Design and development of a seismic monitoring and alarm underwater network in areas highly exposed to seismic risk - Development of a first node in Eastern Sicily (SN-1)

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Introduction

The objectives of the project are:

- to develop and operate a deep-sea seismologic observatory (SN-1) off-shore Eastern Sicily, addressed to seismic monitoring and alarm,
- to integrate the observatory in the existing land based monitoring networks,
- to updated the knowledge of the geology, tectonics and geodynamics of the Eastern Sicily and western Ionian Sea area.

The following Research Unit (RU) have been established to reach the objectives:
RU 1 - Responsible: Prof. Claudio Faccenna, Dipartimento di Scienze Geologiche Roma III University.
RU 2 - Responsible: Eng. Francesco Gasparoni, Tecnomare S.p.A. Venezia.
RU 3 - Responsible: Prof. Giancarlo Neri, University of Messina.
RU 4 - Responsible: Drs. Laura Beranzoli (INGV)
A project synopsis is given both in Italian and English in Annex 1(a,b).

Sub-Tasks

The activities described within the reported Sub-tasks, relate to the second year of project activity.

Sub-task B (RU-2): Observatory development, integration and tests (WP B300-B400-B500)
Foreseen objectives: observatory completely developed and tested in dry and wet conditions, ready for the “long-term” mission.
Fulfilled objectives: observatory tested and ready for the long-term mission at seafloor.
Description of the related activities:
Development of the observatory: The design of SN-1 is derived from the concept of seafloor observatory developed in the framework of previous EC projects GEOSTAR 1 and 2 (1995-1998, 1999-2001). SN-1 is based on a light four-legged frame hosting the scientific sensors and equipment necessary to manage a long-term mission at seafloor. SN-1 is deployed and recovered by means of the same deep-sea Remote Operating Vehicle (ROV) developed in GEOSTAR projects, hereafter referred as to MODUS (MObile Docker for Underwater Science) (Figures 1 and 2). MODUS is a submarine vehicle accurately manoeuvred from the surface by means of specifically developed instrumentation including thrusters (i.e. electric propeller engine) video cameras, sonar. MODUS has been made available for the purpose of the present project,. For the sake of briefness, detailed description of the complete system is given in Annexes 2 to 6. During the second year of the project, the

Research Unit 2 worked on the development of SN-1 subsystems and devices designed in previous sub-tasks (WP B100, B200). To this aim components and materials were acquired in accordance to criteria of low power consumption and resistance to high pressure and corrosion. The frame SN-1 is in Aluminium alloy, while the pressure-resistant vessels for the electronics and batteries are in Titanium grade 5. All components, including underwater connectors and cables, are certified for operation at 4000 m w.d.

The main SN-1 subsystems are the scientific sensors, the Data Acquisition and Control System (DACS), the battery pack and the communication system.

With regard to the geophysical sensors, the reduction of the budget allowed to acquire only a hydrophone, Conductivity Temperature and Pressure sensor (CTD) and the three-component single-point current meter. The other sensors were both purchased with funds of other projects and borrowed from previous GEOSTAR projects. The set of sensors installed in reported in Table 1. It is worth noting that a specific device, designed and developed in GEOSTAR project for the seismometer deployment, was derived ad adopted in SN-1. The seismometer is mounted inside a benthosphere (a sphere of special glass for high pressure applications) and protected by an external additionally housing which is attached to the observatory frame 25-30 cm from the ground. After the deployment of the observatory a special device drops the seismometer to couple it to the ground. The seismometer housing is kept linked to the observatory frame with a slack rope able to sustains the weight of the seismometer and housing during the observatory recovery.

The DACS (see Annex 3 and 4 for further details) poll the sensor in sequence and acquires the data according to a unique time reference given by the clock of the broad-band seismometer. The DACS also drives the data flow toward SN-1 hard disks and provide hourly data message to be sent to the surface. The hardware and software architecture of the DACS is based on 3 CPUs and on dedicated electronic low-power consuming boards designed and developed by Tecnomare. The characteristics of the CPUs are summarised as follows:

1. HDU (CPU unit) manages the acquisition of the hydrophone. Its mass memory is 8Gbyte (Hard Drive);
2. SDU (CPU unit) manages the acquisition of the seismometer, the gravity meter and the CTD+flushing pump. Its mass memory is 8Gbyte (Hard Drive);
3. MCU (CPU unit) manages the acquisition of the current meter, the status sensors (e.g., tilt, heading) and the communication with the surface via cable (during test phases or the deployment) and via the Acoustic Communication System. Its mass memory is 1Gbyte (Flash Card).

The acoustic communication system, also provided by the GEOSTAR projects, is of standard type and is used for periodical checks from the surface. The system allows to an operator on board a ship of opportunity to poll the observatory in order to retrieve status parameters of the sensors and of the other devices (e.g., temperature inside the electronic vessels, battery current and voltage, status of the hard disks). To send commands and data request to the seafloor observatory via cable or via Acoustic Communication System a dedicated User Interface Application for Windows OS 95/98/ME/NT/2000) was developed by Tecnomare.

SN-1 is powered with a lithium battery pack (12 V, 1920 Ah), specially developed to fit into the cylindrical pressure vessel and presently

Table 1: Sensors installed on SN-1 deep-sea observatory

Goal	Sensor	Model	Sampling rate
Continuous recording of seismological signal	Three- comp. broad band seismometer[1]	Guralp CMG-1T	100 sample/s
Continuous recording of seismological signal	Hydrophone	OES E-2PD	80 sample/s
Continuous recording of low frequency seismological signals (lower than the ones detectable by the seismometer)	Gravity-meter	Prototype developed by IFSI-CNR[2]	1 sample/s
Continuous recording of sea water current velocity (to be used in the analysis of seismological data)	Three-comp. Single point Current meter	Falmouth 3ACM-CBP-D	2 sample/s
Complementary measurements with respect to the ones provided by the current meter	Conductivity, Temperature and Pressure sensor (CTD)	Sea Bird SBE-37	1 sample/12 m
Check of status parameters (temp., water intrusion, pressure, tilt, heading, etc.)	On the shelf sensors	Different suppliers	Different sampling rate according to the mission phase.

[1]Provided by GEOSTAR project [2]INGV-IFSI agreement

ensuring an operation time of around 6 months. SN-1 autonomy can be increased up to 1 year by adding a second battery pack; for this purpose SN-1 frame is already provided with supports for the installation and connection of a second battery vessel.
A separate battery pack is used for the acoustic communication system.

Integration and dry tests

All the electrical integration (involving hardware, software, scientific packages, batteries, auxiliary sensors, acoustic communication system) has been carried out in Tecnomare workshop. All the functionalities of the observatory have been tested in dry conditions and simulated missions with duration from 1-2 days up to a week were carried out.
Once the electrical integration and dry test phase was completed, the overall integration (including mechanical parts) was carried out in view of wet tests.

Wet tests

SN-1 and MODUS were moved to the basin of HSVA Institute (Hamburg, Germany) to perform test cycles in controlled conditions (see images of wet tests in Annex 7). The basin and the laboratories are considered "Large facilities" by the EC and accessible at no cost for the users only after approval of a proposal of scientific and technological activity. This was the case of SN-1 tests. Therefore the tests where performed at no- Cost for the project excluding transportation and insurance.
Tests were mainly aimed at:

a) simulate the operational sequences (assembly, deployment, mission, recovery) of SN-1 inside and outside water;
b) verify the overall functionality of the observatory in seawater.

SN-1 tests were carried out in parallel with other tests aimed at the qualification of critical components of another seafloor observatory (MABEL), under development in

the framework of the Italian Antarctic Program (PNRA). This fact offered the unique opportunity to have access at no cost to the test infrastructure, and at the same time to execute a more comprehensive test program (for example, SN-1 components have been tested down to 0°C in water) thus achieving a more significant qualification.
The wet tests carried out at HSVA demonstrated the capability of the observatory to manage the scientific payload and all the other subsystems installed. Data time series were collected during simulated missions at the bottom of the basin (5 m w.d.); at the same time the status parameters were monitored (internal temperatures, battery voltage and currents, etc.) and found in the expected ranges. After the observatory was placed and left in the bottom of the basin, it has been successfully interrogated via underwater acoustics.

Sub-task D (RU-1 and RU-3): Eastern Sicily geological and geodynamic characterisation (WP D100)
Foreseen objectives: geological and geodynamic characterisation of eastern Sicily in the light of new surveys and data.
Fulfilled objectives: geological and geodynamic characterisation of south-eastern Sicily, (Hyblean foreland) and north-eastern Sicily (Mount Etna and Peloritani Mountains)
Description of the related activities: We carried out several geological and geophysical surveys in south-eastern and north-eastern Sicily in order to understand the geological and geophysical setting of the Hyblean foreland, Mount Etna, Peloritani Mountains and adjoining areas. The papers published, in press and submitted on these subjects are mentioned in the References section below (see also Annexes 9 to13).
The Hyblean foreland and adjoining areas are seismically active as testified by several both historical and instrumental data. By stress inversion of earthquake fault-plane solutions, the study area has been shown to be characterized by a clear transition from compressional to extensional seismogenic stress regimes, on-shore (compression) and off-shore (extension) respectively (Neri et al., AGU-EGS 2003, Session SM13).
Collected data are of two types: (i) structural-geological data (i.e. fracture attitude and crosscutting relations) and (ii) geophysical data (i.e. anisotropy of magnetic susceptibility, AMS). In particular, we collected about 5000 fracture data in the area of Hyblean plateau and 204 cores for AMS analysis in 20 sites.
In the Hyblean Plateau, fracture attitude data from rocks of Neogene age show two main sets of extensional subvertical fractures, namely NW-SE and NE-SW striking (Figure 1 of Annex 8,). AMS data on the same rocks (i.e. late-Miocene-early-Pliocene) show two sets of lineations (K1, i.e. “extension”), namely NW-SE and NE-SW striking (Figure 2 of Annex 8). AMS data from Lower Pleistocene rocks exposed on small basins along the southeastern coast of Sicily show K1 axes (i.e. “extension”) as ENE-WSW striking. On the contrary, AMS data from Middle-Upper Pleistocene rocks exposed on small basins along the eastern coast show K3 axes (i.e. “compression”) as ENE-WSW striking (Figure 3 of Annex 8).
Results from data analysis suggest that the Hyblean Plateau is a doubly vergent flexed foreland. Most of the flexural process must have occurred by Middle

Pleistocene. Starting from the Middle Pleistocene a different tectonic regime may have occurred in this area, according to ENE-WSW-striking compression. The double vergence (i.e. NW-SE and NE-SW) of the Hyblean foreland is likely amenable to the continental-to-oceanic lithosphere transition that occurs in the Ionian Sea along the eastern coast of Sicily.
The area of Mt. Etna and Peloritani Mountains is one of the major high-risk areas of Europe, both for the intense active seismicity and for the active volcanism of Etna and Aeolian Islands.
Collected data are of two types: (i) structural-geological data (i.e. fracture attitude and crosscutting relations) and (ii) geophysical data (i.e. anisotropy of magnetic susceptibility, AMS). In particular, we collected fracture and AMS data along the northern coast (northern margin of Peloritani Mountains) and fracture data during the Etna eruptions of 2001 and 2002-2003.
Fracture and AMS data from the northern coast are consistent with a general WNW-ESE extension (Figure 4 of Annex 8). Fracture data and other geophysical data from the literature on the Etna area (Figure 5 of Annex 8) show that eruptions on this volcano often occur in coincidence with contemporaneous intruding dikes along N-S and NNE-SSW directions, in response to perpendicular extensional mechanisms (i.e. E-W extension). By synthesising our data with the data available from the literature, we suggest that seismicity and volcanism in this area may relate to the simultaneous activation of NE- and NW-striking strike-slip faults and N- and NNE-striking normal fault of extensional fracture segments, owing to pure-shear tectonics during pulses of N-S contraction between Africa and Europe (Figure 6 of Annex 8).

<u>Sub-task E (RU-2 and RU-4)</u>: experiment logistics, experiment execution and follow-up (WP E100-E300)
Foreseen objectives: choice of a suitable vessel to carry out the deployment of the observatory, definition of the deployment procedure, mission planning, mission execution and follow-up procedure definition and start

Fulfilled objectives: vessel selected, deployment procedure defined, deployment executed, mission follow-up started

Description of the related activities: Due to the unavailability of the research vessel Urania (the request of ship-time for this vessel can be presented only by CNR Institutions) and suitable for the deployment of SN-1 observatory, the use of a goods-shipping vessel was considered. After an extensive research and inspections of vessels both in the harbour of Catania and of Augusta, the moto-pontoon “Mazzarò” of the Gestione Pontoni s.r.l. company was considered able to host the SN-1 Bottom station, MODUS and the INGV cable-winch system. It is equipped with all of the required devices to perform and assist the operations. Nevertheless a specific procedure for safe uplift of SN-1 from deck, and put-into-water was needed because of high wall of the vessel. The moto-pontoon is shown by pictures of Annex 14 and the description of the equipment and of the deployment procedure is also given.
Before the deployment mission, functionality tests on the auxiliary device for deployment (e.g., cable and winch system) and on the observatory and MODUS were performed also in water. As the deployment operations involve the pontoon

crew, the operators at the MODUS console, the winch operator and the operators for the communication with the observatory, specific trials to train the crew of the vessel to maintain the position during the deployment and to manoeuvre the vessel in coordination with the scientific team were carried out. The sequence of the deployment operations, subject of a videotape recorded during the operations, can be summarised as follows: (1) submersion and assisted descent of SN-1 down to the seafloor through MODUS; (2) observatory touch down at sea bed; (3) start of the mission (e.g., release of the seismometer, acquisition starting); (4) release and recovery of MODUS.
The mission was executed regularly and during the descent toward the sea bottom significant parameters were retrieved with respect to the course of the operations (e.g., distance from the seafloor, pressure, check of water intrusion). The MODUS recovery operations were regular too.
The co-ordinates of the deployment site are: Lat. N 37° 26,53312' and Long. E 15° 23,58716', 2105 m w.d. The deployment cruise lasted 7 days (4-10 Oct., 2002). The mission started on 9 October. A detailed description of the operations is given in Annexes 15 and 16.
After around 1 month of autonomous operation of the observatory, a check on its status was performed by means of the acoustic communication system. To this aim a ship of the Capitaneria di Porto of Catania was used. The outcome of this check revealed status parameter values of the different devices in the expected range and a regular course of the mission. A detailed report of the acoustic survey is given in Annex 17.

<u>Sub-task F (UR-3)</u> : Data integration and joint analysis for marine and land based networks.
Foreseen objectives: analysis of the waveforms recorded by the seafloor observatory, integration of the observatory data with the ones provided by the land-based networks, joint analysis to provide accurate localisation of hypocentres in areas affected by a critical coverage of the land monitoring networks
Fulfilled objectives: achievement of tools and methods for the seafloor instrumentation data analysis and for joint marine-land data analysis.
Description of the related activities: Two main lines of action were followed:
1) analysis of on-shore seismic station data for the determination of the regional crustal structure by tomographic inversion of P- and S-wave arrival times, and subsequent investigation of source parameters for the seismotectonic and geodynamic modelling of the study area;
2) integrated analysis of on-shore and off-shore station data relative to a swarm of low-magnitude earthquakes that occurred during the time interval of the GEOSTAR and TYDE (TYrrhenian Deepsea Experiment) experiments in the southern Tyrrhenian sea.
Concerning line 1, a three-dimensional velocity model has been determined (Neri et al., Geophys. Res. Letters, December 2002) for the crust beneath the region including the southeastern Tyrrhenian sea, the westernmost Ionian sea, northeastern Sicily and southwestern Calabria (Figure 3). A new tomographic inversion is currently being performed on a wider region including all of Sicily and Calabria, and the confining Tyrrhenian and Ionian sectors (Barberi et al., AGU-EGS 2003; session

SM3). The results are expected to be basic for the success of the forthcoming investigations of the on-shore off-shore integrated dataset. Also, the improvements obtained in the seismotectonic knowledge of the study area are expected to furnish the information needed for a correct approach to the dataset integration.
Concerning line 2, a swarm occurring in March 2001 near Santa Lucia del Mela in northeastern Sicily has been investigated for hypoceneter locations with different velocity models (including the one referred to in line 1) using respectively (a) the INGV on-shore station data, (b) the Poseidon on-shore station data, (c) the INGV-Poseidon on-shore station integrated dataset, (d) the OBS and on-shore INGV integrated dataset, (e) the OBS and on-shore Poseidon integrated dataset, (f) the OBS and on-shore Poseidon-INGV integrated data set (Figure 4). Methodological aspects related to integration procedures have been a main goal of the analysis, including some problems discovered during the swarm period regarding the timing systems. The selection of reliable results is being used as a basis for the structural interpretation of the swarm (paper in preparation).

Sub-task G: Integration with parallel activities of other running projects.
Planned objectives: joint workshops for comparison and discussion of results and planning of coordinate studies and/or actions with the parallel GNDT project "Evaluation of geological hazards in the Seas around Italy: earthquakes, tsunamis and submarine slides". Planning of actions coordinated with Istituto Nazionale di Fisica Nucleare for land cable connection of SN-1.
Fulfilled objectives: the foreseen objectives have been accomplished
Description of the related activities:
Coordinated activities with the GNDT project "Evaluation of geological hazards in the Seas around Italy: earthquakes, tsunamis and submarine slides". The project relates on the tectonics of the offshore eastern Sicily. This project, co-ordinated by Dr. A. Argnani from Istituto per le Scienze del Mare (ISMAR-CNR) has focussed on the geometry, kinematics and tectonic history of the Malta Escarpment, i.e. the dominant NNW-striking morphological feature. As the subjects of these two GNDT projects are strictly related, on-going investigations and results of both projects have been compared and discussed in joint workshops.
Main results from the project coordinate by Dr. Argnani's are synthesised as follows (see also Argnani et al., 2003, Boll. Geof. Teor. Appl., in press): (1) The NNW-striking Malta Escarpment can be divided into two portions characterised by different tectonic structures and history; (2) south of Siracusa, the Malta Escarpment, that is originally a slope of erosional-sedimentary nature, is not affected by recent faulting and appears as a steep surface that flattens out eastward into the Ionian Basin. East of the escarpment, recent regional uplifts occur and align along NNW-SSE trends; (3) north of Siracusa and up to the coast of Sicily to the north of Mt Etna, the Malta Escarpment is characterised by NNW-striking, E-dipping extensional faults whose activity can be extended to the recent times. (4) In places, also recent, post-extension contractional deformations reactivate strands of normal faults in the northern sector of the Malta Escarpment.
These results are consistent with our data which indicate evidence of ENE-WSW both extension and contraction onshore eastern Sicily. In addition, the northward "prolongation" of the NNW-striking Malta Escarpment fault system is found along the

northern margin of Peloritani Mountains (Tindari-Barcellona area) where evidence of active NNW-striking extensional faults occurs.
The above-mentioned results pose new constraints for the location of seismic faults and the forecast of seismic activity in eastern Sicily. In particular the integration of data from Dr. Argnani's project and from the SN-1 deep-sea monitoring node will allow a newly-constrained localisation of future earthquakes.
INGV and INFN co-ordinated activities: During the SN-1 project, coordinated actions with INFN have been undertaken in order to develop in the next future the cable connection of the observatory to land. The INFN has already deployed a submarine cable from Catania harbour around 25 km offshore. A cable splitter at around 20 km produces 2 branches, each 5 km long. One of these branches will be devoted to SN-1, while the other one will host a pilot experiment for the detection of neutrinos. In cooperation with the INFN personnel involved in the neutrino detection experiment, the requirements and the development of a special interface (junction box) for the connection of the SN-1 observatory to the cable was agreed. The design of the interface has been completed and the realisation is on-going.

Conclusions

The project activities have developed a seafloor observatory operating in a strategic site with respect to the land-based network of the Ionian Sea and the eastern Sicily regions. SN-1 will become in the next future the first seismological, permanent, sea florr station in Europe thank to the connection on shore through a cable for power supply and data recovery in real-time. The tools and the methodology for the data integration and analysis have been acquired and developed. Relevant data on the geology and geodynamics have been retrieved during new surveys giving new possible interpretative elements to the seismological data.
The data recorded by the observatory will be retrieved and integrated with the ones belonging to other networks and will be analysed with the twofold scope of developing an alarm system and of increasing the seismological knowledge of the area.

References

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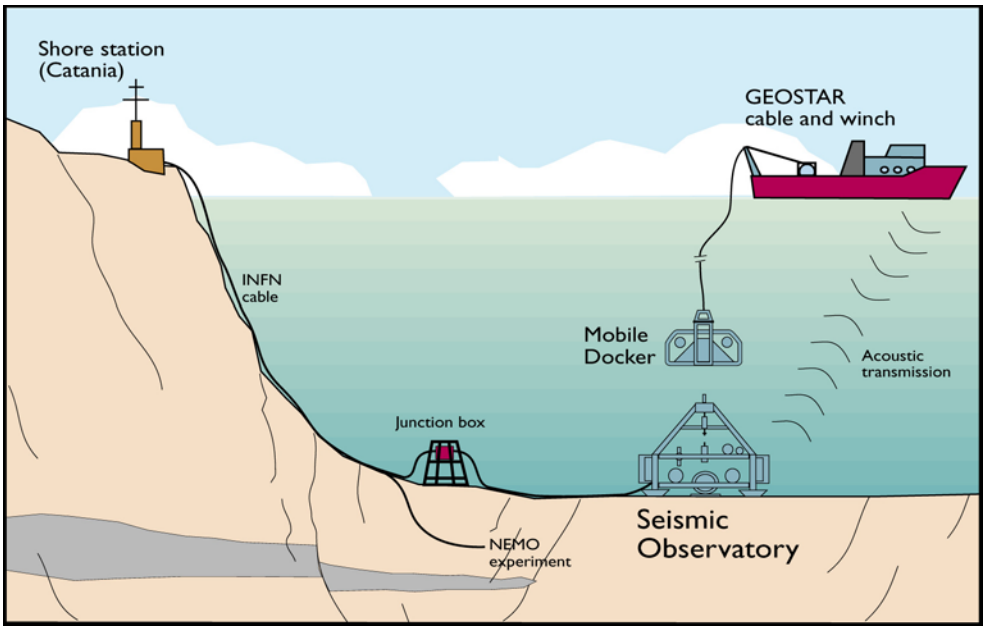

Figure 1. Deployment and recovery scheme of SN-1: the deployment and recovery of the observatory is performed through an underwater vehicle (Mobile Docker for Underwater Sciences, Modus); acoustic communication can be activated from the sea surface in order to retrieve significant parameters related to the seafloor mission course. A junction box will be deployed in the next future to connect the observatory to and existing underwater cable deployed by Istituto Nazionale di Fisica Nucleare. The observatory will be so integrated in the existing land-based monitoring networks.

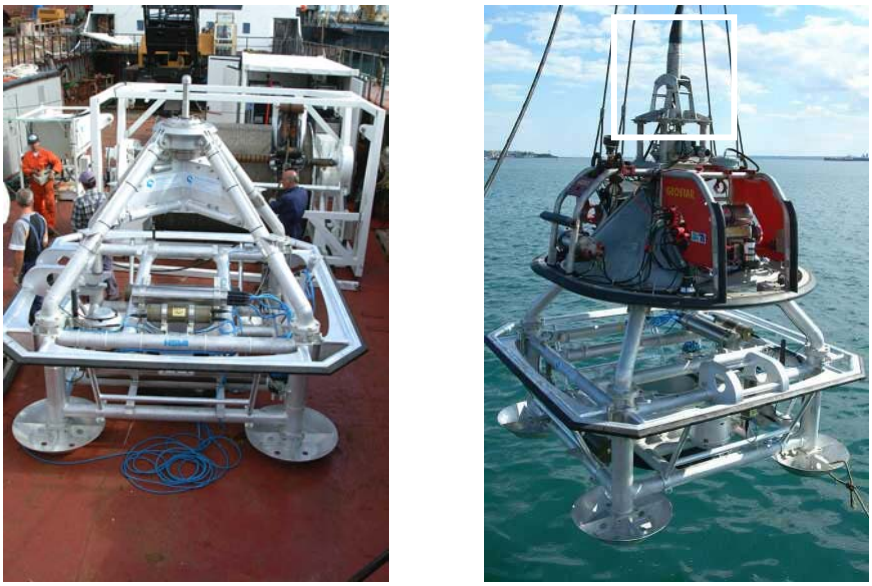

Figure 2. The SN-1 observatory on the deck of the moto-pontoon “Mazzarò” during assembling (left panel) and during a test at sea before the deployment operations (right panel). The operations can be assisted by means of the MODUS telemetry system, based on an electro-optical cable whose termination is visible on top of MODUS (white square in the right panel).

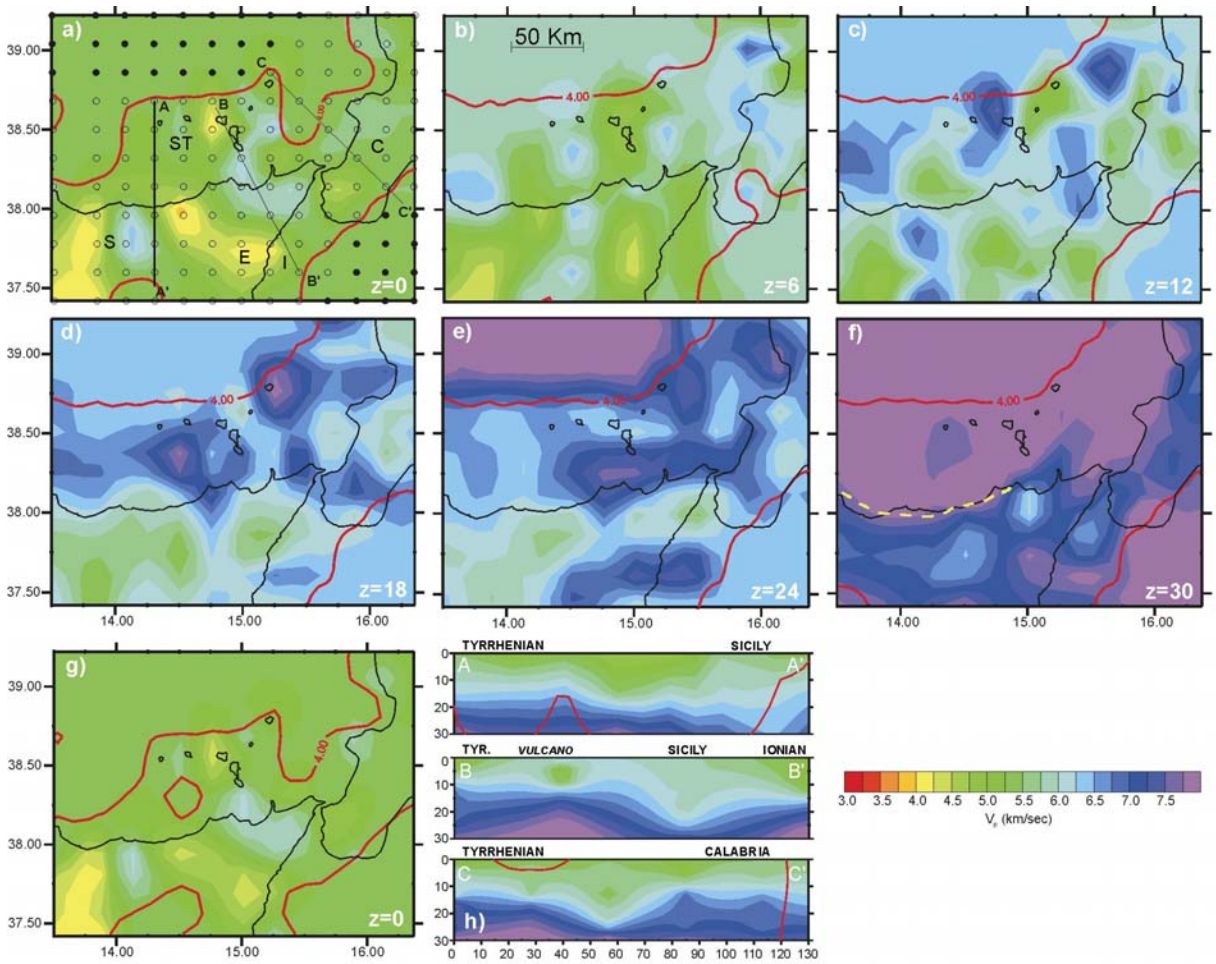

Figure 4. (a-f) P-wave velocity model obtained in the present study. Z is the b.s.l. depth in kilometers. The red curve contours the area where the Spread Function SF<4.0. The dotted yellow curve in 4f indicates the separation between the Tyrrhenian and Sicilian velocity domains (see text). ST, S, E, I and C in 4a stand for Southern Tyrrhenian sea, Sicily, Etna, Ionian sea and Calabria, respectively. Again in 4a the circles indicate the nodes of the inversion grid (full circles mean fixed velocity values), and AA', BB' and CC' are the profiles of the vertical sections given in 4h. (g) Results from the restore test described in the text. (h) Vertical sections of the 3D velocity model of 4a-f along the profiles AA', BB' and CC' indicated in 4a.

Figure 3. A three-dimensional velocity model determined by Neri et al. (Geophys. Res. Letters, 2002) for the crust beneath the region including the southeastern Tyrrhenian sea, the westernmost Ionian sea, northeastern Sicily and southwestern Calabria.

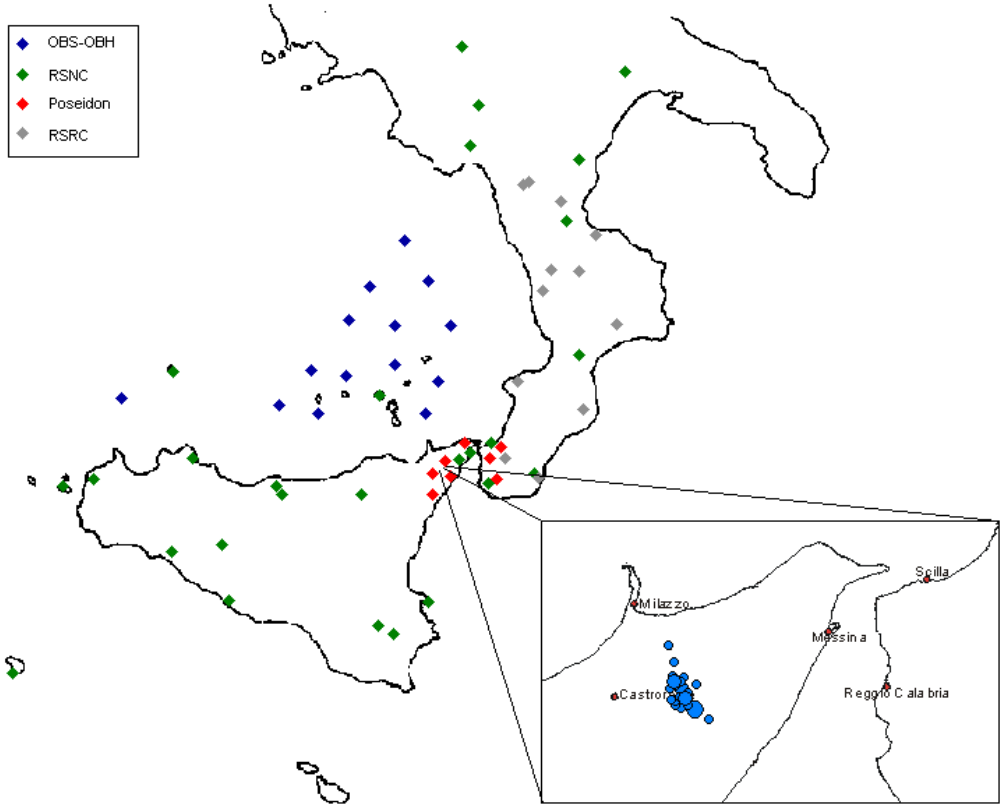

Figure 4. A swarm occurring in March 2001 in northeastern Sicily (see the inserted panel) has been investigated for hypoceneter locations with different velocity models using respectively (a) the INGV on-shore station data, (b) the Poseidon on-shore station data, (c) the INGV-Poseidon on-shore station integrated dataset, (d) the OBS and on-shore INGV integrated dataset, (e) the OBS and on-shore Poseidon integrated dataset, (f) the OBS and on-shore Poseidon-INGV integrated dataset. Methodological aspects related to integration procedures have been a main goal of the analysis, including some problems discovered during the swarm period regarding the timing systems. The selection of reliable results is being used as a basis for the structural interpretation of the swarm (paper in preparation).