Eruptive history, seismic activity and ground deformations at Mt. Vesuvius, Italy

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ABSTRACT. Mt. Vesuvius is an active volcano characterized by a quiescent state of activity since April 1944. The high density of population in this region, combined with the past volcanic history, makes it potentially one of the most dangerous in the world. This paper reports all the results on the seismic and ground deformation monitoring performed during the last 13 years.

The present seismic activity is characterized by a moderate level of microearthquakes, about 1 event/day, which is presently monitored at OVO station, magnitude threshold 1.7. These microearthquakes exhibit a clustering tendency, following a generalized Poisson process, with the grouped events distributed according to Riemann statistics. Horizontal and vertical distance measurements around this volcanic region have not shown any significant deformation, during the last 7 years, in agreement with the present low seismic activity.

The eruptive history and structural framework indicate a possible triggering mechanism for eruptions in the seismic episodes of the neighbouring mountain chain, but further complexities in the feeding system make any simple correlation between eruptions and regional strain release processes difficult.

Key words : seismicity, ground deformation, volcano surveillance, Vesuvius.

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INTRODUCTION

Somma-Vesuvius is a composite strato-volcano formed by an older apparatus (Mt. Somma) within which a new cone (Mt. Vesuvius) is built. Delibrias *et al.* (1979) recognized eight main eruptive cycles in the last 17,000 years each cycle started after a quiescence period with a highly explosive Plinian eruption (volume of the products is of the order of 1 km^3). The famous Plinian eruption of 79 a.D. occurred after a quiescence of several centuries. It buried the towns of Pompei, Herculaneum and Stabia. Several explosive eruptions, described by letters and chronicles, are reported in the period 79-1631 a.D., and the most important eruption occurred in 472 a.D. (Rosi and Santacroce, 1982). After a quiescence of about 150 years the eruption of 1631 a.D. took place. This last episode marks the beginning of a detailed historical record of the activity. The accuracy of the record permitted a statistical analysis of the pattern of activity (Carta *et al.*, 1981). The last eruption occurred in March-April 1944.

STRUCTURAL MODEL OF VESUVIUS

The volcanoes of the Neapolitan area are located along a NW-SE alignement of recent potassic volcanism bordering the Tyrrhenian Sea from northern Latium to Vesuvius (fig. 1). The emplacement of this volcanism is related to a regional stress field of NE-SW direction acting on the upper part of the lithospheric margin of the Tyrrhenian Sea. The existence of predominant normal faulting on a regional scale is shown by the available fault-plane solutions of the main earthquakes in the Apenninic chain (Gasparini *et al.*, 1982). A counter-clockwise rotation of the Italian peninsula hypothesized by Civetta *et al.* (1979) may be the cause of such a stress field. Civetta *et al.* (1979) suggested a rotation of the Italian peninsula based on the migration of the volcanism along the northern Tyrrhenian margin from 14 My to the present. The complex fault system of the neapolitan area is shown in figure 1. The two main fault systems are the one trending NW-SE and the complementary one with NE-SW direction.

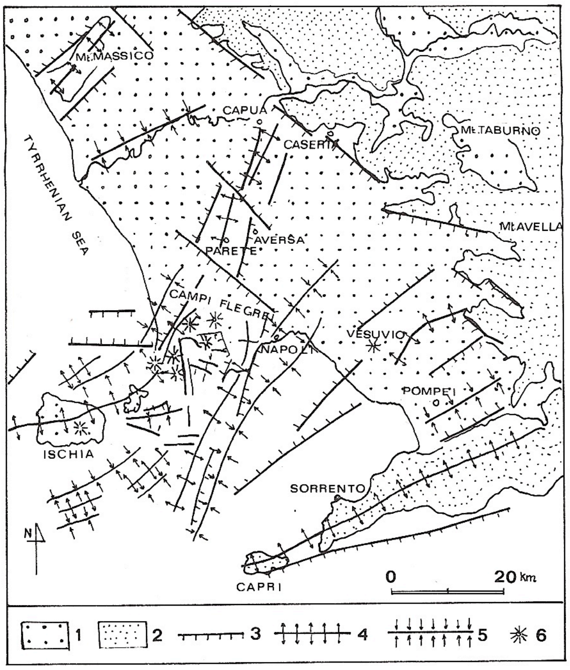


Figure 1

Structural sketch map of Campania volcanic area : 1. Volcanic products and recent alluvial deposits (Quaternary) ; 2. Sedimentary outcrops (Trias-Miocene) ; 3. Normal faults ; 4. Structural high axis of carbonate substratum ; 5. Structural low axis of carbonate substratum ; 6. Main volcanic center.

Finetti and Morelli (1974) showed that two active normal faults exist in the gulf of Naples, elongated in NE-SW direction. Evidence for offshore volcanic activity along these faults also exists. This fault system continues on land as testified by the occurrence of lateral eruptive vents on the flank of Vesuvius along the same directions. The pattern of Bouguer gravimetric anomalies (fig. 2) confirms this interpretation. The directions of regional and local stresses are also shown in figure 2. The directions of the fractures which gave rise to the main historical eruptions of Vesuvius are reported in figure 3. This figure has been derived from historical records reported by Alfano and Friedlander (1929), Delibrias *et al.* (1979) and the field evidence reported by Principe (1979). The length of the arrows accounts for the relative relevance of the eruption. The main structures are the NE-SW and N-S, as shown both by the number of relevant eruptions and by the occurrence of eccentric eruptive episodes located on these systems. The complementary fracture systems of NW-SE and E-W direction are confined mainly to the upper part of the volcano. The occurrence of the older Pollena lateral event suggests that the NW-SE system might be prolonged in a westerly direction.

It is worth noting that the two main fracture systems seem to govern the eruptions in an alternative way, except for the large eruptions of 1631, 1872 and 1906.

A further important point is that the prolongation of the SW-NE fault crosses the Apenninic chain almost exactly in the area of separation of two seismogenetic zones of the southern Apennines (Scarpa *et al.*, 1983). Vesuvius seems to be located on a lateral discontinuity of the Apenninic chain where a transcurrent fault system separates two sliding blocks. Such a transcurrent system is related to local stress field, probably induced by a counter-clockwise motion of the southern block with respect to the northernmost one.

HISTORICAL ACTIVITY OF VESUVIUS

After 1631, Vesuvius was persistently active until 1944. The activity was characterized by several cycles (Alfano and Friedlander, 1929). Each cycle began with a repose period, usually not exceeding seven years. The repose ended with a collapse within the cone of Vesuvius where a small conelet was built by slow effusion of lava and strombolian activity. This activity slowly filled the crater. Occasionally higher effusion rates permitted the outflow of lava, from the main crater. Each cycle ended with an explosive eruption characterized by high effusion rate and the formation of an eruptive column reaching stratospheric heights. The effect of the explosive event was the evacuation of the crater and the subsequent short period of quiescence. Carta *et al.* (1981) made a statistical analysis of the activity pattern of Vesuvius in the time interval between 1694 and 1944. They described the volcanic activity in terms of a Markovian chain of states of equilibrium of comparable energy. An important result of this analysis is that each state is an equilibrium state and the transitions from one state to another are governed mainly by the influence of stochastic perturbations, without any evidence of reloading mechanisms.

The overall pattern of the recent eruptive activity testifies a constant supply rate of the volcano. The recurrence of the cycles of activity suggests the constancy of a physical process by which magma is erupted into the surface.

The slow filling of the crater during the period of gentle effusive activity increases the load on the flanks of the crater eventually permitting the opening of fractures along lines of structural weakness. The resulting emptying of the crater and the sudden unloading of the system then favors a higher effusion rate and an effusion rate and an immediate decompression of the volatile phase of the magma. Eventually the pressure decrease within the volcanic system may favour the interaction with phreatic water and the occurrence of a large phreatomagmatic event.

Such a general pattern is modulated by the effects of stochastic perturbations which may trigger the occurrence of explosive events when the system is close to the instability threshold.

A second important point which was independently shown both by the statistical analysis (Carta *et al.*, 1981) and by geochemical studies on historical lava flows (Cortini and Hermes, 1981), is the change of the activity pattern of Vesuvius around the period 1858-1872. The statistical analysis showed that the length of the states of persistent activity and intermediate eruptions increased after 1858-1872. The Sr isotopic studies showed that in the same period a new batch of deep generated magma was made available.

It is also worth mentioning that the repose time from the last eruption in 1944 largely exceeds the length of all reposes in the period 1694-1944, being comparable with the repose lengths in the period 1631-1694 or before 1631.

PHYSICAL PROCESSES AND POSSIBLE TRIGGERING MECHANISM OF ERUPTIONS

Many authors like for instance Anderson and Grew (1977) and Nakamura (1977) have shown that a deviatoric minimum compressive stress field normal to ascent direction of the magma influences the direction of propagation of cracks within the upper lithosphere. In the previous section we hypothesized how this field is generated in the Vesuvius area and also that magma was available to be erupted between 1694 and 1944. The ascent of magma through the mechanism of crack propagation is mainly controlled by the propping pressure effect of the gases exolved from the magma at the crack tips (Spera, 1980). The deformation rate of a rigid lithosphere is a function of the inelastic properties of the asthenosphere (for a review see Dragoni *et al.*, 1982). Melosh (1977) and Turcotte (1977) illustrated some features of the stress diffusion mechanism, as compared to observations of the expanded aftershock areas of large earthquakes (Mogi, 1968) and stress accumulation along faults. Under the simplified assumption of a purely viscous asthenosphere, the distance d of stress diffusion in a time t is given by $d = (Gbst/\eta)^{1/2}$ where s is the lithospheric thickness, b and η the thickness and the viscosity of the asthenosphere and G is the rigidity. Assuming $G = 3 \times 10^{11}$ dyne/cm^2, $\eta = 10^{20}$ dyne s/cm^2, b and s equal to 100 km, at distances of the order of 100 km a few years are required for stress diffusion.

Strain pulses may be associated with magma production (Brady, 1976) and probably they constitute an important triggering phenomenon when an unstable equilibrium exists between the pressure of magma and the surrounding rocks or during the interaction of magma with pore fluids in the case of phreatomagmatic activity. A quantitative estimate of these effects is not the main aim of this paper, in view of the considerable simplifications made in the present theoretical models and due to the lack of detailed information on the displacement field. However, according to this view some degree of correlation may be observed between seismic and volcanic phenomena if they are both related with changes in the stress field of a plate.

The occurrence of the main seismic and volcanic phenomena which took place in the southern Apennines during the last thousand years is summarized in figure 4. The data are more uncertain as they go back in time, and it is probable that only the more relevant events were reported for the period 1000-1500. The data since 1 500 are of better quality. On this time scale some connection between seismic and volcanic phenomena seems to exist in the period around 990-1000 a.D., 1273-1302 and at the end of XVII century. It is worth noting that the beginning of the pseudo-stationary state of activity of Vesuvius in 1694 fits fairly well with the burst of seismic activity in the Apennines. The

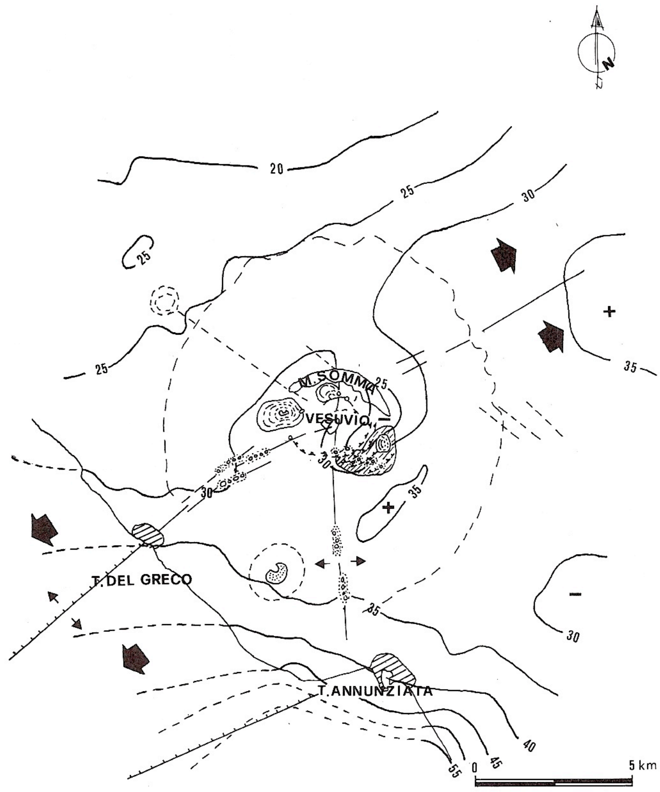


Figure 2

Structural sketch of Vesuvius. The large arrows indicate the direction of the regional minimum compressive stress field. The small arrows indicate the local minimum compressive stress field influencing the feeding system of the eruptions. Major fault systems are indicated by lines. Dashed lines indicate inferred faults. Lateral vents are emplaced on two main N-S *and* NE-SW *systems. Solid lines indicate Bouguer anomalies.*

strongest earthquake of 1456 seems uncorrelated with any volcanic episode.

The time scale can be expanded in the period between the end of 1600 and the present. The strain energy release due to the earthquakes in the southern Apennines and the volume of erupted products of Vesuvius are reported in figure 5. The strain energy was estimated using the magnitude deduced by maximum intensity, through the relation $\log E = 11.8 + 1.5$ M. We find an almost simultaneous change of pattern in the period 1688-1700. Another time correlation is observed at the

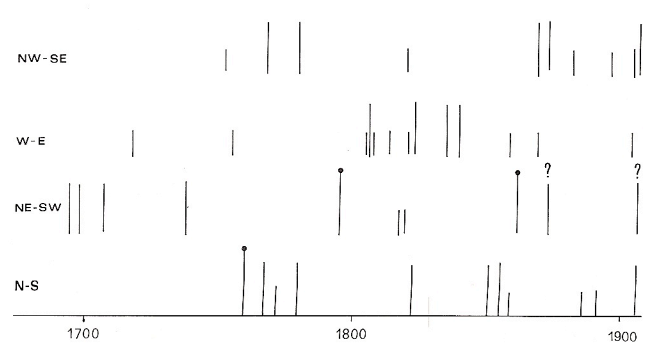


Figure 3

Direction of fractures feeding vesuvian eruptions between 1694 *and* 1944. *The size of lines is proportional to the magnitude of eruptions. Flank eruptions are marked with a closed circle. Eruptions with uncertain direction of fracture are marked with a question mark.*

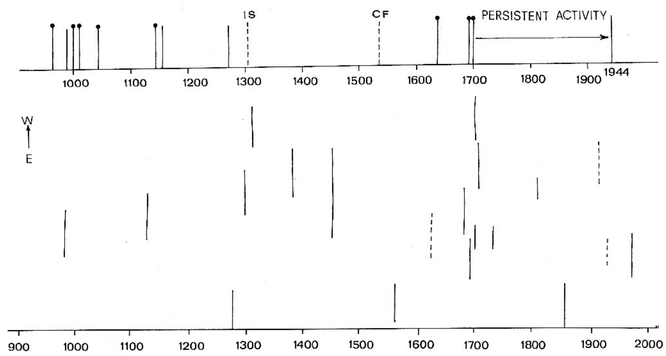


Figure 4
Comparison between the space-time distribution of the largest earthquakes in the southern Apennines (lower part) and the volcanic activity in the Neapolitan area (upper part). The volcanic episodes are referred mainly to the Vesuvius activity (main episodes are marked with a closed circle). From 1694 *the large number of eruptions of Vesuvius is summarized as persistent activity.* IS *is referred to an eruption in Ischia Island in* 1302, CF *is referred to an eruption of Phlegraean Fields in* 1538.

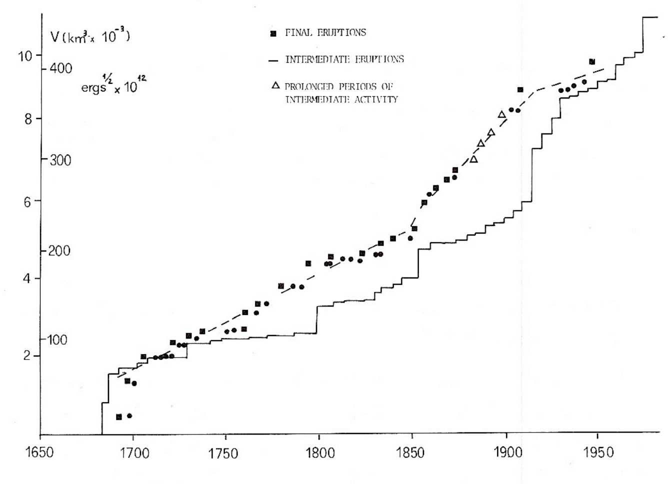


Figure 5
Comparison between the cumulative strain energy released in the southern Apennines (solid line) and the cumulative volume of products erupted from Vesuvius since 1694 *to* 1944.

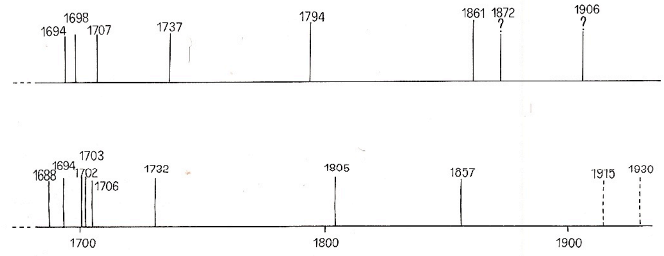


Figure 6
Occurrence of the major earthquakes in the southern Apennines (lower part) and the eruptions of Vesuvius occurring along the NE-SW *fracture system (upper part).*

end of XVII century. A change in the pattern of delivered volcanic energy and seismic energy starts from the second half of XIX century, The volcanic activity seems to increase, whereas the strain release is characterized by an initial decrease and then by a sudden jump with the sequence of 1910-1915-1930 earthquakes, having *M* greater than 6. The observed reliability of homogeneity in the data sample was however not sufficient for applying some statistical methods to check the degree of correlation between eruptions and seismicity as verified for other italian volcanoes (Capaldi *et al.*, 1976; Sharp *et al.*, 1981).

In figure 6 the main earthquakes of southern Apennines are reported along with the eruptions of Vesuvius which occurred on the main fracture system of SW-NE direction, which is likely to be related with the regional tectonic system. In this case the correlation between the seismic events and major eruptions of Vesuvius at the end of 1600 becomes more evident, and we may extend this period up to 1730. A phase offset of 5-6 years between earthquakes and eruptions is evident. A similar time gap of 4 years occurred between the 1857 earthquake and the 1861 lateral eruption. A reverse correlation is apparent for the 1794 eruption and the 1805 earthquake. It must be noted that such earthquakes took place in the northernmost sector of the seismogenetic area. The 1930 earthquake seems uncorrelated with volcanic events, but it must be noted that this earthquake and that of 1915 occurred along fault segments which are apparently displaced laterally with respect to the rupture zones of the others. Therefore a different stress field acting in the last areas may be hypothesized. In conclusion some degree of correlation between volcanic phenomena of Vesuvius and seismic activity along the southern Apennines may exist in the period between 1688 and 1861. After this period, although new magma was available (Cortini and Hermes, 1981; Cortini and Scandone, 1982), the two phenomena became uncorrelated, probably as a consequence of the change in the pattern of volcanic activity (Carta *et al.*, 1981).

The earthquakes occurring in the Apennines indicate that the tectonic strain episodes of this region may be connected to the fault system characterizing the Neapolitan volcano complex through a complex block system. A degree of correlation exists between strain episodes in the Apennines and the Vesuvian activity, particularly in the period 1688-1857. The present state of Vesuvius activity suggests that the present quiescent stage will not continue for a thousand years, but an eruption is likely to occur in the next hundred years, and perhaps in some connection with fault motions in the southern Apennines.

However the assessment of a reliability level for a long term forecasting is highly indeterminate. Continuous monitoring with geophysical and geochemical techniques is necessary. Accurate investigations of the structural characteristics of this region can offer a valuable tool for understanding the eruptive mechanisms and can also provide a basis for a volcanic forecasting program appropriate to the high risks associated with future volcanic episodes.

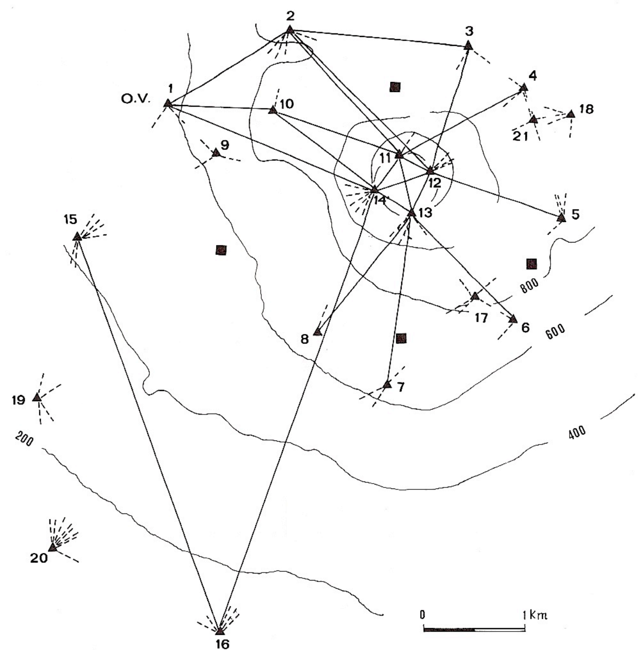
GEOPHYSICAL SURVEILLANCE SYSTEM

a) Ground deformation studies

Studies of ground deformation on Vesuvius were improved in 1974 (Bonasia and Pingue, 1981) and the present monitoring system is based on a levelling network, dry tilt measurements, electronic measurements of distances and analysis of apparent zenithal distance of the crater bottom from a fixed point located on the crater rim. Figure 7*a* shows the network of geodimeter bench marks utilized for horizontal distances and the position of the four small triangular networks utilized for dry tilts. Figure 7*b* shows the levelling network. Presently the measurement intervals are of the order of one year. Most of the bench marks of a previous levelling network, installed in 1927, were destroyed by the 1944 lava flow. Only the bench mark located at Vesuvius Observatory was not destroyed and showed (in 1959) a relative subsidence compared to the bench marks located along coastal towns (Ercolano and Torre Annunziata), of about 20 cm (Giannoni, 1962). A comparison of altitude variations between 1982 and 1959 (Maresca, 1982) indicates vertical displacements, reaching up to 11 cm, at nine bench marks located between Ercolano and Vesuvius Observatory. The interpretation of this result is difficult however due to a possible bias caused by height dependent systematic errors, by the extent of the vertical displacements as compared to the period between measurements and by the lack of a reliable reference level.

Periodic vertical ground deformation measurements were made since 1974 along a levelling network about 20 km long. This network (fig. 7*b*), located at an altitude of 500-1000 m, is divided into four levelling lines, enclosing the central crater with the exclusion of the northernmost side. A Zeiss Ni 1 level with its invar staves was used. Figure 8 shows the vertical ground displacements observed at bench marks located on the upper part of the volcano in the period 1976-1982. The bench mark located at Vesuvius Observatory has been used as reference point, since it is located on a relatively stable part of the volcano, belonging to Mt. Somma structure. Figure 8 indicates a relative subsidence of the bench marks, concentrated in some regions around the volcano. For a better understanding of these displacements, the temporal variation of altitude at consecutive pairs of bench marks has been evaluated. The classical variance method has been used to infer the meaning of altitude variations at these consecutive pairs of bench marks. If we have m samples with n number of measurements within each sample, the total number of observations is, of course, $N = n \times M$. Then the x_{ij} represents the j-th observation belonging to the i-th sample; each sample is characterized by a mean $\bar{x}_i$ and the ensemble of all N observations has a mean $\bar{x}$. It is assumed that each sample, constituted by the ensemble of observations $[x_{ij}, j = 1, ..., n]$ is characterized by a common variance σ^2, belonging to a normal population and the samples have a common mean. The first estimate of σ^2 is the so-called « estimate within » and is provided by summing the squares of residuals of each observation x_{ij} from the average $\bar{x}_i$ of the corresponding i-th sample (with N-m degres of freedom); another equivalent estimate of σ^2 is the so-called « estimate among » and is obtained by summing n times the square of residuals of the average value $\bar{x}_i$ at each sample with respect to the general average $\bar{x}$ (with $m - 1$ degrees of freedom). This leads to the following expressions:

$$\sigma_1^2 = \sum_{i,j} \frac{(x_{ij} - \bar{x}_i)^2}{N - m} \quad \text{and} \quad \sigma_2^2 = \sum_i \frac{n(\bar{x}_i - \bar{x})^2}{m - 1}.$$



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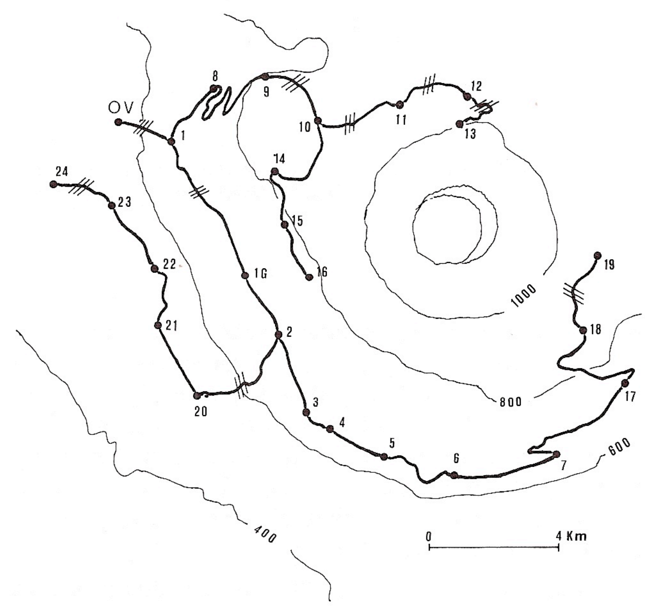


b)

Figure 7

a) Ground deformation networks. The stations of the planimetric network are indicated with a closed triangle. The measured distances are indicated by dashed lines. The distances for which the null hypothesis is false are indicated by a continuous line. The closed squares show the position of four small dry tilt networks; b) Ground deformation networks. The closed circles are the levelling bench marks. The segments unsatisfying the null hypothesis are marked with three slashes.

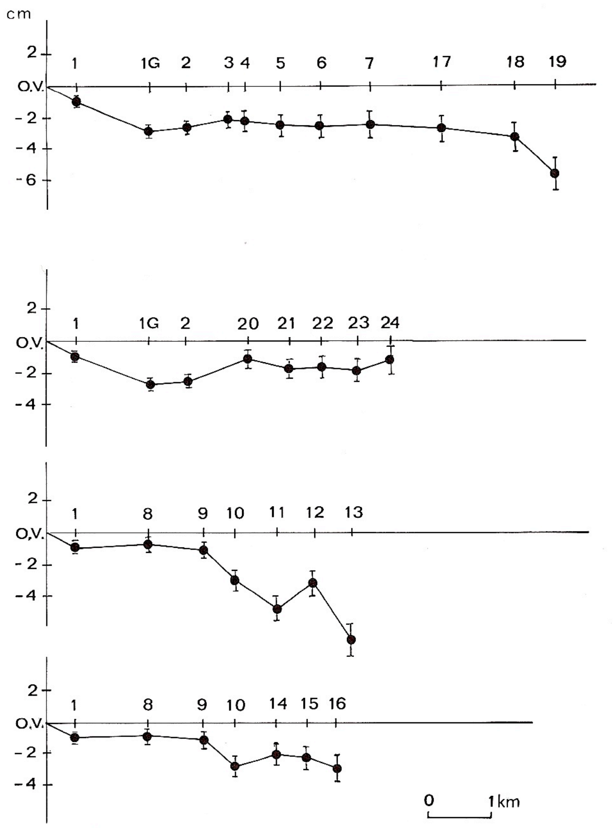
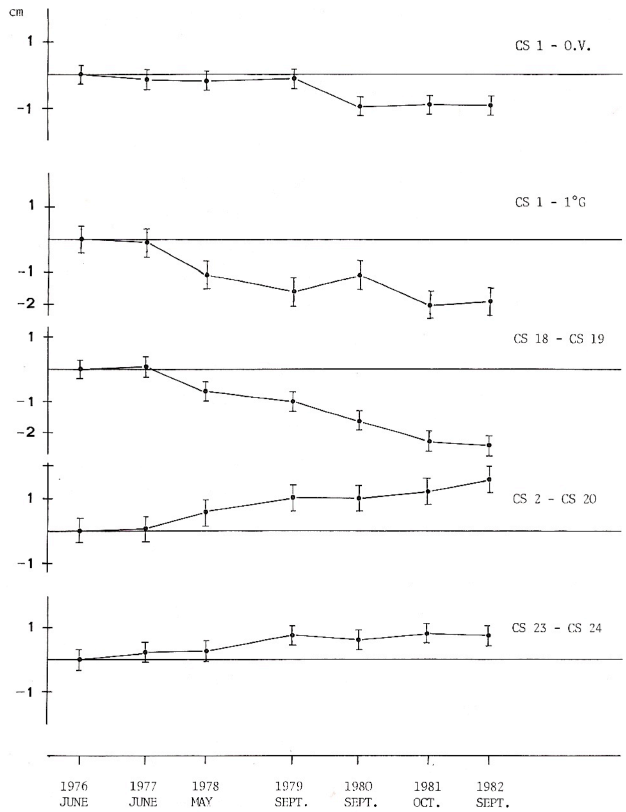


Figure 8
Vertical ground displacements of the four levelling lines in the period 1976-1982. The bench mark OV *(Vesuvius Observatory) is the reference one.*

Because σ_1^2 and σ_2^2 are estimates of the σ^2 variance, it is expected that they are not very different one from the other. It is easy to verify that the ratio $F_0 = \sigma_1^2/\sigma_2^2$ follows the well known Fisher distribution with $m - 1$ and $N - m$ degrees of freedom. Consequently in order to verify the null hypothesis $H_0 : \bar{x}_1 = \bar{x}_2 = \cdots = \bar{x}_n$ it is necessary to show that $F_0 < F_{m-1,N-m,\alpha}$ at the selected confidence level α.

The null hypothesis H_0 is that all the differences in height measured between two consecutive bench marks are equal. The analysis has been applied to vertical distances observed at 25 pairs of bench marks in the period 1976-1982. Each data point corresponds to seven samples having two repeated measures and consequently (at a confidence level equal to 5%) the Fisher test value $F_{6,7,0,05}$ is equal to 3.87; the null hypothesis is false for data having $F > 3.87$. This situation occurs in nine segments listed in table 1; such segments are also marked in figure 7*b* with slashes. Figure 9 shows the temporal variations of such segments. Among these nine segments, five are irregularly spaced. The only exception is represented by the segments distributed between the bench marks no. 9 to no. 13, located up to 1 km in altitude. This tract is long about 9.3 km with an altitude difference of about 200 meters, located close to the summit crater of Vesuvius. Soft sediments constituted by loose pyroclastics characterize this region. The pattern of the altitude variations shows a general trend of a relative subsidence, with the exception of the segment included between the bench marks no. 11 and



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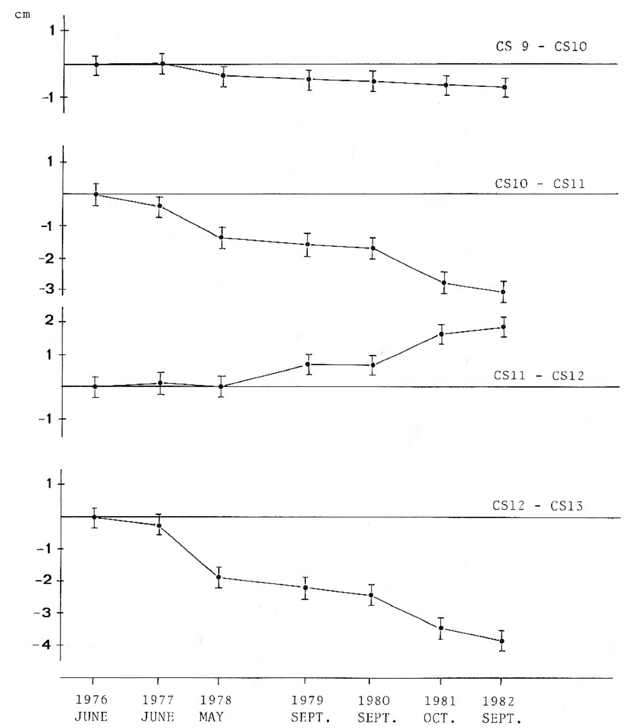


b)

Figure 9
Temporal altitude variations of the lines unsatisfying the null hypothesis.

no. 12; the average rate of relative subsidence is about 1 mm/y along the segment between the points no. 9 and no. 10; this rate reaches up to 5-6 mm/y along the other two tracts connecting the bench marks no. 10 with no. 11 and no. 12 with no. 13, while the segment between no. 11 and no. 12 bench marks shows an average

Table 1

Fisher test applied to vertical displacements.

Segment	n_1	n_2	F-test value	Level of significance
OV-CS1	6	7	10.0	0.3 %
CS1-1 G	6	7	14.0	0.1 %
CS18-CS19	6	7	32.7	0.1 %
CS2-CS20	6	7	7.7	0.8 %
CS23-CS24	6	7	4.6	3.2 %
CS9-CS10	6	7	4.1	4.3 %
CS10-CS11	6	7	44.2	0.1 %
CS11-CS12	6	7	20.2	0.1 %
CS12-CS13	6	7	79.7	0.1 %

rate of relative rising of about 3 mm/y. Different rates of ground subsidence are inferred from these data. The present data indicate low altitude variations in the volcanic complex of Mt. Vesuvius, amounting to about 6-7 cm in the period 1976-1982. The loose characteristics of the soils and the high slope favor the hypothesis of a relative subsidence as compared to the bench mark located at Vesuvius Observatory. An extension of this levelling network is necessary in order to study vertical ground movements in other parts of the volcano characterized by potential hazards.

The first trilateration network was set up around Vesuvius in April 1975 (Bonasia and Pingue, 1981). Since 1978 several azimuthal angles were also measured in order to reduce the distorsion effect caused by single distance measurements. The Mod. 700 AGA Geodimeter and a T3 Wild Theodolite were used for distance and angle measurements, respectively.

Horizontal ground measurements have been analyzed with the same criteria above. The data correspond to 60 measurements of distance with a different number of samples in the period 1975-1982 and with eight measurements for each sample; the triangulation point no. 19 was destroyed in 1979 and replaced in 1980 by the no. 22 triangulation bench mark.

The results obtained from the variance analysis show that 22 times the values of the Fisher test are higher than the corresponding critical value $F_{n_1,n_2,0.05}$ at a significance level of 5 %.

The set of these distance measurements is reported in table 2. Their time variations are illustrated in figure 10. The location of these distances are shown in figure 7*a* by a continuous line connecting the bench marks.

These data indicate that almost all the distances for which the null hypothesis is false have at least an extremum located on the crater rim. These movements are probably affected by the ground stability of the bench marks, located on loose sediments. A distance reduction between the points located on the crater rim is still observed. The most significant strains were about 10^{-5}-10^{-4}, but only for the crater summit zone (Bonasia and Pingue, 1981).

b) Seismic studies

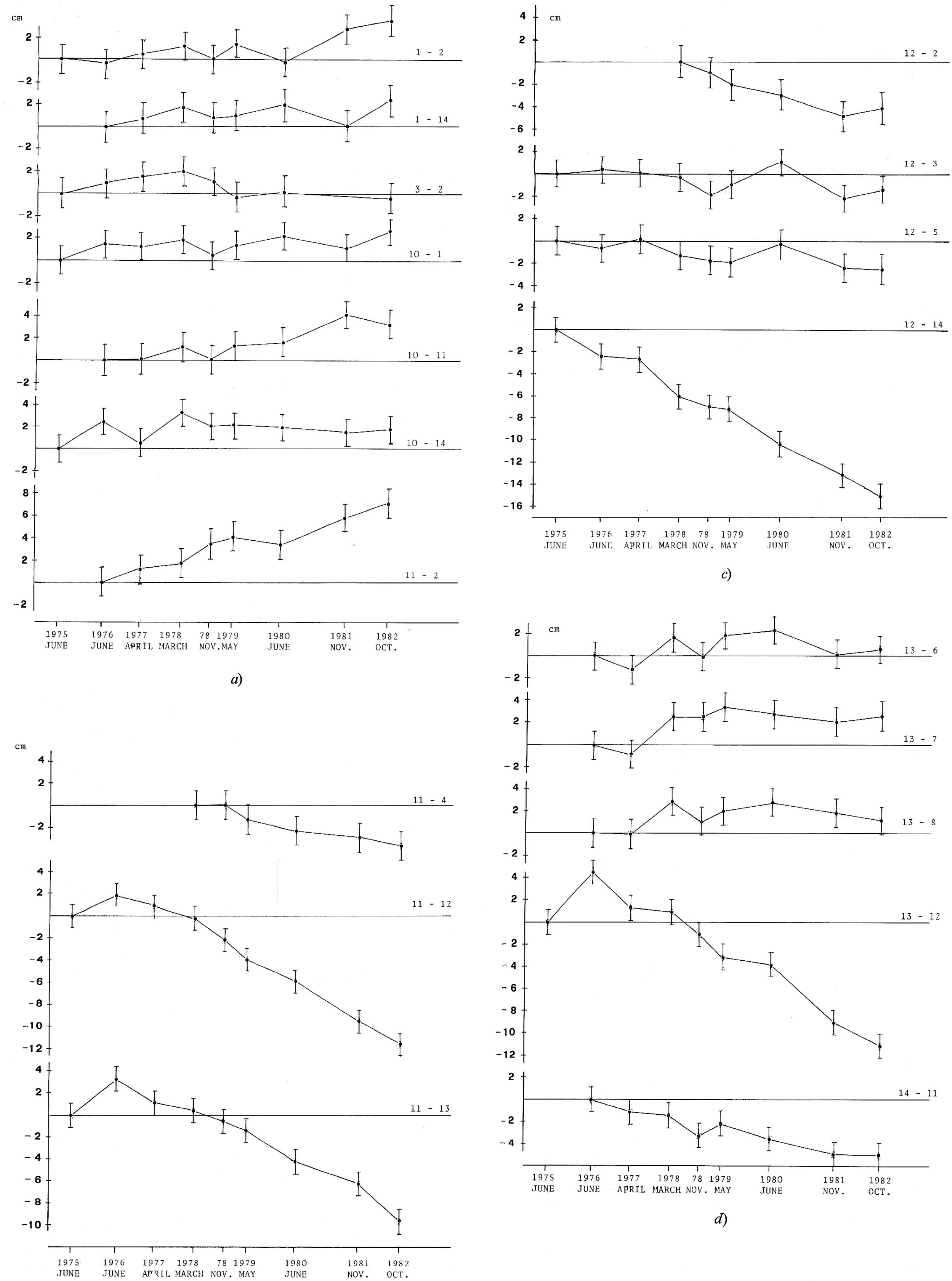
The seismic activity of Vesuvius is generally moderate during the eruptive phases, according to available historical data. The 1944 eruption was accompanied by the so-called spasmodic and harmonic tremor (Imbò, 1952). After the 1944 eruption the seismic activity became very low, with occasionally sharp increases. An example is the peak of energy released on May 11, 1964 (maximum MM intensity IV). Starting from 1971 the old instruments of the seismic station of Vesuvius Observatory (Imbò *et al.*, 1968) began to be renewed. Since November 5, 1971 a three-component seismometer (Geotech S 13) with Helicoder recording has been installed (OVO station, fig. 11). Magnetic tape recording started in 1974 and from December 1977 to August 1978 a quadripartite array with magnetic tape recording was operating (fig. 11). A detailed description of these instruments has been given in Del Pezzo *et al.* (1978). A monthly count of local quakes in the period 1970-1982 is plotted in figure 12. Some scattered periods of higher activity are superimposed to a background seismicity of about 30-40 events per month. A closer examination of the periods of high activity reveals the occurrence of burst of events which can be considered to be classical swarms (Corrado *et al.*, 1976).

The swarm type character of the earthquakes in the area of Mt. Vesuvius is evidenced by studying the statistics of their occurrence. Each earthquake is considered as an event in the generation process. If the process is random in time no cluster should occur. If the process has a Poissonian distribution it follows an exponential given by : $f(t) = e^{-\lambda t}$, where λ is the Poisson rate and t the interarrival time. This theoretical distribution is not well fitted by the experimental interoccurrence times of the Vesuvius quakes (fig. 13). It means that the process is not Poissonian, the events are related to each other and clusters must be present in their occurrence. If the process is a generalized Poisson process the clusters, regarded as a single event, must follow the Poisson statistics. For the catalog of Vesuvius events we determined firstly the clustering length, i.e. the maximum time distance among the events that are considered as a cluster. This calculation has been performed in the following way : a trial initial clustering length of 1 min was chosen. All clusters having this length were counted and the interarrival times of their centers (the time corresponding to half of the duration of the cluster) were least-square fitted with an exponential distribution. The clustering length was changed recursively by adding 1 min at each step. It was found that the best least-square fit with a negative power law distribution was obtained for a clustering length of 30 min. The high number of obtained clusters allowed us to study their distribution. This last follows a negative power law (Shlien and Toksöz, 1970) :

$$q(n) = N^{-E}/Z(E)$$

where E is a parameter describing the cluster size and $Z(E)$ is the Riemann zeta function : $\sum_{i=1}^{\infty} i^{-E}$.

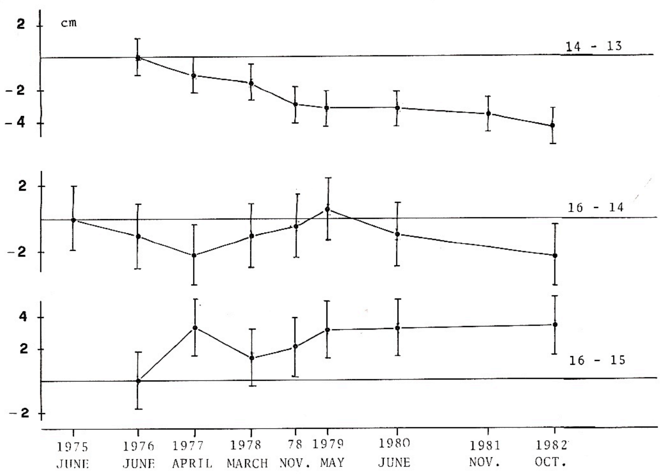
A fit with the theoretical distribution was obtained with the following procedure : the Riemann function was experimentally estimated by truncating the sum after 10,000 points with an initial value of E equal to 0.01 and the sum of squared residuals was then evaluated. The value of E was then slightly increased and step by step the sum of squared residuals was evaluated again, with the value of E equal to 5. The range of possible



b)

Figure 10
Temporal length variations of the lines unsatisfying the null hypothesis.

E values has been chosen to allow twice the experimental range in which E was found to vary by Shlien and Toksöz (1970). The resulting value of E was 1.8, corresponding to the minimum of the sum of the squared residuals. The low E value, with respect to the high values (2.4-3.7)



e)

Table 2

Fisher test applied to horizontal displacements.

Segment	n_1	n_2	F-test value	Level of significance
1-2	8	63	6.6	0.1 %
1-14	7	56	2.6	2.2 %
3-2	7	56	2.6	2.1 %
10-1	8	63	2.4	2.2 %
10-11	7	56	8.7	0.1 %
10-14	8	63	3.6	0.2 %
11-2	7	56	19.9	0.1 %
11-4	5	42	8.6	0.1 %
11-12	8	63	102.4	0.1 %
11-13	8	63	64.2	0.1 %
12-2	5	42	11.4	0.1 %
12-3	8	63	4.0	0.1 %
12-5	8	63	3.6	0.1 %
12-14	8	63	102.1	0.1 %
13-6	7	56	4.9	0.1 %
13-7	7	56	7.8	0.1 %
13-8	7	56	4.6	0.1 %
13-12	8	63	99.6	0.1 %
14-11	7	56	12.5	0.1 %
14-13	7	56	8.2	0.1 %
16-14	7	56	3.8	0.2 %
16-15	6	49	3.9	0.3 %

found by Shlien and Toksöz (1970) for various regions in the world, may indicate a low energy threshold for Vesuvius microearthquakes.

The duration magnitude of the greatest Vesuvius quakes recorded during 1970-1982 is about 3. This estimate was obtained by extrapolating the $M_L - \ln \tau$ relationship (τ is the duration of the event) available for OVO station, valid for magnitudes greater than 3 (Del Pezzo *et al.*, 1983).

S-P times for the Vesuvius quakes are clear only for 30 % of the total events. These values range from 0 to 6 s and their distribution is peaked around 1.5 s (fig. 15), showing that a great percentage of these events is a few km distant from OVO station. The quadripartite array recorded about 60 events with a clear *P* onset, but generally with unclear *S-P* time intervals. So it is possible to obtain only the azimuths of the incoming wave fronts and the apparent velocities. The distribution of the azimuths is plotted in figure 16. A significant percentage of events come from the craters (N90E-

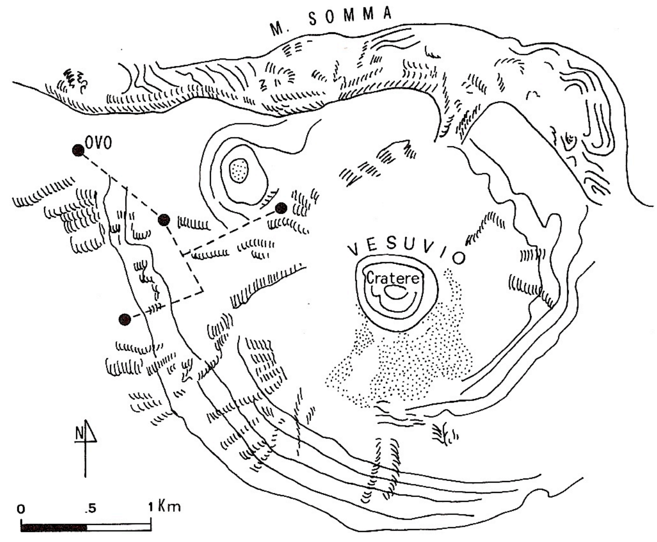


Figure 11

Sketch map of Vesuvius area. Closed circles are the OVO *station and the stations of the quadripartite array.*

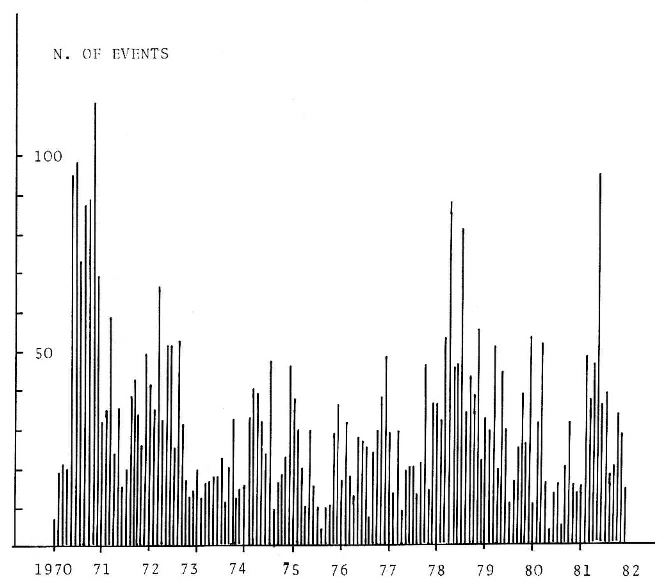


Figure 12

Monthly count of local quakes at Mt. Vesuvius.

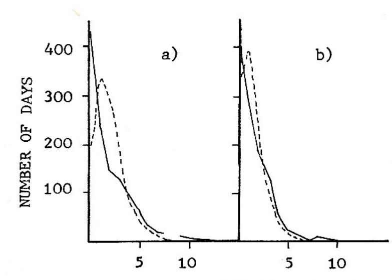


Figure 13

Observed (continuous line) and theoretical (dashed line) Poisson distribution of Vesuvius microearthquakes : (a) for all microearthquakes; (b) same, but with clusters counted as single events.

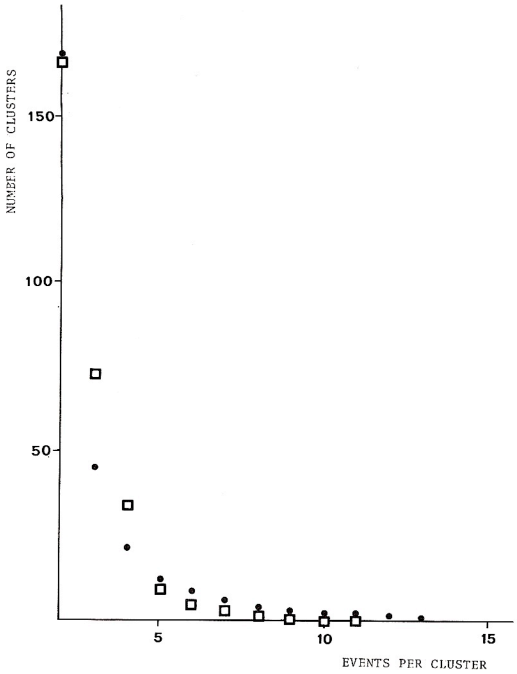


Figure 14

Observed distribution of clusters (open squares) and theoretical Riemann distribution (closed circles).

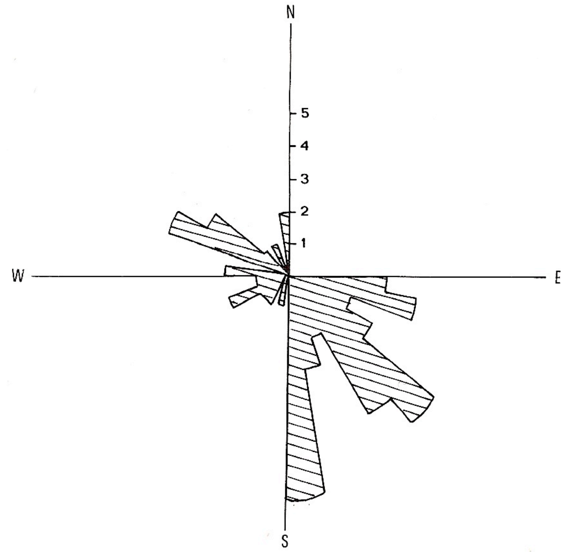


Figure 16

Azimuthal distribution of microearthquakes recorded at the quadripartite array.

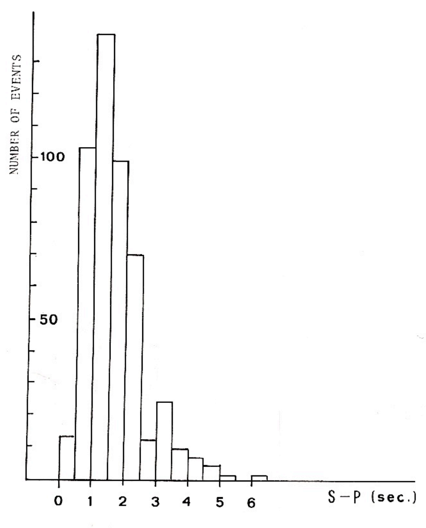


Figure 15

Frequency of occurrence of S-P times for Vesuvius microearthquakes.

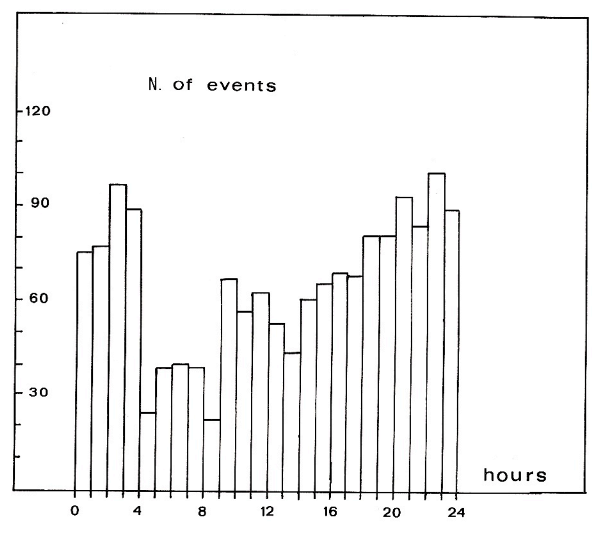


Figure 17

Distribution of the seismic activity during the hours of the day.

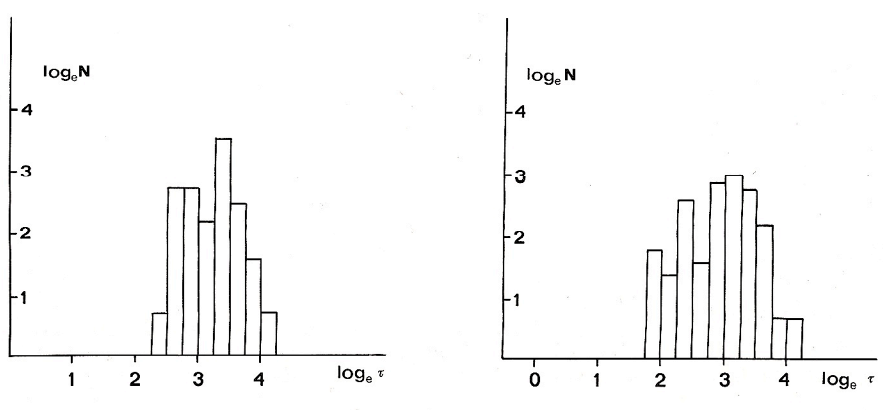


Figure 18

Two examples of $\ln N - \ln \tau$ *distribution calculated for two sets of events (100 events each), randomly sampled in the microearthquake catalogue.*

N135E). Some others come apparently from South and NW directions. The calculated apparent velocities range from 1 to 3.5 km/s, showing extremely shallow foci. Errors in the azimuths are in the range of 10°-20°. No evident contamination of seismic events with man-made shocks is recognizable in the plot of figure 17; in this plot a reduced activity in the morning hours is shown, but this effect is not clearly interpretable as due to a lower cultural activity during this time of the day. The cultural noise is a great problem for OVO station and generally for the entire region of Mt. Vesuvius which is surrounded by a densely populated area. The detection threshold at OVO has been evaluated by plotting the distribution of the log of duration as a function of the log of the number of the events, for several groups of events, each randomly distributed over the time period of investigation (fig. 18). All these plots show a marked difference from a straight line for ln N values lower than about 3. This means that the detection threshold of OVO station is about $M_L = 1.7$ for the Vesuvius quakes.

CONCLUSION

The results of the ground deformation measurements show that no relevant movement concerning the volcanic region of Vesuvius is presently occurring. Only the top of the Vesuvius Great Cone presents a significant strain, but this fact seems related to local effects.

Twelve years of continuous single station monitoring reveal the moderate average level of the microearthquake activity of this volcano. These events seem to originate from the crater area and the SW flanks of the volcano, where the greater tectonic instability seems to exist (Bonasia *et al.*, 1974). Their magnitudes are low, reaching a maximum of about 3, and their time occurrence is of the swarm type. Due to the high noise level, the detection threshold of the OVO station is about $M_L = 1.7$.

The eruptive history and the structural framework indicate that earthquake activity along the southern Apennines is one of the possible mechanisms for eruptions. An implementation of the present geophysical surveillance system and other investigations on the Vesuvius structure and dynamic behaviour are a necessary goal of future research, given the high risk connected with the renewal of volcanic activity.

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