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Istituto Nazionale di Geofisica e Vulcanologia
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Research Project

INTEGRATED SEISMIC METHODS APPLIED TO THE INVESTIGATION OF THE ACTIVE VOLCANO STRUCTURE. AN APPLICATION TO THE CAMPI FLEGREI CALDERA

Coordinator: Prof.Aldo Zollo

REPORT OF THE PROJECT COORDINATOR ON THE SECOND YEAR ACTIVITY

INTEGRATED SEISMIC METHODS APPLIED TO THE INVESTIGATION OF THE ACTIVE VOLCANO STRUCTURE. AN APPLICATION TO THE PHLEGREAN FIELDS CALDERA

Project Scientific Coordinator:
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SECOND YEAR REPORT

PROJECT PARTICIPANTS

RU#	AFFILIATION	RESPONSIBILE
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2	Osservatorio Vesuviano, INGV (OV-INGV)	Paolo Capuano
3	Istituto Nazionale di Geofisica, CNT (CNT-INGV)	Claudio Chiarabba
4	Istituto per la Dinamica dei Processi Ambientali, CNR (IDPA-CNR)	Roberto De Franco
5	Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS)	Enrico Priolo
6	Geoscience Azur, Univ.Nizza, CNRS (GeoAzur)	Jean Virieux
7	Dipartimento di Scienze Fisiche, Univ. Napoli (DSF2-UNINA)	Grazia Giberti

GENERAL OBJECTIVES

The project propose the application of advanced techniques for modeling active and passive seismic data recorded in the Caldera of Campi Flegrei. The main objective is to reconstruct high resolution wave velocity and attenuation images of the volcanic structure and compare the obatined values with laboratory measurements. The physical models of the caldera structure and data on its present thermal state will be the ingredients needed to a preliminary thermo-mechanical modeling of the defomation processes inside Campi Flegrei.
These general objectives are pursued through the partition of the research unit activity according to the following three macro-objectives:
Task 1: Investigation of the Campi Flegrei structure from the integrated analysis of seismic, gravity, heat flux and laboratory data.

- **WP1.1** Modeling of seismic data (Arrival times of primary and secondary waves)
- **WP1.2** Joint modeling of seismic, gravity, heat flux and laboratory data
- **WP1.3** Laboratory measurements and thermo-mechanical modeling

Task 2: Techniques for the study of the volcanic structure based on the inversion / forward modeling of amplitudes and waveforms of seismic waves.
Task 3: Implementation of a (active-passive) seismic data-base for the Campi Flegrei caldera.
Task 4: SERAPIS project: Data formatting, archiving and preliminary analysis

TASK #1 - INVESTIGATION OF THE CAMPI FLEGREI STRUCTURE FROM THE INTEGRATED ANALYSIS OF SEISMIC, GRAVITY, HEAT FLUX AND LABORATORY DATA.

The general objective of task #1 is the reconstruction of 3D seismic velocity and attenuation images of the caldera structure by using seismic data (mostly arrival times of primary and secondary waves) and compare the resulting models with other geophysical data. The task objective is pursued through three sub-objectives (workpackages):

WP1.1 Standard,original and advanced techniques are applied for the inversion of primary and secondary (reflected/converted) phases identified on seismograms produced by active and/or microearthquaje sources.
The objective is the determination of 3D P,S velocity and attenuation models, using observables in the time and frequency domain.

WP1.2 Seismic, gravity, heat flux and rock sample laboratory data, obtained from previous work or during the project , will be assembled and jointly interpreted to validate and/or to provide constraints to the velocity and attenuation models of the caldera structure.

WP1.3 The different physical properties (hydraulic, thermic, electric, elastic, anelastic) of the volcanic rocks will be measured in laboratory and compared to analog measurements at a macro-scopic scale. The information about the thermal state of the caldera and on the mechanical/thermic properties of Campi Flegrei rocks will be used to implement a quantitative modeling of the heat transfer and thermo-mechanical response inside the caldera.

RU PARTICIPANTS:

All the Ru participate to the activities in task 1. In particular this is the list of RU participating to each WorkPackage
WP1.1: UR1, UR2, UR3, UR4, UR5, UR6
WP1.2: UR4
WP1.3: UR7

SECOND YEAR OBJECTIVES

Methods: Development and Application ot synthetic data

- Development of methodologies applied to coda wave scattering tomography (wp1.1)
- Local eq /active seismic tomography: Applicability tests, capability check of different data to highlight the deep structure. (wp1.1)
- Tomographic inversion: code optimisation and generation of "user-friendly" interface (wp1.1)
- Development of thermal models and preliminary thermo-mechanical modelling (wp1.3)

Data Acquisition, Analysis e Modeling

- The seismic attenuation tomography method will be applied to a selected P-wave microearthquake data set.(wp1.1)
- Local eq /active seismic tomography:Inversion to define the reference model.(wp1.1)
- Joint inversion with gravity data and if it is possible with heat flow data.(wp1.2)
- Tomographic inversion: application to real data (i.e. Campi Flegrei, Vesuvio data set)(wp1.1)
- Measurements at room temperature and beginning of the measurements at different pressure and temperature conditions (wp1.3)

SECOND YEAR RESULTS

Methods: Development and Application of synthetic data

During the second project year, a number of existing, advanced methods for the forward and inverse modeling of primary and secondary (reflected/converted) wave arrival times have been adapted and verified in synthetic simulations with an acquisition layout which reproduces the one used for recording microearthquakes and shots at Campi Flegrei caldera during past and future experiments. Furthermore, new techniques for data analysis and modeling have been developed and tested on synthetic data to take into account the heterogeneity of the target volume. Hereinafter are listed and briefly resumed the methodologies and results obtained during the first project year, and refer to the RU reports for details:

Non linear inversion of reflected waves arrival times (NLIRD)(UR1)

A 2D non linear inversion method (inversion technique: Genetic Algorithm) of arrival times of PP and PS reflected phases acquired in wide-angle configuration with sources at the free surface has been developed during the first year. During the second year the accuracy and resolution of the method has been studied as a function of a) distribution of sources and receivers at the surface, b) complexity of the background velocity model, c) complexity of the interface shape. A strategy for the inversion has been proposed based on the progressive increase of the density of points describing the interface. The method is operational for a cost function based on the misfit of observed arrival times. It will be applied for the interpetation of several profiles of the experiment Serapis.

Development of a 2D-3D method for the asyntotic modeling of the seismic wave field in heterogeneous media (UR1)

During the II year a set of software codes for traveltime and amplitude computation, 2D seismic tomography and earthquake location in 1D velocity models has been implemented.Those methods have been applied both to 2D seismic tomography (with active seismic data of SERAPIS 2001 experiment) and to hypocentral location of a resticted dataset of events occurred during the period February-April 1984. 2D seismic tomography images show some relevant structure.

Blind test

In order to compare and validate the different methodologies to be used for the inversion or P and S arrival at Campi Flegrei, a synthetic arrival time data-base in a hypothetic 3D caldera structure has been generated by UR5, using the finite difference eikonal code of Podvin and Lecomte(1991). Travel times relative to 100 events located at a network have been computed by reproducing the acquisition lay-out of the 1984 experiment. The different methodologies to be tested are: 1/ Thurber' method, 2/ Zhao' method 3/ Benz' method 4/ GeoAzur' method and 5/ OGS method. Each group involved in the tomographic imaging of the Caldera using earthquake data will apply the inversion codes it will use for the analysis of real data and will produce images. The detailed comparison of tomographic images retrieved by different methods and inversion approaches will be a useful guideline for the interpretation of the images obtained from real data.

3D Local earthquake tomography. Revision of the existing 3D tomographic models (UR3, UR2)

To critically revise the existing velocity models, particularly the Aster e Meyer (1988) velocity model (the only 3D model available up to now), we start to perform some linearized tomographic (using Simulps13q/14 package) tests, using the recovered travel time of a selected set (about 400 earthquakes), confirming the high heterogeneity of the velocity structure inside the Campi Flegrei caldera. All the earthquakes will be re-located in the inferred model. To extend the revision of the previous models we begun also to use different tomographic technique (with H. Benz package), with the objective of compare the influence of different approach to the tomographic problem.
The inversion of the complete passive seismic data set using the D. Zhao and Simulps13q code is still in progress. The inclusion of a complex geometry for the limestone basement and the topography in the Zhao's-derived code is under study. Considering the available information, it has been decided that its geometry will be constrained by the preliminary results obtained from the interpretation of the Serapis data.

Methodological developments: 3D Seismo-gravimetric inversion (UR4)

A method for 3D integrated sequenzial seismo-gravimetric inversion (SII) has been developed. A first application to TomoVes96 data has been performed. Moreover, a code for the computation of 3D gravimetric response that includes density gradients have been tested on synthetic cases. Considering density gradient is important because it is a parametrization homogeneous to that used in seismic analysis. The procedure SII-3D which includes gradient parametrization and Complete Ray Tracing is now being tested.

The reference model: Inversion for 1D local velocity structure (UR5)

The genetic algorithm (e.g., Goldberg, 1989) has been used to obtain a set of one-dimensional P-wave seismic velocity structures and mean V_P/V_S ratio in the Campi Flegrei (CF) caldera near Naples (Italy). Arrival time data are from Aster and Meyer, (1988, 1989) and collected in 1984 by the temporary stations deployed by the University of Wisconsin in collaboration with the Osservatorio Vesuviano. The data set used in this study consists of a total of 239 earthquakes for 1953 P- and 1023 S-wave arrival times, respectively. Results suggest the presence of a sharp P-velocity contrast with velocities varying from 2 to more than 4.0 km/s between 1.5 and 3.0 km depth. At depths larger than 3 km, the P-wave velocity is generally larger than 4.5 km/s. The V_P/V_S features values ranging between 1.84 and 1.90 in the shallow most layer whereas it attains values between 1.72 and 1.77 for the deeper layers.

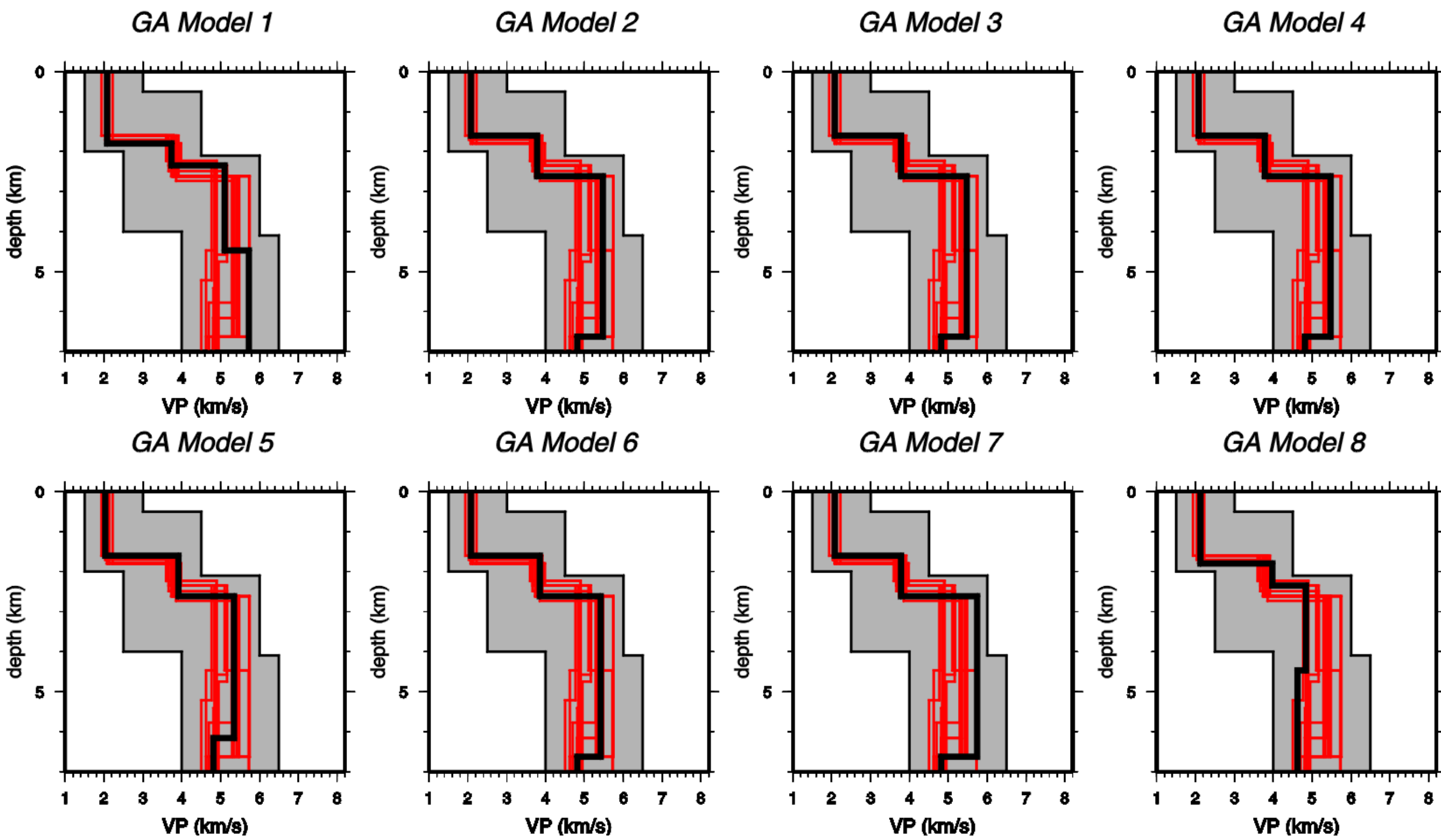

Figure 1 – Genetic Algorithm inversion: the first 8 best-fit 1-D P-wave velocity models.

Linearized tomography with travel times computed by the Podvin & Lecomte method (UR6)

The second year is devoted to the development and implementation of a 3D seismic tomography code based on travel time computation using the finite difference solution of the eikonal equation (Podvin and Lecomte, 1991). The advantage of using such solver of the forward problem is the fast and efficient computation of travel time even in a dense acquisition lay-out and the possibility to image very complex earth structure. The method has been tested on synthetic examples, and shows to be robust and efficient. It will be first applied to the synthetic data base produced for the Blind Test of the project. Using the same kind of interpolation of the seismic tomographic code one is able to compute travel times of converted phases at deep interface. These converted phases could be either reflected phases (active seismics) or transmitted (passive) from deep earthquakes beneath the interface. The two techniques (seismic tomography and interface detection) have been applied on synthetic data and they will be further applied for both the passive and active seismic data at Campi Flegrei.

Data Acquisition, Analysis and Modeling

Attenuation tomography from the inversion of P and S pulse durations and scattered waves(UR1,UR2)

A change in the preliminary program has been performed, since the Campi Flegrei waveform data-set was not yet available. The method has been applied to Mt.Vesuvius local earthquake data collected during 1995-1999 jointly with the active data set recorded during the TomoVes 1996 experiment. More than 200 Mt.Vesuvius microearthquakes recorded at a minimum of 5 stations have been re-located in the now available 3D velocity model (Lomax et al., 2001). About 4000 P-pulse durations and half-widths have been read for the global active and passive data set. Preliminary estimates of source parameters and 3D images of QP underneath Mt.Vesuvius have been obtained. This work is still in progress. The application of this technique to the entire Campi Flegrei data-set depends on the availability of additional research funds for the third year.
A source code to analyse 3D spatial distribution of elastic heterogeneity, and defining scattering processes at Campi Flegrei, using the semblance technique is also on development. A scattering process simulation using a 1D velocity model is in preparation. The results of this test will be compared with those obtained by classical attenuation

tomography, trying to divide anelastic effects from the scattering one, to allow a corrected interpretation of attenuation tomography.

Measurement of the physical properties of Campi Flegrei rock samples (UR7)

Measurements at different pressure conditions have been carried out (on the same Campi Flegrei samples on which measurements at room temperatures were performed) for porosity, P-S ultrasonic velocities, electrical and thermal conductivity and attenuation. Goals of the research at different pressure conditions is to provide information on elastic and poroelastic properties for Campi Flegrei volcanic rocks to have constraints for ground deformation models and seismic data interpretation, and to compare lab results with the in- situ measurements. The elastic (Vp, Vs, K, and μ) as well as the poroelastic parameters (pore stiffness, K_{Φ}) have been measured under fluid and confined pressure conditions. In particular, confining pressure has been increased up to 60 MPa with a step of 5 MPa to simulate up to 3 km overburden. The maximum achieved effective pressure was 45 MPa. Data analysis provide signatures on how petrophysical properties affect seismic response and enables us for a better understanding of the wave propagation mechanisms under pressure and fluid saturated conditions. Well-log data from several Agip's wells have also been collected.

TASK #2 - TECHNIQUES FOR THE STUDY OF THE VOLCANIC STRUCTURE BASED ON THE INVERSION /FORWARD MODELING OF SEISMIC AMPLITUDES AND WAVEFORMS.

The general objective of task #2 is the investigation of the complex volcanic structure by forward / inverse modeling of seismic waveforms recorded during passive and/or active seismic experiments.
Advanced techniques for migrating reflection phases in 2D and 3D media (derived from exploration seismics) will be developed, verified through sinthetic tests and applied to the experimental data. A pseudo-spectral method for the 2D-3D complete wavefield simulation in elastic/anelastic media will be developed and applied to verify and validate the tomographic and interface model obtained for the Campi Flegrei caldera structure.

RU PARTECIPANTS:

UR1 and UR5 are involved in this task.

2ND YEAR OBJECTIVES

Methods: Development and Application to synthetic data

- Use of NLIRD techniques with a semblance cost function
- Development of interpretative methodologies applied to seismic profiles analysis with earthquakes
- Seismic forward modeling: Development and implementation of the Fourier-Chebyshev method.
- Seismic forward modeling: Simulations of active seismics experiments and weak earthquakes

2ND YEAR RESULTS

Methods: Development and Application to synthetic data

2D non linear inversion of reflection seismic waveforms (NLIRD)(UR1)

The technique which has been developed for inverting the reflection arrival times (Task 1 WP1.1) has been extended to consider the reflected/converted phase waveforms. The cost function of the inverse problem is computed through the "semblance" (or "stack") of waveforms extracted from a time window centered at the theoretical arrival time of the considered phase. The code has been developed, implemented and preliminary tested on a set of complete synthetic waveforms computed for a 1D layered structure using the code by O.Coutant which applies the Discrete Wavenumber Method of Bouchon(1981).

Identification of crustal seismic discontinuities through the analysis of 3D reflection waveforms on local earthqauke records. (UR1)

We developed a technique (first year) based on the move-out and stack of reflected and seismic phases from local earthquake seismograms. For a given interface depth and background velocity model, the theoretical travel times of different reflected/converted phases in a 1-D medium are computed and used to align in time the vertical component microearthquake records collected by a local seismic network. The method has been applied to the seismic records of microearthquakes occurring at Mt.Vesuvius volcano. The analysis confirms the evidence for a 8-10 km deep seismic discontinuity underneath the volcano, which has been previously identified by migration of active seismic data and interpreted as the roof of an extended magmatic sill.

Forward seismic modeling(UR5)

An algorithm for the 3D modeling of the seismic wavefield produced by active or passive sources has been developed to simulate the wave propagation in complex geological structures. The algorithm is based on the solution of the full elastic wave equation in heterogeneous media by using the pseudo-spectral Fourier method on a staggered. During the second year a great effort was put in increasing the efficiency of the code. A significant improvement of the performances of the code has been obtained using domain decomposition technique which is suitable for parallel implementation. More details can be found in the RU5 1st year report. To efficiently simulate the propagation of seismic wavefield generated by many sources and recorded at a few receivers (such in the case of a seismic swarm), the reciprocity principle has been implemented and tested. Results are shown in Figure 2. This development allows for the built of a synthetic seismograms database.

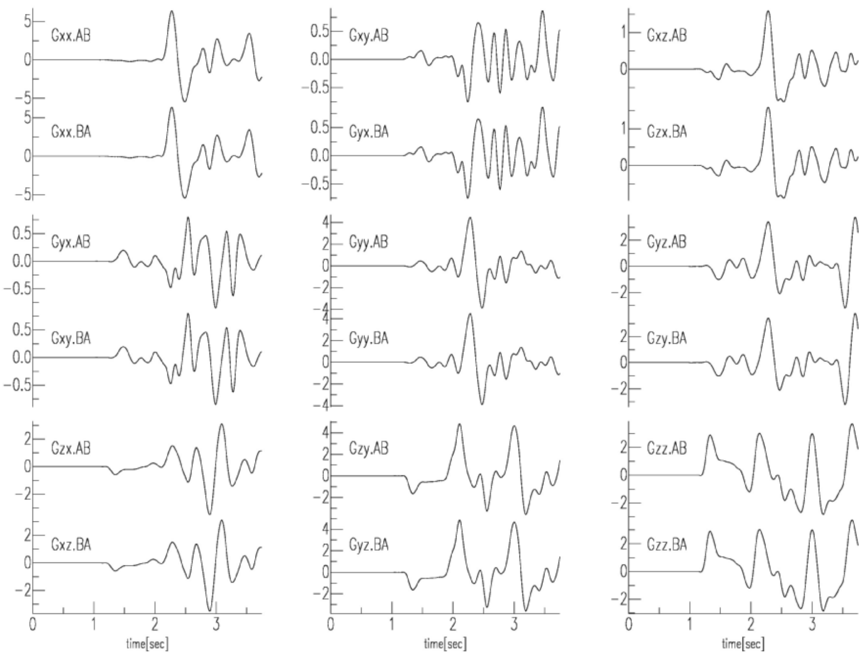

Figure 2 – Validation of the reciprocity principle. Seismograms computed using the Fourier staggered pseudospectral method by exchanging the source-receiver position.

Synthetic waveforms for a hypothetic caldera structure (Blind Test)(UR1,UR5)

A 3-D digital model representative of the structure beneath the Phlegrean Fields has been defined and implemented. The model is used for 1) testing the numerical methods which solve the 3-D seismic waves propagation, 2) computing synthetic seismograms reproducing earthquakes recorded during 1984, and 3) serving as a benchmark for evaluating the tomographic methods used in the framework of the project.
The model represents a hypothetical structure of the caldera and the surrounding Earth’s structure in a cube of size 12 km _ 14 km _ 8 km, in the directions North, East and depth, respectively. The Fourier staggered pseudospectral method has been used to compute a reduced dataset of waveforms. This first set of simulations is mainly demonstrative, and it aims at allowing a first evaluation of the effect of the 3-D structure on the complexity of the waveforms. The simulations have been performed for a maximum frequency of 5 Hz. The model is the same used previously for the computation of the arrival times. The result of the simulations consists in a set of about 3,600 three component waveforms computed at three receivers for the whole set of sources.

TASK #3 IMPLEMENTATION OF A SEISMIC DATA-BASE FOR THE CAMPI FLEGREI CALDERA.

The general objective of task 3 is the implementation of a complete three-component seismic waveform data-base containing data from several hundreds microearthquakes occurred on 1983-1984 at Campi Flegrei during the last bradiseism. Earthquake seismic data have been collected by the digital seismograph network installed by the University of Wisconsin and part of them are still available at the UW labs. The task3 activity will concern the retrieval, formatting and archiving of the whole data set, which is accomplished in cooperation with personnel of the University of Wisconsin. The project data-base will also contain active seismic data acquired in the area during the past 1985 DSS experiments and more recently (1997) during the experiment MareVes97 in the framework of the tomographic researches on Mt. Vesuvius.

RU PARTECIPANTS:

The RU involved in this task are: RU1, RU2, RU4 ed RU7

2ND YEAR OBJECTIVES

Data-Base
- Wisconsin database: implementation and picking
- DSS data base
- Construction and updating of the site "project server".
- Collection of experimental and bibliographic data to be used as constraints for the thermal modeling.

2ND YEAR RESULTS

Data-Base

Implementation of a waveform and arrival time data-base for 1984 Campi Flegrei earthquakes. Re-picking (UR2,UR1)

The activity related to recover information about the seismic acquisition conducted in the 1984 jointly by OV and University of Wisconsin, that deployed in Campi Flegrei caldera 13 digital stations occupying about 20 sites, is consisted in re-read about 30 digital tapes. The time schedule of instrument installation and operation has been recognised and the part of data available at OV has been retrieved. After removing noisy trace and trace corresponding to midnight check of the station functionality, and after the verification of some inconsistency with previous phase picking, the project group decided to re-pick the whole waveform database to reduce any possible heterogeneity between new and previous picking, could bias the tomographic inversion. Five RU participate to this operation furnishing re-picked waveforms to UR1-UR2 coordination group. Now the new dataset is undergone a number of check test to validate the new measurements. All the recognized waveforms, the phase pickings, the stations information will be inserted in the implemented database whose functionality check is in progress and it will be ready at the beginning of 2003. The new picking archive will be integrated with those available at OV also for previous periods (1970-1983).

Digitization of 1985-1987 DSS data (UR4)

The data base of DSS data acquired in Vesuvius and Campi Flegrei area has been buit. Data are now undergoing preprocessing.

The Project Server Site(UR1, UR7)

During the second year the ftp server has been updated to include a/ the whole earthquake waveform data set of the 1984 Campi Flegrei seismic swarm, b/ Aster and Meyer (1991)' readings of the first P and S arrival times, c/ 75% of the new readings of the first P and S arrival times, d/ data concerning the physical properties of rocks at Campi Flegrei. Concerning the point c/ we stress that the whole microearthquake waveform data-base (1982-1984 seismic crisis) has been reconstructed, archived and made available to all participants through the project server web site. Due to the noticeable increment of available waveforms, a global manual re-picking of first P and S arrivals has been performed with the participation of all RU with the exception of RU6 and RU7. The new picking data base is actually under verification and it will be presumably ready for the modeling for the beginning of 2003. In the mean time a synthetic "blind test" has been organized in order to validate and compare the different methods for 3D local earthquake inversion that will be applied to real data. Synthetic waveforms and P/S arrival times are being computed by UR5 assuming a hypothetic 3D structure of the Campi Flegrei caldera. The synthetic travel time data set for blind tests will be soon accessible from the ftp server.

The web oriented, relational data bese, has been also implemented during the second year and now under testing. In the next future, the 1984 Campi Flegrei waveforms and picking could be extracted via web by queries based on time and space windows
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TASK #4 DESIGN AND REALIZATION OF A SEISMIC REFLECTION CAMPAIGN (SERAPIS PROJECT)

Task 4 does not appear in the original, approved project, since it derives from the realization of the seismic reflection acquisition campaign, denoted as SERAPIS. The oceanographic ship NADIR of Ifremer (Brest) produced airgun sources at sea whose signals will be recorded by a 3C digital network of seismographs deployed on land and at the sea bottom. The experiment took place during September, 2001 and all the RU have participated to the acquisition and formatting phase. The task of the second year was the formatting, distribution and preliminary analysis of data.

RU PARTICIPANTS:

The following RU are involved: *UR1,UR2,UR3,UR4,UR5,UR6,UR7*

2ND YEAR OBJECTIVES

Formatting, archiving, distribution and preliminary analysis of Serapis data

2ND YEAR RESULTS

Formatting and Distribution(UR1,UR2,UR3,UR4,UR5,UR6)

60 three-component stations have been installed on-land in the areas of Campi Flegrei, Mt.Vesuvius and on the islands of Ischia and Procida and 72 sea bottom seismographs (OBS) have been installed in the gulfs of Naples and Pozzuoli. A denser 2D network of 35 OBSs has been deployed in the bay of Pozzuoli aimed at detecting and modeling reflected/converted waves from the possible shallow to deep discontinuities beneath the Campi Flegrei caldera. About 5000 shots have been performed during the SERAPIS experiment, at an average spatial spacing of 125 m, for a total ship travel path of 620 km.
A number of difficulties related to the late availability of fundings needed to cover the costs for the back-up and processing of seismic waveforms of ocean bottom stations have delayed by 6 months the delivery of the Serapis data set. Actually, both the waveform data of on land and sea bottom receivers (around 60 Gbyte of data) are ready for distribution, analysis and modeling. The preliminary processing of SERAPIS seismic data is started on September involving researchers from different research units of this project and the unit of INGV-Milan (resp. Gemma Musacchio), that participated to the field experiment. The possibility to apply automatic procedures for identifying and reading first and secondary arrivals are under exploration.

Preliminary analysis (UR1,UR5)

The picking of about 35000 first-P arrivals have been performed. A detailed 3D image of the Campi Flegrei caldera offshore has been reconstructed up to 4 km depth by tomographic inversion using the code developed by Harley Benz. The images are finely resolved (250 m square blocks) and clearly show the buried, anular rim of the caldera at about 1.5 km depth, whose shape and location is well consistent with gravity highs at sea. From the analyisis of refraction profiles in and outside the bay of Pozzuoli there is a strong evidence for the top of the limestone formation gently deepening moving toward the caldera. It is found at about 4 km depth underneath the bay of Pozzuoli.
We're presently working at the analysis of reflection arrivals in order to image crustal discontinuities, and possibly, the magma chamber top.

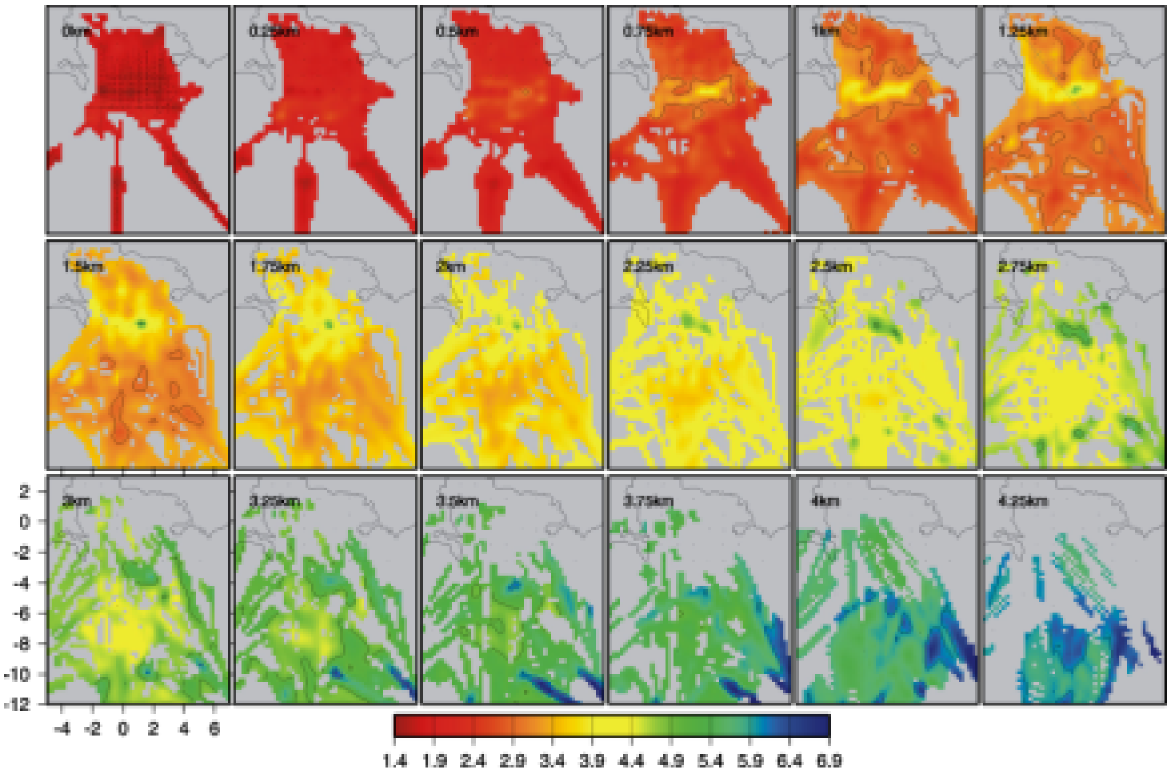

Figure 3. 3D image of the subsurface underneath the Campi Flegrei caldera, as inferred from the first P-arrival time tomography applied to Serapis data (about 35000 pickings). The buried rim of the Campi Flegrei caldera is clearly visible from depths higher than 0.75 km.

PRODUCTS OF THE RESEARCH

n° publications on international journals : 12
n° publications on national journals, proceedings, conference presentations, techniqcal reports, etc.: 11
Data banks:

- Project Server Site (documents, numerical models, seismic data bank, digital terrain models, bathimetry, etc.)
- Archive of selected waveforms of 1984 Campi Flegrei microearthquakes, UW network
- Archive of 1984-1987 Campi Flegrei DSS data and 1997 MareVes data
- laboratory measurements

Computing codes:

- codes for 2D non linear inversion of reflection phase arrivals, migration 3D, ray-tracing 2D, inversion of microearthquake P and S pulses, formatting and pre-processing seismic waveform procedures (UR1)
- codes for reading and transforming UW data to SAC e SEGY (UR2)
- code for the inversion of P and S arrival times from local earthquakes, modified version of the Zhao et al., 1994' code (UR3)
- code for 3D seismic inversion based on ART, modified version of CRT (Prague) (UR4)
- Code for complete wavefield simulation by pseudo-spectral method, implemented on parallel machines (Cray T3E e SGI Origin 2000) (UR5)
- code for linearized 3D tomography using the Podvin & Lecomte method to compute first arrival times (UR6)

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Zollo A., Marzocchi W., Capuano P., Lomax A., Iannaccone G., 2002. Space and time behaviour of seismic activity during last decades at Mt.Vesuvius volcano, Southern Italy, Bull. Seis. Soc. Am.

Zollo A., Virieux J., Capuano P., Chiarabba C., De Franco R., Makris J., Michelini A., Musacchio G., Serapis Group. The project SERAPIS: high resolution seismic imaging of the Campi Flegrei caldera structure. XXVII General Assembly of EGS, Nice, France, April 22-26, 2002.

Zollo A., Virieux J., Kakris J., Auger E., Boschi L., Capuano P., Chiarabba C., D'Auria L., De Franco R., Judenherc S., Michelini A., Musacchio G., Serapis Group. High resolution seismic imaging of the Campi Flegrei caldera, southern italy. AGU Fall Meeting, S. Francisco, USA, December 6-10, 2002.

Gruppo Nazionale di Vulcanologia
Istituto Nazionale di Geofisica e Vulcanologia
Framework Program 2000-2002

Research Project

INTEGRATED SEISMIC METHODS APPLIED TO THE INVESTIGATION OF THE ACTIVE VOLCANO STRUCTURE. AN APPLICATION TO THE CAMPI FLEGREI CALDERA

Coordinator: Prof.Aldo Zollo

REPORT OF THE RESEARCH UNITS ON THE SECOND YEAR ACTIVITY

2-D-3D modeling of reflection arrivals and 3-D velocity/attenuation tomography from the analysis of microearthquake and active source data in volcanic areas. Application to the Phlegrean Fields caldera.

Research Unit responsible: **Aldo Zollo**
Full Professor
RU1: Dipartimento di Scienze Fisiche - Università Federico II di Napoli. (Italia)

ACTIVITY REPORT – SECOND YEAR

UR PARTICIPANTS

Name-Position	Affiliation	Months/man
Aldo Zollo – Full Professor	Università di Napoli	4
Marie-Lise Bernard - post-Doc, EU Marie-Curie Fellow	Università di Napoli	6
Emmanuel Auger - post-Doc – UniNapoli Fellowship	Università di Napoli	11
Roberto Prevete- post-Doc – UniNapoli Fellowship	Università di Napoli	11 (UR-OV)*
Luca D'Auria – Ph.D student	Università di Napoli	6
Gaetano Festa – Ph.D student	Università di Napoli	4
Salvatore de Lorenzo-post-Doc- UniBari Fellowship	Università di Bari	3
Raffaella De Matteis - Researcher	Università del Sannio	2
Claudio Satriano - Student in Physics	Università di Napoli	8
Maurizio Vassallo - Student in Physics	Università di Napoli	6

* Fellowship activity is carried on with UR2 (Osservatorio Vesuviano). The fellowship was funded by UR 1 (DSF-UNINA).

SECOND YEAR OBJECTIVES

A. Set up and application to real data of a 2D-3D non linear inversion method applied to arrival times and waveforms of reflected/converted phases generated by active/passive seismics.(task1 wp1.1 and task2)
B. Development of 2D-3D techniques for seismic wavefield asymptotic modeling in heterogeneous media (task1 wp1.1)
C. Attenuation tomography (task1 wp1.1 and task 2)
D. Set up, maintenance and updating of the FTP server of the project (Project Server Site) containing data archives and several other informations of general interest for participants. Picking of microearthquake records (task 3)
E. Formatting and preliminary analysis of SERAPIS data. (task 4)

SECOND YEAR RESULTS

OBJECTIVE A

A.1 Location of discontinuities in the crust by the analysis of reflected phases generated by local seismic events.

We developed a technique (first year) based on the move-out and stack of reflected and seismic phases from local earthquake seismograms. For a given interface depth and background velocity model, the theoretical travel times of different reflected/converted phases in a 1-D medium are computed and used to align in time the vertical component microearthquake records collected by a local seismic network. Location and origin time of events are preliminarily estimated from first P and S arrival times.
Different seismic gathers are so obtained for each considered reflected / converted phase at that interface and the best interface depth is chosen as the one which maximizes the value of a semblance function computed of move-out records.
The method has been tested on synthetic, complete wave-field seismograms, which include source radiation pattern, attenuation and multiple arrivals in a 1-D layered velocity model.

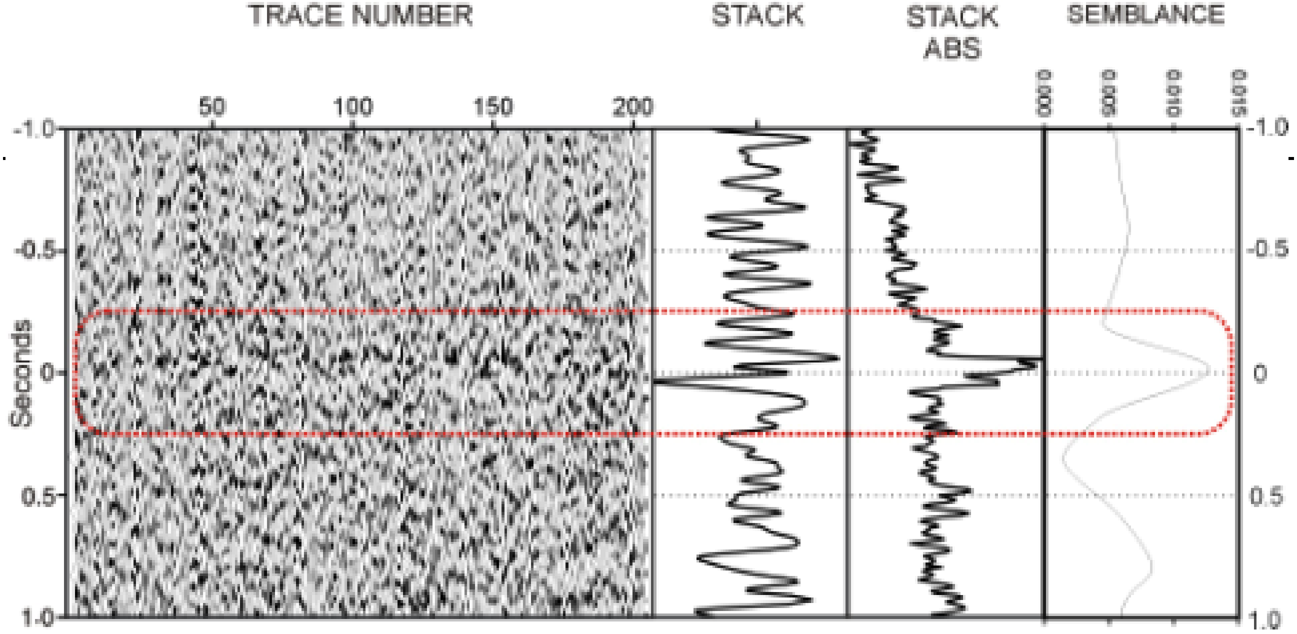

Figure 1. Seismic section for microearthquake records at Mt.Vesuvius. The traces have been shifted according to the theoretical arrival time of a P-to-P phase reflected at the 9 km depth interface underneath Mt. Vesuvius. The figure show the stack , absolute stack and semblance functions versus time. We note a well defined peak of the stack functions, confriming the evidence for a reflected arrival on microearthquake records.

The method has been applied to the seismic records of microearthquakes occurring at Mt.Vesuvius volcano. The analysis confirms the evidence for a 8-10 km deep seismic discontinuity underneath the volcano, which has been previously identified by migration of active seismic data and interpreted as the roof of an extended magmatic sill. Moreover, during the first year was developed a code for computing arrival times of reflected phases in a 3D heterogeneous structure for an irregular reflecting interface. This code has been implemented in a pre-stack migration procedure to applied to earthquake data from the Campi Flegrei Wisconsin data set. In order to test and validate the technique, it has been preliminarly applied to a small subset of seismograms. It will be applied to a significant data-set as soon as the tomographic velocity model and accurate earthquake location will be available.

A.2 2D Non linear inversion of reflected seismic phases (NLIRD)

The aims are the analysis, inversion of arrival times and, migration to depth of reflected/converted phases generated by active and passive seismic in geologically complex areas. A 2D non linear inversion method (inversion technique: Genetic Algorithm) of arrival times of PP and PS reflected phases acquired in wide-angle configuration with sources at the free surface has been developed during the first year. During the second year the accuracy and resolution of the method has been studied as a function of a) distribution of sources and receivers at the surface, b) complexity of the background velocity model, c) complexity of the interface shape. A strategy for the inversion has been proposed based on the progressive increase of the density of points describing the interface. The method is operational for a cost function based on the misfit of observed arrival times. It will be applied for the interpetation of several profiles of the experiment Serapis. Also, it has been implemented the version of the code based on a cost function computed through the "semblance" (or "stack") of waveforms extracted from a time window centered at the theoretical arrival time of the considered phase. The code has been developed, implemented and preliminary tested on a set of complete synthetic waveforms computed for a 1D layered structure using the code by O.Coutant which applies the Discrete Wavenumber Method of Bouchon(1981).We are starting the battery of tests for validating the semblance method for real earth simulations.

OBJECTIVE B

Development of a 2D-3D technique for seismic wavefield asymptotic modeling in heterogeneous media

During the II year, a new class of non-liner inverse methods, based on Genetic Algorithms have been developed. Those methods make use, as forward modeling kernel, of the RTLM algorithm, developed during the I year.
The main research activity was the definition of criteria for evaluating the "goodness" of results through an accurate estimation of variance on model parameters.
A set of software codes for traveltime and amplitude computation, 2D seismic tomography and earthquake location in 1D velocity models has been implemented.Those methods have been applied both to 2D seismic tomography (with active seismic data of SERAPIS 2001 experiment) and to hypocentral location of a resticted dataset of events occurred

during the period February-April 1984. 2D seismic tomography images show some relevant structure, related probably to the Neapolitan Yellow Tuff caldera.

OBJECTIVE C

3D attenuation tomography from inversion of P and S pulse duration data

We use a revised version of the method developed by Zollo and de Lorenzo (2001). The method has been improved to include a 3D ray tracing, the joint use of P and S pulses and, the integration of the seismic data-base with active seismic records. The method provides estimates of the 3D variations of the quality factor and of source parameters (radius, orientation and dip of the fracture plan) of microearthquakes.
A change in the preliminary program has been performed, since the Campi Flegrei waveform data-set was not yet available. The method has been applied to Mt.Vesuvius local earthquake data collected during 1995-1999 jointly with the active data set recorded during the TomoVes 1996 experiment. More than 200 Mt.Vesuvius microearthquakes recorded at a minimum of 5 stations have been re-located in the now available 3D velocity model (Lomax et al., 2001). About 4000 P-pulse durations and half-widths have been read for the global active and passive data set. Preliminary estimates of source parameters and 3D images of QP underneath Mt.Vesuvius have been obtained. This work is still in progress.
The application of this technique to the Campi Flegrei data-set depends on the availability of additional research funds.

OBJECTIVE D

The Project Server Site

The FTP site of the project is running since November 2000. It contains data and several other informations about Flegrei caldera During the second year it has been updated to include a/ the earthquake waveform data set of the 1984 Campi Flegrei seismic swarm, b/ Aster and Meyer (1991)' readings of the first P and S arrival times, c/ 75% of the new readings of the first P and S arrival times.
Concerning the point c/ we stress that the whole microearthquake waveform data-base (1982-1984 seismic crisis) has been reconstructed, archived and made available to all participants through the project server web site. Due to the noticeable increment of available waveforms, a global manual re-picking of first P and S arrivals has been performed with the participation of all RU with the exception of RU6 and RU7. The new picking data base is actually under verification and it will be presumably ready for the modeling for the beginning of 2003. This UR has coordinated the process of re-picking by preparing the SAC data set and performing an after-pick verification.
In the mean time a synthetic "blind test" has been organized in order to validate and compare the different methods for 3D local earthquake inversion that will be applied to real data. Synthetic waveforms and P/S arrival times are being computed by UR5 assuming a hypothetic 3D structure of the Campi Flegrei caldera. The synthetic travel time data set for blind tests will be soon accessible fron the ftp server.
The web oriented, relational data bese, has been also implemented during the second year and now under testing. In the next future, the 1984 Campi Flegrei waveforms and picking could be extracted via web by queries based on time and space windows.

OBJECTIVE E

Formatting, distribution, picking and analyisis of SERAPIS data

A number of difficulties related to the late availability of fundings needed to cover the costs for the back-up and processing of seismic waveforms of ocean bottom stations have delayed by 6 months the delivery of the Serapis data set. Actually, both the waveform data of on land and sea bottom receivers (around 60 Gbyte of data) are ready for distribution, analysis and modeling.
The preliminary processing of SERAPIS seismic data is started on September involving researchers from different research units of this project and the unit of INGV-Milan (resp. Gemma Musacchio), that participated to the field experiment. The work concerns the analysis of several high priority 2D profiles, crossing the bay of Pozzuoli.
The picking of about 35000 first-P arrivals have been performed. A detailed 3D image of the Campi Flegrei caldera offshore has been reconstructed up to 4 km depth by tomographic inversion using the code developed by Harley Benz. The images are finely resolved (250 m square blocks) and clearly show the buried, anular rim of the caldera at about 1.5 km depth, whose shape and location is well consistent with gravity highs at sea. From the analyisis of refraction profiles in and outside the bay of Pozzuoli there is a strong evidence for the top of the limestone formation gently deepening moving toward the caldera. It is found at about 4 km depth underneath the bay of Pozzuoli.
We're presently working at ther analysis of reflection arrivals in order to image crustal discontinuities, and possibly, the magma chamber top.

In the framework of this activity aimed at the modeling of Serapis data it has to be additionally noted 1/ the application of tau-p waveform representation and inversion methods for the identification and modeling of of reflections (Boschi and Zollo, 2002) and 2/ the development a new method for boundary absorption in computing 3D synthetic seismograms using the finite difference method (Festa and Nielsen, 2003).

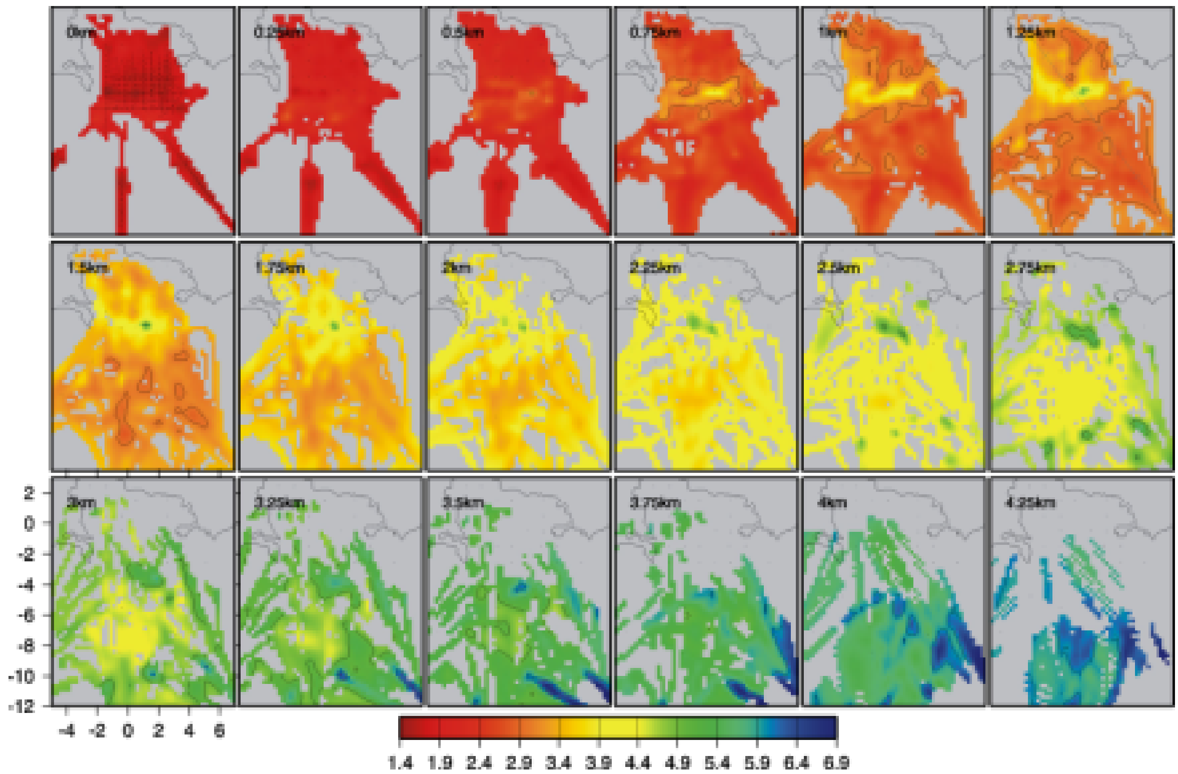

Figure 2. 3D image of the subsurface underneath the Campi Flegrei caldera, as inferred from the first P-arrival time tomography applied to Serapis data (about 35000 pickings). The buried rim of the Campi Flegrei caldera is clearly visible from depths higher than 0.75 km.

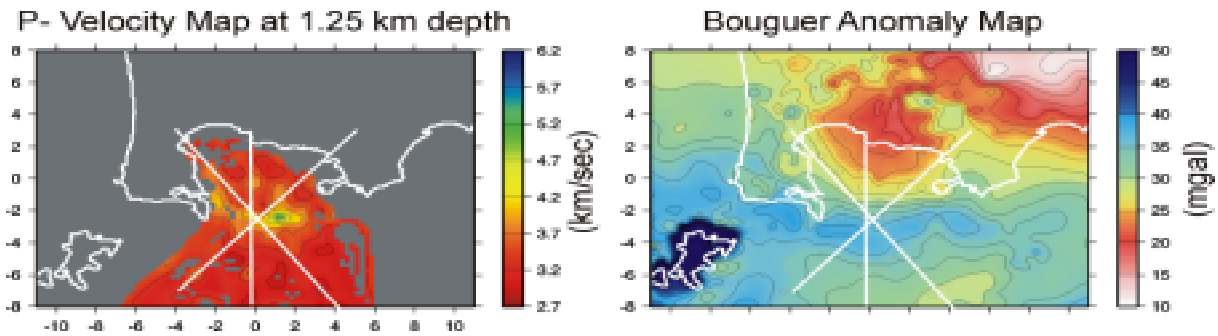

Figure 3. Comparison between the P-Velocity map at 1.25 km depth and the Bouguer anomaly map. The arc-like high velocity anomaly well fit the steepest gradient region limiting the Bay of Pozzuoli in the gravity map.

RESEARCH PRODUCTS

- 9 publications (published, in press, submitted) on international journals
- 4 talks at international congresses (during 2002)
- 1 Degree thesis in Physics, Univ. Napoli (C.Satriano)
- FTP site of the project (documents, numerical models, seismic data-base, DTM, bathimetry, etc.)
- Codes: non linear 2D inversion of reflected phases, 3D migration, 2D ray tracing, inversion of P/S pulse duration data of microearthquakes, procedures to format and pre-analyze seismic data .

PUBLICATION LIST

Papers

E.Auger, J. Virieux and A. Zollo, 2002, *Imaging of a mid-crust reflector beneath Mt.Vesuvius (Southern Italy), and estimation of the associated velocity contrast*, Geophysical J. Int., in press.

E. Auger, P.Gasparini, J.Virieux and A. Zollo, *Seismic evidence of an extended magmatic sill under Mt.Vesuvius*, Science, 294,1510-1512.

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Festa G., Nielsen S.,2003, PML Absorbing Boundary, Bull. Seism.Soc.Am., in press

A. Zollo ,L. D'Auria, R.De Matteis, A. Herrero, J.Virieux and P.Gasparini , 2002, *Bayesian Estimation of 2-D P-Velocity Models From Active Seismic Arrival Time Data: Imaging of the Shallow Structure of Mt.Vesuvius (Southern Italy),* Geophysical Journal International, 151, 566-582

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Presentations

Zollo, A , et al., 2002, High Resolution Seismic Imaging of the Campi Flegrei Caldera, Southern Italy, *Eos Trans. AGU, 83*(47), Fall Meet. Suppl. S72C-05 INVITED

Boschi L. and A. Zollo, 2002, A new technique for seismic tomography of volcanic areas, applied to the Phlegrean Fields , XXVIII General assembly of the European Seismological Commission (ESC)1-6 September 2002, Genova

D'Auria L. and A. Zollo,2002 Recursive Tessellation of Lagrangian Manifolds: a new tool for asymptotic seismic wavefield modeling. XXVIII General assembly of the European Seismological Commission (ESC)1-6 September 2002, Genova

De Matteis, R Vanorio, T Ciulli, B Spinelli, E Fiordelisi, A Zollo, A, 2003 Seismic Velocity Structures of Larderello Geothermal System, Italy: Preliminary Results, *Eos Trans. AGU, 83*(47), Fall Meet. Suppl., Abstract S11C-1168, 2002

Reports and theses

Satriano C., 2002, Analisi dei segnali basata sulla coerenza multipla spaziale: applicazione ai dati di sismica di esplorazione. Tesi di laurea in Fisica, Università di Napoli "Federico II".

Earthquake database implementation at Campi Flegrei. Development and application of seismic methods to investigate the crustal structure of the area.

Research Unit Responsible**: Paolo Capuano**
Associate Professor
RU2: Istituto Nazionale di Geofisica e Vulcanologia – Sezione Osservatorio Vesuviano

ACTIVITY REPORT – SECOND YEAR

RU PARTICIPANTS

Name-Position	Affiliation	man/month
P. Capuano – Professore Associato	Osservatorio Vesuviano-INGV	3
G. Iannaccone – Geof. Ordinario	Osservatorio Vesuviano-INGV	2
M. Martini – Geof Associato	Osservatorio Vesuviano-INGV	1
E. Del Pezzo – Geof. Ordinario	Osservatorio Vesuviano-INGV	1
G. De Natale – Geof. Associato	Osservatorio Vesuviano-INGV	1
G. Saccorotti – Ricercatore	Osservatorio Vesuviano-INGV	3
F. Bianco – Ricercatore	Osservatorio Vesuviano-INGV	3

SECOND YEAR OBJECTIVES

a) Velocity model revision and reconstruction of the 3D velocity structure (TASK 1 WP 1.1);
b) Development of scattering tomography (TASK 1 WP 1.1);
c) Database implementation and database waveforms picking (TASK2);
d) Serapis data acquisition and preprocessing (TASK 4).

SECOND YEAR RESULTS

a) To critically revise the existing velocity models, particularly the Aster e Meyer (1988) velocity model (the only 3D model available up to now), we start to perform some linearized tomographic (using Simulps13q/14 package) tests, using the recovered travel time of a selected set (about 400 earthquakes), confirming the high heterogeneity of the velocity structure inside the Campi Flegrei caldera. All the earthquakes will be re-located in the inferred model. To extend the revision of the previous models we begun also to use different tomographic technique (with H. Benz package), with the objective of compare the influence of different approach to the tomographic problem. We start also to test the different tomographic technique with a synthetic "blind test" using a synthetic data set produced by UR6 assuming a hypothetic 3D Campi Flegrei structure.

b) We are developing a source code to analyse 3D spatial distribution of elastic heterogeneity, defining scattering processes at Campi Flegrei, using the semblance technique. A scattering process simulation using a 1D velocity model is in preparation. The results of this test will be compared with those obtained by classical attenuation tomography, trying to divide anelastic effects from the scattering one, to allow a corrected interpretation of attenuation tomography.

c) The activity related to recover information about the seismic acquisition conducted in the 1984 jointly by OV and University of Wisconsin, that deployed in Campi Flegrei caldera 13 digital stations occupying about 20 sites, is consisted in re-read about 30 digital tapes. The time schedule of instrument installation and operation has been recognised and the part of data available at OV has been retrieved. After removing noisy trace and trace corresponding to midnight check of the station functionality, and after the verification of some inconsistency with previous phase picking, the project group decided to re-pick the whole waveform database to reduce any possible heterogeneity between new and previous picking, could bias the tomographic inversion. Five RU participate to this operation furnishing re-picked waveforms to UR1-UR2 coordination group. Now the new dataset is undergone a number of check test to validate the new measurements. The release of the verified arrival time data base is foreseen for the beginning of 2003. All the recognized waveforms, the phase pickings, the stations information will be inserted in the implemented database whose functionality check is in progress and it will be ready at the beginning of 2003. The new picking archive will be integrated with those available at OV also for previous periods (1970-1983).

d) We participated to the active seismic campaign SERAPIS, installing and managing 14 digital seismic stations (at Campi Flegrei, Ischia island and Procida island) belonging to the OV mobile network consisting of Mars-Lite station recording on magneto-optical disk. We recovered the sea shots recorded at OV surveillance permanent network consisting of 8 stations at Campi Flegrei, 11 at Vesuvius and 3 at Ischia island. We installed, with a co-operation with the University of Granada, a seismic array at Solfatara crater. As regard the pre-processing, UR contributed to data formatting and is starting with picking of first arrival. This delay is due to delay of the second year funding that make impossible, up to now, the start of a required fellowship.

RESEARCH PRODUCTS

- 2 publications on international journals.
- 2 presentations at international meetings
- 3 presentations at national meetings
- Data base: A waveform and picking archive is available. A relational database developed using MySql under Linux operating system is submitted to verification tests.
- Algorithm code: codes for reading and translating original data in different format (like SAC and SEGY) have been developed and revised. Codes for phase picking checking have been developed as well as codes for queries in MySql language.

PUBBLICATIONS LIST

Zollo A., Marzocchi W., Capuano P., Lomax A., Iannaccone G., 2002. Space and time behaviour of seismic activity during last decades at Mt.Vesuvius volcano, Southern Italy, Bull. Seis. Soc. Am.

Lanari R., De Natale G., Berardino P., Sansosti E., Ricciardi G.P., Borgstrom S., Capuano P., Pingue F., Troise C., 2002. Evidence for a peculiar style of ground deformation inferred at Vesuvius volcano, Geoph. Res. Lett.

PRESENTATIONS LIST

Zollo A., Virieux J., Capuano P., Chiarabba C., De Franco R., Makris J., Michelini A., Musacchio G., Serapis Group. The project SERAPIS: high resolution seismic imaging of the Campi Flegrei caldera structure. XXVII General Assembly of EGS, Nice, France, April 22-26, 2002.

Zollo A., Virieux J., Kakris J., Auger E., Boschi L., Capuano P., Chiarabba C., D'Auria L., De Franco R., Judenherc S., Michelini A., Musacchio G., Serapis Group. High resolution seismic imaging of the Campi Flegrei caldera, southern italy. AGU Fall Meeting, S. Francisco, USA, December 6-10, 2002.

Joint tomography using active and passive seismic data together with teleseismic ones in the Phlegrean Fields

Research Unit responsible: **Claudio Chiarabba**
Dirigente di Ricerca
RU3: Istituto Nazionale di Geofisica e Vulcanologia, CNT, Roma

ACTIVITY REPORT –SECOND YEAR

UR PARTICIPANTS

Name-Position	Affiliation	Months/man
Claudio Chiarabba - Dir. Ricerca	INGV-CNT	3
Pasquale De Gori - assegnista	INGV-CNT	2
Marco Cattaneo – Primo Ric.	INGV-CNT	1
Milena Moretti – borsista	INGV-CNT	12

SECOND YEAR OBJECTIVES

a) Implementation of tomographic techniques (TASK 1 WP 1.1)
b) Preparation of the P-and S-wave arrival data set for the 1984 seismicity (TASK 3)
c) Formatting and preprocessing of Serapis data (TASK 4)

SECOND YEAR RESULTS

a) Vp, Vs, and Vp/Vs inversion techniques that can handle both local earthquake and artificial sources data have been implemented for the 3D tomography, mainly the code developed by D. Zhao and Simulps13q code. The inversion of the complete passive seismic data set is in progress. The inclusion of a complex geometry for the limestone basement and the topography in the Zhao's-derived code is under study. Considering the available information, we decided that their geometry will be constrained by the preliminary results from the elaboration of the Serapis data.

b) We contribute to the creation of the seismic database. Local earthquakes recorded during the 1984 swarm have been analysed; P-and S-wave arrivals at the dense local network have been read on digital waveforms with great reading accuracy. Preliminary 1D locations and Vp/Vs estimates have been obtained. We have cautiously verified the high quality of the elaborated data.

c) Serapis data have been windowed and the quality of the records has been quickly verified. Formats have been made homogeneous by a conversion of all data in SAC or SEGY format. After these operations data were sent to UR1 for the creation of the data base. At present, the elaboration of the large data set is starting.

RESEARCH PRODUCTS

- 2 presentations at international meetings
- Computational codes: A tomographic inversion code has been implemented for the local scale of the Phlegrean Fields from the original version by Zhao et al. (1994). The implemented code allows the use of a velocity discontinuity able to represent the buried top of the limestones and velocity gradients in the limestone unit and in the upper sedimentary and volcanic cover.

PRESENTATIONS LIST

Zollo A., Virieux J., Capuano P., Chiarabba C., De Franco R., Makris J., Michelini A., Musacchio G., Serapis Group. The project SERAPIS: high resolution seismic imaging of the Campi Flegrei caldera structure. XXVII General Assembly of EGS, Nice, France, April 22-26, 2002.
Zollo A., Virieux J., Kakris J., Auger E., Boschi L., Capuano P., Chiarabba C., D'Auria L., De Franco R., Judenherc S., Michelini A., Musacchio G., Serapis Group. High resolution seismic imaging of the Campi Flegrei caldera, southern italy. AGU Fall Meeting, S. Francisco, USA, December 6-10, 2002.

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Elaboration and interpretation of Mareves 1997 seismic data and integration with DSS 1980 and Pozzuoli 1985 data

Research Unit Responsible**: Roberto de Franco**
First Researcher
UR4: Istituto per la Dinamica dei Processi Ambientali, CNR, MILANO

ACTIVITY REPORT –2° YEAR

UR PARTICIPANTS

Name-Position	Affiliation	man/month
de Franco Roberto- First Researcher	IDPA	2
Biella Giancarlo- First Researcher	IDPA	1
Corsi Adelmo- Technician	IDPA	3
Tondi Rosaria- Ph.D. Student	IDPA-INGV	3
Caielli Grazia- Contract	IDPA	6
Gaudiosi Germana – Researcher	OV	1

SECOND YEAR OBJECTIVES

a) Implementation of codes for seismo-gravimetric inversion (TASK 1 WP 1.2);
b) Picking of P and S arrival times for the 1984 swarm and inclusion of DSS 1985-87 data in the seismic database (TASK 3).

SECOND YEAR RESULTS

a) A method for 3D integrated sequenzial seismo-gravimetric inversion (SII) has been developed. A first application to TomoVes96 data has been submitted and accepted for pubblication. Moreover, a code for the computation of 3D gravimetric response that includes density gradients have been tested on synthetic cases. Considering density gradient is important because it is a parametrization homogeneous to that used in seismic analysis. The procedure SII-3D which includes gradient parametrization and Complete Ray Tracing is now being tested.
b) The main activity related to the construction of the seismic data base has been the picking of P and S arrival times for the events of the 1984 crisis (Wisconsin network). The data base of DSS data acquired in Vesuvius and Campi Flegrei area has been buit. Data are now undergoing preprocessing.

RESEARCH PRODUCTS

- 1 publications on international journals.
- 3 presentations at international meetings
- Data base: picking of data acquired by Wisconsin network during 1984 crisis; DSS data 1985-87.
- Algorithm code: codes for seismo-gravimetric inversion including gradient parametrization.

PUBBLICATIONS LIST

Tondi R., de Franco R., 2003, 3-D modelling of Mt. Vesuvius with SII. Submitted and accepted J.Geophys. Res.

PRESENTATIONS LIST

Zollo A., Virieux J., Capuano P., Chiarabba C., De Franco R., Makris J., Michelini A., Musacchio G., Serapis Group. The project SERAPIS: high resolution seismic imaging of the Campi Flegrei caldera structure. XXVII General Assembly of EGS, Nice, France, April 22-26, 2002.
Zollo A., Virieux J., Kakris J., Auger E., Boschi L., Capuano P., Chiarabba C., D'Auria L., De Franco R., Judenherc S., Michelini A., Musacchio G., Serapis Group. High resolution seismic imaging of the Campi Flegrei caldera, southern italy. AGU Fall Meeting, S. Francisco, USA, December 6-10, 2002.
Tondi R. & de Franco R., 2002 – Non linear travel time tomography in the H2 sobolev space. ESC XXVIII General Assembly, Genoa, 1-6, sep., 2002.

Forward and Inverse Seismic Modelling for the Investigation of Complex Volcanic Structures

Research Unit Responsible: **Enrico Priolo**
Research Scientist
RU5: National Institute for Experimental Oceanography and Geophysics (OGS), Trieste (Italy)

ACTIVITY REPORT –SECOND YEAR

UR PARTICIPANTS

Name-Position	Affiliation	man/month
Enrico Priolo	OGS, Trieste	4
Alberto Michelini	OGS, Trieste	2
Géza Seriani	OGS, Trieste	3
Alessandro Vuan	OGS, Trieste	6
Peter Klinc	OGS, Trieste	4
Marco Romanelli	OGS, Trieste	2
Lara Lovisa	OGS, Trieste	10

SECOND YEAR OBJECTIVES

Tomographic inversion (Task 1 WP 1.1, Task 3, Task 4) - Local Earthquake Travel time tomography of the Phlaegreans Fields caldera based on the "new" data set of the 1984 activity. P- and S-wave onset reading and preliminary analysis of the SERAPIS data.

Seismic forward modelling (Task 2) – Improvement of the 3-D Fourier staggered pseudo-spectral method. Development of a 3-D multi-domain Chebyshev method. Construction of a digital structural model for the Campi-Flegrei area. Creation of a synthetic dataset of seismograms to be used for testing the tomographic inversion methods and waveform analysis.

SECOND YEAR RESULTS

TOMOGRAPHIC INVERSION

During the second year of the Research Program, the sub-unit focussed on three different aspects part of the project of the Campi Flegrei Caldera - inversion for the local velocity structure, P- and S-wave onset reading and preliminary analysis of the SERAPIS data. As a consequence of the activity performed for picking the first arrival times, originally not planned for our RU, the purely theoretical development planned originally has been reduced.

Inversion for the local velocity structure (Task 1 WP 1.1) **–** We have used the genetic algorithm (e.g., Goldberg, 1989) to obtain a set of one-dimensional P-wave seismic velocity structures and mean V_P/V_S ratio in the Campi Flegrei (CF) caldera near Naples (Italy). We have used the data used by Aster and Meyer, (1988, 1989) and collected in 1984 by the temporary stations deployed by the University of Wisconsin in collaboration with the Osservatorio Vesuviano.

The data set used in this study consists of a total of 239 earthquakes for 1953 P- and 1023 S-wave arrival times, respectively. This data set is slightly larger than that used originally because the data have been augmented with new onset readings done by the group at the University of Naples within the three-year project supported by the Italian Group for Volcanology (GNV) for the study of the CF. The earthquakes used in this study are shown in Figure 1.1 together with the station locations. The earthquakes making up the data set are represented as small circles.

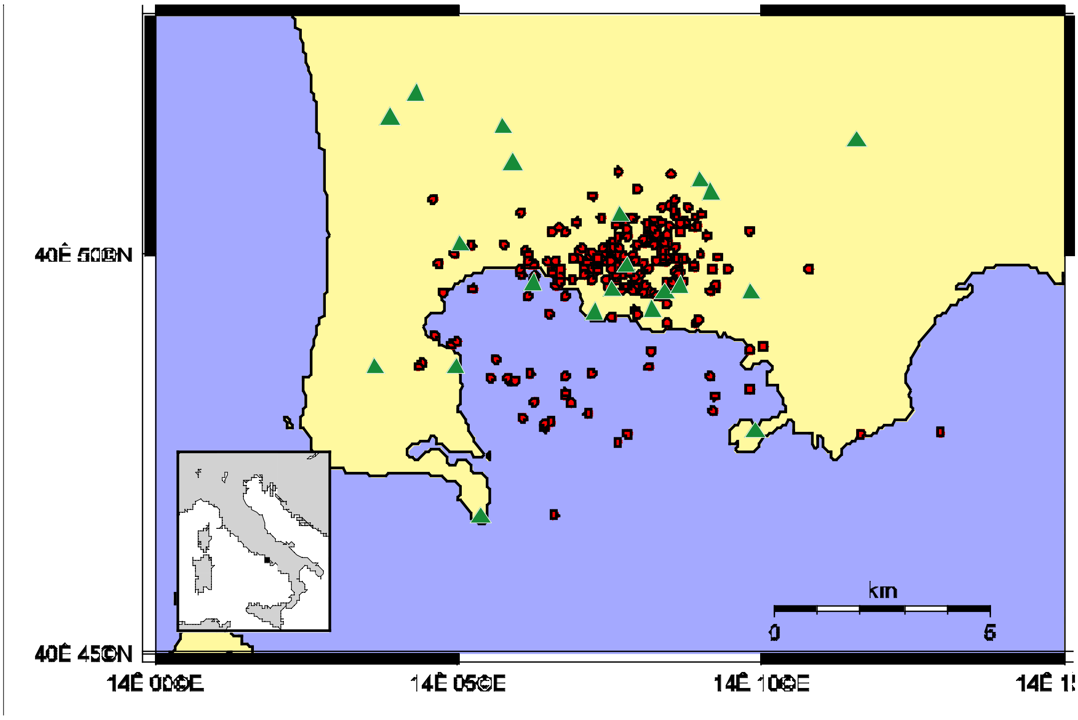

Figure 1.1 - Plan view map of the Phlaegrean Fields. The earthquakes used in this study are shown as red circles.

In our inversion scheme, we have solved simultaneously for P-wave velocity, layer thickness and mean V_P/V_S.

The forward modeling was accomplished using hypoellipse-a well known and robust location program developed by Lahr (1989, 1999). We adopt the average mean of the hypocenters weighted root mean square residual times as the misfit function to be minimized by the GA. Before presenting the resolved 1-D model, we will describe briefly the work done with the "simpler" parameterizations that were tried initially.

First, we have made an attempt to replicate the results obtained by Aster and Meyer (1988) for what concerns the best fitting half-space model. To this end, we have used the genetic algorithm (GA) to invert for the V_P and V_P/V_S. Our results indicate that values of 3.05 and 1.78 for V_P and V_P/V_S, respectively produced the best misfit of 0.117 s. We found it impossible to obtain lower values of the misfit function using this type model representation. This value does not differ significantly from that found by Aster and Meyer (1988) who found values of 0.116 s. However, the half-space model that we have found is somewhat different from that found by these authors.

Second, we have discretized the model into three layers overlying a half-space. Layer boundaries were placed at 1.5, 3.0 and 6.0 km and V_P was determined in the upper four layers (i.e., between the surface and 1.5 km depth, between 1.5 and 3.0, between 3.0 and 6.0 and beneath 6.0 km depth). The V_P/V_S was kept constant at 1.80. The best model featured a value of misfit of 0.086 s while 40% of the population had misfits lower than 0.090 s.

Thirdly, we have parameterized the model again using four parameters but we have represented it as a layer over a half-space structure and solved for *i.)* their P-wave velocities (two model parameters); *ii.)* the depth of the half-space interface and *iii.)* the average mean V_P/V_S of the whole structure.

This parameterization resulted into a final minimum misfit of 0.086 s and 40% of the population was found to produce misfits less than 0.090 s.

The results of these initial tests indicate that parameterization of the model using a half-space is not appropriate for the CF, in that, misfits as much as 25% lower can be obtained by simply introducing a layer over a half space.

After these initial trials aimed mainly toward isolating the most prominent features of the model in order to choose a more proper representation, the best fitting velocity models have been found by searching the velocity of the layers, the layer thickness and the V_P/V_S ratio. In summary, we have represented the velocity model with four homogeneous layers of variable thickness over a half space chosen to have a constant velocity of 6 km/s at 20 km depth. We inverted for the P-wave velocity of the four layers, the thicknesses of the first three layers and the V_P/V_S of the first layer and the deeper ones taken together. The range of V_P/V_S for the shallow most layer is between 1.75 and 1.90 whereas the range for the all the other layers is between 1.72 and 1.87. The total of number of parameters searched is 9.

The parameter sampling interval (i.e., the resolution step) has been chosen to allow for meaningful differences and fine tuning within the parameter search space. In particular, we have used resolution steps of 0.05 km/s for the P-velocity parameters, 0.1 km depth intervals for the layer thickness parameters and steps of 0.01 for the V_P/V_S.

The resolution steps described above result into a chromosome length of 41 bins and a covered search space of 2.199023×10^{12}. In order to perform the global search with the GA, we have used a population consisting of 200 members. The cross-over probability was set to have an exponential decay between 1 and 0.6 in the 200 generations maximum allowed. The mutation probability was also set to have an exponential decay between 0.2 and 0.001 for the iterations allowed.

The mean root mean square (RMS) of the residual times determined from the earthquake set was chosen to provided the misfit function. To test the robustness of the results, the inversion with GA has been tested against other *i.)* settings of the mutation and cross-over probabilities, *ii.)* different data sets, and *iii.)* various sizes of the population. In all our tests, we have found that the model misfit never decreased below values of 0.082 s (the minimum value that we have found was 0.0828 s) and we have found that the threshold of 0.086 s for accepting 40% of the model population was reasonable to the end of the finding hopefully diverse models and test the degree of non-uniqueness of the solution. The resulting 1-D P-velocity models are shown in Figure 1.2.

Our result suggest the presence of a sharp P-velocity contrast with velocities varying from 2 to more than 4.0 km/s between 1.5 and 3.0 km depth. At depths larger than 3 km, the P-wave velocity is generally larger than 4.5 km/s. The V_P/V_S features values ranging between 1.84 and 1.90 in the shallow most layer whereas it attains values between 1.72 and 1.77 for the deeper layers.

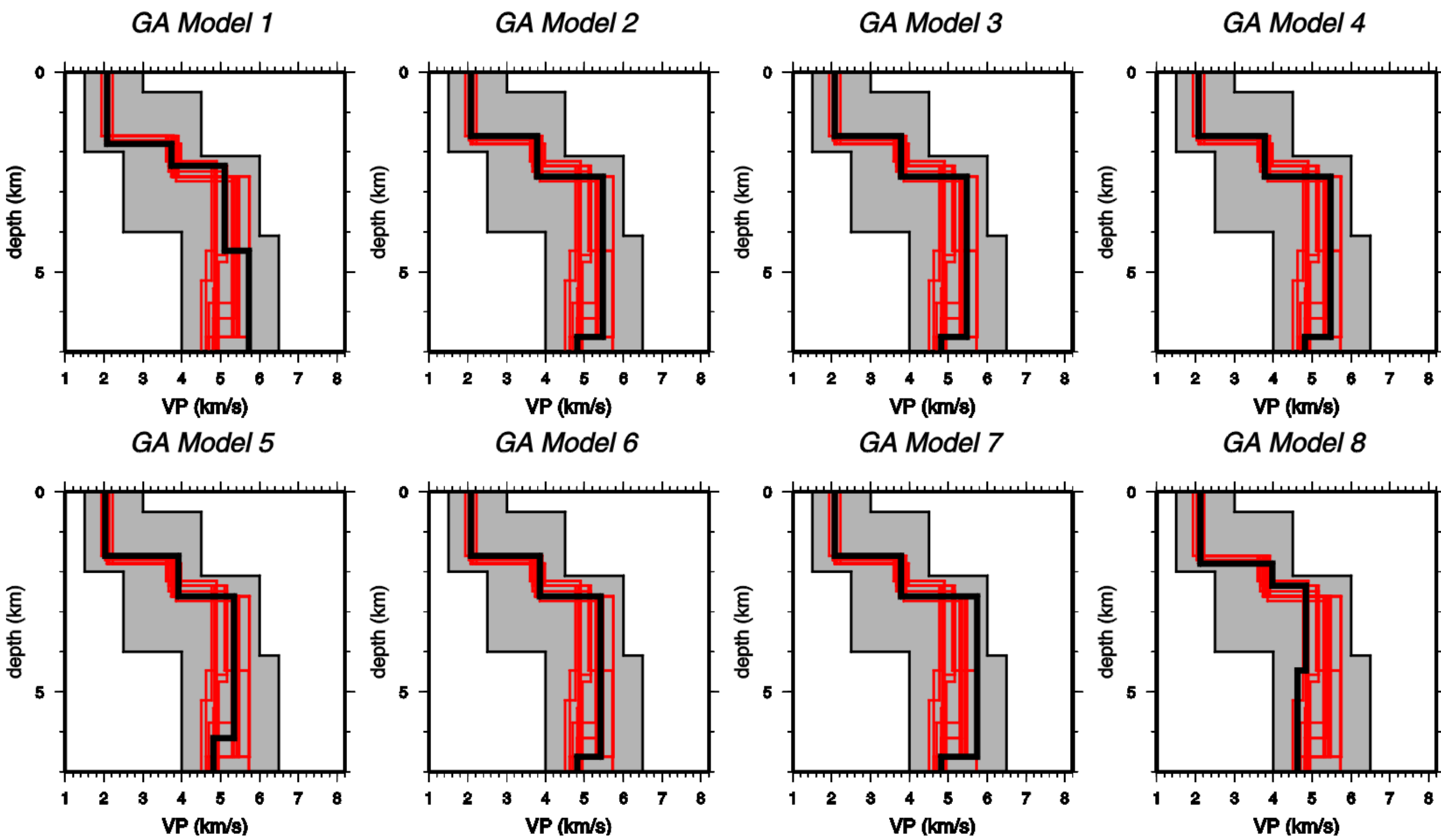

Figure 1.2 – Genetic Algorithm inversion: the first 8 best-fit 1-D P-wave velocity models.

P- and S-wave onset reading (Task 3) – Within the project, it became necessary to read the P- and the S-wave onset readings of some additional earthquakes recorded by the University of Wisconsin stations deployed in 1983-84 but never analyzed before. After the data windowing phase completed by the Naples RUs, the phase onset reading task has been split among the different partners of the tomography part of the project. The OGS RU has analyzed a total of 184 events (from 1984-03-10 23:40 to 1984-04-15 02:59) for a total of 1207 P- and 350 S-wave onset readings. In order to assess the quality of the readings, we have adopted the technique adopted by the RU of the University of Naples. This technique enables to verify the relative consistency of P and S onset readings. The plot in Figure 1.3 shows that the quality of the P- and S-onset readings is consistent and that the data could be used for the structural inversion target of this study.

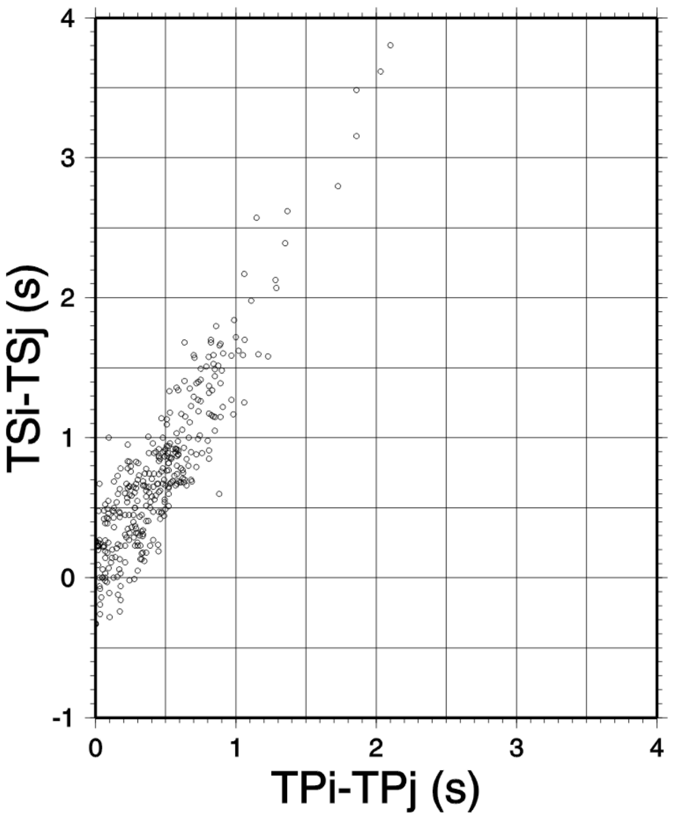

Figure 1.3 - dTp versus dTs plot to assess the relative quality of the P and S-wave onset readings.

Preliminary analysis of the SERAPIS data (Task 4) – This part of the analysis was performed mainly to gain a better idea on the quality of SERAPIS data set. Overall, the entire data set consists of 132, three-component, Common Receiver Gathers (CRG). Each gather consists of 4695 records each associated to an energization of the research vessel Nadir.

We have performed a preliminary test processing on a very reduced part of the entire data set which consisted of only two stations (BAI and CHI) and the vertical component only. The purpose was to test a signal processing procedure aimed toward performing automatically the first arrival picking of the whole data set.

After some initial re-formatting of the data, these have been plotted to check their quality. An example is shown in Figure 1.4 where we have checked the noise level and the spectral contents.

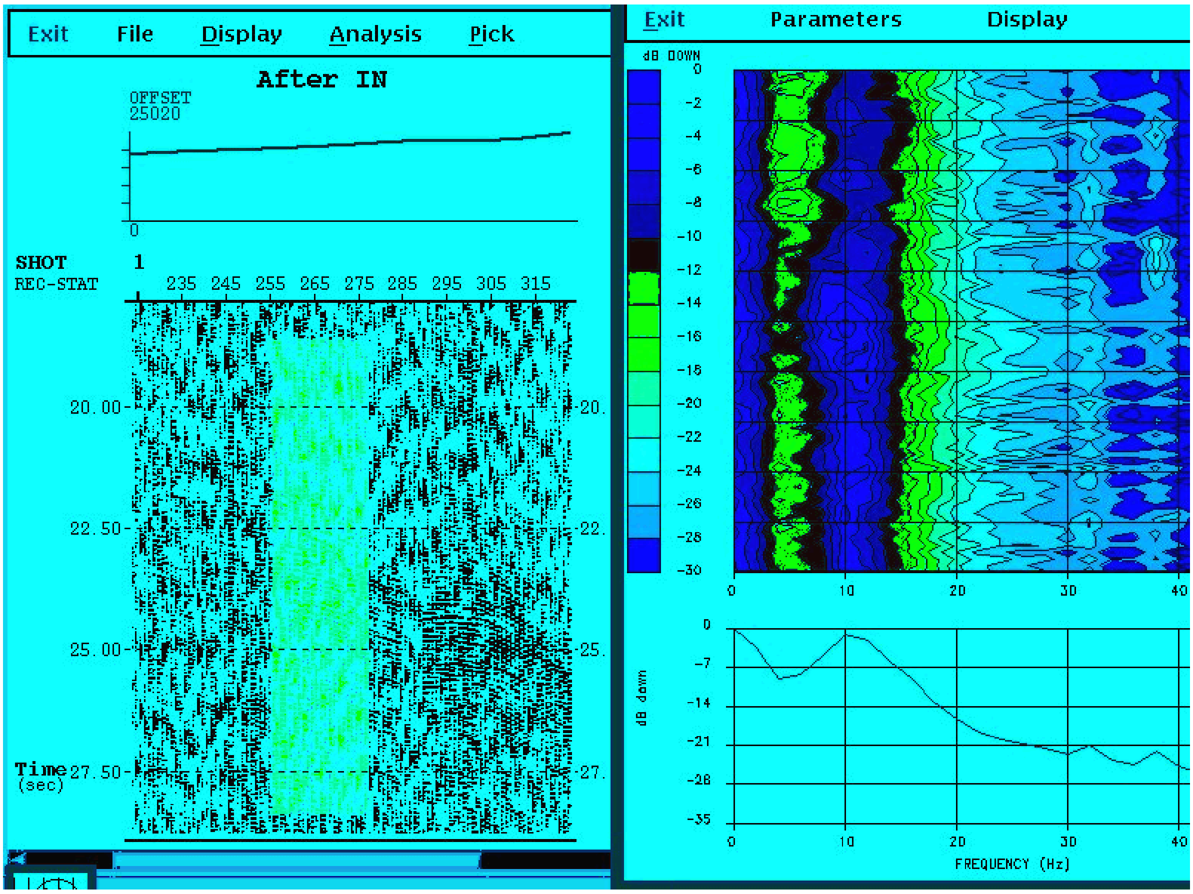

Figura 1.4 – BAI station, shots 225-320. Left: input data. Right: spectral analysis of the selected window.

We see that the frequency content of the signal generated by the air guns on the ship is centered at around 10 Hz though we also see a certain amount of energy also below 4 Hz which, however, can be easily removed through filtering. An example of this bandpass filtering (i.e., 4-24 Hz) is shown in Figure 1.5.

In Figure 1.6, we show the results obtained after using a display with variable area.

Finally, a Linear Move Out filter has been applied to the data using a 3000 m/s velocity with the goal of re-aligning the first arrivals and perform some semi-automatic onset picking.

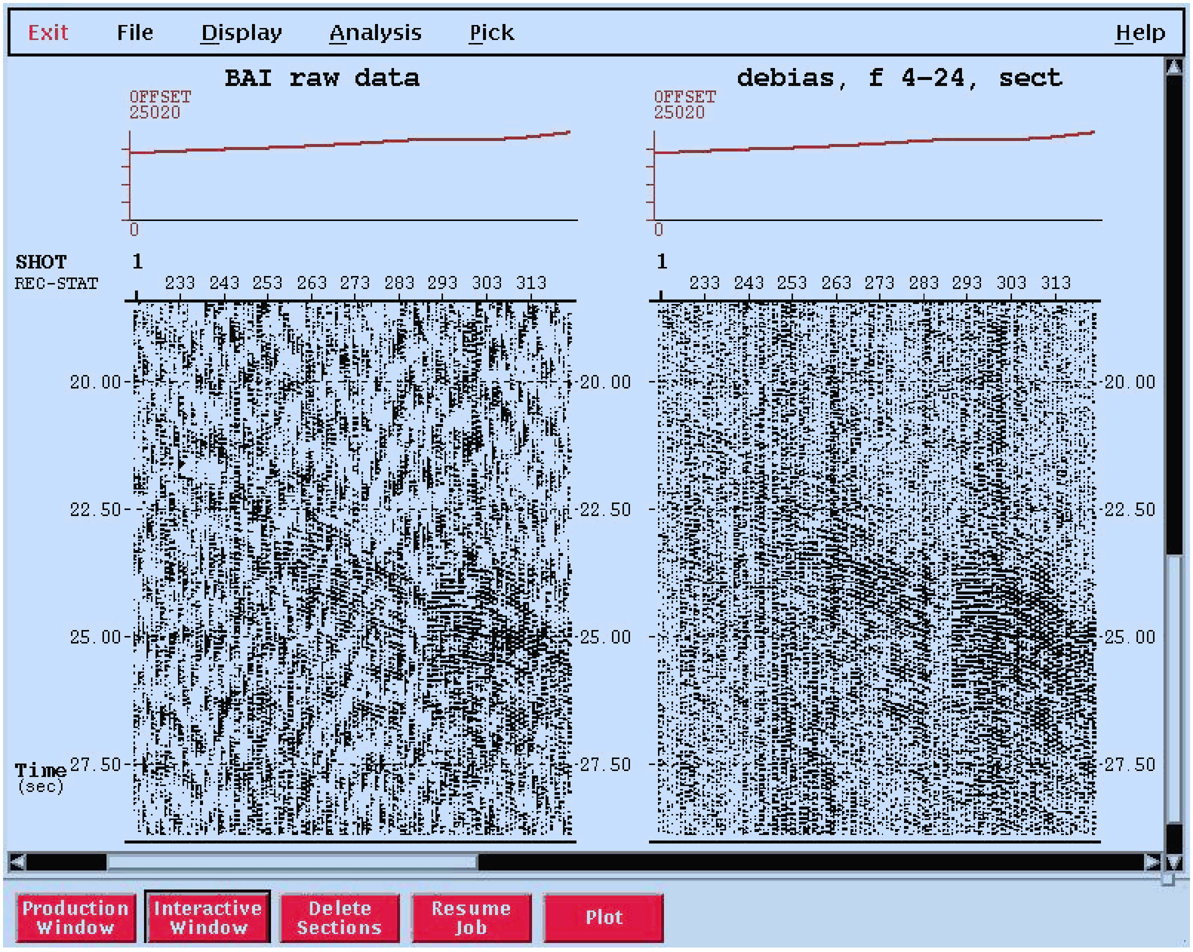

Figure 1.5 – Test of 4-24 Hz trapezoidal passband filter.

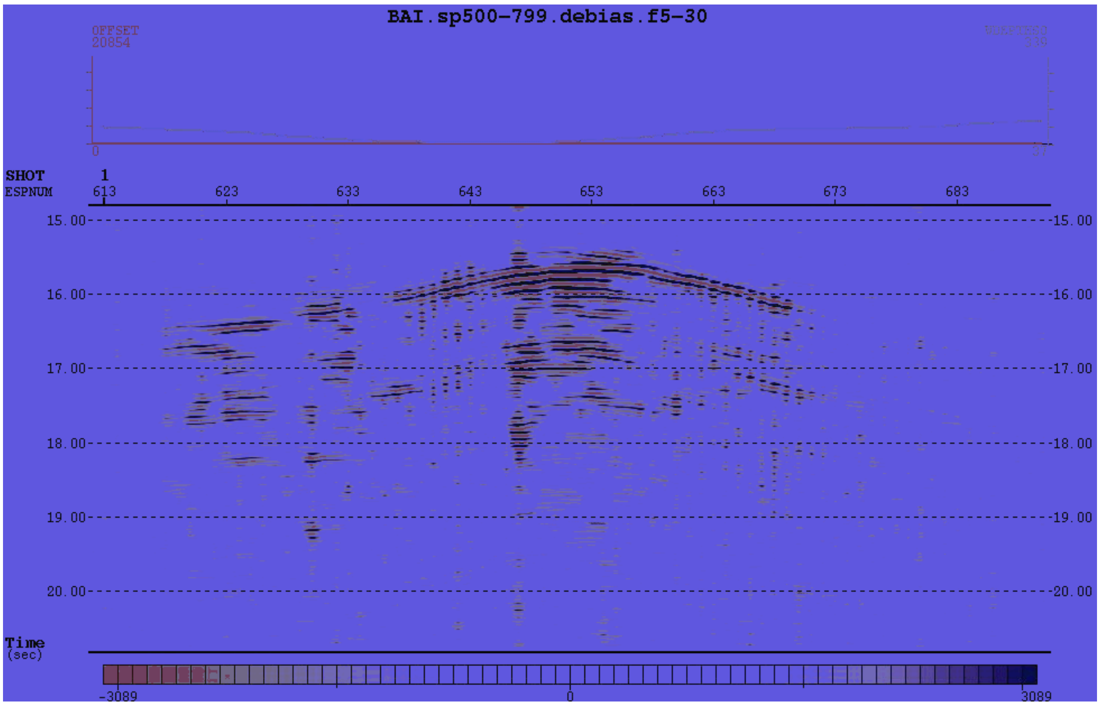

Figure 1.6 - BAI site, shots 500-799, debias and 5-30 Hz filtering. Detailed view plotted with a variable area display. Offset and water depth profiles are also shown.

Before entering in the picking interactive program, data have been conditioned, by applying a debias, bandpass filter, and a gain recovery processes, in order to standardize the signal input. The picking interactive procedure (program FBSURF by FOCUS (TM)) provides both automatic and manual picking of first breaks. Picks can be snapped to the closest peak, trough or zero crossing, and will create a new database attribute for first arrival storage, and/or store them in the trace headers, while all the procedure is greatly helped by many interactive options, as a good LMO control, based on a variable velocity model.

The analysed Serapis test dataset indicated that signal quality is highly variable along the shooting lines, and that F.B. picking can not be performed automatically, except for the shortest offsets, while the job is surely eased by the iteractive procedure until the S/N drops below a useful threshold.

Further development of seimic processing, aimed to enhance the S/N ratio, would surely give satisfactory results, allowing for a sensible extention of FB useful picks. In this respect Serapis data could be probably better processed and analysed as a classic seismic 3D dataset, which allows a greater and easy control on trace gathering.

TASK 2 - FORWARD SEISMIC MODELLING

The following list summarizes the activity performed during the second year of activity as well as the minor changes to the original program:

- *Development of a 3-D multi-domain Chebyshev wave propagation method* - This part has been anticipated to the II year. It replaces the development of a Fourier-Chebyshev method, which was originally scheduled for the III year and is definitely removed from the program.
- *Implementation of the reciprocity principle in the staggered pseudo-spectral method* - This part has been anticipated to the II year. It replaces the implementation of irregular topography with mapping, which was originally scheduled for the III year and is definitely removed from the program.
- *Construction of a digital structural model for the Campi-Flegrei area* - This is a new activity which was not included in the original program and has been performed during the II year.
- *Creation of a synthetic dataset of seismograms* to be used as a benchmark for the tomographic inversion methods and waveform analysis (II and III year).
- The *implementation of realistic attenuation model* (i.e., standard linear solid rheology) has been moved from second to III year.

A multi-domain spectral method for wave modelling – High-order techniques have attracted interest in the last years, as a mean to improve the computational efficiency and reduce the computer time needed for realistic numerical simulation of wave propagation phenomena. In the first part of the project a 3D Fourier pseudo-spectral has been implemented and used for realistic simulations. The main drawbacks of the method are due to the global character of the operator that discretizes the elastic wave equation, i. e. all the nodes of the computational mesh are simultaneously involved during the computation of the wave field at each time step. These drawbacks are: non-causal noise is spread throughout the whole model, a low computational efficiency due to the use of a constant step of spatial discretization, and a dramatic reduction of the computational performance with the increase of the number of processors with parallel implementation. In particular, the loss of computational performance occurs especially with large meshes and it is due the too low speed of inter-processor communications, compared to the high computational speed of the CPU, with large meshes. In our experience, for instance, the performance degrades using more than ten processors.

To overcome these problems, we develop an approach based on domain decomposition (DDM), that is the physical domain is decomposed into sub-domains and the global solution is computed as a sum of the partial solutions obtained in each sub-domain. Our approach is an non-terative overlapping domain decomposition (NIODDM), where sub-domains overlap each other and the continuity of the solution is solved directly. NIODDM schemes based on local Fourier basis have been developed by Israeli et al. (1994) and Liao and McMechan (1993), while different approaches based on Huygen's principle have been introduced by Priolo and Seriani (1992) and Fan et al. (1997). In those methods, the condition which guarantees the continuity of the solution lead to some strong limitations, in particular in the case of strong physical heterogeneities between adjacent regions.

To overcome these problems, our domain decomposition method acts at a lower level. Instead of decomposing the discrete full wave operator and requiring the continuity of the solution, we decompose the discrete derivative operator that build the wave operator. In this way, the condition of continuity across the sub-domain boundary is satisfied automatically by the overlap. This method has several advantages, such as: 1) easier implementation; 2) the approach is more general, i. e. it applies to almost any differential operator; 3) increased accuracy, since the decomposed operator, of any order, is more local and does not propagate non-causal noise; 4) it preserves the interpolation order of the operator along sub-domain interfaces; 5) increased flexibility in discretizing complex geological structures, through the use of local mapping; 6) less critical requirement on the choice of the integration time step; 7) a very efficient parallel implementation, with minimum inter-processor communication (the communication rate goes as n^2 instead of n^3, as needed for global pseudospectral methods); 8) high parallel scalability, since only interface data need to be exchanged between different processors.

In our implementation, sub-domains are quadrangles. In each sub-domain, the wave field is approximated by using a cartesian product of Chebyshev orthogonal polynomials of order *N*. The local grid is defined by the Chebyshev-Gauss-Lobato quadrature points φ_i =- cos(φ_i/N). Adjacent elements overlap on two lines of boundary nodes. Derivatives are computed in the three directions using the 1-D Chebyshev derivative matrix, i.e., $\boldsymbol{D}_{kj}=(d\varphi_j/d\zeta)_{\zeta_k}$. The functions $\varphi_j(\zeta)$ form the Lagrangian interpolant basis on the Chebyshev-Gauss-Lobatto collocation points ζ_k.

The 3-D mesh and interpolation basis are built up as a cartesian product of 1-D collocation points and tensor product of φ_j functions, respectively. The explicit form of the $\boldsymbol{D}_{kj}$ coefficients is:

$$\mathbf{D}_{kj} = \frac{\bar{c}_k}{2\,\bar{c}_j} \frac{(-1)^{k+j}}{\sin\frac{\pi(k+j)}{2N}\sin\frac{\pi(k-j)}{2N}}\,, \quad k \neq j\,, \tag{1}$$

$$\mathbf{D}_{kk} = \frac{1}{2}\frac{\cos\frac{\pi}{N}k}{\sin^2\frac{\pi}{N}k}\,, \quad k \neq 0, N\,, \tag{2}$$

$$\mathbf{D}_{NN} = -\mathbf{D}_{00} = \frac{1}{6}(2\,N^2+1), \qquad \mathbf{D}_{N0} = -\mathbf{D}_{0N} = \frac{1}{2}(-1)^N. \tag{3}$$

Figure 2.1 shows an example of multi-domain discretization. The picture shows a 2-D slice for the sake of simplicity. From the figure, it is evident the analogy of this approach to a sort of *block*-high-order finite difference scheme, where the computational stencil of the derivative uses all the nodes of a sub-domain, and the derivative operator moves over the mesh with a step corresponding to the size of the subdomain length.

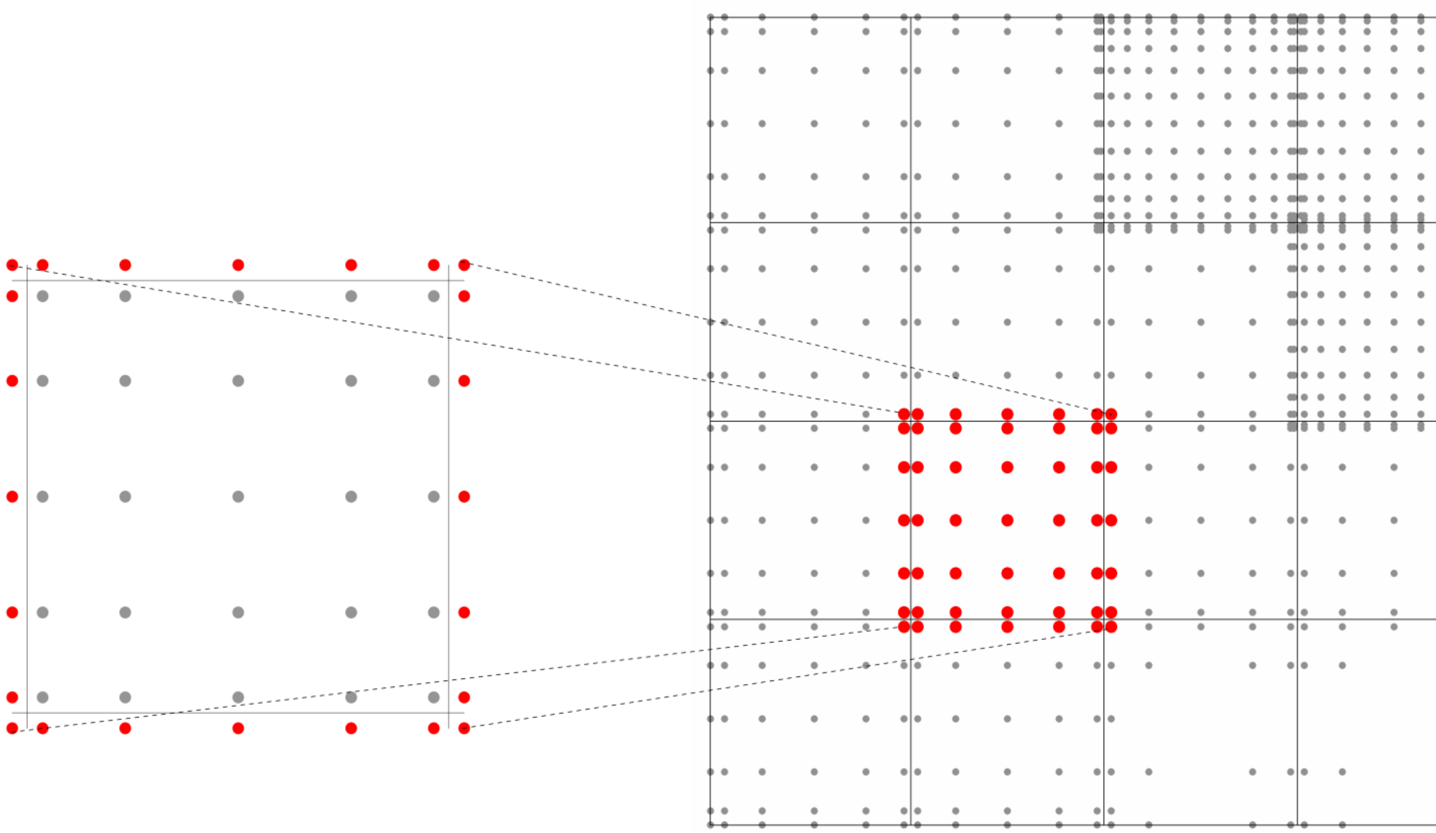

Figure 2.1 - Example of overlapped multi-domain discretization. A 2-D slice is shown for the sake of simplicity. The mesh contains sub-domains with different mesh size. The sub-domain nodes which are active during the local computation of the derivative are colored in red. The left part of the figure shows one sub-domain. Here, the nodes used to for the overlap are shown in red.

The use of the Chebyshev discrete derivative guarantees spectral accuracy (i.e. the accuracy increases proportionally to exp(N), where N is the order of the interpolant). The computation of the derivatives is performed by a matrix-vector product, and, thank to the superscalar architecture of modern processors, the efficiency can even be higher than that obtained using FFT.

Staggered grid operators have the same kind of construction, and use both Chebyshev-Gauss-Lobatto and Chebyshev-Gauss quadrature points as collocation points. The Lagrangian interpolants and matrix derivatives are defined accordingly.

The method has been applied to the solution of the elastic wave equation using the same formulation used for the staggered Fourier pseudo-spectral method (Seriani et al., 2002). The concurrent algorithm uses the MPI communication protocol, that allow to install the code on any kind of workstation cluster. The code is under testing on the IBM SP4 multi-processor (512 CPU) computer of the CINECA computing centre (Bologna).

Reciprocity principle implementation within the staggered pseudo-spectral code - In grid methods, such as the pseudospectral method, the wavefield always is computed at all grid nodes, and it is stored in a subset of nodes, if necessary. In principle, each source needs one run. Thus, creating a set of synthetics for a large numbers of sources means running a large number of simulations. However, the wavefield often is only "recorded" at a small number of receivers. This is the case, for instance, of earthquakes recorded by permanent stations. In those case, the application of the reciprocity principle provide a useful way to reduce the number of simulations dramatically.

In brief, the reciprocity principle tells that the recorded wavefield does not change by exchanging source and receiver locations each other. Formally, given two arbitrary points $\boldsymbol{x}$ and $\boldsymbol{x'}$ anywhere in the medium volume or on its boundary, their reciprocal relation is written as:

$$G_{ij}(\boldsymbol{x},\boldsymbol{x}',t) = G_{ji}(\boldsymbol{x}',\boldsymbol{x},t) \tag{1}$$

where $G_{ij}(\boldsymbol{x}_a,\boldsymbol{x}_b,t)$ is the j-th component of the displacement response at point $\boldsymbol{x}_a$ to the application of an unit force in the i-th direction at point $\boldsymbol{x}_b$.

Seismic sources in volcanic areas can exhibit both explosive and double-couple mechanism, with varying orientation. Having a formalism of the reciprocity principle that allows one to compute any arbitrary mechanism with a small number of simulations is therefore of the maximum importance. The formulation given by Eisner and Clayton (2001) provides a way to do that. While the authors used this approach within a staggered-grid finite difference scheme, here we apply it to the Fourier staggered pseudospectral scheme.

The wavefield due to an arbitrary point source can be formally expressed by (Burridge and Knopoff, 1964)

$$u_q(x_R) = G_{pq,r}(x_R, x)\Big|_{x=x_S} M_{pr}(x_S) \tag{2}$$

where $G_{pq,r}$ is the Green's function gradient, M_{pr} is the moment tensor representation of the source, and u_q is the wavefield at receiver R. x_S and x_R are the coordinates of the source and receiver, respectively. The spatial differentiation of the Green's function is computed at source location x_S. When applying reciprocity (Eq. 1), the Green's function tensor has first to be transposed, i.e.

$$G_{pq,r}(x_R, x) = G_{qp,r}(x_R, x), \tag{3}$$

and then differentiated at the receiver points

$$G_{pq,r}(x, x_S)\Big|_{x=x_R} = G_{qp,r}(x_R, x)\Big|_{x=x_S}. \tag{4}$$

An efficient approach for the calculation of the waveforms for all possible source mechanisms consists in the evaluation of a database of Green's functions spatial derivatives at the location of the formal sources (actual receivers) for a number of elementary mechanisms (e.g.: three directional forces aligned with the Cartesian axes), and then to recompute the wavefield for the appropriate source mechanism during post-processing. The spatial derivatives are computed runtime by the Fourier pseudospectral method at nearly no cost and are applied to the staggered grid through an appropriate half grid step shift-in-space operator

The validity of the reciprocity principle applied to the Fourier staggered pseudospectral method is demonstrated in Figure 2.2, which shows the six Green's function components computed by the Fourier pseudospectral method for the Phlegrean Fields 3-D model (see next paragraph). The two reciprocal points A and B are located at the surface of incoherent pyroclastics material and at depth of 2.5 km, within the layer of solidified magma. The waveform fitting is excellent.

Figure 2.3 shows the validation performed using an independent method, i.e. the wave-number integration method (WIM) by Herrmann (1996). Here, the waveforms are computed at a receiver located at the surface of a homogeneous model for three explosive sources located at different depths h. The physical parameters of the medium are Vp=2000 m/s, Vs=1150 m/s and _= 2200 kg/m^3. The seismograms computed for the three sources using the pseudospectral method have been simulated in a single computer run, exploiting the reciprocity principle. Additional tests are still in progress.

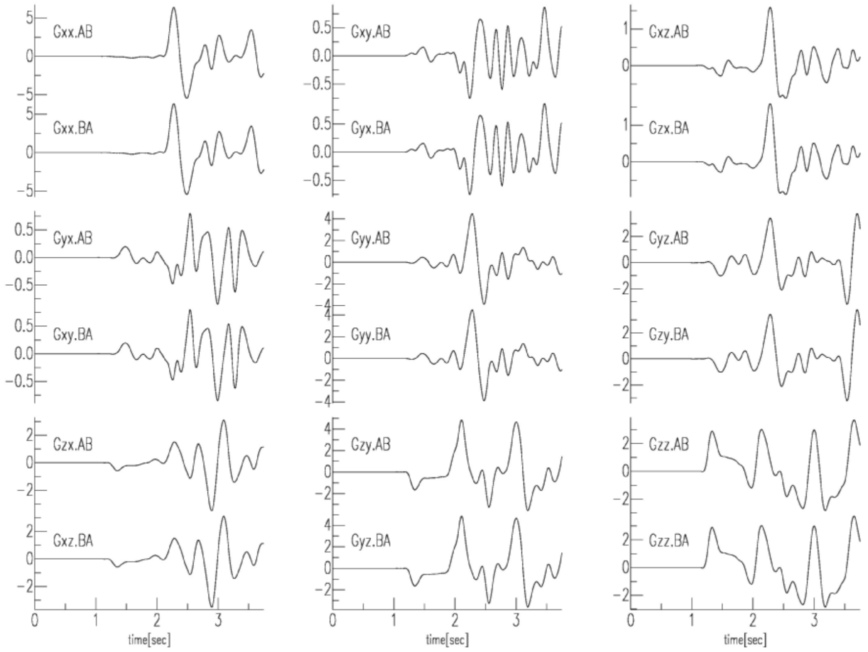

Figure 2.2 – Validation of the reciprtocity principle. Seismograms computed using the Fourier staggered pseudospectral method by exchanging the source-receiver position. Points A and B are located at the surface of incoherent pyroclastics material and at depth of 2.5 km, within the layer of solidified magma of the Phlegrean Fields 3-D model (see Figure 2.4).

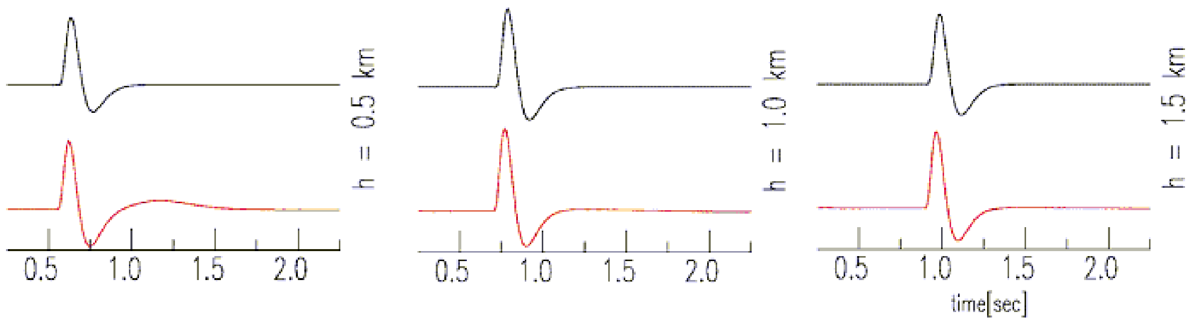

Figure 2.3 - Waveforms (vertical component) computed at the same receiver for three explosive sources located at depths h = 0.5, 1.0, and 1.5 km by the wavenumber integration method (red line) and the Fourier pseudo-spectral method using the reciprocity principle (black)

A digital structural model of the Campi Flegrei area - A 3-D digital model representative of the structure beneath the Phlegrean Fields has been defined and implemented. The model is used for 1) testing the numerical methods which solve the 3-D seismic waves propagation, 2) computing synthetic seismograms reproducing earthquakes recorded during 1984, and 3) serving as a benchmark for evaluating the tomographic methods used in the framework of the project.

The model (Figure 2.4) represents a hypothetical structure of the caldera and the surrounding Earth's structure in a cube of size 12 km _ 14 km _ 8 km, in the directions North, East and depth, respectively. The origin point is (40^{0}47'N, 14^{0}02'E) and is located at sea level. The model has been defined using the Gocad® software. It does not include either topography or sea water layer, as well as it does not take into account the Earth's surface curvature.

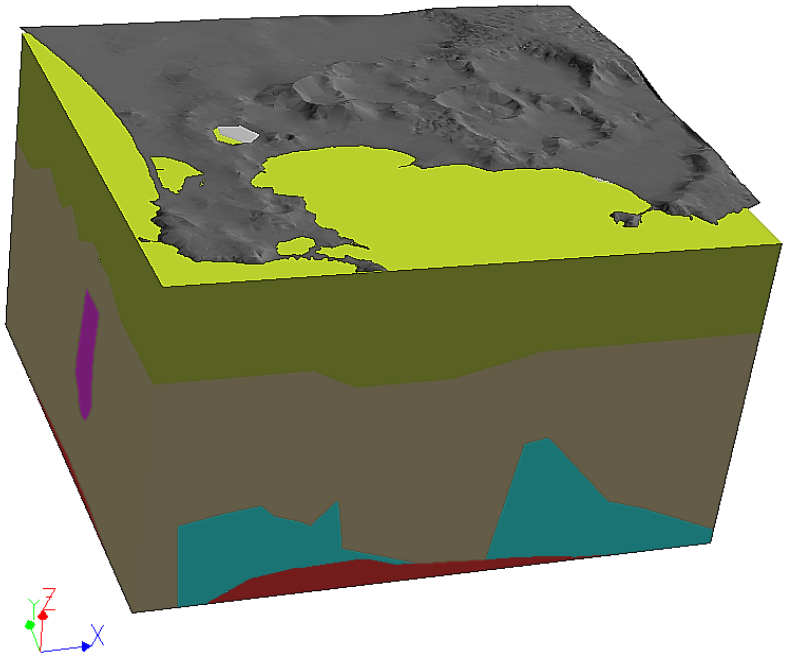

Figure 2.4 – External view of the digital model representing the structure beneath the Phlegrean Fields caldera. The topography is not included in the model and it is shown only for the sake of clearness.

The input data are a set of V_P sections estimated from previous tomographic inversions. The model consists of regions defined by external boundaries and internal physical properties that are defined and stored in vector form. This form has two advantages: the amount of information is reduced to a minimum and the model can be discretized into a structured grid with the desired spatial step. The physical properties of each region are: V_P, V_S, _ and Q. Within regions, they are either constant or vary as a function of depth z. The model has been defined using the following six lithotypes characteristic of the area: A) incoherent pyroclastics, B) tuffs, C) metamorphized tuffs, D) carbonatic rocks, E) solidified magma, and F) fluid magma. Here, we do not specify the values of the physical parameters on purpose, since they must remain unknown until the end of the tomographic blind test.

To perform numerical simulation of seismic wavefield propagation, the information contained in the model must be extracted correctly. For instance, the Fourier staggered pseudo-spectral method uses regular (or structured) grids. This operation is performed by means of the Gocad® "Voxet" object, which uses local interpolation within each region. The output is a binary file which contains the information about the physical parameters at each grid point.

For instance, in the simulation performed to create a synthetic dataset of seismograms by the Fourier staggered pseudo-spectral method we set the maximum frequency at 5 Hz. The model has been discretized with a spatial step of 50 m, in all the directions, corresponding to a minimum number of grid points for wavelength of $G = 2.5$. The resulting grid consists of 280 _ 240 _ 160 nodes, which corresponds to a total amount of 168 MB, to store the four parameters by real type data (4 bytes).

A synthetic data-base of full waveforms and arrival times – The aim is to provide two synthetic dataset of waveforms and arrival times, respectively, computed for a heterogenous 3-D model representative of the structure of the Flegrean Phields caldera. This is extremely important in order to evaluate the effectiveness of the tomographic invertion techniques, and provide a dataset for waveform analysis.

The synthetic dataset of P- and S-wave arrival times has been computed using the eikonal finite-difference method developed by Podvin and Lecomte (1991). This method is implemented in the NonLinLoc software package developed by Lomax (2001). The model used in the computations is the discretized model already described previously. First arrival times have been computed at the thirteen stations shown in Figure 2.5 and for a set of more than 1200 sources. The sources are randomly distributes along five hypothetical fault planes. The complete dataset consist of about 15,600 P- and S-wave arrival times, respectively.

Station	Lon.	Lat.
W03	40.8462	14.1528
W04	40.8352	14.0838
W05	40.8570	14.1930
W09	40.8667	14.0717
W11	40.8210	14.1208
W12	40.8267	14.1443
W13	40.8097	14.0827
W14	40.7963	14.1650
W15	40.8252	14.1640
W17	40.8307	14.1297
W18	40.8217	14.1367
W19	40.8257	14.1257
W20	40.8523	14.0982

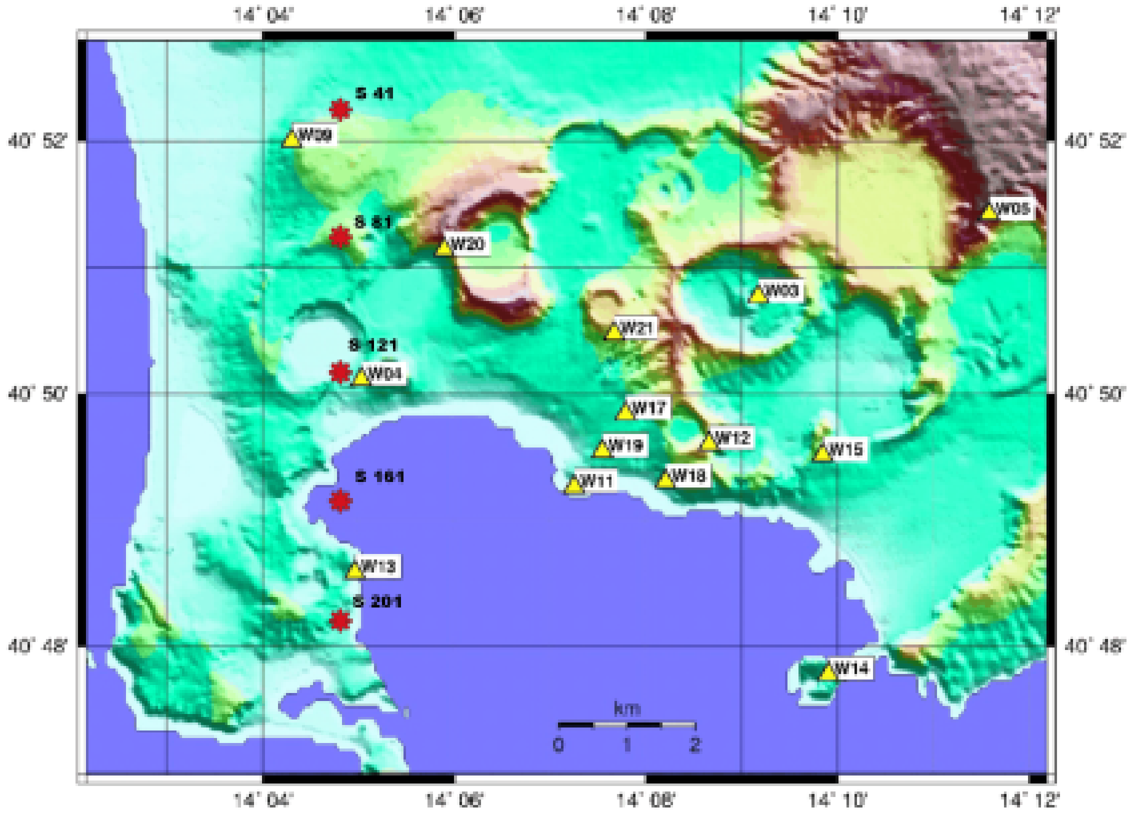

Figure 2.5 - Locations of the 13 stations used in the simulations and the epicentres (red stars) of the five sources whose seismograms are shown in Figure 2.2.

The Fourier staggered pseudospectral method has been used to compute a reduced dataset of waveforms. This first set of simulations is mainly demonstrative, and it aims at allowing a first evaluation of the effect of the 3-D structure on the complexity of the waveforms. The simulations have been performed for a maximum frequency of 5 Hz.

The model is the same used previously for the computation of the arrival times. The result of the simulations consists in a set of about 3,600 three component waveforms computed at three of the thirteen receivers (i.e., W03, W04, and W05) for the whole set of sources. In this first test, we have used the simplest type of source _ a unidirectional force pointing downwards and a Ricker pulse time function _ to allow an easier interpretation of the results.

Figure 2.6 shows the waveforms computed at receiver W03 for five point sources located as shown in Figure 2.5 and at depth of 5 km. Receiver W03 is located at the surface of incoherent pyroclastic material. The arrival times computed by the Podvin and Lecomte method are superimposed. The P-wave arrival times fit accurately the P-wave onset, whereas no S-wave corresponds to the predicted S-arrival times. A preliminary interpretation of this fact is that in the direction of receiver W03 the direct S-wave radiation is weak, whereas the seismograms clearly feature the effect of medium heterogeneity, and in particular the presence of both PS converted phases, at about the arrival time of the direct S wave, and surface waves at later times.

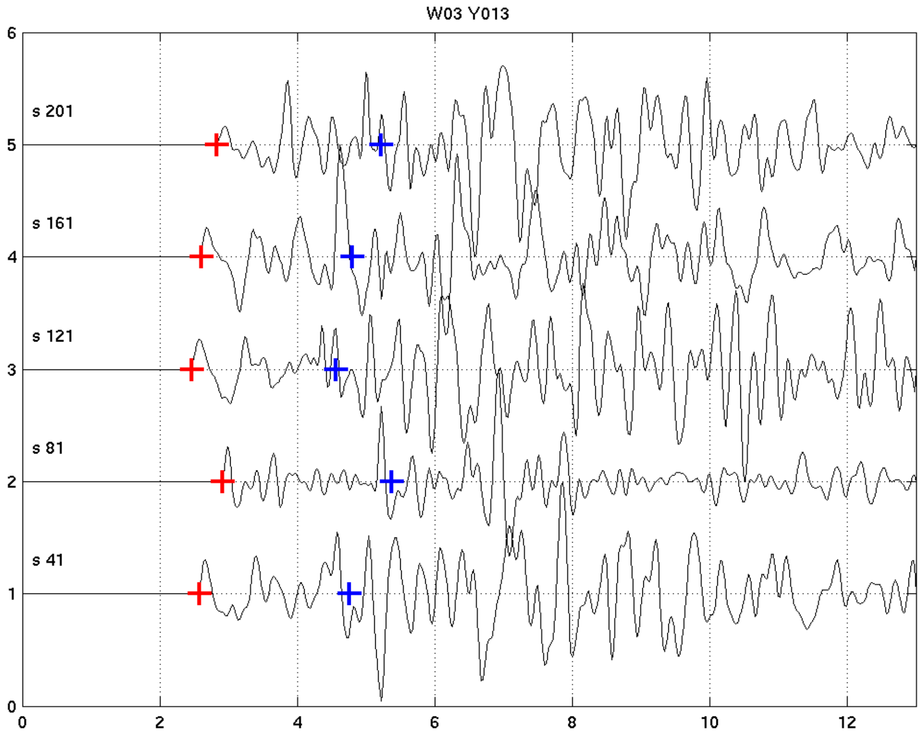

Figure 2.6 – Synthetic waveforms (vertical component) computed at receiver W03 by the Fourier staggered pseudo-spectral method for five sources. Red and blue crosses show the P- and S-wave arrival times, respectively, computed using the Podvin and Lecomte method.

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Seriani G., Vuan A., Priolo, E., and Carcione (2002). Development and validation of a 3D staggered Fourier pseudo-spectral method for wave modelling, *EGS 2002, XXVII General Assembly, Nice (France), April 21-26, 2002. Poster Session.*

RESEARCH PRODUCTS

- 2 presentation at conferences;
- Computer code for parallel computers (i.e., Cray T3E, and SGI Origin 2000);
- Digital 3-D structural model of the Phlegrean Field area.

PRESENTATIONS LIST

Seriani G., Vuan A., Priolo, E., and Carcione (2002). Development and validation of a 3D staggered Fourier pseudo-spectral method for wave modeling. *EGS 2002, XXVII General Assembly, Nice (France), April 21-26, 2002. Poster Session.*

Seriani G., Vuan A., Priolo, E., and Carcione (2002). Parallel 3-D staggered pseudospectral modelling for seismic analysis. *RealMod2002 – San Donato Milanese (Italy), October 2-4, 2002, 4 pp.*

Development of integrated methods to the inversion of seismic data from microearthquakes and active sources

Research Unit Responsible: **Jean Virieux**
Full Professor
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ACTIVITY REPORT -SECOND YEAR

PARTICIPANTS

Name-Position	Affiliation	man/month
Virieux Jean - Professor	GEOAZUR, UNSA/CNRS	2
Operto Stéphane - Researcher	GEOAZUR, CNRS	3
Ribodetti Alessandra - Researcher	GEOAZUR, IRD	3
Latorre Diana - PhD student	GEOAZUR	4
Got Jean-Luc - Professor	LGIT, Grenoble (*)	2
Monteiller Vadim - PhD student	LGIT, Grenoble (*)	6
Tony Monfret - Researcher	GEOAZUR, UNSA/CNRS	4

*participation not initially included in the contract

SECOND YEAR OBJECTIVES

Development and application of a linearized local earthquake tomography method using the finite difference solution of the eikonal equation (TASK 1 WP1.1)

Formatting SERAPIS data (TASK4)

Detecting sub-horizontal interfaces

SECOND YEAR RESULTS

The second year is devoted to the development and implementation of a 3D seismic tomography code based on travel time computation using the finite difference solution of the eikonal equation (Podvin and Lecomte, 1991). The advantage of using such solver of the forward problem is the fast and efficient computation of travel times even in a dense acquisition lay-out and the possibility to image very complex earth structures.
The method has been tested on synthetic examples, and shows to be robust and efficient. It will be first applied to the synthetic data base produced for the Blind Test of the project.
Using the same kind of interpolation of the seismic tomographic code one is able to compute travel times of converted phases at deep interface. These converted phases could be either reflected phases (active seismics) or transmitted (passive) from deep earthquakes beneath the interface. The two techniques (seismic tomography and interface detection) have been applied on synthetic data and they will be further applied for both the passive and active seismic data at Campi Flegrei.

RESEARCH PRODUCTS

- 1 report
- Numerical Codes: 3D tomography, explicit 2-dimensional interface detection

PUBLICATION LIST

Celine Ravaut, Stephane Operto et al.,2002, Analyse et inversion des sismogrammes dans une experience active en Italie (Baragiano), These Universitè de Paris VI

Thermo-mechanical modeling of the heat transfer processes and elastic/anelastic medium response

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ACTIVITY REPORT –2° YEAR

UR PARTICIPANTS

Name-Position	Affiliation	man/month
Grazia Giberti- Associate Professor	Napoli University	4
Giovanni Sartoris - Associate Professor	Napoli University	1
Guido Russo- Researcher	Napoli University	3
Tiziana Vanorio Post Doc	Napoli University	6
Maria Zamora Maître de Conférences	Université Paris 7 et IPG	1
Jean Baptiste Clavaud Etudiant en thèse	Université Paris 7 et IPG	3
Béatrice Yven In geophysics Phd	Université Paris 7 et IPG	3
Hélène Horen Maître de Conférences	(Université de Versailles et ENS)	3

SECOND YEAR OBJECTIVES

Measurements at room temperature and beginning of the measurements at different pressure and temperature conditions (TASK 1 WP 1.3);
Development of thermal models and preliminary thermo-mechanical modeling (TASK 1 WP 1.3)

SECOND YEAR RESULTS

Laboratory measurements under different temperature conditions on the Campi Flegrei samples will not carried out in the next future due to some problems related to the assemblage of the apparatus in the IPGP lab. Measurements at different pressure conditions have been carried out at Stanford Lab bi Tiziana Vanorio on the same Campi Flegrei samples on which measurements at room temperatures for porosity, P-S ultrasonic velocities, electrical and thermal conductivity and attenuation have been measured by the staff of the IPGP lab.
Goals of the research at different pressure conditions is to provide information on elastic and poroelastic properties for Campi Flegrei volcanic rocks to have constraints for ground deformation models and seismic data interpretation, and to compare lab results with the in- situ measurements. The elastic (Vp, Vs, K, and μ) as well as the poroelastic parameters (pore stiffness, K_{Φ}) have been measured under fluid and confined pressure conditions. In particular, confining pressure has been increased up to 60 MPa with a step of 5 MPa to simulate up to 3 km overburden. The maximum achieved effective pressure was 45 MPa. Data analysis provide signatures on how petrophysical properties affect seismic response and enables us for a better understanding of the wave propagation mechanisms under pressure and fluid saturated conditions. Well-log data from several Agip's wells have been collected and will be interpreted in the future.

Furthermore, thermal non-stationary modeling of the Campi Flegrei history and preliminary models of elastic and anelastic response of the earth surface and of the walls surrounding both pressured magma chambers and shallow aquifers has been developed. The major results of the preliminary thermal models is that only localized, recent (on a geological time scale, and related to the entire time of life of this volcanic area) aided by a strong convection in some aquifer for a limited time interval, can explain the anomalous temperature gradients measured in the Agip wells.
The elastic models on ground deformations have put in evidence that asymmetric heterogeneous structure, together with the presence of fractures, can amplify the ground deformations in unexpected way, so that reliable information on the shallow structure of the Campi Flegrei volcanic area coming from the tomography will help in discerning among models.

Future Activity

As said before, laboratory measurements under different temperature conditions on the Campi Flegrei samples will not carried out in the next future due to some problems related to the assemblage of the apparatus in the IPGP lab. Instead, we will utilize both well log analysis [AGIP data] and theoretical rock physics models to characterize reservoir properties as well as its conditions (e.g. effective pressure, formations pressure and, overpressure). By analyzing well logs and core data meaningful rock physics relations can be determined to relate the elastic reservoir properties to porosity, mineralogy, pore fluid, effective pressure and where possible, temperature. These relations will be interpreted by using effective- and granular- porous medium models.
Before the end of the project the entire data set of the measured data will be available.
As far as the modeling concerns, the modeling will be developed as said in the Project Proposal.

RESEARCH PRODUCTS

- 6 publications on international journals
- 1 article published on national journals, proceedings, technical reports
- 2 talks at congresses
- Contribution to data on the FTP site of the project

PUBLICATIONS LIST

Vanorio T., Prasad M., Patella D. Nur A. (2001) Ultrasonic velocity measurements in volcanic rocks: correlation with microtexture, Geophys. J. Int., 149, 4, 1-21.
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Russo G, Zollo A, Constant Q modelling of visco-elastic attenuation of seismic body waves, Accepted to Geophysics (November 2002)

PRESENTATIONS LIST

Russo G. Giberti G (2001) Effects of asymmetries on the surface displacements of Mount Vesuvius (Italy) submitted to J. Volcanol. Geother. Res, EGS Meeting, Nizza, April 2001.
Vanorio T., Giberti G., Prasad M., Nur A. (2002) Petrophysical Properties of Volcanic Samples: A Contribution to Interpret Ground Deformation in Campi Flegrei Volcanic Area, EGS Meeting, Nizza, 21-26 Aprile