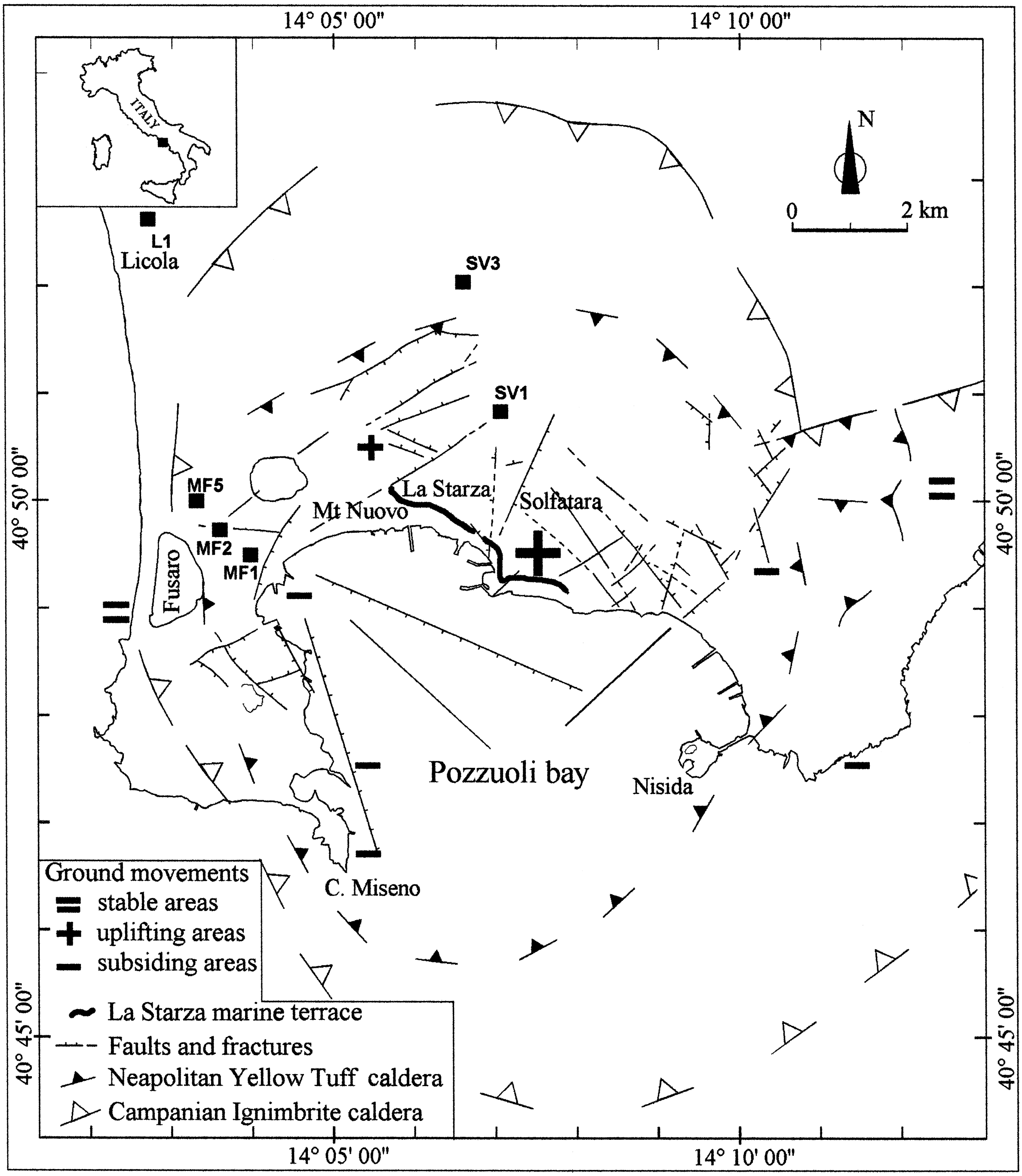

Fig. 1. Schematic structural map of the Campi Flegrei caldera with areas affected by long term ground movements (modified after Di Vito et al., 1999-this issue).

located in a non-homogeneous but still elastic half-space by using the finite-elements method. Dvorak et al. (1986), Ewart et al. (1991) and Yang et al. (1992) supplemented and extended the usefulness of Mogi's source by using rectangular dislocations.

Ground deformation is accompanied by large ductile strain which is followed by intense crustal fracturing and seismicity. Therefore the results of an inversion based on elastic models should be considered as rough estimates. In order to get more realistic results, an interpretative mechanical model has to be constrained and fit to both structural and thermodynamical characteristics of a given volcanic area.

The Campi Flegrei caldera (CFc) is suitable for modeling ground deformations as it has been affected by unrest episodes in very recent times. In this paper we present results of a thermo-fluid dynamic modeling of the 1982–1984 unrest episode. Available geological, magmatic, structural, and mechanical data for the caldera have been used as modeling constraints.

2. Geological, geochemical, and geophysical outlines of the CFc

The volcanic and deformational history of the CFc since its identification was reconstructed by Orsi et al. (1996), while Di Vito et al. (1999-this issue) detailed the past 12 ka (Fig. 1). The CFc results mainly from two collapses related to the Campanian Ignimbrite (CI; 37 ka; Civetta et al., 1997) and the Neapolitan Yellow Tuff (NYT; 12 ka; Orsi et al., 1992) eruptions. The NYT caldera has been affected by two recent bradyseismic events between 1969 and 1972, 1982 and 1984, respectively (Barberi et al., 1984, 1989; Orsi et al., 1999-this issue).

In the past 12 ka, volcanism has been very intense and the NYT caldera floor is undergone resurgence, affecting its central and northeastern sectors. Orsi et al. (1996) suggested that resurgence occurs through a simple-shearing mechanism (Orsi et al., 1991) that generates a disjointing of the NYT caldera floor into blocks with differential movements. The authors have interpreted the bradyseismic events occurred in 1969–1972 and 1982–1984 as episodes of the long-lasting resurgence.

D'Antonio et al. (1999-this issue) have suggested that the magmatic system is presently characterized by a complex long-lived, large-volume reservoir which contains remnants of the trachytic CI and NYT magmas. A less evolved trachybasaltic magma is located deeper in the crust. On the basis of a modeling of the thermal evolution of the Phlegraean magmatic system, Wohletz et al. (1999-this issue) concluded that a significant amount of magma (not less than 500 km^3) is still present under the CFc.

Bradyseismic events in the CFc are represented by two uplift episodes in 1969–1970 and 1982–1984. The area involved was always the same and the displacement field was similar, showing an invariable structural setting. Casertano et al. (1976) firstly hypotesized that hydrothermal circulation is the trigerring mechanism of uplift. Orsi et al. (1999-this issue) on the basis of a reinterpretation of both ground deformation and seismic data, collected through the monitoring networks of the Osservatorio Vesuviano, made a detailed reconstruction of the short-term deformation events occurred inside the CFc since 1969. The maximum detected ground uplift was 174 cm during the 1969–1972 uplift episode and of 179 cm during the 1982–1984 episode. Between 1972 and 1982, the ground subsided of 22 cm, while subsidence has been of 65 cm since the end of the 1982–1984 uplift episode. Orsi et al. (1999-this issue) demonstrated that both geometry and amount of ground deformation are affected by structural lineaments of the CFc, namely the NYT caldera boundary and the faults bordering the resurgent block. Both uplift episodes were accompanied by seismicity, which is always absent during subsi-

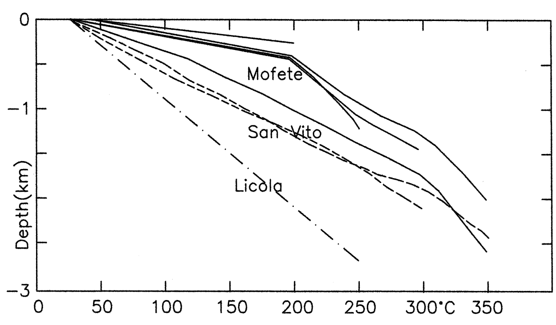

Fig. 2. Temperature profiles along deep boreholes in the Campi Flegrei caldera (modified after Wohletz et al., 1999-this issue).

dence. During the second uplift episode, seismicity was much more intense in both number of shocks and magnitude. The hypocenters of the shocks were clustered inside the La Starza block, which is the

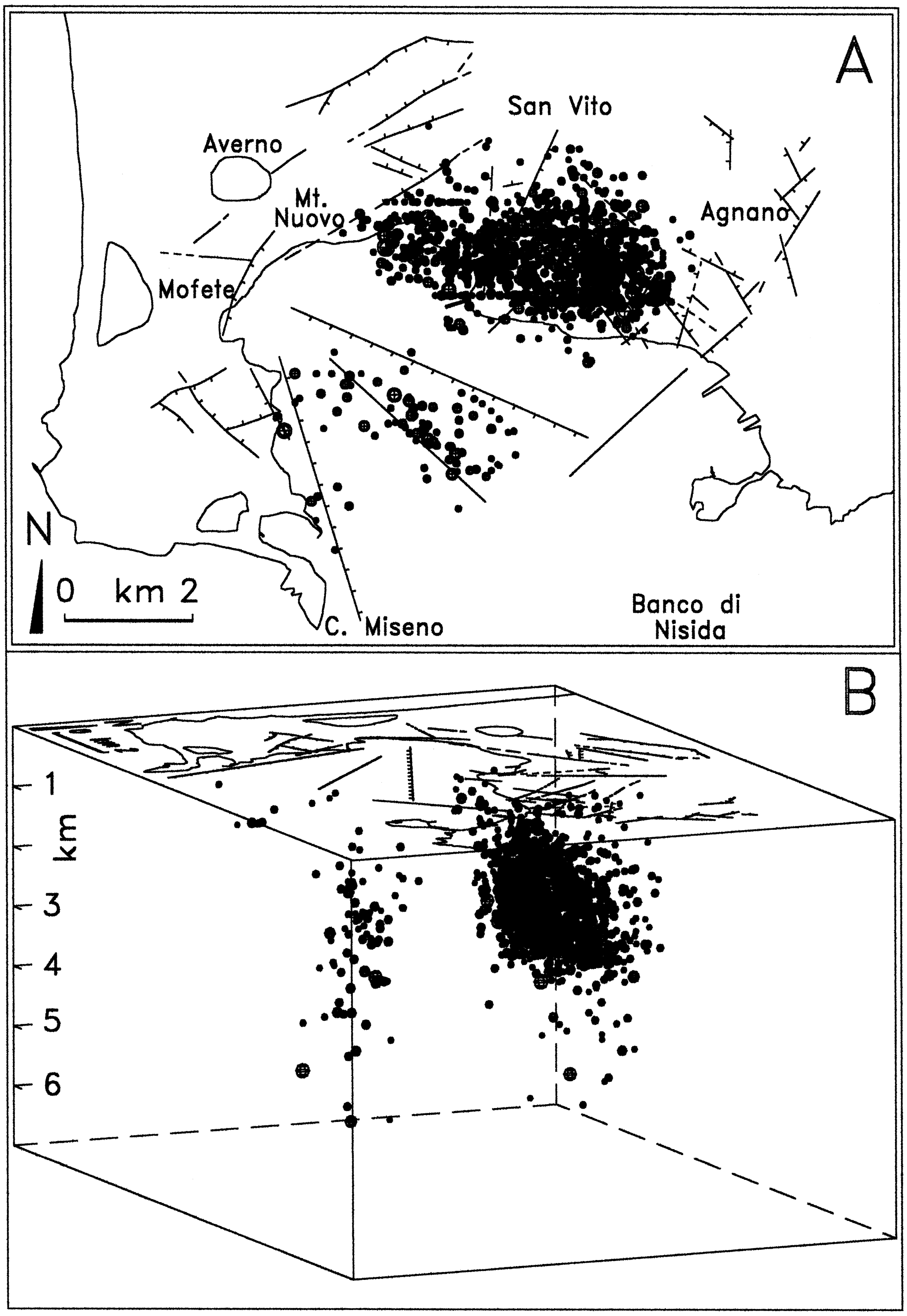

Fig. 3. Epicenters and hypocenters distribution of the seismic activity during the 1982–1984 unrest episode at the Campi Flegrei caldera (modified after Orsi et al., 1999-this issue).

most uplifted component of the resurgent block, and located along a vertical plane that strikes NW–SE within the Pozzuoli bay and has been interpreted as a reverse fault bordering to the southwest the most uplifted La Starza block (Orsi et al., 1999-this issue). The focal mechanisms of the earthquakes (magnitude > 1.2) on this feature, show reverse/strike slip solutions, while those of the shocks in the La Starza block, show a variety of solutions (Gaudiosi and Iannaccone, 1984; Orsi et al., 1999-this issue).

In order to evaluate the suitability of an energetic exploitation of the geothermal field of the CFc, three deep drillings were made by Agip (1987). The thermal profiles reconstructed along these boreholes are reported in Fig. 2. Apart from some difficulties in interpreting the shape of temperature profiles and the very high temperature found in SV1, the geothermal gradient is about at 100°C/km.

3. A critical review of the interpretative models for the 1982–1984 unrest episode

The main features of the unrest episode occurred in 1982–1984 are the large amplitude of the vertical ground deformation (179 cm), not followed by an eruption, and the limited extension of the deformed area (Orsi et al., 1999-this issue). Consequently, any interpretative model has to consider two main linked variables: depth of the magma chamber and overpressure required in order to simulate the detected maximum vertical uplift.

3.1. Mechanical models

The mechanical models proposed for the CFc unrest episodes have been based on the hypothesis that the source of uplift is either pressure or volume increase at depth. These models, although considering two different physical phenomena, are very similar from a mechanical point of view. In fact the volume variation of a magma chamber, according to Volterra's theorem might be simulated also by an equivalent force distribution on its border. In all the homogeneous models stress variation required to match the detected ground deformation is larger than the strength of the shallow rocks and therefore contrasts with the low energy of seismic activity and its absence during the early stages of the uplift. Berrino et al. (1984) analyzed both vertical deformation and gravity changes and suggested that the bradyseismic event was triggered by intrusion of magma in a chamber with a diameter of about 300 m and located at 3 km depth. Such a conclusion is in contrast with seismic data (Aster et al., 1990; Orsi et al., 1999-this issue) which show that hypocenters extend down to 4 km depth (Fig. 3), and therefore suggest that the magma chamber is located even deeper. Furthermore, Ferrucci et al. (1992) identified by means of P-SV conversion a body with a strong anomaly at about 4 km depth.

A first attempt to model the ground deformation taking into account the depth of the source constrained by seismic data and realistic overpressure of few hundreds of bars was made by Bianchi et al. (1984, 1987). The authors performed analysis considering both the contrast in mechanical properties between light caldera fill and surrounding rocks and the presence of a high-temperature zone around the magma chamber. However, to match the measured maximum vertical displacement, they had to impose a too small rigidity (1–4.8 GPa) of the shallow rocks.

The remarkable amount of non-reversible strain during both 1970–1972 and 1982–1984 unrest episodes, shows that a significant amount of the ground displacement was due to creep-like processes which could be responsible also for both large amplitude and limited extension of the deformation (Orsi et al., 1999-this issue). The numerical simulations which take into account the viscous behaviour of the crust (Bonafede et al., 1986; De Natale and Pingue, 1988; Petrazzuoli et al., 1993) demonstrated that creep-like processes induce an increase in ground deformation by a factor of 2 (Fig. 4).

The comparative analysis of both vertical ground displacement and seismic activity through time (Orsi et al., 1999-this issue) shows that: (a) seismic activity is present only during uplift, even for short duration events as in 1989 (Ricco et al., 1991), but is absent during subsidence, and (b) seismic energy released during the 1982–1984 unrest episode is a very limited fraction of both total elastic energy associated to the maximum vertical displacement and potential energy associated to the residual displacement.

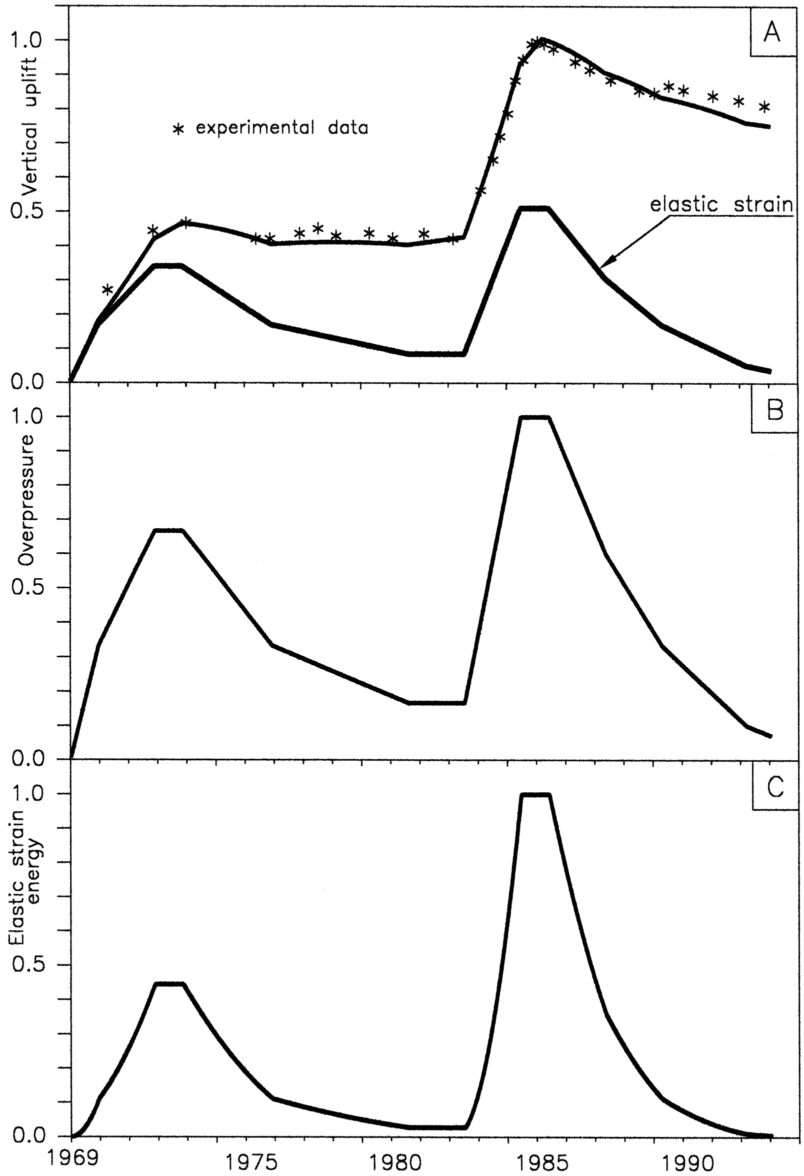

Fig. 4. Results of a viscoelastic modeling of the vertical ground deformation at the Campi Flegrei caldera between 1969 and 1994. (A) measured and theoretical net vertical displacement and its elastic component; (B) pressure variation at source; (C) elastic energy variation.

Civetta et al. (1995) and Orsi et al. (1999-this issue) showed by finite-element modeling that the faults of both NYT caldera and resurgent block have affected the pattern of the ground deformation in the CFc by inducing both a contraction of the size of the deformed area and an amplification of the vertical displacement. De Natale et al. (1997) showed that structural discontinuities induce a limitation of elastic stress accumulation and decrease of seismic energy release of one order of magnitude.

Mechanical models have been able to explain both ground deformation and seismicity in light of an overpressure of few hundreds of bars, compatible with the rock strength and the depth of hypocenters.

Nevertheless, they have not given satisfactory explanation to both the triggering mechanism of bradyseismic events and their time evolution and the absence of seismicity during subsidence.

3.2. Thermo-fluid dynamical models

To overcome the discussed limitations of the mechanical approach, thermo-fluid dynamical modeling can be performed. By using this kind of simulation, the depth of the source is not constrained by hypocenters distribution. Furthermore, the fluid component of the medium bears a fraction of the overpressure so the stress accumulation in the solid component is limited. Thermo-fluid dynamical modeling is very difficult mainly because it requires a thermomechanical analysis of a two-phase medium composed of a fluid and a solid skeleton. Such an analysis implies the evaluation of many physical parameters. In addition, both thermal and mechanical behaviours result from two components. Thermal results from both conductive and convective heat transfer, while mechanical behaviour results from both thermal expansion and stress deformation of the solid skeleton.

McTigue (1986) provided a mathematical formulation of the thermo-mechanical analysis including the fluid–solid mechanical interaction. Because of its complexity, application of this method has been limited to one-dimensional modeling. An application of McTigue (1986) formulation to the CFc was carried out by Bonafede (1990), providing a physical demonstration of the efficiency of convective fluid circulation operating for few years in generating a ground deformation with amplitude of the same order of the measured one. The estimated source depth ($d_s = 1$ km) and permeability coefficient ($k = 10^{-13}$ m^2) however appear to be unrealistic.

Martini (1986) and Martini et al. (1991) showed that a sharp change in gas composition without arrival of magmatic gases occurred before the beginning of the 1982–1984 ground uplift. Such a change suggests a sudden temperature increase (Fig. 5).

Wohletz et al. (1999-this issue) performed a 2D finite difference thermal analysis of the Phlegraean magmatic system over a period of about 100 ka, using an analytical formulation which assumes a non-deformable solid spatial grid. The authors developed 12 models which allowed them to draw some valuable estimations. The present state of the Phlegraean system is the result of processes operating in a long-lived magmatic reservoir, which must be a funnel shaped. A shallow convective zone, separated from the magma reservoir by a conductive layer, is required to match the sharp variation in the temperature gradient at about 1 km depth. The convective zone is confined to the caldera fill whose permeability is large enough for convection to occur. Simulations of hydrothermal convection extending to the top of the magma chamber gives unrealistic high temperature in the caldera subsurface. The estimated volume of magma presently stored in the CFc reservoir is very large (500 km^3). A large amount of magma is also suggested by petrological data (D’Antonio et al., 1999-this issue) but contrasts with the small dimension of the source required by mechanical models.

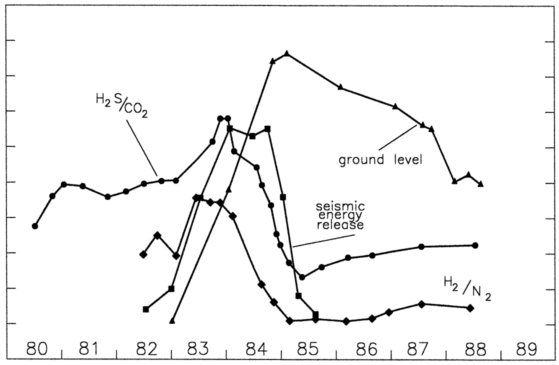

Fig. 5. Variation through time of chemical, seismic and ground deformation parameters (modified after Martini et al., 1991).

Concentration of heat near the center-upper part of the reservoir by magma convection likely resolves this contrast. Following this hypothesis, we assume that the magma reservoir is funnel shaped with a flat top which includes a more active central part (Fig. 6).

4. Triggering mechanisms and thermo-fluid dynamic regime in the CFc

The time evolution of the ground deformation might be dilated with regard to that of the triggering events by non-linear (viscous, plastic, etc.) behaviour of the crust and/or by fluid migration. Among the

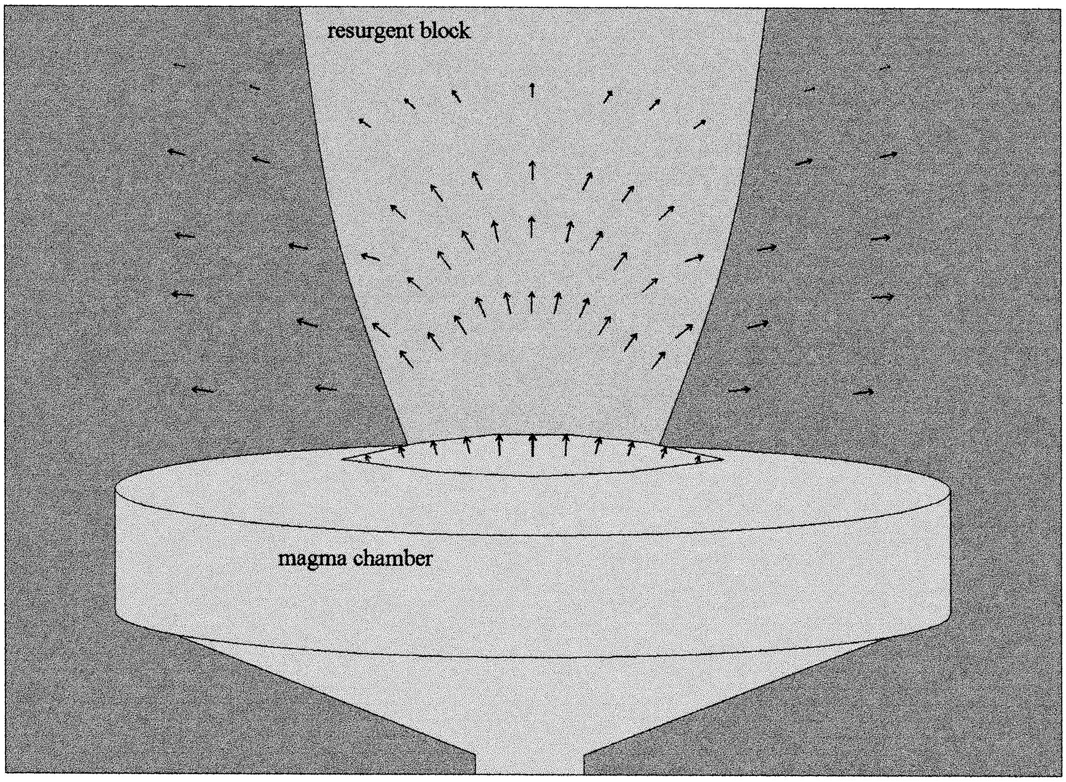

Fig. 6. Schematic representation of the Phlegraean magmatic system, structural setting of the roof rocks. Arrows indicate the flowage pattern of the shallow geothermal fluids in response to a temperature and/or pressure (volume) increase.

geological processes with a short-time evolution which could trigger the ground deformation, the most likely are: (a) remix inside a complex magmatic system, by rising of a hot magma batch that takes the place of cooler magma inducing a temperature change; (b) sudden intrusion of a less differentiated hotter magma batch into a more differentiated, shallow cooler magma reservoir, inducing both temperature and volume increase. Whichever it is, it is difficult to explain the short-time duration through a series of consecutive deterministic events. Therefore, there is likely a sort of accumulation of energy which is suddenly released.

Thermo-fluid modeling can resolve this questions. We can account for the large amount of potential energy accumulation and its sudden release, leading to the two ground uplift episodes occurring in less than 20 years.

The modeling of Wohletz et al. (1999-this issue) was related to the behaviour of the Phlegraean magmatic system over a long period of time. Although these authors did not investigate its behaviour over the period of unrest, they suggested active and convective fluid circulation at shallow depth. Such convection likely has played a critical role in the dynamics of the unrest phenomena.

Trubitsyn et al. (1993), using the same analytical formulation of Wohletz et al. (1999-this issue), found that the main parameters in both formation and stability of convective cells, is the Rayleigh number (R_f) which they defined as follows:

$$R_f = \frac{\alpha g \Delta TKD}{\underline{\lambda}/(\rho c_p)_f \nu}$$

where: α = thermal expansion coefficient, g = gravity acceleration, ΔT = temperature gradient, D = depth, $(\rho c_p)_f$ = heat capacity of fluid, $\underline{\lambda}$ = thermal conductivity of satured medium, K = permeability, ν = kinematic fluid viscosity.

The authors also defined three critical values for R_f (Fig. 7):

R_f* (~ 40) marks the transition between hydrostatic and convective state;

R_f** (~ 100) characterizes the appearance of boundary layers;

R_f*** (~ 1000) marks the transition to the non-steady state (supercritical).

For $R_f > 1000$, at the onset of convection, an initial transient characterized by a remarkable oscillation of the vertical velocity of the fluid, follows a steady state (Fig. 8). The transition time is a small fraction of the characteristic time evolution of the process.

In order to define the present state of the thermodynamical system in the CFc, we have calculated the value of R_f assuming: $\alpha = 3 \times 10^{-3}$ K^{-1}, $\Delta T = 400$ K, $g = 10$ m/s^2, $D = 4$ km, $\lambda = 2.5$ W/mK, $\nu = 10^{-7}$ m^2/s, and $(\rho c_p)_f = 4 \times 10^6$ J/m^3 K. The value of the permeability coefficient K for semipervious rocks is about 10^{-15} m^2 (Lachenbruch et al., 1976; Sorey, 1985; Sorey and Lecois, 1976; Bonafede, 1990), while in geothermal systems, characterized by the intense fracturing, larger values

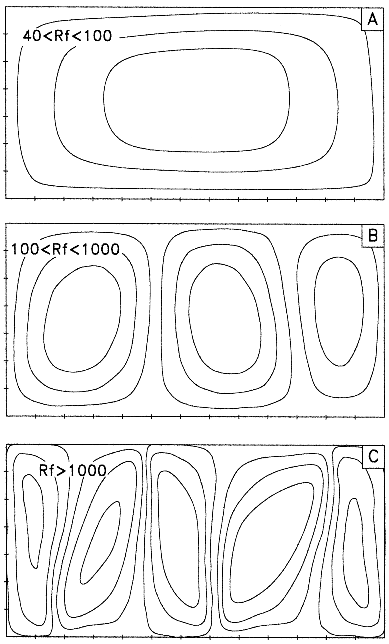

Fig. 7. Configuration of convective cells at increasing Rayleigh numbers (modified after Trubitsyn et al., 1993).

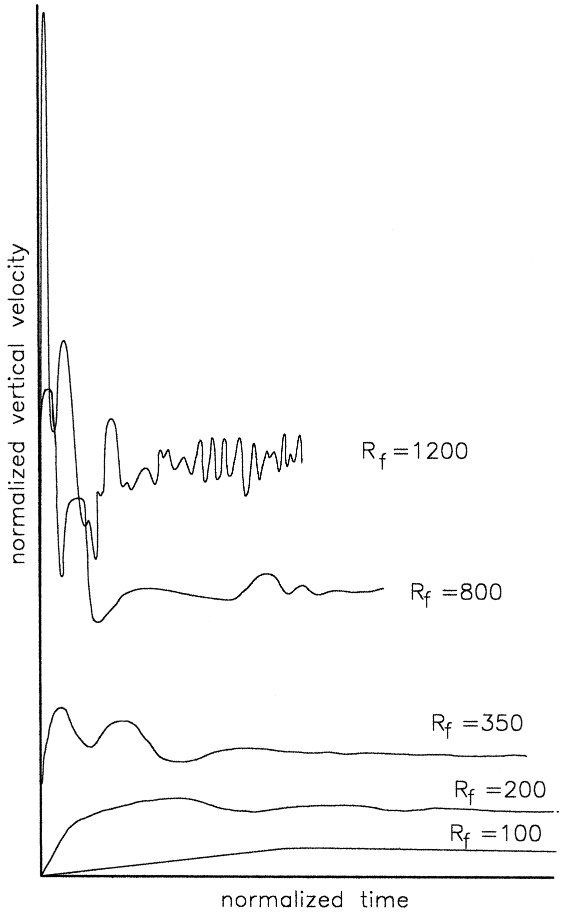

Fig. 8. Maximum values of the vertical fluid velocity as function of dimensionless time for various Rayleigh numbers (R_f) (modified after Trubitsyn et al., 1993).

(10^{-13}–10^{-14} m^2) have been estimated. Permeability is so much influenced by the presence of fractures that it can be considered almost independent from other characteristics of rocks. Although estimations of permeability are not available for the CFc, the presence of various fracture systems allows us to hypothesize a large permeability coefficient ($K = 10^{-14}$–10^{-13} m^2). Using the above presented values for the variables of the equation of Trubitsyn et al. (1993), we obtain $R_f = 7680$–76,800.

This calculated value of R_f implies that the hydrothermal system of the CFc is, at present, in supercritical conditions. On the basis of this conclusion, three possible hypotheses on the triggering mechanism of the bradyseismic events, that is on the changes in convection regime induced by temperature increment, can be put forward (Fig. 9). The uplift episodes could be: (a) distinct events, each linked to sudden temperature increase (Fig. 9B); (b) the initial transient of a convective diffusion characterized by a double oscillation and generated by a single sudden temperature increase (Fig. 9C); and (c) two changes in a convective regime generated by a progressive temperature increase due to an upward migration of a thermal front (Fig. 9D) (i.e., onset of convection → appearance of boundary layer → non-steady-state). Numerical simulations (Cheng, 1978; Cheng and Teckchandani, 1977) show that these processes occur over a period of time in the order of 10^4 years even in geothermal fields with a perme-

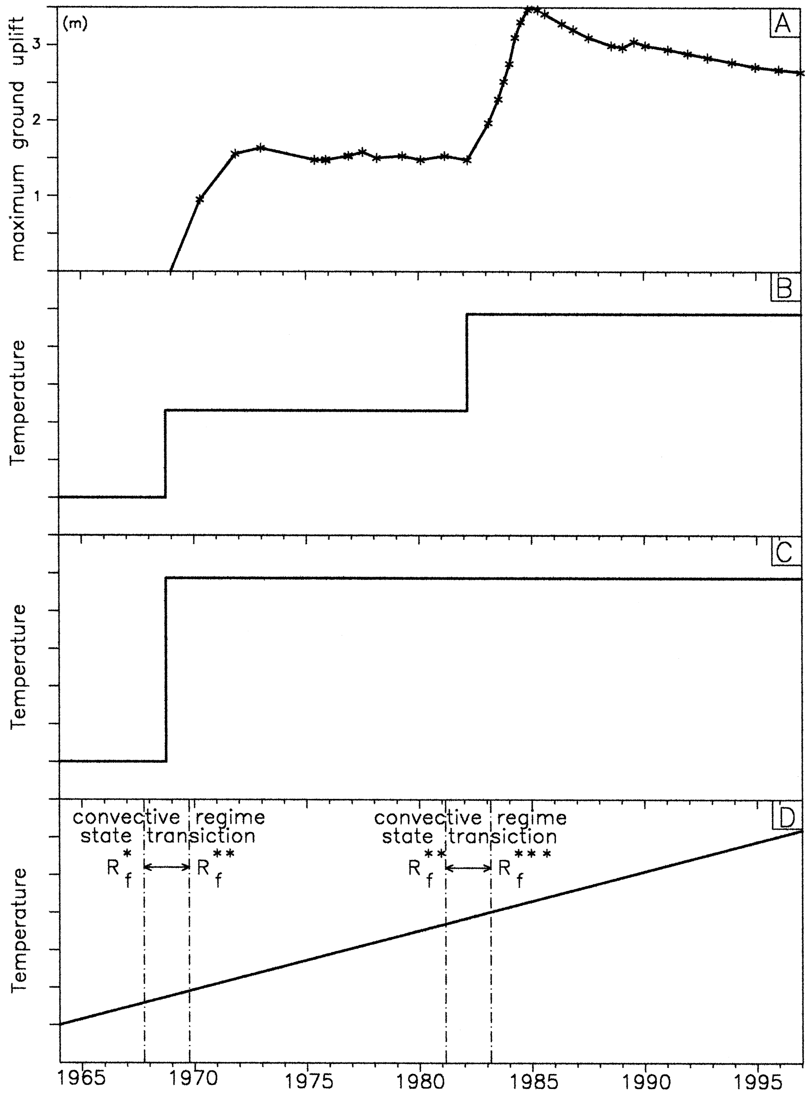

Fig. 9. Unrest episodes as result of variations in convective regime of the shallow geothermal system for three variable temperature increments. (A) net vertical ground displacement in the Campi Flegrei caldera; (B) two distinct temperature increases, each triggering one uplift event; (C) a single temperature increase inducing a transient characterized by two main oscillations; (D) progressive temperature increase inducing two state transitions. R_f is the Rayleigh number.

ability coefficient $K = 10^{-13}$ m^2. Therefore, for any of these processes to be operative in CFc where the length of unrest episodes is in the order of few years, should imply a sudden temperature increase and a very large permeability ($K < 10^{-12}$ m^2). The sudden temperature increase can be achieved by an unrealistic intrusion of hot magma into the shallow convective zone, which also contrast the thermal model of Wohletz et al. (1999-this issue).

Thermal models also imply a mechanical action on the solid skeleton which generates stress accumulation and related seismic activity. In the model proposed by Bonafede (1990) the fluid expansion and the buoyancy forces provide the mechanical action for ground uplift. Therefore even thermal modeling does not provide any explanation for lack of seismic activity during subsidence.

Orsi et al. (1996) on the basis of geological, geochemical and geophysical data, suggested that the short-time deformation episodes result from the interplay of a brittle and a ductile component. The triggering mechanism of the ground uplift is an increase in temperature and pressure in the magmatic system resulting from arrival of hotter and less differentiated magma. Pressure increase results in a vertical stress which in turn generates fracturing and faulting of the roof rocks with related seismicity. Faulting is the brittle and permanent component of the ground uplift. Due to the brittle deformation of the rocks, heat and volatile transfer is increased and generates an increase in temperature and pressure of the shallow geothermal system which results in the ductile component of the ground uplift. Ground subsidence is due to decompression and deflation of the shallow geothermal system when new heat is no longer supplied from depth. Its deformation is only ductile and does not generate seismicity. Following the hypotheses of Orsi et al. (1996), we hypothesize that the uplift events might be generated by a thermal expansion which produces mechanical effects and related seismicity, while subsidence could be related to slow migration of fluids from the most uplifted part of the resurgent block to the remaining part of the NYT caldera (Fig. 6). Hence, the subsi-

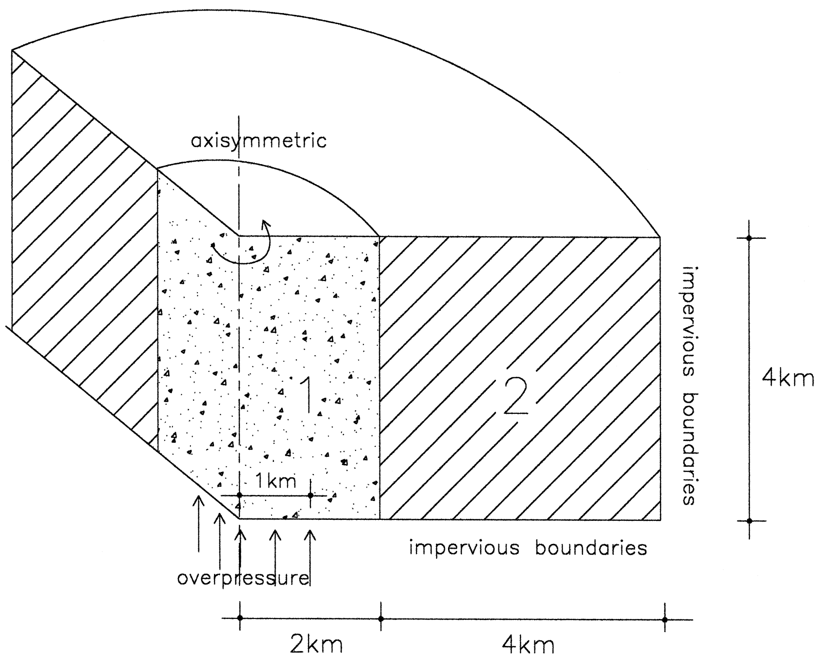

Fig. 10. Model used to analyze the solid–fluid interaction in the Campi Flegrei caldera. (1) Highly permeable resurgent block; (2) less permeable caldera floor.

dence should not be related to significant stress variation, thereby providing a physical explanation for the absence of seismic activity during subsidence.

5. The mechanical model of solid–fluid interaction and its application to the CFc

The followings data on the CFc have been taken as boundary conditions for our modeling.

(a) The NYT caldera, with a mean radius of 6 km, includes a central (resurgent block) and a peripheral part (Orsi et al., 1996). The central part has a lower density and higher permeability (Agip, 1987).

(b) The magma reservoir contains a large amount of trachytic magma and is funnel-shaped with a flat top that includes a more active central part (Wohletz et al., 1999-this issue). The reservoir has been periodically refilled by less-evolved magma batches (Orsi et al., 1995; D'Antonio et al., 1999-this issue; Pappalardo et al., 1999-this issue).

(c) A convective hydrothermal system is operating in the caldera fill and does not interact with the magmatic system (Wohletz et al., 1999-this issue).

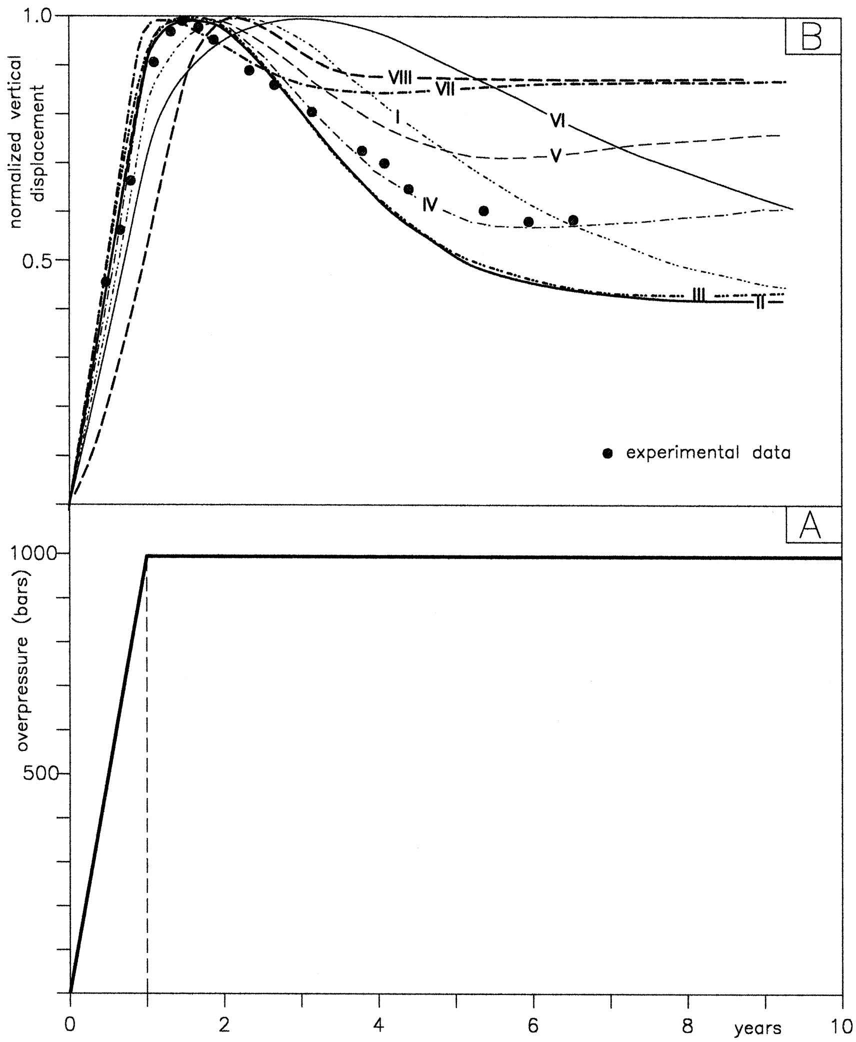

Fig. 11. (B) normalized vertical displacement through time of the central point of the reference model, the physical parameters used to obtain the curves I through VIII are reported in Table 1; (A) imposed pressure at source through time.

If a shallow convective zone is separated from the magmatic system, the main process which constrains the time evolution of the bradyseismic events might be the mechanical response of a two-phase medium to pressure or volume increase. We have performed a mechanical modeling by means of finite-element method, in order to simulate such a fluid–solid interaction. Analytical details are reported in Appendix A. The analysis has been carried out with reference to an axisymmetric rectangular scheme (Fig. 10). The central zone, 2 km in radius, represents the resurgent block inside the NYT caldera. This central zone is characterized by larger permeability and a lower rigidity than that of the surrounding rocks. Variation of these parameters allows to simulate a convective fluid circulation in the central part of the NYT. Such a circulation is favored by the presence of fractures which also increase both permeability and mechanical weakness. This scheme is coherent with the flat top of the magma chamber suggested by Wohletz et al. (1999-this issue) (Fig. 6). The time function of the assumed pressure and volume increase is stepwise (Fig. 11A). It raises to its maximum values in only 1 year and remains constant without any regression. We made a parametric study performing over 100 models in order to match the detected vertical ground displacement versus time function. Elastic modulus (Young modulus) and permeability of central and peripheral part of the NYT caldera are the variables used in our analysis.

Table 1

Model	Young modulus		Permeability	
	E_1 (Pa)	E_2 (Pa)	K_1 (m^2)	K_2 (m^2)
I	2×10^8	10×10^9	1.4×10^{-12}	3×10^{-13}
II	2×10^8	10×10^9	4×10^{-12}	3×10^{-13}
III	2×10^8	10×10^9	1×10^{-11}	3×10^{-13}
IV	5×10^8	10×10^9	1×10^{-11}	3×10^{-13}
V	1×10^9	10×10^9	1×10^{-11}	3×10^{-13}
VI	5×10^8	10×10^9	1.4×10^{-12}	3×10^{-13}
VII	1×10^9	10×10^9	2×10^{-10}	1.5×10^{-12}
VIII	5×10^8	10×10^9	2×10^{-10}	3×10^{-13}

Fluid viscosity: $\mu=2\times10^{-5}$ Pa s.
Fluid modulus: $E=2\times10^{9}$ Pa.
Porosity: $\phi=20\%$.

6. Discussion

The parameters used for the models which have given the best results are reported in Table 1, while the are presented in the Fig. 11B. The triggering event for models I through VII is a sudden pressure increase of 1000 bars at 4 km depth, while for model VIII is a volume increase.

For large permeability of the central zone (case VII in Table 1, and Fig. 11A) the fluid circulation does not affect the ground deformation. The ground vertical displacement through time coincides with the source pressure–time function. For low permeability (case VI in Table 1, and Fig. 11A), the migration of fluids is bounded and the response of the mechanical system is too slow. The best matching of experimental data is provided by model IV. The values of Young modulus ($E_1 = 5\times10^8$ Pa; $E_2 = 10\times10^9$ Pa) and permeability ($K_1 = 1\times10^{-11}$ m^2; $K_2 = 3\times10^{-13}$ m^2) of the central and peripheral part of the caldera are significantly different. Such a difference likely results from intense fracturing of the central zone (Di Vito et al., 1999-this issue; Orsi et al., 1999-this issue). The permeability values coincide with those calculated by Corrado et al. (1998) and are in good agreement with the values of Nusselt number (up to 100) assumed by Wohletz et al. (1999-this issue) for the caldera fill.

A volume increase as a triggering mechanism seems unsuitable to simulate the time evolution of the ground deformation. The best result of modeling using a volume increase (case VIII in Table 1 and Fig. 11B) provides a poorer fit of the detected data and requires unrealistically large permeability.

Pore pressure variation through time is shown in Fig. 12. After 1 year when pressure has reached its maximum values, the pore pressure affects only the resurgent block in the center of the caldera. It acquires its maximum value around 100 bars near the pressure source (Fig. 12A). After 3 years, pore pressure sharply decreases within the central zone and increases in the peripheral zone (Fig. 12B) accordingly to the lateral migration of fluid. Shear stress variation only occurs during the pressure increase (0–1 year) as later changes in pore pressure do not induce any variation of the deviatoric stress field.

Another important result of our analysis is that the time function of the recovery is sensibly different

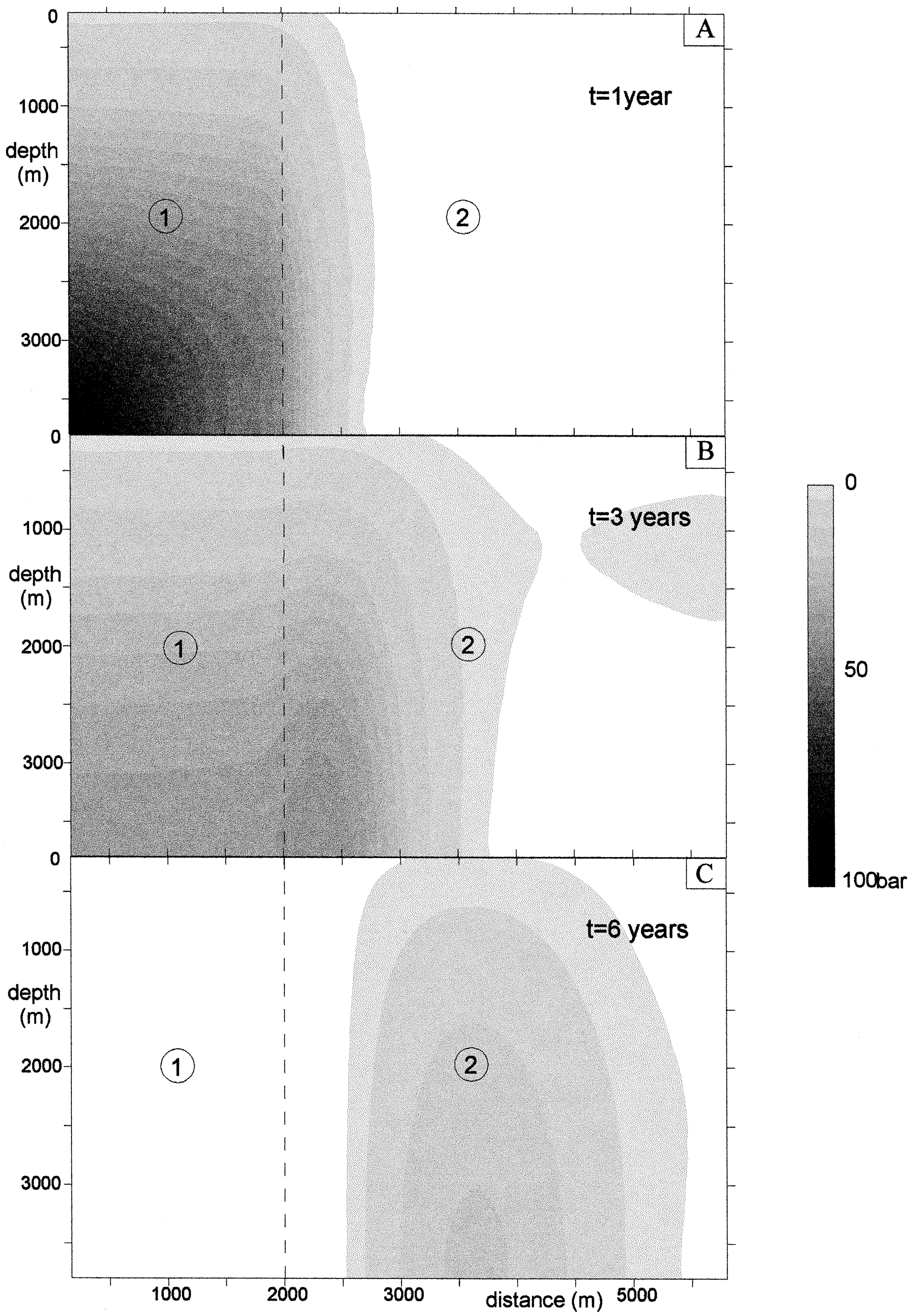

Fig. 12. Pore pressure variation through time.

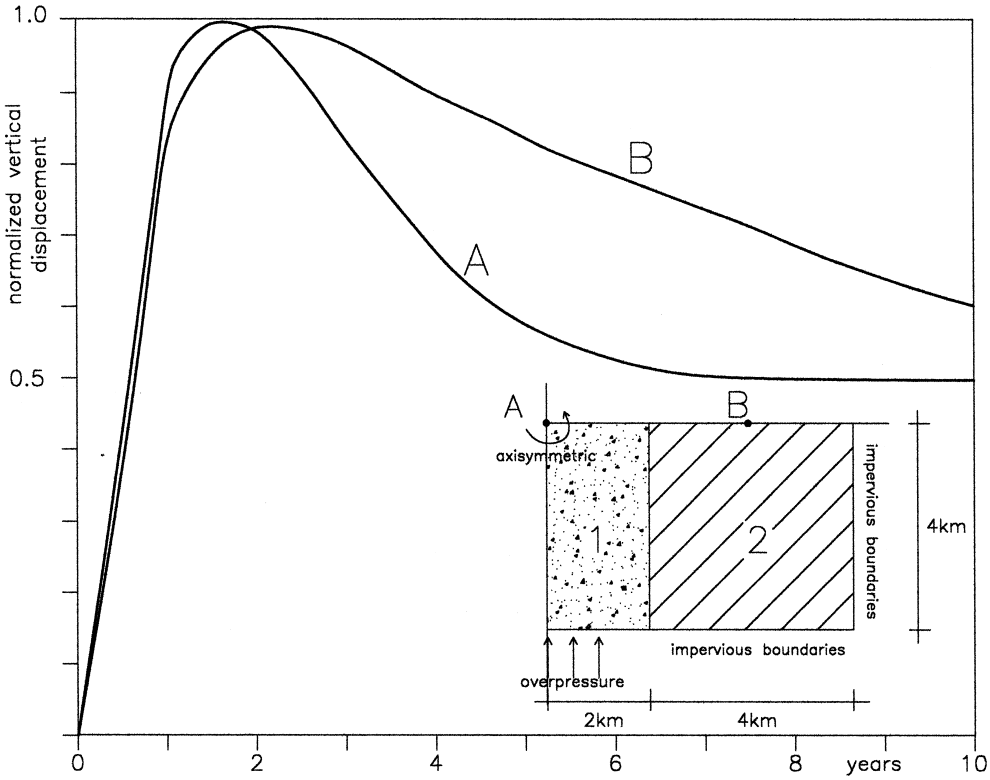

Fig. 13. Normalized vertical displacement of point A located on the resurgent block, and point B on the caldera floor. The used physical parameters are those of case IV, reported in Table 1.

inside and outside the resurgent block, as illustrated in Fig. 13.

7. Conclusions

The analysis performed by means of a mechanical model which takes into account the interaction between fluid and solid phase has allowed us to explain some characteristics of the time evolution of both seismicity and ground deformation occurred during the 1969–1972 and 1982–1984 unrest episodes in the CFc.

Our analysis shows that uplift events cannot result from variation in the convective regime generated by temperature increase, since convection operates on a time scale ($\sim 10^4$ years) incompatible with the time evolution of the monitored ground deformation ($\sim 10^1$ years). To match the detected data, a permeability coefficient lower than those resulting from our modeling (10^{-11}–10^{-12} m^2) had to be assigned to the entire NYT caldera.

We suggest that the ongoing subsidence is related to lateral diffusion of fluids. The variable permeability between the resurgent block in the central part of the NYT caldera and peripheral part induces a variation in the lateral diffusion of fluids. This variation produces a slower subsidence in resurgent block than in the peripheral part of the caldera. This conclusion well matches the ground deformation data collected during subsidence (Orsi et al., 1999-this issue). Our analysis also provides a physical explanation to the absence of seismicity during subsidence as the variation of the pore pressure, induced by lateral diffusion of fluids, does not generate variation of the shear stress. Furthermore, the fluid component soften the stress application on the solid phase which in turn induces a decrease of the solid strain-rate ($d\varepsilon/dt$) reducing the amplitude of the seismic stress-release.

Scattering of hypocenters inside the La Starza block (Orsi et al., 1999-this issue) likely is related to stress diffusion induced by fluid migration. Also the small gravity changes detected during 1982–1984 unrest episode (Berrino and Gasparini, 1995; Berrino et al., 1984; Bonafede and Mazzanti, 1998) could be due to upward migration of fluids.

Another important result of our analysis is that subsidence must be not related to pressure decrease at the source. Therefore, the system likely has not returned to the conditions in which it was before the 1982–1984 or even the 1969–1972 unrest. This conclusion contrasts with the results of previous mechanical models.

Linkage of this model to thermal-history of the caldera could contribute to investigate the source of uplift. The results of petrological (D'Antonio et al., 1999-this issue; Pappalardo et al., 1999-this issue) and thermal (Wohletz et al., 1999-this issue) investigations show that the Phlegraean magmatic system has been periodically refilled with new magma. Therefore the pressure increase might be a consequence of a deep intrusion of less evolved, hotter magma batch in a more evolved and cooler magma inside a complex magmatic reservoir inducing a pressure and a temperature increases.

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Appendix A. Mathematical formulation of fluid–solid interaction

The analysis of solid–fluid interaction has been carried out by finite-element method.

Constitutive equations for solid and fluid phases are the following.

Solid:

$$\{\sigma\} = \begin{bmatrix} K+\frac{4}{3}G & K-\frac{2}{3}G & K-\frac{2}{3}G & 0 & 0 & 0 \\ K-\frac{2}{3}G & K+\frac{4}{3}G & K-\frac{2}{3}G & 0 & 0 & 0 \\ K-\frac{2}{3}G & K-\frac{2}{3}G & K+\frac{4}{3}G & 0 & 0 & 0 \\ 0 & 0 & 0 & 2G & 0 & 0 \\ 0 & 0 & 0 & 0 & 2G & 0 \\ 0 & 0 & 0 & 0 & 0 & 2G \end{bmatrix} \times \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} = [C]\{\varepsilon\}$$

Fluid:

$$\{p\} = \begin{bmatrix} \frac{K_f}{3} & \frac{K_f}{3} & \frac{K_f}{3} & 0 & 0 & 0 \\ \frac{K_f}{3} & \frac{K_f}{3} & \frac{K_f}{3} & 0 & 0 & 0 \\ \frac{K_f}{3} & \frac{K_f}{3} & \frac{K_f}{3} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} (\phi) = [C_f]\{\varepsilon\}\phi$$

For two-phase medium:

$$\{\sigma\} = ([C] + [C_f]\phi)\{\varepsilon\} \tag{1}$$

where: ϕ = porosity, K = bulk modulus = $E/[3(1-\upsilon)]$, G = shear modulus = $E/[2(1+\upsilon)]$, E = Young modulus, υ = Poisson coefficient.

The fluid diffusion equations are the following.

Mass balance:

$$\nabla(\rho_f \boldsymbol{u}) = 0 \tag{2}$$

Darcy's law:

$$\boldsymbol{u} = \frac{k\rho}{\mu}(\nabla \boldsymbol{p} - \rho_f g \boldsymbol{z}) \tag{3}$$

where: k = permeability, ρ = rock density, ρ_f = fluid density, $\boldsymbol{u}$ = convective velocity, $\boldsymbol{p}$ = pore pressure, g = gravity acceleration; μ = kinematic viscosity.

Because of the linearity of Eq. (1), using finite-element method we can separately evaluate the stiffness matrix for solid $[k_s]$ and liquid phase $[k_f]$.

An iterative method is required, in fact the external load induces a pore pressure field which does not match the generalized Darcy's law (Eq. (3)) inducing a change in fluid motion which, by effect of the principle of mass balance (Eq. (2)), influences the pore pressure itself.

If the increment of external load is too large the iterative process cannot achieve the convergence. In our analysis the total process have been subdivided in 100 steps. Finite-element method solves the equation stepwise with a direct time integration.

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