

How can we use seismic tomography to understand volcanic degassing?

- The islands of Vulcano and Lipari are part of a volcanic archipelago, named Aeolian Islands, in Southern Italy.
- A major degassing crisis recently occurred, causing the temporary evacuation of some sectors of Vulcano Island.
- Geophysicists can use the seismic waves from crustal local earthquakes to create a picture of the underground volcanic system.
- Dr Cristina Totaro and the geophysics team of the University of Messina identified a gas anomaly beneath Vulcano that is driving degassing activity.

Volcanoes are among the most fascinating natural hazards on Earth. Volcanic activity can range from small hydrothermal vents releasing hot water on the ocean floor to major explosive eruptions of lava and gases. There are long-lasting effusive eruptions on the volcano Kīlauea in Hawaii, where lava has flowed continuously over many years, and no less dangerous are the bubbling mud pools and shooting geysers that hint at magma chambers below the ground. These activities on the Earth's surface are just a part of the complex volcanic systems beneath the Earth's crust.

Volcanic systems include magma chambers deep underground and a network of fissures and channels along which it can travel, along with areas of gas buildup. However, scientists are unable to see directly into the depths of a volcanic system to know exactly what features there are and how they interact. While volcanologists can analyse erupted materials to understand the chemical composition of magma – which can tell us about the type of eruption that could occur – we need to be able to monitor what an active volcanic system is doing in the present day so that local communities can be prepared for a future eruption. For this, we also need to understand how gases and fluids distribution influence volcanic activity.

Clues from local earthquakes

The movement of magma or gasses through a volcanic system causes vibrations and earthquakes. The vibrations from earthquakes spread across the Earth's surface in elastic waves, known as seismic waves, and scientists can study the volcanic system by intercepting these waves and recording their arrival times at a seismometer.

Seismic tomography helps geophysicists to picture the volcanic structure within the crust by identifying velocity anomalies.

This technique, known as seismic tomography, helps geophysicists to picture the volcanic structure within the crust by analysing the variations in the seismic wave velocity below the surface. Regions with high concentrations of gases will furnish different signatures in seismic wave velocity with respect to areas rich in magma.

Dr Cristina Totaro at Messina University is a specialist in the tomographic investigation in volcanic and tectonic frameworks. She and her colleagues obtain 3D seismic velocity models of the Lipari-Vulcano complex in Italy by using data collected from earthquakes. Their model, improving and refining the knowledge on crustal structure, has shed new light on this complex volcanic system, helping to better understand its behaviour.

Southern Italy's Aeolian Archipelago

Lipari and Vulcano are two of seven islands that form the Aeolian Archipelago in southern Italy. Located in the southern Tyrrhenian Sea, part of the area is crossed by a volcanic band which includes Lipari and Vulcano, an active volcanic system.

Over the last decade, the area has experienced large hydrothermal activity (fluids circulation within Earth's crust, transferring heat



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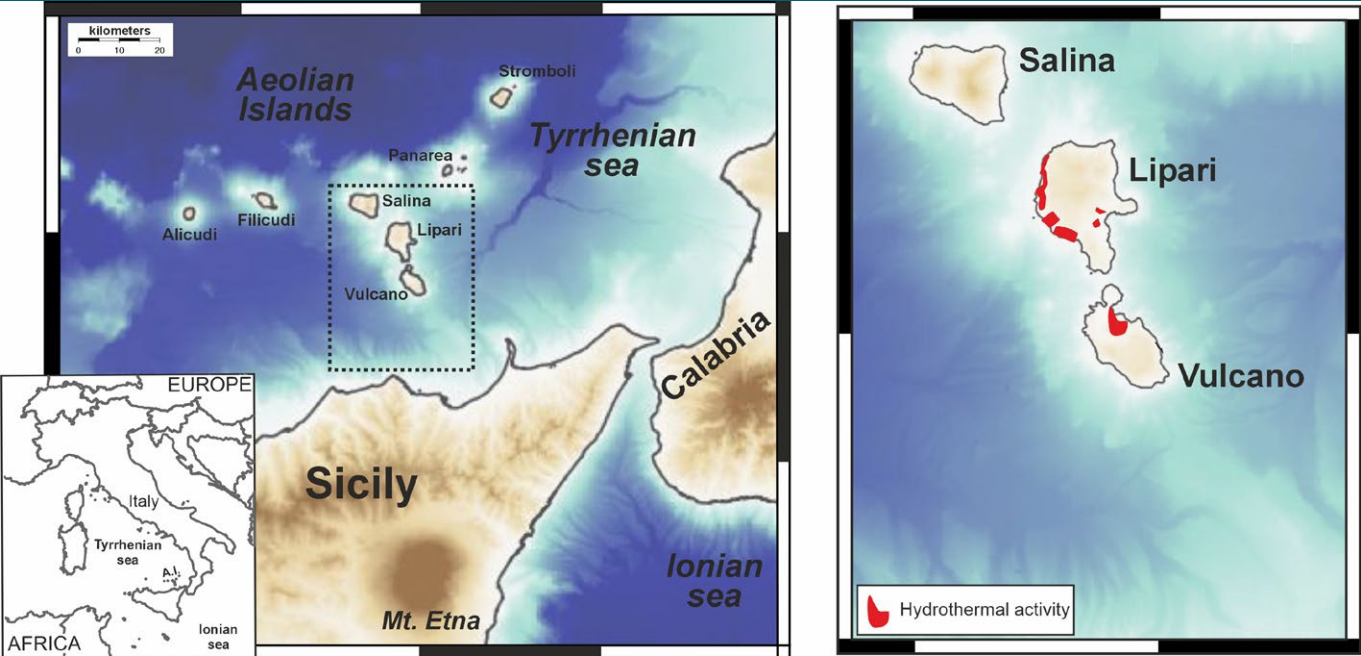


Figure 1. Left: Map view of the Southern Tyrrhenian region showing the area including northern Sicily, southern Calabria and the Aeolian Islands (in the inset, a wider sight of the central Mediterranean region). Right: Enlarged view of the area of main interest of this paper. The location of the hydrothermalized sources (red areas) is also reported.

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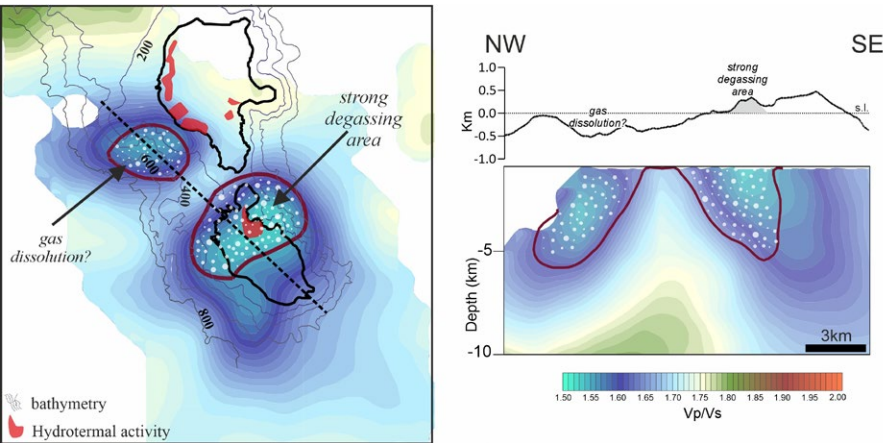


Figure 2. Sketch view of the main results of this study both in map (left) and along a NW-SE vertical section (right). Background colours indicate the ratio of P-wave and S-wave velocity obtained by the tomographic inversion (see the colour scale); purple lines delineate the gas-rich volumes identified beneath central-northern Vulcano and the western offshore of Lipari.

The new seismic imaging reveals gas-rich volumes that influence volcanic activity, degassing phases, and hydrothermal processes.

energy and chemicals towards the surface) and active degassing (where underground magma releases gasses such as carbon dioxide). Vulcano Island, the root of the word ‘volcano’ in English, has experienced a recent increase in volcanic activity and is home to one of the four above-ground active volcanoes in Italy. There are smoking fumaroles across the island (openings that release volcanic gasses and steam), and, from 2021 to 2023, a strong degassing crisis occurred which caused the temporary evacuation of the island and the closure of some stretches of the coast. As a popular tourist destination, with a winter population of approximately 450 residents, increasing to several thousand during the summer, it is

crucial to understand the volcanic behaviour in this system.

Creating a model

Totaro and her team gathered seismic wave data from a vast seismic network, including information from around 4,400 earthquakes that have occurred over the last 30 years. By exploring the velocity (speed) distribution of the seismic waves generated by the earthquakes, the team can observe the volcanic system.

There are two specific types of seismic waves analysed in the investigation, P-waves and S-waves, and they travel at different velocities through the Earth’s crust away from the

earthquake’s origin. P-waves travel faster and arrive at a seismometer first, closely followed by S-waves. Geophysicists have long used seismic waves to calculate the epicentre of an earthquake. In their research, the team uses the ratio of P-wave and S-wave velocity to create 3D seismic velocity patterns that help to discriminate between the presence of gases and fluids under the Earth’s surface.

The Lipari-Vulcano complex

The tomographic investigation revealed a clear presence of gas at very shallow depths, around 8km below the surface, under the island of Vulcano and off the west coast of Lipari. The anomaly beneath Vulcano is close to a caldera area (a hollow caused by the collapse of a volcano), fumaroles, and other degassing activity. The new model helps to define how gas-rich volumes of magma are spread across the area feeding the degassing activity and their impact on this system.

The gas anomaly the team identified off the west coast of Lipari has very similar characteristics to the one under Vulcano, but there is no evidence of degassing in this location. This is because the area is under the sea, so the pressure of the water column would promote gas dissolution (disintegration) into marine water and therefore inhibit the gas bubbling observation.

These seismic tomographic images have provided evidence of gas in the crust in this volcanic system and help to explain how gas-rich volumes feed the Aeolian volcanic arc degassing system in South Italy. By identifying the location of the gas-rich volumes, the team have provided a valuable contribution to improving modelling of volcanic systems and how they may change over time.

Personal response

When did you first become interested in volcanoes?

My interest in the geosciences began in middle school, thanks to a documentary about the catastrophic eruption of the Indonesian volcano Krakatoa in 1883. I live in a small town a few tens of kilometres from the slopes of the largest and most active volcano in Europe, Mount Etna, the activity of which often produces impressive glowing lava flows in the dark night scene, intense ash emissions that hinder vehicular traffic on local highways and impose changes on airplane routes to (or from) nearby Catania airport. Since very young I have walked on (and admired) volcanoes in my and other countries (the stunning Andean volcanic chain in Peru, among others). The possibility to study natural phenomena connected to the Earth always fascinated and intrigued me, so I decided to deepen these topics to better understand the processes that cause them. I graduated in Physics with a thesis in Geophysics and later got my PhD in Geophysics. Today, I try to transfer my passion for Earth sciences to young students in the framework of the International Master’s Degree Course in

Geophysical Sciences for Seismic Risk at the University of Messina.

Is proactive monitoring of volcanoes crucial for protecting local communities?

The continuous monitoring of active volcanoes is a fundamental step for civil protection. At present, thanks to multiparametric observation primarily related to earthquake occurrence, ground deformation and gas emission, it is possible to identify specific signatures in the change of a volcanic system’s behaviour. These signatures enable a proper assessment of the risk level and its potential increase.

What’s your next goal for using seismic tomography to study volcanic systems?

I recently published a new tomographic investigation of Mt. Etna, South Italy, which has furnished new insights on the main features of this volcanic system. Moreover, I am also working to widen the perspectives of my tomographic investigations by taking into account, for instance, the changes in seismic velocities within specific time intervals or the way seismic wave energy attenuates in the crust.

Details



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Collaborators

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Bio

Cristina Totaro, PhD, is a tenure-track researcher of Solid Earth Geophysics at Messina University, where she also teaches in the international MDC in Geophysical Sciences. Her research on seismology focuses, in particular, on methodological improvements in seismic tomography and earthquake location and their application for fault detection and lithospheric characterisation.

Further reading

Totaro, C. et al, (2022) [New insights on the active degassing system of the Lipari-Vulcano complex \(South Italy\) inferred from Local Earthquake Tomography](#). *Scientific Reports*, 12, 18867.



Dr Totaro and her students during a civil defence exercise for seismic and volcanic risk management.

