



# **Observing Volcanoes from the Seafloor in the Central Mediterranean Area**

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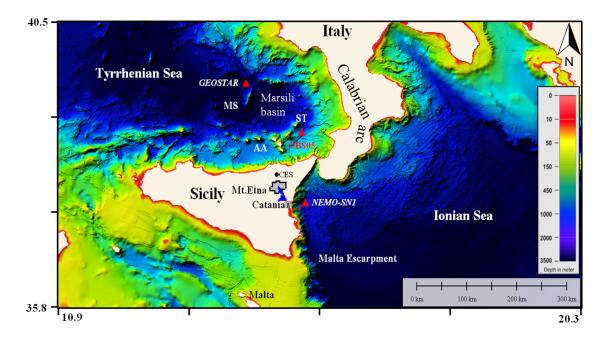
Abstract: The three volcanoes that are the object of this paper show different types of activity that are representative of the large variety of volcanism present in the Central Mediterranean area. Etna and Stromboli are sub-aerial volcanoes, with significant part of their structure under the sea, while the Marsili Seamount is submerged, and its activity is still open to debate. The study of these volcanoes can benefit from multi-parametric observations from the seafloor. Each volcano was studied with a different kind of observation system. Stromboli seismic recordings are acquired by means of a single Ocean Bottom Seismometer (OBS). From these data, it was possible to identify two different magma chambers at different depths. At Marsili Seamount, gravimetric and seismic signals are recorded by a battery-powered multi-disciplinary observatory (GEOSTAR). Gravimetric variations and seismic Short Duration Events (SDE) confirm the presence of hydrothermal activity. At the Etna observation site, seismic signals, water pressure, magnetic field and acoustic echo intensity are acquired in real-time thanks to a cabled multi-disciplinary observatory (NEMO-SN1). This observatory is one of the operative nodes of the European Multidisciplinary Seafloor and water-column Observatory (EMSO; www.emso-eu.org) research infrastructure. Through a multidisciplinary approach, we speculate about deep Etna sources and follow some significant events, such as volcanic ash diffusion in the seawater.

**Keywords:** EMSO; seafloor observatories; stand-alone monitoring systems; volcano seismology; volcanic ash clouds

## 1. Introduction

The Mediterranean area is characterized by the convergence between the Eurasian and African plates, with contemporary collisional and extensional processes occurring along plate margins [1,2]. In this framework, volcanic phenomena have taken place in the Central Mediterranean region since the Oligocene [3], and starting from the Tortonian, the Tyrrhenian basin has opened with the development of the Magnaghi and Vavilov oceanic basins (4.3–2.6 Ma). During the Plio-Pleistocene, the extension changed from E-W to SE-NW [4], forming the Marsili basin that includes the Marsili Seamount (MS; Figure 1), the largest European underwater volcano. MS is associated with the north-westward subduction of the Ionian lithosphere below the Calabrian Arc [5], and its formation is dated between 1.7 and 0.1–0.2 Ma [6,7]. In this region, the coexistence of compression due to slab

roll-back processes and crustal extension has been proposed ([8] and references therein). The Aeolian Arc, formed by several volcanic islands and seamounts, is emplaced between the back-arc and the Calabrian Arc fore-arc region. Their age ranges from 1.3 Ma to the present, and their formation can be related both to the subduction of the Ionian lithosphere ([9] and the reference therein) under the thrust belt and to extensional strain [10]. Stromboli is the northernmost of the sub-aerial volcanoes characterized by an intermittent explosive activity. Etna volcano, the largest sub-aerial volcano in Europe, is located in eastern Sicily about one-hundred km south of Stromboli. The formation of Etna has been explained by several authors (e.g., [11,12]) as due to the interplay between two mutually-reinforcing processes: tearing of the Ionian slab and toroidal flow in the upper mantle. As a whole, volcanism in this area shows an extreme variability, both in the volcanic edifice size and structure and in the type of volcanic emissions (e.g., [13]). Etna, Stromboli and Marsili Seamount are representative of the different types of Mediterranean volcanism, both in terms of activity and structure. At present, Etna and Stromboli are active.



**Figure 1.** Bathymetric map of the Central Mediterranean Sea. The red triangles show three different seafloor systems: a cabled multidisciplinary observatory (NEMO-SN1), an autonomous multidisciplinary observatory (GEOSTAR) and an Ocean Bottom Seismometer (OBS05), part of an array deployed around the Aeolian islands during the Tyrrhenian Deep sea Experiment (TYDE) experiment [14]. NEMO-SN1 is an EMSO node. The color scale indicates the bathymetry. MS: Marsili Seamount; AA: Aeolian Arc; ST: Stromboli Volcano; CES: Cesarò magnetic station.

Volcanoes are explored by the deployment of permanent and temporary networks of sensors, geophysical and geochemical spatial surveys and remote sensing. The use of an array of seismometers allows for the accurate location of local earthquakes (both tectonic and volcano-tectonic [15]), the determination of earthquake source mechanisms and the creation of 3D models of the underlying volcanic structure (e.g., position and extension of a magma chamber [16]). Seismic signals recorded by arrays of free-fall instruments (Ocean Bottom Hydrophones (OBHs) and Ocean Bottom Seismometers (OBSs)) have been the standard way to explore and monitor volcanoes from the seafloor (e.g., [17]). Volcano-related processes can generate signals that occur on short (seconds or less), medium (days, weeks) to long time-scales (months, years). Temporary land-based seismic stations show their limit in the case of submarine volcanoes that have sporadic activity or energy too low to be detected on land. For this reason, great effort is being exerted to increase the duration and

duty-cycle of seafloor seismological observations. The signal quality is also a limiting factor for the detection of low-energy sources. Higher quality signals are recorded by broadband three-component seafloor seismometers that have higher sensitivity (e.g., 360 s–50 Hz) and better ground coupling with respect to free-fall OBS. These instruments are heavy, expensive and more delicate, and they are often connected to an observatory.

Seafloor fixed-point multidisciplinary observatories offer new possibilities to detect signals on a longer time scale. They allow for extensive and long-term synchronous measurements of signals from different sensors (multi-parameter). They are present worldwide, and their number is increasing with time [18], providing useful information on little-known oceanic areas and, in particular, on volcanic structures and activity (e.g., [19,20]). Observatories can host instruments that are less commonly used for volcano monitoring, such as gravimeters, magnetometers and Acoustic Doppler Current Profilers (ADCPs), recording other parameters that can add information on volcanic activity.

Gravimetric on-land volcano monitoring is not routinely performed ([21] and the reference therein) and is even more rare at the seafloor due to the technological challenges related to the marine environment. Nevertheless, this type of exploration is interesting since variations of gravity signals can be caused by the internal dynamics of a volcano, such as magma mass redistribution and density variations under the structure (e.g., [22,23]). Gravity changes can be linked to the degassing processes of hydrothermal systems [24]. To minimize false associations, gravimetric data should be examined with other geophysical parameters, such as seismological and magnetometric data. The joint analysis of gravimetric and seismic measurements has already been carried out in several active volcanic areas (e.g., [25,26]). In particular, this multi-parametric approach was used in Italy to monitor Etna eruptions (e.g., [23,27–29]).

Magnetic measurements can also provide valuable information on volcanoes. The magnetic field is the result of different contributions: the main one comes from fluids moving in the terrestrial outer core; a smaller effect comes from the crustal rocks; and the third contribution is due to the magnetic effects of electric currents in the ionosphere and magnetosphere. Once these contributions are considered, magnetic measurements at the seafloor provide important information on sub-seafloor magnetic and electrical properties, in terms of magnetization and conductivity. The resistivity structure underneath the observation area can be deduced from magnetic variational data taken at different periods [30,31]. Another interesting aspect is the possible connections between magnetic variations and earthquakes and tsunamis. Theoretical studies and fieldwork have shown new possibilities in these fields (e.g., [32]). In volcanic areas, a variation of the magnetic field can be due to changes in rock magnetization caused by temperature changes at depth (e.g., [33]). Magnetic field variations can be also caused by the transport of conductive fluids in a hydrothermal system [34].

A set of oceanographic devices is often installed on seafloor observatories to measure physical and chemical seawater properties. ADCPs are intended to measure the speed and direction of seawater currents, but they can also supply information on volcanic ash dynamics in seawater. An ADCP emits sound pulses and records the signal that is backscattered by the particulate matter that is naturally present in seawater (plankton or other small particles). By using the acoustic Doppler effect, the instrument derives the seawater current (velocity) profiles. A sub-product of these measurements is the echo intensity, which can be used to infer scatterer concentration in the water column [35–37]. This feature is mostly used to monitor sediment and turbidity fluxes in rivers and coastal areas, but it can also be used to detect ash fallout in seawater from volcanic explosive activity.

Italian sub-aerial volcanoes are well monitored, but, given their proximity to the sea, complementary seafloor observations are also needed. Until now, the inner structure of volcanic islands and volcanic seamounts in Italy has been mostly studied with offshore geophysical surveys.

In this paper, we focus on data acquired on the seafloor in the proximity of the volcanoes (Figure 1) by: (1) An ocean bottom seismometer placed at 1500 m b.s.l. (Beyond the Sea Level) at the toe of Stromboli Volcano; (2) A multidisciplinary observatory deployed at ~3300 m b.s.l. at the NW

base of the Marsili Seamount; (3) A multidisciplinary observatory deployed offshore of the eastern coast of Sicily, at a depth of ~2100 m, in proximity to the submerged flank of Etna Volcano.

#### 2. Seafloor Observing Systems

The strong interest in multidisciplinary observations at the seafloor is stimulating the development of marine instrumentation, and it is reasonable to expect a growth with time of sensors capabilities and scope. In addition to disciplines, such as oceanography and marine biology, that have a natural and direct interest in the sea environment, the broader climate science community, geology, seismology, geochemistry and physics are also focusing on seafloor-based measurements.

All over the world, huge infrastructures are being built to meet these scientific and technological needs (e.g., [38,39]). The European Multidisciplinary Seafloor and water-column Observatory [40] large-scale distributed Research Infrastructure (RI) is being developed [41–43] for long-term monitoring of geohazards and environmental phenomena. EMSO spans over eleven nodes, from the Arctic and Atlantic Ocean, and through the Mediterranean Sea to the Black Sea. Seafloor remote sensing with multidisciplinary observatories has been performed in the Central Mediterranean since 1998 [44].

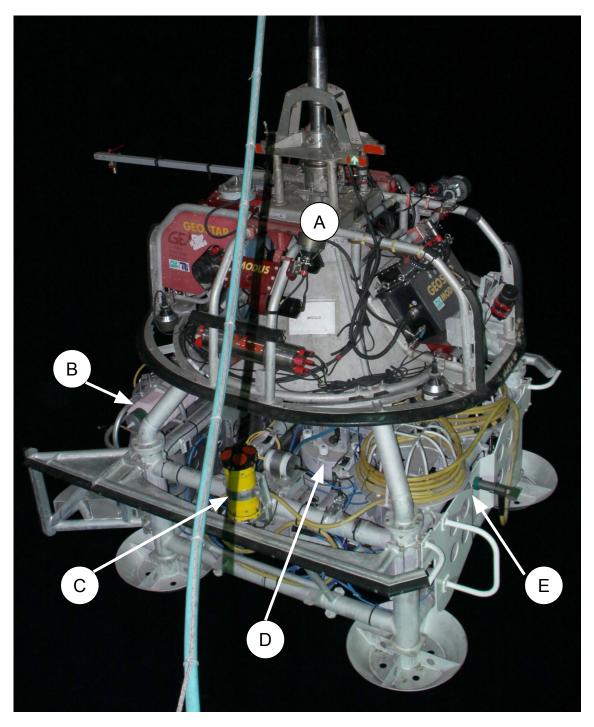
Data described and analyzed in this paper were collected by three different systems: for Stromboli by an Ocean Bottom Seismometer (OBS) part of the Tyrrhenian Deep sea Experiment (TYDE) array [14]; for the Marsili seamount, GEOSTAR (GEophysical and Oceanographic STation for Abyssal Research), a stand-alone multidisciplinary observatory; for Etna, NEMO-SN1 (NEutrino Mediterranean Observatory-Seafloor Network 1), a cabled multidisciplinary observatory [45] located at the Western Ionian EMSO node.

Data acquired from GEOSTAR and NEMO-SN1 are listed on MOIST website [46] and are available upon request. The OBS05 data were collected during the Tyrrhenian Deep sea Experiment (TYDE) European Community project (participants: Istituto Nazionale di Geofisica e Vulcanologia (INGV), Leibniz-Instituts für Meereswissenschaften (IFM-Geomar) and Hamburg University); presently, there is no defined data policy.

OBSs are robust, relatively small and light, battery-powered devices, with low-power consumption. They are formed by a seismometer, a hydrophone, a digital recorder and a release system, and they are deployed from a vessel by letting them fall to the seabed. Thus, the seismometer needs a leveling device in order to work well, even if the whole system is tilted. The release system unfastens the OBS from the ballast, letting it float to the surface at a preset time or, more frequently, by receiving a command through an acoustic modem. A GPS receiver and a radio transmitter can be present to aid recovery in case of accidental release.

Multidisciplinary stand-alone observatories, such as GEOSTAR, are also battery powered, with a limited acquisition period (usually one year) and deferred data retrieval. They are designed to host many different instruments for oceanographic, seismological and environmental monitoring. Unlike OBSs, they have bulky and heavy frames requiring complex marine operations in order to be placed at the selected site and recovered at the end of the measurement campaign. The GEOSTAR observatory is deployed on the seafloor by means of the dedicated vehicle MODUS (MObile Docker for Underwater Sciences ; Figure 2A), connected to the surface ship by an electro-optical armored cable [47]. With MODUS, it is possible to accurately set the orientation and the positioning of the station on the seafloor. The core of the observatory is the Data Acquisition and Control System (DACS) that distributes and manages power supply for all of the equipment and gathers and stores data acquired by the sensors. In order to ensure high precision data time stamping, the DACS is equipped with a low-power rubidium clock with an accuracy of  $10^{-8}$ , resulting in a drift of hundreds of milliseconds per year. The clock is synchronized by GPS before deployment, and the actual drift is accurately measured with a calibration procedure after recovery. Among all of the scientific instruments hosted by GEOSTAR, there is also a three-component broadband seismometer. It is protected from noise due to sea currents by a bell-shaped housing. After the settlement of the

observatory main frame on the seafloor, a release mechanism is operated via an acoustic link, and the seismometer falls to the ground from a height of some tens of centimeters. This procedure decouples the seismometer from the frame, removing frame vibrations as a possible noise source. The weight and shape of the sensor also ensure good coupling with the ground [48].



**Figure 2.** The NEMO-SN1 cabled multidisciplinary seafloor observatory during the deployment operations. The picture shows the MODUS vehicle (**A**), the magnetometers module (**B**), the Acoustic Doppler Current Profiler (ADCP) (**C**), the seismometer housing (**D**) and the electro-optical jumper with a Remotely-Operated Vehicle (ROV)-operable connector in its parked position (**E**). Besides other instruments, the observatory hosts also a gravimeter (not visible in the picture).

The cabled observatory NEMO-SN1 [45] has a mechanical structure similar to GEOSTAR, but with a reduced size  $(2.5 \times 2.5 \times 2.5 \text{ m})$  (Figure 2). It is connected to an electro-optical cable lying on the seabed. The cable runs from the observation site, located at an ~2100-m depth, 25 km offshore Catania, to the INFN (Istituto Nazionale di Fisica Nucleare) shore laboratories at Catania harbor. The cable provides real-time high bandwidth connection and unlimited power supply. The duration of the acquisition campaigns is constrained only by maintenance interventions. All of the scientific instruments (see Table 1) are remotely accessible and reconfigurable during the mission.

Sensor	Acquisition Rate	Vendor - Model
Triaxial broadband seismometer	100 Hz	Guralp-CMG-1T
Gravity meter	1 Hz	INAF-IAPS-prototype #2
Vectorial magnetometer	1 Hz	Sulas Company-prototype
Scalar magnetometer	1 sample/h	Marine Magnetics-Sentinel 3000
ADCP	4 profiles/h	Teledyne RD-Workhorse sentinel 600 kHz
Absolute pressure gauge	4 samples/min	Paroscientific-8CB4000-1
Digital hydrophone	2 kHz	SMID-DT-405D(V)1
Accelerometer + gyros (IMU)	100 Hz	Gladiator-Landmark 10
Conductivity, Temperature, Depth (CTD)	1 sample/h	SBE 16plus SEACAT
Three components fixed point current meter	2 Hz	Nobska-MAVS3
Differential pressure gauge	100 Hz	SCRIPPS-UCSD DPG Prototype V6.0
Hydrophone	100 Hz	OAS E-2PD
4 + 4 high frequency hydrophones	96/192 kHz	SMID-TR-401(V)1
Compass	1 Hz	Falmouth Ostar Compass

Table 1. List of scientific instrumentation on board the NEMO-SN1 observatory.

At the shore facility, event triggers, such as the tsunami detection algorithm [49], are performed; dedicated software parses and stores data locally and inserts them into the MOIST database at INGV in Rome [46]. Here, integrity checks are made, and data are made available to the public in real time. The broadband high sensitivity seismometer (Guralp CMG-1T) is a node of the Italian National Seismic Network, and it provides real-time data for civil protection purposes.

Time synchronization is obtained by a GPS receiver at the shore labs: a 1PPS (one pulse per second) signal is sent to the seabed instrumentation through the optical fiber and distributed to the seismometer digitizer and to digital hydrophones. For other instruments, working at slower sampling rates, absolute data time-stamping is made on shore. Seismological measurements are the most demanding in terms of time precision. The time difference between the on-shore GPS signal and the internal seismometer clock has a measured offset smaller than 400 ms and a null average drift with a standard deviation of 61 ms. This guarantees that time accuracy constraints are met.

To deploy the observatory and connect it to the cable termination, a Remotely-Operated Vehicle (ROV) is also needed. NEMO-SN1 is equipped with a 20-m electro-optical jumper terminated with a ROV-mateable connector (Figure 2E), coiled on the frame before connection. The bell-shaped seismometer housing and release system (Figure 2D) are the same as the ones used for GEOSTAR. A couple of scalar and vectorial magnetometers are placed on a separate module (Figure 2B) that is moved some tens of meters away by the ROV after the deployment, in order to avoid interference from the other devices.

## 3. Seafloor Observations of Volcanic Activity in the Central Mediterranean

#### 3.1. Stromboli

Stromboli is the northernmost of the seven sub-aerial volcanoes of the Aeolian islands, located in the Southern Tyrrhenian Sea (Figure 1). It is a stratovolcano, which rises about 3000 m from the seafloor and stands 924 m above the sea level. Presently, its volcanic activity has consisted of intermittent explosive activity during which gas jets and lava fragments are emitted through short eruptions lasting a few tens of seconds at a rate of 3–10 events per hour. This persistent Strombolian activity is sometimes interrupted by longer eruptions accompanied by lava effusion. These eruptions produce different types of low-frequency seismic signals, including Explosion-Quakes (EQ), Long Period events (LP) and volcanic tremors, at 0.5–5 Hz [50]. These signals are associated with magma movement: EQ are caused by the explosive contact of a magma bubble with air in the summit part of the volcano conduit; LP and tremors are associated with the movement of magma inside the conduit and cracks. LP is an impulsive signal, while tremor is continuous [50].

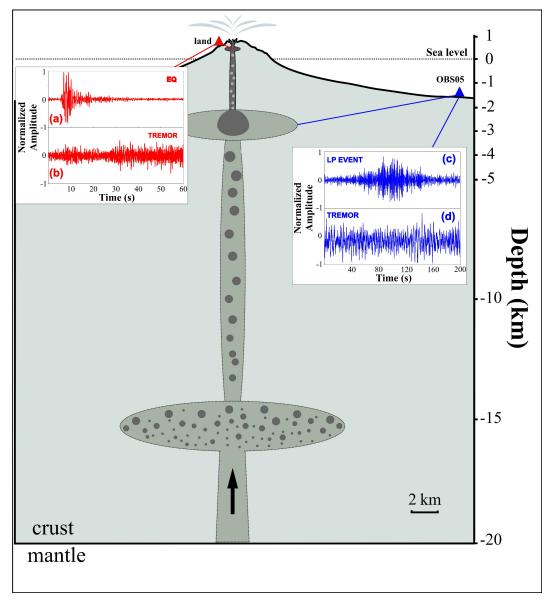
Previous studies suggested the existence for Stromboli of at least three sources placed at different depths (about 0.4, 3 and 14 km; [51–54]). These sources are continuously involved in replacing the magma associated with the gas uprising through the magmatic conduit. The buoyant, volatile, rich magma rises along the conduit from the deep reservoir, displacing the degassed magma downwards. Rising gases form a foam at the shallow source roof. The foam collapses and feeds gas slugs, which drive the explosive activity [55]. The shallow smaller reservoir directly feeds the normal Strombolian activity ([54,56]).

In spite of the great improvements of the land seismic network, the geometry of the Stromboli deep plumbing system remains poorly understood, as the seismic observations of magma storage are limited to the upper few hundred meters of the volcanic edifice, where the land stations are located.

In the period December 2000–May 2001, a network of OBS and OBH was deployed in the Southern Tyrrhenian Sea during the Tyrrhenian Deep sea Experiment (TYDE, [14]). One of the TYDE OBS (OBS05 in Figure 1) was deployed near Stromboli Volcano, at a depth of 1500 m and about 16 km SSE from the central axis of Stromboli Island. It recorded signals from earthquakes and low-frequency seismicity (LP events and tremors; [57]). At the time of the TYDE experiment, only one temporary land seismic station placed on the top of the volcano was available, installed about 100 m from the crater and at about an 800-m altitude. This station recorded volcanic tremors and EQ events, but no LP events.

Sgroi et al. [57] identified the source of the LP events (recorded by OBS05) with the magmatic reservoir at 3 km, and the source of the explosion-quakes (recorded by land station) with the 400-m reservoir. Features of seismic signals recorded by the land station and OBS05 confirm the presence of two different seismic sources (Figures 3 and 4). The EQs appear as impulsive events with a short duration and are characterized by a higher frequency content than the LP events (Figure 4), and they represent the signal generated by the explosion of gas bubbles near the surface of the volcano. The waveform and the long duration of LP events depend on scattering process of the seismic wave along the source-station path, which causes the dispersion of the waves (especially in its high frequency component). EQ, tremors and LP events show similar energy fluctuations and frequency content, which can be associated with the same dynamic process. Although there is variability in their waveforms, there is a similarity in the signal onsets and their behavior in time, which is consistent with the repetitive action of a non-destructive source. Spectra and spectrograms of signals from EQ, LP events and tremors are bimodal (Figure 4). This supports a common generating mechanism of the signals at two distinct sources. Both sources are linked to the continuous uprising of gas bubbles originating from the magmatic column at different depths. The mass removal process from the deeper part of volcanic conduits to its top is the dynamic component of an eruption. It is natural to infer that the OBS05 may be more sensitive to detecting the deeper components in the eruption process, while the land station will be more sensitive to the eruption dynamics near the surface [57].





**Figure 3.** Conceptual model of Stromboli magma feeding system. Explosion-Quakes (EQ) (**a**) and tremor (**b**) signals recorded by the land station are associated with a shallow seismic source (~400 m); Long Period (LP) events (**c**) and tremor (**d**) signals recorded by OBS05 (OBS, Ocean Bottom Seismometer) are linked to a deeper source (~3 km).

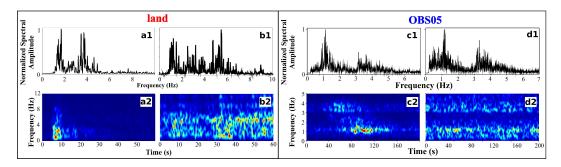


Figure 4. Spectra and spectrograms computed on the EQ event (a1, a2) and tremor (b1, b2) recorded by the land station and the LP event (c1, c2) and tremor (d1, d2) recorded by OBS05. Modified from [57].

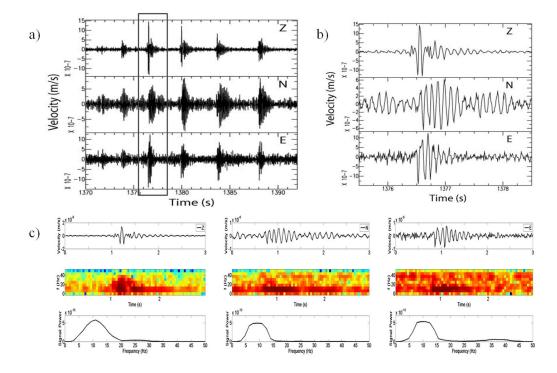
#### 3.2. Marsili Seamount

Marsili Seamount (MS; Figure 1) is about 60 km long and 20 km wide, rising about 3000 m from the seafloor at over 3500 m water depth [58] with an axis along the NNE-SSW direction (Figure 1). It lies in a complex geodynamic setting characterized by active volcanism, high heat flow values (>200 mW/m<sup>2</sup> [59]) and low values of Moho isobaths (10 km depth [60]).

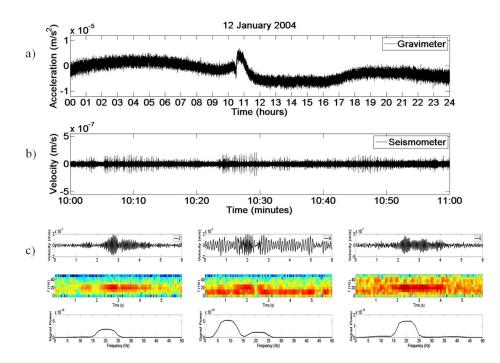
Recent stratigraphic and geochemical studies suggest that in historical times, two submarine explosive eruptions occurred at MS. This is the first evidence of explosive volcanic activity at a significant water depth (500–800 m) in the Mediterranean Sea [61]. Geophysical and morphological observations point to hydrothermal activity in the MS linked to the post volcanic activity [62–64]. The possible existence of a very large underwater explosive volcano together with some encouraging clues that point to MS as an important and possible long-lasting-renewable energy resource [65] has reinforced research and exploitation efforts. The existence of an active magmatic chamber at about 2.5 km below the summit was proposed on the basis of petrological studies of basalts [66], and it is compatible with gravimetric and magnetic data modeling [62], as well as geochemical observations on the summit [67]. High  ${}^{3}$ He/ ${}^{4}$ He anomalies observed at Marsili point to active hydrothermal circulation in several sites [68].

Geophysical monitoring at MS is not straightforward due to its large distance (>100 km) from land. The deployment of two GEOSTAR observatories at 3320 near the NW base of MS allowed for a long-term monitoring of the seamount. Previous studies have presented data collected at MS during the December 2003–April 2004 and June 2004–May 2005 campaigns [30,31,47,69–71].

During the first leg (2003–2004), the seismometer recorded a large number of earthquakes and signals not associated with tectonic events. In this paper, we focus on non-earthquake events observed at the MS that are similar to the ones observed in volcanic/hydrothermal environments [72,73]. These non-earthquake signals are impulsive and have a very short duration, and they are often called Short Duration Events (SDE). Non-earthquake seismic signals containing low energy and high frequency have also been observed by D'Alessandro et al. [64], classified as SDE, and associated with hydrothermal activity at MS. SDEs have been previously observed both in submarine in hydrothermal systems (e.g., [74]) and on land in the proximity of mud volcanoes [75]. A first type of SDE recorded at MS with the seafloor observatories has a frequency spectrum from about 5 Hz–50 Hz (seismometer Nyquist frequency), is monochromatic, with a sharp onset and a very short duration (about 0.5 s; Figure 5). Spectral analysis shows a frequency peak around 12 Hz in all seismic components with an amplitude at -150 dB. Another type of recorded SDE has a duration of about 1 s and a frequency within 12–20 Hz. In Figure 6, we show a short time interval in which SDEs occurred simultaneously with a positive, slow (few hours), gravimetric variation. Given that the gravity field is proportional to the density of subsurface materials, it was possible to associate these gravity variation signals with a mass redistribution occurring close to the site [47,70]. Similar gravity variations lasting a few hours were also recorded by Etna land stations simultaneously with an increase of seismic tremors and explained as being due to mass rearrangement within the volcano [23]. This gravimetric variation was only observed at MS twice during the first leg. Due to the rare occurrence of these signals, longer time series are necessary to perform a significant statistical analysis and to check if this gravity variation can be associated with changes in the seismic signals (such as SDE generation).



**Figure 5.** (a) Example of Short Duration seismic Event (SDE) signals recorded at Marsili Seamount in the Tyrrhenian Sea; (b) vertical (Z) and horizontal (N and E) seismic components waveform of a energetic SDE; (c) waveform spectrogram and Power Spectral Density (PSD) of the same energetic SDE. The traces were high-pass Butterworth filtered with a corner frequency of 5 Hz and four poles.



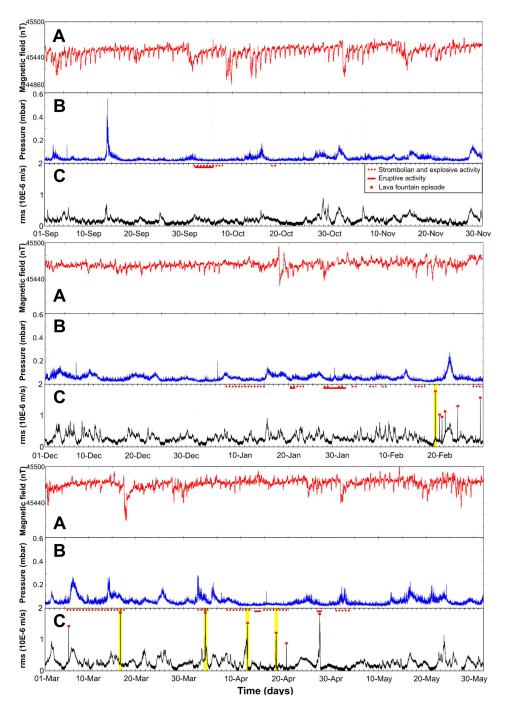
**Figure 6.** (a) Acceleration time series recorded by the gravimeter at Marsili Seamount on 12 January 2004. The temperature effect on the gravimetric data was removed applying a deconvolution method [71]. (b) One hour of the vertical seismic component, high-pass filtered at 5 Hz, recorded during the acceleration variation at about 10:00 a.m. (c) Waveform spectrogram and Power Spectral Density (PSD) of a high frequency seismic signal.

Further evidence in support of hydrothermal activity at MS came from magnetic data modeling. It was possible to estimate the changes in the time of conductivity likely caused by fluid motion below or inside the volcano edifice [31].

#### 3.3. Etna

Mt. Etna is a large basaltic composite volcano, with a maximum diameter of about 45 km and an elevation of 3350 m. The eastern flank extends under the sea surface down to 2000 m b.s.l. Mt. Etna is characterized by an almost persistent activity since 600 ka (Kiloannum). [76] that in the past has caused large destruction in eastern Sicily. At present, its activity is mostly localized in the higher part of the volcanic edifice. It is very well monitored on land, with several geophysical networks installed on top of its sub-aerial part. Although the eruption dynamics of Etna are well known, the deep geometry of its plumbing system is still poorly understood. In fact, knowledge of the magma storage zones is mainly limited to the part of the volcanic edifice above sea level, where geophysical stations are present. The dense instrumental on-land coverage needs to be integrated with measurements on the seafloor, especially at the base of the Malta Escarpment, an important morphological feature that corresponds to tectonic structures intersecting Etna (Figure 1). Previous work pointed out a deep magmatic source and a deep feeding system that possibly originates below the Malta Escarpment (e.g., [77,78]). The volume of volatiles produced by Etna implies the existence of a large magmatic source [52], but their short transition times exclude a magma chamber [79,80]. Hirn et al. [78] resolve this conflict by proposing a melt lens situated on the top of an upwelling shallow mantle, with an important role played by normal faulting and crustal spreading, as well as vertical movement at the edge of the Ionian slab. The existence of a deep source below Etna, at about a 20-km depth, was also proposed by Sharp et al. [77] on the basis of deep sounding techniques. A 3D tomography study that included data from the TYDE OBS array confirmed this result by imaging a strong P-wave low velocity anomaly at the crust-mantle interface below Etna [16].

A multi-parameter analysis of long-term time series data helps us identify the origin of volcanic processes and variations that are associated with volcanic activity. We continue a previously-published analysis [72]. Figure 7 shows a nine month-long simultaneous recording of three parameters at the NEMO-SN1 site. With respect to [72], we added the magnitude of the magnetic field (Figure 7A) along with the water pressure standard deviation computed on a five-minute moving time window (Figure 7B) and the root mean squared of the horizontal component of the ground velocity computed on a 1-min window (Figure 7C). This choice of time windowing allowed us to easily link signals recorded by the pressure sensor and the seismometer and to associate them with a common physical source. The comparison showed that some of the peaks of the pressure signal were also visible in the seismic signal, so we interpreted this energy as being due to the effect of the water column. The peaks that are seen only in the seismic data, and not on the pressure data, are very likely due to Etna's activity, as confirmed by land observations [72].

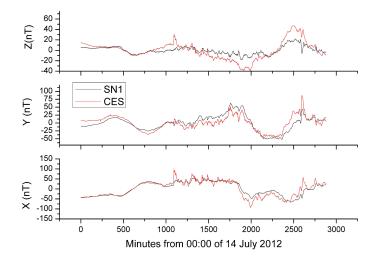


**Figure 7.** Time series of three parameters at NEMO-SN1: (**A**) magnetic field magnitude; (**B**) water pressure standard deviation computed on a five-minute moving window; (**C**) ground velocity rms. Events that affected the ESE sector of Etna are marked in yellow. Series (**A**) is previously unpublished; series (**B**) and (**C**) are modified from [72].

On the other hand, a simple comparison between the geomagnetic signal (Figure 7A) and the other two parameters could lead to possible misinterpretations on the basis of an apparent correlation (simultaneous peaks). It is very likely that changes in the geomagnetic field at the Earth's surface (in this, case at the seafloor) are the response to the external coupling with the solar activity and not driven by Etna's activity.

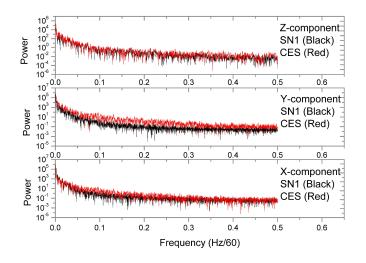
The water column acts as a low-pass filter for the magnetic signal components that are generated above the sea level. Since magnetic sources linked to Etna's activity are below the seafloor,

their signals are not affected by seawater screening. This filtering effect enhances the S/N ratio for the Etna signals generated below the seafloor. Figure 8 shows the behavior in time of the X,Y and Z magnetic components as recorded at the NEMO-SN1 seafloor observatory (SN1; black lines), compared to recordings taken at Cesarò magnetic station (CES; red lines), close to Etna Volcano (Figure 1). NEMO-SN1 records show a smoother behavior with respect to the ones from Cesarò station (CES).



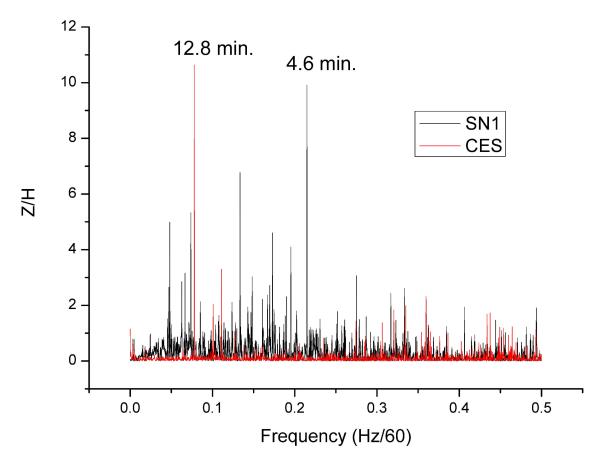
**Figure 8.** X,Y and Z magnetic components as recorded for the NEMO-SN1 seafloor observatory (SN1; black lines) and the Cesarò land magnetic station (CES; red lines).

The screening effect of seawater is further exemplified in Figure 9, which shows the comparison of the geomagnetic field power spectra of NEMO-SN1 and CES. The SN1 power spectra have a significantly lower plateau compared to CES, especially on the horizontal components. Furthermore, the magnetic signal recorded at the seafloor is much cleaner than those typically recorded on land, where artificial (mainly man-made) noise partly overlaps with part of the geomagnetic signal.



**Figure 9.** Geomagnetic field power spectra for NEMO-SN1 (SN1) seafloor observatory and Cesarò land station (CES).

The power spectral ratio Z/H, where H=X+Y is the power of the H component (X and Y are the spectral power of the horizontal magnetic field components), provides information on the electrical resistivity distribution underneath the measurement site. Although the relation between this ratio and resistivity is rather complex, in the first approximation, large values of Z/H at short (or long) periods are associated with larger resistivity at shallow (or deep) layers. Figure 10 shows the comparison of the two Z/H power spectral ratios. The largest peak for NEMO-SN1 is at a 4.6-min period, while for CES, it is at 12.8 min. This simple comparison shows that the resistivity contrast underneath the NEMO-SN1 site is much shallower than underneath CES. This can be explained by the NEMO-SN1 being closer to conductive layers under Etna Volcano.

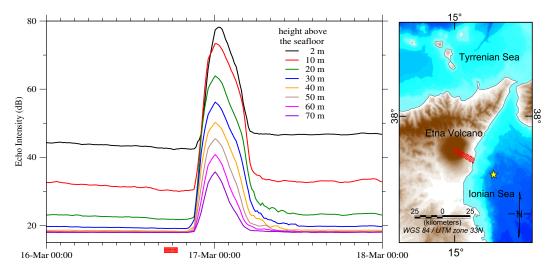


**Figure 10.** Spectral ratio between the Z (vertical) and H (horizontal) components of the geomagnetic field recorded at NEMO-SN1 (SN1) and Cesarò land station (CES).

Conductive layers can be associated with the motion of fluids within the volcano edifice. The presence of fluids in superficial layers of the Malta Escarpment has been also deduced by the observation at the NEMO-SN1 site of SDEs, similar to the ones observed at Marsili [72]. SDEs recorded by NEMO-SN1 have a high frequency (from about 10 Hz–50 Hz, the seismometer Nyquist frequency) and short duration (1–3 s). The production of SDE has been associated with stress changes caused by increased underground movement of magmatic fluids at Etna. In particular, the SDEs have been interpreted as hydraulic fracturing due to the fluid-filled carbonate outcrops [72].

Another interesting signal, observed at NEMO-SN1 during the occurrence of lava fountain episodes, is volcanic tremors, a continuous low-frequency seismic signal typically found in volcanic areas [72]. Large amounts of volcanic ash are released into the atmosphere during Etna eruptive events. The volcano's proximity to the sea means that the transport of volcanic ashes also involves sea dynamics in the dispersion of particulate matter and sedimentation in the water column. This process

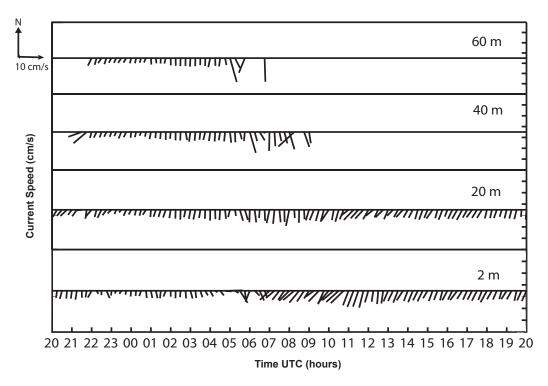
was recorded by the NEMO-SN1 observatory during the 2013 Etna pyroclastic activity. In fact, the tremor pattern recorded at NEMO-SN1 highlights 13 lava fountain episodes that took place during the 2013 Etna eruption (Figure 7, red asterisks). Among these episodes, only five affected the ESE sector of Etna (events marked in yellow in Figure 7C). Each of these fountain episodes had different amplitudes and time durations and was accompanied by an increase in tremor amplitude related to the evolution of the eruptive activity [81]. The 16 March event was classified as one of the most violent paroxysm recorded on 2013 in the SE sector of Etna Volcano. It provides a good example of how the effects of this volcanic activity in the water column can be documented by an ADCP installed at the deep water layer. The ADCP mounted on NEMO-SN1 (Figure 2C) was designed only to monitor possible variations of local deep currents. In fact, it was configured only for the acquisition of current speed and direction in the few tens of meters of the water column above the station (about 30–60 m), and no appropriate calibration was performed to measure the concentration of suspended matter. ADCP echo intensity normally increases with the concentration of particulate matter in the water and decreases with distance from the detector. Figure 11 (left panel) shows the detectable echo intensity (i.e., above the noise level) up to a distance of about 30 m until 20 h UTC on 16 March 2013, when, due to the presence of volcanic ash, the echo intensity strongly increases up to a distance of 70 m from the seafloor. The eruptive activity started around 17:00 UTC with discontinuous lava fountains that progressively increased in height and intensity. Meanwhile, the content of pyroclastic material (ash and lapilli) increases within the eruption cloud, which is driven southeastwards by the wind. The pyroclastic event lasted about two hours, covering the southeastern slope of Etna with abundant fallout of pyroclastic material. The ashes emitted within this period reached the sea bottom layer three hours later. The ADCP data show a fallout peak lasting more than eight hours with a tail of smaller intensity that is still present after 24 h. The map in the right panel of Figure 11 shows the location of the NEMO-SN1 observatory (yellow star) and Etna Volcano. The red shaded area shows the ash dispersion field [82], which is pointing toward the seafloor observatory.



**Figure 11. Left panel**: the detection of Etna ash fallout on the seafloor at the NEMO-SN1 site by the ADCP echo intensity profile at various heights from the observatory during 48 h. Ash volcanic emission at the Etna Volcano site is represented by the red box. **Right panel**: map of the Etna Volcano region and location of the NEMO-SN1 observatory (yellow star). The red dashed area pointing ESE from top of volcano corresponds to the land area where ash fallout was documented (adapted from [82]). The bathymetric metadata and digital terrain model data products were derived from The General Bathymetric Chart of the Oceans, GEBCO\_2014 Grid [83].

Stick diagrams of hourly current data show a prevalent flow steadily oriented southwards through the bottom layers and an average speed of around 10 cm/s (Figure 12). The sea bottom

current appears essentially barotropic (*i.e.*, depth independent with levels of constant pressure parallel to surfaces of constant density) with a strongly polarized flow [84,85]. No significant fluctuations in current direction were recorded, so that the dispersion of particulate matter, at least in the deep layers, can be considered negligible. The analysis of the echo intensity of the backscattered signal along with the seismological and oceanographic data allowed for a multidisciplinary study combining Etna eruptive activity together with the sedimentation process and the local ocean current regime [86].



**Figure 12.** Stick diagram of hourly filtered current data showing the arrangement of the current in the deepest layers after 20:00 UTC of 16 March 2013. Sticks refer to speed and direction variations at a specific time. The length of sticks is scaled to current speed and shows higher speeds in layers that are farther from the bottom. The direction is relative to true north and shows a predominant current flow southward through all of the detected bottom layers.

### 4. Conclusions

At the seafloor, it is possible to record significant volcano-related signals closer to their sources. Seismic data recorded by even a single OBS gave us information on the Stromboli Volcano structure. In this case, the OBS was more sensitive to deeper processes within the volcano conduit with respect to a land seismometer. Thanks to the comparison between the signals from the two instruments, it was possible to identify two different sources (at two different depths) for LP and EQ seismic signals. The use of a tight array of sensors around Stromboli would greatly improve our knowledge of its deeper structure.

Remote sensing from the seafloor is an obvious necessity in the case of a submerged volcano that has activity undetected from land, such as the Marsili Seamount. Multi-parametric observations from a seafloor observatory suggested that the Marsili Seamount is very likely a hydrothermal system. The motion of fluid below or inside the volcano edifice was inferred by magnetic data modeling. Seismological data combined with gravimetric data show signals that are typically associated with hydrothermal activity. In particular, SDEs were observed during a variation in gravity and an increase of high frequency seismic noise. Although these gravimetric variations have been observed only a few times at Marsili during the recording period, similar signals have been detected at other volcanoes, including Etna and Stromboli, and have been linked to mass rearrangement within the volcano. The exploration of Marsili (that shows low-energy and sporadic activity) requires an increase of observation time. Longer data series would allow for reliable statistical analyses and for the evaluation of possible correlations between different parameters.

The on-going intensive improvement of the size and capability of underwater scientific infrastructures allows us to foresee this evolution in the near future.

The seafloor environment can have both a favorable and a negative impact on measurements. Some instruments, such as magnetometers and gravimeters, benefit from lower temperature variations at the seafloor compared to land sites, especially at high water depths [87]. The water column acts as a shield for magnetic signals that propagate from above the sea surface [70], enhancing the sensitivity to the signals that are generated by the volcano below the seafloor. Another positive effect, observed at remote seafloor sites, is the reduction of man-made seismic noise (at frequencies f > 1 Hz). On the other hand, the seafloor presents noise sources that are not present on land, such as sea currents and tides, that affect geophysical instruments (e.g., [48,88,89]). Furthermore, making observations on the seafloor and in the water column presents several technical challenges, due to pressure, corrosion, *etc*.

In the case of volcanoes that have part of their structure under the sea, observation from the seafloor is also necessary to complement land and satellite observations. At the Etna site, long-term multi-parametric observation is possible thanks to a cabled EMSO node, where the NEMO-SN1 observatory is connected. The comparison of the tremor signals recorded at this site with the signals recorded by land seismometers supports the hypothesis of an offshore location for the roots of the Mt. Etna feeding system. Small bursts of high frequency seismic energy (SDE) have been detected at the Malta Escarpment. Variation of SDE energy is a promising parameter, as it could be driven by stress changes associated with Etna activity. The differences between the magnetometric observations from NEMO-SN1 and the ones from a land-based instrument can be explained with a shallower resistivity contrast of the seafloor site. This shallow contrast is likely due to fluid circulation linked to the Etna plumbing system. Further analysis with the application of an inversion technique could provide more complete information on the deeper structure underlying the NEMO-SN1 site.

Long-term sea-based observations are the only possible way to directly observe the dynamics of some volcanic processes, such as ash dispersion in seawater. For the first time, we documented the fallout of Etna volcanic ash in the water column during the 2013 eruption. Thanks to a multi-parameter approach, we were able to document the whole chain of events, from the explosion, the ash emission, to the fallout in the water column and, finally, to its sedimentation at the benthic layer.

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**Author Contributions:** Gabriele Giovanetti and Stephen Monna organized the manuscript and edited and integrated the contributions from other authors. Stephen Monna and Tiziana Sgroi worked on Etna seafloor seismic data. Caterina Montuori and Mariagrazia De Caro performed the data analysis and wrote the contribution for the Marsili Seamount. Tiziana Sgroi performed the data analysis and wrote the contribution for Stromboli Volcano. Davide Embriaco and Nadia Lo Bue performed the data analysis and wrote the contribution about Etna ash fallout recorded by ADCP. Angelo De Santis and Gianfranco Cianchini performed the data analysis and wrote the contribution of the study area. Giuditta Marinaro, Gabriele Giovanetti and Davide Embriaco are in charge of the data acquisition chain of multidisciplinary observatories, from the underwater sensors to the ICT facilities, and wrote the technical descriptions. Paolo Favali and Laura Beranzoli coordinated the projects within which the experiments were performed and, more in general, the research, and they revised the manuscript. Stephen Monna, Nadia Lo Bue, Davide Embriaco, Tiziana Sgroi and Angelo De Santis performed the multidisciplinary analysis of the data.

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