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Recent Ground Movement and Seismic Activity in Campi Flegrei, Southern Italy: Episodic Growth of a Resurgent Dome

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Leveling surveys in Campi Flegrei, an active volcanic caldera in southern Italy, show that this caldera has undergone both subsidence and uplift of a few meters during the past 85 years. A single source located at a depth of about 3 km beneath the center of the caldera can account for almost all elevation changes recorded in Campi Flegrei since the first leveling survey conducted in 1905/1907. This includes leveling surveys that span periods of subsidence (such as between 1905/1907 and 1919 and between January 1985 and October 1986) and periods of rapid uplift (between March 1970 and October 1971 and between January 1981 and December 1984). A possible geometry for the source of uplift and subsidence beneath Campi Flegrei is a rectangular horizontal sheet located at a depth of about 3 km and centered a few hundred meters east of the city of Pozzuoli. The horizontal dimensions of this sheet are about 1.5 km by 3.0 km; the long axis is oriented N70°W. This sheet lies adjacent to the most intense area of seismicity that occurred from mid-1983 to December 1984. During an uplift episode this sheet may represent the top of a magma body undergoing internal pressure changes, possibly by intrusion of additional magma. Subsidence is caused by groundwater removal from the water-saturated deposits that fill this caldera to a depth of a few kilometers. A temporary increase in subsidence rate after an uplift episode is caused by increased rate of groundwater removal from newly fractured regions that lie immediately above the magma body. The close proximity of this water-saturated region and the magma body makes it impossible to separate the depth to these two sources from the results of leveling surveys. Two observations indicate that uplift has occurred in the center of Campi Flegrei for at least the past several thousand years. First, marine deposits in the center of Campi Flegrei were uplifted at least 40 m between 4000 and 8000 years ago. Second, continuous seismic profiles of the undersea portion of Campi Flegrei have identified only one region where rocks are fractured and faulted: adjacent to the uplifted marine deposits that surround the point of maximum uplift indicated by recent leveling surveys. On the basis of these observations and the historical record of activity we suggest that Campi Flegrei caldera is in a stage of growing a resurgent dome. The present diameter of the resurgent dome is about 4 km, and the maximum amount of vertical uplift during the past 10,000 years has probably not exceeded 100 m. The episodes of rapid uplift and shallow earthquake swarms during the past 20 years are probably related to the growth of this resurgent dome.

INTRODUCTION

Campi Flegrei is an explosive caldera located along the west coast of southern Italy near Naples (Figure 1). This caldera is renowned for the long historical record of activity that includes the reporting of earthquakes to differing degrees of reliability during the past 2000 years and many details about activity that occurred before and during the only historical eruption, which occurred in September 1538.

Between 1905/1907 and March 1988, 46 leveling surveys were conducted in Campi Flegrei. The purpose of this paper is to use the results of these leveling surveys and the few trilateration measurements to derive a source model that can reproduce the observed patterns of surface displacements and that conforms to the pattern of seismicity and to the constraints provided by geochemical measurements and geologic observations.

The next section of this paper briefly describes the geological setting and recent activity at Campi Flegrei. A detailed recounting of the 2000-year historical record was given by *Parascandola* [1947] and *Dvorak and Mastrolorenzo* [1990]. The results of 85 years of leveling surveys in Campi Flegrei are presented as a series of maps that show subsidence and uplift patterns in consecutive time periods. Results from the few trilateration surveys are also presented. A review of previous analyses of some of these surface deformation measurements is given in a separate section. Our analyses are based on simple geometries for a pressure source embedded in an elastic half-space that have analytic expressions for surface displacements. The model that we propose consists of a horizontal planar sheet that (1) can reproduce most of the surface deformation measurements and (2) is consistent with the earthquake pattern. The final section of this paper discusses these results in terms of similar studies conducted at other active volcanoes, including Long Valley and Yellowstone in the United States and Rabaul in Papua New Guinea.

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GEOLOGICAL HISTORY AND RECENT ACTIVITY

Campi Flegrei formed by collapse during major explosive eruptions that produced extensive volcanic tuff and ash flow

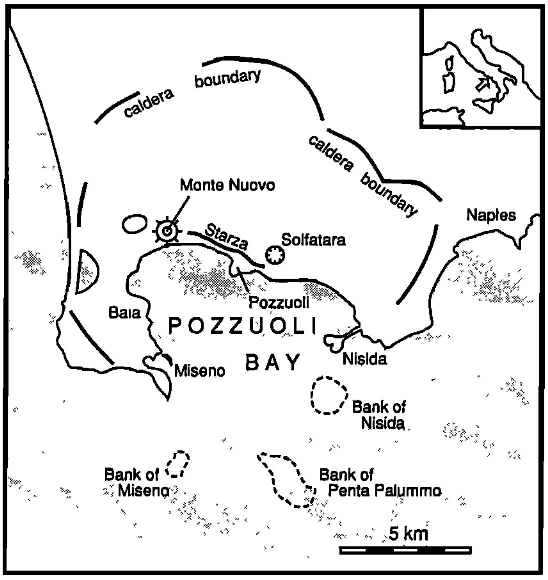

Fig. 1. Location of Campi Flegrei caldera and identification of major geographic names mentioned in the text. The city of Pozzuoli is located near the center of this caldera. Among the features identified are the cone formed by the 1538 eruption (Monte Nuovo), the sea cliff (Starza) that contains uplifted marine deposits, and Solfatara crater, a region of intense steaming and hydrothermal activity. The outer boundary of the caldera is probably defined by three banks.

deposits. Products from many postcollapse eruptions have filled the northern half of the caldera, so that the floor in this part of the caldera now stands well above present sea level. The southern half of Campi Flegrei lies as much as 100 m below sea level forming Pozzuoli Bay, located along the north shore of Naples Bay. The caldera boundaries are defined on land by arcurate, inward facing scarps and at sea by three shallow banks, which are probably submerged eruptive centers.

The two largest eruptions from Campi Flegrei, which produced most of the present caldera structure, occurred 34,000 (±3000) and 11,000 (±1000) years ago [*Di Vito et al.*, 1985]. The larger, earlier event erupted about 80 km^3 of material that formed the Campanian ignimbrite; the smaller, more recent event erupted 10 km^3 of material that formed the Neopolitan yellow tuff. During the past 10,000 years, most eruptive activity has occurred during two periods: from 10,000 to 8000 years ago and from 4500 to 3700 years ago [*Rosi and Sbrana*, 1987]. Most postcollapse eruptions built tuff or scoriaceous cones and deposited pyroclastic flows that did not extend beyond the caldera boundary. Air fall deposits from these eruptions usually fell to the east across the Italian peninsula. Two eruptions within the past 4000 years formed trachytic domes, Accademia and Monte Olibano, near the center of Campi Flegrei.

During the past 2000 years the products of only one volcanic eruption are recognized at Campi Flegrei: ash, pumice, and scoriae from the September 1538 eruption that formed Monte Nuovo. At least several years before this one historical eruption, documents suggest that uplift of the shoreline and local earthquake swarms were centered around Pozzuoli. Eyewitness accounts of the eruption mentioned receding of the shoreline near Pozzuoli by about 200 m during the 2 days immediately before the 1538 eruption, probably caused by 5–8 m of uplift near the eventual eruptive site [*Parascandola*, 1946].

During the past several thousand years the center of Campi Flegrei has undergone tens of meters of vertical movement. Interlayered marine and volcanic deposits are exposed within a 20- to 40-m-high sea cliff, called Starza, that runs along part of the north coastline of Pozzuoli Bay (Figure 1). Dating of the volcanic units exposed in this sea cliff implies that these marine layers represent three separate transgressions of the sea that occurred between 4000 and 8000 years ago [*Cinque et al.*, 1985], which was a dormant period between two major eruptive periods. Since no more than several meters of eustatic sea level rise have occurred in the Mediterranean Sea during the past several thousand years [*Labeyrie et al.*, 1976], the present elevations of these exposed marine layers cannot be explained by global sea level changes but must be the result of at least tens of meters of uplift that occurred within Campi Flegrei. The identification of a 30- to 60-m lowering of the Wurm regression surface (the most recent low stand of the sea, which occurred 15,000–18,000 years ago) in a seismic reflection survey of Naples Bay [*Pescatore et al.*, 1984] suggests that the uppermost marine layer revealed in the Starza sea cliff once may have been 70 m, though probably not more than 100 m, above present sea level.

Historical evidence indicates that subsidence of several meters has occurred along the entire shoreline of Pozzuoli Bay since the Roman age [*Parascandola*, 1947; *Dvorak and Mastrolorenzo*, 1990]. The most visible and the most famous indicator of vertical movement in Campi Flegrei is at the Roman marketplace in Pozzuoli, Serapis, located on a narrow littoral plain at the base of the Starza sea cliff. The last known restoration of this monument was during the reign of Roman Emperor Alexander Severus (A.D. 222–235). Based on illustrations of the coast of Pozzuoli Bay etched on three Roman glass flasks, this monument was probably still in use, and hence above sea level, during the fourth century A.D. (S. E. Ostrow, The topography of Puteoli and Baiae on the eight glass flasks: Puteoli III, Studi di Storia Antica, unpublished manuscript, 1979).

Excavation of Serapis in 1750 revealed that though the floor was above sea level, shells of boring mollusks were embedded in three marble columns at heights of up to 7 m above the monument's floor [*Forbes*, 1829; *Babbage*, 1847]. The existence of marine shells at this elevation on a Roman monument is undeniable evidence that at some time between the end of the Roman age and excavation of the monument, this site must have first subsided several meters below sea level then been uplifted a similar amount.

Beginning in the early 1820s, about 70 years after its excavation, visitors reported that the floor of Serapis was always covered by seawater. Between 1822 and 1960, measurements of water depth on the floor of Serapis indicated gradual subsidence of the monument (Figure 2). A series of leveling surveys conducted along the shoreline of Pozzuoli Bay in 1905/1907, 1919, 1953, and 1968 confirmed this downward movement and showed that the point of maximum subsidence was located in the center of Campi Flegrei. Measurements of the elevation of the floor of Serapis with respect to sea level and results of four early leveling surveys showed that between 1822 and 1968 the average subsidence rate near the point of maximum movement on land was about 14 mm/yr [*Berrino et al.*, 1984].

In late 1969, people living in Pozzuoli first reported the effects of ground uplift [*Yokoyama*, 1970]: offset walls and a raised bridge and wharf. Releveling of bench marks along the shoreline of Pozzuoli Bay in March 1970 showed that in Pozzuoli the ground had been uplifted about 1 m since the previous leveling survey, conducted during the summer of 1968. Results of leveling surveys conducted each month between March 1970 and October 1971 showed that uplift in Pozzuoli was occurring at an average rate of about 1 mm/d [*Zugiani*, 1972]. Leveling surveys between mid-1968 and October 1971 measured a maximum uplift of 1.485 m. During this period of steady uplift, few earthquakes were felt within Campi Flegrei.

The record from a tide gage installed in early 1970 at Pozzuoli showed that this first uplift episode ended in mid-1972 and was followed by about 2 years of slow subsidence [*Berrino et al.*, 1984]. The maximum amount of subsidence measured by leveling surveys between mid-1972 and late 1974 was 0.22 m, corresponding to an average subsidence rate of about 100 mm/yr. Annual leveling surveys conducted during the next several years showed that no elevation changes greater than 50 mm occurred along the shoreline of Pozzuoli Bay between 1972 and 1982.

In mid-1982 the tide gage record from Pozzuoli indicated the beginning of a second uplift episode, which lasted until December 1984. Leveling surveys measured a maximum uplift of 1.789 m, again located near Pozzuoli. Tide gage data between mid-1982 and December 1984 indicated a monthly average uplift rate of about 2 mm/d. Occasionally, a monthly average rate as great as 3 mm/d may have occurred [*Berrino et al.*, 1984]. The maximum uplift measured between the summer of 1968 and January 1985 was 3.000 m. Intense shallow earthquake activity, often occurring as swarms, was felt during this second uplift episode, beginning in early 1983, several months after the start of the uplift, and lasting until mid-December 1984. The largest recorded earthquake during this second uplift episode was a magnitude 4.2 earthquake on October 4, 1983 [*Branno et al.*, 1984]. Earthquake activity during this second uplift episode caused extensive structural damage to many buildings in Pozzuoli, which prompted civil authorities to order a temporary evacuation of the city [*Barberi et al.*, 1984].

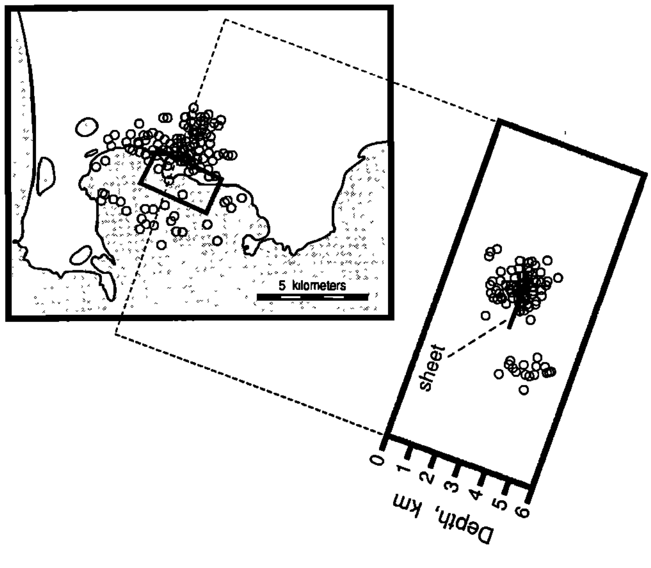

Fig. 3. Locations of earthquakes (circles) that occurred in Campi Flegrei between August 1983 and June 1984 (taken from *Aster and Meyer* [1988]). The large rectangle is the surface projection of the sheet model proposed as the source for elevation changes in Campi Flegrei. The location of this sheet is also indicated in the cross section shown at the lower right. The earthquakes displayed in this cross section were projected along the dashed line shown in the map view. Parameters for the sheet model (listed in Table 1) were derived from elevation changes that occurred between January 1981 and September 1983 and between September 1983 and January 1985.

A detailed analysis of the earthquake activity that occurred between August 1983 and June 1984 showed that most hypocenters were concentrated in a 2-km-wide zone immediately north of Pozzuoli and in a less intense area located beneath Pozzuoli Bay at a depth of 2–4 km (Figure 3, modified from *Aster and Meyer* [1988]). The three-dimensional seismic velocity structure, derived by Aster and Meyer to compute hypocenters, suggested that rocks within Campi Flegrei are highly fractured and saturated with water to a depth of about 3 km.

Since December 1984 the area around Pozzuoli has again been subsiding, so that between January 1985 and October 1986 the maximum measured subsidence is 0.274 m, corresponding to an average subsidence rate of about 150 mm/yr.

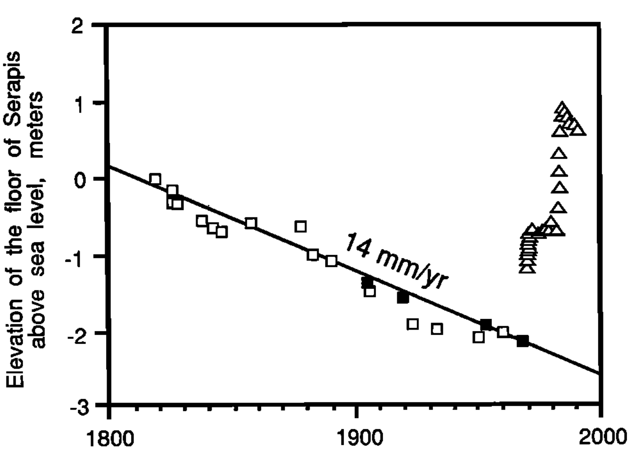

Fig. 2. Change in elevation of the floor of Serapis, the ancient Roman marketplace in Pozzuoli. Open squares denoted measurements of the depth of seawater on this floor. Solid squares are elevations determined by leveling surveys conducted along the shoreline of Pozzuoli Bay. Triangles are elevations determined by numerous leveling surveys conducted between March 1970 and October 1986. The average subsidence rate from the 1820s to 1968 was about 14 mm/yr.

MEASUREMENTS OF GROUND DEFORMATION

Results of the leveling surveys briefly mentioned above will be presented here as a series of maps showing the pattern of vertical movement in consecutive time periods from 1905/1907 to October 1986 (Figures 4*a*–4*h*). All elevation changes, expressed in millimeters, are relative to a bench mark located in Naples at Torre di Chiaia. Elevation changes are contoured only for surveys conducted after March 1970, since too few bench marks were surveyed before March 1970 to permit us to define the two-dimensional pattern of vertical movement. For these earlier pairs of leveling surveys the measured elevation changes are given beside each bench mark. On maps showing contoured

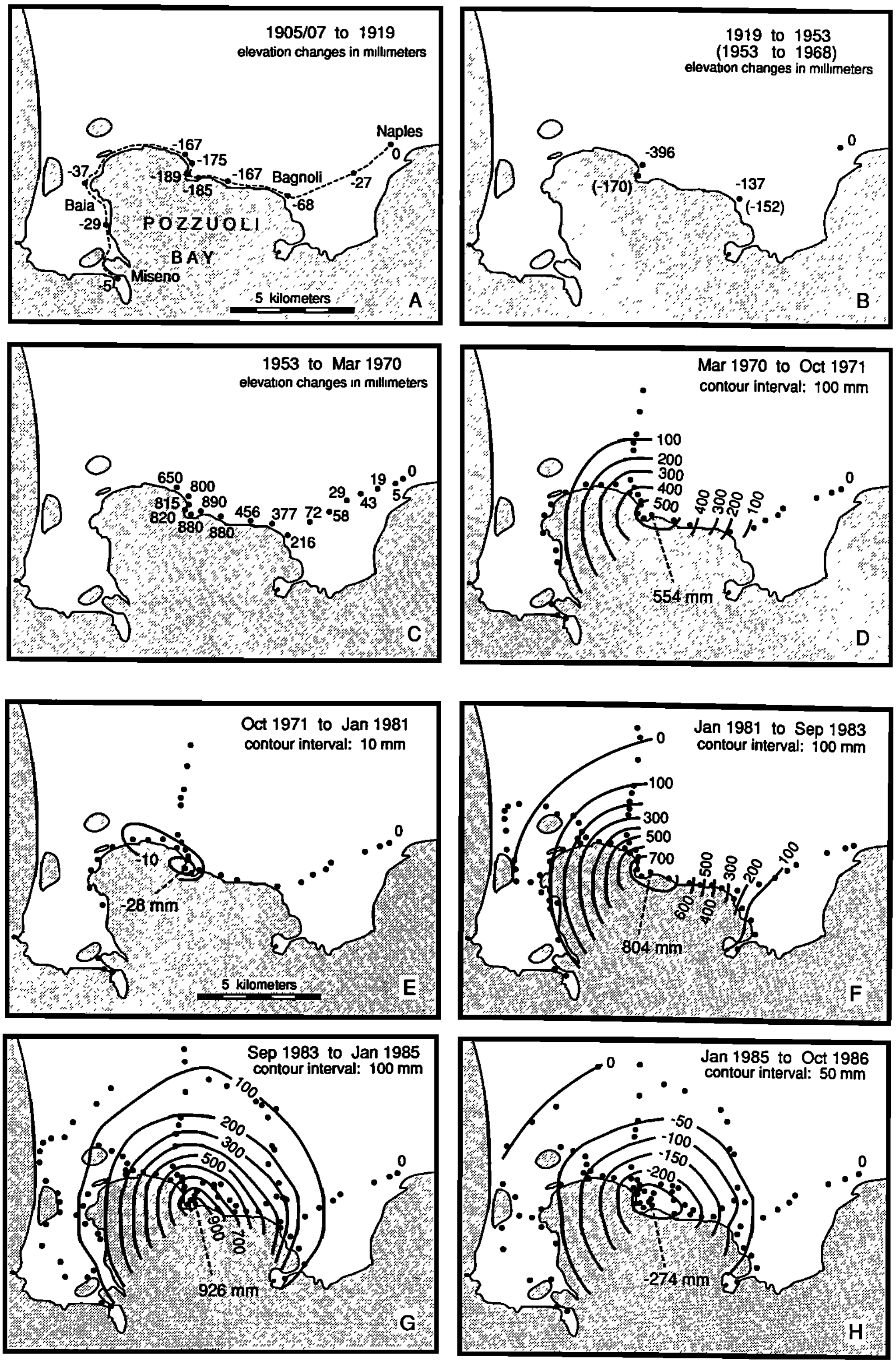

Fig. 4. Patterns of elevation changes determined from 10 consecutive leveling surveys conducted in Campi Flegrei between 1905/1907 and October 1986. All elevation changes are expressed in millimeters and are relative to the easternmost station located at Torre di Chiaia in Naples. In Figure 4*a* the path of the leveling route used in Figures 5, 8, and 9 is indicated by a dashed line that runs from Miseno to Naples. Stations common to each pair of surveys are indicated by solid circles. For earlier surveys (Figures 4*a*–4*c*), measured elevation changes are given for each station. Numbers in parentheses in Figure 4*b* are elevation changes measured between 1953 and 1968. In figures that are contoured, the amount and location of the largest measured elevation change are indicated. Contours were computed by using a linear interpolation scheme.

elevation changes the maximum elevation change is given and located.

Results of the few trilateration measurements available for Campi Flegrei are presented at the end of this section.

Leveling Surveys

Between 1905/1907 and October 1986, 46 leveling surveys were conducted in Campi Flegrei, 42 surveys since March 1970. Results for the four surveys (1905/1907, 1919, 1953, and mid-1968) that predate the two recent episodes of uplift were given by *Digiesi* [1954], *Corrado and Palumbo* [1969], and *Zugiani* [1972]. Zugiani also listed elevation changes for the leveling surveys conducted between March 1970 and July 1971. Contoured maps showing the pattern of cumulative elevation changes between January 1982 and June 1984 were published by *Berrino et al.* [1984].

As mentioned above, between 1822 and 1968, the shoreline around the city of Pozzuoli subsided at an average rate of about 14 mm/yr. The first two leveling surveys (1905/1907 and 1919) showed that the point of maximum subsidence was near Pozzuoli (Figure 4*a*). Because leveling surveys in 1919, 1953, and 1968 had few stations in common (Figure 4*b*), the point of maximum subsidence cannot be identified. The four leveling surveys conducted between 1905/1907 and 1968 suggest that during this time interval the average subsidence rate in Pozzuoli did not significantly deviate from the longer average rate of 14 mm/yr.

The March 1970 leveling survey showed that the point of maximum measured uplift (890 mm) was at a bench mark located near the eastern edge of Pozzuoli (Figure 4*c*). Results of all leveling surveys conducted during the remainder of this first uplift episode and during the entire second uplift episode also showed the maximum elevation change to be at this same bench mark. The larger number of bench marks surveyed between March 1970 and October 1971 revealed an uplift pattern roughly concentric to the point of maximum measured uplift [*Corrado et al.*, 1977] (Figure 4*d*). In this and subsequent maps we have used a linear interpolation scheme to define contours of elevation change.

Results of leveling surveys conducted between October 1971 and January 1981 showed that the small amount of subsidence that occurred between 1972 and 1982 was probably centered near Pozzuoli (Figure 4*e*). Because of the small elevation changes that occurred between 1972 and 1982, it is difficult to determine the shape of the subsidence pattern during this period.

The establishment of additional leveling bench marks before and during the second uplift episode greatly helped define the most recent uplift pattern. By June 1983, 124 leveling bench marks were being surveyed, covering most of the land portion of Campi Flegrei. Uplift patterns during the first (Figure 4*f*) and second (Figure 4*g*) halves of this episode showed very similar, nearly concentric, patterns centered slightly east of Pozzuoli. Note that the deviation from circular symmetry was similar during both intervals: a slight northwest-southeast elongation of the uplift pattern is apparent near the point of maximum uplift (most evident in Figure 4*f* by the 700-mm contour and in Figure 4*g* by the 600- to 900-mm contours). In model calculations presented later in this paper we show that a significant improvement in the model fit to these measurements is achieved by using an elongated source, instead of a cyclindrically symmetric model. The deviations from circular symmetry shown in Figures 4*f* and 4*g* are probably real and not artifacts of our contouring scheme.

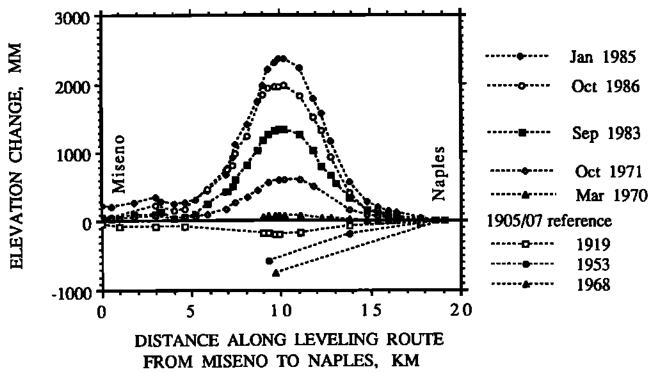

Fig. 5. Profiles of elevation changes for different surveys along the actual leveling route along the coast from Miseno through Pozzuoli to Bagnoli then to Naples. These profiles are relative to the profile measured in 1905/1907. In each profile the easternmost station, located in Naples, was held fixed. The abscissa shows the distance along this leveling route.

The final contour map of elevation changes shows the subsidence pattern that immediately followed the end of the second uplift episode (Figure 4*h*). Between January 1985 and October 1986 the largest measured elevation change was near the eastern edge of Pozzuoli (−274 mm), at the same bench mark where maximum uplift was measured by earlier leveling surveys (Figures 4*d*, 4*f*, and 4*g*). Notice in Figure 4*h* that the two innermost contours are also slightly elongated in a northwest-southeast direction; the subsidence pattern shown in Figure 4*h* is a reverse of the uplift patterns shown in Figures 4*f* and 4*g*.

Profiles of elevation changes along a leveling route in Campi Flegrei are compared in Figure 5. This leveling route begins at Miseno on the west shore of Pozzuoli Bay, follows the shoreline of Pozzuoli Bay through the city of Pozzuoli, and ends in Naples at the easternmost station shown in Figures 4*c*–4*h*. The reference level for these profiles is the 1905/1907 survey. The similarity of the uplift profiles is clearly apparent in Figure 5. The amount of subsidence between 1905/1907 and 1968 was nearly equal to the amount of uplift between 1968 and March 1970. The flatness of the March 1970 profile is further indication that the shape of subsidence and uplift patterns are similar in Campi Flegrei.

Trilateration Surveys

A few trilateration surveys have been made in Campi Flegrei, beginning in June 1970. The purpose of these surveys was to determine horizontal distances from a high point near the center of Campi Flegrei (at the Italian Air Force Academy (Accademia (S))) to three different stations (Figure 6): Baia (A), Ricettone (B), and Nisida (C). Because short-range (less than 2 km) electronic distance measuring instruments were used, horizontal distances to these three stations were determined by making distance measurements along contiguous line segments and by measuring the azimuth of each line segment. For example, the horizontal distance between Accademia and Baia was determined by projecting the length of each line segment (endpoints identi-

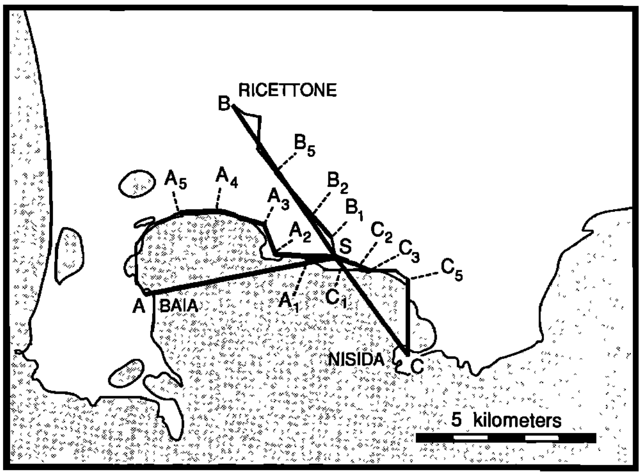

Fig. 6. Line segments used to measure the change in horizontal distance between the central point (S) at the Italian Air Force Academy and points at Baia (A), Ricettone (B), and Nisida (C). Several of these line segments (indicated by thicker lines) were measured in September 1980 and September 1983. Several intermediate stations are identified, using the naming convention of *Dequal* [1972]. Listed in Table 1 are changes in line lengths along the line segments measured by both surveys and along the three major lines between September 1980 and September 1983.

TABLE 1. Trilateration Measurements

Line Segment*	Measured Changes, mm	Point Source, mm	Rectangular Sheet, mm
S-A_1	105	166 (−61)	120 (−15)
A_1-A_2	219	286 (−67)	214 (−5)
A_2-A_3	171	222 (−52)	186 (−15)
A_3-A_4	113	45 (68)	64 (49)
A_4-A_5	4	−47 (51)	−48 (52)
S-A (Baia)	400	440 (−40)	335 (65)
B_1-B_2	148	223 (−75)	158 (−10)
B_2-B_5	89	194 (−105)	116 (−27)
S-B (Ricettone)	205	408 (−203)	229 (−24)
S-C_1	25	33 (−8)	29 (−5)
C_1-C_3	56	42 (14)	33 (23)
C_5-C	126	78 (48)	51 (75)
S-C (Nisida)	89	3 (86)	−7 (96)
Residual model fit		82 mm 58 ppm	45 mm 26 ppm

Changes in line lengths from September 1980 to September 1983. Numbers in parentheses are differences between measured and computed changes in line lengths.
*See Figure 6 for identification of line segments.

fied by a subscripted "A") onto the line connecting Accademia (S) and Baia (A).

Between June 1970 and September 1983, surveys along contiguous line segments beginning at Accademia were conducted eight times to the stations at Baia and Ricettone and four times to the station at Nisida. Unfortunately, these surveys often used different intermediate line segments, so that horizontal length changes between intermediate stations can seldom be determined. The last two surveys, conducted in September 1980 and September 1983, had the most line segments in common: the 10 segments identified by thicker lines in Figure 6. Results of the first two surveys (June and September 1970) and a description of the survey technique and computations are given by *Dequal* [1972]. Survey results are reported for June 1970 to September 1980 by *Barbarella et al.* [1983*a*] and for September 1980 to September 1983 by *Barbarella et al.* [1983*b*]. For the second time interval, measured changes in line length are listed in Table 1.

Figure 7 shows a comparison of elevation changes at Serapis and horizontal distance changes measured between Accademia and Baia. Elevation changes are shown as triangles in the top diagram and as a dashed curve in the bottom diagram. The bottom diagram indicates that between 1970 and 1983 the amount of uplift that occurred at Serapis was, by coincidence, almost identical to the amount of horizontal extension that occurred between Accademia and Baia. On the basis of this correlation, because the total amount of uplift was 3 m near Pozzuoli between 1968 and 1985, we suggest that about 3 m of extension probably occurred between Accademia and Baia during this same time period, corresponding to a total horizontal strain of 580 ppm. This may be the largest amount of surface strain measured across a distance of several kilometers in a volcanic region without an eruption.

PREVIOUS ANALYSES OF GROUND DEFORMATION MEASUREMENTS

A simple point source model embedded in an elastic, isotropic, homogeneous material can reproduce the basic pattern of elevation changes measured at many active volcanoes, including the uplift pattern measured at Campi

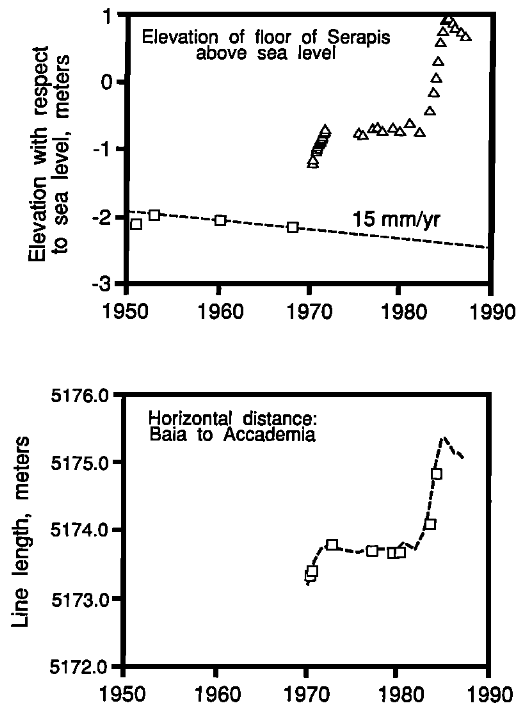

Fig. 7. Comparison of elevation changes of the floor of Serapis (top) and of changes in the horizontal distance between the Italian Air Force Academy (S, Accademia) and Baia (A) (bottom). The dashed curve in the bottom diagram shows the elevation changes measured by leveling surveys at Serapis between March 1970 and October 1986, shown as triangles in the top diagram.

Flegrei [*Corrado et al.*, 1977; *Berrino et al.*, 1984]. Analyses of cumulative elevation changes between January 1982 and June 1984 at Campi Flegrei showed that the location and depth of the point source remained essentially the same [*Berrino et al.*, 1984]: located beneath the point of maximum measured uplift at a depth of 2.8 km.

The success of the point source model at Campi Flegrei and at other active volcanoes is not surprising because, as illustrated by finite element calculations by *Dieterich and Decker* [1975], similar uplift patterns are produced by different source geometries, provided that the source geometry is axisymmetric about an axis perpendicular to the surface. These include spherical, oblate, and prolate geometries. Dieterich and Decker also showed that measurements of horizontal strains or the determination of horizontal displacements would greatly help to distinguish among these different axisymmetric geometries.

Bianchi et al. [1987] rejected a spherical geometry for the pressure source producing uplift at Campi Flegrei because in order to produce the few meters of uplift, this geometry required pressure changes no less than a kilobar (0.1 GPa), which is much larger than the tensional strength of rocks, about 0.05 GPa. To circumvent this problem, Bianchi et al. showed, also using a finite element technique, that an oblate geometry for a source embedded in a medium with varying elastic properties could reproduce the uplift profiles recorded at Campi Flegrei between 1970 and 1972 and between 1982 and 1983 and that the pressure change required by their model to produce the measured amount of uplift was 0.03 GPa. In their calculations, Bianchi et al. used an oblate spheroid with a semimajor diameter of 3.0 km and a vertical height of 1.5 km. The center of their spheroid was 5.4 km beneath the surface. In order to account for the 635 mm of maximum uplift measured between January 1982 and June 1983 they assumed a very low rigidity of 16 kbar (1.6 GPa) for the material surrounding their oblate spheroid and a rigidity of 2500 kbar (25 GPa), more typical of the Earth's crust, for material far from the source. The assumed low rigidity surrounding the source enabled them to use an internal pressure of only 0.03 GPa. The 5.4-km depth to the center of the source used by Bianchi et al. was significantly greater than the 2.8-km depth to the point source determined by *Berrino et al.* [1984], presumably because of the nonhomogeneous elastic values used by Bianchi et al.

G. De Natale and F. Pingue (personal communication, 1990) have proposed a three-dimensional model for the uplift determined from a three-dimensional grid of point sources. The pressure value of each point source was estimated by an iterative technique. Their solution was subjected to two constraints: (1) No point source can have a negative value for pressure and (2) no point source can have a pressure greater than the tensile strength of rock. In their calculations they assumed a value of 0.025 GPa for the tensile strength. Because of the large number of unknown pressure values (approximately 8000, one for each point source) their model gave an excellent fit to the pattern of elevation changes and to almost all measured line length changes. The pressure distribution in their grid showed that most of the pressure increase occurs within 2 km of the surface and extends horizontally about 2 km from the center of uplift.

Bonasia et al. [1984] applied a nonaxisymmetric model to leveling and trilateration measurements that consisted of a two-dimensional planar sheet, that is, a model representing plane strain. Model calculations presented in their paper were for an infinitely long horizontal sheet oriented N70°W and located at a depth of 3 km with a width of 1–2 km.

In their separate analyses, *Corrado et al.* [1977], *Berrino et al.* [1984], *Bianchi et al.* [1987], and *Bonasia et al.* [1984] assumed that the pattern of horizontal displacements was axisymmetric and, based on this assumption, used horizontal displacements derived from the three sets of contiguous line segments shown in Figure 6. Because of the very limited trilateration network at Campi Flegrei, we relax the assumption of axisymmetric horizontal displacements and will make all of our comparisons of measured and computed horizontal movements based on line length changes and not on horizontal displacement. Our nonaxisymmetric model improves by a factor of 2 the degree of model to the trilateration data.

MODEL CALCULATIONS

We have made calculations for two different types of models: the point source and the rectangular planar sheet. We first computed solutions using a point source to determine if, between consecutive pairs of leveling surveys, a migration may have occurred in the position of the pressure source or if a change may have occurred in the inflation rate. In contrast, *Berrino et al.* [1984] determined point source models for only cumulative elevation changes, and so they could not recognize small variations in position of the pressure source or inflation rate.

The rectangular planar sheet model has been applied to elevation changes recorded during two periods of uplift and two periods of subsidence. About a dozen trilateration measurements are also available during one of these periods. These measurements will be used to show that the pattern of horizontal strain measured in Campi Flegrei can be reproduced better by a rectangular sheet model than by an axisymmetric model.

Point Source

A point source model has been determined for the elevation changes measured by each consecutive pair of leveling surveys conducted between 1953 and October 1986. Subsidence occurred only during two of these intervals (from October 1971 to January 1982 and from January 1985 to October 1986). We have also computed a point source model for the time interval between the first two leveling surveys conducted in Campi Flegrei, from 1905/1907 to 1919. For each time interval, five model parameters were determined: latitude and longitude of the point source, depth beneath the surface of the point source, volume of uplift or subsidence, and amount of vertical movement of the reference bench mark at Torre di Chiaia in Naples. An iterative technique was used to determine the five model parameters that minimized in the least squares sense the difference between measured and computed elevation changes.

For all time intervals considered, regardless if uplift or subsidence had occurred, the horizontal position and depth to the point source did not vary by more than a few hundred meters. Table 2 shows the average values for latitude, longitude, and depth determined from surveys conducted since June 1983, that is, those surveys that covered most of the land area of Campi Flegrei. The latitude and longitude position is 250 m east of the station where the maximum

TABLE 2. Model Parameters

	Values
Point source	
Latitude	40°49′21″N
Longitude	14°07′41″E
Depth, km	2.8
Rectangular sheet	
Latitude of the center of the sheet	40°49′21″N
Longitude of the center of the sheet	14°07′41″E
Depth to the center of the sheet, km	3.0
Sheet length, km	3.0
Sheet width, km	1.5
Dip angle	0°
Strike angle along the sheet length	N70°W

Comparison of Solutions	Point Source	Rectangular Sheet
Jan. 1981 to Sept. 1983		
Volume of uplift, m^3	43×10^6	40×10^6
Residual model fit, mm	36	28
Sept. 1983 to Jan. 1985		
Volume of uplift, m^3	47×10^6	45×10^6
Residual model fit, mm	49	30
Jan. 1985 to Oct. 1986		
Volume of Subsidence, m^3	14×10^6	12×10^6
Residual model fit, mm	19	18

measured elevation changes are indicated in Figures 4*c* and 4*d* and 4*f*–4*h*. Because no significant variations were determined for the horizontal or vertical positions of the point source models, the amount of maximum measured vertical movement for any survey is proportional to the volume of uplift or subsidence at Campi Flegrei: 1 mm of vertical movement in the city of Pozzuoli is equal to 50,000 m^3 of uplift or subsidence.

Rectangular Planar Sheet

Examination of exposed cross sections at eroded volcanoes shows that the three-dimensional geometry of many intrusive bodies are approximately tabular in form (one dimension of the body is much smaller than the other two dimensions) so that the general shape of these bodies can be approximated by a rectangular planar sheet. Besides the geometry of a tabular body, the rectangular sheet model also approximates expansion along one side of a large body that may have nearly equidimensional sides. In this case, the sheet model can still be used if the amount of expansion perpendicular to one face of the body is much smaller than the overall dimensions of the body, for example, upheaval of the roof overlying a magma chamber. It is this second case that we feel the rectangular planar sheet model may be appropriate for Campi Flegrei: a magma body up to a few kilometers in horizontal and vertical dimensions has undergone expansion, perhaps by introduction of additional material or by the exsolution of volcanic gases during cooling. This expansion is relieved primarily by vertical displacement of the top of the magma body.

The sheet model used in our calculations consisted of a rectangular surface with at least one edge constrained to be parallel to the surface, allowing any combination of dip and strike angles. The boundary condition on the sheet was displacement directed perpendicular to the plane of the sheet and constant across the sheet. Analytic expressions for surface displacements for this sheet model were given by *Okada* [1985]. Nine model parameters were determined for this rectangular sheet model: latitude and longitude of the center of the sheet, depth to the center of the sheet, sheet length, sheet width, dip angle and strike angle of the sheet, the amount of displacement perpendicular to the sheet, and amount of vertical movement of the reference bench mark. The volume of uplift or subsidence is given by the product of the sheet length, the sheet width, and the displacement.

As for the point source model, an iterative technique was also used for the sheet model to determine the model parameters that minimized in the least squares sense the difference between measured and computed elevation changes. A set of model parameters was computed for January 1981 to September 1983 and another set for September 1983 to January 1985. Both time intervals were periods of uplift. Except for the amount of displacement on the surface of the sheet, all other corresponding parameters derived for the two time periods were nearly the same: horizontal position and depth to the sheet varied by less than 0.4 km; sheet length and width varied by less than 0.3 km; and dip angle and strike angle varied by less than 5°. The average value for each parameter is listed in Table 2. As expected, the latitude and the longitude of the center of the sheet coincide with the latitude and longitude of the point source solutions. Furthermore, the depth to the center of the sheet and the depth to the point sources were within 0.3 km. The projection of this sheet on the surface is shown in Figure 3.

The amount of displacement across the plane of the sheet was 9.7 m for 1981–1983 and 10.9 m for 1983–1985, which correspond to uplift volumes of 40 and 45×10^6 m^3, respectively. For comparison the uplift volumes determined for the point source models for these same two time periods are 43×10^6 m^3 for 1981–1983 and 47×10^6 m^3 for 1983–1985.

The residual model fit listed in Table 2 for the point source and rectangular sheet models for each time period was determined by the square root of the sum of the squares of the residuals divided by the number of stations. The rectangular sheet models reduced the residual model fit by 20% for 1981–1983 and by 40% for 1983–1985. A comparison of measured and computed elevation changes for both time periods along the leveling route used in Figure 5, along the coast from Miseno to Pozzuoli and ending at Naples, is shown in Figure 8*a*.

The point source and rectangular sheet models for 1981–1983 were used to compute changes in line lengths along the 13 line segments indicated by thicker lines in Figure 6. These computed line length changes are compared in Table 1 to measured changes for the time period from September 1980 to September 1983. Leveling surveys and tide gage records showed that vertical movement was less than 0.12 m near the city of Pozzuoli during the 1-year period from September 1980 to September 1981. Numbers in parentheses in Table 1 are the differences between measured and computed changes in line lengths.

Compared to the point source model, the rectangular sheet model is slightly better in reproducing line length changes along the line segments between Accademia and Baia (S–A) and is much better along line segments to the north between Accademia and Ricettone (S–B). Length changes along the

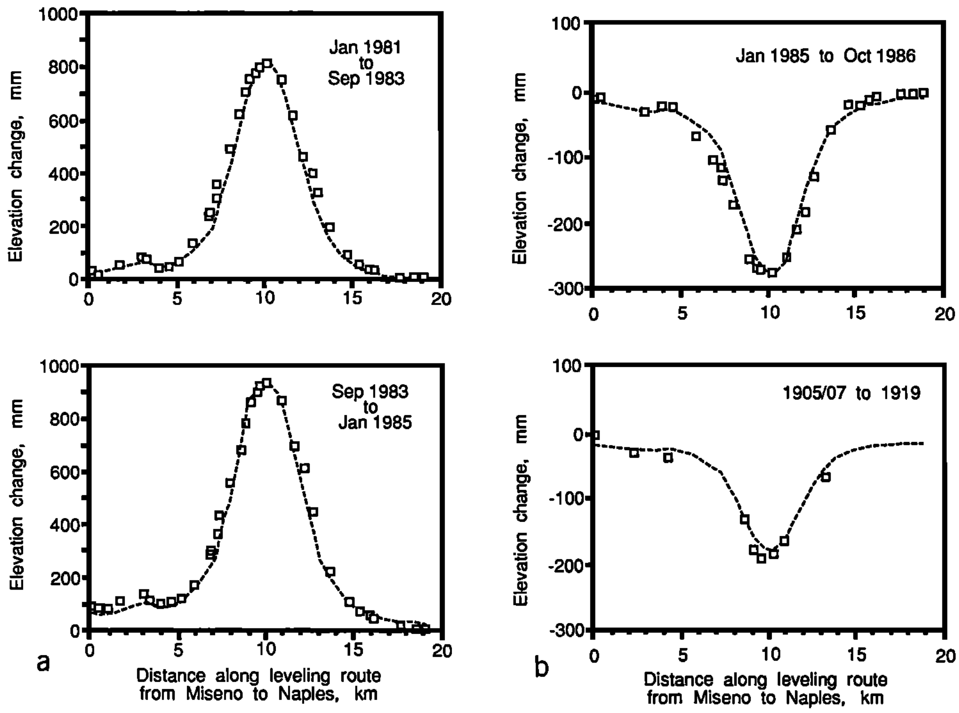

Fig. 8. Comparison of measured and computed elevation changes along the leveling route from Miseno to Pozzuoli to Naples. This is the same leveling route used in Figure 5. The abscissa shows the distance along the leveling route from Miseno to Naples. Measured changes are indicated by open squares; computed changes are indicated by dashed curves. (*a*) Two periods of uplift: (top) January 1981 to September 1983; (bottom) September 1983 to January 1985. (*b*) Two periods of subsidence: (top) January 1985 to October 1986; (bottom) 1905/1907 to 1919.

two lines to Nisida (C) are, however, poorly reproduced by either model.

The residual model fit to trilateration measurements was computed in a similar manner to that used to compute the residual model fit to elevation changes: the square root of the sum of the squares of the residuals divided by the number of lines. For trilateration measurements we computed the residual model fit two ways: in terms of change in line length and change in strain. In either case, the results in Table 1 show that the rectangular sheet represents about a 50% reduction in the residual model fit over the point source.

Parameters for a rectangular sheet model were also determined from elevation changes for one period of subsidence, from January 1985 to October 1986, the only subsidence period that had large vertical movement (maximum of 274 mm) and broad station coverage (Figure 4*h*). The dimensions and location of the rectangular sheet model determined for this subsidence period were within 0.3 km of those determined for the two uplift periods. On the basis of this model, between January 1985 and October 1986 the amount of displacement perpendicular to the sheet was 2.9 m. A comparison of measured and computed elevation changes during this subsidence period is shown in the top diagram in Figure 8*b* along the same leveling route used in Figures 5 and 8*a*.

We used the dimensions, location, and orientation of the rectangular sheet listed in Table 2 to determine if we could also reproduce the subsidence profile measured along the coast of Pozzuoli Bay between 1905/1907 and 1919. The comparison shown in Figures 8*a* and 8*b* suggests that pressure changes from the same source geometry can produce rapid uplift and both short- and long-term subsidence in Campi Flegrei.

We have also examined the residual pattern that remains after subtracting the contribution of the rectangular sheet model from measured elevation changes. The residual pattern for uplift periods, such as 1981–1983, shows a concentric high surrounding a low centered at the point of maximum uplift, shown in the top diagram in Figure 9. The range between the high and low areas is about 120 mm—about 15% of the maximum measured uplift. The concentric high peaks are at a distance of about 3 km from the point of maximum uplift, near the edges of the buried sheet. During subsidence, such as in 1985 and 1986, the residual pattern is inverted, a concentric low surrounding a small central high shown in the lower plot in Figure 9. These residual patterns can be removed by introducing more complexity into our sheet model, for example, by stacking sheets of different widths and lengths to approximate a sheet with tapered edges. One model of stacked sheets that can reduce the total range of residual values to less than 10 mm tapers to zero displacement at a horizontal distance of about 3 km from the point of maximum uplift. The average depth to this model is still about 3 km.

DISCUSSION

The frequent and diverse measurements made at Campi Flegrei during the past two decades, since recognition of the first uplift episode, have provided an opportunity to study the detailed behavior of a large magmatic and hydrothermal system. In the following subsections we suggest that the

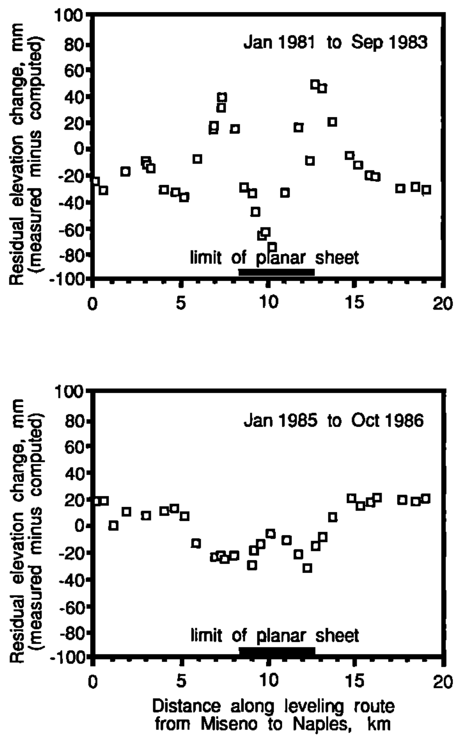

Fig. 9. Residuals in elevation changes (measured minus computed) along the same leveling route used in Figures 5 and 8. (Top) A period of uplift: January 1981 to September 1983. (Bottom) A period of subsidence: January 1985 to October 1986.

existence of a shallow magmatic body beneath Campi Flegrei is consistent with the petrology of material erupted during the past several thousand years and with the absence of a major magmatic gas component. Also, we compare the recent level of activity at Campi Flegrei and other active explosive calderas, placing the recent activity at Campi Flegrei in context with these other calderas. A generalized cross section for Campi Flegrei is proposed in the last subsection.

Previous Objections Raised About a Shallow Magma Body Beneath Campi Flegrei

Martini [1986] raised doubts that increased pressure within a shallow magmatic body could be the source for large vertical movement at Campi Flegrei. As evidence, he cited a systematic change in the petrology of material erupted during the past 10,000 years and the absence of a significant magmatic component to gases emitted within Campi Flegrei.

The first objection centered on the major chemistry of whole rock samples of the latest eruptions of Campi Flegrei. *Armienti et al.* [1983] showed that this rock chemistry was consistent with fractional crystallization of an isolated magma body. While these results support a model in which no new magma has been introduced into the magma body that fed eruptions during the past 10,000 years, other models could also adequately explain the petrology of recent erupted material. A less restrictive interpretation prohibits only the mixing of a more mafic magma with the magma that has been erupted during the past 10,000 years. Intrusion of mafic magma from below would cause expansion of the magma chamber and uplift of the Earth's surface, but because of a much higher solidus temperature and a higher density for a more mafic magma, this new magma would not be able to mix and chemically modify the higher and cooler, more silicic layers in the chamber.

The inability to relate changes in gases emitted at Campi Flegrei to a magmatic source was also used by *Martini* [1986] to argue against expansion of a magma body as the cause for recent seismicity and uplift. Martin ascribed all relative changes in gas concentrations to changes in a hydrothermal system. A similar argument has also been put forward by *Tedesco et al.* [1988] based on numerous measurements of the concentration of several major gas species, including hydrogen, methane, carbon dioxide, and water. Changes in these concentrations were used as geothermometers and geobarometers to estimate the temperature change and the depth where the temperature change occurred. On the basis of measurements and calculations presented by Tedesco et al., since 1985 a 30°C drop in temperature has occurred at a depth of about 400 m. This very shallow depth indicates that all changes in gas emission in Campi Flegrei are not directly related to a deeper magma body but are probably the result of changes in the circulation pattern of aquifers that lie within a few hundred meters of the surface.

By computing the magnitude of tensional stress produced by a pressurized source, we can estimate if conditions permit the opening of cracks and the release of magmatic gases from a deep magma body to the surface. Following the calculations and discussion given by *Rundle and Whitcomb* [1984], we have computed the magnitude of tensional stress along a vertical pathway from the middle of one of the long sides of our proposed horizontal sheet to the surface (Figure 10). In these calculations we assumed a value of 30 MPa for the rigidity of the crust. The dashed curves are parameterized by the maximum amount of surface uplift: the left curve would correspond to conditions after the 1.5 m of maximum uplift measured by 1972 and the right curve would correspond to conditions after the 3.0 m of maximum uplift measured by December 1984. Because the surface is free of tractions, the magnitude of tensional stress goes through a minimum value.

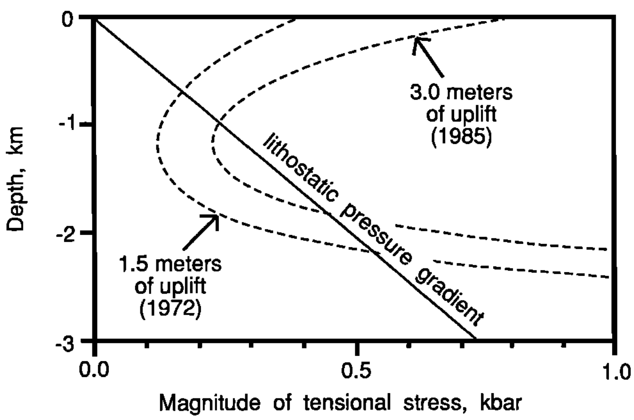

Fig. 10. Magnitude of tensional stress perpendicular to a vertical trajectory that goes from the middle of one long edge of the sheet to the surface. The tensional stress arises from the opening of the horizontal sheet proposed as the source of uplift in Campi Flegrei. Sheet dimensions are given in Table 2. The two dashed curves are parameterized by the maximum amount of uplift. (The years indicate when this amount of uplift had occurred in Campi Flegrei.) The solid line is the compressional stress resulting from lithostatic pressure, assuming a rock density of 2.5 g/cm^3.

The solid line in Figure 10 approximates the lithostatic pressure gradient for a constant density of 2.5 g/cm^3. Tensional stress would first exceed the lithostatic load immediately around the pressure source, then near the surface. Gas and other fluids may flow at greater rates through these two regions but are not able to interact freely between the pressure source and the surface. Under these conditions we would not expect a significant magmatic gas component emitted at the surface. This is supported by the calculations made by *Tedesco et al.* [1988], who showed that the changes in relative gas concentrations quoted by *Martini* [1986] must have occurred within a few hundred meters of the surface, possibly by interactions among previously isolated shallow aquifers. Sufficient pressure has not yet been reached within the magma chamber to form cracks and pathways to allow migration of magmatic gases to the surface. Our calculations also suggest that very little additional pressure of the source is required to open pathways and, possibly, result in an eruption.

Internal Stress State

A rectangular planar sheet model has been used as the geometry for the pressure source that produced uplift at Long Valley caldera in California [*Savage and Cockerham*, 1984; *Denlinger et al.*, 1985] and subsidence at Yellowstone caldera in Wyoming [*Dzurisin et al.*, 1989]. Using both leveling and trilateration measurements, these investigators determined that a major source of vertical movement and horizontal strain could be nearly horizontal bodies located at a depth of about 10 km directly beneath the resurgent domes at both calderas. The horizontal dimensions of the sheet model were 9 km for Long Valley and 15 km for Yellowstone. To reproduce the 0.09 m of maximum uplift measured at Long Valley between 1982 and 1983, the displacement perpendicular to the sheet must be 0.25–0.4 m, depending on the assumed existence and location of other possible sources for surface deformation at this caldera [*Savage and Cockerham*, 1984]. Scaling this model to the total amount of uplift measured between 1975 and 1983, which was about 0.5 m, the amount of sheet displacement at Long Valley since 1975 may have been as much as 2.5 m. The lesser amount of displacement at the surface compared to the amount of displacement at the source is a direct result of the assumed elastic behavior of the crust and the finite geometry of the source: displacements at the surface are distributed over a much larger area than the area of the planar sheet, though the volume of uplift at the surface is probably close to the volume of expansion of the sheet.

We have also assumed a rectangular planar sheet for the source geometry of pressure changes beneath Campi Flegrei. Results from numerous leveling surveys presented in this paper show that this sheet is much shallower and smaller for Campi Flegrei than for either Long Valley or Yellowstone. Because of the large amount of surface uplift and the shallowness of the source, the amount of displacement across the sheet must be much larger than for Yellowstone: for Campi Flegrei, maximum uplift of 3 m at the surface is produced by 40 m of displacement across the plane of the sheet.

A main objection to a point source model for pressure changes at Campi Flegrei has been the large internal pressure increase, about 100 MPa, required to produce the few meters of maximum uplift [*Bianchi et al.*, 1987]. A pressure increase of this magnitude was rejected by Bianchi et al. because it exceeds the maximum tensile strength of typical crustal material, which is about 50 MPa. The pressure within a source can be reduced either by increasing the horizontal dimensions of the source or by assuming a lower crustal rigidity. Bianchi et al. used both a broad source and a low rigidity for the surrounding material in their finite element calculations to reduce the internal pressure of the source to 30 MPa. On the basis of their calculations the ratio of source pressure to crustal rigidity, which is a measure of strain, was 0.02. Because the behavior of the crust is assumed to be linearly elastic, this ratio is also approximately the amount of strain across the source region. In their finite element model, Bianchi et al. used a value of 1.6 GPa for the rigidity of material immediately surrounding the source. In our view, their upper limit on source pressure is not a strong constraint. The intense earthquake swarms at Campi Flegrei from 1982 to 1984 indicate that rock was fracturing at depths of a few kilometers, so that the pressure increase within and immediately surrounding the source did exceed the tensile strength. Only outside the region of intense fracturing did the crust respond elastically.

In our sheet model the 3 m of maximum uplift recorded at Campi Flegrei since 1968 are produced by 40 m of vertical displacement directed perpendicular to the plane of the sheet. This amount of displacement across the 1.5-km width of the sheet gives an average strain at the source of 0.03, nearly the same average strain across the source estimated for Campi Flegrei by *Bianchi et al.* [1987]. Our estimated value for average strain across the source for Campi Flegrei is much larger than for other active volcanic calderas, such as Long Valley, California, which has a ratio of 0.0003 (= 2.5 m/9 km), which probably indicates a much larger buildup of pressure at Campi Flegrei.

Resurgent Calderas

Campi Flegrei is a resurgent caldera: It has a broad structural dome uplifted after the caldera-forming eruption. However, Campi Flegrei is not in the same class as the classic examples of resurgent calderas, such as Valles, Creede, and Yellowstone. Campi Flegrei has a less silicic and smaller underlying magma chamber. The amount of vertical uplift in Campi Flegrei has been at least 40 m, indicated by the present elevation above sea level of the uppermost marine terraces within the Starza sea cliff. Because Campi Flegrei lies within a regional depression that has been subsiding for at least the past 10,000 years, the total amount of uplift has probably been much more than 40 m. Our best indicator of the amount of regional subsidence during the past 10,000 years is provided by interpretations of oceanographic seismic reflection profiles made immediately south of Pozzuoli Bay [*Pescatore et al.*, 1984], which suggest that the Wurm regression surface is depressed 30–60 m [*Dvorak and Mastrolorenzo*, 1990]. On the basis of these estimates the total amount of uplift near the center of Campi Flegrei has probably been 70–100 m.

The continuing growth of the resurgent dome 34,000 years after the caldera-forming event at Campi Flegrei is consistent with the timing of resurgence indicated by detailed field studies at inactive and eroded resurgent calderas. *Smith and Bailey* [1968], who first proposed the term "resurgent caul-

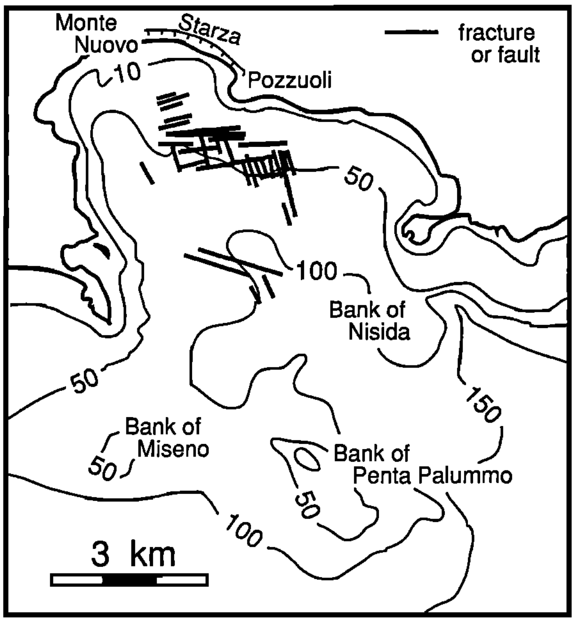

Fig. 11. Pattern of faulting in the undersea portion of Campi Flegrei revealed by seismic reflection profiles (taken from *Colantoni et al.* [1972]). These profiles were made in water depths of 20 m or greater. Bathymetric contours are given in meters.

dron," suggested that resurgence of explosive calderas occurs early in the postcollapse history, probably in less than 100,000 years. They also recognized that minor eruptions, much less in intensity than the caldera-forming event, may occur during resurgence along ring fractures and fractures of the uplifted structural dome. In a recent, more extensive review of field work at several resurgent calderas, *Lipman* [1984] concluded that resurgence may occur within a few tens of thousands of years after caldera formation. Lipman noted that while resurgent calderas are more common in large (i.e., >10-km diameter) calderas in cratonic crust and are related to silicic intrusions, resurgence can occur in interoceanic arc calderas; in fact, the largest resurgent caldera is Lake Toba, located along an island arc in Indonesia.

The lateral extent of the resurgent dome at Campi Flegrei is indicated on land by the uplifted marine terraces exposed in the Starza sea cliff, which extends about 4 km along the coastline (Figure 11). The seaward extent of the resurgent dome is revealed by results of oceanographic seismic reflection profiles that identified a region of fractures and normal faults surrounding the city of Pozzuoli [*Colantoni et al.*, 1972], also indicated in Figure 11. The uppermost stratigraphic layers recognized in the reflection profiles are less disrupted by these fractures and faults, which may indicate that uplift has occurred in several distinct episodes during the past several thousand years.

A volcano very similar to Campi Flegrei is Rabaul caldera, Papua New Guinea, an explosive caldera, about 12 km in diameter, that formed within the last few tens of thousands of years. By coincidence, Rabaul has also undergone dramatic uplift and intense earthquake swarms since 1970 [*McKee et al.*, 1984]. The point of maximum uplift is near the geometric center of this caldera. Rabaul caldera also lies partially submerged beneath the sea: the maximum depth of the caldera floor below sea level is about 75 m. Seismic reflection profiles in this bay revealed that the center of this caldera has been domed, indicated in seismic reflection profiles by parallel trends in normal faulting and in two anticlinal folds [*Green et al.*, 1986]. These structural features, which indicate long-term uplift, are located in the same area as the center of maximum uplift identified in leveling surveys conducted at Rabaul since 1973.

Iwo Jima is a volcanic caldera where there is evidence for recent vertical movement that exceeds the amount of movement at Campi Flegrei. Like Campi Flegrei and Rabaul, Iwo Jima is also a young explosive caldera with a diameter of about 9 km. Unlike the other two calderas, however, uplift at Iwo Jima has probably been steady during the past 200 years, at a rate of about 15 mm/yr. During the past 1000 years this uplift has been episodic (*Kaizuka et al.* [1983], reference taken from *Newhall and Dzurisin* [1988]). At the center of Iwo Jima is a 3-km-wide uplifted tuff deposit, probably the top of a resurgent dome.

During the past century, eruptions have occurred at both Rabaul and Iwo Jima: three magmatic eruptions at Rabaul since 1850, the latest in 1937; and 10 phreatic eruptive periods at Iwo Jima since 1889, the latest in 1982. At Rabaul, dramatic uplift of a few meters and shallow earthquake swarms preceded eruptions by several months to a few years. Details of the uplift and seismic activity at Iwo Jima are not known; however, an increase in earthquake activity did precede the 1982 eruption by at least a few days. In contrast, Campi Flegrei has had only one eruption during the past few thousand years, in 1538, which was preceded by dramatic uplift and damaging earthquake swarms.

Generalized Cross Section of Campi Flegrei

A generalized cross section of Campi Flegrei is proposed in Figure 12. The general earthquake pattern and the existence of a highly fractured, water-saturated zone beneath the center of Campi Flegrei that extends to a depth of at least 3 km were adapted from results of seismic measurements presented by *Aster and Meyer* [1988]. Information about the extent of the thermometamorphic zone is taken from results of several drill holes [*Rosi and Sbrana*, 1987].

Our cross section suggests that the top of a zoned magma body lies at a depth of about 3 km beneath the center of Campi Flegrei, which corresponds to the position of the horizontal sheet model proposed in this paper as the source for surface displacements. Lying directly over this chamber is a low-density region that probably consists of material erupted and deposited during the major caldera-forming event 34,000 years ago. According to *Aster and Meyer* [1987], seismic P and S wave velocities indicate that most of this overlying region is water saturated. We suggest that uplift is primarily caused by rapid expansion of the magma chamber, possibly by intrusion of additional material, and that subsidence is caused by the removal of fluids from a deep hydrothermal system.

The region where the highest concentration of shallow earthquakes occur in Figure 3 probably surrounds the upper portion of this chamber and, to the north, extends to depths below the top and outlines the northern boundary of the magma chamber. A similar close proximity of a pressure source, also a magma body, and an intense earthquake region has been recognized in the summit area of Kilauea

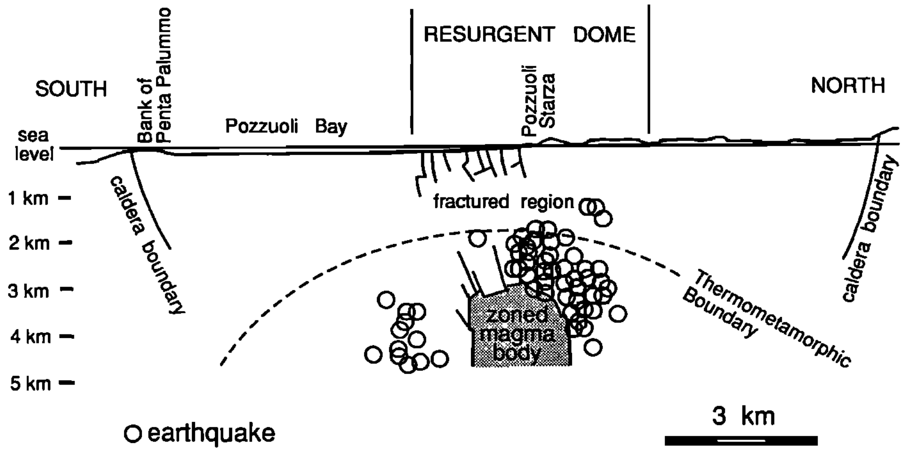

Fig. 12. Proposed north-south cross section across Campi Flegrei. This cross section is partly based on information given by *Rosi and Sbrana* [1986, 1987] and on the three-dimensional seismic velocity model of *Aster and Meyer* [1988]. The existence of the near-surface fracture region south of the city of Pozzuoli is inferred from the map shown in Figure 11. The northern extent of this fractured region is unknown because continuous seismic profiles have not been done in water shallower than 20 m or on land. The earthquake pattern is adapted from the cross section shown in Figure 3.

Volcano in Hawaii. At Kilauea the pattern of hypocenters define a zone that contains few earthquakes [*Klein et al.*, 1987]. The pressure sources giving rise to uplift and to subsidence in the Kilauea summit are located in the upper half of this aseismic region at depths of 2–4 km beneath the surface [*Dvorak et al.*, 1983].

SUMMARY

Campi Flegrei is a young explosive caldera in the early stages of forming a resurgent dome. Evidence for the presence of a resurgent dome is inferred from two features located near the center of the caldera: (1) three 4000- to 8000-year-old marine layers uplifted 40 m above present sea level and (2) a fractured and faulted region along the north shoreline of Pozzuoli Bay, identified in oceanographic seismic reflection profiles. Two recent episodes of uplift and shallow earthquake swarms, also located in the center of Campi Flegrei, were probably activity related to growth of the resurgent dome. Inferences from the historical record suggest that uplift and earthquakes preceding the 1538 eruption were located along the north shore of Pozzuoli Bay. What might be the cause for this episodic activity?

On the basis of field observations at several silicic calderas, *Lipman* [1984] concluded that resurgence is associated with postcollapse magmatic intrusions. Using Lipman's conclusion, we suggest that resurgence at Campi Flegrei could be caused by the intrusion of a hotter, more mafic magma into a body of higher silicic content that forms a zoned magma chamber. Eruptive products during the last 10,000 years, however, have only tapped the uppermost, more silicic layers of the zoned chamber. Though petrological analyses of these eruptive products indicate that no magma mixing has occurred, these analyses cannot rule out the possibility that additional material of a more mafic chemistry and higher temperature has been intruded. The lack of a magmatic component in gases emitted in Campi Flegrei also does not exclude expansion of a magma chamber as the source for recent uplift and the cause for shallow earthquakes. A magmatic component may not be present in emitted gases because the pressure increase within the magma chamber has not yet overcome the confining lithostatic pressure resulting in the opening of pathways from the magma chamber to the surface.

The only compelling evidence for the role of groundwater in causing vertical movement at Campi Flegrei is the long-term subsidence, which has occurred at an average rate of about 14 mm/yr from the 1820s to 1968. The subsidence rate temporarily increased to a rate of about 100 mm/yr after both uplift episodes. We propose that subsidence at Campi Flegrei is mostly the result of the migration of fluids from a hydrothermal system: long-term subsidence is controlled by the constant lithostatic load that provides the force to remove fluids from the water-saturated layer beneath Campi Flegrei. The short-term, more rapid subsidence results from increased permeability and increased pressure at depth that temporarily raises the flow rate from deep regions of the hydrothermal system.

The most compelling evidence for magma as the cause for uplift is the abrupt onset and end to the two recent uplift episodes. The second episode began and both episodes ended in a period of less than a few weeks, possibly within a few days (Figure 13). Changes in flow rate of groundwater require several months to a few years to respond to changing temperature and pressure conditions. Though calculations presented first by *Babbage* [1847] and later by *Grindley* [1976] indicated that uniform heating of a 3-km-thick slab by 10°C will result in about 1 m of expansion, their calculations did not consider the rate of heat transfer or the finite size of the source. More realistic calculations based on a three-dimensional thermal conduction model indicate that thousands of years are required before significant changes occur in the temperature structure around Campi Flegrei [*Giberti et al.*, 1984]. While a convective mechanism would increase the rate of heat transfer, this rate would probably still be insufficient to account for the abrupt beginning and end to the recent uplift episodes.

Our explanation for the observations and measurements recently made at Campi Flegrei is based on a model of pressure changes within a shallow magma chamber and a confined aquifer lying very close to the chamber. The

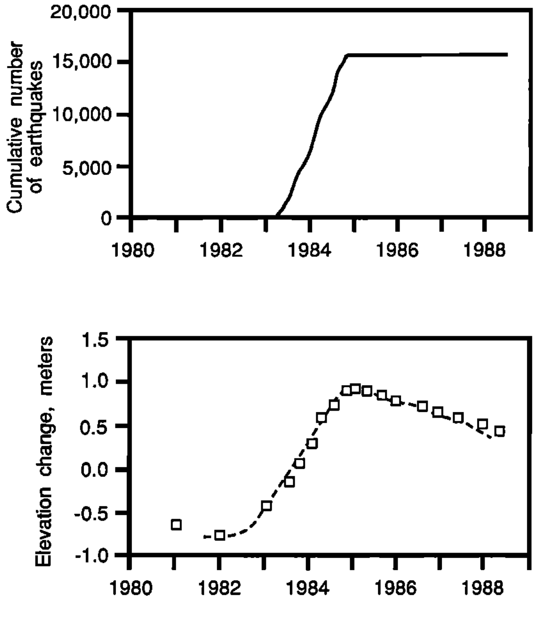

Fig. 13. Number of earthquakes and vertical movement between 1980 and 1989. (Top) The cumulative number of earthquakes recorded by the seismic network operated in Campi Flegrei by Vesuvius Observatory. (Bottom) The elevation change on the floor of Serapis: symbols are elevations determined by repeated levelings to a nearby bench mark; the dashed curve shows the elevation changes inferred from the tide gage record operated about 300 m from Serapis in the port of Pozzuoli. Data were provided by Vesuvius Observatory.

surface displacements can be adequately explained by assuming an elastic behavior. Beneath the surface, especially around the magma body, the elastic constants may be different from the values for normal crust, an effect considered by *Bianchi et al.* [1987], or other mechanical behavior may be important. We have used a homogeneous elastic model because this model displays many important aspects, such as a minimum in the value of tensional stress (Figure 10) and approximate dimensions and location of the pressure source.

We suggest that expansion of the magma chamber produces rapid uplift of the surface and, when sufficient pressure is reached, fractures the surrounding rock. This fracturing increases the permeability, allowing groundwater in an aquifer overlying the magma chamber to flow faster. The increased subsidence rate that occurs for a few years after each uplift episode is caused by the increased flow of groundwater out of this aquifer. Though the magma chamber and aquifer obviously do not occupy the same space, because of their close proximity, perhaps within several hundred meters, the results of recent leveling surveys cannot separate the depths to these two nearby sources of pressure changes.

Will the recent activity in Campi Flegrei culminate in an eruption? No definitive indicator is known that can be used to make an unqualified prediction of a volcanic eruption. Presumably, a buildup of pressure within a magma body produces localized uplift and shallow earthquake swarms. As this pressure buildup continues, the surrounding rock is strained to a yield point. Eventually, cracks and fractures form a pathway to the surface and an eruption occurs. At Campi Flegrei the regions near the surface and surrounding the shallow magma chamber have already begun to crack and fracture. From our rough estimates of the magnitude of tensional stress (Figure 10) we suggest that Campi Flegrei might not undergo another episode of 1.5 m of uplift without an eruption. We qualify this by saying that this uplift must occur within the next few decades. A longer time period between uplift episodes might allow relaxation of the stresses built up by the two recent uplift episodes. Perhaps this is an important characteristic in the growth of a resurgent dome: the crust is uplifted and strained episodically, but the strain rates are too low to open cracks to the surface and to permit major eruptions. Geologic observations at several resurgent calderas show that a resurgent dome can grow to a height of several tens to hundreds of meters without major eruptions accompanying the uplift. If uplift episodes are separated by a long time period, the stress buildup that accompanies each uplift episode has sufficient time to relax. Some support for this suggestion is provided at Campi Flegrei: tens of meters of uplift implied by uplifted marine terraces within the Starza sea cliff occurred during a dormant period, from 4000 to 8000 years ago, that was bounded by two eruptive periods. Whether Campi Flegrei remains in a long dormant state or undergoes a series of eruptions will depend on the amount of time allowed for stresses to relax after an episode of rapid uplift.

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