Seismic location improvements from an OBS/*H* temporary network in Southern Tyrrhenian Sea

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Abstract

We present the first investigation performed on the seismicity of Southern Tyrrhenian Sea, off-shore Sicily with the contribution of data from broad-band ocean bottom seismometers and hydrophones (OBS/*H*). Off-shore data were recorded during the TYrrhenian Deep-sea Experiment (TYDE) from December 2000 to May 2001 in the Southern Tyrrhenian Sea. Hypocenter locations of a cluster of 53 seismic events which occurred in March 2001 in north-eastern Sicily were estimated by the integration of land (permanent network) and off-shore (temporary network) data and compared with locations estimated from land data only. The scatter of the cluster was evaluated by dispersion parameters. The off-shore data significantly reduced the scatter of the swarm hypocenters also restricting the depth range of the cluster. Moreover, space trends of the event distribution originally shown by the land data were only partially confirmed by the land-sea joint data. In order to assess the efficiency of a land-sea integrated network with respect to a land-based network in terms of hypocenter mislocations in the subject area, we performed simulations by assuming a grid distribution of earthquakes and a recent local 3D velocity model, computing synthetic arrival times of body waves to the stations of both network configurations (integrated and land-based) perturbing the computed times and relocating earthquakes by inversion. The results of the synthetic tests demonstrated that the presence of sea bottom stations in the Tyrrhenian Basin can reduce the mislocations of large magnitude and/or superficial earthquakes in the southernmost Calabria and Messina Strait and of low magnitude and/or deep earthquakes in north-eastern Sicily. The accuracy of synthetic earthquake locations obtained including OBS/*H* data provides additional support to the interpretation of the cluster occurred in March 2001 and the opportunity of long-term installation of an off-shore network like TYDE in the study region.

Key words *earthquake location – ocean bottom seismometers and hydrophones – seismic networks – synthetic tests – Sicily*

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1. Introduction

The Southern Tyrrhenian region (fig. 1) is characterised by a fairly rapid transition from a nearly oceanic crustal structure beneath the abyssal plain to a continental-like structure beneath Sicily and Calabria. Fault discontinuities have been mapped on grounds of geological and geophysical investigations: i) major NW-trending fault systems potentially capable to generate magnitude ≥6 earthquakes cross the lithosphere underneath the southernmost Tyr-

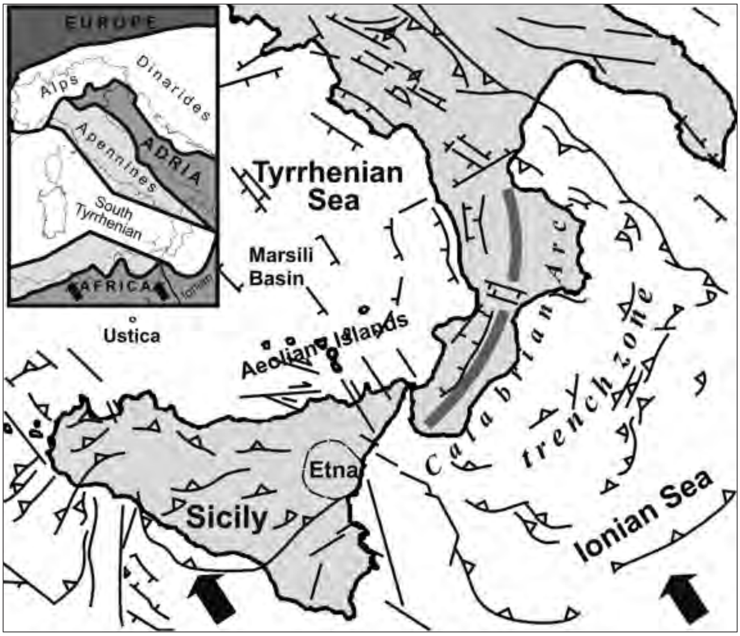

Fig. 1. Structural map of Southern Italy, from Meletti *et al.* (2000) and Neri *et al.* (2005). In agreement with standard symbols, barbs indicate the downthrown blocks in normal faults, fault arrows show the strike-slip component of the fault mechanism, triangles indicate the sense of dipping of thrust structures. The shaded belt indicates the location of the Apennine chain in the Calabrian Arc. The arrows indicate the motion direction of Africa with respect to Europe as predicted by large-scale crustal motion models (Sella *et al.*, 2002; Calais *et al.*, 2003; Nocquet and Calais, 2004). NW-SE plate convergence is considered the main tectonic engine in the study region acting together with gravity-induced southeastward roll-back of the Ionian lithosphere subducting beneath the Tyrrhenian Sea (*e.g.*, Faccenna *et al.*, 2001b). The inset displays a map of the Italian region showing the main tectonic units and microplates identified between the Africa and Europe stable margins (Scandone and Stucchi, 1999).

rhenian Sea (Finetti and Del Ben, 1986; Neri *et al.*, 2003); ii) NNE- to N-trending normal faults are responsible for earthquakes of magnitude up to 7 in the Messina Strait and Southern Calabria (Boschi *et al.*, 1997); iii) *E*-trending reverse faults produce events of magnitude up to 6 seismic in Central and Western Sicily (Ben-Avraham and Grasso, 1990, 1991; Neri *et al.*, 2003). These fault systems cross the crust underneath off-shore areas, and this emphasises the importance of off-shore seismometry in the region.

An Ionian lithospheric slab subducting to WNW beneath the Southern Tyrrhenian Sea (fig. 1) has been suggested on the basis of distribution of intermediate and deep seismicity (*e.g.*, Gasparini *et al.*, 1982; Anderson and Jackson, 1987; Giardini and Velonà, 1991; Selvaggi and Chiarabba, 1995), high velocity revealed in the upper mantle by tomographic images (Piromallo and Morelli, 1997; Lucente *et al.*, 1999; Cimini, 1999) and calk-alkaline volcanism of the Aeolian Islands (Barberi *et al.*, 1973; Argnani and Savelli, 1999). According to many investigators (*e.g.*, Malinverno and Ryan, 1986; Faccenna *et al.*, 1996, 2001a; Hirn *et al.*, 1997; Argnani, 2000; Nicolich *et al.*, 2000; Doglioni *et al.*, 2001; Gvirtzman and Nur, 2001) geological and geophysical evidence in this region can be interpreted in the framework of a geodynamic model assuming an approximately NW-SE slow convergence between the African and European plates (the average motion direction of the African plate respect to the European plate is shown in fig. 1 by black arrows) and gravity-induced south-eastward roll-back of the

Ionian subducting slab. Roll-back is widely believed to have been the primary tectonic source for: i) Tyrrhenian Basin opening; ii) southeastward kinematics of the Southern Tyrrhenian lithosphere, and iii) its thinning and overthrusting onto the Ionian lithosphere. The space-time evolution of the roll-back process would have produced a clear structural differentiation between the Calabrian Arc and the marginal tectonic unit of Sicily. North-eastern Sicily experienced disastrous earthquakes in the last few centuries, often accompanied by tsuna-mis, producing wide destruction and hundreds of thousands of casualties (Boschi *et al.*, 1997; Tinti *et al.*, 2004). Active volcanoes (*e.g.*, Mt. Etna, Aeolian Island Arc) represent additional sources of risk. Although the regional seismometric network, solely land based, has been largely improved in the last two decades both in type of sensors and distribution, the seismicity of several sectors in the study region is still hard to locate accurately because of the presence of large marine areas.

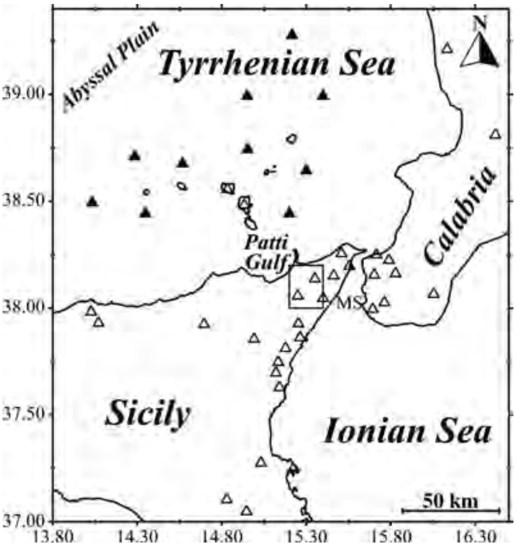

Fig. 2. Map of on-shore (empty triangles) and off-shore stations (full triangles) used in the present study. The on-shore stations belong to the local and national networks of INGV for the Mt. Etna and Italian territory surveillance. The square shows the north-eastern Sicily area of the March 2001 swarm.

A good opportunity to obtain hypocentre locations with an accuracy higher than usual was given by the deployment of a temporary network of fourteen OBS/*H* stations for around six months in the area between the Tyrrhenian abyssal plain and the northern coast of Sicily (fig. 2) in the framework of the TYrrhenian Deep-sea Experiment (TYDE; Dahm *et al.*, 2002) partially supported by the European Commission, coordinated by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) with the cooperation of IFM-GEOMAR and the University of Hamburg. TYDE has been the most important OBS/*H* experiment, in terms of number of sensors installed and duration, ever performed in the Italian region. Two previous shorter experiments were carried out with the installation of OBS in the south-eastern Tyrrhenian Sea off-shore Calabria (Soloviev *et al.* 1990) and around the Aeolian Islands (Beranzoli *et al.*, 1997; Favali *et al.*, 2004). Data recorded in the framework of TYDE allowed an unprecedented joint analysis of on-shore and off-shore seismic data in Italy (see also Sgroi *et al.*, 2006) exploring the advantages of land-sea data integration with respect to local seismicity location.

2. Temporary and permanent networks and data

The TYDE temporary OBS/*H* stations were installed at depths ranging from 1500 m to 3500 m on the sea bottom around the Aeolian Islands from the northern coast of Sicily to Marsili Basin. The stations were equip-ped with broadband seismometers (PMD sensor: flat response in the range 0.025-32 Hz; SpharWebb-SCRIPPS sensors: flat response 0.02-100 Hz) and hydrophones (E-2PD: bandwidth 0.5-50 Hz) and 21bit digitisers with sampling rate of 50 Hz. Further technical details and the description of installation and recovery procedures can be found in the papers by Dahm *et al.* (2002) and Sgroi *et al.* (2006). The network operated in continuous mode and local recording from December 2000 to May 2001. We selected ten OBS/*H* stations, out of the fourteen deployed, the closest ones to the area under investigation. The locations of the ten temporary stations are reported in fig. 2 (full triangles) together with those of the thirty-one permanent on-shore stations (empty triangles) which also provided data for this study. Four stations were also temporarily installed by INGV on land (Sicily and Aeolian islands) to make the coverage of the area denser. The permanent land stations are managed by INGV in the frame of a regional network addressed to monitoring Eastern Sicily, where the Mt. Etna volcanic edifice is located, and in the frame of the Italian national seismological network. The land stations selected for this study are equipped with short-period three-component seismometers (eleven stations) and short-period vertical component seismometers (twenty stations). The signals are acquired with a sampling rate of 50 Hz (national network) and 160 Hz (regional network), and are transmitted via radio or phone cables from the remote stations to the acquisition centres – Catania (Sicily) for the regional network, Rome for the national one – where they are stored and analysed.

3. The seismic swarm of March 2001

During the TYDE experiment, a low-energy seismic swarm occurred from 26 to 30 March, 2001 in north-eastern Sicily (boxed area in fig. 2). This swarm comprised 53 shocks with duration magnitude $1.4 \leq M_d \leq 2.9$, and was originally located by means of the land network data at depths ranging approximately from 25 to 40 km. The characteristics of the events are reported in fig. 3; the upper panel reports the number of events per day with the indication of the maximum magnitude, and the bottom panel shows the number of events per magnitude range. The swarm started close to the locality of Santa Lucia on 26 March with six shocks and maximum magnitude 2.3. Most of the earthquakes are concentrated on 27 and 28 March, with more than twenty shocks per day and maximum magnitude 2.4 and 2.9 respectively. In the last two days of the swarm occurrence, the number of events abruptly decreases to a single shock per day with magnitude 1.7 (29 March) and 2.4 (30 March) to cease completely.

The first step of our analysis concerns the integration of the data belonging to the land-based network and the sea-bottom stations. The integration requires, as usual, the correction of the data time tag as the clock signal of each OBS/*H* module progressively delays over time. The internal clock of each OBS/*H* is indeed synchronised before the deployment and after the recovery and, given a linear trend of the clock drift, data can be corrected before processing. After the correction, the *P* and *S* arrival times of the swarm events are picked on the OBS/*H* waveforms and integrated with the readings of the land stations in a single database to be used for further steps. The final database resulted in 724 *P*-phase and 522 *S*-phase arrival times, 242 and 120 of which from sea-bottom stations for the two types of phases. In order to compare the location results obtainable by the 'integrated' data set and the ones obtainable by the land-based network, the «1D minimum velocity model» and the 3D local crustal model of the study area, both estimated by Neri *et al.* (2002), were used to locate the events of the swarm. In

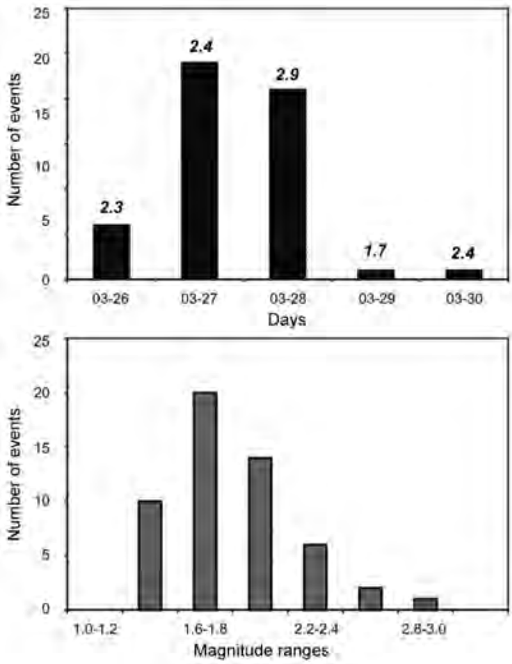

Fig. 3. *Upper*: histogram of the number of events per day: each histogram column reports the maximum magnitude of the day. *Bottom*: histogram of the number of events per magnitude range.

particular, VELEST (Kissling *et al.*, 1994) and SIMULPS12 (Evans *et al.*, 1994) algorithms were applied to carry out the locations in 1D and 3D respectively. As expected, the locations achieved with the 3D model produced a clearly better fitting of the experimental arrival times (rms=0.16s) compared to the 1D locations (rms==0.30s). We therefore decided to use only 3D locations in the subsequent steps of the analysis and to compare the locations of the swarm events obtained using two different network configurations: configuration *LS* – integrated land-sea network; configuration *L* – land network only.

The epicentral map and hypocenter distribution with depth resulting from the location procedure in the 3D model are displayed in fig. 4 for both *LS* and *L* configurations. Hypocenter distribution obtained with configuration *L* shows trends, like for instance a roughly E-W distribution of epicentres, which are not found when using configuration *LS*; on the other hand, the westward deepening trend of the hypocenters of the swarm is confirmed in both cases. Using configuration *LS*, the hypocenter volume appears mainly restricted to depth ranging from 27 to 37 km. These values of hypocentral depths are quite unusual in general for the Italian Peninsular region, characterised by a seismicity hardly exceeding 15-20 km.

As the events are clustered both in time and space, we assumed that they were generated by a single structure or by different structures very closely linked to each other. According to this assumption, the space dispersion of the swarm can be used as an indicator of the overall quality of locations. Starting from these considerations, we defined the dispersion factors D_{xy} and D_{xyz} of the earthquake locations around the swarm barycentre of a given dataset in the horizontal plane and in the 3D space

$$D_{xy}=\sqrt{\frac{\sum_{i=1}^{N}((LAT_i-\overline{LAT})^2+(LON_i-\overline{LON})^2)}{N}}=$$

$$=\sqrt{\frac{\sum_{i=1}^{N}(D_{xy}^{i})^2}{N}} \qquad (3.1)$$

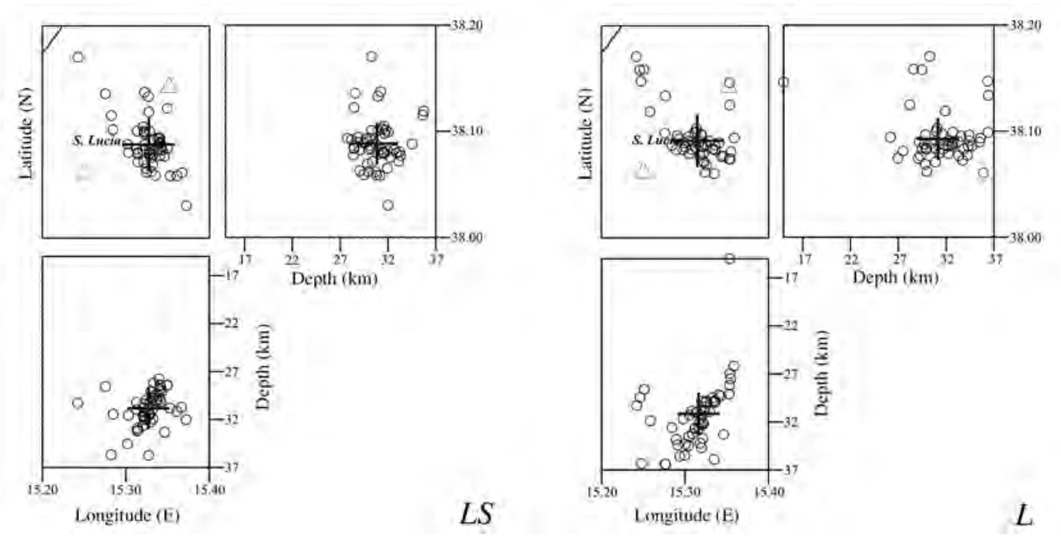

Fig. 4. Epicentre locations and hypocentre depth distribution of the Santa Lucia swarm obtained using the 3D model by Neri *et al.* (2002) and the data from the integrated network (configuration *LS*, left panel) and the land-based network (configuration *L*, right panel). Triangles and crosses indicate the stations lying in the swarm area and the barycentres used for estimates of the D_{xy} and D_{xyz} dispersion factors (see eqs. (3.1) and (3.2) in Section 3).

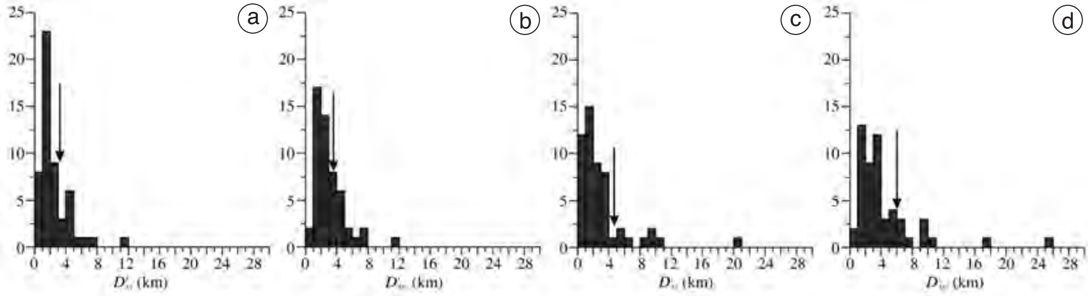

Fig. 5a-d. Histograms of D^i_{xy} and D^i_{xyz} (see equations in Section 3) of the events of the swarm from the integrated network *LS* (panels a and b) and the land-based network *L* (panels c and d). Arrows indicate the average values of *D*.

$$D_{xyz}=\sqrt{\frac{\sum_{i=1}^{N}((LAT_i-\overline{LAT})^2+(LON_i-\overline{LON})^2+(DEP_i+\overline{DEP})^2)}{N}}=\sqrt{\frac{\sum_{i=1}^{N}(D^i_{xyz})^2}{N}} \quad (3.2)$$

with

$$D^i_{xy}=\sqrt{(LAT_i-\overline{LAT})^2+(LON_i-\overline{LON})^2} \quad (3.3)$$

$$D^i_{xyz}=\sqrt{(LAT_i-\overline{LAT})^2+(LON_i-\overline{LON})^2+(DEP_i+\overline{DEP})^2} \quad (3.4)$$

where i identifies the generic event in the dataset including N earthquakes, $\overline{LAT}$, $\overline{LON}$ and $\overline{DEP}$ are the average values of epicentre latitudes LAT_i, epicentre longitudes LON_i and focal depths DEP_i. The terms *LAT* and *LON* represent linear coordinates. Figure 5a-d shows the histograms of the distances D^i_{xy} and D^i_{xyz}: in the case of configuration *LS* (panels a and b) most of the events have distances D^i_{xy} and D^i_{xy} generally smaller than the ones estimated for configuration *L* (panels c and d).

The estimates of D_{xy} and D_{xyz} are 3.19 km and 3.65 km in the case of network *LS* and 4.63 km and 6.04 km for *L*. This result can be considered an element supporting the conclusion that off-shore stations, even far and with an asymmetric distribution around the swarm area, have reduced the uncertainty in the locations of the swarm events. It is worth noting that the rms of the swarm locations is higher for network *LS* (0.16 s) than for network *L* (0.13 s). This can be explained by the fact that the inversion is better constrained by the experimental data of the network *LS*. In addition it should be remarked that the sea-bottom stations were sited in a zone of the 3D model where the spread function become larger than 4 (Neri *et al.*, 2002), suggesting a reduction of model reliability in the marine sector.

4. Synthetic tests for hypocenter location accuracy

We performed a series of synthetic tests to assess the accuracy of the location of events with different energy release occurring in a crustal volume wider than the one involved in the March 2001 swarm both *LS* and *L* configurations. The area selected for the synthetic tests is shown in fig. 6 (grey rectangle) together with the sets of stations chosen to form *LS* and *L* network configurations. We consider a hypo-center distribution coincident with the nodes of a 3D grid extending from the Earth surface down to 35 km of depth with a horizontal and vertical node spacing of 1.5 and 5.0 km respectively. The theoretical arrival times of *P* and *S*-waves from the grid nodes to the stations of the two networks were computed with the 3D-model of Neri *et al.* (2002). The synthetic arrival times were then perturbed to simulate random reading errors. Based on a critical evaluation of the

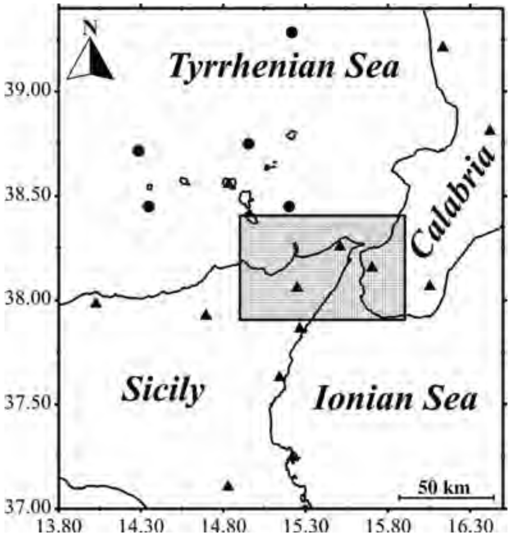

Fig. 6. Network configurations used for tests performed with synthetic earthquakes in order to assess the hypocentral location quality. Triangles and circles mark the land and sea-bottom stations. The integrated network (configuration *LS*) included both sets of stations. The land stations constitute the network configuration *L*. Hypocenters of synthetic earthquakes were positioned on a 3D grid, with horizontal spacing of 1.5 km and vertical spacing 5 km from the Earth surface down to 35 km. The gray rectangle indicates the area selected for the synthetic tests.

reading uncertainties during the investigation of March 2001 earthquakes, we assumed a standard deviation of perturbations of 0.3 s. The perturbed arrival times were inverted using the same 3D velocity model (Neri *et al.*, 2002). The locations were performed by placing the starting hypocenter at a distance ($\Delta_{LAT}=\Delta_{LON}=6$ km; $\Delta_{DEPTH}=8$ km) from the true hypocenter (grid node) larger than the grid spacing. The dislocation of the initial hypocentres is comparable to the largest errors that we expect from routine hypocenter locations in this area. We performed different trials by changing the starting hypo-center locations toward N, S, E, W, NE, NW, SE, SW with $\Delta_{LAT}=\Delta_{LON}=\pm 6$ km and increasing depth of $\Delta_{DEPTH}=+8$ km. We found that these dislocations determine mislocations smaller than the grid spacing.

Two parameters were estimated for each synthetic event (grid node): the epicentral distance *D* and the focal depth difference *H* between the synthetic and relocated event. Figure 7 shows the horizontal distribution at different depths of the *D* values obtained using the network configurations *LS* and *L*. The comparison between the *D* values computed from the two different network configurations reveals that, in spite of the uneven geometry of the sea network with respect to the area, the presence of seismological stations in the Tyrrhenian Basin reduces the horizontal mislocations at all depths, not only in north-eastern Sicily but also in the southernmost Ionian Calabria, south-east of Messina Strait. This reduction appears to be significant in the depth range 25-35 km also for the latter zone where the red areas ($D>6$ km) appear to be less extended. The horizontal distribution of the *H* values for the *LS* and *L* configurations are displayed in fig. 8. It is worth noting that the vertical mislocation of events can be reduced in north-eastern Sicily more than in Calabria by the presence of sea-bottom stations in the Tyrrhenian Sea. This provides an additional element in support of the evaluation of the depth range of the swarm of March 2001 and interpretation.

An additional synthetic test is performed with a standard deviation 0.05 s of the perturbation introduced into the arrival times. This value accounts for energetic and/or superficial events. Figures 9 and 10 show the *D* and *H* horizontal distributions at different depths obtained with this smaller value of perturbation. The results of this additional test show a significant reduction of both *D* and *H* values in configuration *LS* in Calabria and Messina Strait in the depth range 5-25 km.

5. Conclusions

P and *S* arrival times of local seismicity recorded by a temporary seafloor network of OBS/*H* and INGV land-base network, for a total amount of 1246 data, were used to analyse a moderate energy swarm in March 2001 in north-eastern Sicily. Moreover, the sea-bottom station distribution was used jointly with the land station distribution

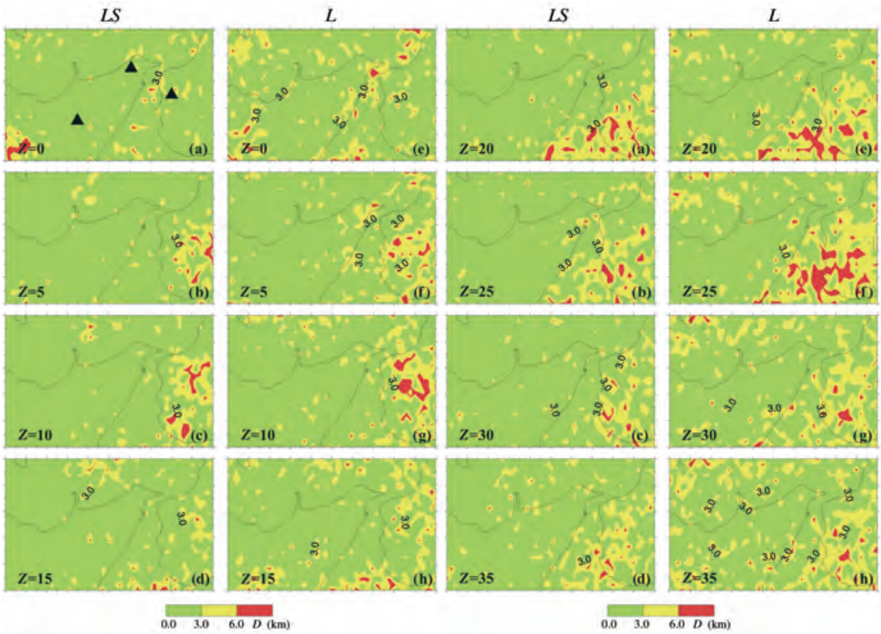

Fig. 7. Comparison of *D*-parameter horizontal distributions at different depths obtained by synthetic tests with the *LS* integrated network (left panels) and the *L* land-based network (right panels). The standard deviation of the random noise perturbation of synthetic arrival times is 0.3 s.

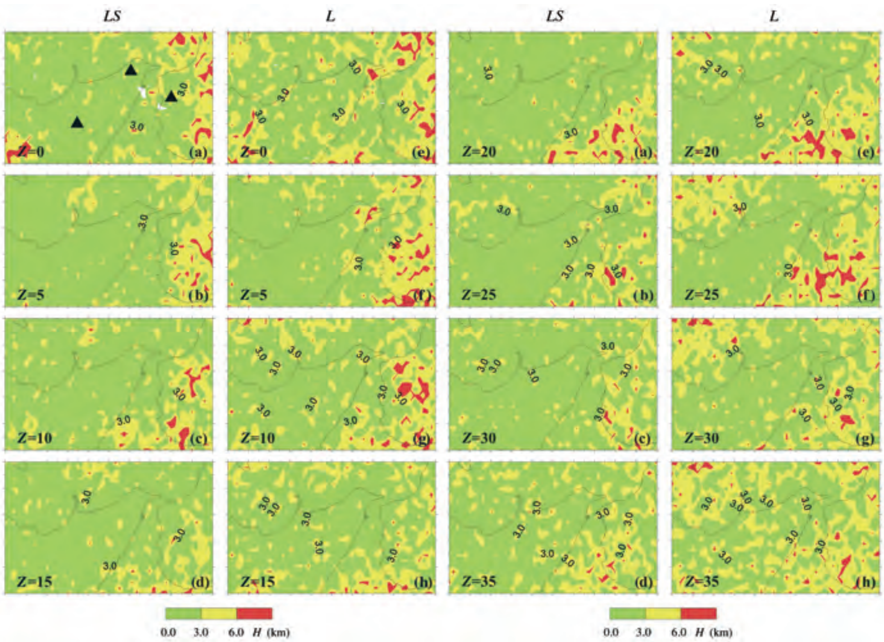

Fig. 8. Comparison of *H*-parameter horizontal distributions at different depths like in fig. 7 with the same standard deviation (0.3 s).

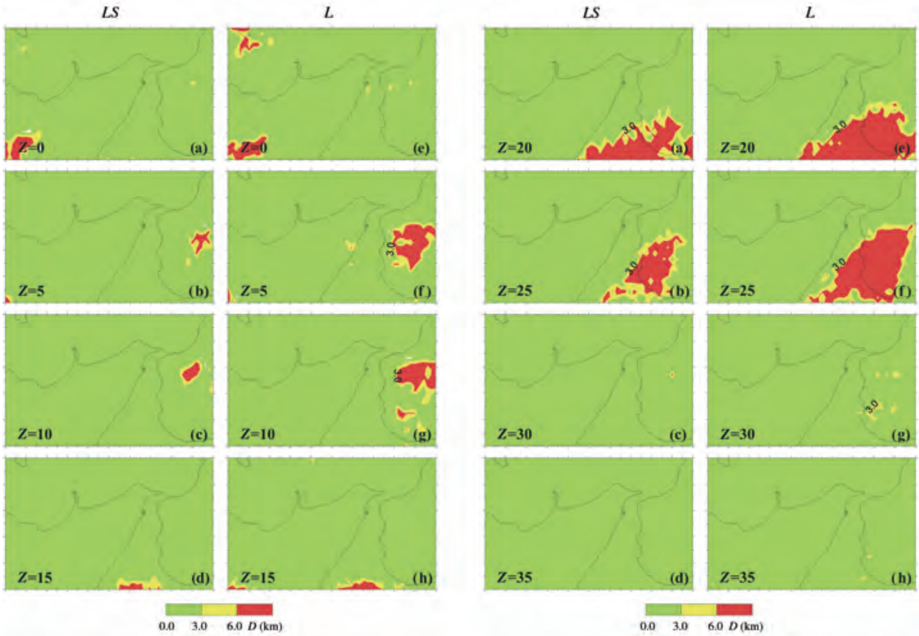

Fig. 9. Comparison of *D*-parameter horizontal distributions at different depths like in fig. 7. The standard deviation of the random noise perturbation of synthetic arrival times is reduced to 0.05 s.

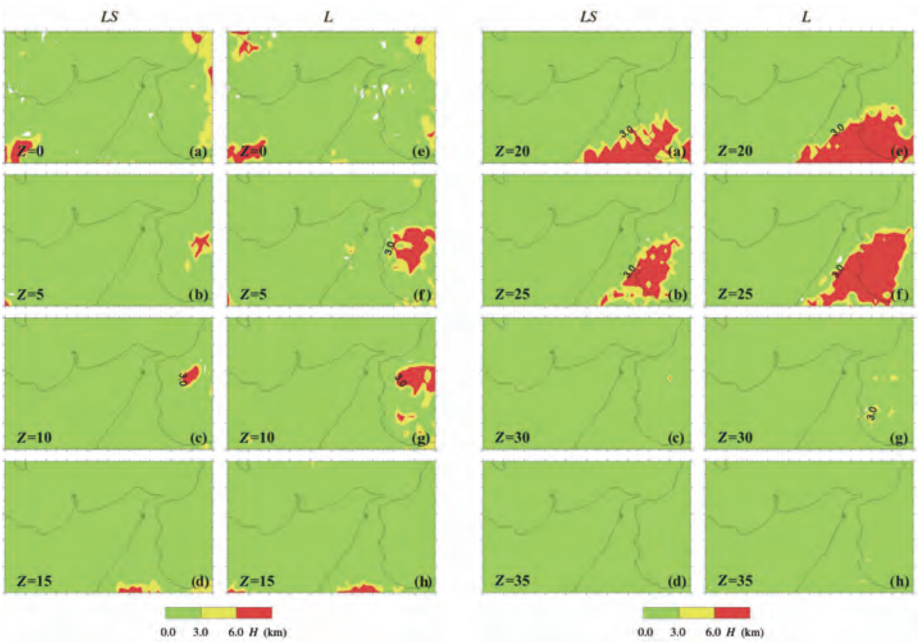

Fig. 10. Comparison of *H*-parameter horizontal distributions at different depths like in fig. 7. The standard deviation of the random noise perturbation of synthetic arrival times is 0.05 s.

to assess the efficiency of a sea-land integrated monitoring network in terms of hypocenters location accuracy for events eventually occurring in north-eastern Sicily and Southern Calabria.

The swarm of 53 events, with maximum magnitude 2.9, was relocated using a 3D velocity model of the region (Neri *et al.*, 2002). The locations were performed twice, the first time using land and sea stations jointly (integrated network) and the second time using only land stations. In the case of integrated network configuration the relocated swarm has dispersion factors D_{xy} and D_{xyz} smaller than those found with the land-based network relocation. That could be attributed to a lower parameter variance due to a smaller scatter of the hypocenters. The westward dipping of swarm hypocenters seems the only feature confirmed by both network configurations. The depth range of the swarm turned out between 27 and 37 km, a quite unusual depth for seismogenesis in the Italian peninsula. The depth range of the swarm could be interpreted in the frame of the transition nature of the area from the geological and geodynamic point of view. North-eastern Sicily belongs to the southernmost sector of the Calabrian Arc unit and is adjacent to the Hyblean foreland. The southern border of the Ionian lithospheric slab has been roughly positioned just beneath north-eastern Sicily by previous studies (*e.g.*, Argnani, 2000). Moreover, Selvaggi and Chiarabba (1995) estimated the depth of the shallower part of the subducting slab in the area to decrease from 50 to 25 km in the NW-SE direction.

In order to assess the improvement of hypocenter location accuracy achievable by the integration of sea-bottom seismological observations and land-based data, synthetic tests for a larger area, including the swarm, and extended up to Southern Calabria were performed. The assessment was accomplished through the evaluation of parameters *D* and *H*, defined as the horizontal distance and depth difference between the 'synthetic' (grid node) and the relocated hypocenters. In order to simulate the occurrence of low and high energy and of deep and shallow earthquakes, synthetic arrival times were perturbed with white noise characterised by two different values of standard deviations (0.3 and 0.05 s). The results of the synthetic tests confirm that the presence of sea-bottom stations in the Tyrrhenian Basin reduce the mislocations of large and/or shallow earthquakes in Southern Calabria and Messina Strait and of low intensity and/or deep earthquakes in north-eastern Sicily.

The definition of proper strategies for the extension of seismometric networks toward marine basins is evidently a basic step in the set of initiatives addressed to the accurate characterisation and knowledge of seismogenic areas and consequently to the mitigation of the seismic risk.

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