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2D seismic tomography of Somma-Vesuvius

Description of the experiment and preliminary results

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Abstract
A multidisciplinary project for the investigation of Mt. Vesuvius structure was started in 1993. The core of the project is represented by a high resolution seismic tomography study by using controlled and natural sources. The main research objective is to investigate the feeding system of the volcano and to retrieve details of the upper crustal structure in the area. A first 2D active seismic experiment was performed in May 1994, with the aim of studing the feasibility of using tomographic techniques for exploring the volcano interiors. Particularly, this experiment was designed to obtain information on the optimal sources-receivers configuration and on the depth extension of the volume sampled by shot-generated seismic waves. 66 three-component seismic stations and 16 single-component analogue instruments were installed by several Italian and French groups to record signals generated by three on-land, underground explosions. Sources and geophones were deployed along a 30-km NW-SE profile passing through the volcano crater. Receivers were placed at an average spacing of 250 m in the middle of the recording line and at 500 m outside. The arrival time data base was complemented by first *P* and *S* readings of microearthquakes which occurred in the recent past within the volcano. The first arrival data set was preliminarily used to determine the shallow structure of the volcano by applying Thurber's (1983) tomographic inversion technique. This analysis shows evidence for a high-velocity body which extends vertically from about 400 m below the crater down to at least 3000 m and for a shallow 300-500 m thick low-velocity cover which borders the edifice. Data from the distant shot show evidence for arrivals of deep reflected/converted phases and provide information on the deeper structure under the volcano. The results from the interpretation of 2D data are used for planning a 3D tomographic survey which will be carried out in 1996.

Key words *Vesuvius – tomography*

1. Introduction

The National Group of Volcanology (GNV) of the Italian National Council of Research (CNR) decided to foster a research project aiming at reconstructing the structure of Mt. Vesuvius and its feeding system. In fact, the present models of structure of the volcano are based on scarce geophysical data and rely mostly on large extrapolation of these and of surface geological data.

The highest resolution geophysical data which are available for this area are those collected during a seismic reflection survey carried out by Osservatorio Geofisico Sperimentale in the Bay of Naples in the early seventies (Finetti and Morelli, 1974). A strong reflector was identified (Horizon K) and interpreted as the carbonate basement of the volcano which appears to be down faulted from the Sorrento peninsula towards the centre of the Bay.

A deep borehole drilled by AGIP at Trecase on the SE slope of Mt. Vesuvius crossed the whole volcanic sequence reaching the carbonate rocks of the basement at a depth of about 2200 m (figs. 1 and 5a,b). Santacroce (1987) suggested a structural model of Mt. Vesuvius, which integrates geological data with the interpretation of an aeromagnetic map and of gravity data (Cassano and La Torre, 1987).

Models of the Vesuvius feeding system are uniquely based on inferences from petrology, isotope geochemistry and volumes of erupted products. A minimum depth of about 3 km was inferred for the top of the magma reservoir from mineral equilibria of metamorphic carbonate ejecta (Barberi *et al.*, 1981). Study of gas inclusions in ejected nodules indicates a fluid trapping pressure in minerals corresponding to a depth range of 4-10 km (Belkin *et al.*, 1993). Santacroce (1991) on this basis tentatively indicated a depth of 3-6 km, a vertical extension of 1.5-2.5 km and an overall volume of $100\text{-}200 \times 10^6$ m^3 for a magma body which may reside underneath Vesuvius.

A detailed reconstruction of the feeding system and volcano structure is needed to model explosive eruptions (Dobran, 1991). The identification and estimate of the size of the magmatic reservoir may also be relevant for predicting the magnitude of the next eruption, according to the model of continuous magma refilling proposed by Santacroce (1987).

On these grounds, the application of a high resolution method of earth imaging, such as seismic tomography, was required in order to obtain a refined image of the volcano interior. This method of earth investigation based on inversion of seismic arrival times and waveforms is increasingly applied worldwide to retrieve structure details in tectonic and volcanic provinces. Maps of structure velocity anomalies inferred from tomographic analyses may provide a preliminary model which can be corrected and refined by adding information from lower cost complementary geophysical exploration techniques.

Most tomographic studies of volcanic structures are based solely on the interpretation of body wave arrival times from microearthquakes occurring in the investigated region. The use of data from microearthquakes for local structure tomography has the advantage that seismic sources are located within the explored medium which can therefore be densely and uniformly sampled by a large number of seismic rays. However, locations and origin times of earthquakes are unknown parameters and the same arrival time data set has to be used for retrieving both source and medium parameters. Generally, this inverse problem may be weakly constrained because of the large trade-off between source and medium parameters often related to a poor data coverage.

On the other hand, the use of both data from natural and controlled seismic sources (explosions) for high resolution tomography imaging has greatly improved the resolution on the structure model (Kissling, 1988).

The feasibility of a 3D high resolution seismic tomography experiment at Mt. Vesuvius using active sources was uncertain due to the high population density (hence high urban noise) and to the limitation set by law to the maximum exploitable explosive charges (500 kg) for research objectives.

Because of the high cost of a 3D experiment it was decided to carry out a preliminary feasibility 2D study. This consisted in recording seismic waves generated by three explosive sources (having size similar to the maximum allowable charges) at a number of densely spaced seismic stations located along a NW-SE profile passing through the volcano.

The objectives of the feasibility study were:

a) to check the propagation efficiency of the seismic signal through the heterogeneous volcanic structure;

b) to check the quality of the recorded signals against the high environmental noise;

c) to define the penetrating depths of the seismic phases generated by the shots;

d) to construct a preliminary 2D model of the structure of the volcano and of the underlying upper crust.

The seismic field work was done in May 1994. In the present paper we describe the experiment and we report our conclusions on the feasibility of the 3D high resolution seismic experiment in the area.

A very preliminary 2D model of the shallow structure of Mt. Vesuvius, which is inferred from the inversion of first arrivals from the shots and the local microearthquakes is also presented.

2. Description of the experiment

Mt. Vesuvius is located at the SE edge of the Campania Plain, a tectonic graben formed since the Miocene by tensional stresses acting along SW-NE and NW-SE striking fault lines. The graben is filled by alluvial sediments and volcanic rocks and it is bordered by Mesozoic carbonate formations. Carbonate rocks outcrop about 10-15 km SE of Mt. Vesuvius, forming the Lattari mountains, and about 50 km NW of Mt. Vesuvius, forming the Massico mountains.

For the 2D experiment, we selected a SE-NW oriented seismic profile, which starts on the carbonate rocks of Mt. Lattari and passes through the *Gran Cono* of Mt. Vesuvius and Mt. Somma, terminating about 15 km NW of Mt. Vesuvius, at the outskirts of the city of Naples (fig. 1).

The seismic energy was generated blasting 340 to 410 kg of explosive at the following three sites:

S1: this site is located at the SE edge of the profile about 17 km from Mt. Vesuvius crater. The explosive was loaded in two 70 m deep boreholes, drilled in the Mt. Lattari limestones;

S2: this shot was located on the SE slope of Mt. Vesuvius, 3.5 km SE of the crater. Two

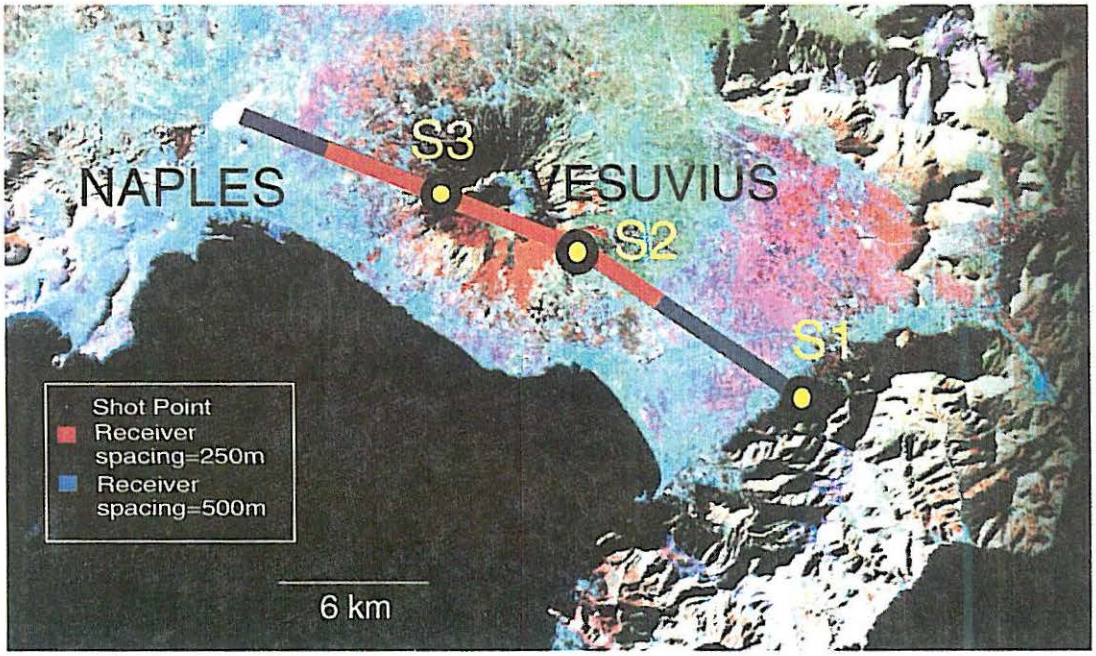

Fig. 1. Map of Vesuvius area with receivers and source locations. The recording line for the May, 1994 2D experiment is shown. Different colors along the line represent segments with different spacing of receivers.

50 m deep boreholes were drilled in the recent lavas;

S3: this shot was located on the S edge of Mt. Somma, 2.5 km NW of Mt. Vesuvius crater. Two 50 m deep boreholes were drilled in the pyroclastics forming the caldera rim.

A few kilograms of explosive were blasted preliminarily at each site for safety reasons. In fact they were used to measure the accelerations produced at the nearest dwellings and to estimate the acceleration expected from the main shots. The preliminary shots produced some damage to the boreholes, preventing us using all the permitted explosive.

The main shots were blasted on May 4 (S1), May 5 (S2) and May 6 (S3) 1994, at 7.00 (S1 and S3) and 6.00 (S2) p.m.

82 recording stations were deployed along the profile. 60 of them were 3-components digital recording, 6 were analogue recording 3-components and 16 were analogue recording vertical component seismographs. Stations were equipped with Mark and Kinemetrics geophones with natural frequencies of 1 and 2 Hz.

Receivers were spaced 250 m in the central part of the profile (*i.e.*, as far as 5 km NW and SE of Mt. Vesuvius crater) and 500 m in the outer portions of the profile (fig. 1). Geodetic positioning of receiver and source sites was performed by Folco Pingue and his team of the Osservatorio Vesuviano, which provided measurements with an average accuracy of 5 m.

The layout of the experiment was meant to image the volcano structure and the underlying upper crust using different phases. The dense spacing of the central part of the profile allows a reconstruction of wave fronts generated by shots S2 and S3 which are reflected from deep discontinuities below the volcano. It also improves the resolution of the 2D tomographic image of the shallow volcano structure sampled by first arrivals from the shots and the local microearthquakes.

3. Data

Representative record sections for the three shots are reported in figs. 2 to 3a,b. The seismic phases generated were clearly recorded at a high percentage of receivers and show a good space coherence, particularly in the central part of the profile. This is a remarkable result considering that only 70 to 80% of the permitted explosive was used.

Shot S1 was very efficient, having been recorded as far as 23-25 km from the source, as shown in fig. 2. Both *P* wave first arrivals and delayed phases are fairly well correlated in the part of the profile lying on Mt. Vesuvius. Strongly delayed phases, which probably penetrated deep in the crust and must have crossed the feeding system of the volcano, are discernible in the section. At first glance these data indicate a good propagation of seismic energy through the supposed highly heterogeneous and absorbing structure of a typical volcano.

The seismic waves produced by shots S2 and S3 were not recorded farther than 10-15 km from the sources, as shown by the record sections of fig. 3a,b. The lower propagation efficiency as compared to shot S1 is probably due to a higher absorption of the volcanic rocks surrounding the boreholes of shots S2 and S3 with respect to the limestones of site S1. Large amplitude delayed phases, probably due to conversions/reflections at deep reflectors, occur in both record sections. The quality of the recorded signals deteriorates abruptly in sites located close or within densely populated areas.

Three-component receivers are very useful to identify converted phases. In fact, arrivals with a prominent horizontal component, such as those shown in fig. 4, can be reliably ascribed to converted phases. Their amplitudes and arrival times can be used to constrain the depth and lateral extension of the discontinuities where such waves were converted.

4. Joint inversion of first arrival times from shots S2, S3 and microearthquakes

A correct interpretation of delayed phases on seismograms requires knowledge of the effects of the shallow structure and morphology of the volcano on the propagation of seismic waves. Consequently we started processing first arrivals from the shots located on the volcano, because the information they contain

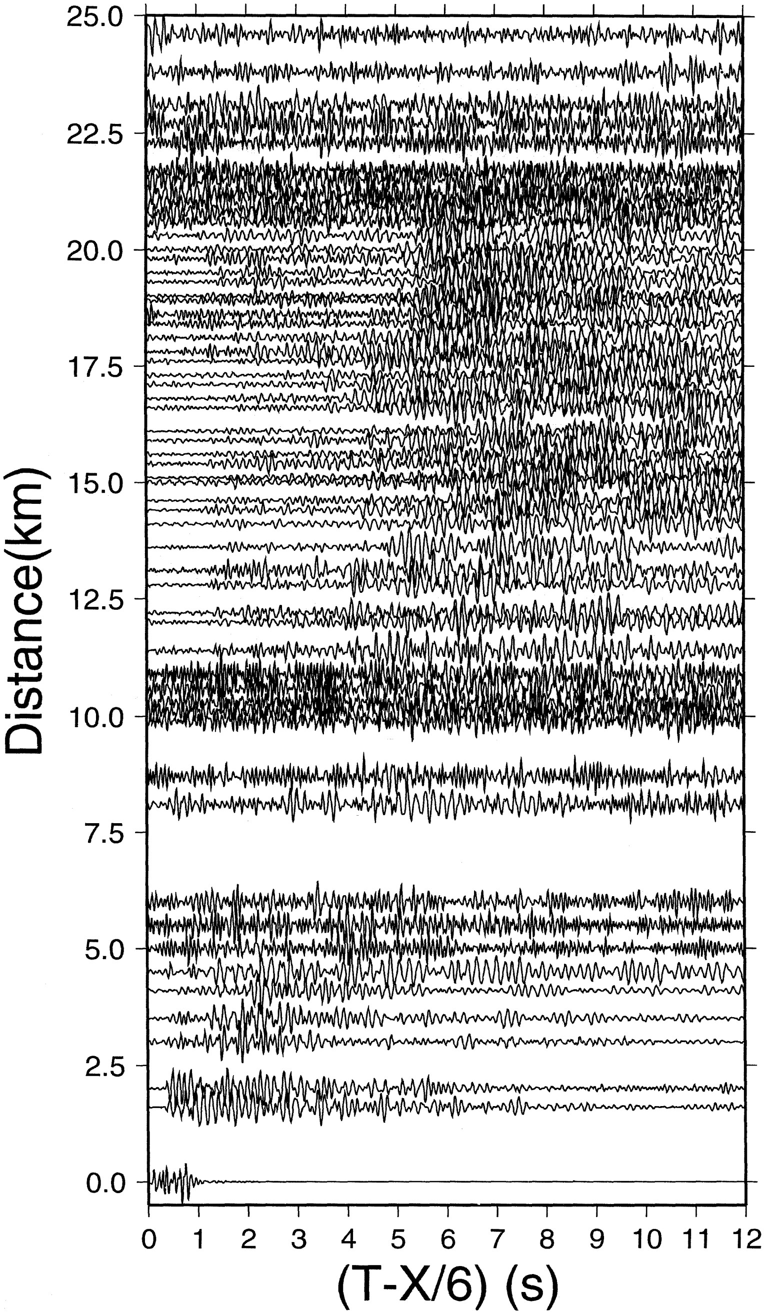

Fig. 2. Example of recorded seismograms represented as a function of distance from the shot. Signals are filtered in the 5-15 Hz frequency band. Vertical component records for shot S1. Traces are shifted in time according to a reduction velocity of 6 km/s.

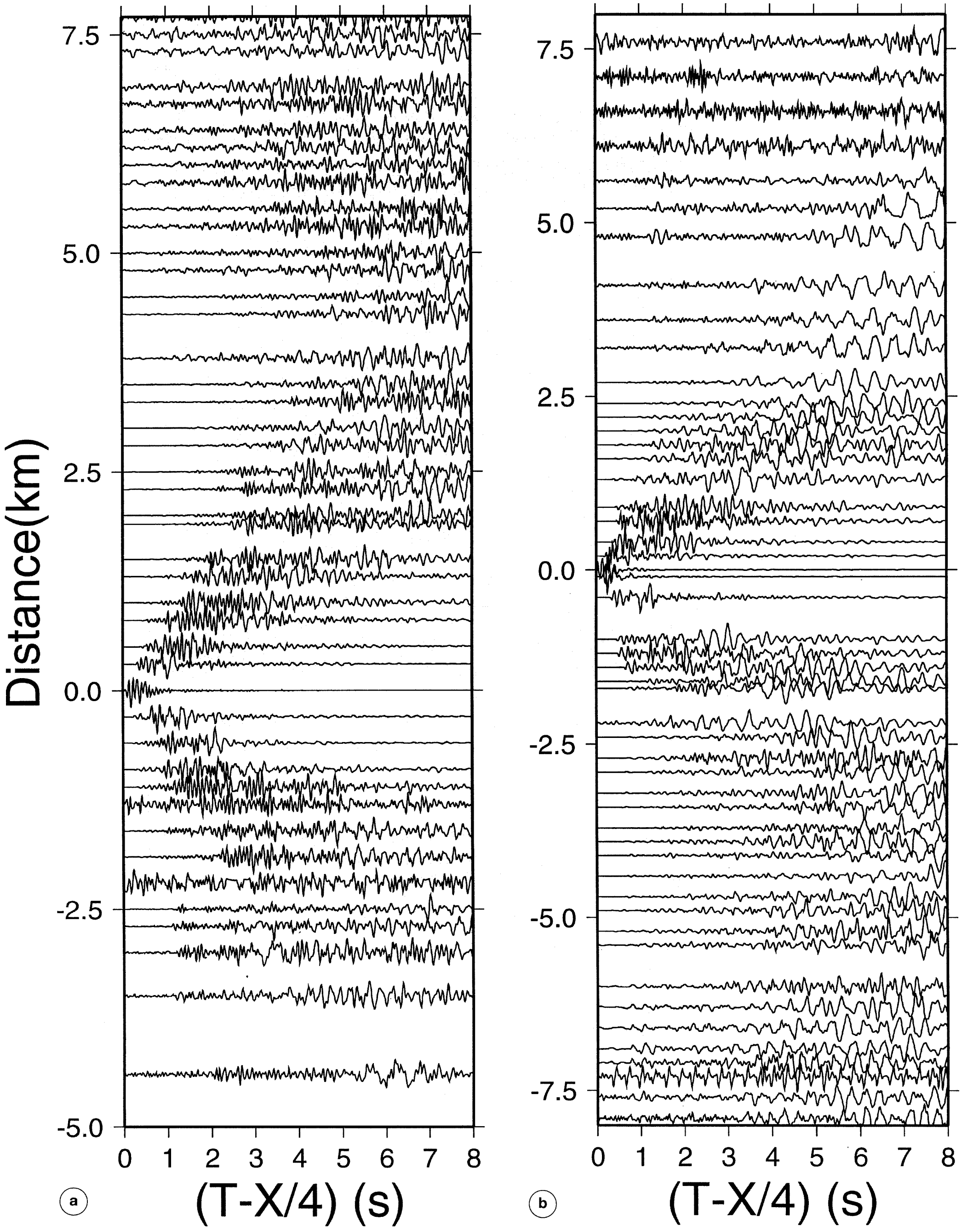

Fig. 3a,b. a) Vertical component records for shot S2. The reduction velocity used is 4 km/s. b) Vertical component records for shot S3. The reduction velocity used is 4 km/s.

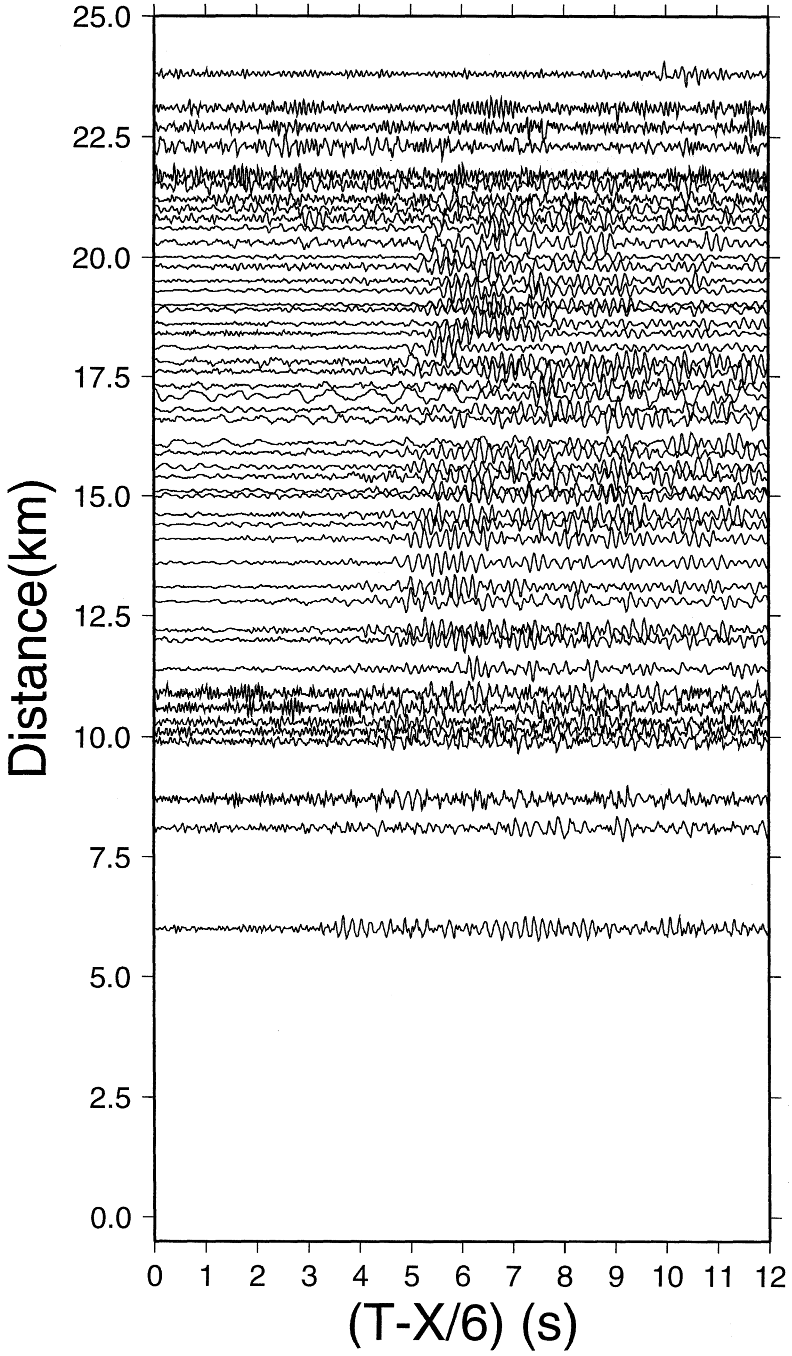

Fig. 4. East-West horizontal component records for shot S1. Signals are filtered in the 1-15 frequency band and represented using a reduction velocity of 6 km/s.

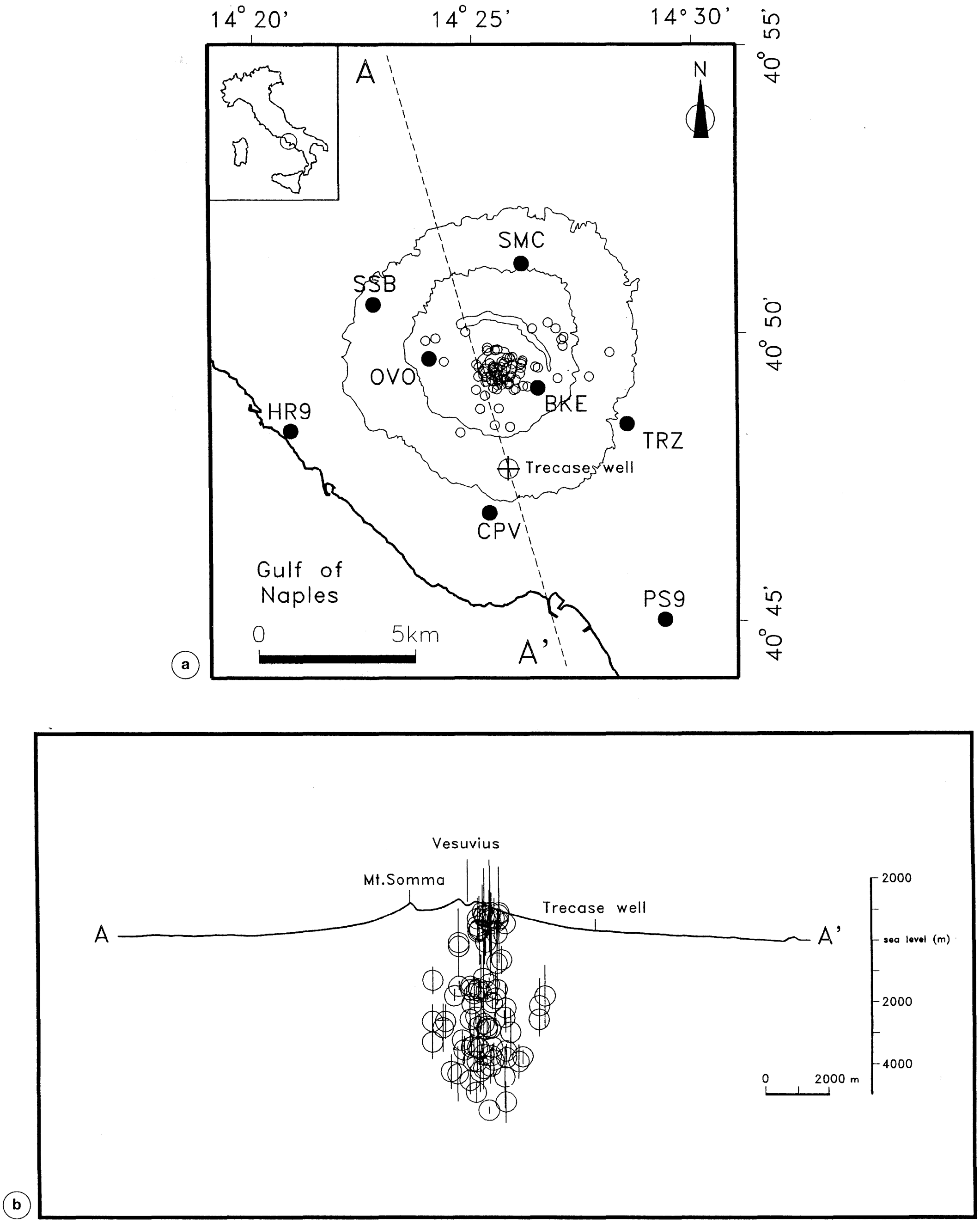

Fig. 5a,b. a) Map reporting seismic activity of Mt. Vesuvius. Closed circles represent permanent seismic network of Osservatorio Vesuviano. b) Section along the *AA′* profile reporting hypocenters located in (a). Vertical bars indicate the computed errors on the hypocenter depth.

mainly relates to the shallow structure of Mt. Vesuvius. The delayed arrivals (refracted, reflected, and converted phases) penetrating deeper in the crust can then be cleaned of the shallow effects and give reliable information on the deeper structures.

In determining the shallow structure of the volcano, the arrival times from local microearthquakes may provide additional constraints on the deeper part of the volcano edifice.

Mt. Vesuvius is affected by a quite regular micro seismic activity ($M < 3$) localised beneath the crater area down to a depth of 5-6 km (fig. 5a,b). These events are recorded at the Osservatorio Vesuviano permanent seismic network and processed by the research staff of this organisation (Vilardo *et al.*, 1993).

In order to determine a detailed 2D image of the shallow volcano structure and velocity anomalies we chose to use a tomographic technique, which is the most appropriate to infer lateral velocity variations.

4.1 *Method*

Cross correlation techniques were used to read the first *P*-arrival times. We applied Thurber's tomographic method (Thurber, 1983; Eberhart-Phillips, 1993) to first *P*-arrival times from shots S2 and S3 and a selected group of microearthquakes which occurred in the recent past. The use of local earthquakes in the framework of a 2D tomographic profile is not obvious, and requires an appropriate scheme. For this purpose, local earthquakes were previously located using an 1D velocity model. We selected earthquakes according to location errors (ERH, ERZ < 500 m) and epicentral distance, which had to be shorter than 0.75 km from the crater. Hypocenters were then projected on the vertical plan defined by the profile in order to be considered as shots in the inversion scheme.

The computation of ray paths from local earthquakes was performed by rotating both the hypocenter and the station locations on the profile. Each hypocenter-station couple defines a single ray path datum which was used in the inversion. Rotation was performed in the following way: the epicenter position was reported on the profile by a rotation around the station position; then, the station position was rotated on the profile, using the new earthquake location as center. The rotation of epicenters and stations was computed using the minimum angle from the profile (fig. 6). By this kind of projection we defined two half-spaces separated by the y,z plane. In each half space we assumed the same *P*-wave velocity for points at equal distance from the crater.

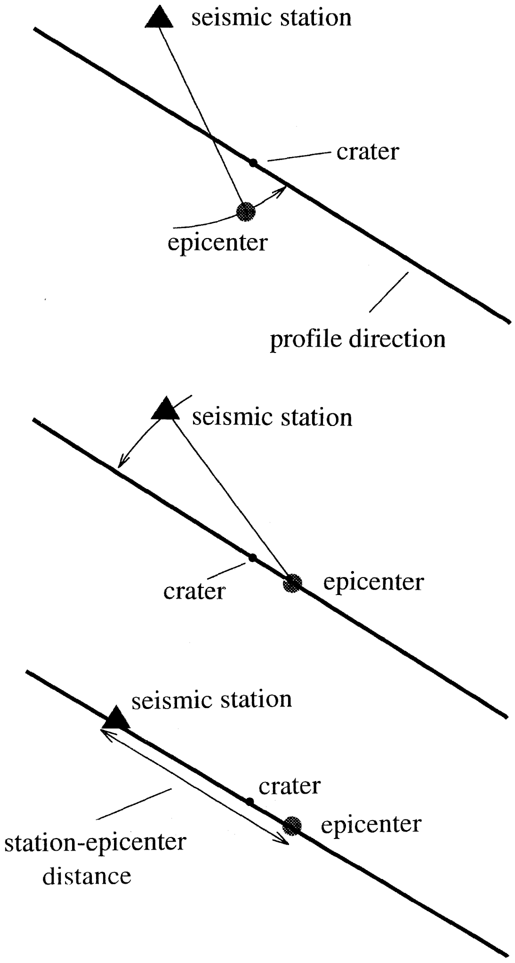

Fig. 6. Description of the procedure applied to project ray paths and earthquake sources/stations on the vertical plane profile.

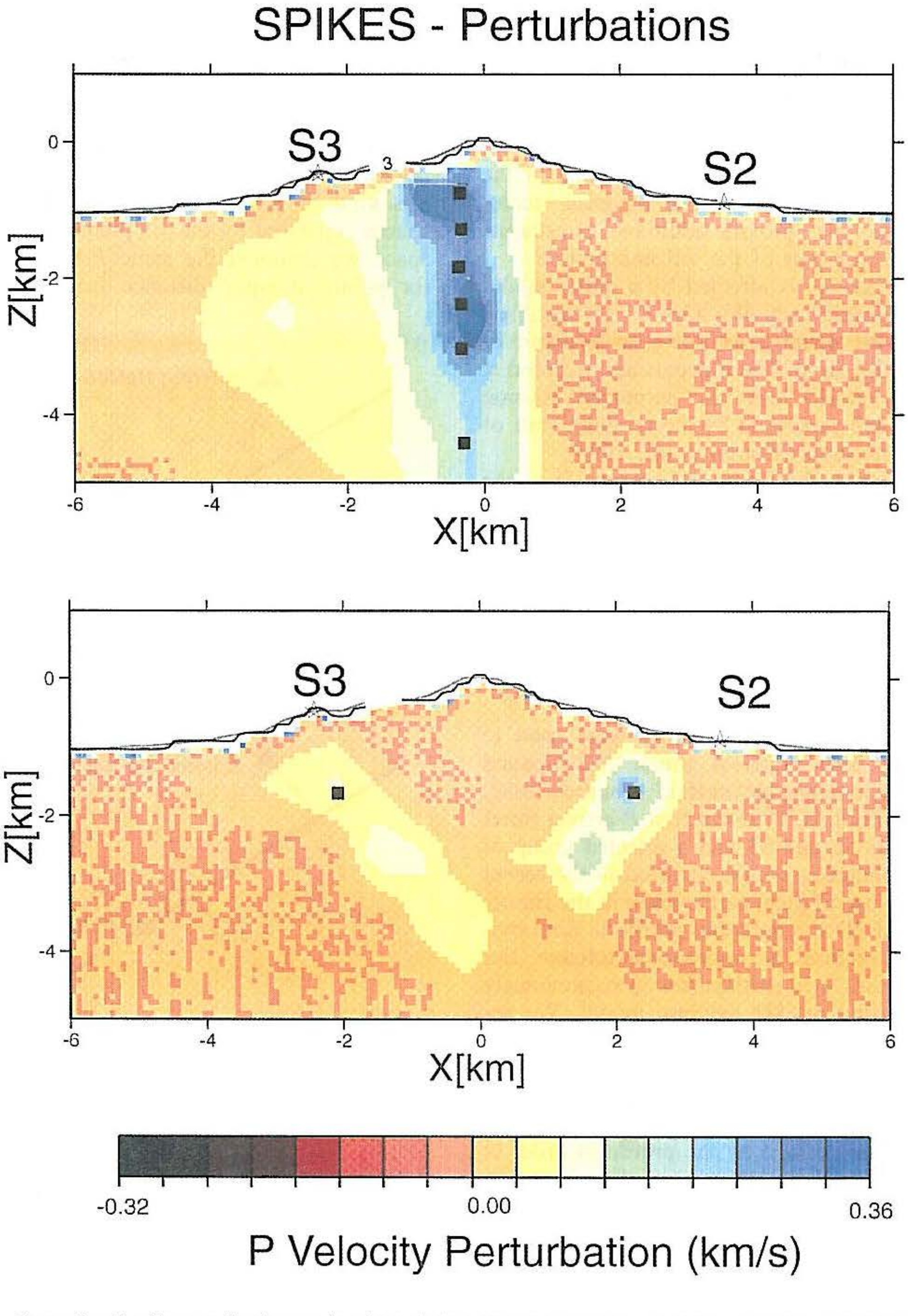

Fig. 7. Example of spike-test for the study of resolution. Black points are positive unit point anomalies over a homogenous background medium. The spreading of inverted anomalies provides information on the lateral and vertical resolution.

This assumption is reasonable as it is suggested by the preliminary analysis of shot data which show different velocity models in the two half-planes.

A mean velocity model where the lateral velocity heterogeneities are averaged in each half-plane was obtained in this way.

The procedure used for rotations implicitly assumes that epicenters are very close to the crater, so that the ray paths pass very close to the crater axis. This is the reason for selecting only earthquakes with epicenters very close to the crater.

The medium was parameterized by three layers with a spacing of 50 km on y and a variable size grid on x-z (between 200 m and 500 m), representing the vertical plane along the profile. Inversion was performed on the central layer of the xz grid; given the large distance of the border layers, their velocities did not affect the central grid. Only rays on the xz plane were allowed, thus implying a true 2D inversion. Stations recording shots were located on the profile in terms of the distance from the shot points. We included both artificial shots and local microearthquakes in the inversion.

Inversion statistics on the tomographic results were computed by means of spike-tests, thus inverting synthetic data computed for a homogeneous model except at single points. The spreading of the single point anomalies over larger grid patches, after the inversion, gives a measure of the resolution at the given points. Results of resolution spike tests are shown in fig. 7.

4.2 *Results*

We inverted 253 travel times (47 from shots, 206 from earthquakes) from sources within 0 and 5 km of depth. We used for inversion a value of the Levemberg-Marquardt damping $\lambda = 1$, which gave stable results. The velocity model was parameterized by 108 grid points, with a minimum spacing of 0.5 km at the crater axis and a maximum of 1.0 km at the borders.

The first 2D tomographic images of Somma-Vesuvius volcano are reported in fig. 8a,b.

It is well known that the obtained tomographic images strongly depend on the velocity model assumed as reference for the inversion procedure. The image in fig. 8b shows velocity perturbations from the reference model, in fig. 8a, using a limited data set.

Figure 8b is the result of 6 iterations of the inversion algorithm, giving a variance reduction of 60% with a final standard deviation $\sigma_f = 0.07$ s.

The image in fig. 8b was obtained using a reference model with a sharp velocity transition at 2.2 km under Trecase, in agreement with the results of the deep well drilled by AGIP, and an irregular morphology of the top of carbonate rocks, as inferred from gravity data. The comparison of the two images showed that its main features are fairly independent of the assumed reference model.

The main common characteristics of this preliminary 2D image can be summarized as follows.

A central zone extends vertically underneath Mt. Vesuvius *Gran Cono*, with *P*-wave velocities about 0.5-1.0 km/s higher than the surrounding. Resolution tests indicate that the apparent lateral extension of the high velocity zone (about 1 km) is controlled by the chosen discretization interval and by the real resolution. Qualitative considerations on the minimum wavelength of the seismic signals produced by the shots indicate that the high velocity body has a minimum lateral extension of 300-500 m. The top of this high velocity plug is quite well constrained at a depth of about 400 m. It may represent either a high concentration of slowly cooled magmatic dikes or of volcanics which have suffered an intensive propylitic alteration by high temperature hydrothermal fluids.

A low velocity layer of varying thickness occurs at the top and on both sides of the high velocity plug. This layer is 1-1.5 km thick on the SE slope and corresponds to a zone where eruptive activity in recent centuries produced some lateral vents and large accumulation of lava and pyroclastics. The high fracturation, low density and high porosity of the rocks account for the observed low velocities.

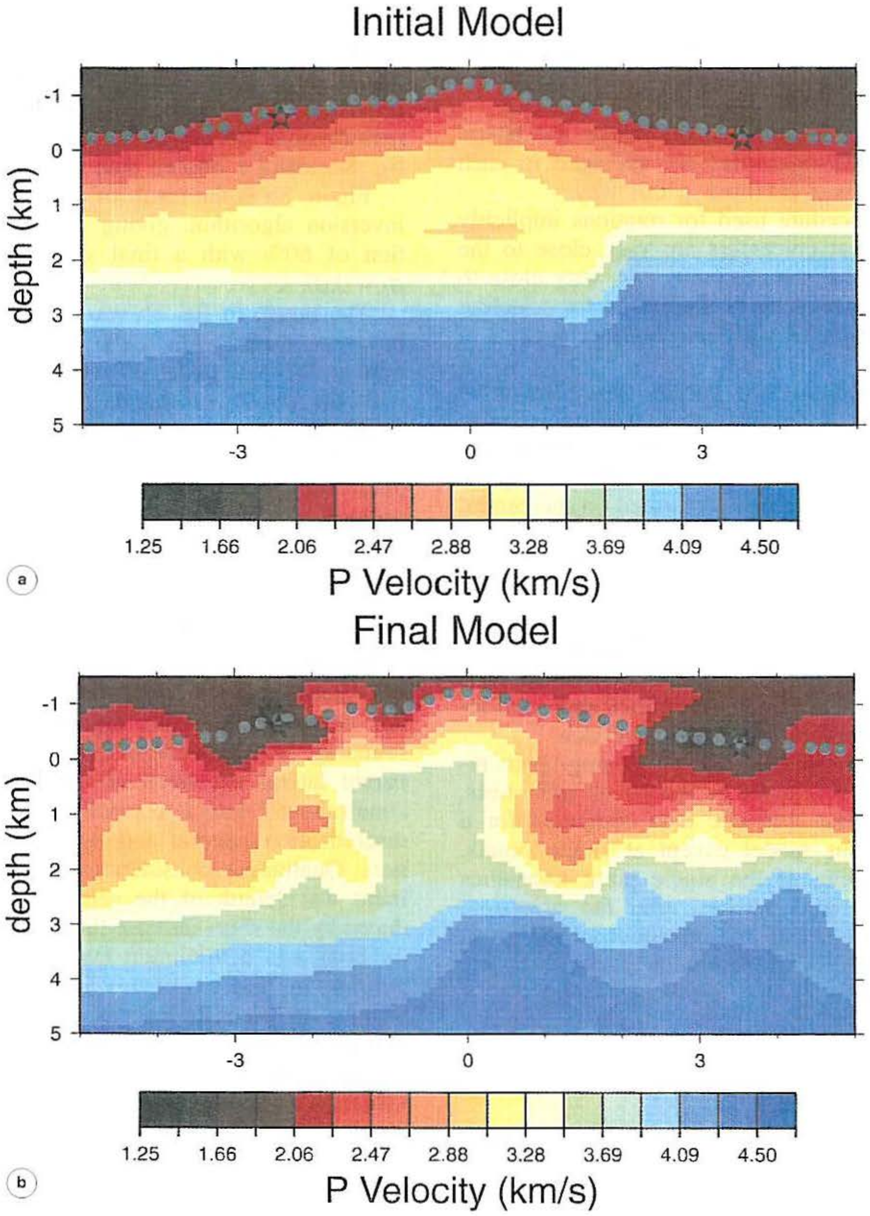

Fig. 8a,b. Results of tomographic inversion of first P arrivals from earthquake and shot data. a) Reference model. The shallower part ($z < 1$ km) is constrained by 1D velocity models inferred from $\tau-p$ inversion of first P-arrivals from shots (De Matteis *et al.*, 1996). The reference models also account for the sediments/limestone discontinuity whose shape is constrained by gravity and Trecase well data. b) The 2D velocity model obtained by inversion of shot and earthquake travel time data. This figure shows that data cannot resolve the Vesuvius structure for depths greater than 3.5-4 km. Resolution is also variable laterally deteriorating at large distances from the crater axis.

We point out that the resolution is not uniform throughout the sampled section. It is obviously dependent on the spacing between receivers, on the location of the sources (shots and micro earthquakes) and on the real variations of *P*-wave velocities in the sampled section. The best resolution is obtained down to a depth of 3.5-4.0 km as far as a distance of 4 km on both sides of the crater. The resolution deteriorates quickly outside this zone because of an insufficient sampling by the seismic rays considered.

The models of fig. 8a,b can be considered a good starting point for future research on the Vesuvius structure using data from this 2D and the next 3D experiments.

5. Evidence for secondary arrivals and their interpretation

A work based on seismic processing of waveforms from shots S2 and S3 has also been started to identify and interpret late secondary arrivals on seismograms. The main objective of this analysis is to infer information on sharp discontinuities by detecting and interpreting reflected wavefronts which are coherently recorded along the array.

The dense spacing of stations (250 m) in the central part of the profile and the clear evidence of coherent reflected phases along large portions of the recorded seismic sections suggest the extensive use of data processing techniques widely used for seismic exploration purposes. The Seismic Unix data processing package was used for this analysis (Cohen and Stockwell, 1994).

The vertical component seismograms recorded for shots S2 and S3 were been preliminarly used for this analysis. The seismic records were arranged along a section corresponding to the recording line direction. Data were band-pass filtered in the 5-7 Hz band and processed using the Automatic Gain Control procedure, which normalizes amplitudes along the seismograms (fig. 9a,b).

An early reflected wave is clearly detected on both seismic sections from shots S2 and S3. It is likely probably to the strong velocity discontinuity between volcanics and alluvium sediments and carbonatic formations whose evidence is inferred from gravity and Trecase well data. The interpretation of this phase is ongoing.

An interesting problem which deserves further investigation is the interpretation of the energy arrival at about 8 s, clearly detected on shot S1 seismograms, recorded along the volcano slope at a distance of 13-17 km from the source. The impulsive character, large amplitudes and relatively low frequency content on the horizontal components suggest that this could be a *P*- to-*S* phase converted at a deep interface. Calculations using 2D ray-tracing indicate a depth of 12-14 km for the reflector assuming a 2-layer medium (see fig. 10a,b). For a specific distance and incidence angle range, P-to-S conversion is favoured by the presence of a zone with very low rigidity beneath the discontinuity. If the nature of the phase is confirmed by further analyses, this should provide additional evidence for a mid-crustal seismic velocity discontinuity in active volcanic regions, as recently observed by various authors (*e.g.*, Sanford *et al.*, 1973; Mizoue *et al.*, 1982; Matsumoto and Hasegawa, 1996).

6. Conclusions and future research

The 2D seismic tomography experiment, meant as a feasibility study of a higher cost 3D experiment, has given information well beyond expectations.

Although the used explosive was 70 to 80% of the permitted charge, well recorded signals were obtained as far as 25 km from the source, in the case of shot S1 blasted in the limestones. The seismic signals from all the shots contained a number of clearly identified delayed phases which are amenable to further processing, indicating that energy propagates satisfactorily in the crust underneath the volcano.

A preliminary 2D tomographic image of the volcano down to a depth of 3 km was obtained using only first *P*-wave arrivals from shots and local microearthquakes.

This information suffices to establish that the 3D tomography of Mt. Vesuvius is feasible

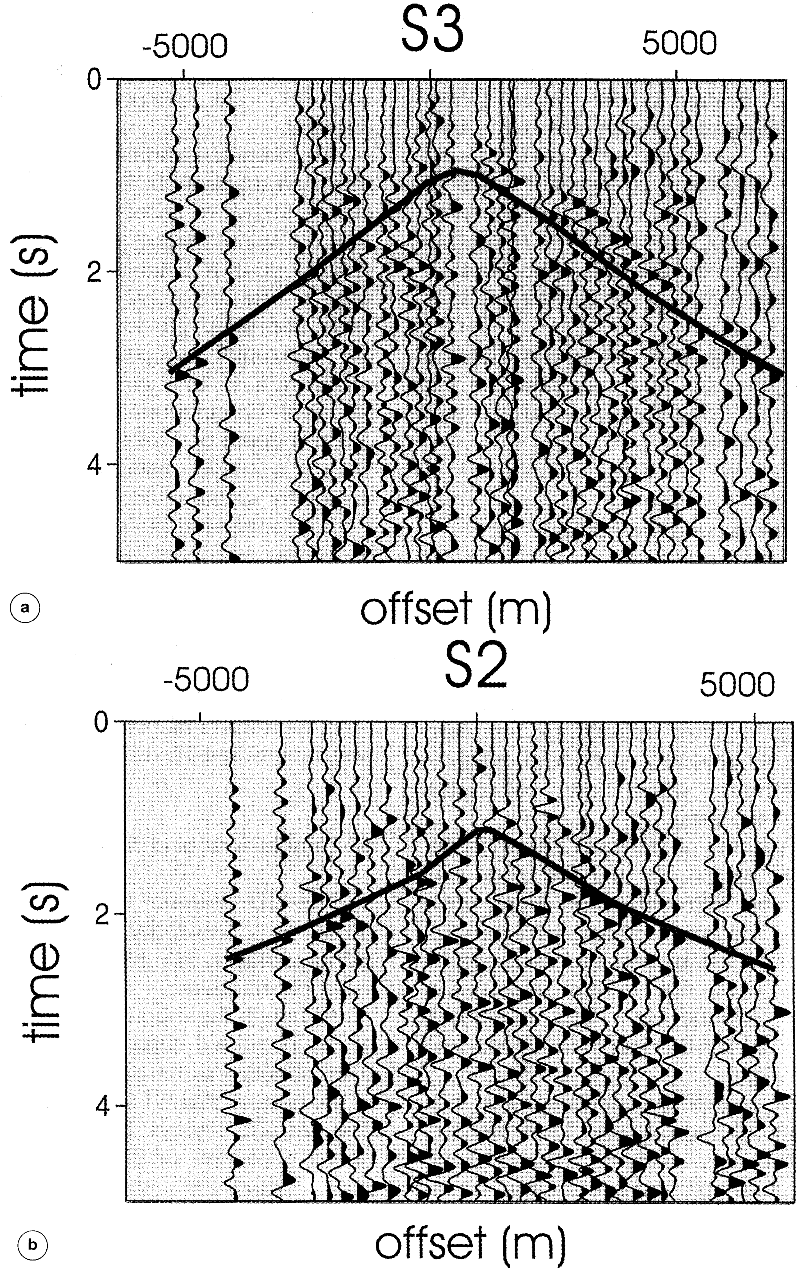

Fig. 9a,b. 5-7 Hz band pass filtered and AGC (Automatic Gain Control) corrected records for shot S2 (b) and S3 (a). A static correction was applied to data by using the 2D model inferred from seismic tomography. Early reflected waves are clearly detected at close distances from the shots (grey lines) which probably originated at the sediments/limestone discontinuity.

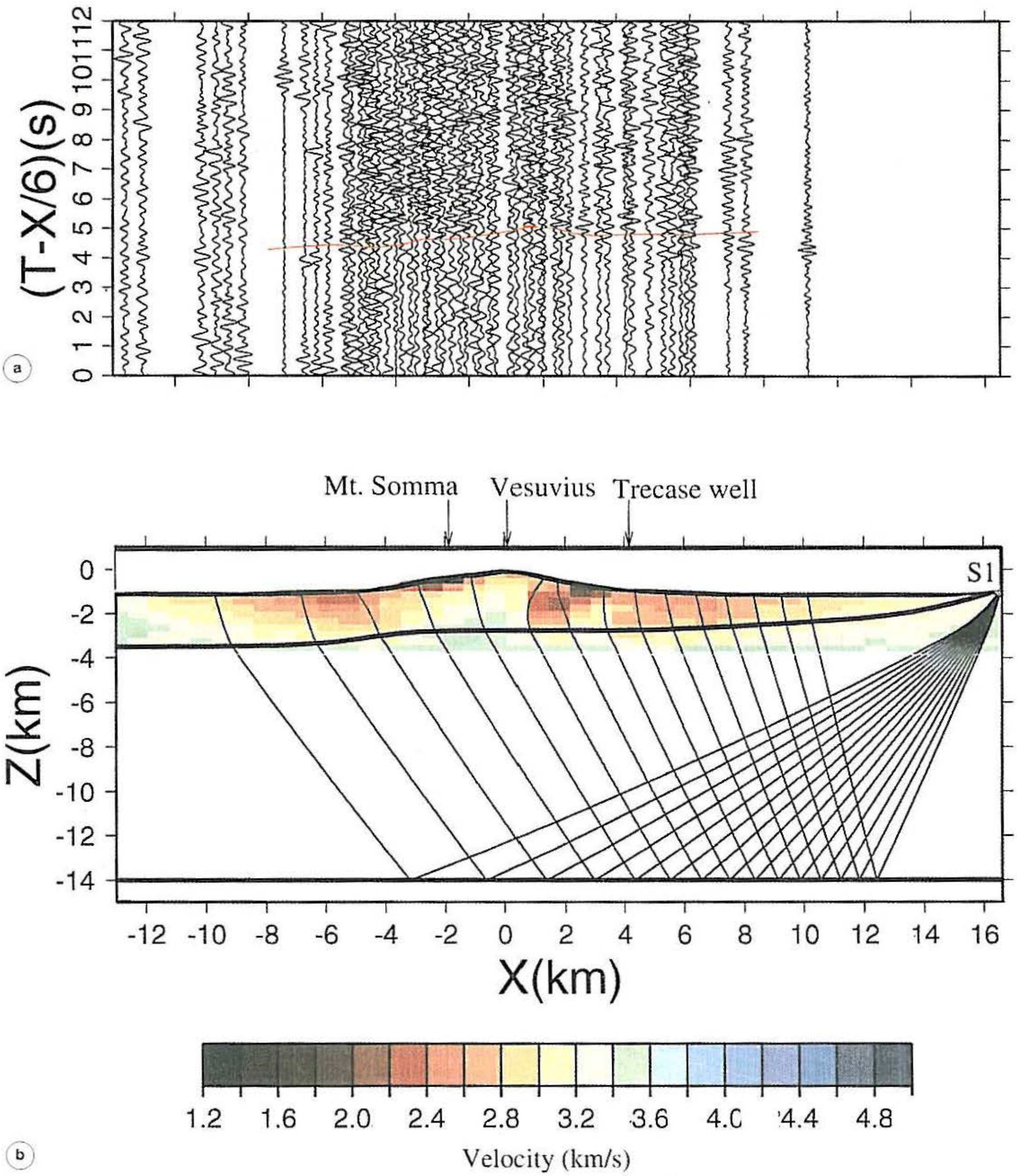

Fig. 10a,b. a) EW horizontal component seismograms for shot S1 recorded along the Mt. Vesuvius slope. Note the presence on seismograms of late coherent arrivals (at about 4-5 s in reduced time plots) in the section examined. The continuous line on seismograms indicates the theoretical arrival of the *P-S* phase converted at a 14 km deep interface. This phase is clearly detected at stations on the volcano for a range of distances between 12 and 20 km from the source. b) Section of the Vesuvius area showing the ray-path of the simulated *P-S* arrival.

and the relative project has already been presented to GNV. The project will investigate a circular area of about 10 km radius around Mt. Vesuvius. Shots will be made on land at 16 sites. Air-gun energization will be made at sea; their sites and energy will depend on the authorisation obtained. About 150 receivers will be deployed along four lines at 45 crossing Mt. Vesuvius crater. The final design of the source and receiver coverage will be established, however, after processing and interpretation of the 2D is complete. It will in fact be designed with the aim of optimising the detection of the many delayed phases which will allow the extension at depth of the models based on first arrivals. The experience gained in the 2D experiment indicates that a 250 m spacing of receivers is adequate for an accurate correlation of wave fronts and the massive utilisation of 3-component receivers is essential for an unambiguous identification of reflected and converted phases.

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