Seismic Sensors Probe Lipari's Underground Plumbing

An international team of scientists installed a novel, dense network of 48 seismic sensors on the island of Lipari to invest active magma system underground.

The magma system underneath the island of Lipari, shown here, is connected to a regional fault system formed by tectonic activity rather than to volcanoes lik and Stromboli. A research team recently deployed a dense network of seismic sensors to investigate Lipari's unusual setting. Credit: F. Di Luccio

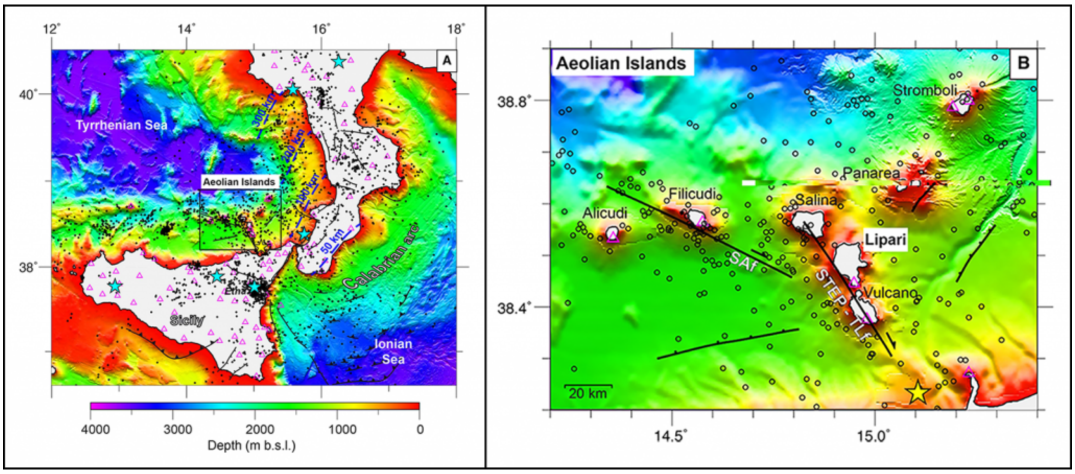
By Francesca Di Luccio, Patricia Persaud, Luigi Cucci, Alessandra Esposito, Guido Ventura, and Robert W. Clayton 20 hours ago

Just north of the island of Sicily, near the toe of Italy's "boot," a chain of volcanic islands traces a delicate arc in the Mediterranean Sea. This chain, the Aeolian popular tourist resorts in proximity to some of Earth's most active and well-known volcanoes, including Etna and Stromboli. Lipari, the largest of these islands of the island of Vulcano, for which these eruptive features are named. Lipari is less well characterized than some of the other nearby volcanoes, but one researc setting out to change this.

This is the first time that a dense seismic array has been deployed to investigate a hydrothermal system in the volcanically active Aeolian Islands.

Lipari is located ~80 kilometers north of the well-monitored Etna volcano. The island's hydrothermal system, in which magma heats the water underground, i to eruptive centers, but, rather, is connected to the regional fault system that delimits the western boundary of the active Ionian subduction zone.

Lipari holds a unique place in our understanding of the tectonic evolution and hydrothermal activity of volcanoes emplaced in subduction zones (https://eos.org/ updates/understanding-volcanic-eruptions-where-plates-meet). Within the framework of the ring-shaped Aeolian arc, the unexpected NNW–SSE alignment of Lipari and been related to a major regional discontinuity, the Tindari-Letojanni (https://www.researchgate.net/publication/311738886_Structural_architecture_and_active_deformation_pattern_in_the_northern_sector_of_the_Aeolian-Tindari-Letojanni_fault_system_SE_Tyrrhenian_Sea-NE_Sicily_from_integrated_analysis_of_field_marine_geophys) subduction transform edge propagator (STEP (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2015JB012202)) fault, a tear in a tectonic plate that allows one part of the plate to plunge downward while an ad remains on the surface (Figure 1).



(https://eos.org/wp-content/uploads/2019/05/seismic-sensor-array-tectonic-bathymetric-maps-italy-aeolian-islandsy.png?x64983)

Fig. 1. These tectonic and bathymetric maps show (a) southern Italy and (b) the Aeolian Islands. The bathymetric data are from *Ryan et al.* (https://doi.org/10.1029/2008GC002332) [2009]. Major faults are shown as black lines. Regional earthquakes larger than magnitude 3 (black dots) were recorded over the past 3 decades by the permanent Italian seismic network (http://cnt.rm.ingv.it/) (magenta triangles). Events larger than M 3 that occurred in the time window of the current experiment are shown as cyan stars. The yellow star off the northeastern coast of Sicily shows the location of the 1 November 2018 M_L 3.2 earthquake whose waveforms are shown in the left-hand plot of Figure 3. In Figure 1a, blue dashed lines in the Tyrrhenian Sea indicate the isodepths (50, 100, 200, and 300 kilometers) of the slab [*Barreca et al.* (https://doi.org/10.1016/j.jog.2014.07.003), 2014]. Shown in Figure 1b are the locations of Lipari, the Sisifo-Alicudi fault (SAf), and the Tindari-Letojanni STEP fault (STEP-TLf). Click image for larger version.

One innovative way to monitor the deep and shallow dynamics of magmatic systems is to deploy dense arrays of seismic sensors over active volcanoes [*Hanser* (https://doi.org/10.1002/2015GL064848), 2015; *Ward and Lin* (https://doi.org/10.1785/0220170051), 2017; *Farrell et al.*, 2018]. Thus, to understand Lipari's unusual setti a dense array comprising 48 wireless, self-contained seismic instruments. This is the first time that a dense seismic array has been deployed to investigate a hy system in the volcanically active Aeolian Islands and the volcanism in the proximity of a STEP fault.

Transporting the seismic sensors, called nodes, to Lipari required a transatlantic shipment from Louisiana State University (LSU) to Istituto Nazionale di Geof Vulcanologia (INGV) in Rome, followed by a ferry trip to Lipari. Over the course of 2 days, two crews of two people each placed 48 instruments, spaced ~0.1–1 apart, in a wide variety of locales: with homeowners and hotel owners, at the Lipari observatory, on the sides of streets, and buried in the near surface beneath centimeters of soil (Figure 2).

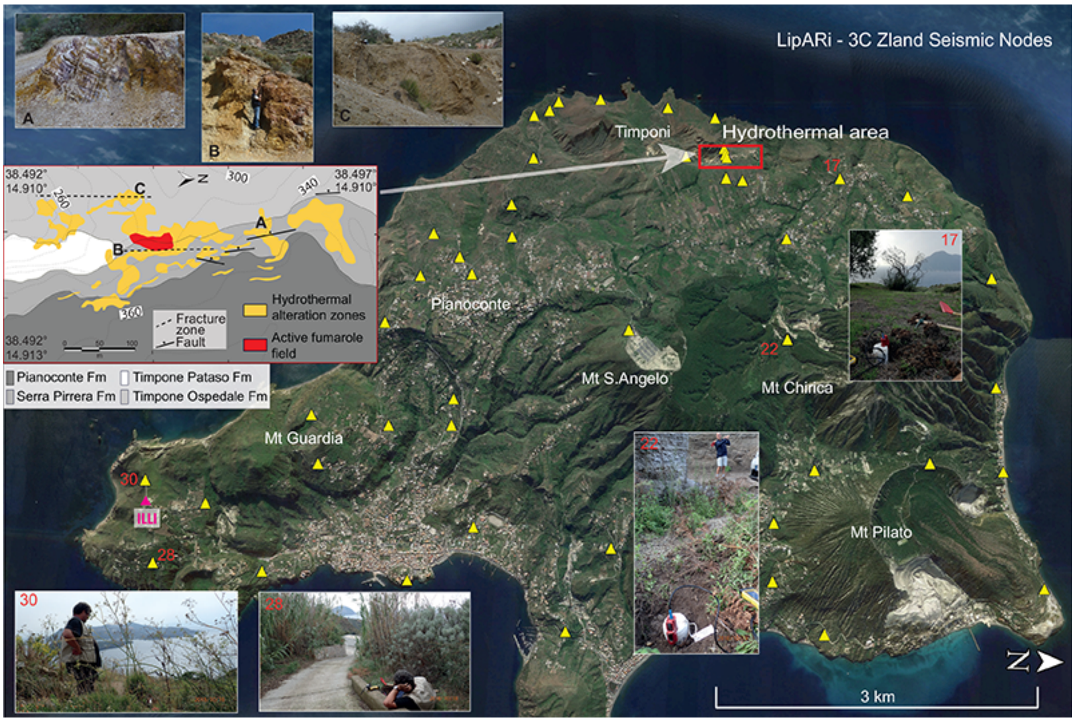


Fig. 2. Three-dimensional perspective view of a Google Earth map of Lipari Island, which covers an area of about 35 square kilometers. The last eruption on this island was in 1220 CE at Monte Pilato. The locations of the ZLand three-component seismic nodes are shown as yellow triangles. A magenta triangle indicates broadband station ILLI of the Italian permanent seismic network. Site photos taken at selected locations are also shown. The inset shows a detailed map of the hydrothermal area (modified from *Cucci et al.* (https://doi.org/10.1038/s41598-017-00230-8) [2017]) and the locations of photos A, B, and C, which characterize the hydrothermal alteration.

Researchers from INGV in Rome, the Department of Geology and Geophysics at LSU, and the Seismological Laboratory of the California Institute of Technolog
48 FairfieldNodal ZLand three-component nodes, which have a 5-hertz corner frequency. The nodes recorded one data point every 4 milliseconds from 16 Octo
November 2018.

After their transatlantic voyage from Louisiana to Rome, seismic sensors await a ferry trip to Lipari. Credit: A. Esposito

Lipari's Tectonic Neighborhood

Lipari Island belongs to the Aeolian archipelago, a group of subaerial and submarine volcanoes located in southern Italy between the southern Tyrrhenian Sea and the Calabrian Arc, an orogenic belt (https://www.sciencedirect.com/topics/earth-and-planetary-sciences/orogenic-belt) affected by late Quaternary extensional tectonics. SSE Lipari-Vulcano alignment (Figure 1) coincides with the regional tectonic boundary of the Ionian Sea–Calabrian Arc subduction system that is marked by t Letojanni STEP fault [*Barreca et al.* (https://doi.org/10.1016/j.jog.2014.07.003), 2014].

To the west of the archipelago, the WNW–ESE oriented Sisifo-Alicudi fault accommodates shortening related to the eastern termination of the contractional b
The Tindari-Letojanni and Sisifo-Alicudi fault systems are characterized by shallow seismicity, at depths of less than 25 kilometers, and recorded earthquakes

including the *M* 4.7 Ferruzzano earthquake in 1978 [*Gasparini et al.* (https://doi.org/10.1016/0040-1951(82)90163-9), 1982].

The Aeolian volcanoes, emplaced on 15- to 20-kilometer-thick continental crust, are the most recent evidence of the magmatism that started during the Pliocer 2.6 million years ago). This magmatism started in the central sectors of the Tyrrhenian Sea and migrated southeastward toward the Calabrian Arc.

From about 1 million years ago to the present time, the volcanoes have been producing magma with calc-alkaline (https://www.tandfonline.com/doi/abs/10.2747/0020- shoshonitic (https://www.sciencedirect.com/science/article/pii/0024493780900675), and alkaline potassic (http://www.alexstrekeisen.it/english/provincie/aeolianarc.php) compositi *al.* (https://doi.org/10.1029/2003TC001506), 2003; *Barreca et al.* (https://doi.org/10.1016/j.jog.2014.07.003), 2014]. The geochemical affinity of these rocks and the deep se (reaching depths of 550 kilometers) in the southern Tyrrhenian Sea indicate that the Aeolian Islands represent a volcanic arc related to the subduction and roll Ionian slab beneath the Calabrian Arc [*Milano et al.* (https://doi.org/10.1016/0040-1951(94)90139-2), 1994; *De Astis et al.* (https://doi.org/10.1029/2003TC001506), 2003].

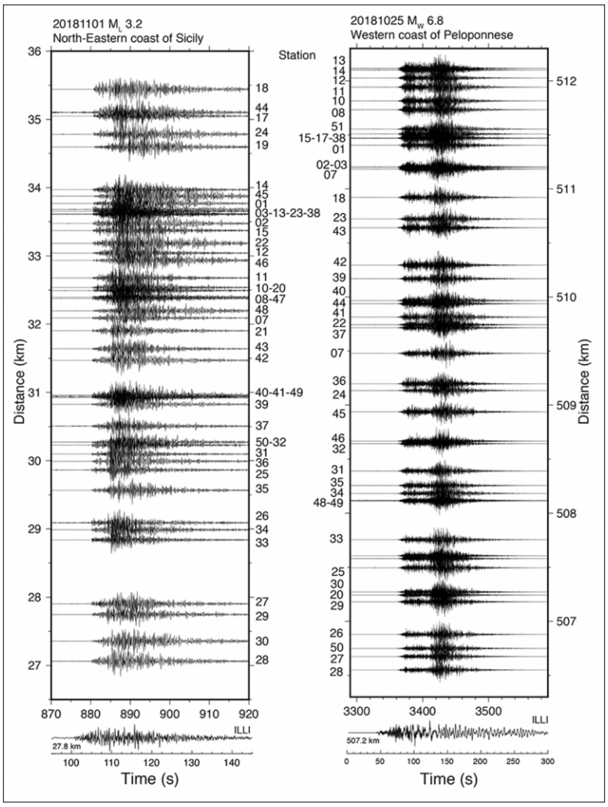
Early volcanic activity at Lipari ejected lava and rocks into the air, but today, geothermally heated water is more common. Credit: L. Cucci

Early volcanic activity on Lipari (150,000 years ago and earlier) was concentrated in the western part of the island and focused along north–south aligned vent between 119,000 and 81,000 years ago, the Sant'Angelo and Monte Chirica volcanoes deposited lava and pyroclastics (https://eos.org/editors-vox/caught-on-camera-vo flight) (volcanic material that is forcibly ejected into the air) in the central sector of the island (Figure 2).

Hydrothermalism on Lipari is not associated with centers of recent volcanic activity, and fluid pathways are strictly controlled by faults and fractures.
From 42,000 years ago to 1220 CE, the activity was concentrated in the southern and northern sectors. This activity included pyroclastics related to subplinian (https://www.sciencedirect.com/science/article/pii/B9780123859389000298), domes, and lava flows. Currently, hydrothermal activity (the expulsion of geothermally heate characterizes Lipari, Vulcano, and areas offshore of Panarea and Salina. The Lipari hydrothermal field (approximately 0.5 × 0.15 kilometer; see inset in Figure along a north–south striking alteration belt in the western and older sector of the island and is characterized by gypsum-filled veins, normal faults with a preva SSE to north–south strike, and active fumaroles (https://eos.org/research-spotlights/looking-inside-an-active-italian-volcano).

Hydrothermalism on Lipari is not associated with centers of recent volcanic activity (less than 40,000 years old), and fluid pathways are strictly controlled by f fractures [*Cucci et al.* (https://doi.org/10.1038/s41598-017-00230-8), 2017]. Vein networks of gypsum (a type of sulfur mineral) affect the hydrothermal system in the scorias of the oldest Timponi volcanoes, the overlying pyroclastics of Monte Sant'Angelo, the 27,000-year-old Pianoconte pyroclastic deposits, and the present in Figure 2). The hydrothermal alteration process has been going on for less than 27,000 years and is still active [*Cucci et al.* (https://doi.org/10.1038/s41598-017-00

A Mountain of Data



(https://eos.org/wp-content/uploads/2019/05/lipari-aeolian-islands-seismic-sensors-seismograms-earthquakes.png?x64983)

Fig. 3. Seismograms from two earthquakes at local (left) and regional (right) distances recorded at the Lipari array. Vertical components of the ground velocity are low-pass filtered at 5 and 2 hertz for the M_L 3.2 and M_W 6.8 magnitude events, respectively, to improve the signal-to-noise ratio. Waveforms at the bottom of each plot are the seismograms of the two events recorded by the permanent broadband seismic station ILLI located on the southern tip of Lipari, as shown in Figure 1b, with numbers in bottom left corners indicating the epicentral distances. Click image for larger version.

We collected more than 300 gigabytes of data, which include local, regional, and teleseismic (distant) earthquakes as well as ambient noise and volcanic tremo
the period of the experiment, about 50 earthquakes occurred within 100 kilometers of Lipari. Half of these had magnitudes of less than 2, but we also recorded
larger than M 5 that occurred in the region and farther away. In Figure 3, we show two examples of recorded seismic waveforms from an M_L 3.2 local earthqua
6.8 regional earthquake.

We aim to investigate in detail the crust and upper mantle beneath Lipari Island using receiver functions (http://eqseis.geosc.psu.edu/~cammon/HTML/RftnDocs/rftn01.
characterize Earth's structural response near the instrument and regional tomography (http://eost.u-strasbg.fr/semipgs/Sergei_Lebedev_Strasbourg.pdf) to construct a th
dimensional image of Earth's nearby interior. We will also analyze ambient noise (https://eos.org/meeting-reports/extending-recent-seismic-imaging-successes-to-south-ameri
volcanic tremors.

We plan to merge the seismic data set with other observables such as geochemical measurements and structural data to get a more robust and complete pictur
setting. We will apply modern and sophisticated processing and analysis techniques used in seismological studies to the nodal seismic array data.

The deployment of nodal arrays fills a unique niche in monitoring active volcanoes. In comparison to traditional portable seismic stations, nodal arrays enable
data set to be obtained over a short deployment period, at lower costs, with easier site selection capabilities, and with easy and quick installation procedures.

Our collaborative field experiment is the latest vehicle for learning about the seismic structure of Lipari and an excellent approach to linking the unrest at dept
and hydrothermal activity at the surface in similar settings. This project will contribute to the evaluation of the geohazards of the Mediterranean region, where
Eurasian plates converge.

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