Phlegraean Fields 1982-1984: Brief Chronicle of a Volcano Emergency in a Densely Populated Area

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ABSTRACT

The essential features of the ongoing potential pre-eruptive crisis at the Phlegraean Fields begun in August 1982 are summarized and the main problems faced by scientists responsible of volcanic hazards evaluation in such a densely populated area are discussed.

INTRODUCTION

Nearly 400,000 people live in Phlegraean Fields, an active volcanic area of approximative 80 km^2 in Southern Italy. Population is concentrated in the city of Naples, whose western part lies within the Phlegraean caldera, and in a series of medium and small towns. Pozzuoli, located at the center of the volcanic structure, counts about 72,000 people (Fig. 1). Important industrial factories are located in the area as are several military settlements (Italian Army and Air Force Academy, and NATO Headquarter).

Beginning in the summer 1982 an anomalous dynamic activity developped in the Phlegraean Fields which was characterized by uplift, seismicity and chemical changes on the fumarolic gases. This activity has resulted in a state of volcano-seismic emergency that, in October 1983, culminated with the evacuation of nearly 40,000 people from the historical center of the town of Pozzuoli.

The aim of this paper is to provide a brief chronicle of this still-progressing crisis with particular emphasis on the problems faced by scientists when involved in a short-term volcano prediction in a densely populated area.

CURRENT ACTIVITY

Phlegraean Fields are a complex volcanic structure consisting of a 35,000 years old caldera of approximately 12 km of diameter hosting a series of mostly monogenetic pyroclastic vents (Fig. 1). The post-caldera activity was subdivided into three main cycles (ROSI *et al.*, 1983) characterized by a latitic-trachytic magma composition and a progressive decrease in the volume of the emitted products (ARMIENTI *et al.*, 1983), with an overall migration of the eruptive vents towards the center of the caldera. The last eruption occurred in 1538 producing Monte Nuovo, a pyroclastic cone built up by phreatomagmatic and magmatic activity. A minor phreatic explosion is reported (BONITO, 1691) to have occurred in 1198 at the Solfatara, a pyroclastic cone formed about 4,000 years B.P. that still contains the most spectacular fumaroles of the Phlegraean Fields. Several fumarolic zones and hot springs occur along active fractures throughout the area both on land and in the Gulf of Pozzuoli. Because of this thermal activity, Phlegraean Fields have been traditionally considered as a thermally anomalous area. Recent deep geothermal drilling has found tempera-

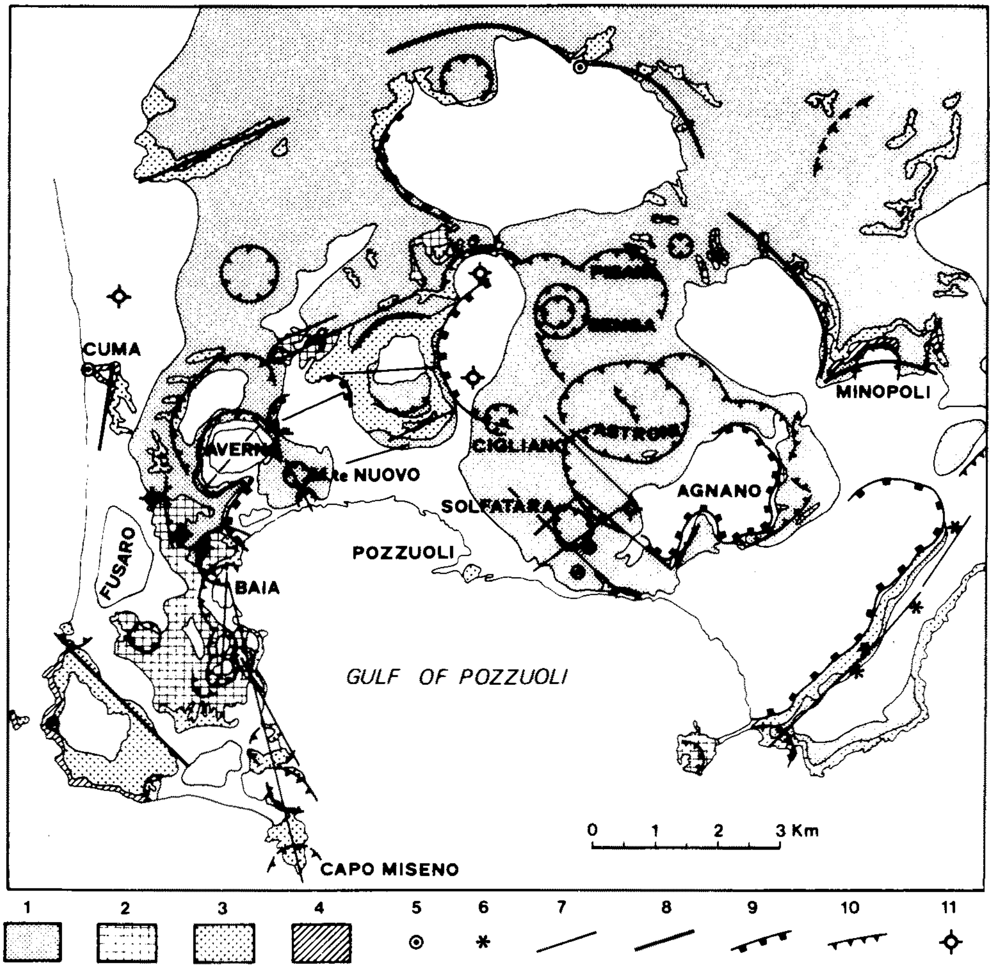

FIG. 1 – Volcanological sketch-map of Phlegraean Fields (simplified after ROSI *et al.*, 1983). - 1: Recent post-caldera subaerial activity (Phases D and E: 4,500 years B.P. - 1538 A.D.). - 2: Ancient post-caldera mostly subaerial activity (Phase C: 10,500-8,000 years B.P.). - 3: Post-caldera mostly submarine activity (Phase B, Yellow tuffs: 35,000-10,000 years B.P.). - 4: Pre-caldera activity and Campanian Ignimbrite (Phase A: 35,000 years B.P.). - 5: Lava domes. - 6: Inferred eruptive centers. - 7: Faults and fractures. - 8: Phlegraean caldera rim. - 9: Post-caldera volcano-tectonic collapses. - 10: Craters. - 11: Geothermal wells.

ture in excess of 420° C at 3 km depth in wells located approximately 3 km from the zone of the present maximum uplift. Intensive geothermal drilling has also provided information on the subsurface lithology and structure, allowing a more complete reconstruction of the volcanic history.

Phlegraean Fields are known worldwide to be a site of notable slow vertical movements (bradyseism). Many Roman buildings are found submerged along the coast of the Gulf of Pozzuoli by nearly 14 m below present sea level. Sinking has been then the dominant process in historical times, but phases of uplift are also documented mainly from the classical evidence in the Serapeo columns (Roman market in Pozzuoli) (LYELL, 1847).

The only well documented reversal of ground motion before the present century refers, however, to the marked uplift preceding the 1538 Monte Nuovo eruption (PARASCANDOLA, 1947). Levelling survey dates back to early's 1900 and indicates a general sinking trend interrupted by arrests or minor uplifts until 1969.

Early in 1970, a remarkable uplift affected the town of Pozzuoli, which was accompanied by a low seismic activity. Uplift lasted from mid-1969 to mid-1972, producing a maximum vertical displacement of 170 cm with a maximum initial rate of 5 mm/day (CORRADO *et al.*, 1977). From mid-1972 to late 1974 the ground sunk of about 20 cm, leaving then a permanent deformation of 150 cm.

Data from continuously recording tide gauges since 1970 (interrupted in the period 1977-mid 1981) and levelling data indicate that, apart from minor « annual » oscillations the largest of which occurred at the end of 1976, the ground remained substantially stable from late 1974 to August 1982.

The present crisis began in July 1982 with a sustained uplift that became evident in early 1983. Since the onset of this sustained uplift, the following evolution of monitored physical and chemical parameters (Fig. 2) has been observed.

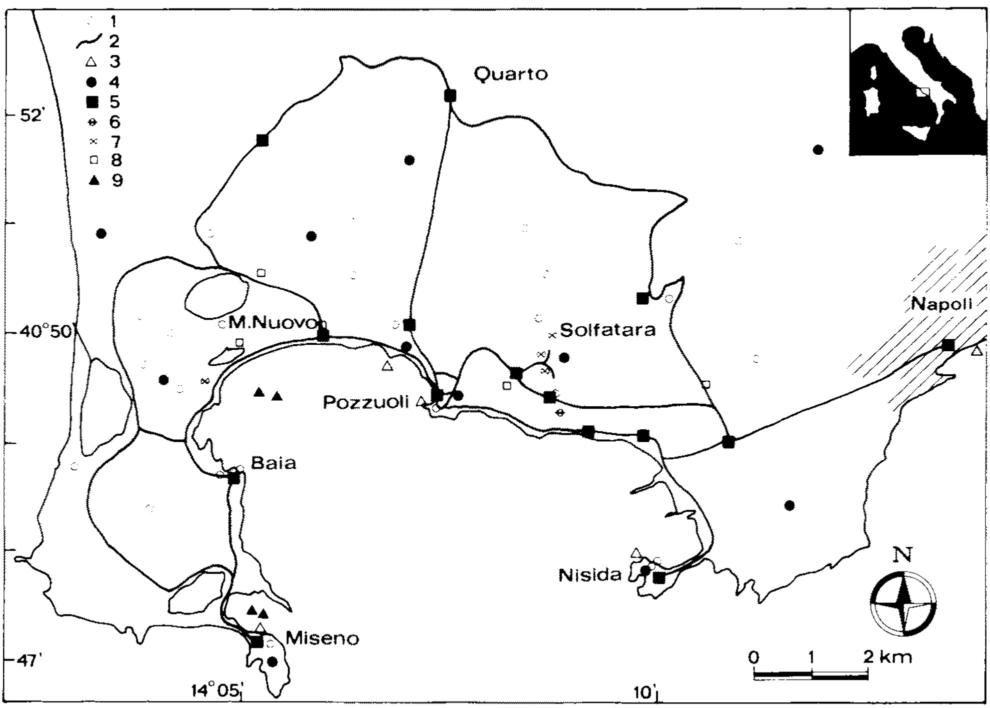

FIG. 2 - Volcano surveillance network at Phlegraean Fields. - 1. Seismic station - 2. Levelling line - 3. Tide gauge - 4. Trilateration benchmark - 5. Gravity station - 6. Permanent gravity monitoring station - 7. Fumarole sampling site - 8. Rn monitoring in water wells - 9. Submarine fumarole sampling site.

Ground Deformations (for details see BERRINO *et al.*, this volume)

Uplift has continued with no break reaching a total of 160 cm at the Pozzuoli harbour by the end of September 1984. So far the total uplift in the site of maximum deformation has reached 310 cm since 1969.

The area affected by the uplift has a circular shape with a radius of about 6 km essentially coincident with the Phlegraean Caldera (Fig. 3). Vertical deformation has a radial simmetry and a bell-shape. It is worth noting however that no data are available for the Gulf of Pozzuoli. To a first approximation the shape of the inflation and the dimensions of the affected area remained unchanged since the beginning of the crisis; the only variable is the uplift rate. During the period 1980-1983, horizontal displacements reached values up to 35 cm with a roughly radial pattern centered on the maximum uplift center in Pozzuoli based on observations in the central and eastern part of the Phlegraean structure. A local trilateration network established in May 1983 at the Solfatara crater has shown a maximum N-S extension with a strain of about 4×10^{-4} in the period June 1983 - September 1984. Gravity changes have been monitored by a high-precision network and by a continuously recording microgravimetric station operating since October 1983. The measurements show a continuous gravity decrease during the entire inflation period, with rate of changes showing a strong linear correlation with the uplift rate. Free air rate alone, however, cannot explain the observed gravity changes, and a mass addition at depth would be involved (see BERRINO *et al.*, 1985).

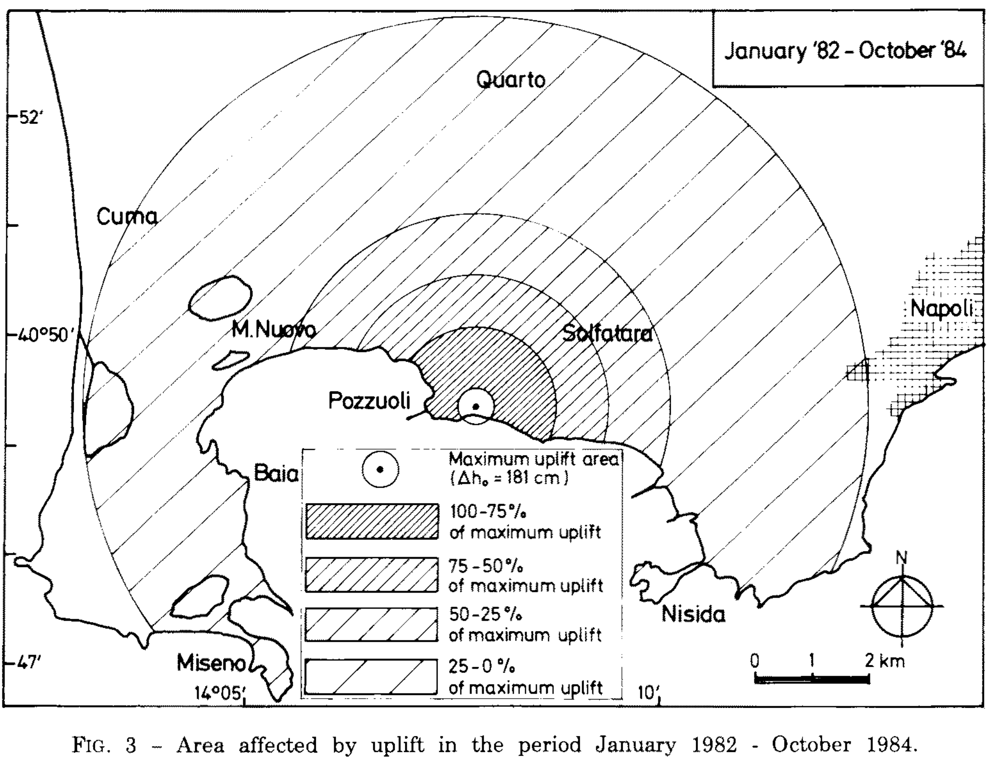

FIG. 3 – Area affected by uplift in the period January 1982 - October 1984.

Seismicity (for details see CASTELLANO *et al.*, DE NATALE *et al.*, DEL PEZZO *et al.*, GAUDIOSI and IANNACONE, this volume)

Seismic activity began several months later than the onset of the sustained uplift. An initial minor seismic swarm occurred in November 1982 and a clear increase of seismicity was recorded beginning in the spring 1983 with the occurrence of the first M = 3.5 earthquake beneath the Solfatara (May 15th, 1983). Since then the following main features have been observed.

a) A marked increase in seismic activity was registered in September-October 1983, when an earthquake of M = 4.0 shook the town of Pozzuoli (October, 4th) and was felt up to nearly 30 km distance from the epicenter. Seismic energy release increased up to September 1983 and remained substantially stable in the following year.

b) Activity is characterized by spatial-temporal clusters of earthquakes; single events with M up to 4.0 alternate with swarms of varying duration and energy; two major swarms occurred on October 13th, 1983 and 1st April, 1984 totalling 250 shocks over 3 hours and 500 shocks over 5 hours, respectively. These totals include all shocks with $M \geq 0.4$.

c) Epicenters are concentrated on land along a E-W belt centered on the town of Pozzuoli and extending from the Solfatara crater to the harbour zone. Minor activity is recorded within the Gulf, near the west coast (Fig. 4). Most of the earthquake distribution does not match the circular vertical deformation pattern as a wide

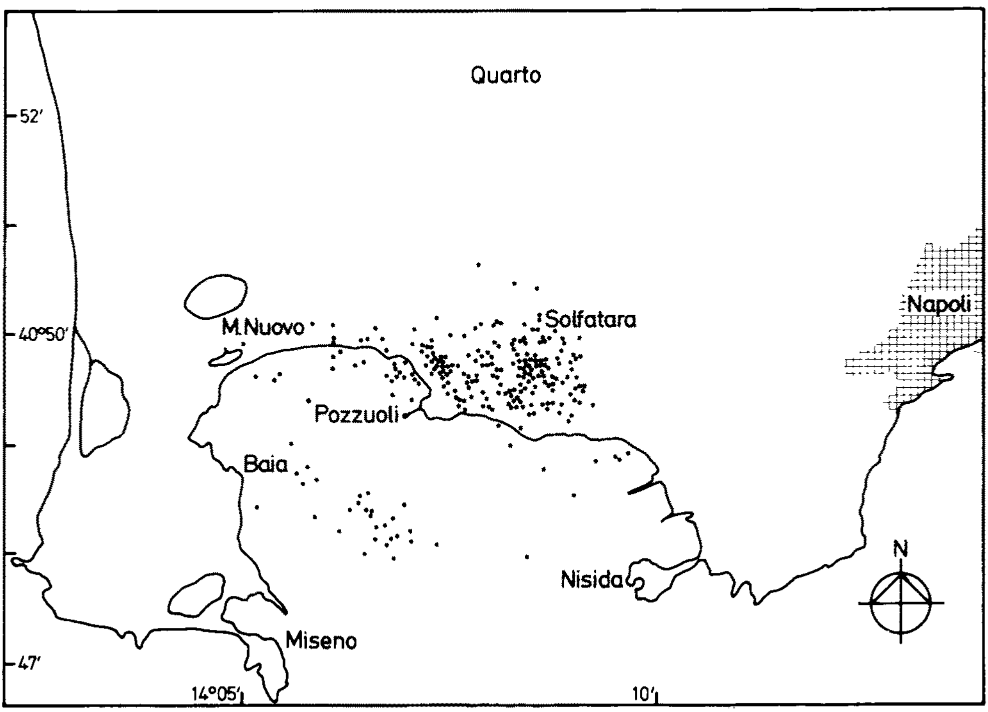

FIG. 4 - Distribution of earthquake epicenters with $M \geq 2.4$ recorded in the period Jan. 1983 - Sept. 1984.

nearly aseismic zone persists in the Gulf to the South of Pozzuoli.

d) Foci depth is uncertain by a few hundred meters (less than 500 m) on land and by higher inaccuracy on sea due to the lack of sea-bottom seismometers. Within these errors no migration of the foci depth with time has so far been observed. Also the epicentral area has remained essentially the same; the western part of the Gulf has however been affected by significant seismic activity only since the end of 1983.

e) Since the summer of 1983 the *b* coefficient of the Gutenberg-Richter frequency-magnitude relation has shown a decrease reaching a nearly stable value (1.0-1.1) in the spring of 1984. An anomalous increase in the frequency of high energy shocks with respect to the Gutenberg-Richter distribution has however been observed in the last months (autumn 1984).

f) Fault-plane solutions show a complex pattern with dominant tensile stress in the center and compressive stress at the border of the area of maximum seismic activity.

Geochemistry (for details see CARAPEZZA *et al.*, CIONI *et al.*, MARTINI *et al.*, this volume)

Geochemical surveillance of Phlegraean Fields consists of periodic sampling and analysis of gases, condensates and water mostly of the fumaroles in the Solfatara crater and of few other hot water points. In addition, the «reducing capacity» R.C. (*i.e.* the supply rate of gases that can release H^+ ions) has almost continuously been registered in the Solfatara fumaroles with a specific sensor. Periodic campaigns for the detection of He in the soils have also been carried out in order to help identifying the most extensively fractured zones (see LOMBARDI *et al.*, this volume).

Some minor but clear changes in the composition of the Solfatara fumarolic gases have been observed at the beginning of the crisis. These changes consist of:

— an increase of the steam/gas ratio

— an increase of the S/C ratio, essentially due to a H_2S increase

— an increase of CH_4.

The gas composition remained practically constant after these initial changes; the maximum temperature of the fumaroles also remained essentially constant (ca. 156° C) throughout the crisis. A tendency towards the pre-crisis values was however observed in the gas composition during 1984.

Unfortunately, apart from an isolated and incompletely analyzed sample collected from the Solfatara fumarole in May 1982, there is no geochemical information for the year preceding the present uplift phase. This isolated sample shows S/C and CH_4 values much higher than the background measured in the years 1978-81, indicating that geochemical changes in the fumaroles probably preceded the beginning of the uplift. The small chemical changes in the gases are interpreted as indicative of a fumarolic system fed (and buffered) by geothermal aquifers, the shallowest of which is located at approximately 1500 m depth as indicated by an old geothermal drilling near the Solfatara. There is no geochemical evidence for a magma ascent; however, data indicate an initial increase of the thermal energy input in the deep feeding system, probably accompanied by a pressure increase (CH_4 increase). Reducing capacity shows large fluctuations, with a tendency towards high values during the periods of major seismic energy release. A fluctuation in the H_2O content and the S/C ratio in correspondence with a major earthquake (M = 4.0) was observed in October 1983, the only case in which the Solfatara fumaroles were extensively sampled during seismic shocks.

* * *

As a whole, the observed phenomena (seismicity, uplift, geochemical changes in the fumaroles) are typical precursors of a potential eruptive crisis. The earthquake foci depth, shallower than 3-4 km, and the geometry of the deformation field suggest that the source of the process (an inflating magma body?) is very shallow. Similar to the 1970-72 crisis, uplift and seismicity are not synchronous, the latter following several months after the beginning of the former (Fig. 5). The change in the fumarolic gases composition probably occurred some months before the beginning of the uplift; a promising correlation in time seems to exist between the gas flow rate (as expressed by the R.C. values) and the seismic energy release.

Variations in the geochemistry of the fumarolic gases seem to be the earliest indication of a changing dynamic regime in Phlegraean Fields. These would be followed by an uplift and months later, by seismic activity. All these data still need to be incorporated into a coeherent quantitative model. However, the initial pre-uplift and pre-seismicity geochemical changes, unfortunately not well documented, may suggest a process of pressure increase in a system that is only partly confined as it looses hot gases to the surface. The delay between the beginning of the uplift and the seismicity suggests that the rocks in the Phlegraean Fields seismic source region have a mechanical threshold that must be exceeded in order to produce an earthquake. The later temporal correlation between seismicity and increase of thermal input in the deep-seated aquifer, as indicated by the gas geochemistry, may be explained by the increase of permeability by fracturing which favours the uprise of fluids from the depth.

On the other hand no sure evidence of a magma ascent has been observed since the beginning of the crisis. In fact the maximum depth of earthquakes has remained the same within the experimental errors; the major component composition of the fumarolic gas has remained constant (aside fluctuation) after the initial change; no major mass variation is revealed by microgravimetric measurements. This in spite of the afore-described continuous uplift and progressive increase (until September 1984) of the seismicity.

In conclusion, the variations observed in the monitored physical and chemical parameters are interpreted as an effect of a pressure build up, and consequent energy release in the form of uplift, earthquakes and thermal flux, in a shallow magma chamber of small dimensions. This interpretation finds support also in the general volcanological and petrological features of Phlegraean Fields. The post-caldera volcanic history is in fact characterized by a progressive decrease in the volume of the erupted products accompained by a migration of the vents towards the centre of the structure. In addition, petrology suggests that all eruptions were fed by a chemically zoned shallow magma chamber at the top of which trachytic liquids had accumulated (ARMIENTI *et al.*, 1983). Volcanic history would therefore suggest that the residual (trachytic) liquid potentially available for an eruption should be limited to the inner part of the by-now largely cooled magma chamber, that is located at shallow depth (4-5 km) beneath the center of the caldera. Its volume should be so small that it may be difficult to detect with geophysical methods: a thermal model based on the past volcanic history results in an estimate of about 0.4 km^3 (ARMIENTI *et al.*, this volume). No evidence exists, since the monitoring began in 1970, suggesting that the system has been refilled with magma from depth.

For these reasons, in the case of an eruption, the most probable event is one of low energy similar in size to the 1538 Monte Nuovo eruption. The possibility of a larger eruption has been, however, also prudentially considered in the scenarios provided to the Civil Defense Authorities for the preparation of evacuation plans (see ROSI and SANTACROCE, this volume).

VOLCANOLOGY AND CIVIL DEFENCE

The first crisis of recent years in the Phlegraean Fields with serious civil defence implications occurred in 1970. On March 2nd, 1970 when uplift had totalled about 80 cm at Serapeo, and a minor seismic swarm had occurred, an order of

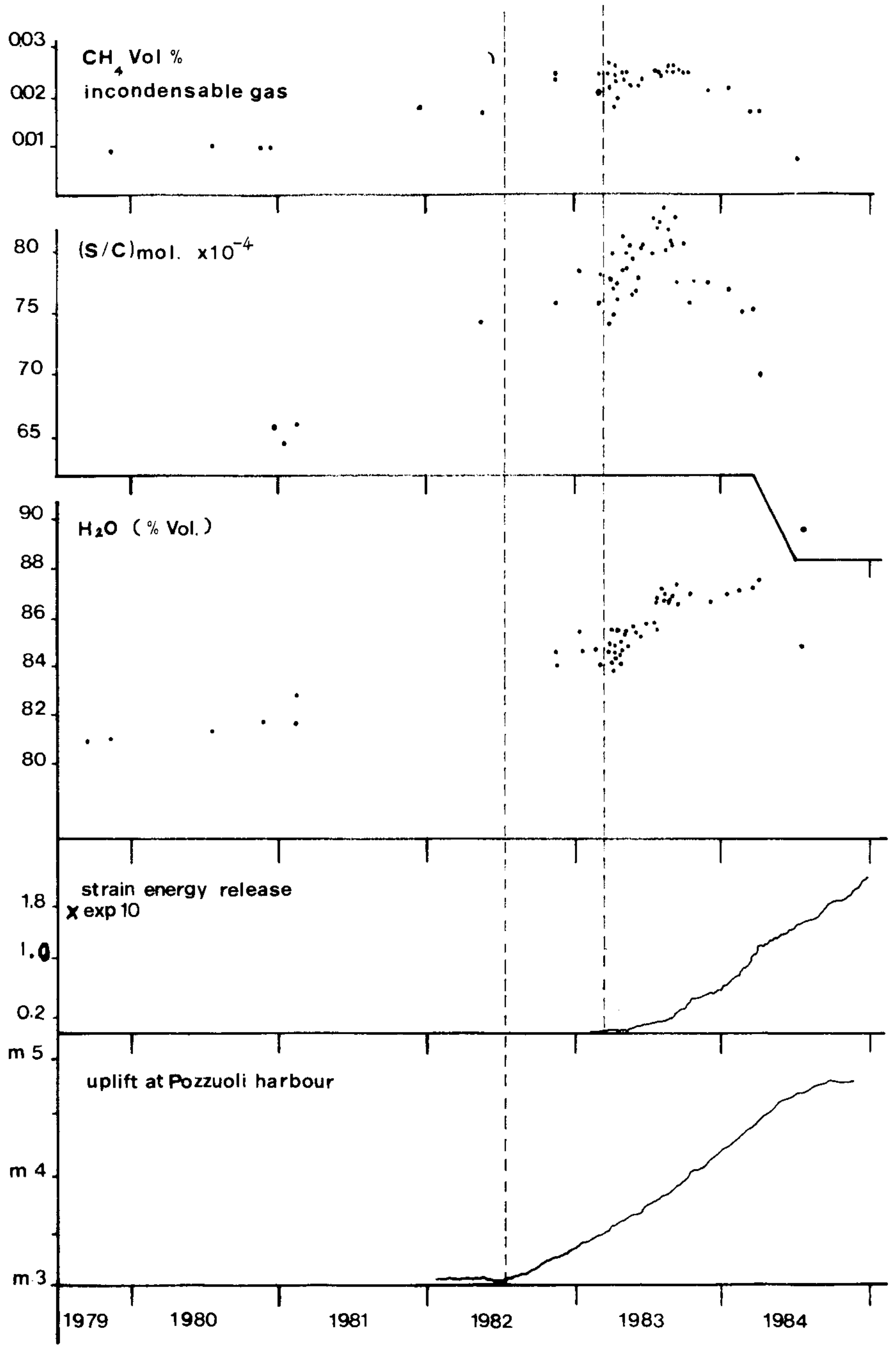

FIG. 5 - Temporal correlation between uplift, seismic energy release and some chemical parameters of La Solfatara fumarolic gases in 1982-1984.

evacuation was issued for the nearly 3,000 people living in an old quarter (Rione Terra) of the Pozzuoli harbour. A violent controversy developed with deep involvement of mass-media, which lasted for ten years. The arguments centered on the need and reasons for this evacuation and on the alleged (or denied) interpretatioon of uplift and seismicity as precursors of an impending volcanic eruption (see for instance TAZIEFF, 1971, 1977; IMBÒ, 1977, 1980).

The confusion was total. Two scientific commissions were appointed, one by the Ministry of Public Works (MLP), the second by the National Research Council (CNR). Both included Italian and foreign scientists. Separation of responsability between the two Commissions was not clear, and conflict rapidly arose reaching violent polemic levels.

In retrospective the main problems that emerged during the 1970 crisis were due to:

– the lack of an official Civil Defense Authority (Ministry of Civil Defense was firstly created in Italy after the November 23rd, 1980 earthquake)

– the lack of a volcano monitoring system with a minimum standard

– the lack of a precise (and unique) scientific responsability officially charged of the hazard evaluation.

After the 1970 crisis the Vesuvius Observatory developed a permanent geophysical monitoring system (vertical deformation, seismicity and gravimetry), whereas the fumaroles and horizontal deformation were periodically monitored by several C.N.R. research teams. This allowed a timely warning to be given to the Civil Defense Authority at the beginning of the present crisis. In 1983-84 the surveillance system was furtherly improved: the number of seismic stations and tide-gauges was increased, permanent microgravimetric and R.C. stations were installed, and the frequency of campaigns to measure deformation and gas geochemistry was increased, and new periodic surveys (Rn, He, geoelectrical and magnetotelluric soundings), thanks also to a cooperation with the French Volcanic Study Group (PIRPSEV) and the Spanish National Research Council, were established. The scientific responsability of the hazard evaluation was entrusted to the newly created National Group for Volcanology (GNV), a committee coordinating and financing all Italian research teams operating in the field of active volcanology. The technical coordination of the entire monitoring activity remained under the responsability of the Vesuvius Observatory.

The progressive development of the crisis created a series of problems to the Pozzuoli population. The harbour became practically unutilizable. The conditions of the life in the town and its neighbourings became increasingly more difficult, mostly due to the high level of seismicity that included a large number of felt shocks. Earthquakes produced damage to old houses of Pozzuoli and the number of buildings evacuated because they became structurally unsafe also increased progressively. On the days following October 4th, 1983 when the first $M = 4$ earthquake occurred, nearly 40,000 persons were evacuated from the old center of Pozzuoli because the seismic hazard was judged too high, considering the structural characteristics of most buildings. Systematic vulnerability survey in the evacuated area demonstrated the hazardous state of many houses. Some of these structures collapsed in the following months during phases of particularly intense seismicity. Thanks to the civil defense adopted measures no one has been killed or seriously injured.

Paradoxally, the high level of seismic risk has simplified the volcanic hazard problems because of the drastically reduced population in the area most threatened in the case of an eruption. Evacuation plans for the remaining population were prepared based on scenarios provided by GNV.

Obviously a completely balanced view of this experience will be possible only at the end of the crisis. The major problem faced by volcanologists during an emergency of this kind arises from the difficulty of finding answers to questions such as:

— what are the early symptoms of an acceleration of the process, and how can we recognize the point when the process begins an irreversible course toward an imminent eruption?

— what kind of eruption is heralded by the observed precursors?

In a densely populated area like the Phlegraean Fields, such uncertainties translate into dramatic consequences. Errors in the evaluation of the potential hazard may have serious consequences. The time required for an orderly evacuation of up to 400,000 people is such that the probability of a false alarm become very high. The alternative is a failed alarm if the warning is issued too near the beginning of the eruption.

Finding answer to these questions (that is, attaining a reliable capability for predicting the behaviour of active volcanoes) seems an objective in the reach of the present generation of volcanologists. It requires, however, a major organizational and research effort from the entire international scientific community. A basic prerequisite is certainly that political authorities recognize that volcanoes must be monitored and studied continuously and not just during emergencies.

NOTE ADDED IN PROOF (April 30, 1985)

In the last months of 1984 the dynamic activity began to slow down. Uplift rate had progressively decreased since October and became null in December. The total uplift recorded since the beginning of the crisis has been of 185 cm at Pozzuoli harbour. A slow deflation began in January 1985 with a daily average rate of 0.4 mm, totalling 5.1 cm by the end of April.

Seismicity also decreased and since December 1984 is stable at very low levels (23-60 mostly instrumental shocks per month) with epicenters concentrated in the Gulf of Pozzuoli.

Some months before the uplift and seismic activity decrease, the gas composition of the Solfatara fumarole had already attained nearly pre-crisis values. It is therefore confirmed that, at least in the Phlegraean Field case, the fumarolic gas geochemistry is very sensitive to changes in the dynamic regime.

The process initiated in late 1982 can then be considered, at least temporaneously, exausted by the end of 1984.

The order of evacuation has not yet been formally revoked, as the Civil Defense Authorities took the wise decision of reducing drastically the density of population in Pozzuoli in order to mitigate the risk of future crises, a new settlement being built to this aim.

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