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Looking Inside Mt. Vesuvius

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Italy's Mt. Vesuvius has been slumbering for a long time, but its silence could preface an eruption with potentially disastrous effects for 600,000 people living on the volcano's slopes. To assess the scenario of the next eruption, the National Group of Volcanology (GNV) of the Italian National Council of Researches (CNR) has fostered research aimed at mitigating eruption risk to the densely populated area. In this framework, researchers have gathered high-resolution seismic tomography data to better understand the internal structure of Mt. Vesuvius. The experiments were carried out during the last 4 years.

The data will be used in three-dimensional modeling of the structure of Mt. Vesuvius and underlying upper crust. Seismic velocities and attenuation and density contrasts will be calculated, with special emphasis on the delineation of significant magma reservoirs of more than 1 km in diameter. In modeling Mt. Vesuvius, tools are being developed for using seismogram information to obtain high-quality seismic imaging of heterogeneous structures such as volcanoes.

Pompei: One of Many Eruptions

Mt. Vesuvius last erupted in March 1944, following a period of almost continuous activity since 1631. The event was mostly effusive. During the last 25,000 years, at least seven violent Plinian, as well as numerous sub-Plinian, eruptions have occurred—many of which were separated by centuries-long periods of repose. The famous Plinian eruption of 79 A.D. destroyed Pompei and neighboring towns. The most recent sub-Plinian eruption in 1631 killed more than 4000 people.

Because a sub-Plinian eruption could be disastrous to populations residing on the slopes of the volcano, a comprehensive research program and a civil defense emergency plan were initiated to mitigate these dangers. The scenario for a possible eruption includes models of precursor phenomena, which are used to establish different alert levels. The interpretation of precursors depends heavily on the availability of reliable models of crustal structure. Information on the seismic velocity structure of the volcano and the underlying crust is needed to locate earthquakes and determine focal mechanisms. Location of significant volumes of magma is also needed to understand relationships of ground deformations and seismic activity with pressure variations in the magmatic system and to model magma ascent.

Mt. Vesuvius is located within a Plio-Pleistocene tectonic graben bordered by Mesozoic carbonaceus rocks. Structural models of the volcano are based on surface geology and on scarce geophysical data. A strong reflector, identified by an offshore seismic reflection survey, was interpreted as the carbonate basement of the volcano [*Finetti and Morelli*, 1974]. A deep borehole drilled by the Italian oil company AGIP at Trecase (on the southeast slope of the volcano, see Figure 1) reached the carbonate basement at a depth of 1.885 km. Bouger gravity anomalies, calibrated with these data, were used to model the deepening of the basement down to about 2.3 km beneath the western edge of the volcano [*Santacroce*, 1987]. Using mineral equilibrium of metamorphic carbonate ejecta, a minimum depth of about 3 km was inferred for the top of the magmatic reservoir feeding the 79 A.D. Plinian eruption [*Barberi et al.*, 1981]. Fluid inclusions in minerals from cumulates and nodules from the same eruption indicate a trapping pressure corresponding to a depth range of 4 to 10 km [*Belkin and DeVivo*, 1993]. The most recent

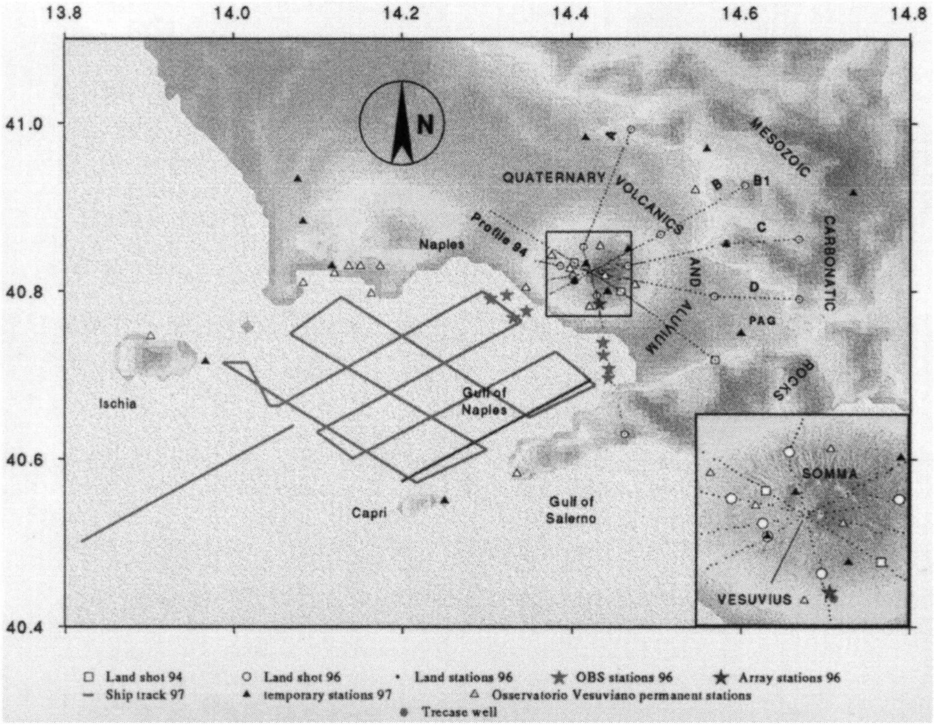

Fig. 1. Map of the TomoVes experiments. Profile 94 was used as a feasibility study for the entire experiment. Ship tracks of 1997 campaign by NADIR are shown. Recordings at PAG station of the blue shot line are shown in Figure 4. Original color image appears at the back of this volume.

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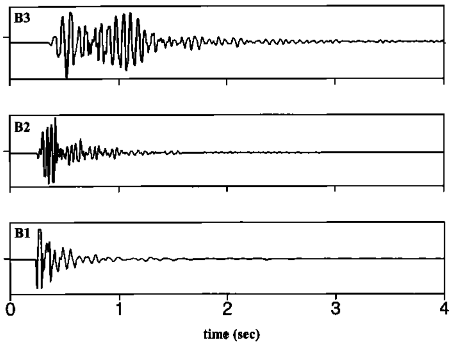

Fig. 2. Accelerometer vertical recording of Shot B1 (770 kg in dry limestone), B2 (250 kg in water saturated alluvial sediments), and B3 (504 kg in dry lava sequence).

activity of Mt. Vesuvius (1631-1944) was fed by a tephritic phonolitic magma for which there is no evidence of long-term residence in a crustal reservoir at depths greater than 1 km [*Belkin et al.*, 1993].

Experimental Design

Although many seismic tomography studies of volcanoes have used local, low magnitude earthquakes as energy sources, such an approach was not possible for Mt. Vesuvius. In fact, although local microseismic events (M<3.5) occur approximately a hundred times per year, most earthquakes are located just below the crater area and are more shallow than 4 km. An unrealistically large number of seismometers would be necessary to obtain a well-resolved image of the volcano structure. In addition to the usual complications due to the trade-off between earthquake location, origin time, and medium velocity, spacial resolution would be extremely unfavorable at depths greater than 4-5 km.

Therefore, the Tomography of Mt. Vesuvius (TomoVes) project is a controlled source experiment using onland and offshore energy sources. Controlled source data were integrated with a selected earthquake set recorded at the Osservatorio Vesuviano (OV) permanent network and at temporary short period and broadband networks deployed in the Campania area. The acquisition geometry was designed to obtain a refined structural image of the volcano using both transmitted and reflected waves. Because detecting magma reservoirs requires reliable identification of converted phases and a study of the attenuation, carefully calibrated 3C seismometers were used to allow full utilization of the arrival time and waveform amplitude information. The project, begun in 1994, was organized in five phases: a single profile (two-dimensional seismic tomography) feasibility study; analysis and interpretation of collected data, combined with the best quality local earthquake data; a three-dimensional field experiment using explosive sources onland and air gun sources at sea; processing and interpretation of data from field experiments and selected earthquake data; and elaboration of a structural model of Mt. Vesuvius, integrating seismic data with gravity, magnetotelluric, aeromagnetic, and geoelectrical data.

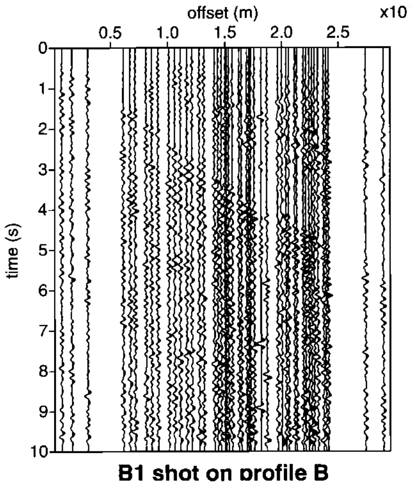

Fig. 3. Vertical recordings of Shot B1 along B profile. A band-pass (4-15 Hz) filter and Automatic Gain Control were applied. The two traces at more than 25 km offset are OBS recordings.

Phase 1, carried out in May 1994, consisted of a 30-km-long NW trending seismic profile passing through the center of Mt. Vesuvius (Figure 1). Blasting of about 400 kg of explosive generated seismic energy at three on-land sites along the profile. The signals were recorded at 82 (60 digital 3C) receivers deployed along the profile with a spacing of 250 m on the volcano and 500 in the outlying regions. A linear array of 47 vertical geophones was deployed at the top of the volcano. The inversion of direct and reflected arrivals from shots and local earthquakes provided a two-dimensional image of the Mt. Vesuvius structure down to about 5 km depth. We also identified a low velocity zone at a depth of about 10 km. No information was obtained on its horizontal and vertical extension [*Zollo et al.*, 1996 a,b]. These results encouraged us to implement phase 3, which was carried out in June-July 1996 and February 1997.

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Three-dimensional Onland Experiment

The highly urbanized area prevented the performance of a true three-dimensional experiment, which would have required a very dense source and receiver coverage of the target zone. Therefore, a multi-two-dimensional configuration was chosen for the acquisition geometry. Sources and receivers were deployed along two pairs of quasi orthogonal profiles (Figure 1, A-C and B-D), which intersect at the Mt. Vesuvius crater. Seismic signals of each shot were recorded simultaneously along the longitudinal and the quasi-orthogonal directions. This configuration allows access to information on both lateral and along-profile seismic velocity variations. More than twenty scientific institutions from European countries and the United States participated in the experiment. A total of 250 people participated in the field operations, including scientific personnel, students, soldiers, and volunteers of the Italian Civil Protection.

One hundred forty digital seismic stations were deployed in the field. The geophones' natural frequency was 1-4.5 Hz. Seismic stations were set to sample the signal at 125 samples/sec. Along-profile receiver spacing was the same as in the preliminary experiment of 1994. Receivers on quasi-orthogonal profiles

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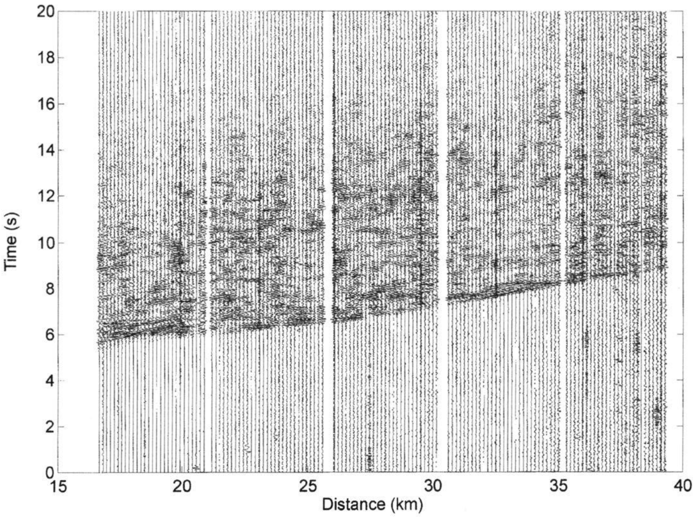

Fig. 4. Common station section obtained by recordings at PAG station (located on limestone) of the 112 l air-gun shot-line shown in Figure 1.

were at 500 m interval. A two-dimensional semicircular seismic array of 200 m of diameter, with 64 channels and 4.5 Hz geophones, was installed near the site of Trecase borehole. On-land source and receiver locations were determined with a horizontal accuracy of 5 m and a vertical accuracy of 10 m using leveling and GPS methods.

Ship *Thetys* from CNRS/INSU installed 8 ORSTOM/CNRS ocean bottom seismographs (OBS). All the OBS were deployed close to the coast line. Precise location and orientation of OBS were determined by calibration shots using the Tethys air-gun. At the beginning of the experiment, one 5-kg and one 10-kg charge were shot at a distance of about 3 km from the base camp, where all seismographs had been closely installed in order to calibrate all of the stations simultaneously. Also, 250 to 800 kg of seismic gel were shot in the 14 on-land sites shown in Figure 1. The largest explosions were performed at the end of profiles on Mesozoic carbonate outcrops because the results of the 1994 campaign showed that large energy shots on limestone outcrops produce primary and reflected/converted waves which penetrate down to at least 10-12 km. Two accelerometers were installed within 200 m of the site of each explosion in order to have an unsaturated signature of the source time function. This information is relevant both for deconvolution of seismic signals and for the study of spectral amplitude attenuation with distance. Acceleration records of shots in limestone, in alluvium, and in a lava sequence (Figure 2) show the variability of the signal produced under different conditions.

The percentage of successful recording was 93% for the total experiment. Signal/noise ratio of first arrivals was satisfactory up to distances of 25-30 km for the 800-kg shots. Lower energy shots located at intermediate distances and on the volcano have been recorded as far as the coast (10-15 km away). Shots located on the volcano have the lowest recording efficiency, probably because of bad coupling of the source due to the complex lava-scoriae-voids environment. Recordings of Shot B1 are reported in Figure 3. First arrivals and many later phases are clearly recorded along all the profile, including the two OBS which prolong it about 4 km offshore.

Offshore Experiment

The on-land shots were integrated with offshore air gun shots performed in two different campaigns. The first one was contemporaneous to the on-land experiment and consisted of about 830 shots performed by two 16-liters air-guns by Thetys along profiles run in the bays of Napoli and Salerno at a rate of 1 shot every 4 minutes (about 500 m). Twenty 3C seismographs deployed along the profiles recorded these shots during the nights. Four series of 16-airgun shots were performed along a 200 m radius circles, near the coast. These shots were recorded by the global array of instruments and they were stacked to increase the signal to noise ratio. In spite of their low energy, these shots were recorded as far as 10 km inland.

The obtained information was used to plan the second offshore experiment. It was carried out in February 1997 when IFREMER made available its oceanographic ship NADIR to shoot in the Bay of Naples in the framework of a transit valorization project. NADIR was equipped with eight 16-liter air guns and performed a dense network of profiles in the Bay of Naples (about 1900 shots) with one shot per minute (spacing about 125 m) during about 30 hours (Figure 1). The shots were recorded at 16 sites by temporary digital 3C stations, at a 64-channel seismic array and at 12 stations of the Osservatorio Vesuviano network. The acquisition layout was designed to image the crustal discontinuities down to Moho in the Bay of Napoli, and beneath Mt. Vesuvius and Phlegraean Fields using reflected/converted waves.

Most of the recording sites were grouped in three sets at increasing distance from the volcano, to provide a continuous spatial coverage of the crustal reflectors beneath Mt. Vesuvius and the surrounding plain. Each site was equipped with up to three 3C digital seismographs, to improve the signal/noise ratio by stacking. The overall signal quality was satisfactory for all the digital stations. Useful recordings have been obtained also at the most distant station in the Apennines. An example of the quality of recordings a common station section obtained at a site about 10 km inland is shown in Figure 4. The complexity of the crustal structure shows up clearly from the articulated pattern of first and later arrivals.

Future Directions

The collected seismic data provide very detailed information about the crustal structure beneath Mt.Vesuvius and the surrounding area. This experimental effort warrants an approach that exploits both the arrival time and the waveform information contained in the data. The acquisition, a mixture of near vertical, intermediate, and wide angle refraction/reflection geometry, was not conventional. The acquisition geometry, highly irregular topography, expected small- and large-scale lateral heterogeneity, and the availability of three-component records require the development of adequate processing and two-dimensional and three-dimensional inversion methodologies.

A working group was organized to join different expertise in processing and interpreting seismic data and integrating it with other geophysical information. The goal, which is financially supported by the European Union (Division XII), is to develop final seismic models of the volcano that are consistent with other geophysical information.

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stall the base camp. Computing network and equipment were organized by the Centro Didattico Scientifico of Università di Napoli Federico II.

References

Barberi, F., H. Bizouard, R. Clocchiatti, N. Metrich, R. Santacroce, and A. Sbrana, The Somma Vesuvius magma chamber: A petrological and volcanological approach, *Bull. Volcanol.*, *44*, 295-315, 1981.

Belkin, H. E., and B. De Vivo, Fluid inclusion studies of ejected nodules from Plinian eruptions of Mt. Somma-Vesuvius, *J. Volcanol. Geotherm. Res.*, *58*, 89-100, 1993.

Belkin, H. E., C. R. J. Kilburn, and B. DeVivo, Sampling and major element chemistry of the recent (AD 1631-1944) Vesuvius activity, *J. Volcanol. Geotherm. Res.*, *58*, 273-290, 1993.

Finetti, I., and C. Morelli, Esplorazione sismica a riflessione dei Golfi di Napoli e Pozzuoli, *Boll. Geofis. Teor. Appl.*, *16*, 175-222, 1974.

Santacroce, R., (ed.), *Somma-Vesuvius, Quaderni Ricerca Scientifica*, CNR Roma, 200 pp., 1987.

Zollo A., P. Gasparini, J. Virieux, H. Le Meur, G. de Natale, G. Biella, E. Boschi, P. Capuano, R. De Franco, P. Dell'Aversana, R. De Matteis, I. Guerra, G. Iannaccone, L. Mirabile, and G. Vilardo, Seismic evidence for a low-velocity zone in the upper crust beneath Mount Vesuvius, *Science*, *274*, 592-594, 1996.

Zollo A., P. Gasparini, G. Biella, R. De Franco, B. Buonocore, L. Mirabile, G. De Natale, G. Milano, F. Pingue, G.Vilardo, P. Bruno, R. De Matteis, H. Le Meur, G. Iannaccone, A. Deschamps, J. Virieux, A. Nardi, A. Frepoli, I. Hunstad, and I. Guerra, 2D seismic tomography of the Somma-Vesuvius, Description of the experiment and preliminary results, *Ann. Geofis.*, *XXXIX*, 471-486, 1996.

As U.S. Ice Core Lab Reaches Capacity, Scientists Plan Future Storage Efforts

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Joan Fitzpatrick, technical director of the U.S. National Ice Core Laboratory (NICL), says that most visitors to the curatorial research facility at the Denver Federal Center in Colorado first notice the temperature: -34 °C in the main storage area, and -24 °C in the lab. Afterwards, they may note that the approximately 5000 sq. m repository is packed full with cores, primarily from Antarctica and Greenland.

NICL, which is jointly operated by the National Science Foundation (NSF) and U.S. Geological Survey (USGS), and jointly funded at $380,000 per year, currently holds about 15,838 m of ice cores in 14,069 canisters of aluminized cardboard. The facility, which houses cores collected through NSF's Office of Polar Programs and USGS' Geologic Division, probably is the most comprehensive collection of ice cores in the world, according to Fitzpatrick.

And at a storage cost of $24 per m each year, she and others say the price is a bargain, given the scientific advances the cores have yielded. Cores in good condition "are the only known faithful recorder of ancient atmosphere," Fitzgerald says.

But with the lab now reaching 97% storage capacity, the ice core community faces some hard choices.

To free up space for thousands of new meters of cores expected at the facility over the next few years, the U.S. Ice Core Working Group (ICWG)—an ad hoc advisory committee of scientists—has recommended the "deaccessing," or removal, of about 10% of the ice from the lab. The ice to be removed is in poor condition and of less scientific value than other ice stored there, according to ICWG.

"We've never thrown away a core before," says Mark Twickler, executive director of the NICL science management office that is housed at the Climate Change Research Center at the University of New Hampshire, Durham. "It's not what we want to do, but something that needs to be done."

As part of the deaccessing process, NICL is offering scientists the opportunity to obtain some of the ice for research purposes for the cost of preparing and shipping them.

"We'd rather have scientists get some good science out of [the cores] than have them melt in the parking lot," says Julie Palais, Antarctic glaciology program manager for NSF's Office of Polar Programs.

While the deaccessed cores may have limited value for paleoclimatologists, some researchers could find them useful for studying cosmic particles, volcanic dust, and other variables.

Palais says the decision to deaccess was reached after nearly 3 years of discussion. "We don't take this kind of deaccession lightly."

Palais, along with Twickler and Fitzgerald, says that of the 1200 m of cores slated for removal, many have deteriorated over time, through evaporation, sublimation, or contamination. Much of the ice lacks robust age-depth relationships, with researchers no longer even knowing which ends of some core sections face the top or bottom—which invalidates that ice for many types of research. Other core samples are duplicates or easily replaceable if ever needed again. No deep cores (those drilled from depths beyond 200-300 m) are slated for removal.

"People don't want to spend a lot of time on samples they can't trust," says Palais. "Most people want newer cores."

Twickler says that ice cores are a "snapshot of time" that record dozens of variables such as the gas composition (including greenhouse gases) of the atmosphere, temperature history, volcanic eruptions, net annual accumulation, ocean surface productivity, and solar activity.

"You get little bubbles of ancient atmosphere" in the ice, Twickler says. "It's a direct link to what was in the atmosphere and the atmospheric circulation patterns, and a proxy to understanding climatic events in the past." He says that unlike other records, such as ocean cores or tree rings, ice cores have a direct link with the atmosphere.

Research into ice cores has yielded a number of important discoveries, including a correlation between historical shifts in the levels of greenhouse gases in the atmosphere and the temperature, and the finding of abrupt and dramatic changes in climate.

Richard Alley, professor of geoscience at Pennsylvania State University, says that ice core data indicates that about 20 abrupt jumps in climate took place during the last 100,000 years, where major changes had occurred over several years or decades rather than during smoother, hundred or thousand year transitions. He says that sometimes climate changes "stumble drunkenly" into and out of glacial and interglacial periods.

Fitzpatrick says "you can count [shifts] right in front of your eyeball, looking at the core." Because no intrinsic property of ice yields its age, researchers manually count off

Fig. 1. Checking cores at the National Ice Core Laboratory. Photo by Ken Abbott

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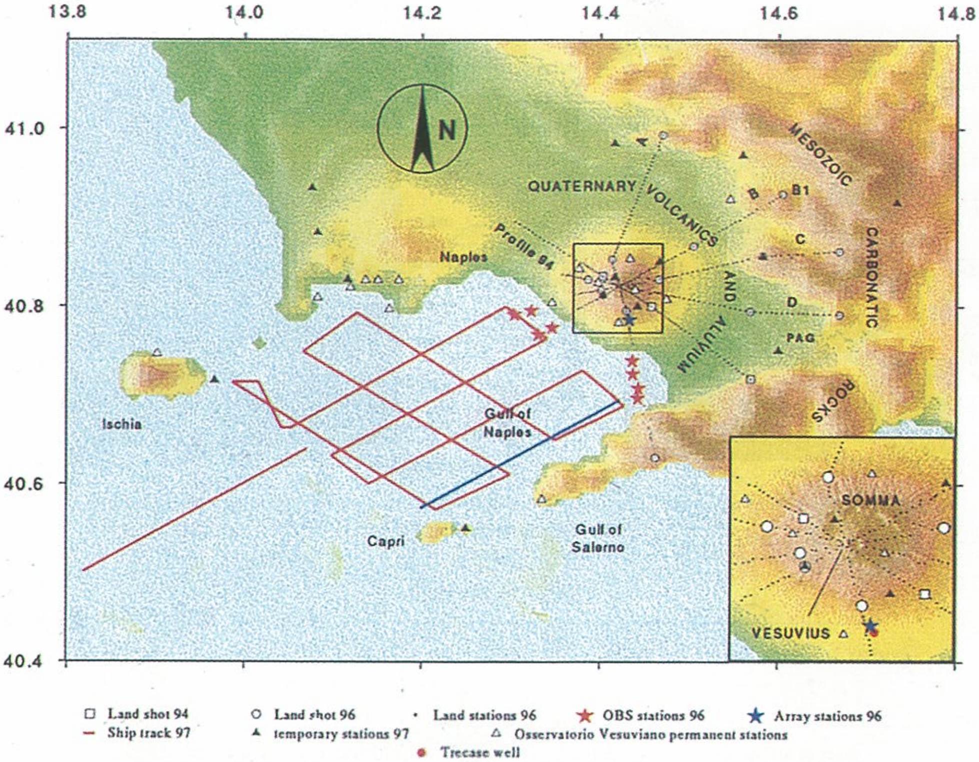

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