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A model for earthquake generation during unrest episodes at Campi Flegrei and Rabaul calderas

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Abstract. We have analysed the seismicity that occurred at Campi Flegrei caldera (Italy) in the period 1982-1984, during an unrest episode. Earthquake locations describe a system of inward dipping ring faults. Focal mechanisms of such events show a normal dip component, which is not in agreement with the differential uplift of the inner caldera, as defined by static ground deformations. We have performed a simulation of the stress field generated by overpressure in a magma chamber in presence of lateral discontinuities, using a boundary element method. Lateral discontinuities simulate the ring fault system marking the border of the inner caldera collapse. Results allow us to hypothesize that reverse fault slip on the ring fault is mainly aseismic, and such aseismic movement is able to focus normal fault shear stress along the lateral discontinuities. Aseismic slip on the ring fault in response to static deformation is also supported by the low seismic moment released ($M_0 \cong 10^{15}$ Nm), about two orders of magnitude lower than expected from the shear slip on the discontinuities needed to accomplish the total static surface deformation (1.8 m). Such results have been compared with observations at Rabaul caldera, during a similar unrest episode. In this area, the seismic moment release is in good agreement with shear slip produced on a system of outward dipping ring faults, and seismicity is much more focused on the fault structures. Such a different behaviour can be interpreted, in the framework of our model, as due to the different sign of the stress normal to the ring faults, for inward and outward dip. The comparison between the two areas shed new light about the dynamics of earthquakes in calderas, in terms of the role played by ring fault systems.

Introduction.

Unrest episodes at active calderas have been observed several times in recent years. Such episodes involve intense ground deformation, from centimeters up to some meters in few years, and strong increase of seismicity. Recent observations of ground deformation in calderas include Yellowstone and Long Valley (USA), Rabaul (New Guinea), Campi Flegrei (Italy). In these areas, unrest phenomena are occasionally observed, involving increased seismicity and considerable ground deformation. Observed maximum rates of vertical deformation range from about 2 cm per year at Yellowstone during 1976-77, to 0.5 m per month at Campi Flegrei (1982-1984). At Campi Flegrei, on April 1984, when rate of deformation was at the maximum level (0.02 m per day), seismicity reached peaks of 500 earthquakes ($0<M_L<3.0$) per 6 hours (Aster et al., 1992). Unrest episodes at calderas show some peculiar features different from other volcanic areas. One of the most striking features is the occurrence of large static deformation and seismicity without eruptions. Furthermore, at Campi Flegrei and Rabaul calderas, ground deformation appeared concentrated in a small area about in 3 km radius. Large static deformation, concentrated in a small area, has been recently modeled 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. Both at Campi Flegrei and Rabaul calderas, seismicity appears concentrated close to such discontinuities (Mori and McKee, 1987; De Natale et al., 1995). Although the effect of lateral ring discontinuities on ground deformation appears to be well established, the mechanism of generation of seismicity during unrest episodes is not yet clear. At Campi Flegrei, for instance, focal mechanisms of local seismicity show a relative movement of the shallow crust which is opposite to what expected from ground deformations (De Natale et al., 1995).

In this paper, a model is proposed for seismicity at Campi Flegrei, that is linked to the presence of collapse discontinuities. We also compare these results with the observations at Rabaul. Such model is able to explain the observational evidence at both the calderas, and interprets the differences in the seismic occurrence in terms of the differences in the geometry of the collapse discontinuities.

Seismic and ground deformation observations at Campi Flegrei.

Seismicity at Campi Flegrei occurs during unrest episodes, and is practically absent in normal periods (Corrado et al., 1976; De Natale et al. 1995). During the 1982-1984 crisis, more than 15000 earthquakes occurred, ranging in magnitude from 0.4 up to 4.2. Only about ten events had a magnitude larger than 3, the largest one, a M_L=4.2 event, on 1983, October 4 (De Natale and Zollo, 1986). A large number of earthquakes was felt by the population, mainly at the town of Pozzuoli, which is located at the center of the caldera and where about 100,000 people live. Several studies about the seismicity of the 1982-1984 unrest have been performed (De Natale and Zollo (1986), De Natale et al. (1987), Aster and Meyer (1988), Aster et al. (1992)). De Natale et al. (1995) have recently shown that earthquake locations and mechanisms indicate the presence of inward dipping ring faults, associated with inner caldera collapse structures. The presence of such system of ring fractures is strongly supported by studies of ground deformation associated to unrest episodes. De Natale and Pingue (1993) and De Natale et al. (1997) have shown the effect of lateral discontinuities, interpreted as the borders of collapsed areas, on the ground deformation field. They have also shown that the high concentration of ground deformation in small areas, as observed at Campi Flegrei and Rabaul, is consistent with the effect of lateral discontinuities linked to inner collapse areas.

Fig. 1 shows a global picture of seismicity and structural features at Campi Flegrei area, as resulting from the various studies performed in the papers mentioned above. Earthquake locations for about 200 events that occurred in the period 1982-1984 are shown as obtained in the three-dimensional velocity model by Aster and Meyer (1988).

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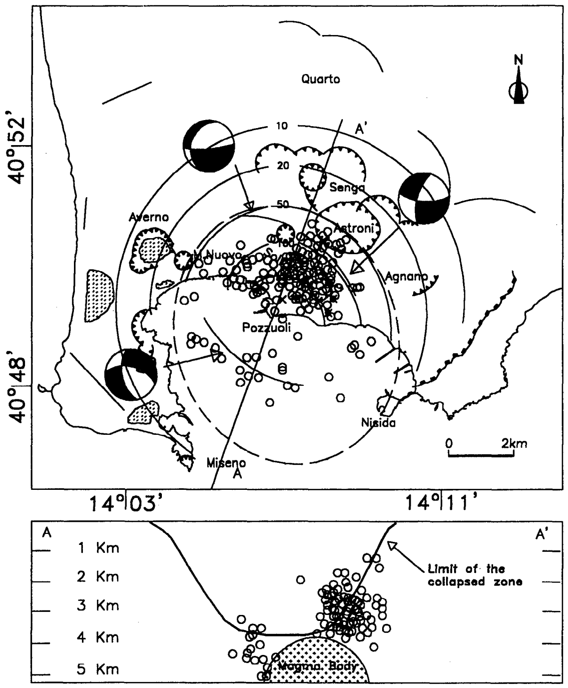

Figure 1 Summary map of various geophysical observations at Campi Flegrei. The approximate zero contour line of the Bouguer anomaly is shown (dotted line), together with contours of vertical elevation and earthquake hypocentres; the projection of the collapsed zone as modelled from gravity anomalies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

As it 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 ring fault system. Such structures are likely to be related to an inner caldera collapsed area, as indicated by the maps of gravity Bouguer anomaly (AGIP, 1987). Fig. 1 also shows contours of vertical displacements between 1982 and the beginning of 1985, when the uplift phase ended. They are consistent with a differential uplift of the central block bordered by ring faults (De Natale and Pingue, 1993; De Natale et al., 1997)

The most intriguing feature of focal mechanisms is that they show, superimposed on a large strike slip component, a normal dip component (fig.1). This kind of faulting movement, implying downdrop of the inner block, is opposite to the differential uplift as seen by geodetic data. In fact, uplift of the central block would produce focal mechanisms with reverse dip component, on the inward dipping ring faults (Fig. 2).

2D simulation of stress field at depth.

In order to understand the possible mechanism for the generation of seismic events with a normal fault dip component, we have performed simulations of the stress field at depth as generated by an overpressure in a magma chamber with top at 4.0 km of depth, in presence of lateral, inward dipping discontinuities simulating 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 an half-space with Poisson ratio ν=0.3 and rigidity μ=5GPa (De Natale et al., 1991). A circular (cylindrical in 3D) source of overpressure, of radius r=1.0 km, is located at a depth of 5.0 km. Planes of inward dipping, stress-strain discontinuities, are located at both sides of the circular source of overpressure. The distance of the discontinuities from the center of the source simulates the case of Campi Flegrei area where the borders of the inner caldera, as seen by Bouguer anomalies, are at about 2-3 km from the caldera center. The dip of discontinuities is 45°, the top edge is located at a depth of 0.5 km, the bottom at 3.5 km. The distance from the surface simulates the burying of collapse structures by recent pyroclastic deposits. This is consistent with the absence of traces at surface, and with the lack of discontinuities in the vertical deformations on the levelling lines crossing the collapse borders. The distance from the magma chamber simulates the effect of high temperatures, which closes the fractures at depth. The model is assumed laterally symmetric, so that only one side needs to be shown.

In our simulation, the lateral discontinuities are assumed free of shear (shear stress $\sigma_s=0$, no shear strength), and with possible opening (normal strain $\varepsilon_n \geq 0$). With such assumptions, we implicitly consider the state of stress after shear stress on lateral discontinuities is accommodated by slip.

Results for the state of stress, as a fraction of the overpressure in the cylindrical source, are shown in figs. 3 through 5. Fig. 3 shows the maximum shear stress together with planes of maximum shear. As a comparison, the shear stress distribution for a circular source in a homogeneous half space without lateral discontinuities is shown in fig. 4.

Comparing fig. 3 and fig. 4, we can see that the main effect of lateral discontinuities is to relieve shear stress from the center of the system and to concentrate it in the neighbourhood of the discontinuities. The resulting pattern of maximum shear stress is well correlated with the seismicity, which is absent in the central part, and clustered around the lateral discontinuities, mainly at depths close to the magma chamber top (see fig. 1). The horizontal stress is tensional in the seismic zone, and, close to the discontinuities, it is maximum for inward dipping faults with dip δ=45°-70°. The resulting pattern of shear stress is in fact the product of two effects: the near vertical compression due to overpressure at

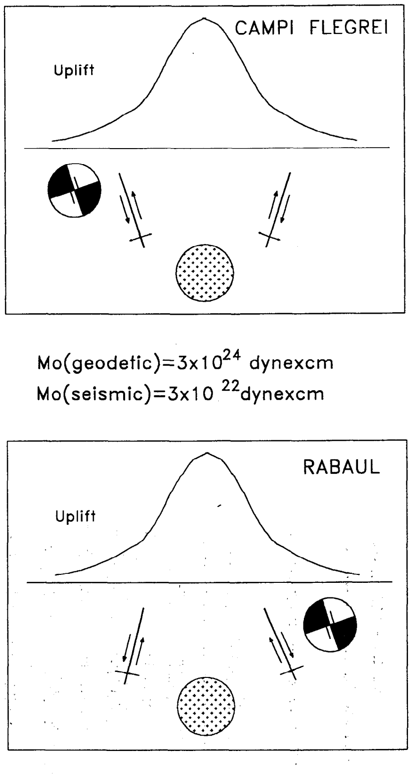

Figure 2 Schematic view of the movements along the lateral discontinuities produced by a pressure source of uplift, as compared to the movement indicated by the normal fault component of local earthquakes. Note that, at Campi Flegrei, the two movements are opposite. The uplift source also produces extension normal to the discontinuities, whereas at Rabaul it produces compression (see fig.5). The cumulative moments released by seismicity and computed from ground elevations are also indicated (see text).

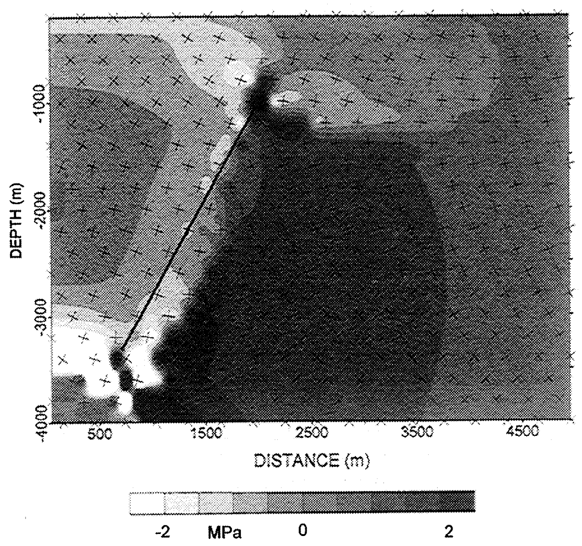

Figure 3 Map of maximum shear stress computed in 2D for a cylindrical source of overpressure in presence of lateral discontinuities (negative stress indicates normal faulting). The overpressure at the source is $\Delta P=10$ MPa. Also indicated are the orientations of the planes of maximum shear stress.

the source, consistent with horizontal extension, and the accumulation of normal fault shear stress close to the discontinuities as due to the reverse slip on the discontinuities.

Fig. 5 shows the normal stresses, generated by overpressure in the circular source for a homogeneous half-space, in a system rotated 45°. It gives then a picture of the stresses normal to outward dipping (fig. 5a) and to inward dipping (fig. 5b) discontinuities, respectively, before their movement accommodates shear and normal stress. We observe that the normal stress is tensional on inward dipping fractures, whereas on outward dipping ones it is compressive.

Modeling the generation of seismic activity during unrest phenomena

The simulation of the stress field at depth helps build an interpretative model for the seismicity at Campi Flegrei during unrest episodes. The first, noteworthy result of the stress analysis is that, due to the joint contribution of the pressure source and of the shear slip on the discontinuities, shear stress concentrates close to the discontinuities and the top of the magma chamber, generating normal faulting along planes with dips similar to that of the lateral discontinuities. Fig.3 shows the agreement between computed maximum shear zones and seismic zones. In principle, also the effects of normal stress, contributing to the Coulomb stress, should be considered; however, at Campi Flegrei pore pressure should be very high, so that the contribution of normal stresses would be negligible . The absence of seismicity in the central zone, which is not expected in a homogeneous medium, is due, in the framework of our model, to the presence of lateral discontinuities. Then, the observed seismicity during unrest phenomena at Campi Flegrei can be well explained, both in terms of distribution and of focal mechanisms, by the combined stress modifications due to a pressure source at depth and to the presence of inward dipping, lateral discontinuities. If seismicity were directly caused by slip on the discontinuities themselves during the upward movement of the central block, the seismicity should show reverse slip, contrary to observations.

An important, independent test on the mechanism of generation of seismicity, comes from the computation of the total seismic moment release, as compared with the expected shear slip over the lateral discontinuities. 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 since 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 and the shear dislocation at the borders of the discontinuities. Actually, the maximum vertical deformation and the average shear dislocation on the discontinuities are strictly 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 on the order of one meter, on average. It is important to note that, although the use of an axisymmetric or three-dimensional model_can significantly change the ratio between overpressure at the source and maximum displacements at the surface (De Natale et al., 1997), the ratio between maximum surface displacement and discontinuity dislocation remains approximately constant. 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 as $\mu = 5$ GPa (see for instance De Natale et al., 1991); the total fault area A can be estimated from the radius r=3 km of the inner caldera collapse as seen by gravity anomalies (AGIP, 1987) and from the maximum depth (about 3 km), as A=3x6.28 km x 3 km=60 km^2; d=1 m is the average slip on the fault system. The resulting expected moment is $M_0=3\times10^{17}$ Nxm. The observed seismic moment released by seismic activity in the period 1982-1985 can be well approximated as the moment released by the earthquakes with magnitude in the range 3.0-4.2. The result is about 2×10^{15} Nm, i.e., about two order of magnitudes lower than expected if earthquakes were directly linked to shear dislocation on the ring fault system due to the uplift of the central block. This observation strongly supports the conclusion that shear dislocation on the ring faults, implying reverse faulting, was essentially aseismic, whereas seismic activity was due to the stress changes induced close to such faults, because of aseismic slip. Aseismic slip on the ring faults is favoured, in our opinion, by the strong tensional stress normal to the faults (fig.6a) and, possibly, by high pore pressures of fluids in the area. Aseismic sliding of fractures due to high pore pressure, and activation of seismicity due to the static stress changes associated with the aseismic slip, have been recently documented during hydraulic forced fracture tests performed in the field by Cornet et al. (1994).

A further support to our model comes from the observation of Rabaul seismicity during the unrest period 1980-1984. The main features of the Rabaul seismicity were the strong clustering along an outward dipping ring fracture system, and the higher intensity and number of earthquakes as Campi Flegrei. In contrast, the maximum vertical deformation was of the same level as Campi Flegrei. In the period 1973-1985, three earthquakes with magnitude larger than 5 occurred (5.2, 5.1, 5.1), and three of magnitude over 4.5. The total seismic moment released was then $M_0=3\times10^{17}$ Nm. The moment released by slip on the outward dipping ring fractures was of the same order of magnitude than Campi Flegrei, $M_0=\mu Ad=3\times10^{17}$Nxm, with μ=5GPa, A=60 km^2, d=1m. It is evident that, in this case, the released seismic

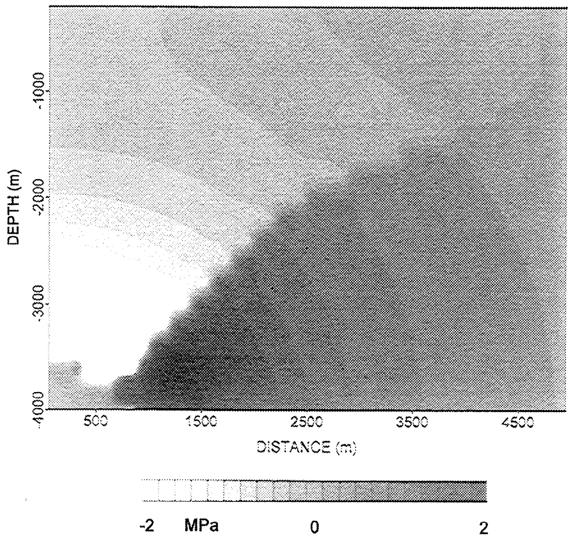

Figure 4 Map of maximum shear stress computed in 2D for a cylindrical source of overpressure, without discontinuities. Overpressure at the source is $\Delta P=10$ MPa.

moment matches very well that expected from direct shear slip over the ring faults. This also agrees with the observation that, at Rabaul, seismicity is much more concentrated along the ring faults than is the case for Campi Flegrei, where seismicity occurs adjacent to the ring faults. The main difference between the two areas involves the different sign of the stress normal to the fractures, induced by the source of overpressure, because of the different dip. In fact we noted, in the previous section, that, for outward dipping discontinuities, the normal stress is compressional (fig.5b), thus not favouring aseismic slip. Seismicity in this area is then interpreted as directly linked to slip on the ring faults in response to the upward motion of the central block. In this case, due to the outward dip of the ring faults, normal faulting mechanisms are expected, as indeed observed (Mori and McKee, 1987).

Conclusions

A model has been proposed to explain the generation of seismicity at calderas during unrest episodes.

In the framework of such model, earthquakes are generated as a response to overpressure in a shallow magma chamber, and focused along the discontinuities marking the caldera borders.

On such discontinuities, shear slip takes place due to the magma chamber overpressure, which causes the upward motion of the inner collapsed area (De Natale and Pingue, 1993). At Rabaul, where the innermost collapsed block is bordered by outward dipping ring faults, seismicity appears directly linked to the shear slip along such fault system.

At Campi Flegrei, in contrast, the differential uplift of the central block appears mainly aseismic. The seismicity is due to the static stress changes produced by magma chamber overpressure plus the aseismic shear slip on the ring faults bordering the innermost collapsed area.

The difference between the two mechanisms of generation, which is made evident by comparing the total seismic moment released by local earthquakes with that expected for shear slip over the ring fault systems, appears mainly due to the different dip of the ring faults. On inward dipping discontinuities, as at Campi Flegrei, the magma chamber overpressure generates a strong tensional normal stress, thus favouring aseismic slip; on outward dipping discontinuities, on the contrary, compressive normal stress inhibits aseismic sliding.

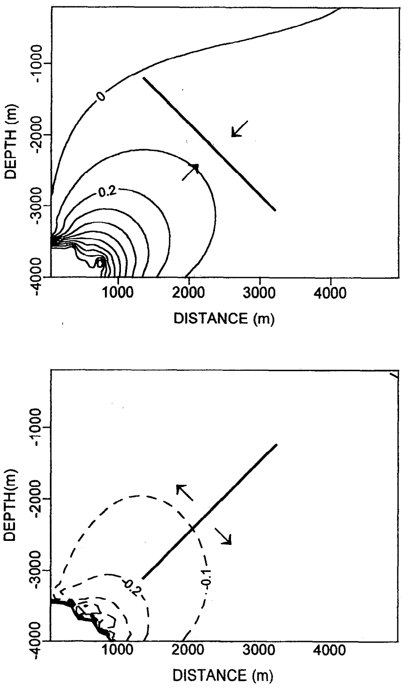

Figure 5 Map of stress normal to planes oriented like the assumed discontinuities, computed for a cylindrical source of overpressure in a halfspace: a) stress normal to outward dipping planes (case of Rabaul, dip=45°); b) stress normal to inward dipping planes (case of Campi Flegrei, dip=135°). Dashed lines indicate negative values of normal stress (extension). $\Delta P = 10$ MPa

In the framework of this model, we are able to explain many observations at the two areas. In particular, the very sharp focusing of seismicity along the ring faults at Rabaul is explained as due to direct shear slip along such faults, whereas at Campi Flegrei seismicity is less focused, because induced by static stress changes not directly on, but close to the ring faults.

Also, our model explains the marked difference in the level of seismic activity with the same level of deformation, implying a difference of two order of magnitudes in the brittle versus ductile deformation.

Finally, the model explains the presence of normal fault components in the earthquake mechanisms at Campi Flegrei, contrasting with the observed uplift of the central block.

The active rôle played by collapse discontinuities at Campi Flegrei has important volcanological implications. The tensile normal stress generated by magma chamber overpressure favours magma injection within such fractures. Recent volcanic centers (younger than 12000 years) are in fact strongly clustered along such discontinuities (Lirer et al., 1987). It is likely that also the next eruptions in the area will follow a similar pattern.

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