Large calderas with areas of 100 km^2 or more are among the of elastic-brittle rock behaviour[23,24] to demonstrate that the increasing levels of VT seismicity associated with successive uplifts reflect changes in how the crust accommodates the strain energy supplied by magmatic intrusions. In particular, the behaviour follows the trend expected as the dominant factor controlling deformation changes from the elastic storage of strain energy to the release of that energy by faulting. Continuation of the trend will favour bulk failure in the crust and, hence, a greater potential for eruption than during previous emergencies. The results emphasize the importance of incorporating rock-physics criteria into strategies for evaluating the potential for eruption, especially at volcanoes that have yet to establish an open pathway for magma to reach the surface. They also highlight the need to raise awareness among vulnerable communities that a lack of eruption during recent emergencies cannot be used to infer that an eruption is also unlikely during a future crisis.

Results

. After correction for secular subsidence[2,15], the three major unrests at Campi Flegrei since 1950 have been characterized by initial uplifts for 2–3 years at mean rates of 0.3–0.6 m per year at the Serapeo in Pozzuoli, followed by minor corrected subsidence and subsequent recovery over 10–33 years (Fig. 2). The total corrected uplift at Serapeo has been c. 4 m (Fig. 2).

Rapid uplift occurs when the crust is extended over a newly intruded sill. We thus view the post-1950 unrest as equivalent to a total of 6–7 years of rapid uplift under increasing differential stress during intrusions, interrupted by decadal intervals of approximate stasis (Fig. 2). As a result, we expect the combined episodes of uplift to show the VT-deformation behaviour of an elastic crust with a large number of small faults[23,24] (Fig. 2).

. The ideal sequence of behaviour starts from lithostatic equilibrium. Initial deformation is elastic, for which strain is accommodated by deformation of unbroken rock around faults (Fig. 3). As the total strain increases, the crust's behaviour becomes quasi-elastic, for which most deformation is elastic, but a small proportion is accommodated inelastically by fault movement (which is recorded as VT seismicity). The proportion of faulting increases until it becomes the only mechanism for accommodating additional strain. At this stage, the strain stored elastically remains constant and additional deformation is controlled inelastically by fault movement alone[23,24] (Fig. 3; see equations (2)–(4) in the Methods section). In addition, the rock between faults is expected to become increasingly damaged, with a greater linkage in the inelastic regime among cracks much smaller than the faults themselves[25]. The sequence finishes with bulk failure and the potential escape of magma through a newly propagating fracture. The stored strain can then be released as the crust relaxes elastically around the newly opened fracture, as well as around the pressure source[26] that caused the precursory deformation.

The quasi-elastic and inelastic regimes are described by exponential and linear trends between inelastic and total deformation[23,24] (see equations (3) and (4) in the Methods section). The total number ΣN of VT events is a natural proxy for total inelastic deformation (not only vertical deformation), whereas the ratio h/R of maximum uplift to the horizontal radius of ground uplift is a field measure proportional to total deformation. In terms of field parameters, the exponential trend for the quasi-elastic regime becomes[23,24]

$$\Sigma N \text{ ¼ ð}\Sigma N\text{Þ}_0\text{exp½ð } h/R\text{Þ}/\text{ð}l_{ch}/R\text{Þ}$$
$$\text{¼ ð}\Sigma N\text{Þ}_0\text{exp ð } h/l_{ch}\text{Þ} \qquad \text{ð1Þ}$$

where $(\Sigma N)_0$ denotes the number of VT events at the start of quasi-elastic behaviour and l_{ch} is a characteristic displacement. Equation (1) uses the number of VT events to measure the amount of damage in the crust caused by an increase in differential stress, regardless of the source of stress.

In extension, h/l_{ch} ¼ S_d/s_T, the ratio of differential stress to tensile strength, which has a maximum value of 4 or 5.6 for eventual bulk failure in tension or in mixed tension and shear[27–29]. Here S_d refers to the accumulated differential stress in the crust after stress relaxation due to fault movement has been taken into account. Among large calderas, equation (1) has been tested[24] at Rabaul, in Papua New Guinea, where a caldera-wide uplift of 2.3 m near its centre occurred for 23 years before an intra-caldera eruption in 1994. The uplift changed from quasi-elastic to inelastic when h/l_{ch} ¼ 4 (Fig. 3), with the quasi-elastic regime accounting for about 80% 3the start of

quasi-elastic behaviour and lresults emphasizte6549.67m(ch)Tj/F8m(ch)Tj46510.5(to)Bn dimensions and process timescales, and supports our hypothesis that bulk deformation at volcanoes can be approximated to that of a crust with a large and distributed population of small discontinuities.

[illegible]. The combined corrected uplift at Campi Flegrei (with intervals of stasis removed) also follows the classic elastic-brittle sequence for deformation in extension (Fig. 5). The crust behaves elastically for $h < 1.75$ m and, after a short transition, becomes quasi-elastic for $h > 2.3$ m with l_{ch} ¼ 1 m (Fig. 5). The current corrected uplift of about 4.2 m gives $h/l_{ch} \approx 4.2$, which suggests that the crust is now approaching the transition from quasi-elastic to inelastic deformation (Fig. 5). Virtually the same VT-uplift trend appears when using uplift uncorrected for secular subsidence (Fig. 5). Background subsidence since 1950 has thus not had a significant effect on events differential stress accumulation in the shallow crust.

The VT-uplift trend is similar to that observed at Rabaul and supports our view that the entire sequence of unrest since 1950 reflects a long-term accumulation of stress in the crust (Fig. 5). This interpretation is reinforced by the remaining interval of significant VT seismicity between 1972 and 1982 (Fig. 2), which was characterized by a gradual decay in VT event rate from 200 to 300 events per month and a minor corrected, ground subsidence and recovery of about 5% of the total uplift. This was followed by a new 30-month episode of corrected uplift that, for its first 8 months until March 1983, raised the ground at Pozzuoli by 0.4 m without significant seismicity. When VT events again occurred, they accelerated to rates of about 300–500 events per month in < 3 months (Fig. 2).

The VT decay with minor ground movement resembles an extended aftershock sequence, in which fracturing and fault slip relax stresses in the surrounding rock under a constant bulk strain[34]. Before faulting can resume, the surrounding rock must be re-stressed elastically until the local stresses have returned to their values before relaxation[35]. Renewed uplift will thus occur without VT events until the stress necessary for continued faulting has been regained. From equation (1) the mean VT event rate dN/dt ¼ $[d(\ h)/dt][dN/d(\ h)]$ ¼ $[d(\ h)/dt][\Sigma N/h_{ch}]$. If the same seismic sequence is maintained across uplifts, the final VT event rate in 1972 and the starting rate in 1982 will be characterized by the same value of $\Sigma N/h_{ch}$. Hence, the ratio of their respective event rates should be similar to the corresponding ratio of their mean rates of uplift. Such similarity is indeed observed: the ratio of VT event rates lies in the range 0.7 ± 0.3, which embraces the uplift-rate ratio of 0.8 for mean uplift rates of 0.57 m per year in 1969–1972 and 0.72 m per year in 1982–1984.

The increase in differential stress during elastic recovery is proportional to the accompanying uplift; it is also numerically equivalent to the stress previously lost by seismic relaxation. To a first approximation, stress and uplift change in proportion when behaviour is quasi-elastic[23], so that the fraction of total stress lost during relaxation is approximately the ratio of uplift during elastic recovery to total uplift before relaxation, that is 0.4 out of 2.5 m or 16%. This value is consistent with independent estimates of the proportion of energy lost by seismicity during 1972–1982. The proportion of total stress relaxed by seismicity is $\sim(E_s/E_T)^{1/2}$, where E_s and E_T are the seismic energy released and total energy supplied[36]. Extrapolating the analysis of the 1982–1984 unrest[19,20], the seismic energy lost during 1972–1982 is $\sim 10^{13}$ J, whereas the total energy supplied until release [illegible] additional increase in h by c. 1.8 m. The corresponding suggests that long-term stress accumulation may be a general feature of unrest at large calderas.

Discussion

Our interpretation predicts that if the current uplift continues to a corrected value of about 4.5 m at Pozzuoli, the crust in Campi Flegrei will have returned to the stress conditions that prevailed in 1984 at the end of the last major uplift (Fig. 6). We would then expect any additional uplift to continue the VT-deformation trend interrupted in 1984 and, hence, to be accompanied by a significant increase in VT seismicity, regardless of the specific mechanism that is increasing the applied differential stress. Should the rate of uplift also return to the rapid values of 1982–1984, we would further expect the onset of VT event rates as high as 800–1,000 per month. Rapid uplift, however, is not essential. At Rabaul, for example, the approach to eruption was preceded by 2 years at a maximum recorded uplift rate of about 0.15 m per year, which was about three times smaller than the peak rates that had been registered 10 years previously[24]. A return to the long-term VT-deformation trend at Campi Flegrei may thus occur at uplift rates and VT event rates slower than observed during previous emergencies.

The indirect stress ratio h/l_{ch} suggests that the differential stress accumulated in Campi Flegrei's crust is about four times its tensile strength (Fig. 5) and so is approaching the transition from quasi-elastic to inelastic deformation regimes. An increase in linkage among small-scale cracks between faults is also expected to occur at the transition to inelastic behaviour. This would favour an increase in bulk permeability and, hence, a faster escape of fluids from the geothermal system, which is consistent with the onset of corrected subsidence in 1984. A return to the long-term VT-deformation trend may therefore be characterized by inelastic behaviour under a constant maintained stress, for which increases in total deformation are determined by additional fault movement (Fig. 3). Such a transition would be associated with VT event rates increasing in proportion to the rate of uplift.

The few field data available for large calderas and stratovolcanoes suggest that the quasi-elastic regime contributes between 40 and 80% of the total precursory deformation (Fig. 4). Assuming this range, a corrected uplift of 4.2 m at the end of quasi-elastic behaviour at Campi Flegrei (Fig. 5) indicates that the inelastic regime may continue until reaching a total corrected uplift of between 5 and 10 m before an eruption can be expected. A transitional value of 4 for h/l_{ch} assumes that bulk failure occurs in tension. The value increases towards 5.6 as the failure mechanism involves tension with an increasing component of shear[27–29]. Increasing shear could thus raise the transitional uplift by some 25% and, hence, yield a total corrected uplift of between 6.25 and 12.5 m before an eruption.

The estimated limits on total uplift are smaller than the 17 m of caldera-wide uplift inferred to have occurred during the century before the caldera's last eruption in 1538 (refs 2,6). A greater total uplift would be favoured by a larger uplift before the transition to inelastic behaviour, without necessarily changing the proportion of uplift in the two deformation regimes, or by a greater proportion of uplift in the inelastic regime alone. A larger transitional uplift would be favoured if the pre-1538 intrusions had been required to break connected horizons of rock stronger than those providing resistance today (to increase the uplift required before tensile failure). Otherwise, the difference may indicate that mechanisms for reducing effective bulk rigidity, such as bedding-plane slip[43,44], become significant as deformation proceeds (to enable greater uplift for a given applied stress); that, at timescales of $\sim 10^2$ years, non-brittle (and seismically quiet) processes, such as viscous flow[19], also contribute to deformation (to permit greater uplift than from elastic-brittle behaviour); that additional intervals of fault slip