A MODEL FOR SEISMICITY RATES OBSERVED DURING THE 1982-1984 UNREST AT CAMPI FLEGREI CALDERA (ITALY).

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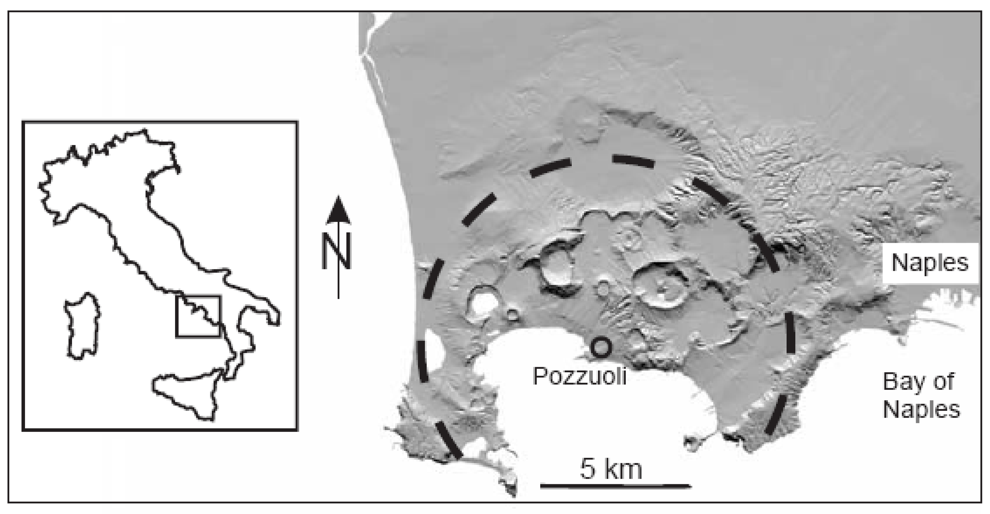

Figure 1.
Digital elevation model of Campi Flegrei area. The area affected by ground movements since 1972 is highlighted with a broken line. This area coincides with the morphological expression of the Campi Flegrei caldera (modified from Gottsmann et al., 2006).

1. Introduction

Two intense episodes of surface uplift without culminating eruptions were observed in Campi Flegrei caldera near Naples (Italy) in recent times . These episodes of caldera unrest, also called bradyseisms, occurred from 1969 to 1972 and from mid-1982 to December 1984 generating maximum uplifts larger than 1.5 m. The 1982-1984 uplift was followed by a still continuing stage of slow subsidence with superimposed mini-uplift episodes (Figure 2a). Uplift stages correlate with swarms of earthquakes located in the unrest region (Troise et al. 2003). In general the temporal distribution of surface deformation and seismicity in the unrest region suggests a correlation between deformation rate and seismicity rate (Figure 2). In this work, by means of a model we aim to explain this correlation during the 1982-1984 unrest episode, which was monitored by several geodetic and seismic data.

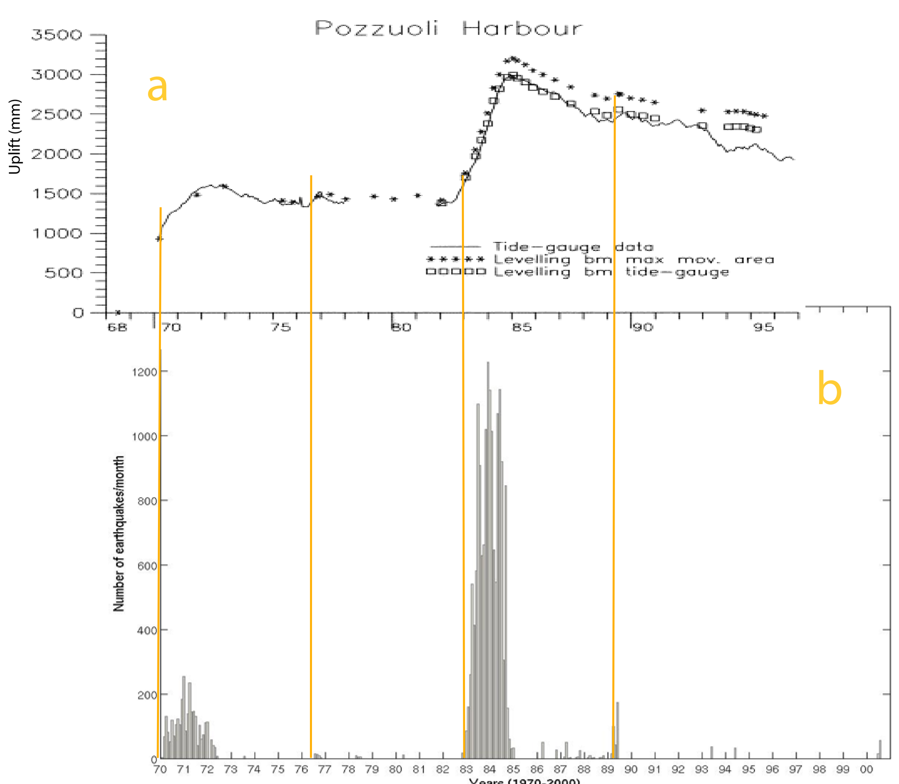

Figure 2.
During the period of the two main unrest episodes in the Campi Flegrei caldera, the figure shows the following data recorded in the Pozzuoli harbour:
a) vertical displacement as a function of time according to different measurements (tide-gauge and levelling data, Berrino, 1998).
b) seismicity rate as a function of time. From R. Scandone (personal communication).

2. Induced stress-changes

In order to model seismicity during the 1982-1984 unrest at Campi Flegrei caldera (Italy), we compute static stress changes caused by an inflating source in a layered half-space, with a code from Wang et al. (2006). Stress changes are evaluated on optimally oriented planes for shear failure (OOPs), assuming a regional deviatoric stress with horizontal extensional axis trending N36°E (e.g. Troise et al. 2003). The inflating source is modelled as inferred by previous studies (Amoruso et al., 2006) from inversion of geodetic data with the same crustal model here assumed (Table 1). In particular we model stress changes due to a point-like, vertical, penny-shaped spheroid located near Pozzuoli at 4.8 km depth. Stress changes are evaluated at 3 km depth, the average depth of seismicity observed during the 1982-1984 unrest at Campi Flegrei. In Figure 3 the maximum shear stress associated to the regional stress is equal to 5 MPa, comparable with the largest shear stress changes caused by the inflating source. The area affected by the largest Coulomb stress changes (dark red area in Figure 3) is elliptical in agreement with the observed distribution of earthquakes during the 1982-1984 unrest (Aster and Meyer, 1988). Inverse slip over the source is discouraged by the assumed regional stress, so that fault mechanisms are mostly normal with oblique components near the source. These results are in agreement with observations of the 1982-1984 Campi Flegrei swarm (e.g. Troise et al., 2003). Only decreasing the amplitude of regional stress with respect to the value assumed we obtain OOPs with thrust mechanisms over the inflating source, in agreement with previous studies of stress changes induced by volcanic sources in homogeneous half-spaces (Feuillet et al., 2004). We evaluate the average static values of shear and normal stress change on OOPs in the region where most of seismicity produced during the unrest episode locates (i.e. within the white box in Figure 3). In case of Figure 3 the average shear stress change is around 3.6 MPa and the normal stress change is tensile around 0.5 MPa.

Table 1

Depth (km)	Vp (km/s)	Density (kg/m^3)
0.00	1.60	1800
0.62	2.50	2100
1.40	3.20	2270
1.55	3.90	2380
2.73	3.95	2400
3.92	5.20	2580
≥4.03	5.92	2700

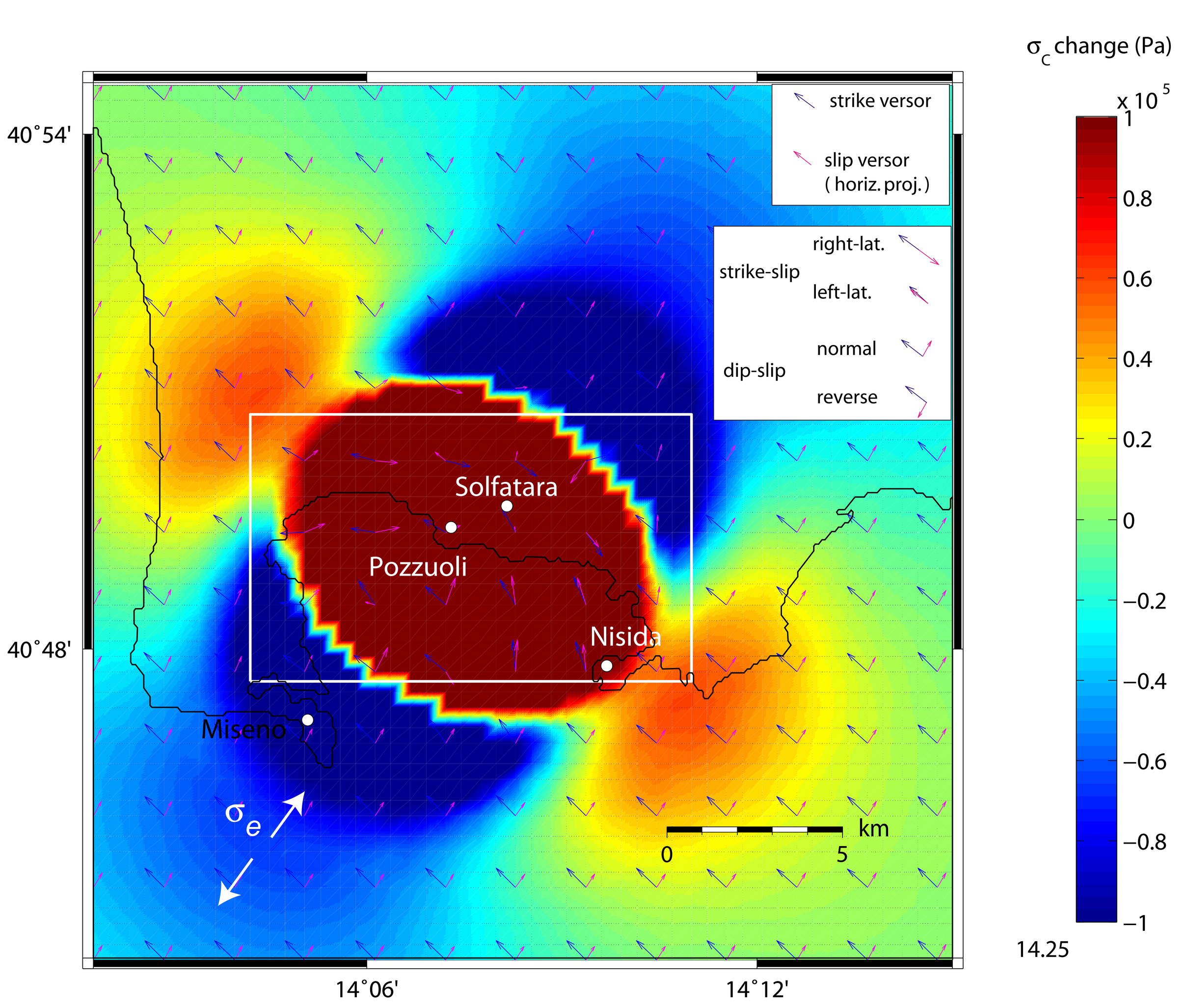

Figure 3.
Coulomb stress, σ_c, change due to the inflating source responsible of the 1982-1984 unrest episode at Campi Flegrei evaluated at a depth of 3 km. In each location stress changes are evaluated on optimally oriented planes for shear failure (OOPs). In order to determine OOPs the sum of the induced stress change and a regional stress, σ_e, with vertical compression and N36°E-trending extension is considered. Both principal regional stresses have 5 MPa amplitude. The fault mechanism of one of the two "conjugate for stress" OOPS (affected by the same total Coulomb stress) is represented in each location by magenta and blue arrows. The white box encloses most of seismicity observed during the unrest episode here studied.

Acknowledgements

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Abstract

In order to model seismicity during the 1982-1984 unrest at Campi Flegrei caldera (Italy), we compute static stress changes caused by an inflating source in a layered half-space. Stress changes are evaluated on optimally oriented planes for shear failure, assuming a regional deviatoric stress with horizontal extensional axis trending NE-SW. The inflating source is modelled as inferred by previous studies from inversion of geodetic data with the same crustal model here assumed. The area affected by the largest Coulomb stress changes is elliptical. Inverse slip over the source can be discouraged by the assumed regional stress. These results are in agreement with observations concerning seismicity developed during the 1982-1984 unrest at Campi Flegrei. In order to evaluate rates of stress change, we assume that the temporal evolution of uplift observed by a tide-gauge at Pozzuoli, normalized to the maximum value, was due mainly to time dependent processes occurring at the inflating source. Then we attribute the same normalized time dependence to each component of average stress change in the region affected by observed seismicity. We then model seismicity rate changes associated to the time-dependent stress changes, by following the approach indicated by Dieterich (1994) on the basis of the rate- and state-dependent rheology of faults. The seismicity rate as a function of time resulting from the model is in general agreement with observations; in particular the observed correlation with the deformation rate history is present also in model results.

3. Seismicity rate-changes

We consider a temporal record of deformation during the 1982-1984 unrest at Campi Flegrei measured by a tide-gauge near Pozzuoli (Aster and Meyer, 1988). We normalize the record of uplift to the maximum value of 1.7 m. We assume that the time dependence of normalized uplift is due mainly to time dependent processes occurring at the inflating source. We reproduce this temporal dependence with a piecewise linear approximation (assuming a constant deformation rate in each time sub-interval considered in the period 1982-1984, Figure 4a). Then we attributed the same normalized time dependence to the shear stress and normal stress change (averaged within the white box of Figure 3). In this way we obtain shear stress and normal stress induced by the inflating source as a function of time, τ(t) and σ(t), respectively. The latter are translated into seismicity rate changes, by following the approach indicated by Dieterich (1994) on the basis of the rate- and state-dependent rheology of faults. According to this approach, the distribution of initial conditions and the stressing history control the timing of earthquakes on a fault population. In particular we develop the application to the case of piecewise constant rates of normal and shear stress. In Figure 4 we can see that fluctuations of deformation rates (and then stressing rates) correspond to fluctuations of seismicity rates both according to observations and the present model. In particular peaks in seismicity rates corresponds to relatively faster uplift. A first comparison between model and observed seismicity rates is shown in Figure 4b. It suggests a value of the rheological parameter $A\sigma_0$ at the beginning of the simulation of the order of 1.2 bars and a background shear stressing rate in the region of 1.3 10^{-3} MPa/year. In the comparison we assumed fixed other parameters that are easier to be constrained on the basis of the current knowledge about the Campi Flegrei unrest. The previous estimates of model parameters can be compared with those assumed by Toda et al. (2002) for seismicity induced by the 2000 dike intrusion in the Izu volcanic Island. A better knowledge of both the deformation record and the observed seismicity rates as a function of time (possibly from the original data) than it is currently available to us should improve the agreement between observed and model seismicity-rate, as it will be tested in future work.

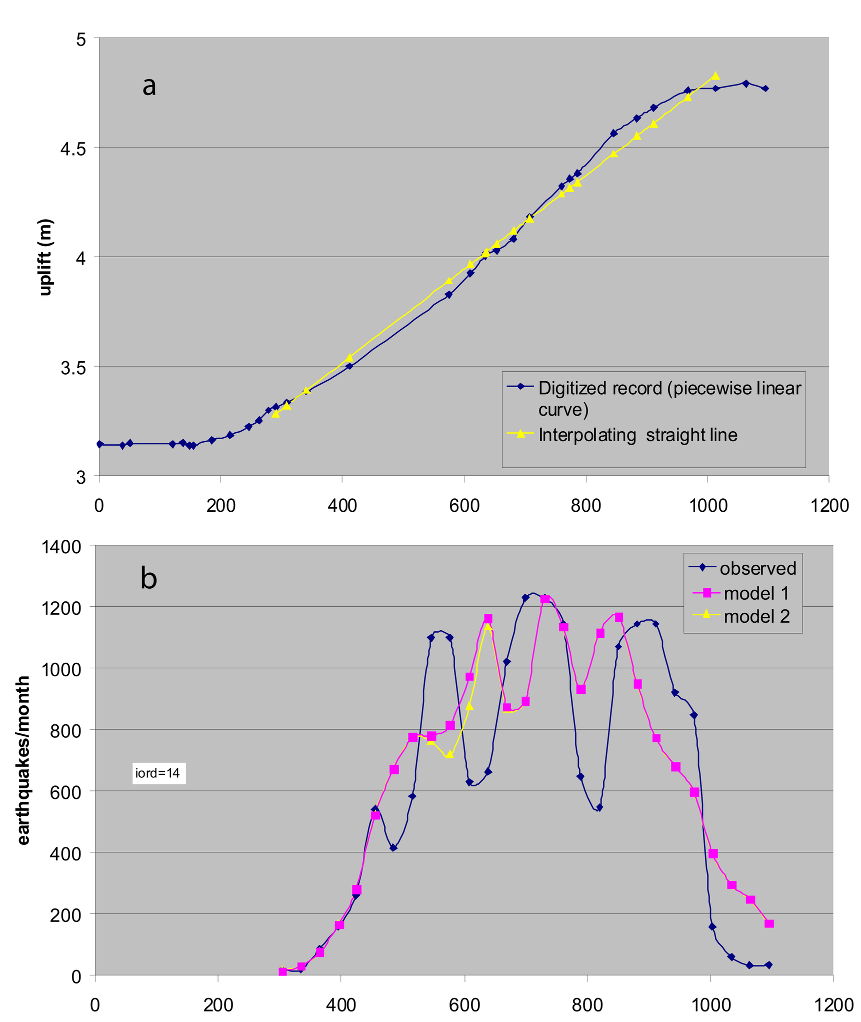

Figure 4.
a) Piecewise linear approximation of uplift as a function of time recorded by a tide-gauge at Pozzuoli (blue diamonds). The linear regression of the uplift record (in the period during which seismicity occurred, yellow triangles) is shown in order to make evident small fluctuations in the deformation rate. The record of uplift is obtained retracing by hand Figure 3a of Aster and Meyer (1988).
b) Seismicity rate changes (s.r.c) as a function of time during the 1982-1984 unrest at Campi Flegrei. "Observed" s.r.c. (blue diamonds) are evaluated by visual inspection of figure 1b. "Model 2" s.r.c. (yellow triangles) are obtained starting from the Dieterich formulation with assuming variables values of Aσ(t) and τ(t)/σ(t). In "Model 1" these parameters are assumed constant (equal to those at the beginning of the simulation, magenta squares), as it is common in previous studies estimating s.r.c..

4. Concluding remarks

Previous applications of rate- and state- dependent friction to swarm-like seismicity in volcanic areas (e.g. Toda et al., 2002) were mainly devoted to explain the spatial distribution of seismicity rates or they did not consider the effect of slowly decreasing stressing rates as that expected near the end of the uplift stage at Campi Flegrei. The model here developed explains several features of the seismicity observed at Campi Flegrei during the inflating stage. Particularly it shows that seismicity rates can be affected by either decreasing or increasing the inflation rate in a volcanic region.

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