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The mechanics of Campi Flegrei unrests as related to plastic behaviour of the caldera borders

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Abstract

We present here a model which explains the mechanism of generation of unrest episodes at Campi Flegrei caldera from a mechanical point of view. The mechanism involves the effects of plastic zones at the borders of the inner collapsed area on both static deformations and seismicity. The large amount of ground uplift observed necessarily calls for plastic effects. These effects are interpreted as concentrated at the caldera borders: the generation of such plastic zones is simulated in terms of the mechanisms leading to the caldera collapse. In order to simulate the influence of such plastic zones on both ground deformations and seismicity we model them as surfaces of discontinuities free from shear stress within an elastic homogeneous half-space. The presence of such discontinuities allows the inner caldera block to move differentially from the outer areas, by slip along the plastic bordering zones. Such a differential uplift of the central block causes the concentration of the ground deformation. Our model explains a lot of puzzling observations at Campi Flegrei in terms of the effects of the caldera structure. The model is applicable to other caldera areas, which show typical evidence for the effects of such discontinuity zones, during unrest episodes.

Key words *Campi Flegrei – unrest mechanism – caldera structure – discontinuities– plastic effects*

1. Introduction

Unrest episodes at active calderas have been observed several times in recent years. Such episodes involve intense ground deformations, from some centimetres up to some metres in a few years, and a strong increase in seismicity.

Recent observations of ground deformation in calderas include Yellowstone and Long Valley (U.S.A.), Rabaul (Papua New Guinea), Campi Flegrei (Italy). In these areas unrest phenomena are episodically observed, involving increased seismicity and considerable ground deformation. The maximum rates of vertical displacement observed range from about 0.02 m/yr at Yellowstone during 1976-1977 and 1983-1984, to 0.5 m/month at Campi Flegrei during the last unrest of 1982-1984. The maximum amounts of vertical deformation observed to date range from about 0.7 m in the period 1923-1976 at Yellowstone (Pelton and Smith, 1982) to about 3.3 m in the period 1969-1984 at Campi Flegrei (Corrado *et al.*, 1976; Berrino *et al.*, 1984). None of these recent unrest episodes resulted directly in an eruption, although both deformation and seismic activity reached very intense peaks. Geochemical changes in fumaroles were also observed at Campi Flegrei (Martini, 1986; Tedesco *et al.*, 1988; Allard *et al.*,

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1991). The most characteristic elements of these unrest episodes, however, are the large surface deformations and seismicity.

At Campi Flegrei, in April 1984, when the rate of uplift was at the maximum level (0.02 m per day), seismicity reached peaks of 500 earthquakes ($0 < M_L < 3.0$) per 6 h (Aster *et al.*, 1992). At Rabaul (Papua, New Guinea), seismicity was also much more intense, both in number and in magnitude (Mori and McKee, 1987).

Unrest episodes at calderas show some peculiar features, different from what is generally observed in other volcanic areas. The most striking one is the occurrence of such large static deformation and seismicity without eruptions. Furthermore, at Campi Flegrei and Rabaul calderas, ground deformation appeared very concentrated in a small area, about 3 km in radius. The large amount of ground deformation observed at Campi Flegrei (1.8 m in two years) is likely to imply some kind of plastic rehology of the shallow crust. Plastic effects should be concentrated at the borders of the inner collapsed area, as a result of intense fracturing produced during the collapse. The feature of large static deformations, concentrated in a small area, has recently been modelled by De Natale and Pingue (1993) and De Natale *et al.* (1997) as due to the effect of the ring discontinuities bordering the caldera collapsed areas. Such discontinuities are a mathematical idealisation of the fractured zone produced during the collapse, representing weakness zones which cannot hold shear stress. Both at Campi Flegrei and Rabaul calderas, seismicity appears concentrated close to such zones, proving to be related to shear fractures close to these weakness zones (Mori and McKee, 1987; De Natale *et al.*, 1995). At Campi Flegrei, however, focal mechanisms of the local seismicity during unrest episodes evidence a relative movement of the shallow crust which is opposite to what expected from ground deformations (De Natale *et al.*, 1995).

Figure 1 shows a global picture of seismicity and structural features at the Campi Flegrei area, as resulting from the various studies performed in the mentioned papers. Earthquake locations have been computed for 200 events which occurred in the period 1982-1984, using the three-dimensional velocity model by Aster and Meyer (1988). As is clear, earthquake locations are consistent with a ring fault system. Composite focal mechanisms, obtained by De Natale *et al.* (1995) for groups of earthquakes located in different zones along the ring structure, are consistent with an inward dipping fault system.

This paper presents a coherent model for the unrest episodes recently observed at Campi Flegrei. It is based on the evidence for large plastic effects, both on surface deformations and on the earthquake generation process. Such plastic behaviour appears concentrated close to the borders of an inner collapsed area, and is a direct consequence of the processes which formed the caldera collapse. In fact, ground deformation phenomena leading to caldera formation involve large plastic deformation of shallow crustal layers generating ring fractures thus defining the boundary of the caldera itself.

The first mechanical studies on the caldera fractures was carried out by Anderson (1936) showing that their formation should be in some way relate to stress increase due to overpressure. Afterwards Phillips (1974) gave a clear explanation of the genesis of cone-sheets in terms of shear fractures during crustal doming. That was also confirmed by two well known volcanologic works: Smith and Bailey (1968) and Komuro *et al.* (1984) that, referring to Valles Calderas (Smith and Bailey, 1968) and Motojoku volcano (Komuro *et al.*, 1984), found some discontinuities in the distribution of volcanic products inside and outside the caldera, suggesting that border faults developed before the collapse (subsidence).

In the case of a renewal of volcanic activity the accumulation of shear stress in the plastic zone is strongly limited. Residual resistance, *i.e.* the strength of material that had experienced plastic strain, is lower than peak resistance in some cases even by one order of magnitude (Kirby and McCormik, 1984). Hence we can observe large shear strain related to low increment of shear stress (small G modulus) and moderate and/or negligible seismic activity. That has a double implication: eruption can occur without appreciable seismic forerunners, small overpressure inside the magma chamber may generate large superficial displacements with an apparent linear behaviour.

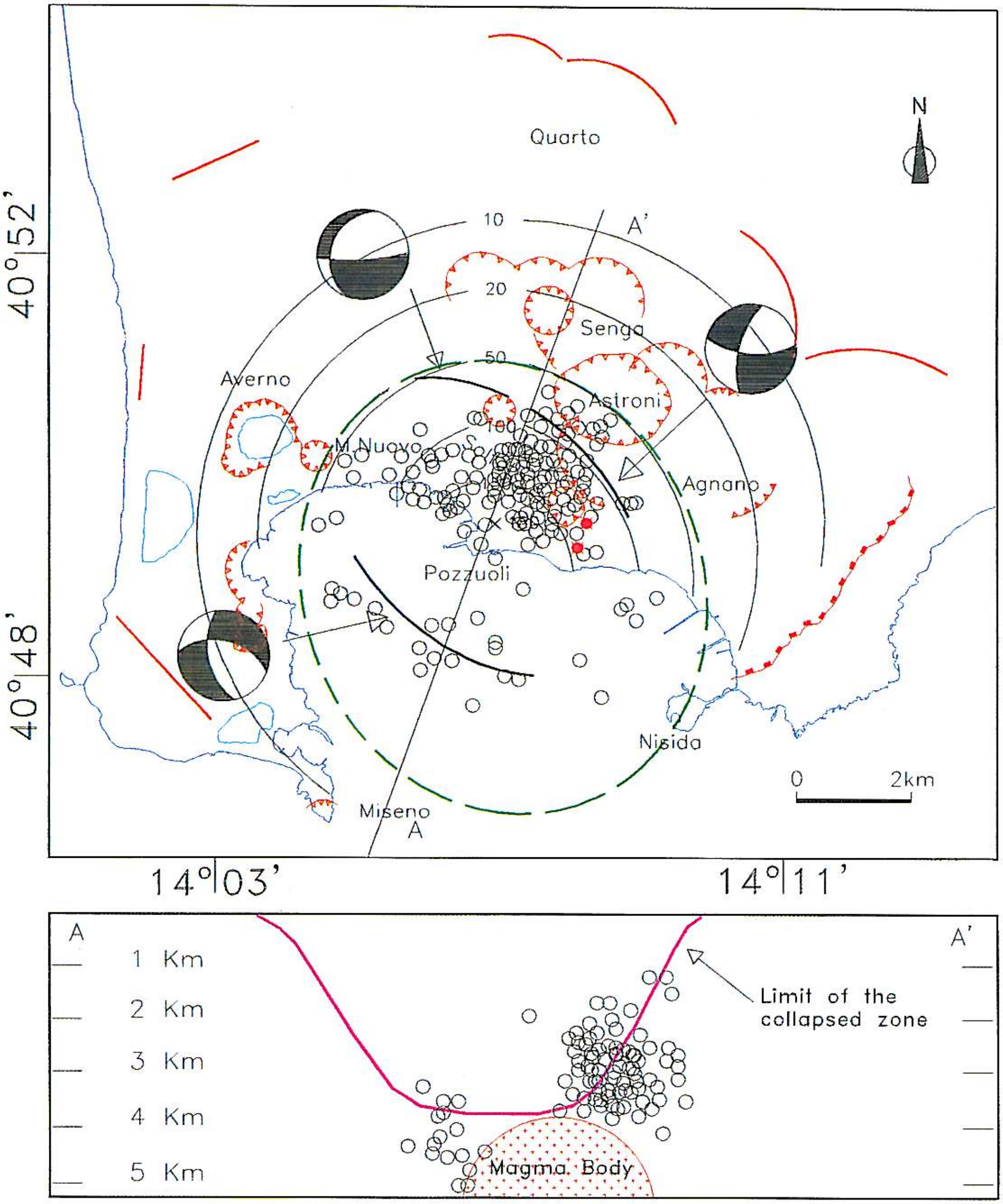


Fig. 1. Summary map of various geophysical observations at Campi Flegrei. The approximate zero contour line of the Bouguer anomaly is shown (dotted line), together with contours of vertical elevation and earthquake hypocentres; the projection of the collapsed zone as modelled from gravity anomalies is superimposed on the depth section of hypocentres. Also shown is the location of the magma chamber as inferred by Ferrucci *et al.* (1992).

In this work we illustrate that the stress-strain fields in a jointed crust may be very different from the ones predicted by a homogeneous model accounting for some anomalies in the pattern of ground deformation and in the amplitude and distribution of seismic activity. In particular, it is shown that most of the peculiar observations collected during recent unrest episodes can be explained in terms of the strong effects of the inner collapse weakness zones on both ground deformations and seismicity. A coherent mechanical model explaining geophysical observations at Campi Flegrei is then presented.

Many features of this model can be generalised to other calderas, some of them here analysed too.

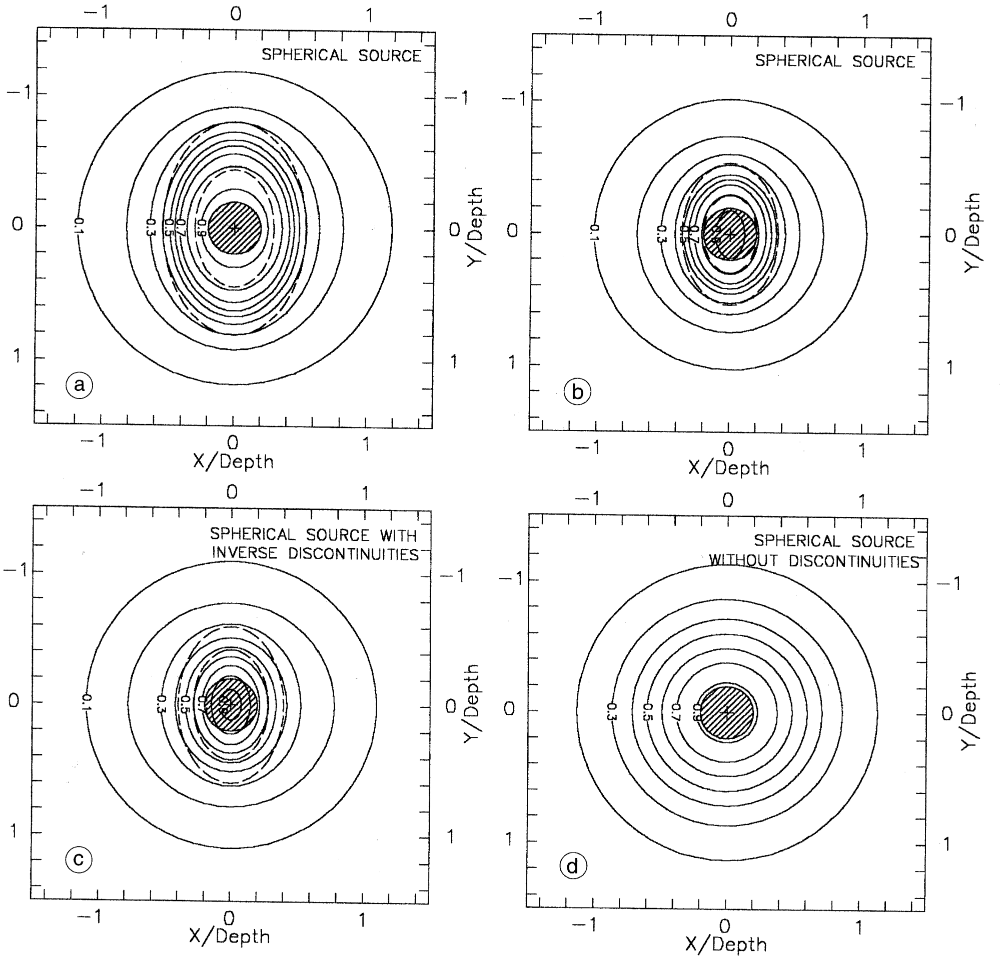


Fig. 2a-d. Contour lines of theoretical vertical displacements computed by a 3D finite element technique. Dashed lines indicate the position of stress-strain discontinuities simulating the limits of an elliptical caldera collapse. Figure (a) and (b) are for inward dipping discontinuities simulating cone sheet structures; c) is for outward dipping discontinuities, simulating ring dikes; d) is for non discontinuity. The shaded circle represents the location of the spherical source of overpressure, and simulates a spherical magma chamber. Note the very good correlation of uplift contours with the elliptical shape of the discontinuities.

2. Modelling of the effects of ring fractures system on ground deformations

To simulate the influence of a generic caldera structure on the deformation field, we used a three-dimensional finite element scheme, involving an overpressured spherical magma chamber at depth and an elliptical fracture system defining the caldera boundaries, considered free from shear stress. The location of the ring fracture system is simulated from a shallow depth (0.5 km) down to a depth of 3.5 km, just above the top of the magma chamber. The shallowest limit means that fractures do not reach the surface, due to the covering of pyroclastic deposits from eruptions subsequent to caldera formation.

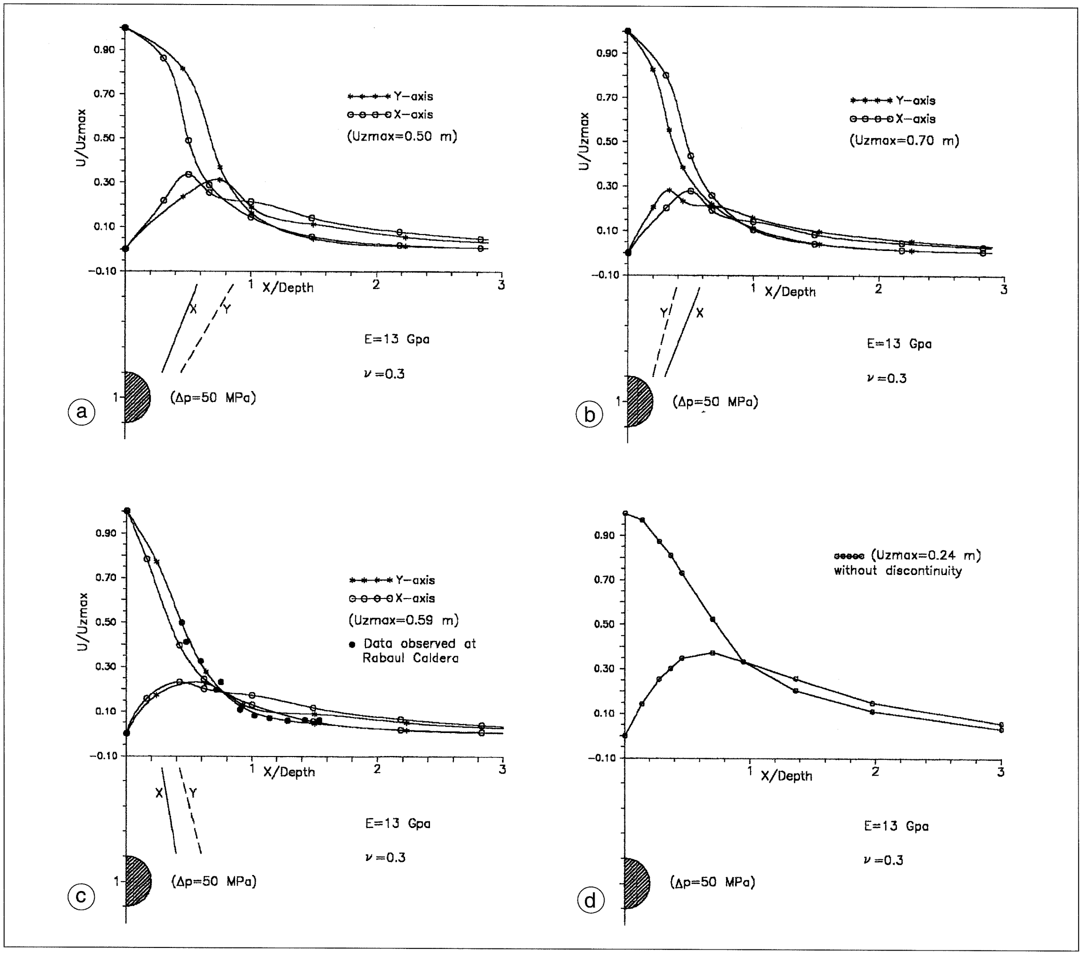


Fig. 3a-d. Profiles of vertical and horizontal theoretical displacements at surface normalised to the maximum value. For case (a), (b) and (d) see caption of fig. 2a-d. The location of the discontinuities, projected along the *x* and *y* sections, is reported as *x* and *y*. In (c), which is for outward dipping fractures, the geometry of the discontinuities and the source depth has been taken to simulate the case of Rabaul caldera. Vertical displacement data observed at Rabaul are shown superimposed.

The deepest limits take into account the high temperature zone close to the magma chamber, which homogenises the rock rheology and closes the fractures. Results obtained assuming a spherical magma chamber with an elliptical cone sheet (inward dipping) and ring dike (outward dipping) caldera structures are shown in figs. 2a-d and 3a-d. The plain views (fig. 2a-d) emphasise a rapid decay of vertical uplift occurring across the caldera fracture system. Even for a spherical pressure source, for example, the resulting pattern of ground deformation is elliptical, closely matching the shape of the caldera.

For ring-dike caldera structures the decay of the displacement field at short distance is sharper (figs. 2c and 3c) than the one obtained using a homogeneous medium (figs. 2a and 3a) and even than the ones relative to cone-sheet structures (figs. 2b, 2d, 3b and 3d). These results agree very well with the displacement pattern observed at Rabaul caldera (fig. 3c). The size of the caldera used for these simulations was in fact chosen to match the case of the innermost collapsed area at Rabaul. Figure 4 shows the effect of the ring discontinuities on the deformations produced by spherical sources located at different depths. These simulations are for axisymmetric discontinuities. As is clear, the shape of the deformations for different source depths is very similar, in contrast with what happens in a medium without discontinuities. This is an important result, because it implies that the presence of discontinuities prevents estimating the source depth from the deformation shape. It means that shallow intrusive episodes could not be detected by a change in deformation pattern and can explain the marked constancy of ground deformation patterns over a wide range of deformation amplitudes and times. In the case of Campi Flegrei, such constancy is very evident, by normalising vertical deformation curves, in a range of maximum deformations going from about 0.01 to 1.8 m (fig. 5a).

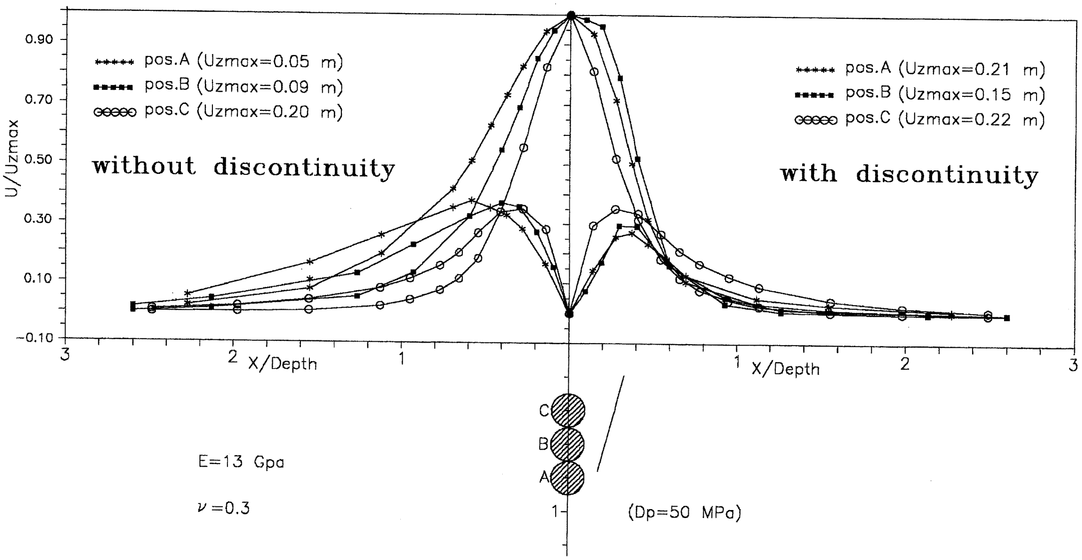


Fig. 4. Normalised theoretical vertical and horizontal displacements at the surface computed by 3D finite element, axisymmetric models for various depths of the pressure source. Curves at left are for a homogeneous medium, without discontinuities; curves at right are for the same case, but in the presence of the discontinuities represented as a straight line. Note that, without discontinuities, the curves are very different, involving areas of size comparable to the source depth. On the contrary, with the ring discontinuity, curves are very similar to each other (mainly the vertical ones), involving an area whose size is determined by the position of the ring discontinuity.

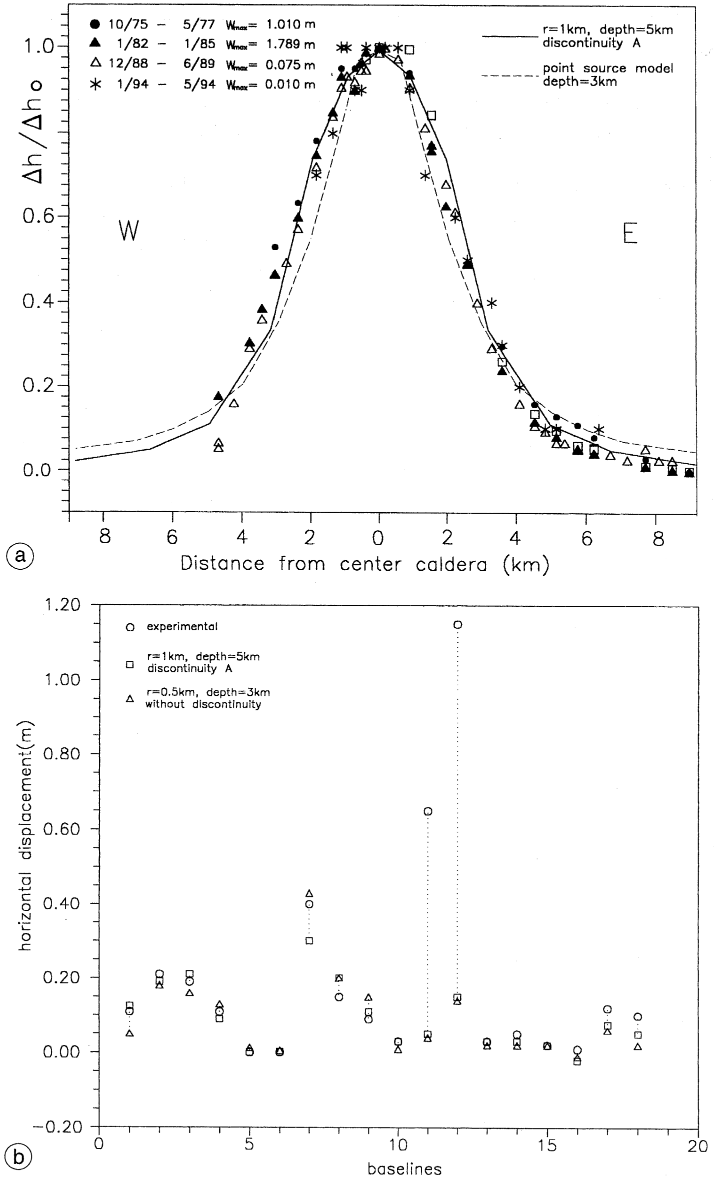


Fig. 5a,b. a) Fit of the theoretical, finite element model described in the text to observed vertical displacements measured along a levelling line running Naples-Pozzuoli-Miseno at various periods (solid line). Also shown, for comparison, is the fit for a point source (Mogi, 1958) at 3.0 km in depth, in a homogeneous half-space (dashed line). The position of benchmarks along the line is reported as radial distance from the caldera centre (Pozzuoli). Data for each period are normalised to the maximum value. Note the constancy of the shape of ground displacement for the various periods, and the good fit given by the model. b) Sketch diagram showing observed line length changes (circles) compared with the result obtained from the finite element model described in the text (squares) and for a point source model (Mogi, 1958) at 3.0 km of depth, in a homogeneous half-space (triangles), plotted as a function of the number of baselines (see Berrino *et al.*, 1984).

Another important result obtained by simulations in the presence of caldera discontinuities is the lower overpressure required to attain the same level of maximum deformation with respect to a continuous medium. Due to slip on the discontinuities, in fact, maximum deformation increases by about a factor 4 for the same geometry and overpressure of the strain source.

Figure 5a shows the fit of theoretical ground deformation data to the observed ones. For theoretical computations the model consists of a homogeneous half space with rigidity μ = 5 GPa, and axisymmetric ring discontinuities dipping 70° towards the inner caldera. The distance of ring discontinuities from the caldera centre has been assumed to be 2 km for the top part. The minimum and maximum depths are 0.5 and 4 km respectively from the free surface. The assumed depth for the source of overpressure simulates the shallow magma chamber whose top was located by Ferrucci *et al.* (1992) at about 4 km. The magma chamber was hence simulated as a sphere, with centre at 5 km of depth and radius r = 1 km. The overpressure required to simulate the total amount of deformation from 1982 to 1985 (1.8 m) turns out to be about 100 MPa.

Figure 5b shows the fit of the model to horizontal deformation data, namely to the line length variations measured in the period 1982-1983. Assuming the invariance of the deformation shape, line length variations can be projected at the end of 1984 (at the point of maximum uplift) by simply multiplying them by the ratio between maximum uplift and uplift in the period 1982-1983. Figure 5a shows experimental data for various periods, normalised to the maximum uplift (1.8 m), as compared with theoretical results for a point source located at 3.0 km of depth and with the model described in this paper. As is clear, the agreement is very good for vertical data and also for line length variations, except for the baselines No. 11 and 12. Such baseline shows very large positive changes up to 1.15 m for line No. 12 which are very difficult to model even with heterogeneous strain models (De Natale and Pingue, 1992). Because the baseline No. 11 is practically a small part of baseline No. 12, it is likely that such high length variation reflects a local anomaly positioned along line No.11 (De Natale and Pingue, 1992)

3. Modelling earthquake generation

Earthquakes which occurred at Campi Flegrei during the 1982-1984 unrest episodes showed some peculiar features. The first one, that the seismic zone remained practically constant during the two year duration of the uplift phase. Furthermore, seismic locations appeared to define a ring fault structure and, when regarded along appropriate depth sections, they proved to be mostly correlated with the inner caldera borders as inferred by gravity Bouguer anomalies (fig. 1). The good correlation with the caldera borders was clearly observed at Rabaul during the 1980-1985 unrest (fig. 6a,b) (Mori and McKee, 1987). The evidence for constant seismicity location calls for the effect of weak zones, which appear located at the borders of the inner caldera. Another striking observation regarding Campi Flegrei earthquakes is that the dip component of focal mechanisms is normal (De Natale *et al.*, 1995). This kind of faulting movement, implying downlift of the inner block, is opposite to the movement of differential uplift of the central block as seen by geodetic data. In fact, uplift of the central block would produce, on the inward dipping ring faults, fracture mechanisms with a reverse dip-slip component (fig. 7).

The absence of reverse fault mechanisms at Campi Flegrei suggests that slip over collapse discontinuities is mainly aseismic, once again calling for plastic behaviour of the caldera borders.

Troise *et al.* (1997) recently simulated the stress field at depth as generated by an overpressure in a magma chamber with the top at 4.0 km of depth, in the presence of lateral, inward dipping discontinuities, at the borders of the inner caldera collapse. Stress computations were performed by the discontinuity method (Crouch, 1976) in a two-dimensional medium. The medium is a half-space with Poisson ratio $\sigma = 0.3$ and rigidity $\mu = 5 \times 10^9$ Pa (De Natale *et al.*, 1991). A circular source of overpressure, of radius r = 1.0 km, is located at 5.0 of depth. Planes of stress-strain discontinuity, inward dipping, are located at both sides of a cylindrical source of overpressure. The distance of the discontinuities from the epicentre of the source (at about

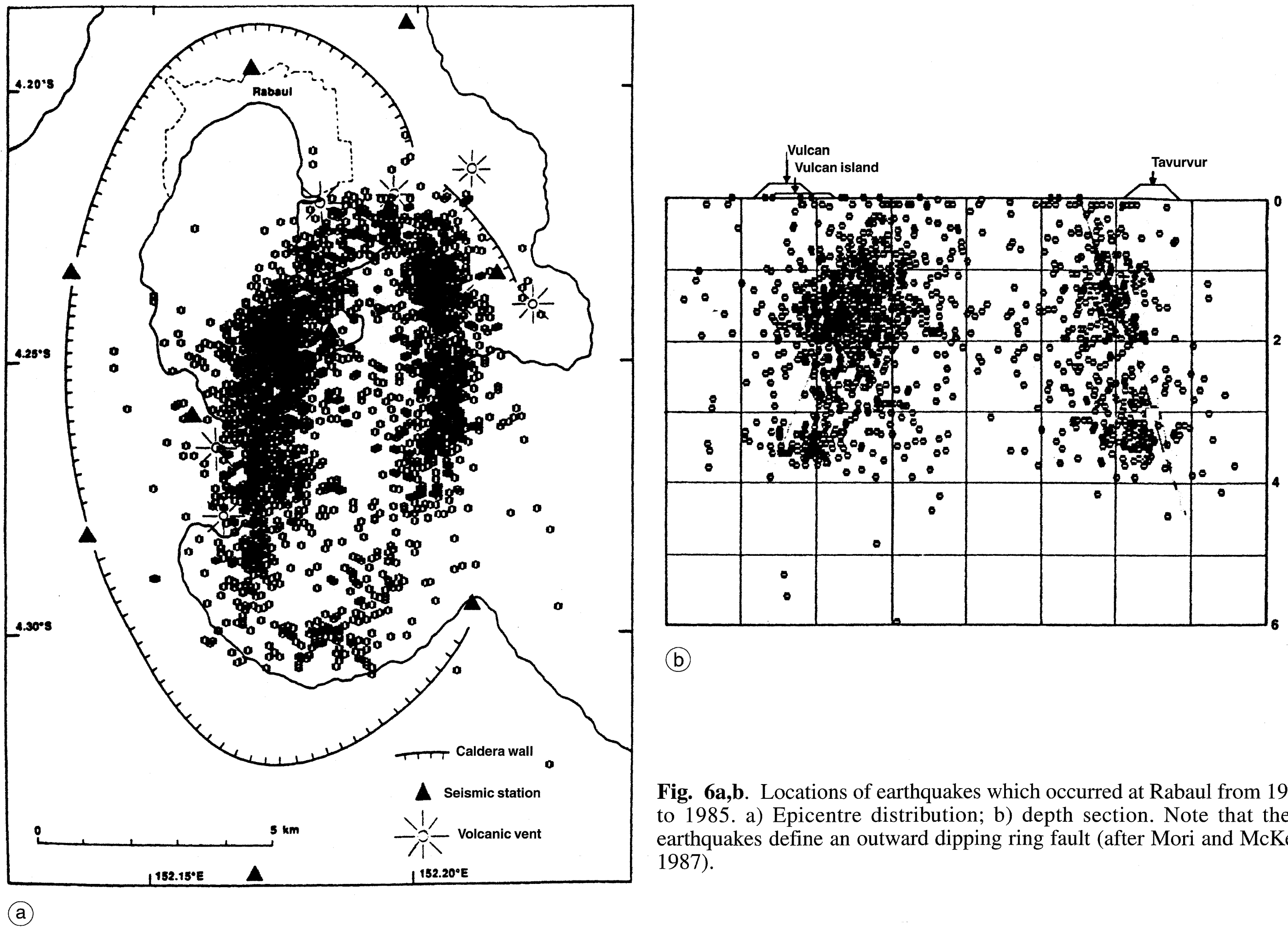
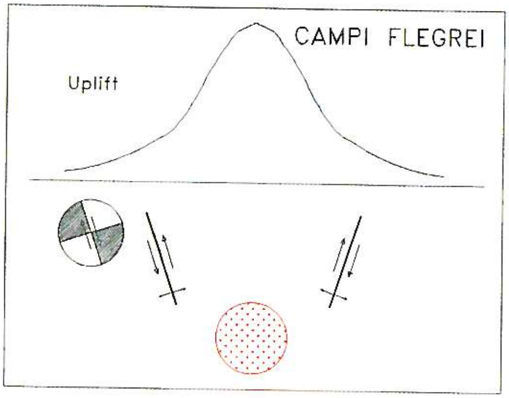
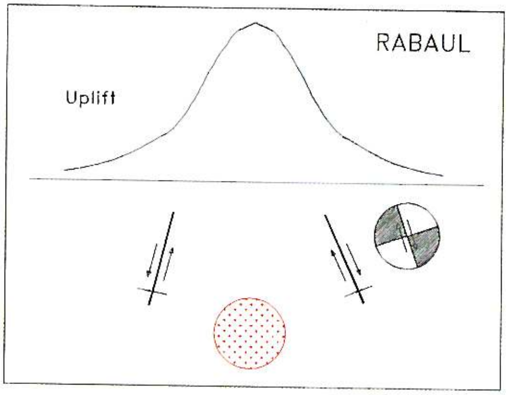


Fig. 6a,b. Locations of earthquakes which occurred at Rabaul from 1983 to 1985. a) Epicentre distribution; b) depth section. Note that these earthquakes define an outward dipping ring fault (after Mori and McKee, 1987).



Mo(geodetic)=3x10^{24} dynexcm
Mo(seismic)=3x10 ^{22}dynexcm



Mo(geodetic)=4x10^{24} dynexcm
Mo(seismic)=3x10^{24} dynexcm

Fig. 7. Schematic view of the movements along the lateral discontinuities produced by a pressure source of uplift, as compared to the movement indicated by the normal fault component of local earthquakes. Note that, at Campi Flegrei, the two movements are opposite. The uplift source also produces extension normal to the discontinuities, whereas at Rabaul it produces compression. The cumulative moments, as released by seismicity and as computed from the amount of ground elevations and from the slip assumed to occur along the plastic collapse zone, are also indicated (see text).

2.5 km from the caldera centre) well simulates the case of Campi Flegrei area. The dip of discontinuities is 45°; the depth of the top is 0.5 km, and the maximum depth is 3.5 km, just as for simulations of ground deformations. The model is assumed axisymmetric, so that only one side needs to be shown.

In our simulations, the lateral discontinuities are assumed to be free to slip (shear strength $\sigma_s = 0$), and to open (normal strain $\varepsilon_N > 0$).

Results for the state of stress, as a fraction of the overpressure in the source, are shown in fig. 8a. As a comparison, shear stress distribution for a cylindrical source in a homogeneous half space without lateral discontinuities is shown in fig. 8b.

Comparing fig. 8a and fig. 8b, we can see that the main effect of lateral discontinuities is to drain shear stress from the centre of the system and to concentrate it in the neighbouring of the discontinuities. The resulting pattern of maximum shear stress is very well correlated with the seismicity, which is null in the central part, and clustered around the lateral discontinuities and mainly at depths close to the magma chamber (see fig. 1). More interestingly, the stress field is such to produce normal faulting. The resulting pattern of shear stress is in fact the product of two effects: the near vertical compression due to overpressure in the circular source, consistent with horizontal extension, and the accumulation of normal faulting shear stress close to the discontinuities, due to the reverse faulting slip. Moreover, the stress normal to the discontinuities is also extensional (Troise *et al.*, 1997). This occurs essentially because of the inward dip of the discontinuities. For outward dipping discontinuities, such as those observed at Rabaul caldera, the stress normal to the discontinuities is indeed compressive (Troise *et al.*, 1997).

An important independent test on the mechanism of generation of seismicity, and of the plastic behaviour of caldera borders, comes from the computation of the total seismic moment release, as compared with the expected shear slip over the lateral discontinuities (Troise *et al.*, 1997). The average slip on the lateral discontinuities can be computed, in the framework of the model by De Natale and Pingue (1993), from the total amount of vertical deformation observed at Campi Flegrei from 1982 to 1985. Considering a circular source of overpressure in a homogeneous half-space with lateral discontinuities, the amount of vertical deformation depends on the amount of overpressure at the source, in the same way as the shear dislocation of the borders of the discontinuities. Actually, the maximum vertical deformation and the average shear dislocation on the discontinuities are closely linked. A computation of shear dislocation can be performed, from the best fitting model of De Natale and Pingue (1993), from the relative displacement on the two sides of the discontinuity. It turns out to be about one meter, on average. Once the average expected slip on the lateral fractures is estimated, the expected moment release can be computed from the relation: $M_0 = \mu A d$, where μ is the average rigidity of the area, estimated by several researchers as $\mu = 5$ GPa (see for instance De Natale *et al.*, 1991); A is the total fault area, which can be estimated from the radius of the inner caldera collapse as seen by gravity anomalies (Rosi and Sbrana, 1987), $r = 3$ km, and from the maximum depth (depth = 3 km), as $A = 2\pi \times 3 \times 3 \cong$ $\cong 60\ \mathrm{km}^2$; $d = 1$ m is the average slip on the fault system. The resulting expected moment is $M_0 \cong 3 \times 10^{17}\ \mathrm{N \cdot m}$. The observed seismic moment released by seismic activity in the period 1982-1985 can be well approximated as the moment released by two earthquakes with magnitude over 4.0 and by 15 earthquakes with magnitude greater or equal to 3.0. The result is $M_0 \cong 2 \times 10^{15}\ \mathrm{N \cdot m}$, *i.e.*, about two order of magnitude lower than expected if earthquakes were directly linked to shear dislocation on the ring fault system. This observation strongly supports the conclusion that the shear slip along the ring faults, implying reverse faults, was essentially aseismic because of plastic behaviour of the caldera borders, whereas seismic activity was due to the stress changes induced close to such aseismically moving faults. Aseismic slip on the ring faults was favoured by the strong extensional stress normal to the faults and, possibly, by high pore pressures of fluids in the area.

The same computations, performed for Rabaul seismicity during the last unrest (1982-1985), helps to clarify the conditions for the caldera borders to behave in a plastic way. The main features of the Rabaul seismicity were the strong focusing over a ring fracture system, outward dipping, and the higher intensity and number of earthquakes, with respect to Campi Flegrei. In contrast, the maximum vertical deformation was of the same level as Campi Flegrei. In the period 1983-1985, two earthquakes occurred with magnitude larger than 5 and four of magnitude around 4.5. The total seismic moment released was then $M_0 = 3 \times 10^{17}$. The moment released by slip on the outward dipping ring fractures was of the same order of magnitude as Campi Flegrei, $M_0 = \mu A d = 4 \times 10^{17}\ \mathrm{N \cdot m^2}$. It is evident that, in this case, the released seismic moment matches very well that expected from direct shearing over the ring faults. This also agrees with the observation that, at Rabaul, seismicity is much more focused on the ring faults with respect to Campi Flegrei, where seismicity is modelled as occurring in the neighbouring, the ring faults and not directly over them, due to induced stress changes. The main difference between the two areas appears to be linked to the different sign of the stress normal to the fractures, induced by the source of overpressure, because of the different dip, inward for Campi Flegrei, outward for Rabaul (Troise *et al.*, 1997). For outward dipping discontinuities the normal stress is compressive, thus not favouring aseismic slip. Seismicity in this area is then thought as directly linked to slip on the ring faults due to the upward motion of the central block. Also in this case, due to the outward dip of the ring faults, dominance of normal faulting mechanisms is expected, as indeed observed (Mori and McKee, 1987). It then appears that, under the effect of considerable normal compression, the fractured zones at the caldera borders behave in a brittle way.

4. Discussion

On the basis of the modelling results, it is now possible to build a complete description of what could be the mechanical behaviour of the Campi Flegrei caldera during unrest episodes. In particular, it is possible to explain the two main features of the episodic unrests as observed during 1970-1972 and 1982-1984: the

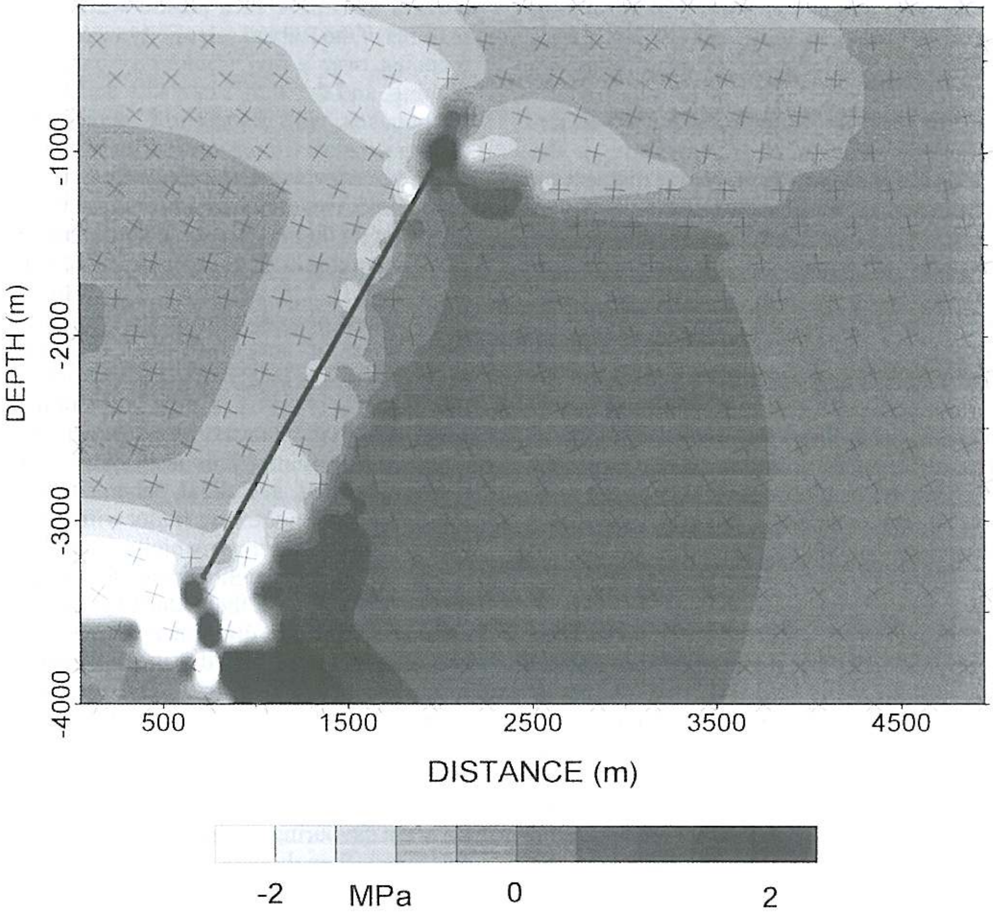


Fig. 8a. Map of maximum shear stress computed in 2D for a source of overpressure in presence of lateral discontinuities (negative stress indicates normal faulting). The overpressure at the source is $\Delta P = 10$ MPa. Also indicated are the orientations of the planes of maximum shear stress.

large ground deformation and the seismic activity. Both ground deformations and seismicity which occurred at Campi Flegrei during unrest episodes appear strongly controlled by plastic deformation confined to the borders of the innermost caldera, well evidenced by gravity Bouguer anomalies, and generally interpreted as associated to the Neapolitan Yellow Tuff eruption of 12 000 years ago (Lirer *et al.*, 1987). Ground deformation at Campi Flegrei appears confined within a small area; vertical deformations sharply decay after about 3 km of distance from the centre of the caldera. This particular feature has long attracted the attention of researchers because it requires a very shallow source of overpressure, on the basis of classical models of volume expansion in elastic medium without discontinuities. In the framework of our model, the presence of stress-strain discontinuities marking the borders of the innermost caldera collapse is able to concentrate ground deformation within the collapsed area. The evidence for the innermost collapsed area comes from gravity Bouguer anomalies, and it is gen-

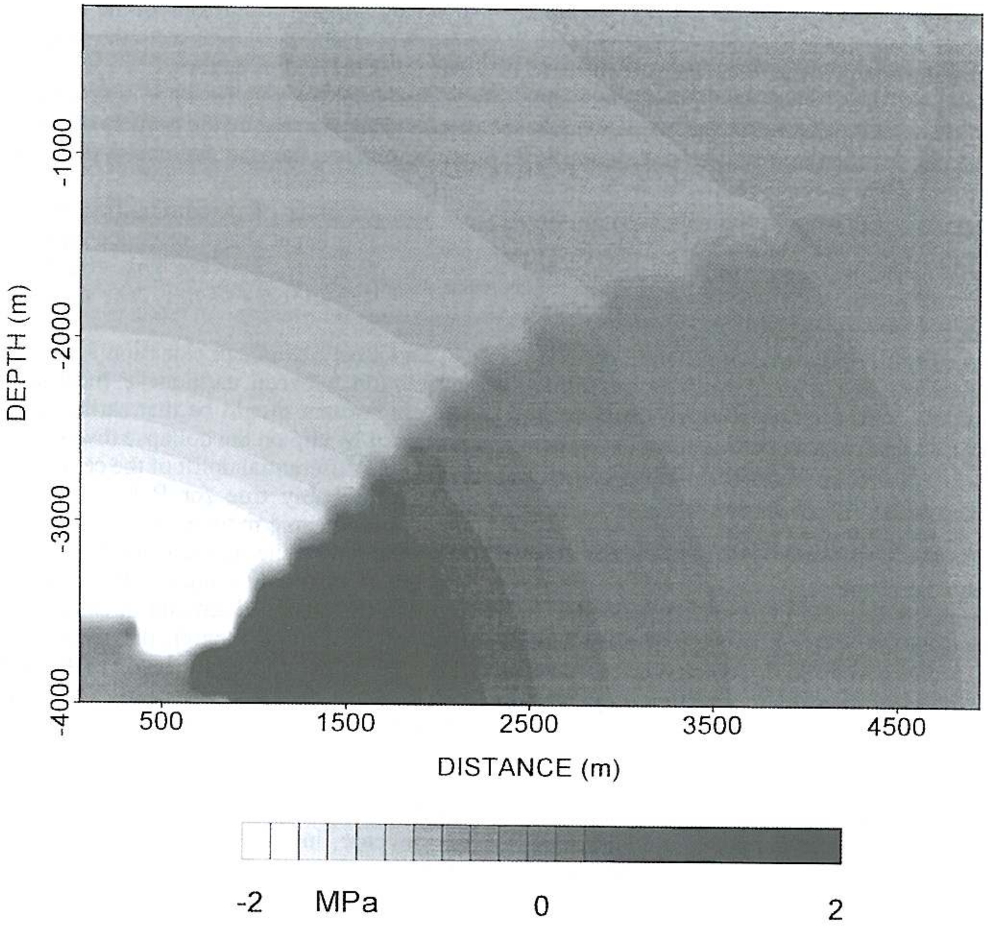


Fig. 8b. Map of maximum shear stress computed in 2D for a source of overpressure, without discontinuities. Overpressure at the source is ΔP = 10 MPa.

erally interpreted as related to the «yellow tuff» ignimbritic eruption about 12 000 years ago (Lirer *et al.*, 1987).

The borders of this collapsed area, marked by lithological discontinuity between inner caldera pyroclastics and the outer caldera rocks, appear free to slip in response to strain pulses generated in the magma chamber. The generation of such fracture zones at the borders of a collapsed caldera, which exhibit a plastic behaviour in response to applied stresses, can be schematically described by simulating the evolution of fracturing of the shallow crust under high incremental pressures in a shallow magma chamber. The results of such simulations, performed with a finite elements elasto-plastic program, evidence that the progressive increase in pressure within a shallow magma chamber produces the progressive formation of a narrow fractured zone, marking the borders of the subsequent collapse. The formation of this fractured zone during caldera formation can explain the plastic behaviour observed to control the ground deformation pattern. The relative movement of the innermost block will be positive (uplift) for increases in pressure occurring at the walls of the magma chamber, negative otherwise, causing in any case a strong confinement of the ground deformation within the inner caldera. Moreover, the possibility to accommodate shear stress by slip concentrated along the caldera borders causes an amplification of the ground deformation by a factor of about four, as indicated by finite elements axisymmetric modelling. The presence of ring discontinuities at caldera borders can explain many features of observed unrest episodes. For instance, the constancy of the shape of ground deformations during time, which has been widely observed at Campi Flegrei (Berrino *et al.*, 1984; De Natale *et al.*, 1991, 1997), at Rabaul (McKee *et al.*, 1989) and recently at Yellowstone. The main effect of the presence of discontinuities at caldera borders is, however, the strong correlation between the shape of the caldera and the shape of ground deformation pattern. This feature is observed at any caldera areas, and should be taken as the most striking demonstration of the strong effect of the caldera structure on ground deformations.

All of these features of the ground deformation field in calderas, due to the effect of caldera borders, have important implications on the relation between source depth and the lateral extension of the deformed area. The relation has been classically assumed to be very strict, based on the features of the deformation pattern due to strain sources of whatever shape in homogeneous elastic media. In the presence of ring discontinuities, however, the relation between source depth and size of the deformed area is almost null or very weak; in fact, the shape of deformation, and hence the size of the deformed area is strongly controlled by the position of discontinuities, and hence by the caldera shape. This result has in turn many other important consequences for interpreting ground deformations in calderas. One of the most striking is that it can be very difficult, if not impossible, to discriminate an intrusive episode from the variation in shape of ground deformation. Another one is that it is difficult to discriminate the effects of magma chambers from those of shallow aquifers, as sources of deformation. Strictly speaking, it not possible to infer the depth of the source of strain in calderas from the shape of the ground deformation pattern.

At Campi Flegrei, the shape of ground deformation is controlled by the borders of the innermost collapse, the one evidenced from gravity Bouguer anomalies.

The presence of discontinuities at caldera borders also has a sharp influence on the generation of seismic activity. This effect is very clear at Rabaul, only slightly less so at Campi Flegrei.

The most obvious explanation for the close correlation between earthquake locations and caldera borders should be that earthquakes are produced by slip on the collapse discontinuities due to the differential uplift of the central block. This is probably true for Rabaul, where the amount of seismic moment released is in good agreement with the moment inferred from the amount of slip on the caldera borders needed to produce the observed amount of surface deformation; for Campi Flegrei, the mechanism is more complex, and again involves the plastic behaviour of the caldera borders. The evidence of normal faulting dip components in the local earthquakes contrasts with an interpretation in terms of slip on the inward dipping caldera borders as due to the uplift of the central block; in this case, in fact, reverse fault mechanisms should be observed. This evidence, together with the very low amount of seismic moment released during the last unrest, as compared to that inferred from the relative uplift of the central block (two orders of magnitude higher) implies that slip on the collapse discontinuities is mostly aseismic. In the framework of our model, seismicity at Campi Flegrei is generated by the induced shear stress close but not directly on the collapse discontinuities, as due to the joint effect of the overpressure in the magma chamber and the aseismic slip on the discontinuities. Such aseismic slip is able to focus normal faulting shear stress close to the discontinuities and to the top of the magma chamber, releasing it from the central zone.

Why the uplift movement of the central block occurs aseismically at Campi Flegrei and not at Rabaul can be explained in terms of the different geometry of the ring discontinuities at the two areas. At Campi Flegrei, ring faults are inward dipping, and a large amount of tensional stress normal to their surface is generated by overpressure in the magma chamber. Such a tensional stress (together with a probable high pore pressure) favours a plastic behaviour of the caldera border discontinuities, causing the aseismic sliding of the inner caldera block. At Rabaul, on the contrary, ring discontinuities are outward dipping, and a large amount of compressive stress normal to them is generated by magma chamber overpressure. The coupling among the fractures marking the caldera borders is then increased, and they are forced to behave in a brittle way.

This model then explains one of the most striking differences between the Rabaul unrest and that at Campi Flegrei: the large discrepancy in the seismic efficiency, for a very similar amount of static deformation.

The two main characteristics of unrest episodes in calderas, namely the surface deformation and the seismic activity thus appear strongly affected by the caldera structure, in particular the ring fault systems at the borders of the collapsed areas. This is a rather general and original observation, which has been evidenced in the framework of the research aimed to understand the Campi Flegrei unrests. In terms of these effects the most puzzling observations regarding Campi Flegrei unrests have been clarified. What remains to explain is the link between the proposed mechanical model and the role of shallow fluids of the hydrothermal system. The need to consider hydrothermal circulation comes from many observations: the most evident one is perhaps the large body of evidence, both at Campi Flegrei and in other calderas, for geochemical variations in the fluids of fumaroles, which show a close correlation with geophysical anomalies. At Campi Flegrei, in particular, geochemical variations in fumaroles have been evidenced to precede both the start and the end of the large uplift phases (Allard *et al.*, 1991). Filling the gap between geophysical and geochemical modelling of volcanic unrests should be one of the main guidelines of future volcanological research.

In any case, at Campi Flegrei the role of shallow fluid circulation is probably essential for a more basic question: the interpretation of the time evolution of the recent unrests in which a fast uplift phase is followed by a slower decrease of the ground level.

Without eruptions, it is very difficult to interpret the decreasing phase in terms of purely mechanical models. Answering these questions requires building and solving appropriate thermal-fluid-dynamical and thermal-poroelastic equations.

5. Conclusions

We have built a coherent model explaining the mechanism for surface deformations and seismicity occurring at Campi Flegrei caldera during unrest episodes. Such a model involves the strong effect of the fractured zones at the borders of the collapsed areas on both the deformation pattern and earthquake generation. The model is able to explain a large body of observations in calderas, not only at Campi Flegrei but also at the other major recently active calderas.

As a general consideration, the surface deformation patterns in calderas are strongly conditioned by the caldera borders. At Campi Flegrei, in particular, the presence of an inner caldera collapsed area is able to explain the small size of the deformed area; similar arguments also explain the concentration of deformation in a small area as observed in Rabaul unrests.

The presence of discontinuities at the inner caldera borders, which behave in a plastic way, also explains the location and mechanism of local earthquakes, which would be generated by the stress change due to overpressure in the magma chamber and to the aseismic slip along the inward dipping ring fractures.

The low ratio between the amount of total uplift and the seismic moment released can be also explained by this model by the fact that seismicity should be a second order effect, due to the perturbation of the stress field caused by the presence of ring fractures.

The effect of fractured zones marking the caldera borders on both seismicity and ground deformations is an original result obtained by the researches aimed to explain the unrest episodes at Campi Flegrei. However, most of these effects appear evident also in other recently active caldera areas; the results of these researches should shed new light on the interpretation of unrest phenomena in calderas, which appear more complex than what was generally observed in typical central volcanoes like, for instance, Hawaiian shields.

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