Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields caldera, Italy

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ABSTRACT

The importance of Pozzuoli's archaeological ruins in linking sea-level change and Earth deformation with volcanic activity has been recognized since the nineteenth century. The pillars of the Roman market were used as a paleotide gauge by pioneer geologists such as Lyell. For the first time, we have radiocarbon dated biological indicators on these remains, showing three 7 m relative sea-level highstands during the fifth century A.D., the early Middle Ages, and before the 1538 eruption of Monte Nuovo. These repeated uplift and subsidence cycles, not always followed by volcanic activity, have important implications for the evaluation of volcanic hazard.

Keywords: volcanology, archaeology, sea level, caldera, Phlegrean Fields, Italy.

INTRODUCTION

Pozzuoli's Roman pillars became famous for their role in the nineteenth century debate opposing catastrophists and uniformitarians (Lyell, 1830; Ager, 1995; Dolan, 1998; Rudwick, 1998; Gould, 2000). These remains have since come to symbolize a triumphant icon of actualism—the postulate that the present is a key to the past. The Roman pillars, pierced by biological borings, were used as a paleotide gauge, elucidating rapid sea-level changes over the past 2000 yr. Built near the shoreline, and in the center of an active caldera, the columns have recorded a series of ground motions since antiquity. Several authors have used the monument to propose a deformation history for this volcanic system (Parascandola, 1947; Dvorak and Mastrolorenzo, 1991; Orsi et al., 1999). Until now, however, scholars had deplored the absence of fossils on which to perform absolute dating, without field verification (Dvorak and Mastrolorenzo, 1991; Gould, 2000). Given that ground uplift may represent a precursor of eruptive activity (Newhall and Dzurisin, 1988), detailed reconstruction of past deformation history has important implications for the evaluation of the caldera's present state (Orsi et al., 2004).

GEOLOGICAL SETTING

Pozzuoli is at the centre of the Phlegrean Fields caldera (southern Italy), an active volcanic complex characterized by significant recent ground deformation (Fig. 1). Volcanic activity is documented back to ca. 60 ka, since which time two major events have occurred: the Campanian Ignimbrite eruption (39 ka) (De Vivo et al., 2001) and the Neapolitan Yellow Tuff eruption (15 ka) (Deino et al., 2004). According to Di Vito et al. (1999), intense volcanic activities occurred between 12 ka and 3.8 ka. After a long period of quiescence spanning many millennia, chronicles report a small phreatic event in 1198 (Rosi and Sbrana, 1987). The last eruptive activity in the caldera occurred in 1538, with the Monte Nuovo eruption.

Historically, secular subsidence has been interrupted by rapid crustal uplifts. Concomitant relative sea-level movements are therefore exceptionally intense in the Pozzuoli area, in stark contrast to the average ~50 cm sea-level rise recorded in the northwest Mediterranean Sea since Roman time (Pirazzoli, 1976). In the decades preceding the 1538 eruption, repeated episodes of ground uplift were reported in local chronicles: two royal acts were released in 1503 and 1511 to distribute newly emerged littoral lands below Rione Terra. Two days before the eruption, uplift had culminated in a +7 m ground movement (relative to present sea level), as attested by Delli Falconi's A.D. 1539 gravure (Fig. 2). A 200 m seaward shift of the coastline was recorded at that time. The two major events of 1969–1972 and 1982–1984 resulted in

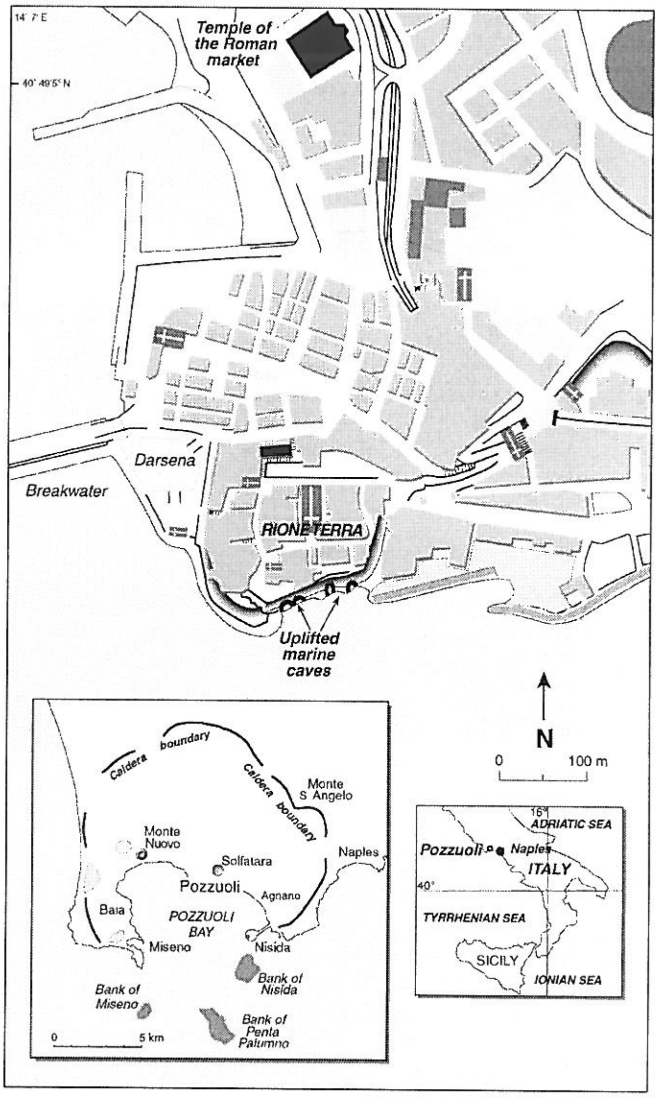

Figure 1. Location of studied site, Pozzuoli, Phlegrean Fields, southern Italy.

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Figure 2. Delli Falconi's A.D. 1539 gravure, showing crustal deformation of Pozzuoli Bay in connection with 1538 volcanic eruption of Monte Nuovo (in Toledo, 1539).

a total uplift of ~3.5 m (Barberi et al., 1984). Shallow seismic activity required the evacuation of the town of Pozzuoli in 1984. Despite concern for a possible renewal of the volcanic activity, no eruption occurred at that time, and the slow subsidence that started in 1985 continues today (Orsi et al., 1999; Milia et al., 2000). Only minor (a few centimeters) and short-lasting uplift episodes have since been recorded in 1989, 1994, and 2000 (Gaeta et al., 2003).

METHODS

Fossil marine organisms are excellent tools in measuring former sea-level positions in microtidal environments (Laborel and Laborel Deguen, 1994). The limit between the midlittoral and subtidal zones is marked by a sudden increase in species diversity, which corresponds to biological sea level. This benchmark appears as a line between the lower cupulae of midlittoral limpet erosion and the subtidal bioconstructions (e.g., vermetid rims). The accuracy obtained depends upon the preservation state of the upper limits of fossil populations. Pirazzoli et al. (1996) and Morhange et al. (2001) achieved accuracy of ±5 cm for elevated populations of *Lithophaga* burrows and marine organisms fixed on archaeological remains. Quantifying the magnitude of the sea-level lowstands is more complex, because evidence has been destroyed by more than 2000 yr of marine bioerosion and human impacts.

Fossils were found at three different sites in Pozzuoli: the ancient columns, nearby volcanic cliffs, and an excavated Roman cave (Fig. 1). Marine fauna elevations were obtained by leveling surveys using a tacheometer, the reference datum being present biological sea level, e.g., the upper limit of living subtidal *Corallina* algae. We sampled the upper limit of populations of fixed or boring molluscs, including *Lithophaga lithophaga*, *Ostrea edulis*, *Vermetus* sp., *Chama gryphoides*, and *Astroides calycularis* (Table 1; Fig. 3). Specimens collected for dating were in situ and in excellent taphonomic condition. Biological material was ^{14}C dated at the Lyon and Oxford radiocarbon laboratories. Radiocarbon dates from marine specimens have been conventionally corrected via $\delta^{13}C$ measurements and calibrated using a local marine reservoir age. Two articulated valves of *Tellina planata*, collected alive by Di Fiore in 1932, yielded ages of 645 ± 30 yr B.P., corroborated by data from Siani et al. (2000) and Reimer and McCormac (2002) (Table 2).

RESULTS

Three groups of radiocarbon dates can be identified. The first group is composed of three dates. Two *Lithophaga* (+7 m) from the market yielded ages of 2185 ± 50 yr B.P. and 2250 ± 35 yr B.P. (Fig. 3). The hard marble columns are characterized by the absence of developed erosional notches, suggesting that the period of submersion was short. Also at +7 m, vermetid shells yielded an age of 2225 ± 45 yr B.P. The mean age of this group is 2230 ± 25 yr B.P. (calender [cal.] yr A.D. 334–527). After rapid submersion of the Roman market, crustal uplift explains the death of the marine organisms. These radiocarbon dates are compatible with epigraphic data, which mention the Roman market for the last time in A.D. 394. This implies a rapid relative sea-level rise during the fourth century A.D.

The second set is composed of three dates. *Chama gryphoides* valves, from a Neronian wall in a Rione Terra cave, were dated to 1735 ± 45 yr B.P. This date is consistent with the high relative sea level recorded on the market pillars (1875 ± 60 yr B.P. and 1955 ± 40 yr B.P. at +7 m). The mean age of this group is 1860 ± 25 yr B.P. (cal. yr A.D. 698–884). Substratum uplift explains the death of the organisms. These data can be correlated with a bedded sandy marine beach infilling the same Roman cave (Morhange et al., 1999). This marine layer is dated to seventh to ninth centuries A.D. by potsherds, such as Dressel 2/4 amphorae and A & C sigillata. No eruption followed this second episode of ground movement.

Four recent dates compose the third group. *Astroides calycularis* colonies were dated to 1245 ± 55 yr B.P. and 1110 ± 45 yr B.P. at +7 m. In the same marine cave, an *Ostrea edulis* shell was dated to 1225 ± 40 yr B.P. *Lithophaga* from the Roman market yielded an age of 1235 ± 40 yr B.P. The mean date for this last group is 1205 ± 20 yr B.P. (cal. yr A.D. 1336–1454), a chronological range concomitant with the beginning of a crustal uplift phase. Historical sources testify to uplift of the substratum at the end of the fifteenth century, several decades before the eruption of Monte Nuovo in 1538 (Dvorak and Mastrolorenzo, 1991). Our data suggest that ground motion could have begun earlier, ca. A.D. 1400.

DISCUSSION

Relative sea-level curves drawn by various authors suggest different scenarios for crustal-related sea-level changes in Pozzuoli since Roman time (Parascandola, 1947; Dvorak and Mastrolorenzo, 1991;

TABLE 1. RADIOCARBON DATES OBTAINED FROM FOSSIL MARINE ORGANISMS IN THE POZZUOLI AREA

Laboratory reference	Material	$\delta^{13}C$ (‰)	Age (^{14}C yr B.P.)	Calibrated age (A.D.) using 645 ± 30 yr B.P.	Location
Lyon967 (OxA)	*Astroides calycularis*	−2.12	1245 ± 55	1286–1451	Rione Terra
Ly 9412	*Ostrea* sp.	Est. 0	1225 ± 40	1310–1445	Rione Terra
Ly 8558	*Astroides calycularis*	Est. 0	1110 ± 45	1383–1563	Rione Terra
Lyon 829 (OxA)	*Lithophaga lithophaga*	2.67	1235 ± 40	1306–1441	Columns
Lyon 948 (OxA)	*Chama gryphoides*	1.55	1735 ± 45	795–1021	Excavation
Ly 8559	*Lithophaga lithophaga*	Est. 0	1875 ± 60	648–911	Columns
Lyon 1667 (OxA)	*Lithophaga lithophaga*	3.04	1955 ± 40	603–785	Columns
Lyon 1234 (OxA)	*Lithophaga lithophaga*	3.32	2185 ± 50	330–606	Columns
Lyon 1666 (OxA)	*Lithophaga lithophaga*	3.56	2250 ± 35	264–492	Columns
Lyon 1233 (OxA)	*Vermetus* sp.	1.26	2225 ± 45	276–544	Columns

Note: All samples taken at 7 m above present mean sea level (msl).

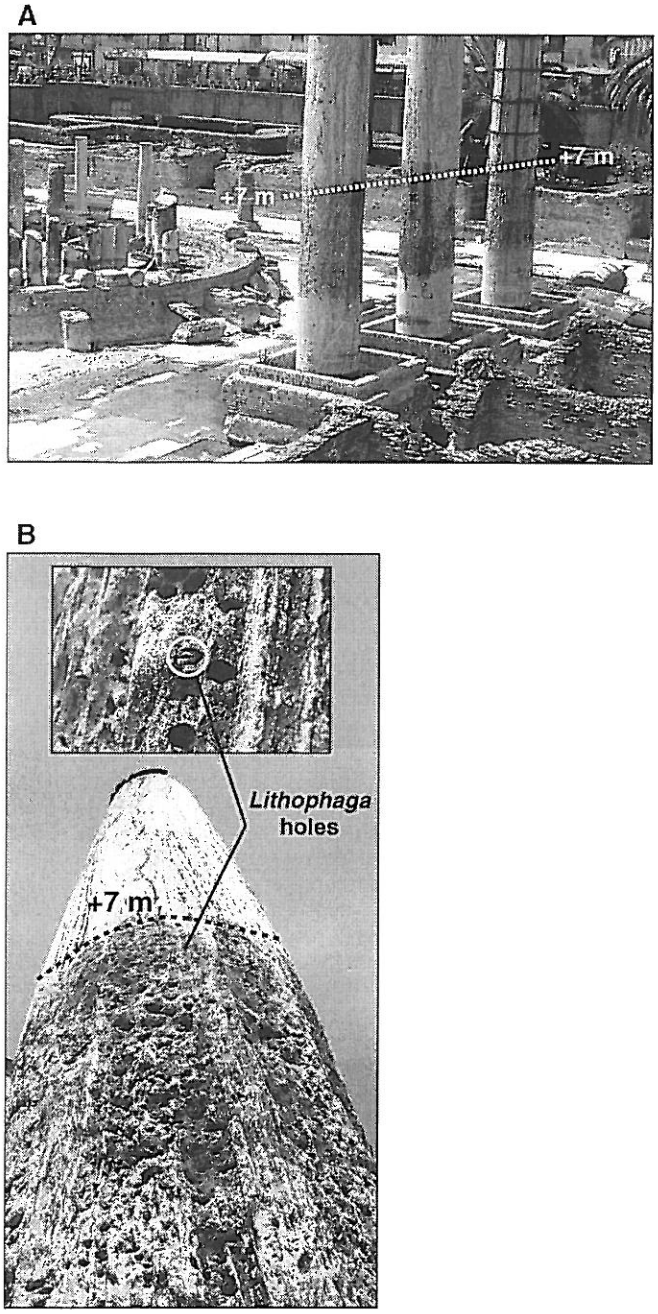

Figure 3. A: Remains of Pozzuoli's Roman market, showing biological perforations up to height of 7 ± 10 m above present biological sea level. B: Biological perforations with in situ *Lithophaga* shells on column of Roman market.

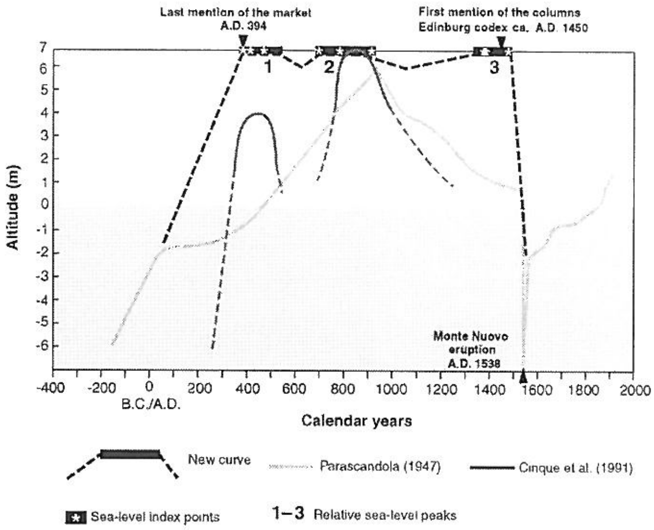

Figure 4. Relative sea-level changes in Pozzuoli during past 2000 yr.

Cinque et al., 1991; Giudicepietro, 1992; Fig. 4). The absence of erosional notches on the columns confirms that sea level did not remain stable at ~+7 m, and the constant elevation of marine fauna is concurrent with a maximum threshold for ground subsidence after episodes of uplift. Portus Julius, just offshore from the Roman market, is currently drowned −10 m below mean sea level and serves as a lower threshold (i.e., a 17 m envelope of crustal mobility since antiquity). According to the new data, submersion of Pozzuoli was not a unique event, but included three maximum threshold oscillations between the fifth and fifteenth centuries A.D. (1) During the first phase, marine transgression of the Roman market ended ca. A.D. 400–530 after its last restoration in A.D. 394 (Parascandola, 1947). No eruptive activity followed this phase. (2) An early Middle Ages oscillation occurred ca. A.D. 700–900, with no postdeformation volcanic eruption. (3) A late Middle Ages submersion, followed by a well-documented period of land uplift, culminated in the 1538 eruption of Monte Nuovo. Chronicles describe ground motion at the end of the fifteenth century, several decades before the Monte Nuovo eruption (Giamminelli, 1996).

Vertical ground movements, followed by eruptive activity or not, are common in active calderas (Newhall and Dzurisin, 1988). Ground deformation is generally ascribed to an inflation of a magma reservoir at depth, produced by arrival of new magma or by fluid exsolution. In these cases, uplift reflects an evolution of the magmatic system, possibly culminating in a new eruption. Ground deformation therefore represents a clearly detectable precursor. The link between ground deformation and the onset of eruptive activity, however, is not always straightforward. Sometimes, subsidence begins even if no eruption occurred to relieve overpressure at the magma chamber level; in other cases, only phreatic activity is recorded at the end of the unrest crisis (Newhall and Dzurisin, 1988). To explain the deformation observed in the Phlegrean Fields, where remarkably rapid uplift was followed by subsidence with no eruption, great emphasis has been given to the role of hydrothermal fluids circulating between the magma chamber and the surface (Bonafede, 1991; Gaeta et al., 1998; Orsi et al., 1999; De Natale et al., 2001). Significant amounts of deformation have been shown

TABLE 2. ^{14}C FOR KNOWN AGE SHELLS FROM THE NAPLES AREA

Laboratory reference	Material	Year of collection	Age (^{14}C yr B.P.)	Location	Reference
GifA 96717	*Arca tetragona*	1873	535 ± 40	Naples	Siani et al. (2001) Reimer and McCormac (2002)
GifA 96725	*Nucula nucleus*	1892	610 ± 110	Naples	Siani et al. (2001) Reimer and McCormac (2002)
Ly 2296(OxA)	*Tellina planata*	1932	645 ± 30	Cuma	Present paper

to derive from heating and pressurization of pore fluids, which may result from an increased magmatic degassing (Todesco et al., 2004). Subsidence occurs when pore pressure is dissipated through fluid discharge at the surface, and as deep magma degassing is again reduced. Involvement of hydrothermal fluids in unrest crises has also been suggested by seismological data collected during the last small uplift, in A.D. 2000 (Bianco et al., 2004).

Our new data describe a history of deformation that is more complex than previously thought. Noneruptive uplift events are more common than formerly recognized, suggesting a prolonged involvement of the hydrothermal system in the geodynamics of the caldera. The occurrence of a phreatic event in 1198 confirms such involvement. Within this context, the 1538 Monte Nuovo eruption appears to follow 1000 yr of ground deformation. If this time frame is too large to establish a direct causal link between deformation and eruption, centuries of ground motion certainly contributed to establish favorable conditions for magma ascent toward the surface.

CONCLUSIONS

Our new data corroborate Gould's (2000) remark that evidence for changing relative sea levels in Pozzuoli is more complex than previously stated. The proposed reconstruction of the Phlegrean Fields geodynamic deformation history suggests that during the past 2000 yr, noneruptive uplift episodes have been the rule rather than the exception.

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