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Seismic surveillance at Vulcano by use of a portable digital array: features of the seismicity and relocation of the events in a 3-D heterogeneous structure

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Abstract

A considerable rise in temperature in the fumarolic gases, observed at Vulcano throughout 1988, was not accompanied by correlated geophysical markers indicating clear renewal of the volcanic activity.

Microseismicity remained at very low energy levels and was monitored during two months by use of a temporary array of three-component digital stations, in addition to the permanent seismic network of the Aeolian Islands. Comparison of the seismic activity recorded during this experiment with the seismicity detected during a previous survey carried out in 1987, suggests that no substantial changes occurred in both the hypocentral volumes and energy release.

Relocation of the events within a three-dimensionally heterogeneous medium, observation of waveforms similarities and kinematic analysis for reconnaissance of the seismic phases allow to draw a preliminary quantitative picture of the seismic behaviour of the volcanic field during the surveillance period.

Riassunto

Il significativo aumento della temperatura delle fumarole rilevato a Vulcano non ha trovato immediati riscontri in livello e tipologia della sismicità registrata nell'isola nel corso dell'intervento straordinario di sorveglianza (coordinato dal Gruppo Nazionale per la Vulcanologia) del Luglio-Settembre 1988.

L'attività microsismica è stata controllata con l'ausilio di una rete mobile di stazioni digitali a tre componenti, centrata sull'area craterica e disposta con geometria sostanzialmente complementare a quella della rete fissa facente capo all'Istituto Internazionale di Vulcanologia di Catania: essa si è mantenuta su deboli livelli energetici comparabili, sia in Magnitudo che in frequenza giornaliera, con quelli rilevati nel corso di una precedente campagna effettuata dall'Osservatorio Vesuviano nel Settembre-Ottobre 1987.

Viene qui effettuata una prima valutazione quantitativa di detta sismicità; gli eventi sono stati rilocalizzati nell'ambito di un'inversione dei tempi di tragitto delle onde P, onde tener conto della fortissima eterogeneità locale della distribuzione di velocità.

Tra le caratteristiche salienti dell'attività viene altresì individuato il raggruppamento in «famiglia» di una lunga sequenza di eventi localizzati in area Piano di Vulcano. Tale osservazione, unita all'identificazione accurata degli arrivi delle onde di taglio mediante orbite particellari, consente di porre vincoli determinanti sulla sua posizione focale.

1. Introduction

The island of Vulcano is characterized by constant and shallow microseismicity, spatially clustered in the Fossa crater area (Blot, 1971; Latter, 1971; Del Pezzo and Martini, 1981; Falsaperla et al., 1989).

The crater is at fumarolic stage since the 1888-1890 eruption eye-witnessed by Mercalli (De Fiore, 1922). Significant increase in the gas temperature has been observed at least three times, particularly in 1924 (estimated T>600°C), in 1979 (T>300°C) and, very recently, in 1988 (T>450°C). The latter event led the Gruppo Nazionale per la Vulcanologia, upon request of the Civil Defence Ministry, to start a two-months lasting, global surveillance operation during which, although no geophysical markers indicating a renewal of the volcanic activity were observed, we were allowed to improve the knowledge of both seismic behaviour and structural features of the site (C.N.R.-G.N.V., 1988).

The seismological surveillance of the area was shared between the permanent array, operated by Istituto Internazionale di Vulcanologia (filled squares, Fig. 1), and Osservatorio Vesuviano (open circles, Fig. 1).

We made use of digital, three-component stations, signal-triggered on short-term/long-term signal average comparison. Two seismic cables (respectively 1.2 km and 0.7 km long) were installed on the western flank of the crater. The array was improved and expanded with time and growing seismicity level up to a maximum of 7 stations.

Stations AGP and CGR were kept in the position they occupied during a former microseismic survey, we had carried out in 1987 by use of the same type of equipment (open triangles, Fig. 1). Also recording points GDR, LEN and PSM were successively restored, but during shorter lapses of time. A large landslide, occurred in Spring 1988, impelled us to re-install the crucial station PNR (at the sea-side, north of the crater): this recording point was replaced by station CSB, which was implemented with a fourth, vertical geophone placed 0.25 km further east.

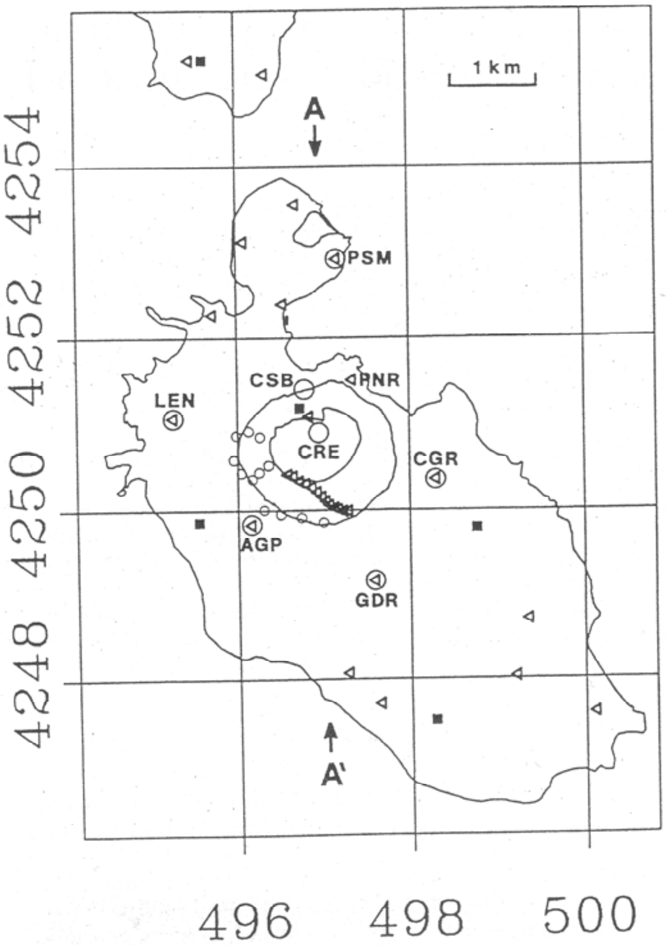

Fig. 1 – Location map. The stations of the temporary array are indicated by open circles (1988 survey) and open triangles (1987). Filled squares locate the permanent array.
Smaller symbols correspond to seismic cables installed, both in 1987 and 1988, on the western flank of the crater.
Cross-sections of Fig. 3b is taken along A-A'.

2. Evaluation of the seismic activity

Near-total lack of seismicity, even at the very low detection threshold allowed by our equipment, occurred until the first days of August 1988 (Fig. 2b).

Microseismicity was then restored to a «normal» level (see Falsaperla et al., 1989), comparable to that we observed in 1987 (Fig. 2a), as from August 10, when a ten-events sequence occurred. It was followed, on August 14, by a similar sequence of shocks, which also included the stronger event recorded during the two-months surveillance (M_L=2.6).

Because of the technical characteristics of the seismic array (composed of only signal-triggered stations, without continuous recording), daily frequency histograms of Fig. 2 are computed taking into account the only events on which three stations at least simultaneously triggered.

A subset of events recorded by N≥4 stations (only the 1988 survey, black bars of Fig. 2b), provides a rough indication of the frequency of occurrence of relatively stronger earthquakes.

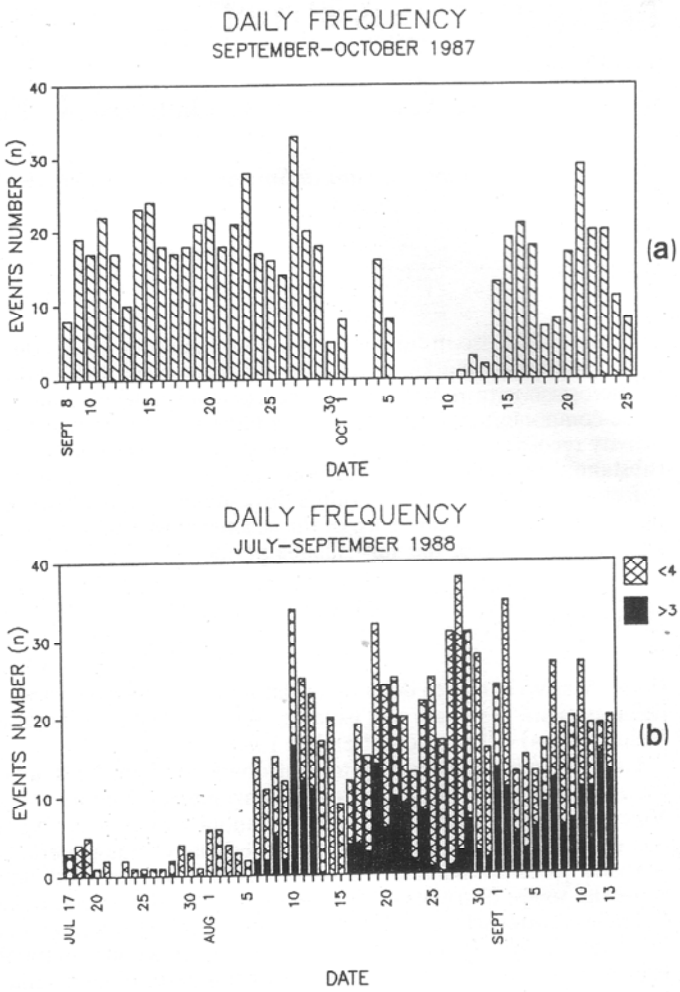

Fig. 2 – Daily frequency histograms during the 1987 (a) and 1988 (b) observation periods as accounted by triggering on event of a number of stations N≥3.
A subset N≥4 (black bars) provides a rough estimate of the daily frequency of occurrence of slightly stronger events during the 1988 survey (b).

3. Relocation of the events in a very heterogeneous medium

The bulk of the seismicity observed during the 1988 surveillance remained substantially unchanged, both in energy and location, with respect to the survey carried out in 1987. This can be fairly well illustrated by merge of events recorded during both surveys into a P-times inversion routine (after Tarantola & Valette, 1982) and relocation of them into a three-dimensionally heterogeneous environment.

Because in 1987 we had run an exceptionally dense array, the data set is largerly composed (93 events) by local earthquakes recorded at 15 recording points at least during that survey. Thirty more events were chosen among those we recorded in

1988 (Table I): we consider this sample highly significant, both in energy and type of seismicity, for illustrating the activity recorded during the observation period. Events nrs. 1 to 10 were located by merge of our data with those from the permanent array.

TABLE I

nr.	Date	T_o	X_o	Y^o	Z_o
1	880814	0623	4.9	3.1	4.0
2	880814	0810	4.8	3.1	3.9
3	880818	1245	1.9	4.7	2.7
4	880818	1736	2.6	5.2	2.0
5	880819	0712	3.0	5.3	2.4
6	880819	0730	2.3	4.7	2.4
7	880821	1640	2.8	4.8	2.0
8	880822	0524	2.2	4.6	1.6
9	880828	1950	3.5	5.4	1.1
10	880829	1328	2.7	5.1	2.6
11	880821	0418	1.8	5.6	2.1
12	880821	0504	2.1	6.1	2.1
13	880822	0448	2.0	5.6	3.1
14	880824	0505	1.9	4.6	3.8
15	880824	2204	1.4	6.8	1.8
16	880825	2113	1.5	6.2	3.1
17	880827	1131	2.7	5.6	2.4
18	880828	0021	2.6	5.5	1.8
19	880901	0334	2.5	4.4	2.3
20	880901	0457	2.6	4.8	2.5
21	880901	0628	2.7	4.3	2.3
22	880901	1710	2.9	4.6	1.2
23	880901	1816	2.9	4.6	1.3
24	880902	0919	2.9	5.1	2.2
25	880906	1128	5.1	4.9	1.3
26	880908	2056	3.0	5.1	0.7
27	880910	1401	2.9	4.9	0.4
28	880913	0233	3.0	5.1	0.2
29	880913	0417	2.8	4.9	0.2
30	880913	1958	2.7	4.9	0.1

For inversion and relocation purposes we adopted the following a-priori, horizontally-layered P-velocity model:

2.5 km/s $\rightarrow [+0.4< z< -1.0]$ km
4.5 km/s $\rightarrow [-1.0< z< -3.5]$ km
5.5 km/s $\rightarrow$ half-space.

The half-space velocity is inferred from the upper crust velocities obtained by data collected during a short-range DSS survey carried out in 1986 (Milano et al., 1988; Ferrucci et al., 1991).

Figures 3a and 3b respectively show epicentres and hypocentres projected onto the inverted P-velocity anomaly calculated in a shallow layer ($0.0<z<0.5$ km) and along the A-A' (north-south) cross-section. The velocity anomaly is expressed in terms of the amount of P-velocity increase (white) or decrease (black) which would be needed for minimizing the traveltimes residuals variance with respect to the a-priori model.

The 30 events of Table I are marked by filled circles in figures 3a and 3b. An asterisk marks events nrs. 1 and 2, also later discussed in 6.

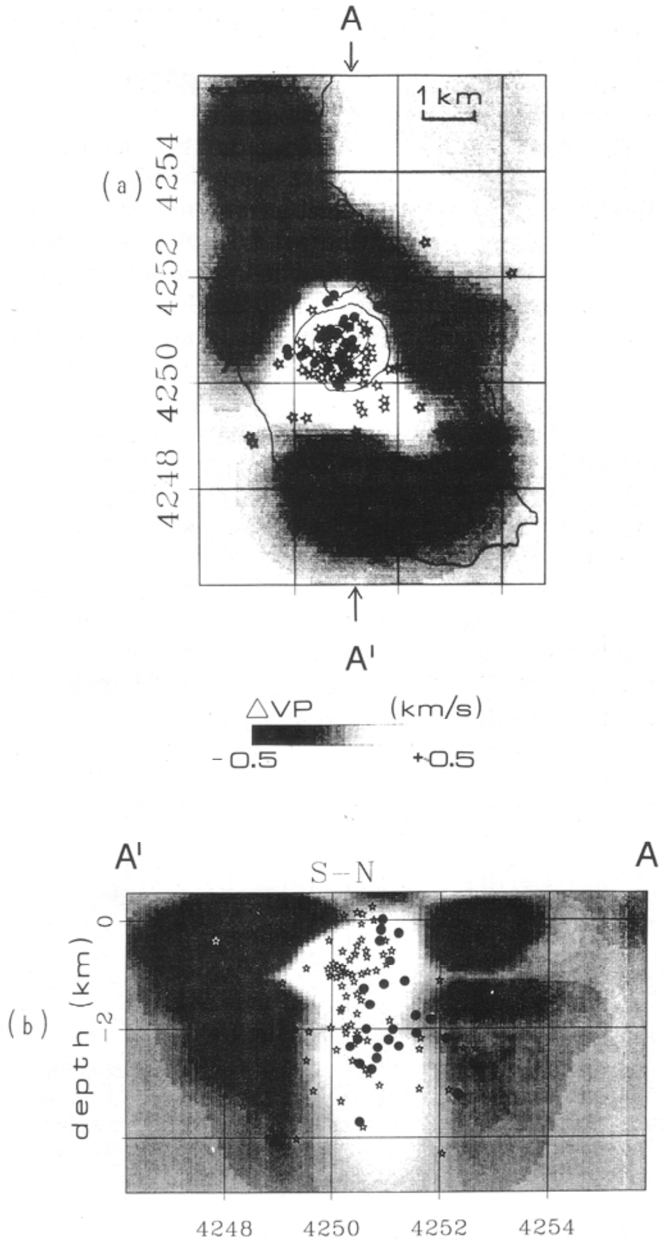

Fig. 3 – General map of the seismicity at Vulcano, overlayed to the Vp anomaly (velocity anomaly scale shown left-below). The 30 events of Table I are marked by filled circles; an asterisk marks the best location of the earthquakes-family observed during August 1988.
a) Vp anomaly computed in a 0.5 km thick layer ($0.5<z<1.0$ km) and epicentral location.
b) north-south depth-section of the Vp anomaly and hypocentral location.

We observed that: (1) the bulk of the local seismicity is almost entirely confined in the Fossa crater area and (2) the hypocentral volumes defined by the 1987 and 1988 events are coincident. This suggests that no substantial change occurred in the seismic activity, although geochemical indicators emphasized large-scale changes in temperature and composition of the volcanic fluids (CNR-GNV, 1988).

Relocation of the events in a three-dimensionally heterogeneous model could significantly help in avoiding bias of the interpretation, as demonstrated in Fig. 4.

Fig. 4a is obtained by location in the horizontally-layered Vp model before inversion, while Fig. 4b shows the epicentral map after inversion (i.e., after location in the model of Fig. 3). Although both the a-priori and the a-posteriori models display similar average velocities (about 3 km/s in the range of depths 0.0-2.5 km b.s.l.), spatial clustering of the focii occurs on dramatically different geometries.

The alignment of Fig. 4a, in fact, could be interpreted as a tectonic feature. On the contrary, after relocation of the events in the 3-D heterogeneous medium (Fig. 3b), the alignment disappears and the events just cluster in the crater area.

We conclude that, in areas characterized by major and short-wavelength heterogeneity, clustering can be unequally (and often uncontrollably) shared between real tectonic features and inadequacy of mono or bi-dimensional velocity laws.

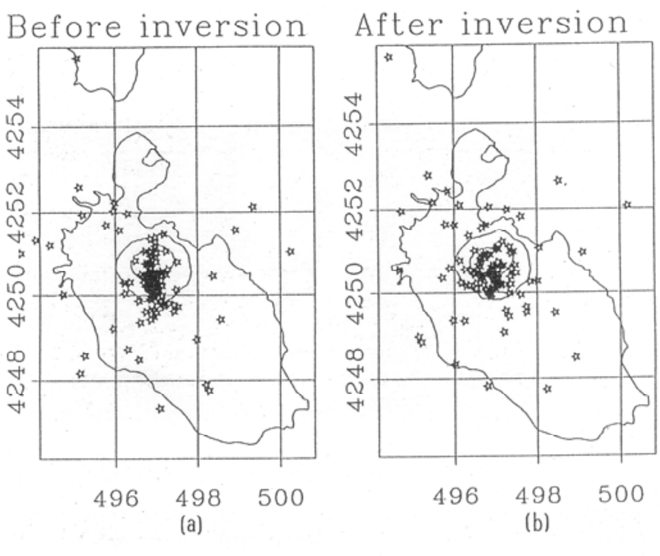

Fig. 4 – Epicentral maps computed (a) in the horizontally-layered (a-priori) model and (b) in the three-dimensionally heteregeneous model of Fig. 3: the alignment of Fig. 4a is essentially due to the model.

4. Early development of surface-waves

Let us first take into consideration (Fig. 5) a shallow event, recorded at station CRE (close to the top of Fossa Grande, 250 m a.s.l.) on September 6th, 11:28 a.m. local time. The event is a morphologically typical example of the seismicity connected to the shallow crater structure (see, for comparison, Blot, 1971 or Latter, 1971). The three components are shown both unfiltered (above) and 2-6 Hz, band-pass filtered. Sampling frequency: 125 Hz.

The first 100 samples of filtered signal are pro-

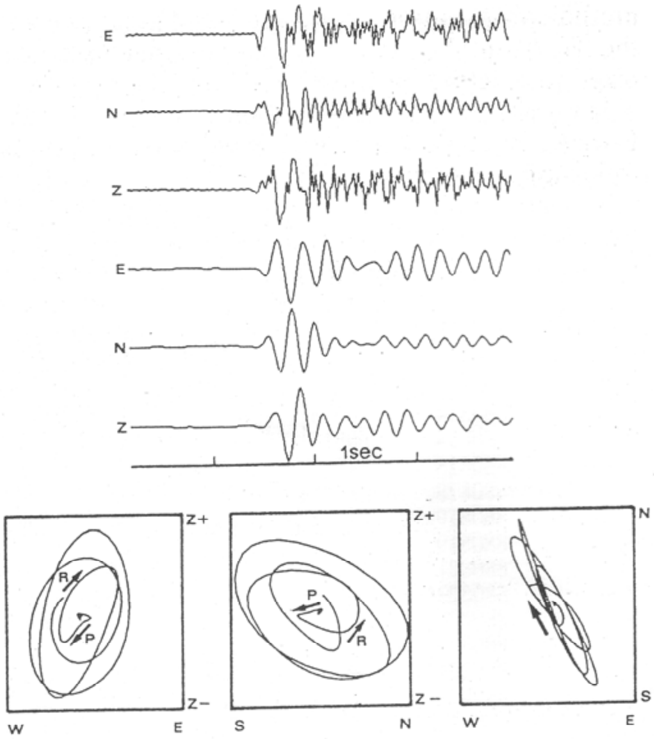

Fig. 5 – Particle-motions of the earliest wavetrains of a typically shallow event recorded at station CRE (Fossa Grande, 250 m a.s.l.): a very weak P-phase is immediately followed by a large-amplitude Rayleigh wave (R).

Misidentification of the arrivals could occur both without use of three-component sensors and in presence of a even slightly higher ground noise.

cessed in order to recognize nature and type of the earliest arrivals. Ground motion is reconstructed by use of particle-motion diagrams, projected onto the three reference planes shown in Fig. 5, below:

- Vertical/Horizontal E-W (below left);
- Vertical/Horizontal N-S (center);
- Horizontal plane (right).

We can observe:

i) practically null P-phase and sharp avangrade motion of the (R) wave in the Vertical/east plane;

ii) a short-duration, linearly polarized first-arrival (P), with weak Vertical component and slightly stronger amplitude in the south-north direction; a sharp retrograde motion characterizes the major and later phase (R);

iii) the polarization of the main phase (R), observed in the horizontal plane, is linear and lies on the SSE-NNW direction.

From the 1.2s duration frames it is possible to recognize the very weak P-phase as a compressional wave, practically seen on the only horizontal, north-south component.

The larger amplitude phase (R), on the contrary, shows retrograde motion in the Vertical/N-S plane, opposite to the one observed in the Vertical/east plane.

Once the latter motion is projected onto the azimuthal propagation direction NNW-SSE seen in the Horizontal plane (right), the wave is recognized as a Rayleigh-wave.

Its amplitude, eight to ten times larger than the P-wave, hinders later body-waves arrivals in the following 2.5 seconds: therefore the source signature is essentially contained in the weak and early P-phase which, most probably, would not be observed at even slightly larger distances.

As a conclusion, misidentification of nature and type of the arrivals in such a kind of events, very frequent at the Fossa crater, could severely affect their correct location because of hindering of P-arrivals by much larger amplitude surface wave groups.

On the contrary, observation of a Rayleigh wave at such a short epicentral distance, requiring least source-to-station distances, can directly help in costraining the source depth.

5. Reconnaissance of direct S-wave

One of the stronger events of the noteworthy sequence occurred on August 14th (06:23 a.m., local time, nr. 20 in the Table I) is shown in Fig. 6 as recorded at CGR and AGP.

Although weak, P-arrivals are clear on both the vertical components and allow a high time-picking accuracy; the S-waves reconnaissance, on the contrary, appears much more complex and requires a closer analysis for the correct S-time picking.

At station CGR, by observation of the only vertical component, S-time would be picked in correspondance of the first, large amplitude arrival following the P: and S-P time of about 0.9s would consequently indicate a focus-to-station distance not exceeding 2.5 km in the velocity model above discussed in 3.

Horizontal components, on the contrary, allow to recognize two wavegroups: the first corresponds in time to the apparent S-wave read on the vertical component.

Particle motions are computed, on the three time-windows pointed out by arrows on the seismograms (Fig. 6), after vectorial sum of each couple of components defining the three reference planes:

- Vertical/Horizontal E-W (above);
- Vertical/Horizontal N-S (middle);
- Horizontal plane (below).

At this stage of the processing, we did not care to rotate the horizontal components with respect to azimuth of approach (as usually done for effective separation of SV and SH polarizations) both because of the very short epicentral distance, and of the expected, consequent, wavevectors incidence angles close to normal incidence.

The P-arrival, recognized in [1] shows an incidence angle of about 30°. The phase [2], which could be interpreted as an S-wave by observation of the only vertical seismogram, is on the contrary recognized as a second, stronger P-arrival.

It is, in fact, linearly polarized on both the Z-E and Z-N planes, with incidence angle in the range 30°-45° and almost complete lack of linear polarization of appreciable amplitude in the horizontal plane [1, 2, below].

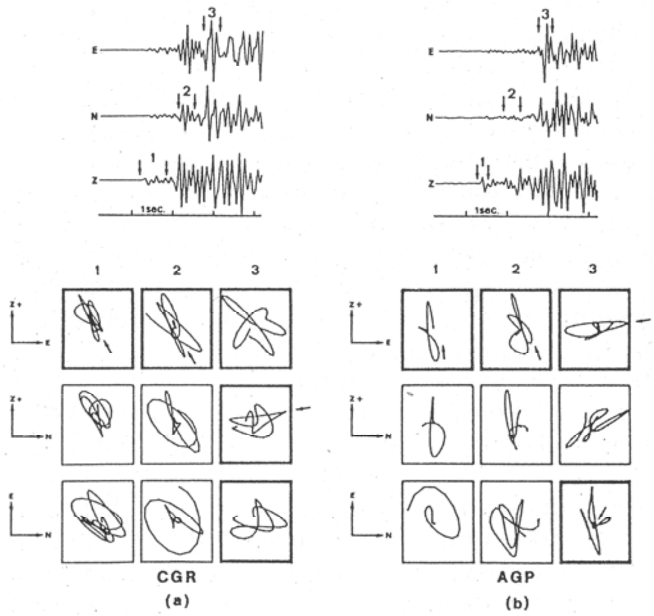

Fig. 6 – Three-component seismograms and corresponding particle-motions for the event recorded on August 14, 06:23 at stations CGR (left) and AGP (right). The phase [3] is recognized as the direct S-wave, while the P-arrival [2] could be due to SV→P conversion at a boundary close to the source.

A first attempt of interpretation suggests that this strong, later P-arrival could be due to an SV→P conversion, on reflection, at a boundary close to the source and about 2 km distant from it.

The later arrival [3] is finally recognized as the S-wave on all the references planes, specially polarized along the E-W horizontal component.

As a conclusion, a real S-P time difference as large as 1.8s is obtained after correct phases identification by particle-motions.

These statements are fully confirmed by particle-motions computed at station AGP (Fig. 5, right), where sharp linear polarizations of both P and S wavegroups confirm the clear indications directly observed in the three-component record.

The 1.7s S-P times difference, in addition to the 1.8s value formerly obtained at station CGR, definitely constrain a deeper (about +1.5 km) source than would have been obtained by S-time picking on the only vertical components.

6. Observation of earthquakes-families

Observation of the shape-similarity of two events, even spaced in time, constitutes the most simple and recursive analysis performed by a seismological observer.

It usually allows seismologists in charge of the surveillance of an assigned area to recognize the signature of the medium and to roughly locate the event, often with acceptable errors.

A quantitative application of this idea, as a further constraint on sources location, can be successfully illustrated by the events of the above mentioned swarm-like sequences.

In fact, both before and after relocation in the 3-D heterogeneous medium, the epicenters of these events remained spread over a 1.5 km wide area, in the southern part of the island.

A closer observation of their waveforms led us to suspect that variable signal-to-noise ratios of the emergent P-arrivals (due to the broad range of Magnitudes of the sequence) could severely affect the time-picking accuracy and lead to scattering of the calculated focal positions.

The seismograms of Fig. 7 (E-W horizontal component of station CGR) show that the events have exactly the same time-delay between any couple of direct or scattered phases. Correspondence in phase and in normalized amplitudes (a relevant feature, once the very high sensitivity of the horizontal components to even small azimuthal variations is considered) allows us to infer that these events belong to the same «earthquakes-family» (in the sense of Hokada et al., 1983).

Focal positions can, therefore, be reduced to a single focal volume, independent on the calculated hypocenter. The complete earthquakes-family was composed of the 24 events of Table I and lasted fifteen days.

It could be located, for instance, by means of its only strongest events (06:23 and 08:10, August 14th; nrs. 20 and 21 in Table I and Fig. 7), for which seven P and six S time-pickings with best signal-to-noise ratios are available.

The best location of the earthquakes-family is marked by an asterisk in Fig. 3.

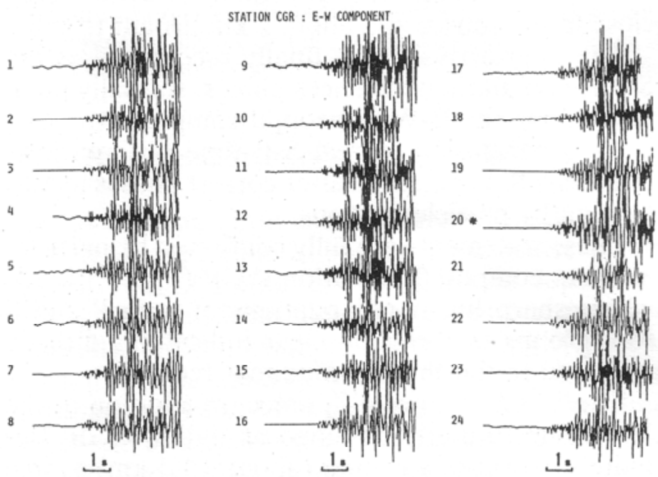

Fig. 7 – The complete Earthquakes-Family (24 events) observed on the N-S horizontal component at station CGR.

TABLE II

Nr	Time	Date	Nr	Time	Date
1	01:40	880810	13	16:19	880812
2	01:48		14	00:43	880813
3	01:56		15	23:42	
4	01:57		16	05:32	880814
5	02:07		17	05:56	
6	02:28		18	05:57	
7	04:39		19	06:22	
8	08:03		20	06:23	
9	16:24		21	08:10	
10	19:24		22	09:29	
11	01:10	880811	23	48:32	880815
12	06:47		24	03:04	880825

7. Conclusions

In absence of major seismic activity, the approach to the seismic behaviour of Vulcano herein illustrated has been «negative» on purpose: in fact, we have chosen to discuss some features of the seismicity by showing how they were likely to be misinterpreted.

Such an approach can be helpful for future closer and denser seismic observation of small and very heterogeneous areas as the one under study. In particular, the continuously upgraded performances of the equipment allow to obtain more detailed and reliable informations: therefore, they require almost new field strategies.

The present surveillance routine allowed us to outline and develop a field strategy, proper to a portable array and consisting in the adequation of the temporary geometry to the space-time distribution of the seismicity; the geometry was eventually modified keeping, in any case, three to four stations always in the same position.

Although demanding hard field work, this strategy allowed us to approach even the weakest seismicity ($M_L < -1$), essentially in the northern part of the crater; this kind of data acquisition should be better accompanied, during future surveys, by direct location into a pre-calculated 3-D heterogeneous structure.

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