Ground deformation at Campi Flegrei, Italy: implications for hazard assessment

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Abstract: Campi Flegrei caldera, west of Naples in southern Italy, has an exceptional documented record of ground deformation from Roman times onwards. Systematic recording began in the nineteenth century. For earlier dates, information has been obtained from archaeological studies and from contemporary descriptions of the locations of buildings, usually Roman, with respect to sea-level. Especially important have been accounts related to the Serapis, a Roman market-place built in the second century BC and now incorporated within the modern town of Pozzuoli. The long-term patterns of ground deformation have conventionally been investigated on the premise that Campi Flegrei naturally tends to a state of static equilibrium. This study argues that, instead, the area naturally tends to a steady rate of subsidence, at about 17 mm a^{-1}. After this background rate has been removed, the data indicate that a permanent uplift of some 33 m has occurred from Roman times (up until the present day: 2005 at the time of writing), attributable to the intrusion of 1.85 km^3 of magma, of which only 1% has been erupted. Uplift has occurred in three episodes, the third of which is still in progress. The behaviour can be interpreted in terms of the intermittent ascent of magma between a reservoir of *c.* 10^2–10^3 km^3 at depths of 8–15 km or greater, to a much smaller, shallower system at depths of about 3–4 km. Should the current pattern of deformation follow previous trends, uplift is expected to continue for another 80–90 years, during which time Campi Flegrei will be characterized by an elevated possibility of eruption.

as subordinate lava domes. Most of these eruptions expelled *c.* 0.1–1 km^3

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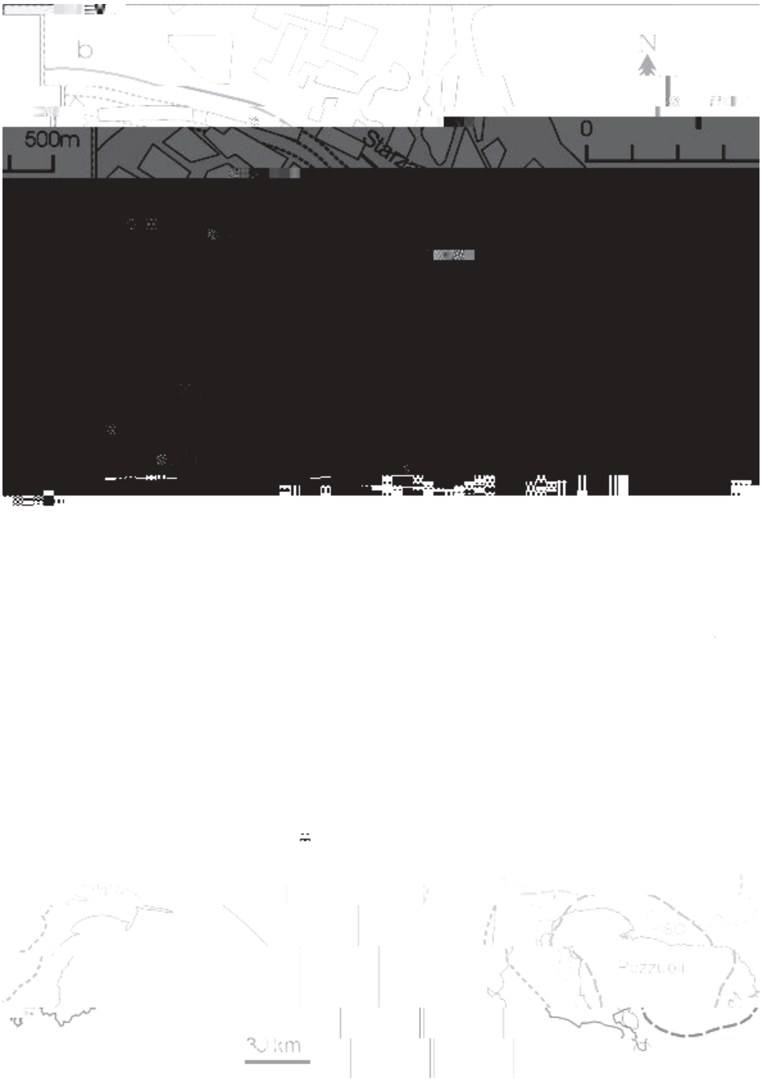

Fig. 1. Location maps for key sites in Campi Flegrei. (**a**) Pozzuoli lies in the northern half of the caldera produced by the NYT eruption (large dashes); a larger caldera (small dashes), inferred from modern topography, has been proposed as the source for the Campanian Ignimbrite (e.g. Rosi *et al.* 1983), although seismic tomographic surveys have since suggested that this feature is superficial only (Judenherc & Zollo 2004). The principal eruptive centres since the NYT eruption (*solid lines*) are scattered across the caldera floor. The Starza terrace (*grey line*) runs between Monte Nuovo (MN) and Solfatara (SO) parallel with the coast behind Pozzuoli. (**b**) Data for historic ground movements in Pozzuoli have been obtained from the Serapis archaeological site and from caves by the *Rione Terra*. Also shown is the location of the Cantariello spring, which was closer to the coast in the fifteenth Century (Fig. 6), indicating a net ground uplift since that time.

in an eruption, they both raised concern about imminent volcanic activity. Indeed, a pressing question remains as to the precursory conditions that must be fulfilled for an eruption to take place.

In this paper, we reconsider the pattern of ground movements at Campi Flegrei since Roman times, in order to identify constraints for better evaluating the likelihood of a future eruption. The study builds on the comprehensive review by Dvorak & Mastrolorenzo (1991), incorporating new data from historical documents, as well as archaeological information from Morhange *et al.* (1999) that has yet to be

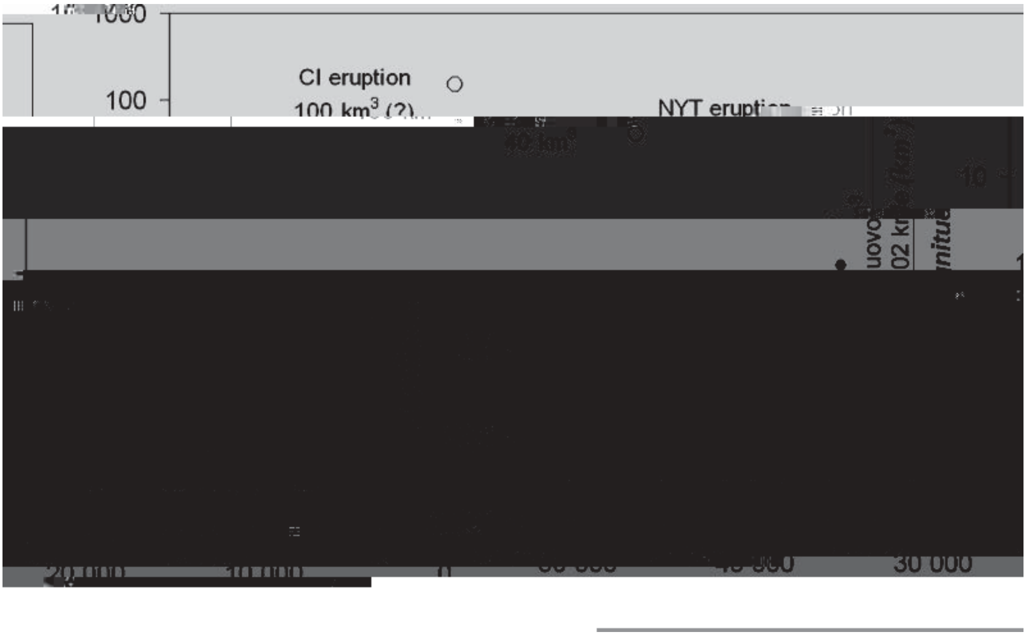

Fig. 2. Magnitude of eruptions from the Campi Flegrei caldera in the past 50 000 years.

integrated into the volcanological literature. The data suggest that the district is naturally subsiding at about 17 mm a^{-1}, and so, to investigate the processes controlling variations in deformation rate, this background value must first be subtracted from observed movements. The analysis thus contrasts with previous studies, all of which have assumed implicitly that Campi Flegrei should naturally remain in a stationary condition (*e.g.* Parascandola 1947; Dvorak & Mastrolorenzo, 1991; Morhange *et al.* 1999; Orsi *et al.* 1999).

The results support the argument of Morhange *et al.* (1999) that Campi Flegrei underwent two episodes of major uplift between Roman times and the sixteenth century. The uplift involved a total permanent displacement of about 33 m, and can be attributed to the injection to shallow depth (about 3–4 km) of some 1.85 km^3 of magma – a volume 100 times greater than the amount expelled in 1538 by the only eruption during the same period (Di Vito *et al.* 1987). They also suggest that the smaller uplifts since 1969 represent the early stages of another major episode; if verified, this inference implies that, compared with the interval since 1538, the twenty-first century will be characterized by an elevated probability of eruption.

Reconstructing ground movement in Campi Flegrei

Three key points of reference for reconstructing ground movement in Campi Flegrei are located in and around modern Pozzuoli, on the coast of the Bay of Pozzuoli 13.5 km west of Naples (Fig. 1). These are: (1) the cliff of La Starza, which, set about 300 m inland, runs some 3 km west from Pozzuoli, subparallel with the coastline; (2) Serapis, a Roman market-place built in 200 BC in Pozzuoli; and (3) the old town of Pozzuoli (founded as a Greek colony by at least the sixth century BC), or *Rione Terra*, built on a promontory about 500 m south of Serapis (Fig. 1). These nearby locations are important because levelling surveys since at least 1905 (Dvorak & Mastrolorenzo 1991) suggest that the onshore pattern of elevation changes across Campi Flegrei has been remarkably consistent, with episodes of both subsidence and of uplift showing a broadly radial decay in vertical deformation away from Pozzuoli to the edge of the volcanic field. In detail, numerical simulations by Troise *et al.* (2004) suggest that, due to the presence of ring-faults around the caldera rim, the rate of radial decay during uplift will be different from that during longer-term episodes of subsidence. Assuming similar patterns for earlier episodes of subsidence and uplift, therefore, elevation changes inferred for the Pozzuoli district can be taken as representative scales for deformation across the whole caldera.

12 m from 200 BC until sometime around 900 AD, followed by 12 m of uplift until the 1538 eruption of Monte Nuovo, the most recent event in Campi Flegrei, and then about 4 m of subsidence until the first geodetic measurements in the early 1800s

Reference horizons at Serapis

Excavations at Serapis began in 1750 (Breislak 1792; Dvorak & Mastrolorenzo 1991). Covering some 55 × 70 m^2, the site was buried by 9 m of sediment. Today, it is dominated by three marble columns, each 13 m tall, at the northeastern end of the market (Fig. 5). The columns form part of a temple, the *Aedes Serapis*, the foundations of which mark the first stage of construction on the site (according to an inscription found nearby, the *Lex Parieti Facendo*). The initial foundation supported a mosaic floor, dated to the second century BC (Levi 1969; Dvorak & Mastrolorenzo

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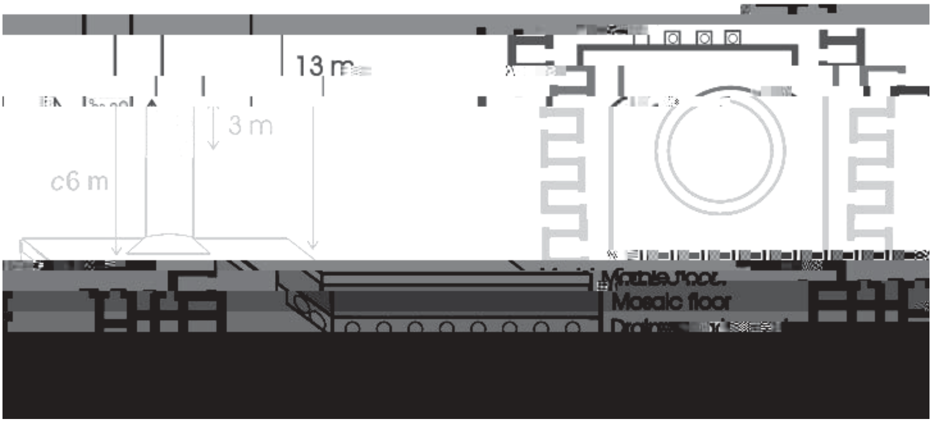
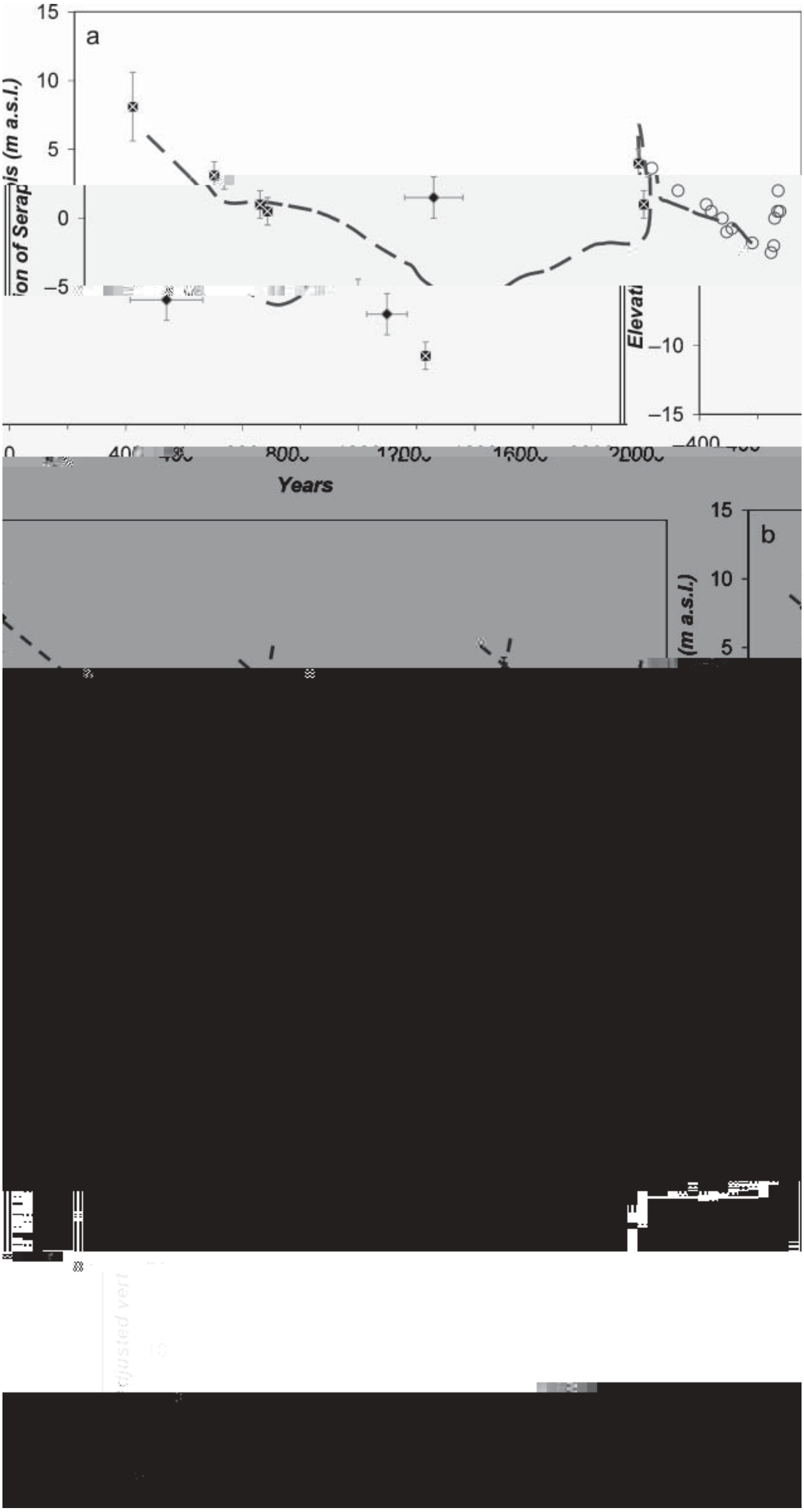

13 m
3 m
c6 m
Marble floor
Mosaic floor
Drainage

In addition to the two floors, a remarkable reference horizon for sea-level is provided by the three 13-m columns. Each has been perforated by marine bivalves (notably *Lithodomus lithophagus*) over a vertical thickness of about 3 m – the base of which stands 3 m above the

Fig. 6. Engraving from 1430 of the Cantariello thermal spring and its surrounding area, looking approximately SSW (Fig. 1). Rione Terra, the old town of Pozzuoli, is on the left. The tops of two of the columns at Serapis (about 130 m distant; Fig. 1) are clearly visible behind the figures in the foreground.

The maximum-depth estimates can be refined by new data from the 1430 engraving *Bagno del Cantariello* (Fig. 6), part of the famous *Balneis Puteolanis* of the Edinburgh Codex (Di Bonito & Giamminelli 1992). The engraving depicts the *Rione Terra* encircled by vertical yellow tuff walls, from which the beach of *Marina Della Postierla* extends (towards the viewer) to the base

of the *S. Francesco* hill, the source of the thermal
spring


a
15
10
5
0
−5
−10
−15
Elevation of Serapis (m a.s.l.)
400
800
1200
1600
2000
−400
Years
b
15
10
5
(m a.s.l.)

a major episode of uplift, it is plausible that the average rate in the long term will be similar to that before 1538. Accordingly, it is inferred that sustained uplift can occur at mean rates of about 120–150 mm a^{-1}.

The combined mean rates of subsidence and of uplift are consistent with the few data points available for uplift and subsidence during the first and second episodes respectively. The inferred trends are shown in Figure 7, applying mean rates of subsidence and uplift of 17 mm a^{-1} and 150 mm a^{-1} respectively. Although the trends between 750 and 1430 are not well constrained, they have the value of simplicity by assuming that their behaviour lies within the ranges provided by the better-constrained trends.

Magmatic intrusions beneath Campi Flegrei

The observation that vertical movements at Serapis have been dominated by subsidence at similar mean rates suggests that such behaviour represents a typical background state (possibly as a result of compaction in the crust or deeper magmatic system following formation of the NYT; e.g. Dvorak & Mastrolorenzo 1991), which occasionally has been punctuated by shorter, but much faster, intervals of uplift. To investigate the nature of the uplifts, therefore, the background rate of subsidence must first be subtracted from the observed trends; this procedure contrasts with previous analyses, for which it has been implicitly assumed that background equilibrium corresponds to no movement.

The results show that the first two uplifts each raised the Serapis by some 15–17 m (Fig. 7), almost ten times greater than the individual episodes of uplift witnessed since 1969 (Fig. 8). Moreover, these displacements are permanent; they appear otherwise only when the background rate of subsidence is ignored. Interpretations of unrest since 1969 suggest that recent deformation has been controlled by a small magma reservoir at a depth of 3–4 km, supplemented by pressure

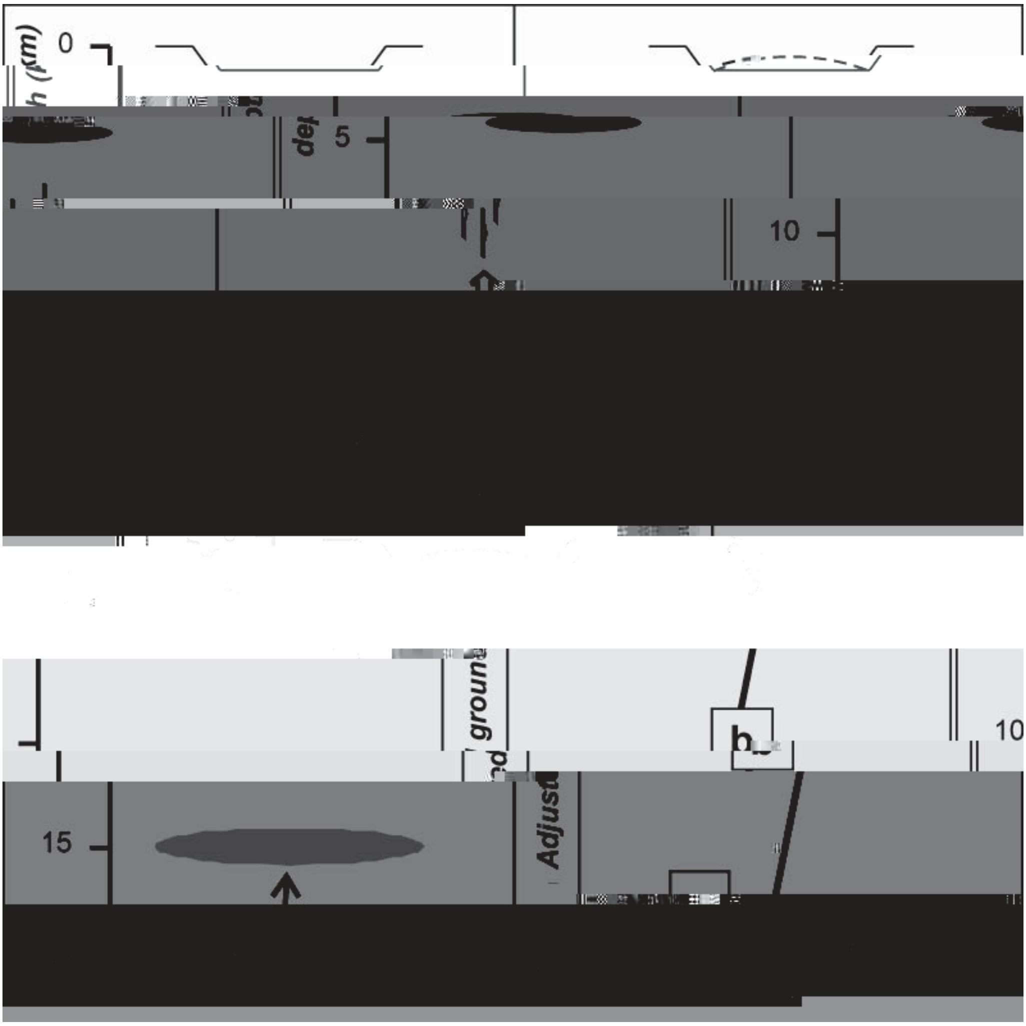


Fig. 9. The patterns of vertical deformation since Roman times are consistent with a two-reservoir system beneath Campi Flegrei. Magma is fed persistently into the lower reservoir (**a**) until it has accumulated an excess volume ΔV sufficient to cause the overlying crust to stretch and break. The excess volume escapes as a series of magma batches (**b**) that intrude into the upper reservoir (**c**). The rate of escape is faster than the rate of magma supply from depth, so that the lower reservoir returns to equilibrium until another excess volume ΔV has accumulated and the cycle is repeated. Periods of magma accumulation in the lower reservoir do not induce significant surface deformation, whereas those of magma ascent generate significant, and permanent, surface uplift (lower right; compare with Fig. 7c). The implication is that, since at least Roman times, Campi Flegrei has been subject to major magma intrusion, even though accompanied by only a modest eruption in 1538.

hundreds of cubic kilometres; indeed, it is interesting to speculate on the possible role of such a body on caldera formation.

Future eruptions in Campi Flegrei

Deformation since 1969 suggests that Campi Flegrei is currently undergoing an episode of major, intermittent uplift. By analogy with the uplifts in the Middle Ages and before 1538 (Fig. 7) the episode may continue until the vertical displacement has achieved a total adjusted value (after subtracting the background rate of subsidence) of some 15–17 m, that is, some 12–14 m in addition to its displacement since 1969 (Fig. 8). If the adjusted mean rate of uplift remains similar to that for previous episodes (150 mm a^{-1}; Fig. 7), the current episode can be expected to continue for another 80–90 years. Hence, because increased crustal displacement favours the possibility of eruption, the twenty-first century is likely to remain a period of elevated volcanic threat in Campi Flegrei, so heralding a return to a potential pre-eruptive state that has not been observed

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