

MISCELLANEA INGV

Abstract Volume

Geo-INQUIRE:
Sicily Summer School 2025

Aci Castello (Italy), 16 | 23 October 2025



ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

99

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ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

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Geo-INQUIRE: Sicily Summer School 2025

Novel technologies and observing systems for geohazard and
environmental monitoring: integrated approach of the
Eastern Sicily test bed

Aci Castello (Italy), 16 | 23 October 2025

Editors: Giuseppe Puglisi^{1,*}, Gilda Currenti¹, Giorgio Riccobene², Laura Beranzoli^{3,4}, Sara Pero⁴

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Cover Mount Etna seen from the Ionian Sea (G. Puglisi) | In Copertina Etna visto dal Mar Ionio (G. Puglisi)



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The Summer School is organized in the frame of the Geo-INQUIRE Project, WP9 Fostering cross-disciplinary research of the Earth through training and workshops.

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Introduction

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This volume compiles the proceedings of the 2nd Summer School organized in the framework of the EC Project *Geosphere INfrastructures for QUestions into Integrated Research* (Geo-INQUIRE). It also includes the guides for the school's field trips.

The overall objectives of the Geo-INQUIRE project are: i) to consolidate and enhance access to multidisciplinary and interoperable datasets; ii) to improve access to new and innovative observables and products; iii) to open new research opportunities to enhance the understanding of the interface between the solid earth and its fluid envelope; iv) to support cross-disciplinary and integrated studies of extreme geohazards; v) to game-change research possibilities in georesource management by providing innovative data, products, and services; vi) to provide innovative data-management, simulation, and visualisation techniques at the interface with HPC facilities.

The strategic aim of the Geo-INQUIRE project is to integrate the resources and capabilities of the major environmental European Research Infrastructures (RIs) Consortia (ERIC), such as EPOS-ERIC, EMSO-ERIC, and ECSEL-ERIC.

The Geo-INQUIRE Sicily Summer School 2025 '*Novel technologies and observing systems for geohazard and environmental monitoring: integrated approach of the Eastern Sicily test bed*' is one of the activities coordinated under the project's Work Package 9 - *Fostering cross-disciplinary research of the Earth through training and workshops*.

This summer school is centred on the *Eastern Sicily Test Bed*, a key component offered within the Geo-INQUIRE project framework. The *Eastern Sicily test bed* includes facilities of the Etna Volcano Observatory (Etna VO), part of EPOS RI, and the Western Ionian Sea (WIS), part of EMSO RI.

The motivation of such a concentration of RIs in Eastern Sicily stems from the unique feature of the area in being a natural laboratory for observing, monitoring and studying land- and seafloor-born geological and environmental processes. In fact, Mt. Etna volcano is the largest southernmost volcano in Europe and one of the world's most intensively monitored volcanoes, and the scientists have the opportunity to collect a wide spectrum of volcanological, geophysical and geochemical data related to the continuous activity. Similarly, western Ionian basin is a key site for investigating water exchanges between the eastern and western Mediterranean, trophic chain and migratory routes of oceanic fauna and in particular cetaceans.

The INGV multiparametric volcano monitoring system at Mt. Etna is designed to continuously collect data that characterize the ongoing volcanic processes. This work is inherently multidisciplinary, requiring the deployment of sensor networks to measure essential physical

and chemical parameters (e.g., seismicity, ground deformation, gravity/magnetic field variations, and volcanic gas flux from the ground or plumes). Additionally, the system relies on regular field surveys. Most of the data, products, and facilities resulting from this monitoring activity are made virtually, physically or remotely accessible through the EPOS platform.

EMSO WIS facility consists of seafloor multisensor platforms (*Calipso and Dione*) placed at about 25 km from shore, at a depth of about 2000 m, and cabled to shore by means of an electro-optical cable for supplying the platforms with power and transmitting data in real-time. A stand-alone oceanographic mooring deployed nearby the platforms complements the suite of data of the seafloor observatories. The data acquired by WIS provide scientists with oceanographic, geophysical and environmental data time-series accessible through the EMSO Data Portal. WIS accessible according to the Transnational Access and RI Physical Access schemes, is jointly operated by INGV, INFN and CNR and shares assets with the KM3NeT.

The KM3NeT underwater neutrino telescope is aimed at observing high energy neutrinos. KM3NeT utilizes the water-Cherenkov technique to reconstruct neutrino originated events in seawater. The telescope consists of two detectors located offshore Toulon, France, at 2500 m water depth (ORCA, Oscillation Research with Cosmics in the Abyss) and at 90 km South-East offshore Capo Passero, Italy, at about 3500 m water depth (ARCA, Astronomy Research with Cosmics in the Abyss).

ARCA is connected to shore through a network of electro-optical cables providing power and data connection from/to the telescope. ARCA is a 3-D matrix of a few hundred thousand of 3-inches Photomultiplier Tubes (PMTs). In its full configuration ARCA will cover a volume of 1km³ in water. Currently, about a quarter of the system is in operation. Despite that, in February 13th 2023 ARCA detected the highest energy muon neutrino event ever recorded, with an energy exceeding 10¹⁷ eV, opening a new window into the extreme phenomena of the Universe.

In complementarity with the activities of KM3NeT, another cabled infrastructure is in operation in the Gulf of Catania, jointly operated by INGV and INFN. The subsea site is connected to shore through a 28km-long electro-optical fiber-cable reaching a depth of 2100 meters. It supports several devices, including a Brillouin Optical Time Domain Reflectometer (BOTDR) unit and a DAS system operated by the Centro Siciliano di Fisica Nucleare e Struttura della Materia (CSFNSM).

The Geo-INQUIRE Sicily Summer School focuses on new technologies used in Environmental Sciences, Earth Sciences and Oceanic studies. In particular, the theory and the practical use of fibre optic sensing addressing strain changes on a wide spectrum is presented, together with some cutting edge techniques applied to volcanology and environmental studies. Cross fertilization sessions between the Solid Earth Sciences and Marine Science are part of the school's program. The school is organized in three main training modules (Figure 1).

Module 1: Fiber Optic Sensing

Module 2: Sensors and Observation systems for environmental monitoring

Module 3: RIs Services and Geo-INQUIRE project's objectives

Each module consists of lectures and hands-on activities. The training modules are enriched with day field trips to visit the INFN KM3Net facility in Capo Passero and the INGV - EPOS facilities at Mt. Etna. This latter trip will give trainees the opportunity to get closer to the most amazing volcanic features. The school also offers to the trainees the opportunity to present their own research results during the poster sessions and to have informal scientific discussions with the teachers in the Pint of Science session.

The school is hosted in *Malavoglia* hotel in Aci Castello (Catania, Italy) from 16th to 23rd October 2025. The forty trainees come from universities and research institutions based in nineteen different countries (Austria, Croatia, Denmark, France, Germany, Greece, Hungary, Iran, Ireland, Italy, Morocco, Netherlands, Poland, Portugal, Saudi Arabia, Spain, Türkiye, United Kingdom, and United States), representing 22 different nationalities (Albanian, British, Chinese, Colombian, Croatian, Danish, Egyptian, Eritrean, Filipino, French, German, Greek, Indonesian, Iranian, Irish, Italian, Kenyan, Moroccan, Portugal, Russian, Spanish, and Turkish). They were selected over more than one hundred applicants from sixty-six different countries that applied to the call opened in March 2025.

The trainees submitted extended abstracts of their ongoing research that are included in this volume. Overall, the studies are at top level for the quality of the data and the originality of the methods adopted for the analysis. It is worth to note that most of the studies are multidisciplinary embracing geophysical, geochemical, geological or environmental processes.

Most of the abstracts deal with the application of DAS to characterize seismicity in specific environments or the development of new algorithms for efficient DAS data analysis either in urban or seismic areas. Other abstracts report results of seismological studies based on advanced analysis of conventional seismological signals. Research on ground deformation or strain in seismic and volcanic areas are also reported, as well as studies on geohazard assessment or marine geology. The volume also includes the Mt. Etna field trip guide. This guide provides an overview of the main volcanological characteristics and details the stops where specific examples of volcanological features and nodes of the multidisciplinary monitoring system are presented.

Keywords Geo-INQUIRE; Summer School

GEO-INQUIRE Sicily Summer School (IT), 16-23 October 2025																
16 Oct (Thu)		17 Oct (Fri)		18 Oct (Sat)		19 Oct (Sun)		20 Oct (Mon)		21 Oct (Tue)		22 Oct (Wed)		23 Oct (Thu)		
		08:30	Opening Session	08:00		08:00	Fieldtrip (Capo Passero)	08:30	Module 3 (lectures)	09:00	Module 3 (lectures)	08:45	Module 2 (lectures)	Departure		
		09:30	Module 3 (lectures)													
		10:30	Coffe Break					11:00		11:00						
		11:00	Module 1 (lectures)					11:00-11:30	Coffe Break	11:00-11:30	Coffe Break					
		12:30						13:00	Module 2 (lectures)	11:30	Module 2 (lectures)	13:00	Module 2 (lectures)			
15:00	Registration	12:30	Lunch Break	08:00		08:00	Fieldtrip (Etna)	13:00		13:00		13:00		Departure		
		14:00						13:00	Lunch Break	13:00	Lunch Break	14:30	Lunch Break			
		14:00	Module 1 (lectures)					14:30	Module 1 (lectures)	14:30	Module 2 (lectures)	14:30	Module 2 (lectures)			
		15:30	Coffe Break					16:00	Coffe Break	15:15	Module 3 (Hands on activities)	16:00	Coffe Break			
		16:00	Poster Session (Students presentations)					16:00-16:30		16:15	on activities)	16:00-16:30	Coffe Break			
19:00	Icebreaker	19:30	Presentation of fieldtrips	20:00		20:00	Dinner	20:00	Module 1 (Hands-on activities)	16:15-16:45	Coffe Break	16:30	Module 2 (Hands-on activities)	Departure		
										16:45	Module 3 (Hands on activities)	16:30	Module 2 (Hands-on (Hands-on activities)			
										17:45		17:45	Pint of Science (question and answers in school subjects)		18:30	Closure of the School
										18:00		18:00			18:30	
										20:30-21:00	Dinner	21:00	Dinner		21:00	Dinner

Program of the Geo-INQUIRE Sicily Summer School 2025

17 October (Friday)	
	Opening session
08:30-08:50	<u>Welcome</u> INGV Osservatorio Etneo Director and INFN Laboratori Nazionali del Sud Director
08:50-09:10	<u>Presentation of the Geo-INQUIRE Project</u> Mariusz Majdański Institute of Geophysics - Polish Academy of Sciences
09:10-09:30	<u>Objectives of the School</u> Summer School Organizing Committee
	FAIR Principles & Open Science
09:30-10:00	<u>Research Data management in geoscience: EPOS ERIC</u> Daniele Bairo, INGV-Roma 1 and EPOS ERIC
10:00-10:30	<u>FAIR data from a solid Earth science perspective</u> Javier Quinteros, GFZ - Helmholtz Center for Geosciences, Potsdam
10:30-11:00	<i>Coffe Break</i>
	Fiber Optic Sensing: Principles and Techniques
11:00- 11:45	<u>An Introduction to Distributed Optical Fiber Sensors</u> Ali Masoudi, University of Southampton
11:45- 12:30	<u>An Introduction to Distributed Acoustic Sensing</u> Ali Masoudi, University of Southampton
12:30-14:00	<i>Lunch Break</i>
	Fiber Optic Sensing: Principles and Techniques
14:00-14:45	<u>Interferometry with coherent lasers: integrated fiber sensing in coexistence with internet traffic</u> Cecilia Clivati, Istituto Nazionale di Ricerca Metrologica, Torino (IT)
14:45-15:30	<u>Early Earthquake Detection Using State of Polarization in Optical Networks as Distributed Sensors: Feasibility and Perspectives</u> Vittorio Curri, Politecnico di Torino- DET
15:30-16:00	<i>Coffe Break</i>
	Poster Session
16:00-19:30	Trainees presentations
	Field trips on 18 and 19 October: presentation and directions
19:30-20:00	<u>Mt. Etna</u> Danilo Cavallaro, Rosanna Corsaro, Letizia Spampinato, INGV-Osservatorio Etneo, Catania
20:00-20:30	<u>Capo Passero</u> Giorgio Riccobene, INFN-Laboratori Nazionali del Sud, Catania

20 Oct (Monday)

	Research Infrastructures and Data Portal
08:30-09:00	<u>From disconnected data to open, integrated, multidisciplinary research: Introducing EPOS, Europe's unique Research Infrastructure for solid Earth science</u> Daniele Bailo INGV-Roma 1 and EPOS ERIC ,
09:00-09:45	<u>EPOS Platform - new standard for research in the future?</u> Jan Michalek, Institute of Geophysics of the Czech Academy of Sciences
09:45-10:15	<u>Taking the Pulse of the Ocean: Insights from the European Research Infrastructure EMSO ERIC</u> Ingrid Puillat, EMSO ERIC
10:15-11:00	<u>Building the EMSO Data Portal: Harmonising Data Across Research Infrastructures</u> Aljaz Maslo, EMSO ERIC
11:00-11:30	<i>Coffe Break</i>
	Fiber Optic Sensing: Geophysical Applications
11:30-12:15	<u>Fiber optic sensing for geohazard and environmental monitoring, with focus on Sicilian volcanoes</u> Philippe Jousset, GFZ Helmholtz Center for Geosciences, Potsdam
12:15-13:00	<u>Modelling distributed fibre optic sensing observations in the framework of marine geodesy</u> Shane Murphy, IFREMER, Brest
12:30-14:00	<i>Lunch Break</i>
	Fiber Optic Sensing: Data Access and Processing
14:30-15:15	<u>DAS experiments: Standard metadata creation and access to data in the cloud</u> Javier Quinteros, GEOFON - GFZ Helmholtz Center for Geosciences, Potsdam
15:15-16:00	<u>Validation of DAS signals against seismic-derived strain estimates</u> Gilda Currenti, INGV-Osservatorio Etneo
16:00-16:30	<i>Coffe Break</i>
	Fiber Optic Sensing: Hands on activities
16:30-20:00	<u>Fiber optic data acquisition, access and analysis</u> Cecilia Clivati, Gilda Currenti, Philippe Jousset, Shane Murphy, Javier Quinteros, Salvo Viola

21 October (Tuesday)	
	Cross-disciplinary fertilization
09:00-10:00	<u>The impact of Mount Etna's emission on the Mediterranean atmosphere and climate: the experience of the EPL research cluster</u> Pasquale Sellitto, Laboratoire Interuniversitaire des Systèmes Atmosphériques, Université Paris-Est Créteil (FR) and Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Etneo (IT)
10:00-11:00	<u>Robotic and Digital Technologies for Ecological Monitoring</u> Jacopo Aguzzi, ICM-CSIC, Barcellona
11:00-11:30	<i>Coffe Break</i>
	Sensors and Observation Systems: Marine applications
11:30-12:15	<u>Acoustic Phase Arrays</u> Salvatore Viola, INFN- Laboratori Nazionali del Sud
12:15-13:00	<u>Seafloor geodesy: Measuring deformation of Mt Etna's submerged flank</u> Morelia Urlaub, GEOMAR - Helmholtz Centre for Ocean Research, Kiel
13:00 -14:30	<i>Lunch Break</i>
	Sensors and Observation Systems: Marine applications
14:30-15:15	<u>Water Column observation systems</u> Nadia Lo Bue, INGV-Roma 2
	EPOS and EMSO Research Infrastructures – Data Portals Hands on activities
15:15-16:15	<u>EPOS Data Portal</u> Jan Michalek , Institute of Geophysics, Czech Academy of Sciences
16:15-16:45	<i>Coffe Break</i>
	EPOS and EMSO Research Infrastructures – Data Portals Hands on activities
16:45-17:45	<u>EMSO Data Portal</u> Aljaz Maslo, EMSO ERIC
	Pint of Science
17:45 -20:00	Trainees-driven discussion

22 October (Wednesday)

	Sensors and Observation Systems: Marine applications
08:45-9:30	<u>Post deployment estimation of OBS orientation in the Smart Cable System</u> Francesco Simeone, INGV – Roma 2
09:30-10:15	<u>Ocean Bottom Magnetometers (OBMs): Exploring the Secrets of Earth's Magnetism from the Ocean Floor</u> Domenico Di Mauro, INGV- Roma 2
	Sensors and Observation Systems: Terrestrial applications
10:15-11:00	<u>The magnetic method in volcano monitoring</u> Rosalba Napoli, INGV - Osservatorio Etneo, Catania
11:00-11:30	Coffe Break
11:30-12:15	<u>OE mobile seismic network: an essential resource for enhancing the real-time seismic monitoring in Sicilian volcanic areas</u> Ornella Cocina, INGV - Osservatorio Etneo, Catania
12:15-13:00	<u>Characterization of volcanic ash plume by Lidars</u> Simona Scollo, INGV - Osservatorio Etneo, Catania
13:00-14:30	Lunch Break
14:30-15:15	<u>Study of active volcanoes by IR and UV ground-based remote sensing</u> Letizia Spampinato, Giuseppe Salerno, INGV - Osservatorio Etneo, Catania
15:15-15:35	<u>The lithotheque of Etna Volcano Observatory: a precious casket of volcanic samples for monitoring and research activities</u> Rosanna Corsaro, INGV - Osservatorio Etneo, Catania
15:35-16:00	<u>From Field to Lab: decoding explosive eruptions through tephra analysis</u> Daniele Andronico, INGV - Osservatorio Etneo, Catania
16:00-16:30	Coffe Break
	Sensors and Observation Systems: Hands-on activities
16:30-18:30	<u>Training on monitoring instruments</u> Gilda Currenti, Letizia Spampinato, INGV - Osservatorio Etneo, Catania
18:30-19:30	Closure of the Summer School
19:30-21:00	Social Dinner

Employing Deep Learning for removing anthropogenic noise on DAS recordings in urban volcanic areas

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Fiber-optic sensing, supported by recent improvements in optical and atomic interferometry, has been adopted in many fields; specifically, the high-quality data recording at high spatio-temporal resolution using Distributed Acoustic Sensing (DAS) technology has led to its widespread application in seismology. Among its strengths, the ability to interrogate telecommunication cables has enabled the detection of a variety of seismo-volcanic events in poorly instrumented environments as densely populated urban areas.

However, the sensing of commercial fiber optic cables has to deal with unavoidable human interferences that frequently corrupt the seismic signal with anthropogenic noise. Ground vibrations induced by transportation, industrial and construction activities significantly reduce the signal-to-noise ratio, potentially masking target events and hindering their analysis [Biondi et al., 2021]. Relevant examples are the low-frequency seismic events recorded during the Vulcano crisis in 2021 [Currenti et al., 2023], frequently corrupted by anthropogenic noise due to a large portion of the telecom cable being located in the urban area (see *Figure 1*).

Exploiting the large spatial-temporal density of DAS data, a deep learning approach has been leveraged for the purpose of removing anthropogenic noise. The neural network architecture and the ad-hoc training procedure have been developed with the aim of preserving salient information while neglecting noise. The promising outcomes show the potential of the proposed strategy to improve DAS recordings prior to subsequent analysis.

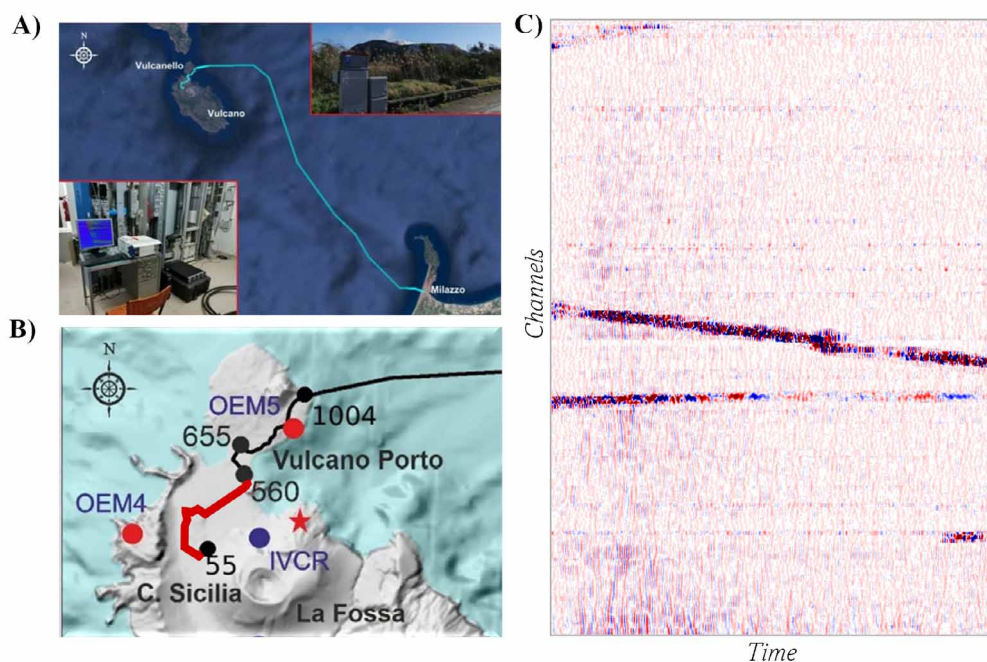


Figure 1 Interrogated telecommunication fiber connecting Vulcano to Milazzo (A) and zoom in (B) of the cable on-land (in red the channels running through the urban area). (C) Example of recorded low-frequency event corrupted by anthropogenic noise (i.e. stripes crossing groups of channels in time).

Methods

The employed neural network is the Residual Convolutional Autoencoder (RCAE), whose architecture involves an encoder, a bottleneck and a decoder. The *encoder* E_φ - parameterised by φ - compresses the input $\{x_1, \dots, x_n\} \subset \mathcal{X}$ by extracting the most representative features until they are enclosed in the *bottleneck*, i.e. the input representation in a lower-dimensional latent space $\mathcal{Z}$. Then, the decoder D_θ - parametrized by θ - reconstructs the input in $\mathcal{X}$ space starting from the low-dimensional vector. Thus, $E_\varphi: \mathcal{X} \rightarrow \mathcal{Z}$ and $D_\theta: \mathcal{Z} \rightarrow \mathcal{X}$.

By varying the architecture hyper-parameters (*see Table 1 - Architecture*) - i.e. the number of output channels of the first layer and the number of layers exclusively reducing the height and width of their input - nine RCAE models are built with a residual block prior and following the bottleneck in order to prevent gradient degradation [He et al., 2016]

Due to its structure and operating process, the Autoencoder is usually trained in a self-supervised approach: it learns by comparing the predicted outputs with the corresponding inputs [Gui et al., 2024]. If the loss function L is the Mean Squared Error, then the task is expressed by:

$$\min_{\varphi, \theta} L(\varphi, \theta) \text{ where } L(\varphi, \theta) = \frac{1}{n} \sum_{i=1}^n (x_i - D_\theta(E_\varphi(x_i)))^2$$

The learning of salient features in the training phase determines which information the autoencoder will later be able to process and reconstruct during the inference. Taking advantage of this peculiarity, all 9 RCAEs are trained on data free of anthropic noise.

Specifically, the signals of the first 551 channels – i.e. 2 out of 16 km of the sensed fiber – are filtered below 5.5 Hz and downsampled to 20 Hz before extracting 20-second windows. All matrices have dimension [551x400]: half of them contain low-frequency events detected on the seismic signal by INGV and the other half background noise extracted from the time slot with the highest average noise. Then, the data are normalized in the interval [-1,1].

All nine RCAE models are trained for 100 epoch with minibatch gradient descent and ADAM optimizer, setting the learning rate to 0.0001 and the batch size to 128.

The denoising capabilities are evaluated on a test set $\mathbf{T}$ of 146 originally uncorrupted and unseen low-frequency events $\{t_1, \dots, t_n\} \subset \mathbf{T}$ to which anthropic noise ϵ is superimposed, so that $\hat{t}_i = t_i + \epsilon$. If $\hat{\epsilon}_i$ is the model reconstruction of the corrupted part of $\hat{t}_i$, the *Gain* metric is computed as

$$Gain = \frac{1}{n} \sum_{i=1}^n \frac{SNR(\hat{\epsilon}_i)}{SNR(\epsilon_i)}$$

i.e. the increase in the Signal-to-Noise ratio (SNR) of the prediction over the input.

Results and Conclusions

The visual inspection of the RCAEs' predictions demonstrates their success in not reconstructing noise (*see Figure 2*). As a matter of fact, none of the reconstructions for the test set exhibit anthropogenic noise, regardless of the Signal-to-Noise ratio of the processed input. Furthermore, the performances of all models do not appear to be contingent on the energy of the low-frequency event; indeed, filtering is properly performed on both weaker and stronger events. When expressed in quantitative terms, the *Gain* metric exceeds 1 for all RCAEs that have undergone training (*see Table 1 - Performance*).

However, a rigorous analysis reveals discrepancies between the target and the prediction in the portion of the signal that has not been corrupted by anthropogenic noise. For low-energy events with low SNR, the reconstructions may not be perfectly faithful to the original “clean” signal.

In conclusion, deep learning models provide promising performance for denoising tasks,

succeeding in removing anthropogenic noise in unseen and corrupted events. The presented methodology could be a valuable starting point, certainly subject to improvement concerning the quality of the reconstructed, which currently appears to be overestimated.

Model	Architecture								Performance
	N. of output Features Maps (1° Layer)		N. of Layers Input and Output 256 Feature Maps			N. of Layers Input and Output 512 Feature Maps		N. Of Encoder or Decoder Layers	Gain on Test set
	32	64	0	1	2	1	2		
RCAE 1	✓		✓			✓		7	3.94
RCAE 2		✓		✓		✓		7	3.72
RCAE 3	✓			✓		✓		8	4.09
RCAE 4	✓				✓	✓		9	4.24
RCAE 5	✓				✓		✓	10	4.34
RCAE 6	✓		✓				✓	8	4.34
RCAE 7	✓			✓			✓	9	4.45
RCAE 8		✓			✓	✓		9	4.32
RCAE 9		✓			✓		✓	9	4.34

Table 1 Main difference of trained RCAE architectures (*Architecture*) and corresponding performance on test set in terms of *Gain* metric (*Performance*).

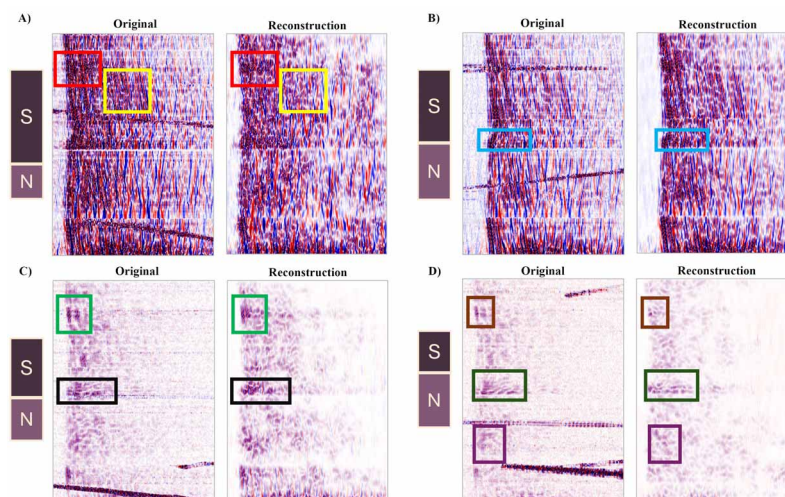


Figure 2 Reconstructions for 4 test samples with various SNR. For **A-B-C-D**: input (*Original*) and corresponding prediction (*Reconstruction*). The boxes highlight some differences in reconstructing the original event.

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Afterslip Patterns on the East Anatolian Fault System After the February 2023 Earthquake Sequence

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6 February 2023 Kahramanmaraş Earthquake Sequence

On 6 February 2023, a devastating magnitude 7.8 Pazarcık earthquake occurred on the East Anatolian Fault (EAF) in Türkiye. 9 hours later, another devastating magnitude 7.6 Elbistan earthquake occurred on the East Anatolian Fault (EAF) in Türkiye. 9 hours later, another devastating magnitude 7.6 Elbistan earthquake occurred on the Çardak Fault whose epicenters were approximately 100 kilometers apart.

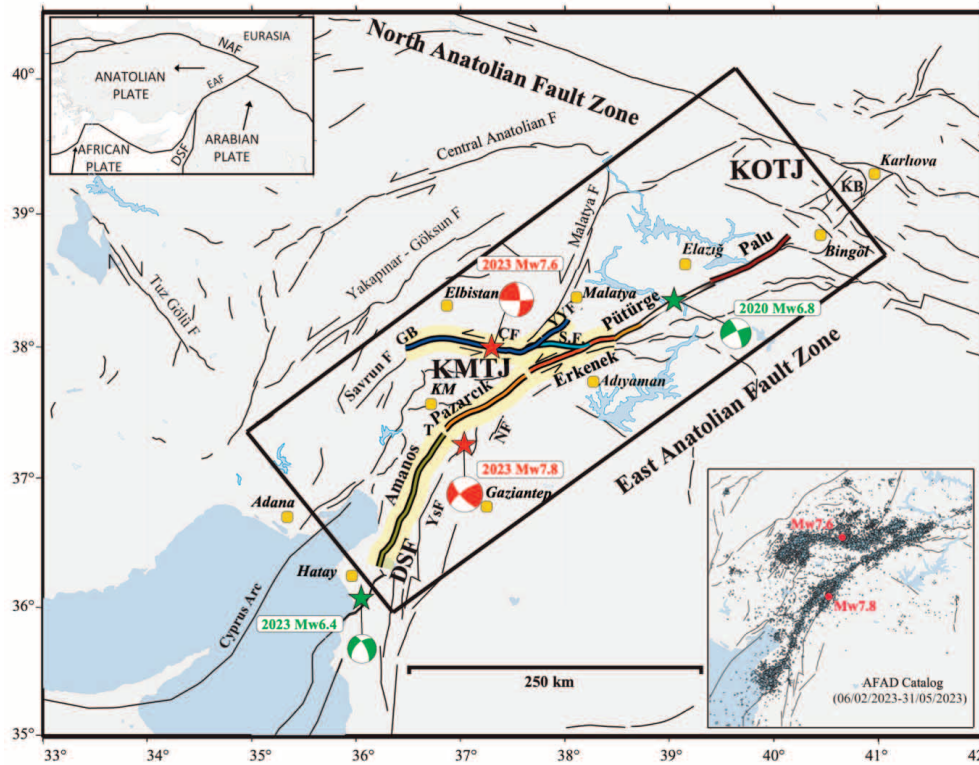


Figure 1 Locations of the Kahramanmaraş earthquakes [Ergintav et al., 2024].

Afterslip of the Kahramanmaraş Earthquakes

Following these devastating earthquakes, a slip deficit can be expected along the fault. Measuring afterslip is important for understanding fault behaviour. This can result from stresses associated with local coseismic slip deficits. To measure this afterslip, we installed 11 creepmeters. These were installed at both ends of the fault rupture and where optical data showed afterslip on the fault.

A creepmeter is an extensometer that measures linear strain or displacement between two points. The afterslip creepmeters have a resolution of 3 μm and a range of 1.8 m. They consist of 4 mm diameter carbon-fibre rods buried at a depth of 30 cm within 15 mm ID plastic pipes at an angle of approximately 30° to the surface fault [Bilham and Castillo, 2020].

We also established three GNSS stations in an array (Figure 2).

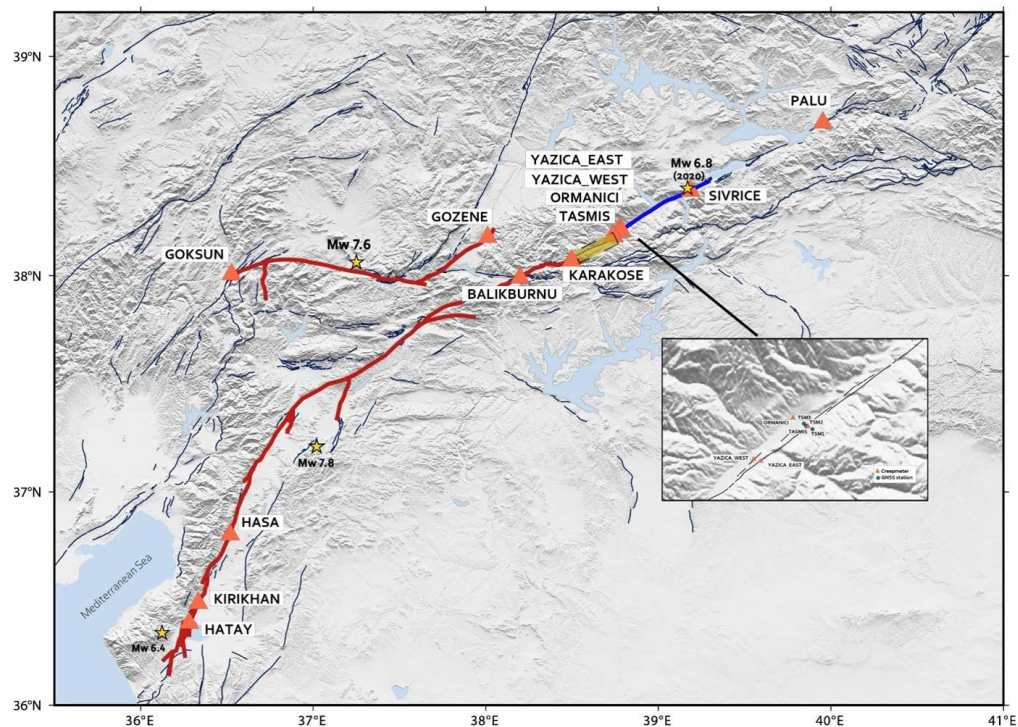


Figure 2 Locations of the creepmeters and GNSS stations.

Results

Göksun stations were installed on the fault rupture at the western end of the Çardak Fault. Afterslip continued at this station for a while after the earthquakes. Some of these afterslips are related to aftershocks, while others were aseismic creep. This aseismic creep may have been triggered by external factors, such as aftershocks or temperature fluctuations. (Figure 3).

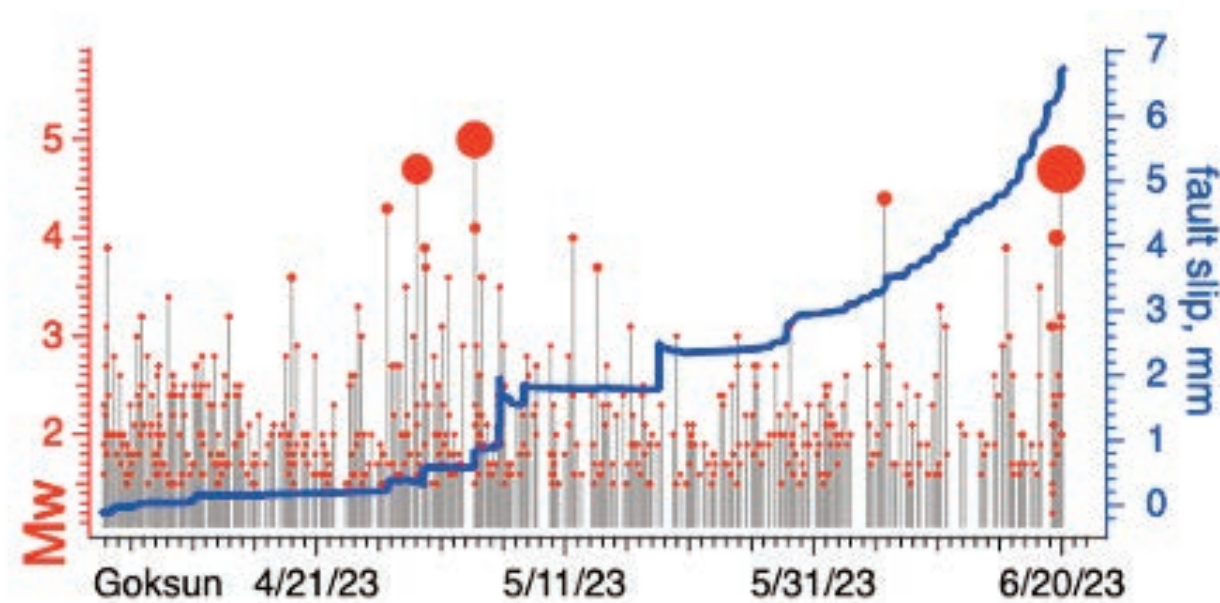


Figure 3 Time series of the Göksun station. Blue line shows the fault slip. Red circles show aftershocks.

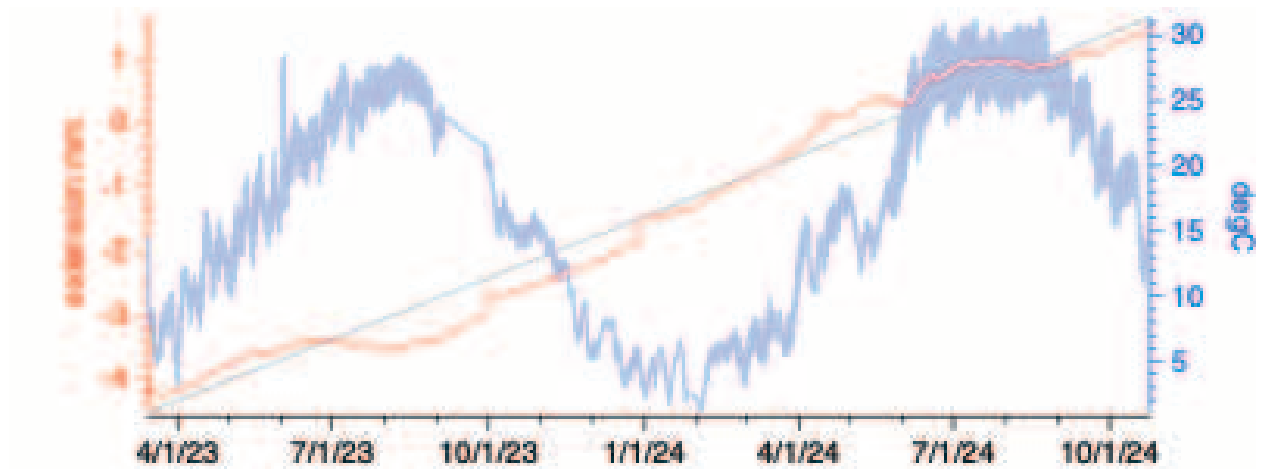


Figure 4 Time series from the Gözene station, showing fault slip (red line) and embedded temperature sensor data (blue line)..

Gözene station was installed on the fault rupture at the eastern end of the Çardak Fault. The rate of fault slip at this station is 3.8 mm/yr (Figure 4).

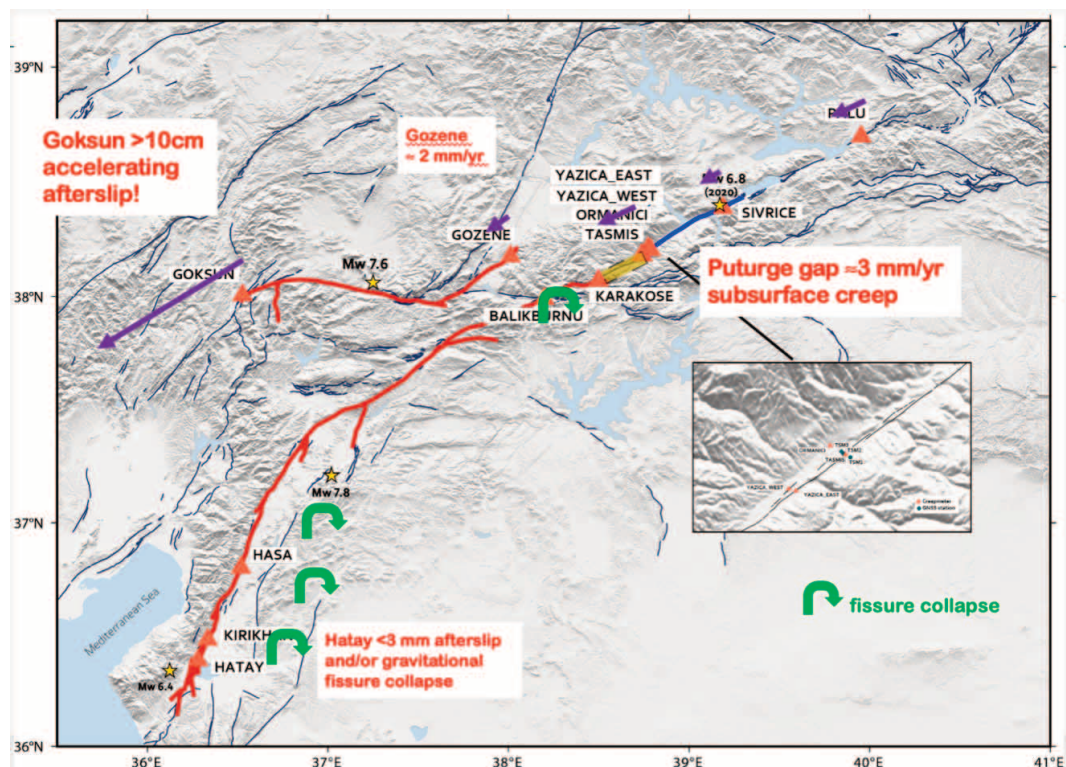


Figure 5 Total afterslip of Kahramanmaraş earthquakes.

Figure 5 shows the total afterslip results detected by creepmeters. According to creepmeter stations, there is no evidence of creep at the south of the EAF.

The Sivrice earthquake of 24 January 2020 and the Kahramanmaraş earthquakes of 6 February 2023 stopped at a specific location on the EAF. This location is called the Pütürge Gap. We

installed three creepmeters and three GNSS stations at the Pütürge gap to investigate whether it is creeping (Figure 2 shows the Pütürge gap in a yellow box). We estimated approximately 3 mm/yr subsurface creep in the Pütürge gap.

At the ends of the Çardak fault (Göksun and Gözene stations), afterslip continues.

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Tsunami Hazard Assessment along the Northern and Central Moroccan Atlantic Coast Using COMCOT

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On November 1, 1755, a destructive earthquake and tsunami struck several countries bordering the Atlantic Ocean, including Portugal, Spain, and Morocco. With an estimated magnitude of Mw 7.8, the earthquake generated tsunami waves that significantly impacted the Moroccan Atlantic coast. Numerous studies have investigated the 1755 earthquake and tsunami to identify potential source mechanisms. In this study, we focus on the tsunami generated by the Gorringe Bank Fault (GBF), one of the proposed sources for this historical event, and assess its impact specifically along the northern and central Moroccan Atlantic coastline.

The simulation results indicate that the most impacted Moroccan cities are El Jadida, El Mohammédia, Casablanca, Bouznika and Kenitra with maximum wave heights ranging between 4.56 and 5.7 meters, El Jadida and Safi are the earliest impacted cities.

Introduction

Morocco is bordered by two distinct maritime façades: the Atlantic Ocean to the west and the Mediterranean Sea to the north. In recent years, the Moroccan Atlantic coastline has emerged as a strategic hub for economic and maritime development, driven by increasing national investments in port infrastructures. Flagship projects such as the Tanger-Med port—now the largest in Africa—and the planned construction of the Dakhla Atlantic port illustrate this growing reliance on maritime trade and coastal logistics. These investments are part of a broader strategic vision outlined in Morocco's National Port Strategy to 2030, which also highlights the importance of integrating environmental risk considerations into port planning and development [1].

In this context, the present study conducts a regional-scale tsunami hazard assessment along the northern and central Moroccan Atlantic coast. Using numerical simulations based on a rupture scenario of the Gorringe Bank Fault (GBF), we estimate maximum wave heights in multiple coastal zones. Based on these results, cities were classified into hazard levels to highlight key areas of potential vulnerability. This classification provides a first step toward prioritizing future high-resolution studies and supports national efforts to protect critical maritime infrastructure in accordance with safety and resilience objectives.

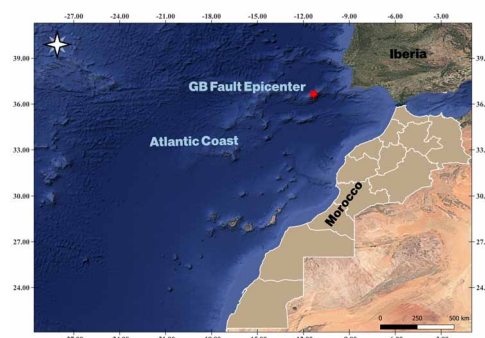


Figure 1 Regional map highlighting the Gorringe Bank, Fault epicenter and the Moroccan Atlantic coast.

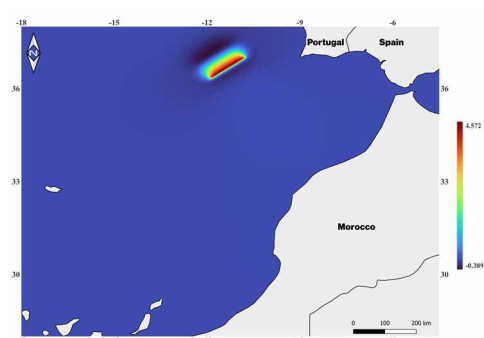


Figure 2 Initial surface displacement.

Methodology

- Numerical simulation:

The model used for the simulation is COMCOT (Cornell Multi-grid Coupled Tsunami Model), an open-source code, capable of efficiently studying the entire life-span of a tsunami, including its generation, propagation, runup and inundation [Wang, 2009]. It solves both linear and non-linear shallow water equations in spherical or Cartesian coordinates using an explicit leap-frog finite difference numerical scheme [Liu et al., 1998]. Multiple tsunami generation mechanisms can be implemented in COMCOT, including instantaneous seafloor rupture computed via fault models [Okada, 1985]. COMCOT code has been used to study several tsunami events, such as the 2004 Indian Ocean tsunami [Al'ala et al., 2015].

In this study, we used the COMCOT model to simulate the tsunami generated by the Gorringe Bank Fault, including its generation, propagation across the Atlantic Ocean, and inundation along the northern and central Moroccan Atlantic coastline (Figure 1).

- Parameters of the Earthquake and Bathymetry data:

The parameters of the earthquake used in the model were obtained from previous literature studies [Omira et al., 2009] with details of the scenario parameters summarized in Table 1.

Bathymetric data used in the tsunami simulations were obtained from the ETOPO [2] global relief model, with a spatial resolution of 15 arc-seconds and area of 3458 m × 2599 m.

The simulation was configured with a total duration of 3 hours and a time step of 60 seconds. The fault rupture was initiated at simulation time $t = 0$ s, indicating that the rupture began at the start of the simulation.

Scenario name	Length	Width	Epicenters coordinates (°)		Depth (Km)	Slip (m)	Strike (°)	Depth (°)	Rake (°)	Moment Magnitude (Mw)
	(Km)	(Km)	Longitude	Latitude						
(GBF)	127	60	-11.332	36.665	5.0	8.3	233	35	90	8.4

Table 1 Earthquake Scenario Parameters.

Results and Discussion

- Initial Surface Displacement, Wave Height Distribution, Maximum Wave Height, and Tsunami Arrival Time:

Figure 2 illustrates the initial sea surface displacement resulting from the Gorringe Bank Fault. The maximum uplift reaches approximately 4.6 meters, concentrated near the fault location.

Figure 3 shows the tsunami propagation pattern and the initial interaction between the tsunami waves and the Moroccan coast. The first contact occurs at approximately 6,840 seconds after the fault rupture. According to this map, wave heights range between -4.27 m and 3.30 m during the early stages of coastal impact. The cities of El Jadida and Safi are the first to be affected, experiencing wave heights of approximately 2.0 m and 1.9 m, respectively.

The tsunami reaches the full extent of the northern and central Moroccan Atlantic coastline at $t = 7,866$ seconds, with wave heights ranging between -3.19 m and 5.70 m.

Figure 5 presents the simulated maximum tsunami wave heights along the Atlantic coasts of Portugal, Spain, and Morocco. The results indicate a higher concentration of tsunami energy along the Moroccan and Portuguese coasts. The most impacted Moroccan cities include El Jadida (5.7 m), Mohammedia (5.0 m), Casablanca (4.9 m), Bouznika (4.56 m), and Kenitra (4.35 m). These wave heights reflect significant hazard potential, especially for urban and port areas.

In contrast, the cities of Asilah (2.69 m), Salé (2.55 m), Agadir (2.32 m), and Tangier (1.6 m) show comparatively lower wave heights, suggesting reduced tsunami hazard levels. Figure 4 presents a classification of northern and central Moroccan coastal cities based on maximum wave height, highlighting the most and least exposed locations. These findings offer valuable insights into tsunami hazard levels along the northern and central Moroccan Atlantic coast and underscore the importance of developing coastal preparedness and risk mitigation strategies for future tsunami events.



Figure 3 Tsunami wave height at $t = 6840$ s.

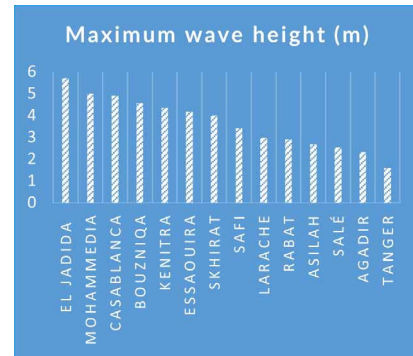


Figure 4 Maximum tsunami wave height per city.

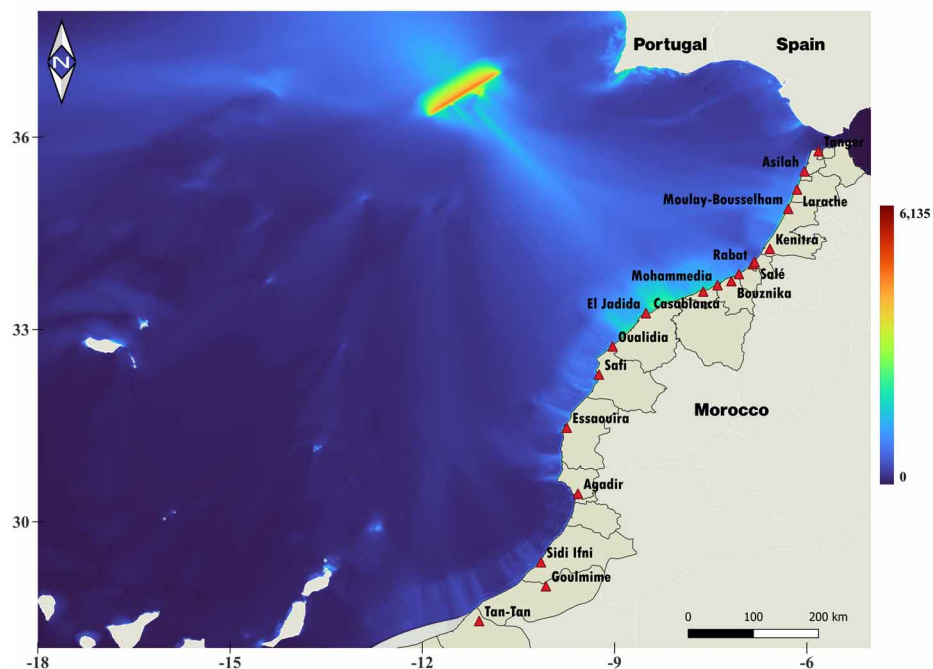


Figure 5 Maximum wave height distribution in m.

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Sitography

[1] <https://www.anp.org.ma/en/publications/strategieportuaire>

[2] <https://www.ncei.noaa.gov/products/etopo-global-relief-model>

Constraining source parameters of the main events in the 2020 earthquake swarm in North Iceland

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The Tjörnes Fracture Zone (TFZ) in northern Iceland is one of two fracture zones in Iceland capable of generating earthquakes of magnitude $\sim M7$. While such large events are rare, earthquake swarms are frequent, occurring every 2-3 years [Jónsdóttir et al., 2021]. Previous studies have suggested that these seismic swarms might release considerable tectonic strain accumulated with aseismic slip. However, no evidence of aseismic slip transients has been identified in geodetic (GNSS) time series so far [Passarelli et al., 2018]. Still, a full understanding of the role of earthquake swarms in releasing strain is key to determine the seismic potential of faults. Of particular interest is the Húsavík-Flatey fault (HFF) that is located close to coastal communities in northern Iceland. It is one of the two main structures in the TFZ that accommodates the offset between the offshore Kolbeinsey Ridge (KR) and the onshore Northern Volcanic Zone (Figure 1). The HFF is a right-lateral strike-slip fault with an estimated slip rate of mm/yr that is presumed to be locked [Barreto et al., 2025].

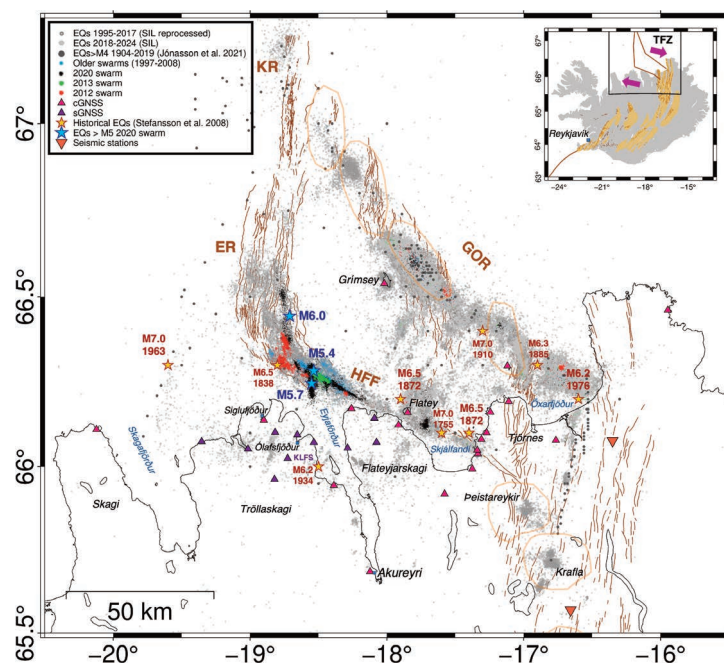


Figure 1 Tectonic setting, seismicity, continuous (cGNSS) and survey (sGNSS) stations, and broadband seismic stations in northern Iceland. Mapped faults and fractures are shown as brown lines and fissure swarms and central volcanoes with orange outlines. KR: Kolbeinsey Ridge, ER: Eyjarfjarðarallí Rift, GOR: Grímsey Oblique Rift, HFF: Húsavík-Flatey Fault.

In June 2020, the strongest earthquake sequence in the TFZ since 1976 started at the western end of the HFF. The swarm had three mainshocks above magnitude M5. On June 20, a M5.4 and a M5.7 struck within four hours of each other on or near the HFF. On the following day a M6.0 occurred 20 km northwest of the first two mainshocks in the Eyjafjarðaráll Rift (ER), which is a magma-starved southern continuation of the Kolbeinsey Ridge [1]. This M6.0 event is the largest normal faulting event ever recorded in Iceland. More than 12000 earthquakes were detected in the HFF and the ER between June 19 and October 19, 2020, with the highest seismicity rates on June 20 and 21, and most of the seismic moment release associated with the three mainshocks. The swarm activated the ER north and south of the M6.0 event and roughly a 40 km section of the western HFF. The swarm also illuminated ~N-S seismicity trends, possibly corresponding to conjugate faults [Viltres et al. 2022, Barreto et al., 2025].

In this study, we aim to constrain the earthquake source parameters of the three mainshocks of the swarm by combining local data from the Icelandic seismic network (SIL) and regional seismic waveform data with GNSS coseismic offsets using Bayesian inference [Vasyura-Bathke et al. 2020]. We also aim to shed some light on the ratio of seismic/aseismic strain release. For the source parameter estimation, we used data from 9 to 12 broadband seismic stations per event, rotated the waveforms into their radial, transverse, and vertical components, and filtered the waveforms from 10 to 100 seconds. In addition, cumulative surface displacements of the three events were recorded by 20 continuous and 10 survey GNSS stations [Viltres et al., 2022]. Implementing double-couple sources for the mainshocks, the parameter inference was carried out by fixing the event locations to those reported by the SIL catalog of the Icelandic Meteorological Office (IMO) [1]. We estimated the depth, strike/slip/rake, magnitude, time and duration, as well as station specific time-shifts.

Our results reveal surprisingly diverse faulting styles of the three mainshocks. The first mainshock was dominated by right-lateral strike slip and occurred on a WNW-ESE-trending fault, i.e., on a branch of the HFF. The mechanism of the second event was similar, indicating almost pure strike slip, but relocated aftershocks indicate that a left-lateral ~N-S conjugate fault was ruptured. The third and final mainshock was mainly a normal faulting earthquake, occurring on a ~N-S oriented fault, dipping steeply to the west.

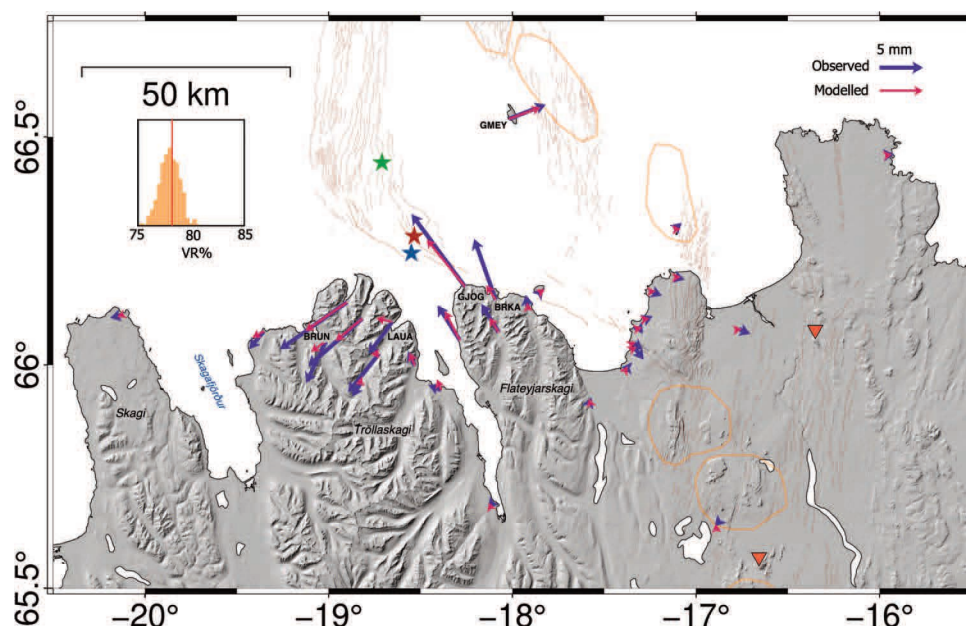


Figure 2 Observed and predicted coseismic offsets from the joint double couple source inversion for the three mainshocks (M5.4, M5.7, and M6.0) of the 2020 earthquake swarm in North Iceland.

Comparing our results with reports of global earthquake catalogs, such as GCMT or GEOFON, we find that our estimated depths (3–5 km) are consistently shallower than the fixed values of ~10 km in these catalogs and our magnitudes are also somewhat smaller, i.e., $M_w5.26^{+0.02}_{-0.03}$, $M_w5.63 \pm 0.02$, and $M_w5.87 \pm 0.02$ for the three mainshocks, instead of 5.4, 5.8, and 6.0. Our smaller magnitudes might be in part due to a trade-off between depth and magnitude in our estimations, or due to underestimation of waveform amplitudes that can arise from combining local and regional data and inaccuracies in the used velocity model. Further constraining the depth of the events remains challenging due to the offshore occurrence of the earthquakes [Hensch et al., 2013].

Although the geodetic data have a high variance reduction (>75%), some of the coseismic offsets are underestimated in our inference (Figure 2). Using a forward model with the magnitudes reported by GEOFON and keeping the rest of our inferred parameters tends to overestimate the observed offsets. This suggests that our estimation reduces the magnitudes to compensate for the shallower depths. However, our depths are in the range of the seismogenic zone of previous studies [Abril et al., 2018].

Finally, our magnitude estimates from using only seismic data to using both seismic and geodetic data combined do not show a large increase. The magnitudes estimated only with seismic data are $M_w5.25 \pm 0.03$ for the first event, $M_w5.61 \pm 0.02$ for the second event, and $M_w5.83^{+0.04}_{-0.02}$ for the third event. The slight increase in the best-fit magnitude estimate in the joint inference is within uncertainty levels of the seismic inference, which would indicate little hidden aseismic strain release in the earthquake swarm. No other signals, such as transients have been identified in the GNSS time series that would indicate aseismic slip associated to this swarm. Future work includes to let the location of the sources be estimated in the inference process and testing deviatoric and rectangular sources.

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Sitography

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Urban DAS data enhancement and coherent noise removal with deep learning: insights from the WAVE seismic network

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Introduction

Distributed acoustic sensing (DAS) is a technology that leverages fiber-optic cables for high-rate multi-channel seismic measurements. Within the WAVE Initiative [1], 15 km of optical fiber has been installed and connected to a DAS interrogator in the facilities of DESY and the European XFEL. For the high-precision experiments conducted in these facilities, a detailed understanding of the ambient seismic wavefield is crucial for noise mitigation. A first analysis of the DAS measurements of the WAVE network has been carried out by Kiel et al. [2024] and Bölt et al. [2025], who have clustered noise sources in the data.

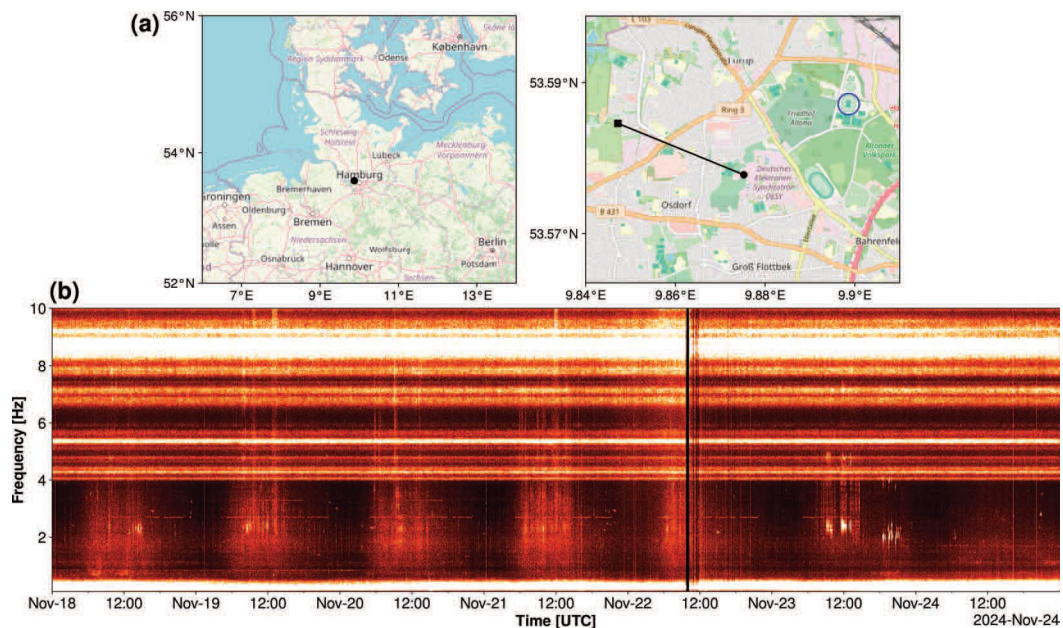


Figure 1 (a) Map of a 2 km subset of the fiber located in the accelerator tunnel of the European XFEL in Hamburg, Germany. The blue circle indicates the location of the Volksparkstadion, in ca. 2 km distance to the fiber start (black circle); (b) spectrogram of one week of DAS data from Monday, Nov. 18 to Sunday, Nov. 24 (local time is UTC+1).

As a next step, we propose to directly image and remove the coherent seismic wavefield using coherent wavefield subtraction [Schwarz 2019], a scheme originally developed for diffraction separation in seismic data, which models and adaptively subtracts the dominant wavefield from

the data, and has been applied to DAS measurements in the recent past [Jousset et al., 2022; Ehsaninezhad et al., 2024]. Combining coherent wavefield subtraction with a largely automatized synthetic data generation pipeline, we have recently introduced *DiffractionNet*, a deep learning model for diffraction separation [Bauer et al., 2025]. Building on this research, we propose a deep learning approach that removes coherent noise and simultaneously enhances the complex seismic wavefield measured by the WAVE seismic network.

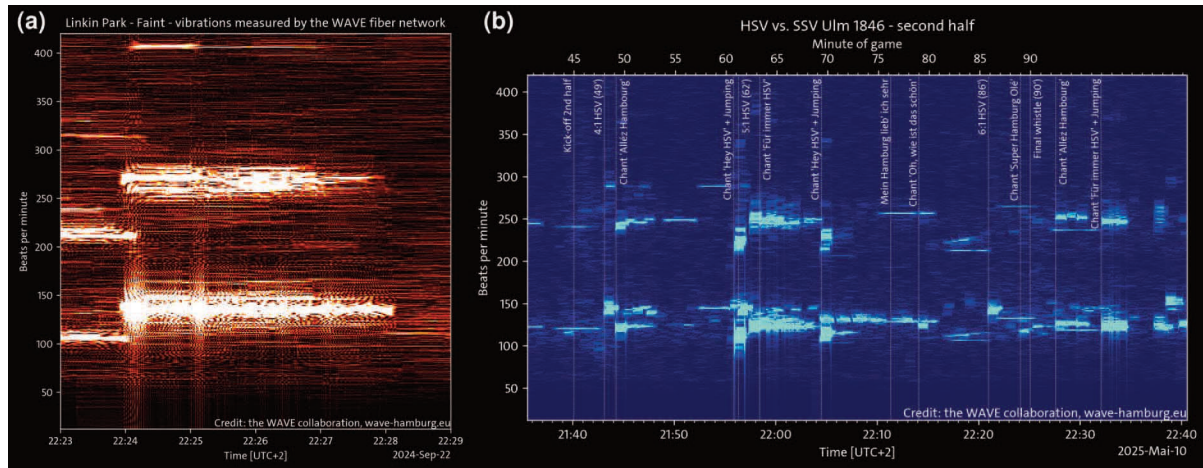


Figure 2 (a) A spectrogram of the DAS data measured during a concert of the band Linkin Park on Sep. 22, 2024, in the arena next to the Volksparkstadion; (b) spectrogram of the data measured on May 10, 2025, during the second half of the football match Hamburger SV vs. SSV Ulm in the Volksparkstadion with identified events marked.

Data and applications

The black line in Figure 1a shows the location of the 2 km subset of the fiber used in this study (the circle and the square mark the first and last channel, respectively) located in the accelerator tunnel of the European XFEL. Figure 1b shows a spectrogram of one week of data measured in November 2024. While the data contain a lot of quasi-static instrument noise, a clear pattern of anthropogenic noise can be observed during the weekdays Monday to Friday. On Saturday evening, distinct signals around 2 Hz are caused by a football match in the nearby Volksparkstadion (marked by a blue circle in Figure 1a). Since the WAVE network is located in an urban area, the fiber is subject to a multitude of coherent noise sources, most of which are of anthropogenic origin. Among the highest-amplitude signals are those caused by large events such as concerts and football matches that take place in the Volksparkstadion and in an arena next to it, as illustrated in Figure 2 by two examples. Figure 2a is a spectrogram of data measured during a concert of the band Linkin Park, in which we could easily identify the songs by the frequency of their beats. Figure 2b shows a spectrogram of data measured during a football match of Hamburger SV in the Volksparkstadion, in which we identified certain moments of the game related to goals and fan chants. In both cases, the highest-amplitude signals are most likely caused by large numbers of people jumping.

To generate the training dataset for the neural network, we took three hours of data from the week shown in Figure 1b. After filtering and downsampling the data, we applied coherent wavefield subtraction to it. Figure 3a shows a data excerpt (left) and its enhanced (center) and denoised (right) counterparts obtained from coherent wavefield subtraction [Schwarz, 2019]. While the denoised data contains only a few residuals of the higher-amplitude signals, the

enhanced data contains less random noise and cleaner wavefields, albeit preserving their complexity. With the results for the three hours of data, we compiled the training dataset with 12960 sets of images and trained a U-Net-type convolutional neural network (CNN) with the same architecture as *DiffractionNet* [Bauer et al., 2025]. To test the generalization capabilities of the trained CNN, we applied it to unseen data examples. Figure 3b shows one data example (left) measured during the football match on May 10, 2025 (see Figure 2b) and its enhanced (center) and cleaned (right) counterparts. The neural network successfully enhanced the data, and although the denoised data still contains some residuals of the high-amplitude arrivals, also a previously hidden fainter wavefield likely caused by traffic on the roads above the fiber was revealed.

Conclusions

We have introduced a deep-learning scheme for the removal of coherent noise and the simultaneous enhancement of urban DAS measurements. To generate training data and labels, we have applied coherent wavefield subtraction, a deterministic technique for wavefield decomposition to a data subset of a long-term DAS measurement deployed by the WAVE initiative in a research facility in Hamburg, Germany. With this dataset, we have trained a CNN based on the recently introduced *DiffractionNet*. Applications to unseen data show that the trained neural network can generalize to different kinds of coherent noise, suggesting a broad range of applicability of the proposed scheme.

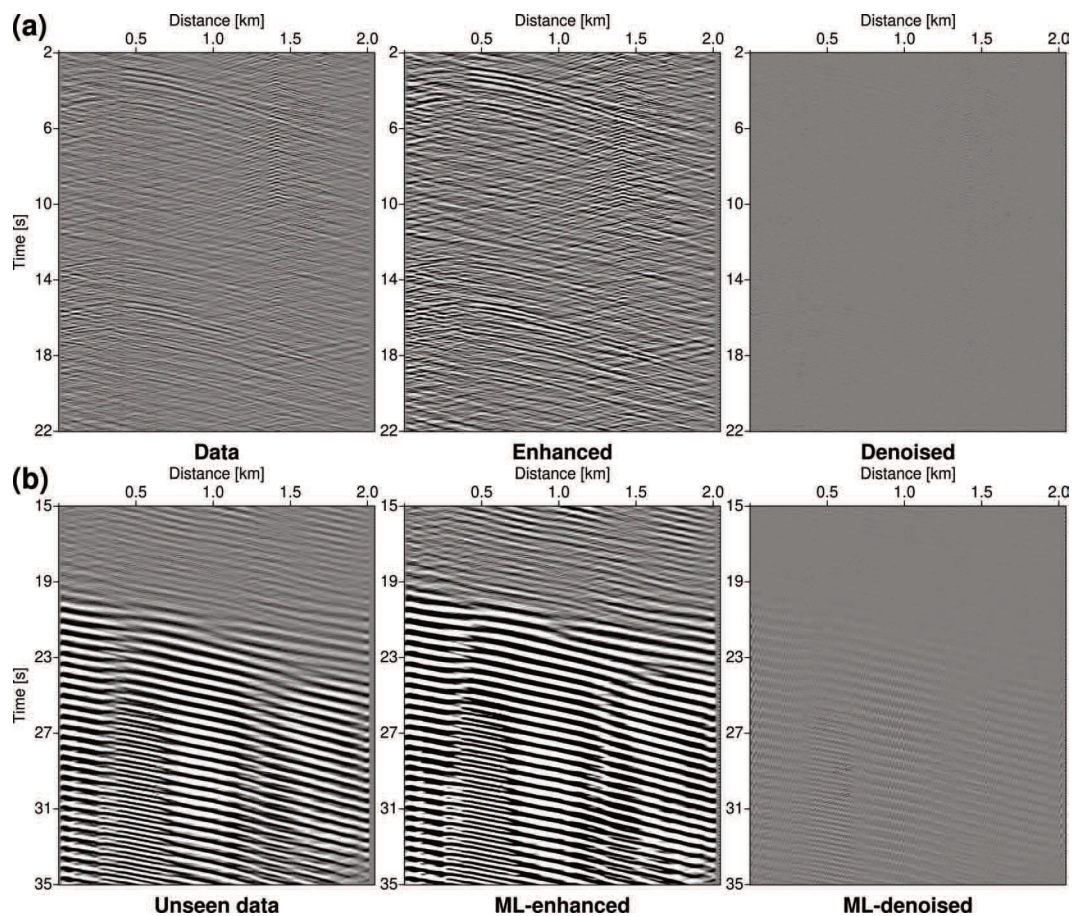


Figure 3 (a) Application of coherent wavefield subtraction to a data excerpt (left) from Nov. 18, 2024, at 14:14 UTC resulting in enhanced (center) and denoised versions (right); (b) Application of the trained CNN to unseen data (left) from May 10, 2025 at 19:56 UTC resulting in enhanced (center) and denoised versions (right).

Acknowledgments

We thank the WAVE Team [1] for installing and operating the DAS measurements and continuous discussion, in particular M. Hoffmann (DESY), who implemented the software for reading and converting the DAS recordings. This work was funded by the Federal Ministry of Education and Research of Germany (BMBF, 05D23GU5).

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[1] wave-hamburg.eu

Passive seismic methods for monitoring and characterizing gas emitting structures in inland and offshore systems: case studies from the Nirano mud volcanoes and the Sea of Marmara

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The analysis of ambient seismic vibrations has proven to be a powerful tool for subsoil investigation, particularly for detecting and characterizing hydrocarbon-bearing formations. In recent years, a recurring spectral feature characterized by the presence of a minimum in the Horizontal to Vertical Spectral Ratio (HVSr) curve has been observed in correspondence with hydrocarbon reservoirs in both inland and offshore settings [Frehner et al., 2006; Saenger et al., 2009]. This extended abstract presents an integrated overview of two case studies: one from the Nirano mud volcano system (Northern Italy) and the other from a gas-emitting seabed area in the Marmara region. Despite their different geological and environmental contexts, both studies converge on the conclusion that HVSr minimum can serve as reliable indicators of subsurface gas reservoirs.

Beyond the detection of the characteristic HVSr minimum, both inland and offshore case studies pursue two interrelated yet distinct geophysical objectives. The first focuses on estimating and monitoring surface gas flux by analysing seismic signals known as "drumbeats," which are thought to reflect the dynamics of shallow gas seepage [Brindisi et al., 2023]. These signals, interpreted as resulting from stick-slip interactions among exsolved gas bubbles, mud plugs, and vent walls, enable estimates of gas outflow that are consistent with independent CH₄ and CO₂ emission measurements [Carfagna et al., 2024]. These findings support the potential of seismic observations as a reliable and quantitative tool for gas emission monitoring, particularly in environments where direct measurement is challenging, such as offshore seepage zones [Domel et al., 2022; Embriaco et al., 2014]. The second objective is directed toward the characterization of the gas reservoir that feeds the system. This is accomplished by integrating HVSr analysis with inversion modelling based on Biot-Gassmann theory (BGTL) [Brindisi et al., 2025]. Together, these approaches allow the investigation of fluid migration and gas accumulation processes across different spatial scales, ranging from the shallow seepage dynamics to the deeper reservoir properties, thus offering a comprehensive understanding of the entire system.

In the inland context of the Nirano mud volcanoes, a dense network of single-station and array-based ambient vibration measurements was deployed across a caldera-like basin, with an average inter-station distance of 30 m. The HVSr curves showed a pronounced minimum at ~0.5 Hz exclusively in correspondence with active mud vents. This spectral anomaly was interpreted as a result of a strong P-wave (V_p) impedance contrast at a depth of approximately 450 m, corresponding to the lithological boundary between the Pantano (marls and marly turbidites) and Termina formations (sandy marls) [Giambastiani et al., 2024] (Figure 1b). Further modelling based on the BGTL provided compelling evidence that this interface marks the base of a gas-charged reservoir system extending upward for about 300 m, with an estimated porosity of ~30% [Nespoli et al., 2023]. S-wave (V_s) profiles appeared largely unaffected by gas presence, consistent with

the known insensitivity of shear waves to pore fluid type and saturation [Lee, 2004], whereas V_p values were significantly reduced, especially in correspondence of the area where the emitting vents are located (Figure 1).

The BGTL-based inversion of HVSR data revealed that the Young's modulus within the reservoir is approximately half of that found in surrounding lithologies (1.13 GPa compared to 2.17 GPa), reinforcing the hypothesis of a gas-bearing, mechanically weak zone [Saenger et al., 2009]. The reconstructed geological model suggests that ascending fluids (predominantly methane and water) are transported along subvertical conduits located in the deeper reservoir and terminating near the surface within the Argille Azzurre Formation (clays) [Carfagna et al., 2024; Accaino et al., 2007].

Parallel findings emerge from the marine case study in the Marmara Sea, where Ocean Bottom Seismometer (OBS) measurements of ambient vibrations were analyzed. Despite the inherent complexity introduced by the water column, HVSR curves obtained from sea bottom stations displayed an identifiable minimum at ~ 0.8 Hz, whose characteristics were shown to be only weakly influenced by ocean dynamics. Through a dedicated correction procedure that compensates for resonance effects of the water layer, the marine HVSR curves were adjusted to resemble those observed in onshore conditions [Brindisi et al., 2025]. This methodological innovation allows the direct application of established inland HVSR inversion techniques to OBS data, with the aim to determine subsoil V_p and V_s profiles (Figure 2).

Inversion of the corrected HVSR data suggested a significant V_p impedance contrast at around 500 m depth, likely marking the contact between unconsolidated Quaternary sediments and underlying Triassic bedrock (Figure 2). This interface is interpreted as the base of a gas-bearing formation, where gas saturation levels reach up to 90% in the 175–495 m depth interval. The results are consistent with forward modelling based on the BGTL and align with previously reported observations of gas-charged sediment layers in similar settings [Brindisi et al., 2025]. Both case studies validate the application of HVSR minimum as seismic indicators of gas reservoirs and demonstrate that passive seismic methods can reliably characterize subsoil stratigraphy, even in challenging environments such as active mud volcanoes or marine domains. Furthermore, the BGTL-based interpretation of seismic velocity profiles (V_p and V_s) provides quantitative estimates of reservoir properties such as porosity, fluid content, and mechanical contrast.

One of the main advantages of this methodology is its non-invasiveness and adaptability across different settings.

The combined findings from the Nirano and Marmara case studies provide a consistent methodological approach for using ambient seismic noise, particularly HVSR analysis complemented by BGTL modelling, as a cost-effective, high-value tool in hydrocarbon exploration.

In conclusion, the integration of HVSR measurements with BGTL inversion represents an effective technique for identifying and characterizing subsurface gas-bearing formations in both continental and marine environments. This passive seismic technique enables the estimation of reservoir geometry, depth, and fluid content, offering valuable insights for geoscientific studies related to fluid migration and geohazards, while also supporting practical applications in energy exploration and environmental monitoring. Future developments will aim to further test and refine this methodology by integrating additional geophysical prospecting techniques, such as seismic reflection and refraction, which can provide independent constraints for the inversion models.

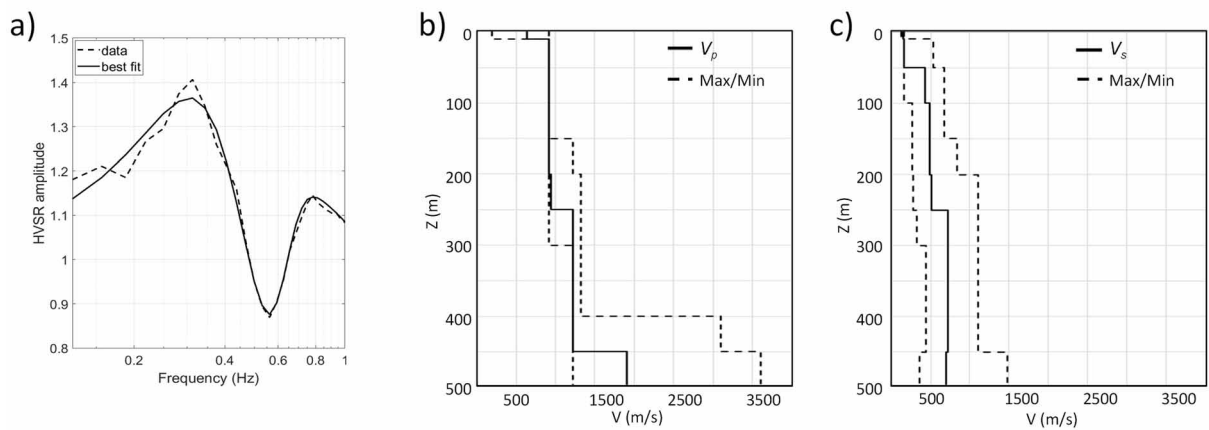


Figure 1 Inversion of the HVSR experimental curve. a) Comparison between the best fitting HVSR curve obtained by the inversion procedure (solid line) and the data, represented by the mean HVSR curve (dashed line). The corresponding V_p and V_s profiles considered to obtain the best fitting curves are reported in (b) and (c) respectively (solid lines). The dashed lines in the body wave velocity profiles represent the profile of the maximum and minimum V_p (b) and V_s (c) value at each depth.

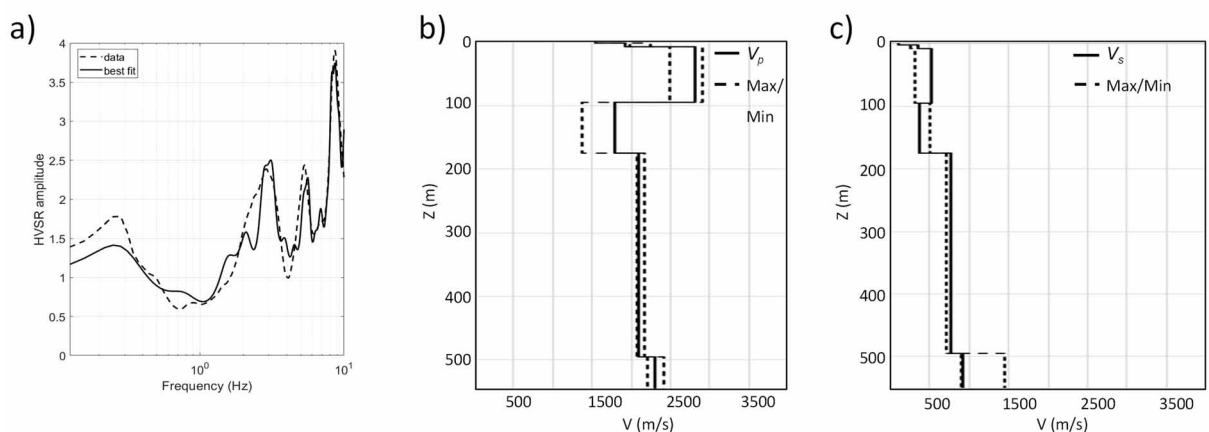


Figure 2 Inversion of the HVSR experimental curve after the removal of the water column effects. a) Comparison between the best fitting HVSR curve obtained by the inversion procedure (solid line) and the data, represented by the mean HVSR curve (dashed line). The corresponding V_p and V_s profiles considered to obtain the best fitting curves are reported in (b) and (c) respectively (solid lines). The dashed lines in the body wave velocity profiles represent the profile of the maximum and minimum V_p (b) and V_s (c) value at each depth.

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Automated detection and classification of signals in DAS

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Distributed acoustic sensing (DAS) has gained wide recognition within geophysical and environmental applications, offering high resolution, 24/7 sensing capabilities. However, the DAS system often generates more than 1 Terabyte of data each day, depending on the acquisition parameters, putting high demand on efficient methods to handle huge data volumes. Signals of interest in DAS are often identified using manual labour, such as looking through the extensive amount of data or correlation with external data sources, e.g. earthquake databases or Automatic Identification System (AIS) data [Wilcock et al., 2023]. However, this quickly becomes quite a tedious task, and we therefore looked for a way of automatically detecting signals in the vast amount of DAS data, independent of any manual work.

The methodology for finding signals in DAS data is based on simplicity, to reduce the computational demands, but also on efficiency, meaning all signals are found with almost no noise detected. We establish a normal representation of the DAS data, when no signals are present, usually created from 24 hours of data. New and unseen data is compared to the normal representation of the data and if it deviates it is flagged as a signal.

Based on the signals detected following the methodology described above, an unlabelled and labelled dataset are created. The dataset is labelled using external data sources such as earthquake databases or AIS. It should be noted that these labels are correlated automatically, without the need for manual intervention, as the timestamp and geolocation is sufficient to make this correlation. Other signals such as vehicles or damages to the cable are labelled manually based on prior knowledge.

Signals in the labelled dataset are analysed using the power spectral density (PSD) of the signals, which shows the most dominant frequencies from that signal. All the PSD of the labelled signals are stacked, and their dimensionality is reduced using Principal Component Analysis (PCA). This enables for visual representation of the signals using the first few principal components, while maintaining 90% of the spectral information from the PSDs (Figure 1).

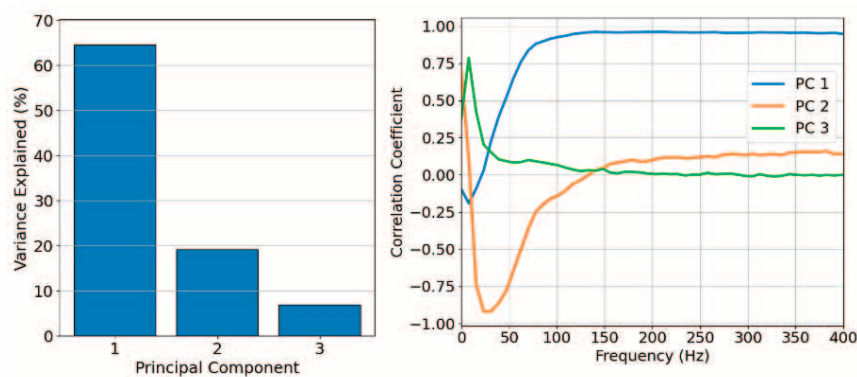


Figure 1 (left) Variance explained from the first 3 principal components of the reduced PSD dimensionality. (right) Frequency context captured by the first 3 principal components.

Figure 1 further highlights which frequencies are captured by the first 3 principal components.

Hierarchical Density-Based Spatial Clustering of Application with Noise (HDBSCAN) is applied after the PCA to cluster the signals. The t-distributed stochastic neighbour embedding (t-SNE) is used for visualization, as this captures non-linear features. The workflow is shown in Figure 2 going from the PSD of the signals to the final analysis.

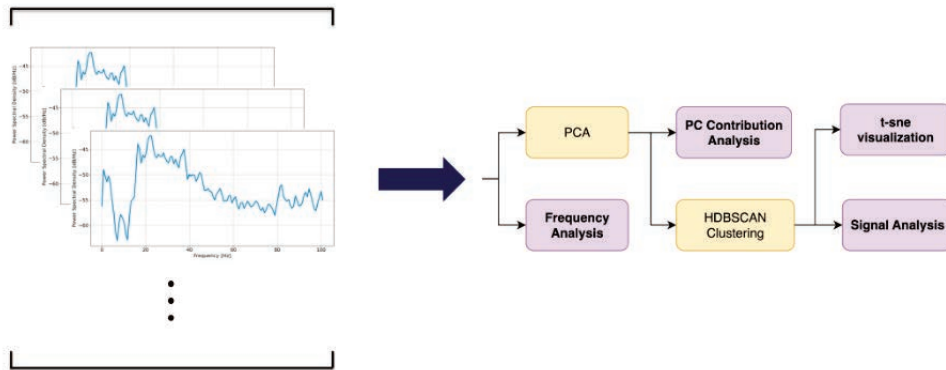


Figure 2 Workflow of classifying signals in DAS data based on the power spectral density, principal component analysis and clustering using HDBSCAN.

Signals from the labelled and unlabelled datasets are represented in Figure 3 using the t-SNE algorithm. It is clearly seen that signals originating from different sources are distinguishable based on their spectral properties. It is further seen that unlabelled data can be associated with known clusters based on the labelled dataset. This facilitates the possibilities of quickly and easily creating labelled dataset to train AI models, which has already shown promise in signal detection for DAS [Huang et al., 2025]. Further, it can enhance signal interpretation, if no external data sources are available to verify the origin of these signals.

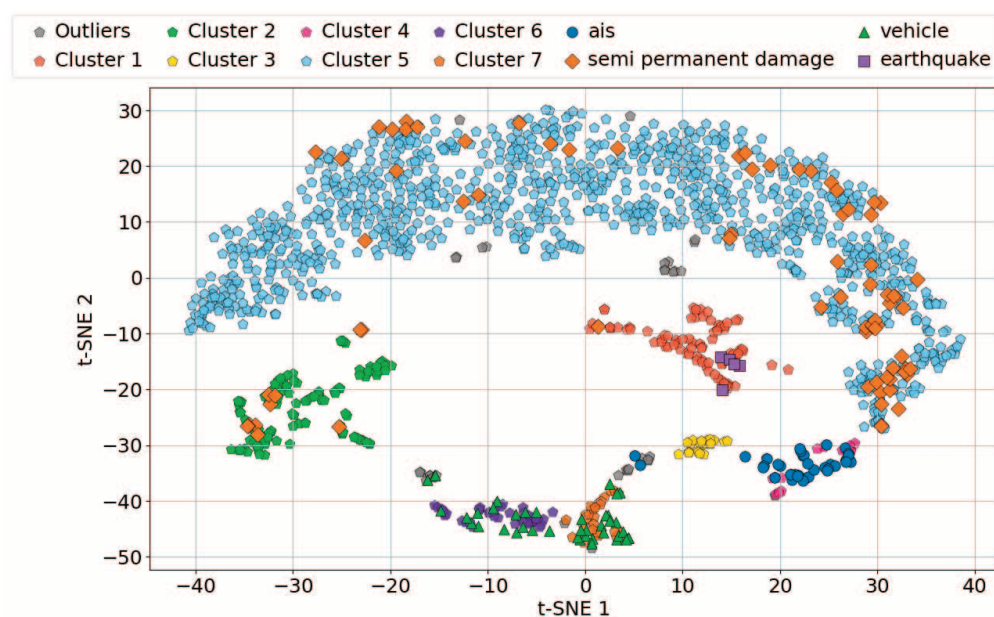


Figure 3 t-SNE visualization based on the spectral signatures of different signals in DAS data using a labelled and unlabelled dataset to classify unknown signals.

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The role of offshore geodetic data in characterizing sources of deformation at marine volcanoes: a case study from the Santorini unrest 2025

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Marine volcanoes are crucial to monitor due to their cascading hazard potential, which can impact many coastal communities worldwide. At least 57% of known active volcanoes are situated on the coast or as an island [McGuire, 2006], and much of their volume is “hidden” as it is submerged below the sea surface. For many marine volcanoes, this can be up to 90% of the edifice volume [Klein et al., 2023].

Monitoring volcano deformation is key to understanding the behavior of volcanoes and detecting periods of unrest [Ebmeier et al., 2013]. Different processes such as inflation and deflation of reservoirs [e.g., Davidge et al., 2017] or the propagation of magma [e.g., Polcari et al., 2025], and slow edifice subsidence [e.g., Bonforte et al., 2011] are responsible for causing surface deformation, and geodetic measurements can constrain the sources responsible for the observed phenomena. Interferometric Synthetic Aperture Radar (InSAR) can reveal high-resolution deformation patterns, and Global Navigation Satellite Systems (GNSS) provide high temporal coverage of ground deformation events. Both the spatial and temporal aspects of a deformation event are key to evaluate for understanding what is occurring in the subsurface. The joint inversion of both datasets allows constraints to be made on the source of deformation by minimizing the difference between modelled displacements and the observed data. Analytical inversion solutions are quick methods to gain a first approximation of the source of deformation, but often have limitations in their complexity due to not accounting for topography and using simple-shaped solutions, such as point sources [e.g. Mogi, 1958] or planar dislocations [e.g., Okada, 1985]. However, numerical methods, like boundary element models, can incorporate both the topography [Cayol & Cornet, 1997] and more complex source-shaped solutions, which can be necessary to explain InSAR datasets in particular [Fukushima et al., 2005]. Accounting for topography and complex sources is particularly relevant at marine volcano settings, where significant deformation can occur offshore as an effect of the topography [Campbell et al., in review], and, for dike modelling simple shapes, like a single dislocation plane, can often underestimate the true nature of pathways in the subsurface [Fukushima et al., 2005].

Only small areas of island volcanoes can be monitored through typical subaerial geodetic techniques, and challenges can sometimes occur in recording deformation events. For instance, poor InSAR coverage can occur from both vegetation-related decorrelations and the shape of the terrain of volcanic islands [Polcari et al., 2025]. Limitations in GNSS station placement can also occur from steep terrain, and economic challenges associated with instrument installation and maintenance. Limited signal coverage can lead to uncertainty in the type of deformation source. This has been observed for Anak Krakatau, an island volcano in the Sunda Strait, Indonesia. Here, deformation has been observed as deflation [Chaussard & Amelung, 2012], while later it has been suggested that the flank was sliding [e.g., Kim et al., 2024]. This ambiguity associated with the

source of deformation has the potential to arise from the lack of signal coverage prevalent at many island volcanoes worldwide. A possible solution to this would be to incorporate submarine geodetic observations where available, which give insight into the deformation occurring below sea level. Submarine geodesy is an emergent field, and despite its logistical and economic challenges, it has proven efficient to measure offshore deformation at many different case studies worldwide. For example, Axial Seamount, a submarine volcano off the west coast of Oregon, USA, has near-continuous monitoring of deformation which has allowed insight into its eruptive behavior [e.g., Chadwick et al., 2006] and campaign seafloor geodetic surveys have allowed different volcanoes to be monitored such as Kilauea [Phillips et al., 2008] and Mount Etna [Urlaub et al., 2018]. Due to the challenges with offshore monitoring and limited case studies, the potential improvements and reduction of uncertainty of using offshore observations in source inversions at island cases is, to these authors' knowledge, unknown.

This could have particular relevance for the Santorini seismic crisis, which occurred in early 2025. Santorini is an active volcano situated in the Aegean Sea, famous for both its historic caldera-forming eruptions [e.g. Druitt et al., 1989] and as a popular tourist destination, with around 3 million visitors per year. Just northeast of Santorini is a submarine volcano, Kolumbo, which is known for its explosive history [e.g., Karstens et al., 2023] and hazards that it poses to the nearby populations of Santorini and other Greek islands. From the end of January until the beginning of March 2025, Santorini and neighboring islands experienced a seismic crisis, where significant seismicity was located offshore between the islands of Santorini and Anhydros and large ground deformation signals were recorded on nearby islands stations [Briole et al., 2025; Isken et al., 2025]. Whilst GNSS-only modeling attributes the unrest to slip on a south-east dipping normal fault [Briole et al., 2025], using GNSS in combination with InSAR and OBSP data attributes the unrest to an offshore propagating dyke [Isken et al., in review]. The study from Isken et al (in review) used freely available subaerial geodetic datasets, as well as OBSP data from two of seven stations which were deployed offshore Santorini, around Kolumbo from the 1st of January 2025 [Berndt et al., 2025] - presenting a unique case where cross-domain geodetic data are available.

In this study, we aim to present a case where the inversion for deformation source characteristics can be improved by utilizing data collected in the offshore domain, at the case study of Santorini, where seven OBPS were placed during a period of unrest. We will use a modelling method that accounts for topography and complex source shapes and compare model simulations with and without the OBPS data to quantify its role in inversion methods. This work will aim to highlight the importance of seafloor observations for understanding the behavior of marine volcanoes.

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Characterizing the 2012-2023 Etna lava fountains through machine learning techniques applied on high-precision strain signals

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At Etna volcano (Italy), lava fountains (LF) are explosive eruptions of duration of few hours consisting of jets of hot volcanic gas and solid particles reaching heights of more than 10 km above the sea level. These events pose serious risks for the air traffic and the civil infrastructures due to the ash dispersal and fallout, respectively. For these reasons, the lava fountains have drawn particular attention of civil authorities and researchers to better characterize these eruptive phenomena and support decision-making tasks for risk mitigation.

Despite the Etna lava fountains belong to the same eruptive category, they show different characteristics in terms of duration, explosiveness and erupted volumes and thus have a different degree of associated hazard. The extrapolation of these characteristics is usually performed manually, which can result in a characterization that is biased by the subjective evaluation of the experts involved. An objective characterization of the lava fountains is necessary for better distinguishing the different level of risks that can be associated to the LFs. From 2011 to 2023, the Etna volcano experienced sequences of lava fountains that count more than 100 events. During these eruptions, the borehole strainmeter network managed by the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, detected tiny ground deformations representing the response of the volcano edifice to a depressuring source feeding the eruption [Bonaccorso et al., 2021]. Carleo et al. [2023] found objective features of the strain signal that characterize the 58 lava fountains in 2020-2022 at the South-East Crater (SEC) of the Etna volcano. By means of machine learning methods (k-means algorithm), they found four clusters of events characterized by similar strain responses.

In this work, the analysis of the strain signal is extended to the 84 SEC lava fountains occurred in 2012-2023. Unsupervised machine learning models are optimally designed to properly characterize the strain signal and discover particular patterns in the data. The results provide a clearer picture of the strain characteristics that lava fountains at SEC may exhibit.

Data and methods

The borehole strainmeter records the volumetric deformation of the rock in a wide frequency band (10^{-7} to > 20 Hz) and with the highest resolution (10^{-12}) among geodetic techniques [Roeloffs and Linde, 2007] making this instrument highly suitable to detect the tiny ($<10^{-7}$) ground deformation that the Etna lava fountains produce. At Etna, four strainmeters are installed (Figure 1a). In this work, the signal recorded at the DRUV station, characterized by an optimal rock-sensor coupling, is used. The DRUV signal is accurately filtered from the disturbing effects of the Earth tides and the barometric pressure to improve the capacity of the signal of detecting volcano-related strain variations up to the order of 10^{-10} at time scales of few hours [Carleo et al., 2022a]. The DRUV strain variations (Figure 1b) induced by LFs are first detected with the automatic procedure of Carleo et al. [2022b] and then characterized by extracting three main signal features [Carleo et al., 2023]: the amplitude, A , and the duration, D , of the strain change and the average time derivative of the strain signal (strain rate) from the beginning of the variation up to the time when 75% of the maximum strain rate, $SS_{0.75}$, is reached. These features

can be related to specific characteristics of the eruption: A can be associated to the erupted volume [Bonaccorso et al., 2023], D and SS_{0-75} are related to the duration and the intensity of the event, respectively [Carleo et al., 2023]. These three strain features are used to characterize the 84 strain changes recorded during the 2012-2023 SEC lava fountains. Since the features are in different units and ranges, to ensure a balanced weight for the characterization, their values are normalized.

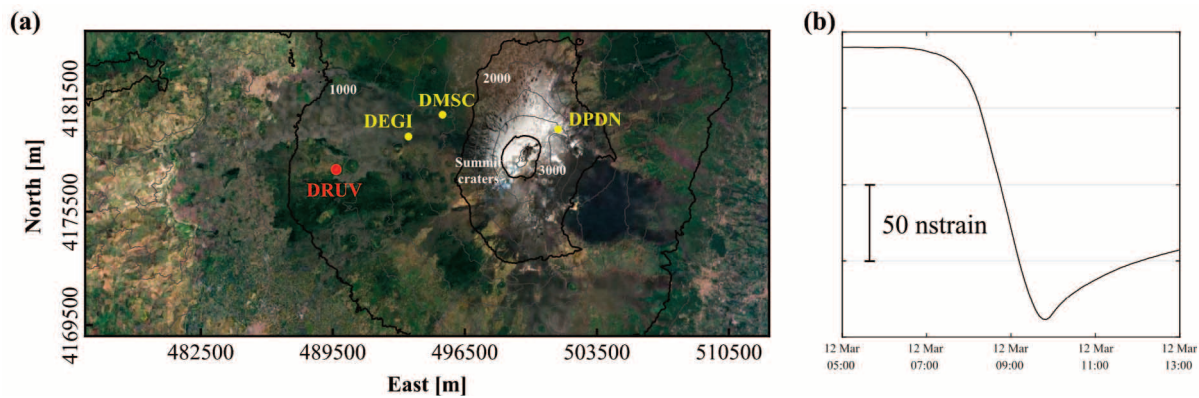


Figure 1 (a) Location of the strainmeter stations at Etna. (b) Example of strain change during the 12/03/2021 LF.

Each eruption is thus represented by the related strain variation as a data point in a 3D domain whose coordinates are given by the three normalized strain feature values. These data points represent the input dataset to investigate. Self-Organizing Maps (SOMs, Kohonen 2013) are used to explore the data distribution. The SOM consists of a grid of neurons to each of which a weight vector with the same dimensionality of the input dataset is associated. The map iteratively updates the weight vectors to learn both the distribution and the topology of the data. Once the map is self-organized, the neurons distribute in the feature domain according to the spatial density of the data. Each input datum, namely each eruption, is then associated to the closest neuron. Various information, such as neuron weights and distances, can be extracted from the SOM to represent the multidimensional input dataset in a lower, usually two-, dimensional domain. In this work, the SOM is implemented using MATLAB R2022a. A hexagonal topology of the map and an Euclidean distance function between the neurons are considered. The number of neurons and the aspect ratio of the map, the number of iterations and the neighbourhood parameter are optimized considering both the quantization and the topology errors [Kiviluoto 1996].

Results and conclusions

The strain features related to the 2012-2023 eruptions exhibit a wide range of values: A varies in the range [21 297] nstrain, D in the range [0.6 9.3] hours and SS_{0-75} in the range [10 184] nstrain/h. The optimal SOM and its characteristics are presented in Figure 2. The normalized values of the neuron weights A , D and SS_{0-75} are shown in Figure 2a, b and c, respectively. The normalized distances between the neurons are presented in Figure 2d. On the basis of the neuron weights and distances, four different homogeneous groups of neurons C , quite well cohesive and separated from each other and characterized by similar weight values, can be identified. The first group, $C1$, comprehends neurons very close each other and characterized by low values of all the neuron weights (Figure 2a-c). The second group, $C2$, gathers sparser

neurons that exhibit intermediate weight values. The third, C3, and fourth, C4, groups collect higher sparse neurons but with distinct and opposite characteristics: C3 neurons shows high values of the weight SS_{0-75} (Figure 2c) and low values of the weight D (Figure 2b) while C4 neurons exhibit low values of SS_{0-75} and high values of D . Since each eruption is associated to a neuron and thus to a group C, four different groups of lava fountains can be retrieved from the SOM. Most of the LFs ($\approx 80\%$) belong to C1 and C2 and exhibit low to intermediate values of all the features A , D and SS_{0-75} . The rest of the lava fountains ($\approx 20\%$) are either very short ($D < 2$ hours) and fast-evolving (very high strain rates; C3) or very long ($D > \approx 5$ hours) and slow-evolving (very low strain rates; C4). Carleo et al. [2023], which analyzed the 58 eruptions occurred at SEC in 2020-2022, also found four homogenous groups of SEC eruptions using similar strain characteristics. The analysis extended over the larger dataset of 84 SEC lava fountains occurred in the period 2012-2023 confirm the existence of such groups and enrich their description in terms of frequency of occurrence and associated strain response.

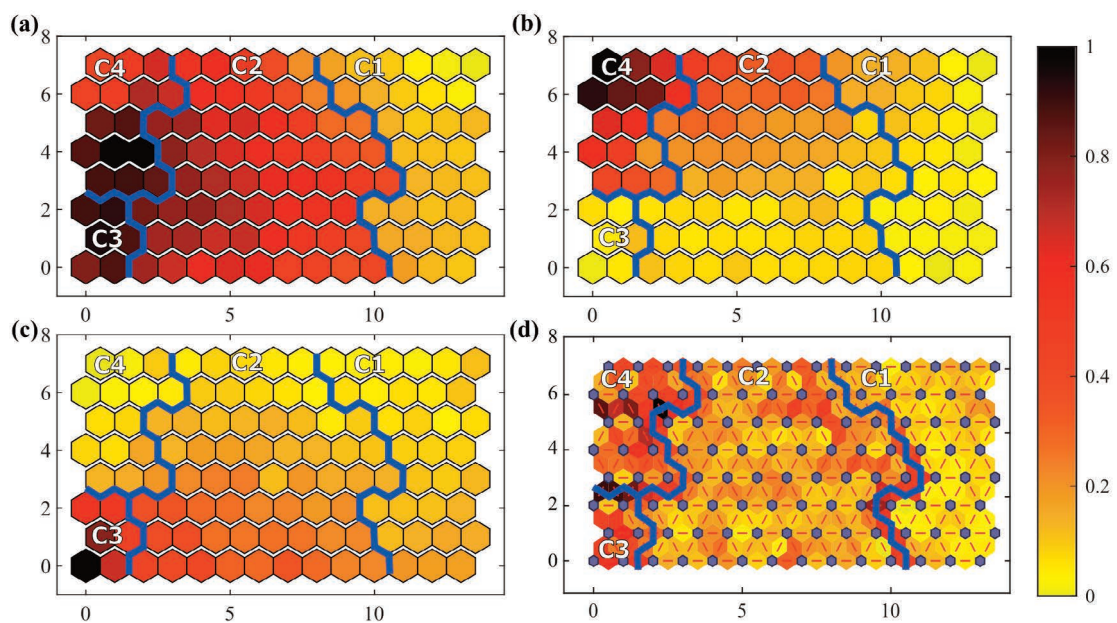


Figure 2 Optimal SOM for the 2012-2023 SEC lava fountains. Normalized values of the neuron weights A (a), D (b) and SS_{0-75} (c) and of the distances between the neurons (d). Bright and dark colours correspond to low and high weights and distance values, respectively. Four homogenous groups of neurons C are identified.

The findings from the SOM analysis reveal that the strain characteristics A , D and SS_{0-75} which can be related to the erupted volume, the duration and the intensity of the event, respectively, objectively characterize the SEC lava fountains and may support decision-making tasks for risk mitigation actions.

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Seismic Analysis of the Oltenia Area in Romania Using Ambient Vibration and Earthquake HVSR for Enhanced Hazard Evaluation

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The SW part of Romania is characterized by crustal seismicity. Oltenia region is one of the seismic areas known for its significant seismic activity, mainly due to its complex geological and tectonic setting, consisting of multiple sedimentary layers. These geological features have the potential to amplify the seismic energy and alter the patterns of ground motion experienced during seismic events. Given the region's history of seismic events and ongoing activity, continuous observation and research are essential to accurately evaluate seismic hazard and improve disaster preparedness [Radulian et al., 2023]. The moderate-magnitude crustal earthquakes that struck in February 2023 highlighted the seismic vulnerability of Oltenia. This sequence was initiated by two significant shocks (a 4.8 Mw event on February 13 and a 5.4 Mw event on February 14) followed by more than 4000 aftershocks over nearly a year (Figure 1, bottom), according to the Romplus catalogue [1]. Historical records reveal that Oltenia has been affected by several earthquakes in the past, such as those on July 9, 1912, June 20, 1943, and May 4, 1963, with epicentral intensities ranging between V and VI on the MSK scale [Oncescu et al., 1999]. The recent February 2023 earthquakes also registered intensities of V to VI (MSK scale), leading to minor to moderate structural and infrastructural damage [Oncescu et al., 2023a].

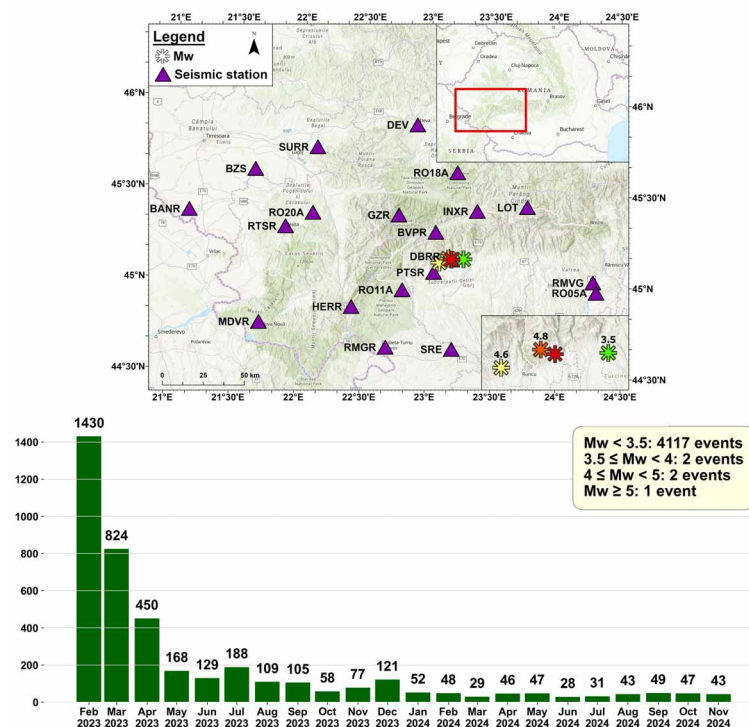


Figure 1 Top - Location of the seismic events and stations analyzed in the current study. The investigated zone is marked by the red rectangular frame. Bottom - Distribution of the earthquakes from February 2023 to November 2024.

The present study focuses on evaluating the seismic response of the Oltenia zone through the computation of the Horizontal-to-Vertical Spectral Ratio (HVSr; [Nakamura, 1989] approach, utilizing ambient vibration (nHVSr - noise Horizontal-to-Vertical Spectral Ratio) and seismic signals (eHVSr - earthquake Horizontal-to-Vertical Spectral Ratio) recorded at local seismic stations (Figure 1, top). Measurements of continuous 24-hour ambient vibrations and data from crustal earthquakes (above magnitude 3.5 Mw and depth between 12.9 – 17.5 km) compose the dataset. All data were collected by Romania's National Institute for Earth Physics (NIEP), utilizing both their established permanent stations (17 - RSN [NIEP Romania, 1994]) and temporary stations (4 - AdriaArray project, Y8 [Neagoe, 2022]) installed during recent seismic events.

In order to assess the local site effects and identify the fundamental frequency of resonance of the site, noted as f_0 (Figure 2), the widely utilized HVSr method was computed [Apostol, 2008], [Coman, 2024], [Manea et al., 2020], [Dal Moro & Panza 2022]. It involves calculating the spectral ratio between the Fourier spectra of the horizontal components ($F_{east}(f)$, $F_{north}(f)$) and the Fourier spectrum of the vertical component ($F_{vertical}(f)$) of the waveforms recorded by a single station equipped with a three-component sensor. The Fourier transform is computed for each seismic signal and is used to generate the frequency spectrum. With the notations introduced earlier, it can be formulated mathematically as follows [Nakamura, 1989]:

$$\frac{H}{V}(f) = \frac{\sqrt{F_{east}(f)^2 + F_{north}(f)^2}}{|F_{vertical}(f)|} \quad (1)$$

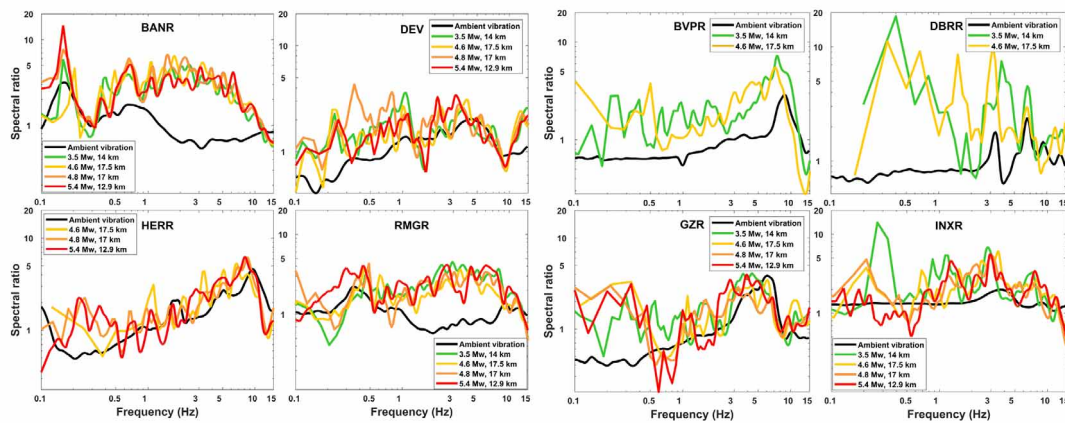


Figure 2 nHVSr and eHVSr curves for the stations located far-field (left) and close-field (right) related to each earthquake (the colored lines).

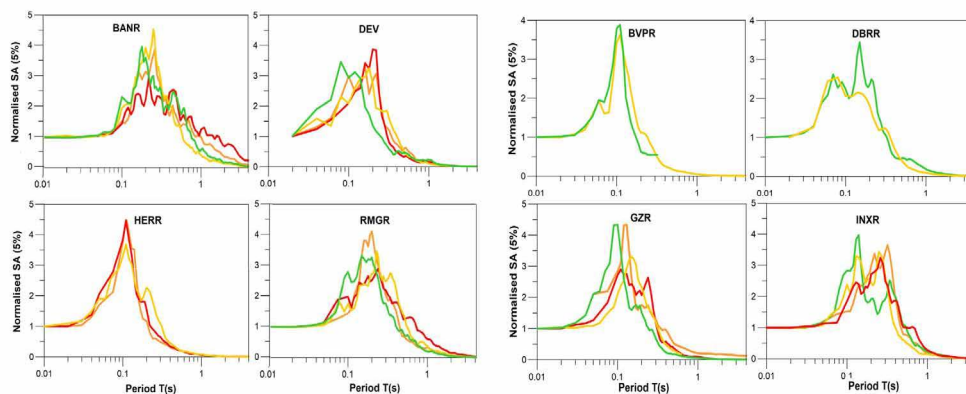


Figure 3 Normalized response spectra for the analyzed seismic events (the colored lines are unitary as in Figure 2) for far-field (left) and near-field (right).

Investigating the signal-mixed dataset with this technique reveals essential information about site characteristics and their capacity to enhance ground shaking. The composite spectral responses from individual stations, coupled with HVSR results derived from earthquake records, illustrate the real ground motion behavior during significant seismic events. In Figure 2, the black plots show the nHVSR computed using ambient vibrations, and the colored plots present the eHVSR curves obtained using earthquake signals. Each color line represents an individual seismic event, with its characteristic magnitude (M_w) and depth (km). In Figure 3, the same earthquakes were analyzed, and the colors represent the same data as in Figure 2 (unitary). The spectral acceleration (SA) curves (Figure 3) represent the geometric mean horizontal component of the 5% damped linear elastic response spectra, a type of ground motion measure widely used in modern ground motion predictive models [Campbell & Bozorgnia, 2008; Kale et al., 2015].

The seismic sequence that occurred in 2023 in the investigated region offers the opportunity to clarify the local soil behavior. The southwestern region of Romania was characterized by combining ambient vibration and earthquake signals in order to improve the seismic hazard assessment. Local site effects and seismic response in the studied area were analyzed for future engineering applications in the scenario of a major seismic event. The obtained results can be used to mitigate the seismic risk in the region. The results illustrate complex characteristics associated with geology and the presence of lateral variations within the subsurface layers. The peaks in the colored lines (Figure 2) indicate frequencies at which the ground motion from the earthquakes is significantly amplified compared to the ambient vibration. Both e- and nHVSR peak amplitudes are clearly different from (and not connected to) the actual soil response used in microzonation. Near field effects - average epicentral distance from 5 km (DBRR) to 42 km (GZR) - a rather fast attenuation of the low frequencies excited by seismic sources (around 0.5 Hz) in local structures is observed; important/highest amplifications occurring around f_0 are also retrieved at in the maximum spectral response (normalized in Figure 3) which is decreasing as M_w increases (BVPR, GZR, INXR stations). Far field effects - average epicentral distance from 65 km (HERR) to 160 km (BANR) - site effect prevails in eHVSR curves with the predominant peaks close to the fundamental one; only at DEV station the maximum spectral response is reached around the fundamental frequency of resonance f_0 ($f_0 \sim 4.4\text{Hz}$).

The study's conclusions will improve knowledge of the seismic behavior and site effects in the Oltenia region, providing essential information to support earthquake engineering practices and disaster mitigation efforts.

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Sitography

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Seismic Event Detection using Distributed Acoustic Sensing and Artificial Intelligence

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Summary

The Campi Flegrei caldera, located in southern Italy near the city of Naples, is one of the most hazardous volcanic systems in Europe due to its explosive potential, high population density, and ongoing unrest. Since 2005, the area has been experiencing a renewed phase of ground uplift and increased seismicity, raising significant concerns about volcanic reactivation. In this context, enhancing monitoring capabilities is critical for early warning and risk mitigation.

To support ongoing monitoring efforts, a Distributed Acoustic Sensing (DAS) device was installed in October 2023 interrogating an existing underground telecommunication dark fiber optic cable that crosses the urban area of Campi Flegrei. The DAS installation [Currenti et al., 2025] enables dense, high-resolution monitoring of seismic and vibrational activity over a 22 km long fiber, complementing the data from the permanent INGV-OV seismic network.

DAS technology transforms standard optical fibers into thousands of distributed sensors by sensing strain-induced phase changes in backscattered laser pulses (phase-OTDR). For this deployment, the selected fiber was interrogated with a Pulse Repetition Frequency (PRF) of 4000 Hz, using a gauge length of 10 meters and a spatial sampling interval of 4.8 meters. This configuration provides 4,584 virtual sensing channels along the fiber, with a data rate of approximately 3.85 MB/s at 200 Hz acquisition frequency.

The deployment at Campi Flegrei poses unique challenges, primarily due to the complex coupling between the optical fiber and the ground, as well as the presence of an urban environment that generates high levels of anthropogenic noise. Consequently, the raw DAS data are often contaminated by intricate noise patterns, which significantly degrade the effectiveness of conventional seismological processing techniques for reliable event detection and characterization. To address these limitations, the research has focused on the adoption of advanced data-driven methods based on deep learning architectures. These Artificial Intelligence (AI) techniques are designed to enhance the sensitivity and interpretability of DAS measurements by learning to identify and extract meaningful seismic signatures embedded within highly noisy and heterogeneous datasets.

Detection method

The detection approach is grounded in state-of-the-art deep learning models, specifically Vision Transformers (ViTs) [Dosovitskiy et al., 2020]. ViTs are a class of architectures that extend the original transformer model, developed for natural language processing, to the domain of computer vision. In particular, the DINOv2 framework [Oquab et al., 2023] was utilized. It is a self-supervised foundation model capable of learning rich and generalizable visual representations without requiring labeled data.

Within this framework, DAS data are reinterpreted as images, segmented into fixed-size

patches and subsequently embedded into a sequence suitable for transformer-based processing. The multi-head self-attention mechanism of the ViT architecture captures both short- and long-range spatial dependencies among patches, making it well-suited for recognizing weak seismic patterns embedded in complex and noisy environments. The high-dimensional features extracted by DINOv2 are subsequently fed into a downstream Multi-Layer Perceptron (MLP) classifier trained to distinguish between seismic events and background noise. This architecture has demonstrated strong performance in detecting low-magnitude seismic signals, even under intense anthropogenic interference, owing to the robustness and transferability of the representations learned by the pretrained ViT.

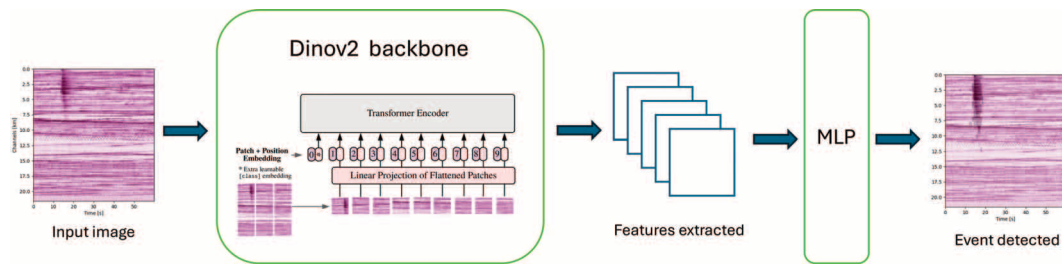


Figure 1 Architecture of the proposed method.

Experimental results

To evaluate the performance of our model, we used a dataset consisting of seismic events recorded by the INGV-OV network between October 19, 2023, and February 18, 2024. During this period, 567 seismic events were catalogued [Ricciolino et al., 2024], as shown in Figure 2.

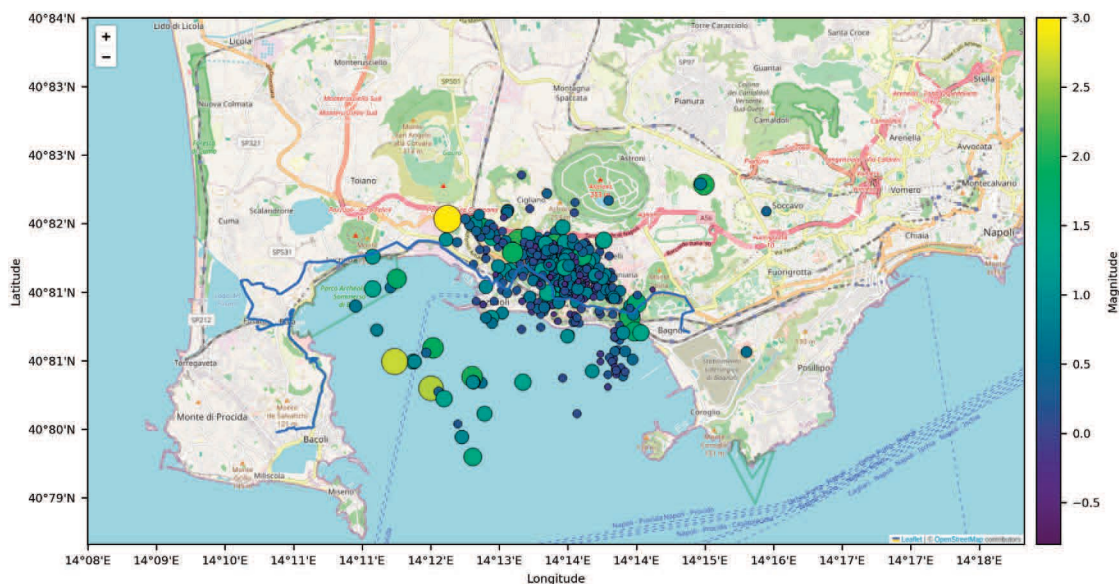


Figure 2 Map showing the spatial distribution of seismic events recorded by the INGV-OV network during the DAS acquisition period (19 October 2023 – 18 February 2024). Marker size and color correspond to event magnitude.

Our method successfully detected 548 of these events, with 19 missed detections (false negatives). This corresponds to a detection rate of 96.6%, indicating high sensitivity (Figure 3), even with very low magnitude and in the presence of high anthropogenic noise (Figure 4)

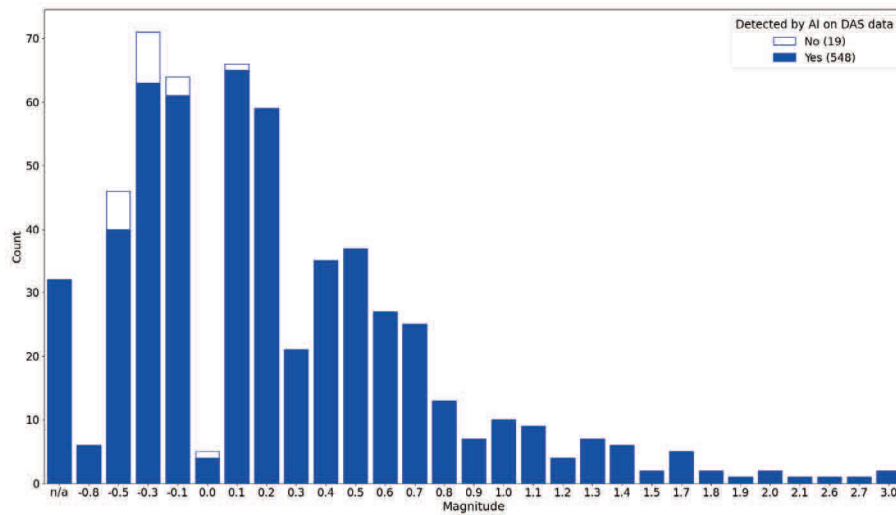


Figure 3 Detection capability of the proposed model (left) and an example of detection of three events (right).

To further evaluate the model's reliability in detecting seismic activity, a continuous analysis of DAS data was conducted over an 18-day period, from 1 February 2024 to 18 February 2024. During this timeframe, the algorithm detected a total of 259 previously unreported seismic events and identified 45 false positives.

These results suggest that the model is capable of revealing otherwise undetected seismicity, while maintaining a relatively low false positive rate. This highlights the enhanced resolution and sensitivity provided by the DAS-AI system in detecting fine-scale seismicity.

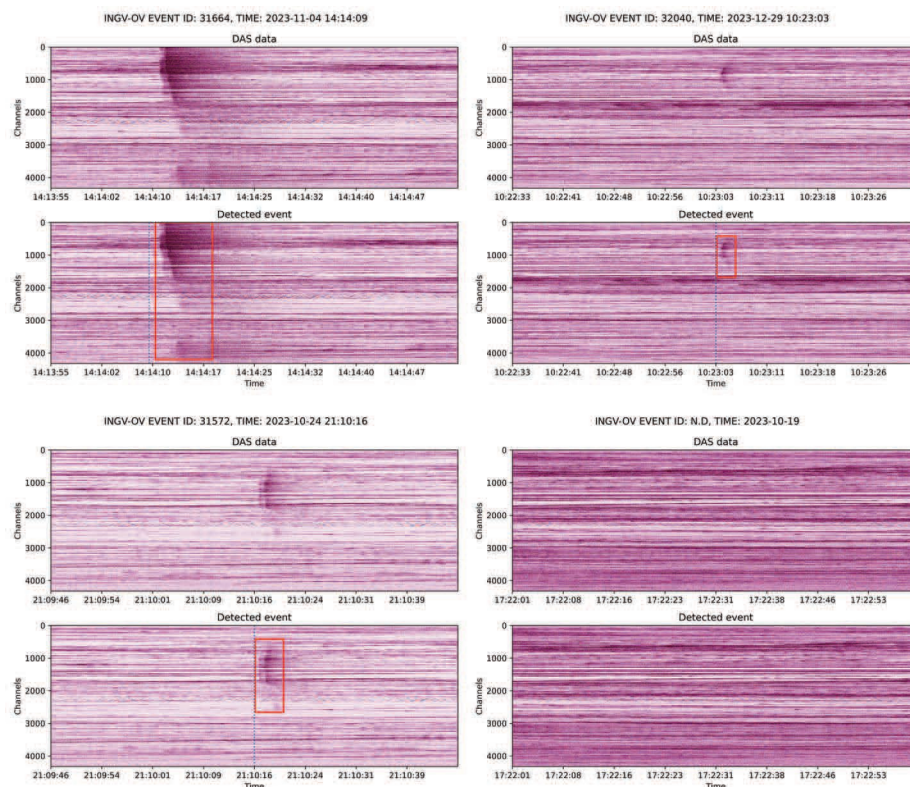


Figure 4 Example of a four-minutes analysis using our detection network. The top-left panel shows a detected event with a magnitude of 1.7, the top-right a magnitude 0.1 event, and the bottom-left a magnitude 0.6 event. The bottom-right panel contains noise-only data with no seismic events, demonstrating the method's ability to perform reliably without producing false positives.

Conclusions

The combination of high-density DAS measurements and advanced AI techniques significantly improves the detection of seismic events, even in environments with intense anthropogenic noise. Leveraging DAS technology alongside sophisticated deep learning architecture offers a scalable, non-invasive solution to enhance volcanic monitoring in densely populated and seismically active regions such as Campi Flegrei. In particular, the integration of DAS data with the proposed deep learning detection method has demonstrated increased sensitivity, enabling the identification of a greater number of seismic events - especially during seismic swarms.

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Operational integration of submarine DAS for earthquake monitoring: a case study from the Canary Islands

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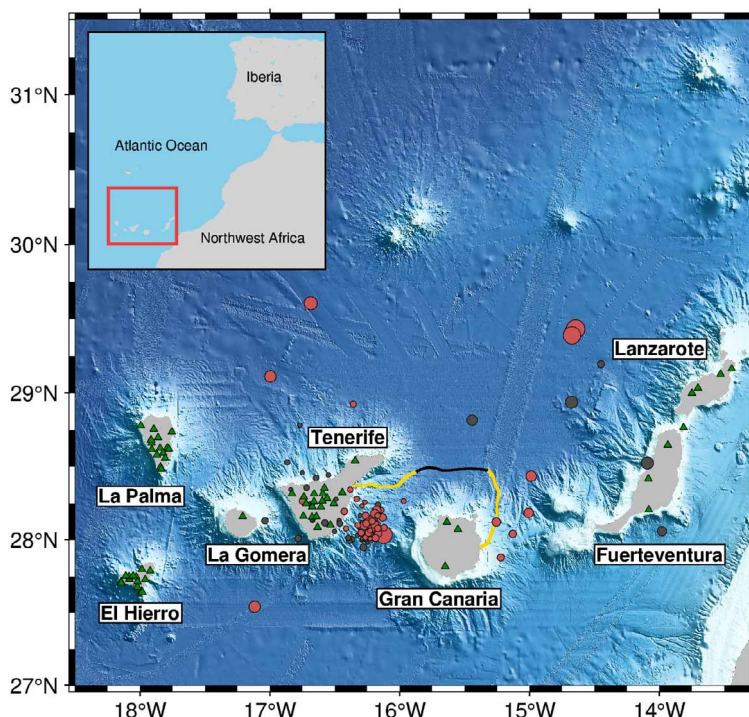
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Submarine fibre-optic cables can be instrumented with distributed acoustic sensing (DAS) technology to serve as dense seismic arrays for earthquake monitoring in offshore regions that lack conventional instrumentation [e.g., Lindsey et al., 2017; Zhan, 2020]. However, despite recent advances, the operational integration of DAS into established seismic networks remains limited, among many causes due to the high data volume and variability in signal quality along the cable [Rodriguez et al., 2025].

In this study, we propose a practical approach for incorporating DAS-derived seismic-wave arrival times into standard earthquake location workflows [Bozzi, 2025; Cubas Armas et al., 2025]. The methodology prioritizes high-quality and spatially representative phase picks along the cable to improve event characterization. We apply this strategy to a sequence of regional earthquakes near Enmedio volcano, an active zone located between Tenerife and Gran Canaria, and one of the most seismically active areas in the Canary Islands. For this purpose, DAS observations from a nearby submarine cable are combined with official catalogue data from the National Geographic Institute (IGN) permanent seismic network. The DAS experiment, conducted from July to September 2020 [Ugalde et al., 2022], interrogated two ≈ 60 km-long sections of the cable, yielding 5,984 channels per section. We identified 32 earthquakes detected by both IGN and DAS, all with local magnitudes greater than or equal to 1.1 (Figure 1).

Figure 1 Map of the Canary Islands showing the Canalink submarine cable (black line), with DAS-interrogated segments highlighted in yellow. Seismic stations from the IGN network are shown as green triangles. Earthquake epicentres are represented by circles: grey for all events detected by IGN during the study period, and red for those also detected by the DAS system [modified from Cubas Armas et al., 2025].



To extract phase information from the DAS data, each regional earthquake detected by IGN was time-windowed around its origin time and processed with PhaseNet-DAS [Zhu et al. 2023], to pick P- and S-wave arrival times. For events exhibiting coherent energy across multiple adjacent channels, a five-channel stacking procedure was applied prior to picking to enhance waveform coherence. This step proved particularly effective in reducing noise and improving pick consistency. To further optimize input quality, low-quality channels were filtered using CQI-DAS [Rodríguez et al., 2025], a machine learning-based tool that assesses each DAS channel's ability to record earthquake signals.

To avoid overrepresentation of densely spaced DAS channels, we applied spatial decimation to the DAS dataset. From the subset of high-quality channels with valid picks, the cable was divided into ten segments to approximate the inter-station spacing of the IGN network, and one representative channel was selected per segment. Selection was based on PhaseNet-DAS confidence scores, with a minimum spacing criterion to maintain a uniform spatial distribution. This approach balances channel reduction with the preservation of spatial information critical for accurate event location. The resulting subset of up to ten DAS channels was then merged with seismic arrivals from IGN stations. Earthquake relocation was performed using the latest version of NonLinLoc (NLL-SSST-coherence) [Lomax & Savvaidis, 2022], which accounts for velocity model uncertainties via station corrections (SSST) and arrival-time weighting based on inter-event waveform coherence.

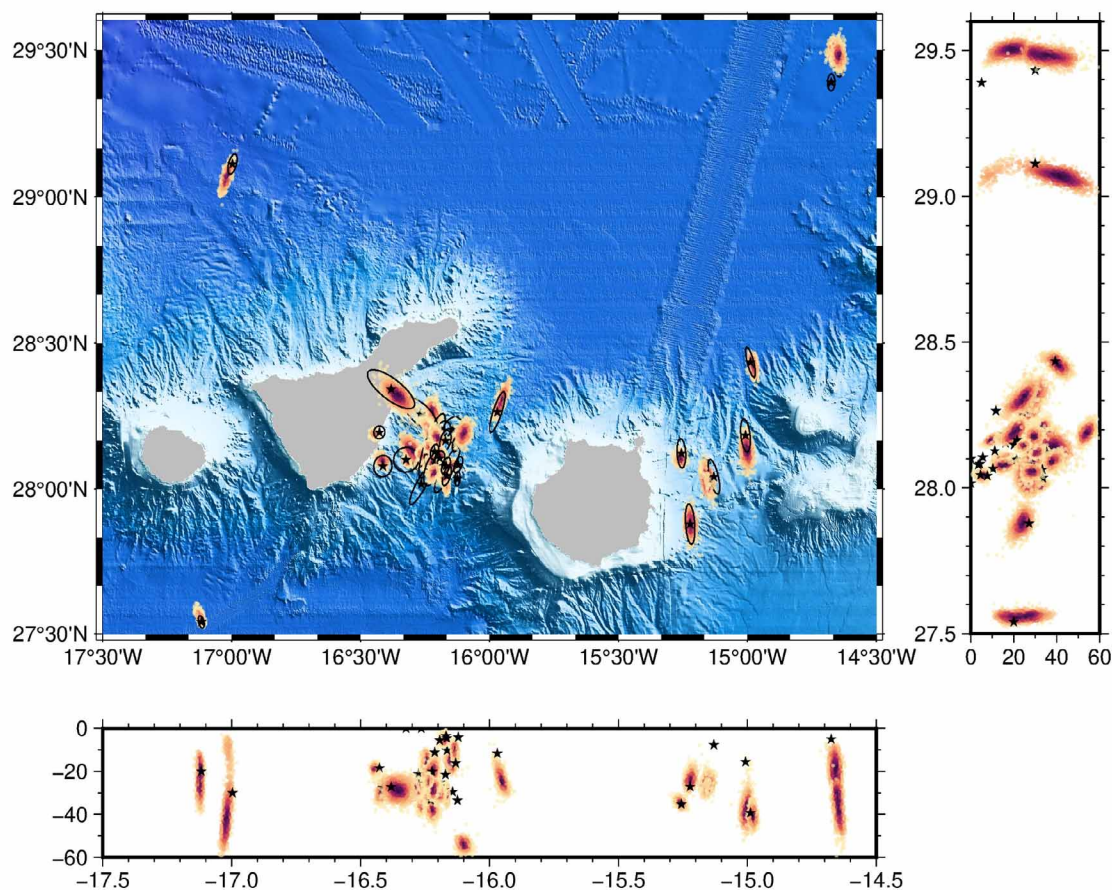


Figure 2 Earthquake locations obtained with NonLinLoc using both IGN picks and DAS-based picks, shown in three orthogonal views: map view (longitude vs. latitude, top left), vertical cross-section (longitude vs. depth, bottom), and cross-section (latitude vs. depth, right). Black stars and their associated ellipses represent the locations and uncertainties from the IGN catalogue. Coloured point clouds correspond to our relocations [modified from Cubas Armas et al., 2025].

Applying this integrated workflow yielded clear improvements in event location performance (Figure 2). Compared with the official IGN catalogue, our approach lowers the RMS residual for every event to ≤ 0.08 s and tightens the location uncertainties: the median 1- σ depth error drops from over 12 km to 3.3 km (–73 %), while the mean 1- σ horizontal semi-major axis contracts to 2.95 km (–72 %). The inclusion of selected DAS picks enhances azimuthal coverage and proximity to the epicentre, while avoiding the overweighting of spatially dense or low-quality data. By retaining only the most informative channels, the method remains compatible with existing real-time workflows and storage constraints. This makes it especially well-suited for submarine environments and offers a scalable framework for improving seismic monitoring in offshore regions.

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Improving Seismic Hazard Assessment Through Physics-Based Source Modeling

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The destructive potential of an earthquake, particularly in near-fault regions, is critically controlled by the complex dynamic processes occurring on the rupture plane. While macroscopic parameters like magnitude provide a general scale of the event, the kinematic heterogeneities of the seismic source determine the specific characteristics of the damage. These include: the non-uniform distribution of slip, featuring high-slip patches known as asperities; the acceleration and deceleration of the rupture front, which generate high-energy directivity pulses; and the local slip rate and rise time, which govern the intensity of the energy release.

These parameters do not vary independently but exhibit complex intercorrelations. Previous studies have demonstrated that rupture speed and rise time are dependent on the slip distribution. For instance, Graves and Pitarka [2004] considered a magnitude-dependent scaling relationship for the correlation between slip and rupture speed, while Aagaard et al., [2008] proposed a correlation between slip and rise time. Furthermore, key properties of seismic rupture show a depth-dependence [Mikumo, 1992; Scholz, 2002]. Analysis of recent earthquakes has revealed that shallow-rupturing events tend to generate relatively weak high-frequency ground motion compared to deeper ruptures [Shearer et al., 2006; Pitarka et al., 2009].

A detailed description of the spatio-temporal characteristics of the rupture process is therefore fundamental for estimating the expected ground motion and, consequently, for an accurate seismic hazard assessment of specific sites. Empirical Ground-Motion Models (GMMs), while useful, may not always capture the full complexity of shaking in a specific area. Their validity is limited as they are based on statistical regressions from a restricted number of past events, often with a scarcity of data in near-source regions where attenuation and propagation effects are minimal and damage is greatest.

The project SECURE (*Regional-Scale Earthquake Ground Motion Prediction Through Physics-based and Empirical Approaches: A Case Study Central Italy*) in which we are involved, addresses the challenge in ground motion prediction through a systematic investigation using physics-based simulations. Our approach is centered on the explicit and advanced modeling of the seismic source, applying the methodology of Graves and Pitarka [2016]. The core of this method is its ability to generate a wide range of physically plausible, heterogeneous rupture models. Once a sufficiently detailed velocity model is defined, the source rupture process can be convolved with calculated Green's Functions to obtain the full elastodynamic solution. This allows for the generation of synthetic scenarios essential for improving seismic hazard assessments.

The Graves and Pitarka [2016] method separates cases based on whether a slip distribution map for a specific event is available. If an initial slip model exists (e.g., from geodetic or seismic inversions), a two-step procedure is applied. As an example from the Mw6.2 Amatrice 2016 earthquake, first, the model is low-pass filtered to identify the major slip patches (in red and orange in Figure 1a). Subsequently, high-frequency details are added stochastically to create a more realistic, broadband source model.

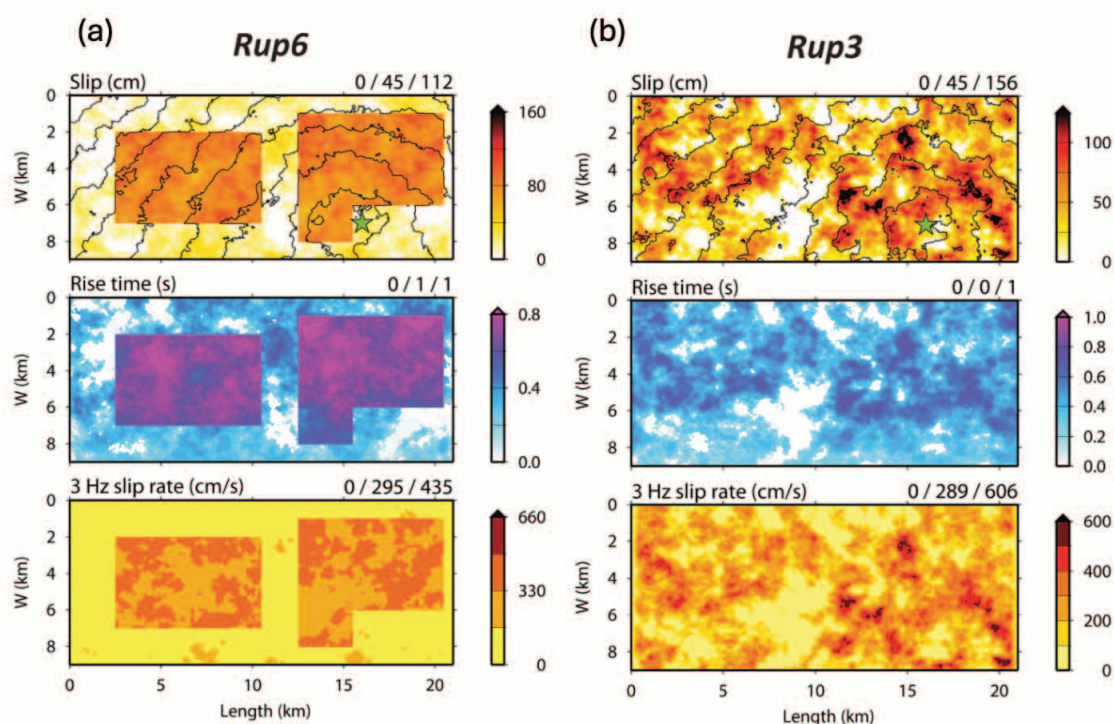


Figure 1 The kinematic hybrid rupture model used in the simulations of the Mw 6.2 Amatrice earthquake was generated using the Graves and Pitarka's rupture generator, as being a) hybrid and b) stochastic [Akinci et al., 2024],

Conversely, if a slip distribution is not available, a fully stochastic approach is used to generate a suite of plausible rupture scenarios (see Figure 1b). In both cases, the resulting source models are used to simulate ground motion time histories, which can be validated against instrumental recordings where available.

The primary objective of this work is to apply this methodology to investigate the rupture processes of selected seismic events such the Mw 6.5 Norcia event of 30 October 2016 [Pitarka et al., 2022] the Mw 6.2 Amatrice event of 24 August 2016 [Akinci et al., 2024; Artale Harris et al., 2024]. By generating extensive suites of simulations, we aim to better constrain the range of possible ground motions at specific sites, thereby providing a more robust basis for seismic hazard analysis and contributing to the mitigation of seismic risk, particularly in near-fault environments. The application of this framework to relevant case studies will be presented.

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Application of multiple approaches to estimate the misorientation angle of an ocean-bottom seismometer using body and surface waves: the case study of the Western Ionian Sea

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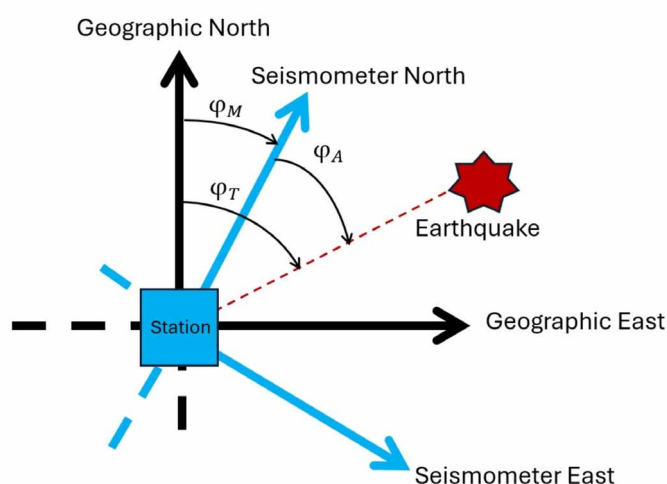
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Introduction

Accurate horizontal orientation determination in three-component seismometers is essential to ensure the reliability of critical analyses such as receiver-function computation, shear-wave splitting assessment and real-time alerting, since even a few degrees of misalignment can introduce significant biases in magnitude estimation, back-azimuth, and subsurface property interpretation. In particular, seismometers deployed on the ocean floor (Ocean-Bottom Seismometer - OBS) lack an absolute-north reference, making post-deployment azimuth correction indispensable for trustworthy seismic-waveform interpretation. In the 1990s, Laske et al., (1994) laid the groundwork by adopting a manual pick of Love and Rayleigh waves across multiple frequency bands, demonstrating the importance of realignment but proving unscalable for large networks. From the late 1990s, P-wave polarization methods gained popularity: initial transverse-energy minimization at first arrival was later improved with more advanced energy-minimization algorithms. At the same time, automated surface-wave pickers and ambient-noise correlation techniques greatly accelerated data processing, and fitting observed waveforms to synthetics—whether receiver-function or moment-tensor based—provided added resilience to complex subsurface structures. More recently, open-source Python packages: DLOPy by Doran & Laske (2017), P-pol/R-pol by Scholz et al., (2017), and OrientPy by Braunmiller et al., (2020) have automated and reproduced these workflows. Empirical studies [Büyükkapınar et al., 2021] demonstrate that combining P-wave and Rayleigh-wave criteria can achieve sub-degree precision when seismicity is sufficient. However, each algorithm remains sensitive to filter choices, windowing, and noise conditions, validating the best practice of integrating multiple independent techniques for robust estimates.

Figure 1 Scheme of the theoretical (φ_T) and measured (φ_A) azimuth angles and the deviation angle (φ_M) between the seismometer and geographic North.



Data and Methods

To overcome the limitations of individual algorithms, we developed a modular framework that applies three independent methodologies in parallel to a teleseismic dataset recorded by the WIS01 OBS throughout 2024. WIS01 is part of the CALIPSO multiparametric cabled seafloor observatory deployed by INGV in December 2023: installed at ~2000 m depth and 25 km offshore eastern Sicily [Marinaro 2023; Marinaro et al., 2024], its Guralp Orcus CMG-3T broadband sensor (100 Hz) provides near-real-time data streaming and sustained operation over extended periods, thus overcoming the typical temporal limitation of conventional OBS. We used three-component waveforms from the USGS catalogue covering the whole 2024, selecting 21 teleseisms ($M_w \geq 6$, depth ≤ 150 km, epicentral distance 90° – 180°) to minimize overtones and multipathing [Doran & Laske, 2017].

Our modular framework then runs in parallel three independent techniques: (i) P-wave transverse-energy minimization at first arrival (PminT), (ii) Principal Component Analysis (PCA) analysis based on the maximum variance of P-wave particle motion, and (iii) broadband Rayleigh-wave polarization [Doran & Laske, 2017]. Each method carries out exhaustive grid searches over filter parameters and time windows, with quality thresholds validated via bootstrap, thus eliminating the need for a co-located reference network.

We then aggregate the resulting misorientation angles through weighted circular means and compute confidence intervals.



Figure 2 Distribution map of the teleseisms analyzed in this case study (red stars) and the position of the WIS01 OBS (blue square) inside CALIPSO seafloor observatory.

Results and discussion

Applying three distinct polarization-based methods: PminT and PCA-Ppol for P-wave arrivals, and Rayleigh-wave polarization for surface waves, we derived φ_M values of $66.3^\circ \pm 5.2^\circ$, $61.8^\circ \pm 0.6^\circ$, and $69.4^\circ \pm 4.9^\circ$, respectively. These seismic estimates closely match the Remotely Operated Vehicle (ROV) based orientation of $67.48^\circ \pm 2.0^\circ$ during the CALIPSO observatory deployment, with a maximum spread of just 7.6° between the methods. Averaging these results yields a final misorientation $\varphi_M \approx 66.0^\circ \pm 3.5^\circ$.

The final result is a unique and reliable estimate of the misorientation angle of our OBS, whose integrated approach ensures the instrument orientation accuracy, significantly improving the reliability of any subsequent three-component seismic analysis and providing guidance for future OBS reorientation operations.

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Sitography

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12 years of seismicity in the Gulf of Corinth, Greece: insights from high-quality earthquake catalog and application to other Mediterranean areas

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12 years of seismicity in the Gulf of Corinth, Greece

The Gulf of Corinth, Greece, presents a considerable deformation rate of 10-15mm/year [Briole et al., 2021], associated with prolific seismicity. This seismicity presents itself either as mainshock-aftershock sequences, such as the $M_s = 6.2$ 1995 Aigion earthquake sequence [Bernard et al., 1997], or as earthquake swarms, which regularly take place within the Gulf [e.g., De Barros et al., 2020]. These behaviors motivated the extensive and multiparametric instrumentation (GNSS, seismology, etc) of the area for more than 20 years [Cornet et al., 2004]. Both the continuous activity and the dense instrumentation make this area a natural laboratory to study the dynamics of seismicity. In this work, we process more than 12 years of continuous seismological data to obtain a high-quality relocated earthquake catalog. After using an AI-based phase picker [Mousavi et al., 2020], associating waveforms and a first location of events [Zhang et al., 2019; Lomax et al., 2000, 2014], we obtain a first catalog of >400.000 events for the years 2010 to 2021. Because of the high computational cost, we do not perform template matching directly but rather implement a first step of waveform stacking between similar events. This reduces the number of waveforms to be used for template matching and improves computational efficiency. Template matching leads to an enriched earthquake catalog of $\sim 1.000.000$ events with a completeness magnitude down to $M_c = -0.05$. We compute arrival cross-correlation time delays between events before using GrowClust [Trugman et al., 2023] to relocate seismicity.

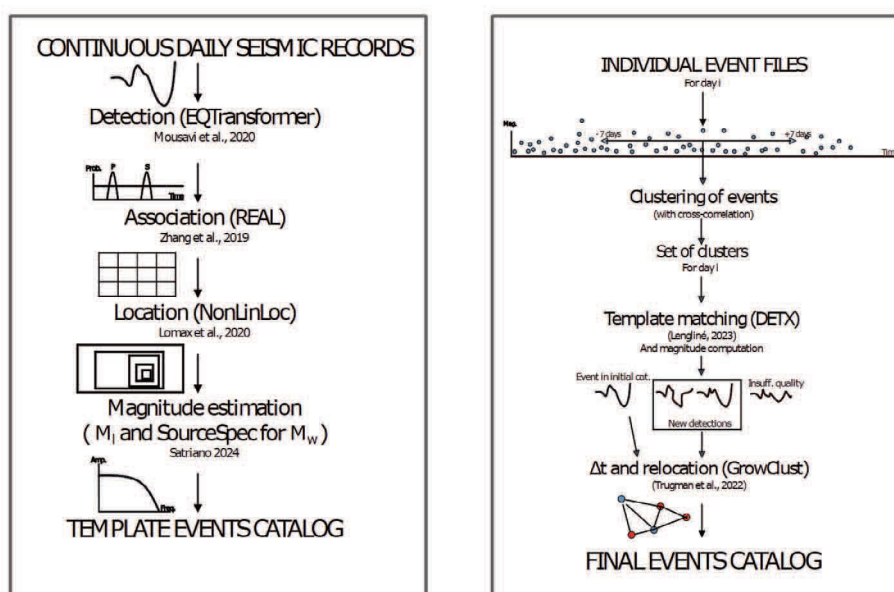


Figure 1 Schematic illustration of the workflow used in our work, aiming at obtaining a high-resolution earthquake catalog for 12 years of continuous seismic records in the Gulf of Corinth, Greece.

Implications for seismicity dynamics

Obtained relocated events highlight seismogenic structures at depth that show a complex interplay between normal faulting and low-angle detachment layer, with well-defined dips (Figure 2a,b), while we also retrieve previously identified seismicity gaps (Figure 2a), [Duverger et al., 2018]. Some complex seismicity migration episodes can also be observed, likely involving fluid processes at depth as well as aseismic slip (Figure 2c). These complex migration patterns are however S consistent with fluid-induced earthquake sequences [Danré et al., 2022, 2024].

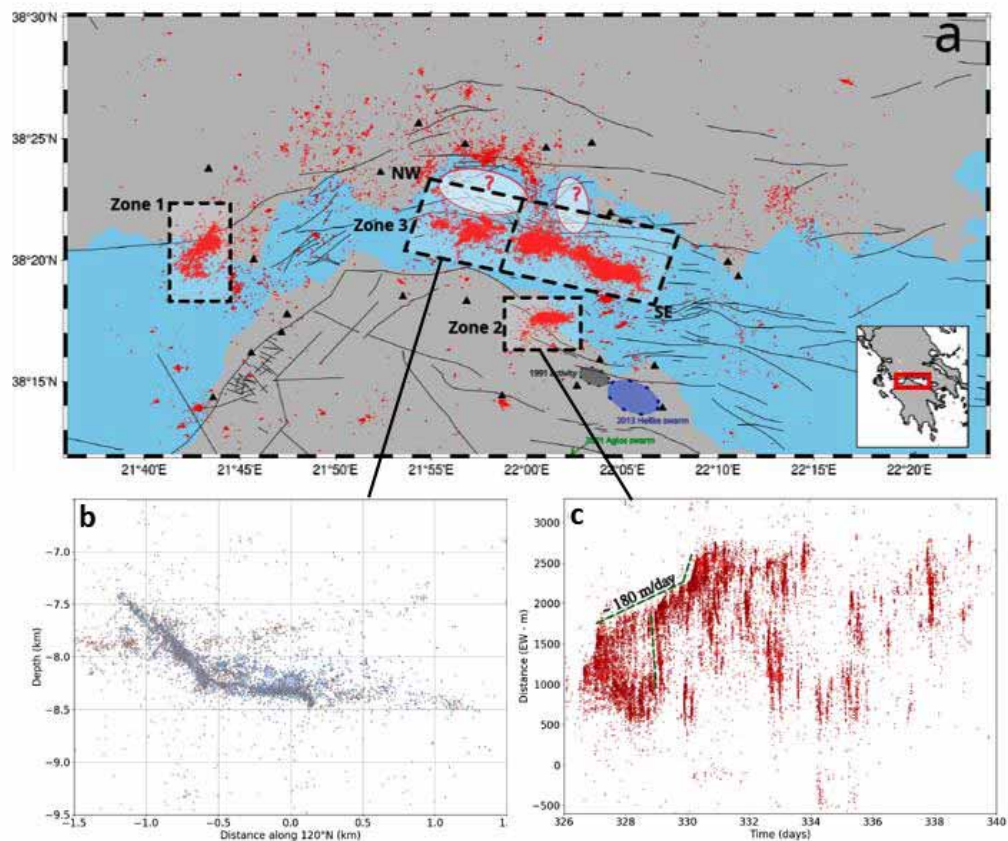


Figure 2 Example of features of our earthquake catalog, for the year 2017. (a) Map of relocated seismic events (70k out of 116k). Several zones of interest can be distinguished. Ellipses indicate seismic gaps identified by Duverger et al., [2018]. (b) Zoom on the NW area of Zone 3, with a 120°N cross section of relocated hypocenters. Two different dipping fault planes can be identified. (c) Seismicity migration observed for an earthquake swarm occurring in Zone 2, with distance computed along the EW axis and time in Julian days of 2017. A global migration velocity can be identified at a rate of approximately. 180m/day and faster transients can also be observed.

Application to other areas in the Mediterranean

The workflow presented here illustrates how enriched earthquake catalogs can shed light on long-term dynamics of seismicity in active areas. For areas with prolific seismicity, the number of events can become an issue for template matching, given the size of initial catalogs and often high network coverage, leading to elevated computing needs [e.g., Ross et al., 2019]. The clustering approach performed here prior to template matching is one way to tackle this issue, by reducing the number of template events, as well as improving signal-to-noise ratio [e.g. Thurber et al., 2014]. This could be of interest in areas of Eastern Sicily, especially around and on Mt Etna. For instance, the Pernicana fault presents an elevated deformation rate of 28 mm/year [Azzaro et al., 2001]. Its seismicity reveals precious information of the dynamics of

the Eastern flank of Etna, like through repeating earthquakes [Cannata et al., 2021]. INGV catalogs contain ~2000 events for 20 20-year period surrounding the Pernicana fault [Cannata et al., 2021] with a minimum magnitude of 0.5. Adapting our workflow to this area could help track the dynamics of seismogenic processes along the Pernicana Fault.

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Nonlinear Dynamical Analysis of Seismic Signals Using the Largest Lyapunov Exponent (LLE): A Chaos-Based Analysis of Full Waveform

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Introduction

Seismic waveforms, though traditionally analyzed within the framework of linear systems, exhibit complex, often nonlinear characteristics due to the heterogeneous nature of the Earth's interior and the diverse range of seismic sources and their different characteristics. Lyapunov exponents, which provide a qualitative and quantitative characterization of dynamical behavior, are related to the exponentially fast divergence or convergence of nearby orbits in phase space [Wolf et al., 1985]. As Wolf et al., (1985) point out, noise can affect Lyapunov exponent estimation both statistically—by introducing jitter that biases distance measurements—and catastrophically—by pushing unrelated points into neighborhood thresholds. Since high-frequency components of seismic time series often contain measurement noise, Wolf et al., (1985) suggest applying a low-pass filter before estimating Lyapunov exponents.

In dynamical systems, Lyapunov exponents measure the local rate of divergence or convergence of nearby trajectories around a given orbit. This is key to understanding chaos, i.e., sensitive dependence on initial conditions. In the context of seismic signal analysis, the chaotic behavior may help to distinguish different sources. When the state space is a complete metric space and the flow is topologically transitive with a dense set of periodic orbits, the system satisfies Devaney's notion for chaos; see [Colonius & Klieman, 2000] and [Devaney, 2003]. The positive largest Lyapunov exponent indicates local instability, but it does not imply global topological properties like transitivity [Pikovsky & Politi, 2016]. Nevertheless, the magnitude of the exponent may provide a useful and simple measure of divergence, which can be used to differentiate seismic signals from varying sources. Modeling seismic data as orbits of a dynamical system enables us to use the powerful tools of nonlinear dynamics and its numerical analysis [Stuart & Humphries, 1996].

Data and Preprocessing

This study is based on the Curated Pacific North-West (PNW) Seismic Dataset compiled by Ni et al., [2023], which contains over 190,000 three-component waveform traces from more than 65,000 seismic events recorded across the region. To ensure both statistical robustness and a balanced representation of different seismic source types, we selected a subset of 1720 events from the Curated PNW Seismic Dataset [Ni et al., 2023], spanning earthquakes, explosions, sonic booms, thunder events, and surface events. Specifically, the dataset comprises 500 earthquakes, 500 explosions, 500 surface events, 126 sonic booms, and 94 thunder events. Figure 1 displays the geographic distribution of the selected events and seismic stations. Location metadata was only available for earthquakes and explosions and thus only these two types of events are included in the spatial map.

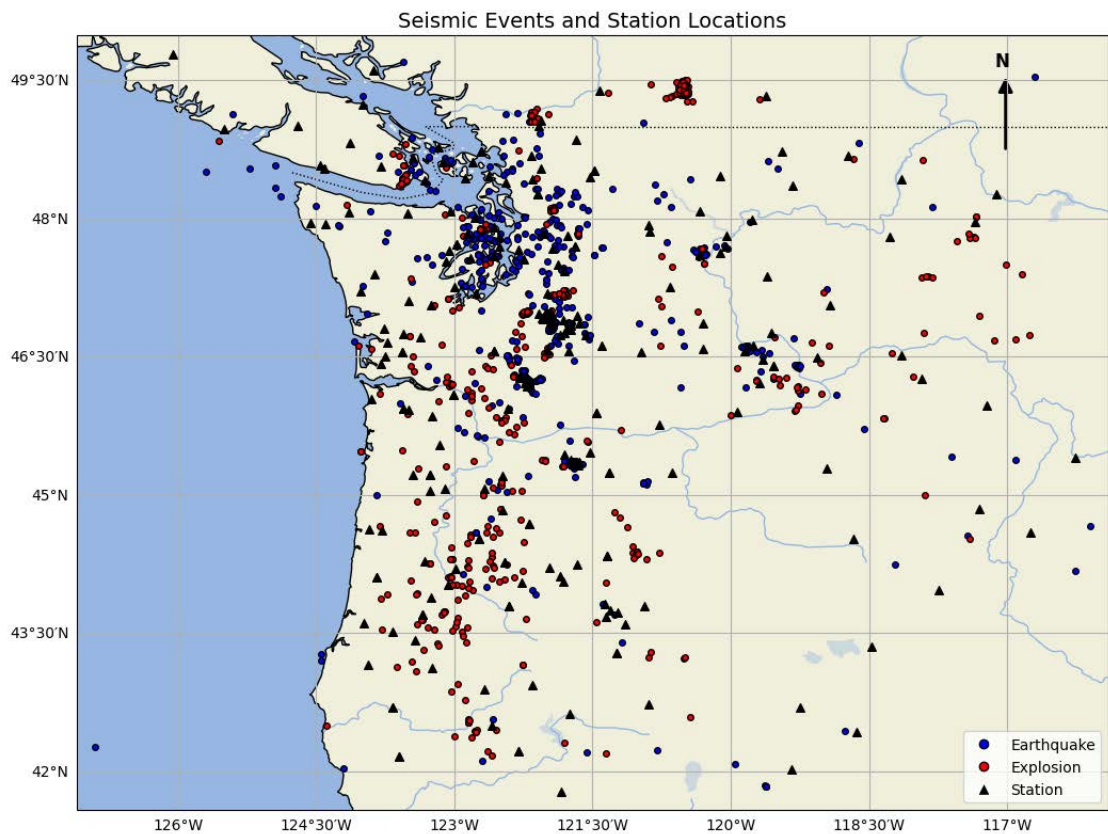


Figure 1 Spatial distribution of events (blue: earthquakes, red: explosions) and stations (black triangles). Event locations are based on data from Ni et al. [2023].

Time Window Selection

In this study, we applied a 55-second fixed-length time window to each seismic waveform, starting from the P-wave arrival time as manually picked and annotated by experts in the original dataset. This windowing strategy was chosen to ensure that the waveform includes all major seismic phases, particularly the P-wave, S-wave, and surface waves, which are essential for characterizing event types and understanding wave propagation patterns. A shorter window might exclude late-arriving phases, while a longer window could incorporate unrelated noise or overlapping events. Figures 2 and 3 show representative waveforms from earthquakes and explosions, with the analysis window (P to P+55 sec) shaded in light blue and light red, respectively.

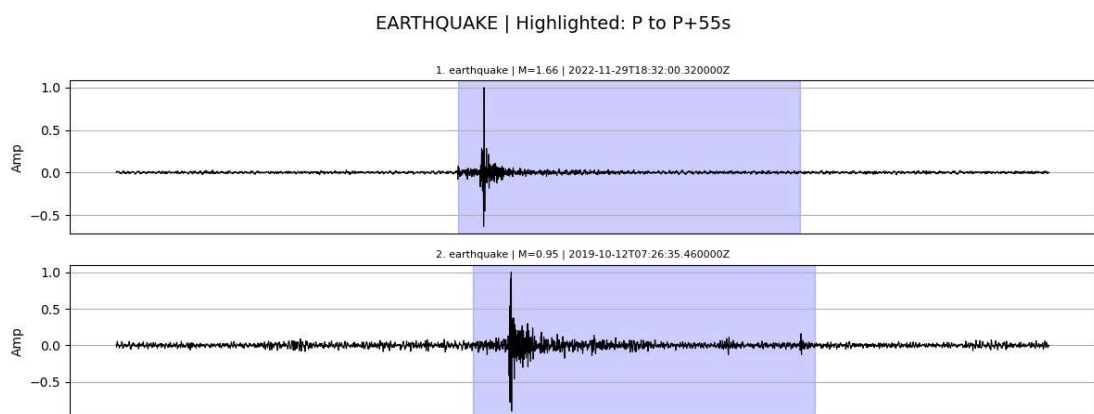


Figure 2 Seismic waveforms from two earthquake events. The analysis window, extending from the P-wave onset to 55 seconds post-arrival, is indicated by the light blue shaded box, based on data from Ni et al. [2023].

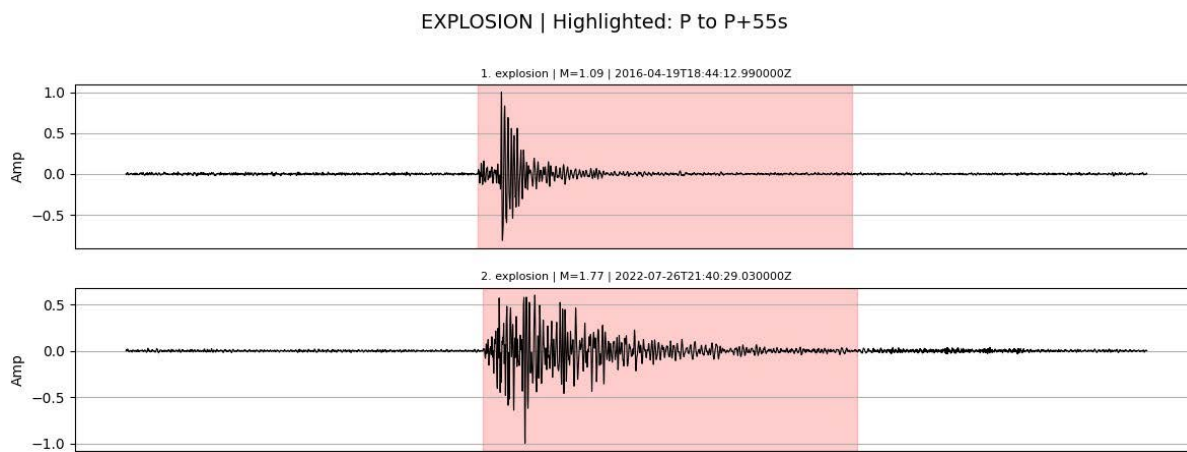


Figure 3 Seismic waveforms from two explosion events. The analysis window, extending from the P-wave onset to 55 seconds post-arrival, is indicated by the light red shaded box, based on data from Ni et al. [2023].

Estimation of the Largest Lyapunov Exponent (LLE)

To assess the presence of chaotic dynamics within the seismic time series, we estimated the Largest Lyapunov Exponent (LLE) using the algorithm introduced by Rosenstein et al., (1993), as implemented in the Python module nolds [Schölzel, 2019].

Results and Discussion

Our analysis reveals that, in a direct comparison between earthquakes and explosions, earthquakes exhibit significantly higher values of the largest Lyapunov exponent, indicating the strong presence of chaotic dynamics likely resulting from the complexity of fault rupture processes. In contrast, explosions show substantially lower LLE values, suggesting that they originate from more deterministic, human-controlled sources, and thus produce simpler waveform characteristics. Similarly to explosions, events labeled as "surface events" in the dataset also show lower LLE values compared to earthquakes, thunder and booms. These findings support the idea that LLE can serve as a useful indicator of the underlying dynamical complexity of seismic events.

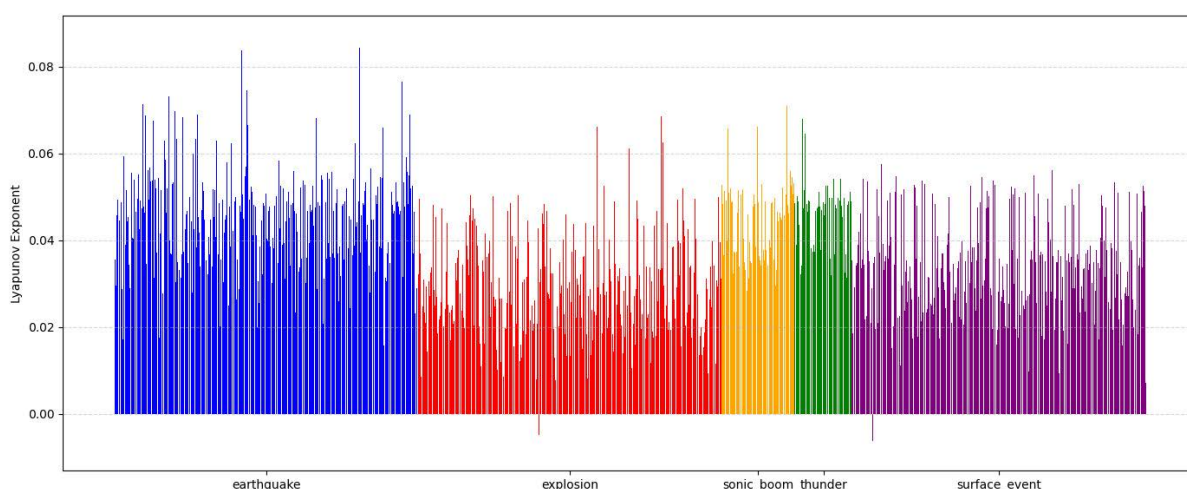


Figure 4 Largest Lyapunov exponent (LLE) values across seismic event types. In direct comparison, earthquakes exhibit significantly higher LLEs than explosions. Surface events show LLEs similar to explosions and lower than those of thunder, earthquakes and sonic booms.

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Structural Vulnerability and Damage Patterns During the Al Haouz Earthquake of 8 September 2023

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Morocco, situated along the convergent boundary of the African and Eurasian plates, is prone to seismic activity. While northern Morocco experiences more frequent moderate earthquakes, central and southern regions are also vulnerable. On 8 September 2023, a magnitude 6.8 earthquake struck the High Atlas Mountains near Al Haouz, about 75 km from Marrakech. The earthquake engendered nearly 3,000 deaths and over 5,500 injuries, making it the deadliest in Morocco since the 1960 Agadir earthquake.

The earthquake was caused by reverse faulting along a fault within the High Atlas orogenic belt (Figure 1). Intense ground shaking devastated villages such as Tizi N'Test, Talat N'Yaaqoub, and Amizmiz, destroying entire clusters of buildings. While the region has experienced several seismic events in recent decades [Peláez et al., 2007], this earthquake ranks among the largest in Northwestern Africa. Furthermore, the area's remote location and challenging accessibility hindered emergency response efforts, worsening the human consequences.

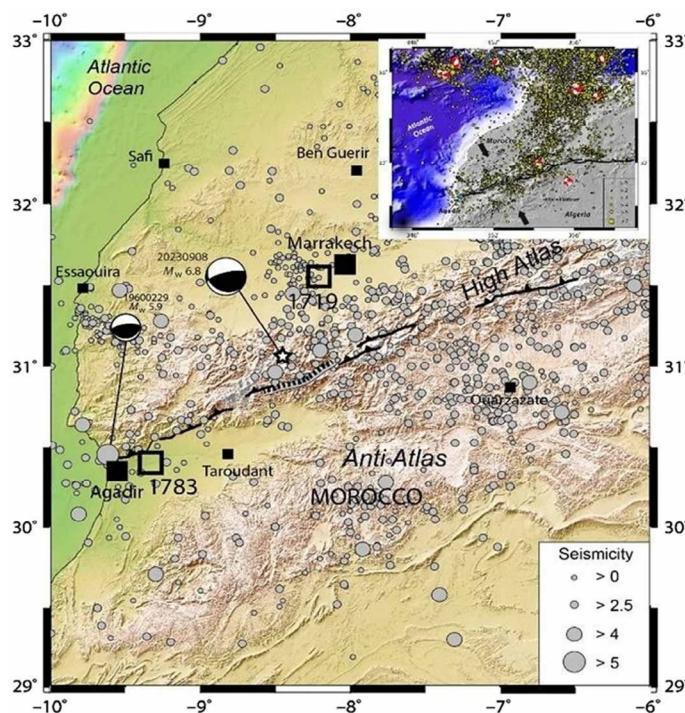


Figure 1 Morphostructural Domains and Seismicity of the High Atlas Mountains and the South Atlas Suture Zone (1959–2023), Morocco: Contextualizing the 8 September 2023 Earthquake Within Regional Seismic Activity [Global CMT; Ekström et al., 2012]. The major historical seismic events in 1719 and 1783 are from El Mrabet [1991].

The National Institute of Geophysics (NIG)

The NIG of Morocco serves as the principal institution responsible for the continuous surveillance and monitoring of seismic activity within the country. It manages an extensive network of seismological stations (Figure 2) strategically deployed across Morocco to systematically record and analyze seismic events (NIG). The institute's mandate includes the acquisition, processing, and interpretation of seismic data to characterize regional seismicity and assess seismic hazards. By providing critical scientific insights and real-time information, the institute supports disaster risk reduction strategies, informs national seismic codes, and facilitates emergency response planning. Its efforts are aimed at enhancing Morocco's resilience to earthquake hazards through improved monitoring, early warning capabilities, and the promotion of seismic risk mitigation policies.

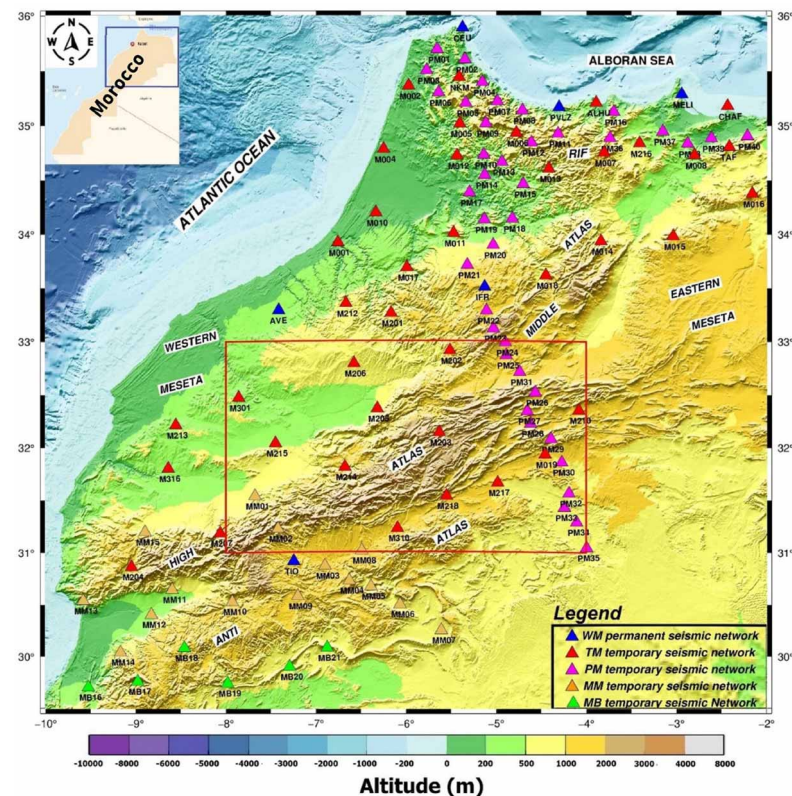


Figure 2 Map showing the distribution of seismic broadband stations in central and northern Morocco [EL Moudnib et al., 2025]. The red box highlights the High Atlas area investigated in this study.

Strong motion results

The 2023 Mw 6.8 Al Haouz earthquake caused severe ground shaking and extensive damage across the western High Atlas, particularly affecting unreinforced masonry and adobe buildings in remote areas (EL Hilali et al., 2025). Around 3,000 people were killed and 6,000 injured. Ground motion parameters such as PGA, PGV, and SA were analyzed to evaluate site effects and inform seismic hazard models. Strong-motion data, including a peak horizontal acceleration of 0.28 g recorded 24 km from the epicenter, highlighted the earthquake's intensity (Figure 3). Vertical motions and Vs30 estimates further contributed to understanding local site response. Response spectra showed peak amplification at 0.1 seconds, indicating heightened vulnerability of low-rise buildings to short-period ground motion. These findings emphasize the need to update design codes and improve structural resilience in the region.

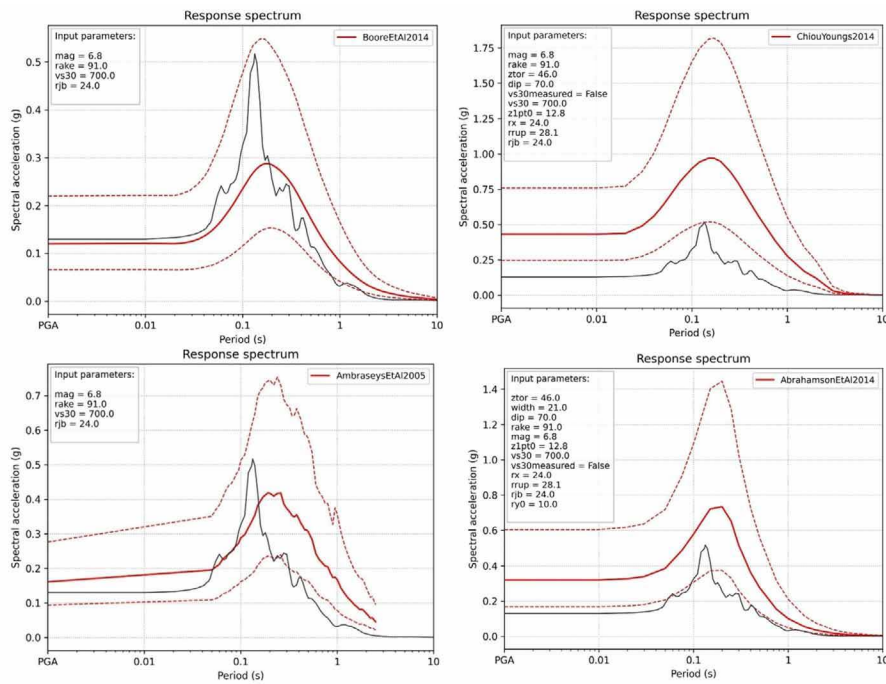


Figure 3 Analysis of Ground Motion Response Spectra Across.

Buildings structure damage

Stone masonry buildings in the affected areas sustained the most severe damage during the earthquake, primarily due to poor construction practices. Typical deficiencies included the use of rounded, irregular stones with thick earthen mortar and inadequate connections between wall leaves, which significantly compromised structural integrity under seismic loading. These weaknesses led to widespread fissuration and frequent partial or total collapses, further exacerbated by flexible traditional floor systems lacking effective diaphragm action. In contrast, better-performing structures featured regular stone units, thinner mortar joints, and structural enhancements such as geometric regularity and tying elements. Although some buildings incorporated modern interventions (e.g., reinforced concrete elements), these were largely ineffective when combined with substandard masonry. These observations highlight the essential role of material quality and structural detailing in enhancing the seismic resilience of traditional masonry buildings.



Figure 4 Impact of Masonry Quality and Structural Detailing on the Seismic Response of Stone Masonry Buildings: Insights from the Al Haouz Earthquake.

Conclusion

The 2023 Mw 6.8 earthquake in Al Haouz revealed significant vulnerabilities in traditional stone masonry buildings, especially those constructed with poor materials and inadequate structural design. Strong ground shaking notably affected small structures, emphasizing the need for improved seismic resilience. To enhance earthquake monitoring and risk mitigation in Morocco, integrating advanced technologies such as dense seismic networks, real-time GPS, remote sensing, and early warning systems is essential. Coupled with updated building codes and community awareness, these measures will strengthen Morocco's capacity to manage seismic hazards and protect vulnerable populations and infrastructure.

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Integrated Geophysical and Geochemical Assessment of Hydrothermal Sulphide Mounds in the Mid-Atlantic Ridge

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Introduction

Hydrothermal vents along mid-ocean ridges generate sulphide-rich deposits containing copper, zinc, iron, and trace elements such as cobalt and gold. These polymetallic sulphide systems are of growing interest due to their resource potential and ecological sensitivity, but their inaccessibility and geological complexity present significant assessment challenges. This study focuses on three sulphide mounds in the Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge, a site known to host over 2.7 million tons of sulphide material [Petersen et al., 2000]. By integrating bathymetric, magnetic, and geochemical data, we assess mound morphology, magnetic intensity, and elemental composition. Geographic information system (GIS)-based modeling supports both resource estimation and environmental interpretation. This multidisciplinary approach aligns with best practices in seafloor exploration and monitoring [Zhang, 2024], and incorporates environmental impact assessment (EIA) frameworks used in Clarion-Clipperton Zone studies and other deep-sea mining contexts [Durdin et al., 2018]. The study introduces a combined geophysical-geochemical workflow to infer the relative age and zonation of SMS deposits—offering new insight into the evolution of sulphide mounds in the TAG field.

Methodology

This study assessed three sulphide mounds in the TAG hydrothermal field using integrated bathymetric, magnetic, and geochemical datasets. High-resolution digital elevation models (DEMs) generated in QGIS enabled volumetric estimates based on elevation thresholds and pixel analysis. Magnetic anomaly maps identified zones of intense crustal magnetization linked to fresher, iron-rich sulphides. Geochemical analyses of chimney samples were used to estimate average concentrations of Fe, Cu, Zn, Au, Cr, and Co, converted to total tonnages using a uniform rock density of 5.0 t/m³. While this approach provides a first-order assessment of sulphide resource potential, limitations include surface-biased sampling and lack of subsurface data.

Results and Discussion

Bathymetric and magnetic datasets were used to characterize the morphology, structure, and relative age of three sulphide mounds in the TAG hydrothermal field. As shown in Figure 1, the mounds are steep-sided, rising 50–120 meters from the seafloor, with lateral extents exceeding 250 meters. Irregular outlines, central depressions, and offset peaks indicate structural control from underlying faults and episodic magmatism—typical of seafloor massive sulphide (SMS) systems on slow-spreading ridges.

Magnetic anomalies (Figure 2) reveal two mounds with pronounced highs, interpreted as zones of iron-rich, relatively unaltered sulphide associated with more recent hydrothermal activity. The third mound displays subdued magnetic intensity, likely due to oxidation of magnetic minerals such as pyrrhotite or magnetite, reflecting a more evolved or inactive system. These magnetic trends, combined with bathymetric morphology, provide a first-order temporal framework distinguishing active, waning, and extinct hydrothermal phases across the mound field.

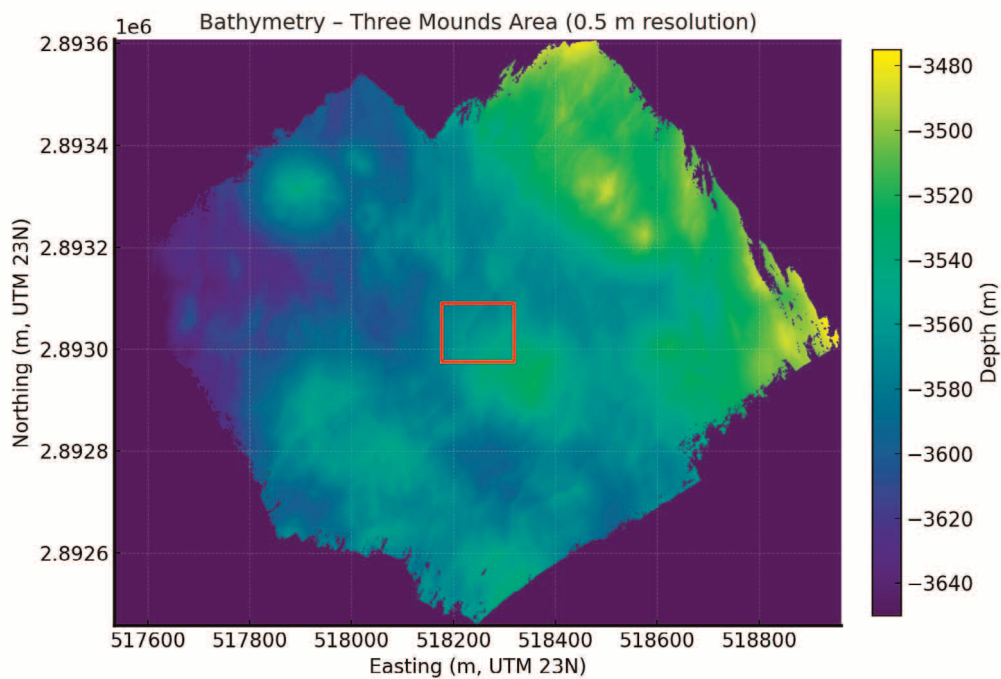


Figure 1 High-resolution bathymetric map of the Three Mounds Area in the TAG hydrothermal field, located at $\sim 26^{\circ}08'N$, $44^{\circ}50'W$ on the Mid-Atlantic Ridge. The mapped area covers approximately 1.2×1.0 km (1.2 km²) with a resolution of 2 m. The three mounds range in height from ~ 50 to 120 meters and span lateral widths of ~ 250 –400 meters. Contour intervals are 10 m. This region corresponds to the inset area marked in Figure 2. A geographic locator inset (top right) indicates the study site's position along the Mid-Atlantic Ridge.

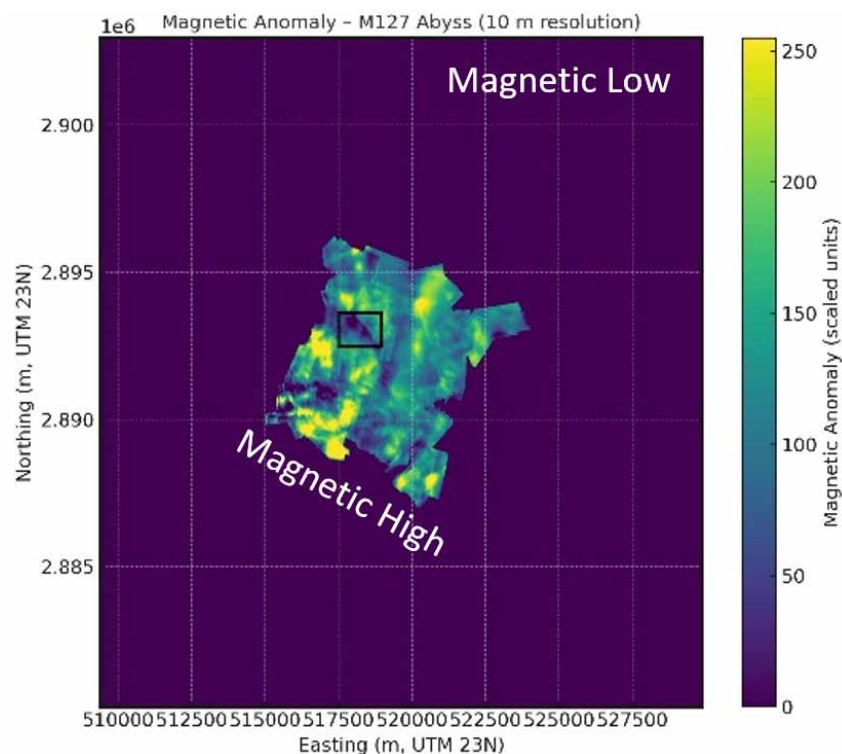


Figure 2 Magnetic anomaly map (10 m resolution) of the TAG hydrothermal field, centered around $26^{\circ}08'N$, $44^{\circ}50'W$. The total mapped area is $\sim 2.5 \times 2.5$ km (6.25 km²). The black rectangle outlines the same 1.2×1.0 km region shown in Figure 1. Two zones labeled as Magnetic High indicate iron-rich, relatively unaltered sulphides. A separate area marked as Magnetic Low shows significantly weaker magnetic response, likely reflecting alteration of magnetic minerals such as pyrrhotite or magnetite. These magnetic patterns provide insights into the hydrothermal history and mineral zonation of the mound field.

Geochemical analyses of chimney samples (Figure 3) reveal notable trace metal enrichment across the three sulphide mounds. Cobalt averages over 130 ppm, indicating incorporation into sulphide phases such as pyrite and chalcopyrite. Gold concentrations (~35 ppm) suggest localized high-temperature venting, while chromium (~25 ppm) remains lower, likely due to its limited mobility under reducing, acidic conditions. Although present in trace amounts, cobalt and gold are economically significant due to their strategic relevance in renewable technologies. These concentrations were used to estimate metal tonnages by converting ppm to weight percent and multiplying by mound volume, assuming a sulphide density of 5.0 t/m³.

The broader geochemical profile is dominated by Fe, Cu, and Zn (not shown), with subordinate but valuable trace metal enrichment. This supports a multi-phase, zoned metallogenic system with economic potential beyond conventional SMS indicators.

Seafloor reflectivity (Figure 4) from EM122 backscatter mapping complements the geophysical data. Brighter zones, aligned with elevated bathymetry and magnetic highs, suggest hard substrates such as sulphide outcrops and chimneys. In contrast, darker zones indicate finer sediments or altered areas, likely associated with inactive hydrothermalism. These patterns reinforce the structural and mineralogical heterogeneity of the TAG mound field and aid in distinguishing active from relict systems.

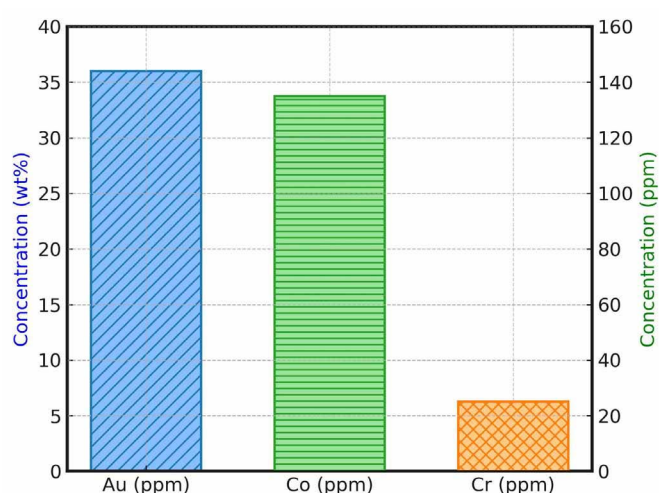


Figure 3 Average concentrations of trace metals—gold (Au), cobalt (Co), and chromium (Cr)—measured in chimney samples from the Three Mounds Area (within the 1.2 × 1.0 km region shown in Figures 1 and 2). Sampling locations were georeferenced within ~10 m accuracy. Mean values: Co = 132 ppm, Au = 35 ppm, Cr = 25.7 ppm. These data were used in tonnage calculations over a total estimated mound volume of ~35,500 m³, based on QGIS-derived DEM analysis and threshold elevation criteria. Dual-axis representation shows concentration in ppm (primary axis) and wt% (secondary axis).

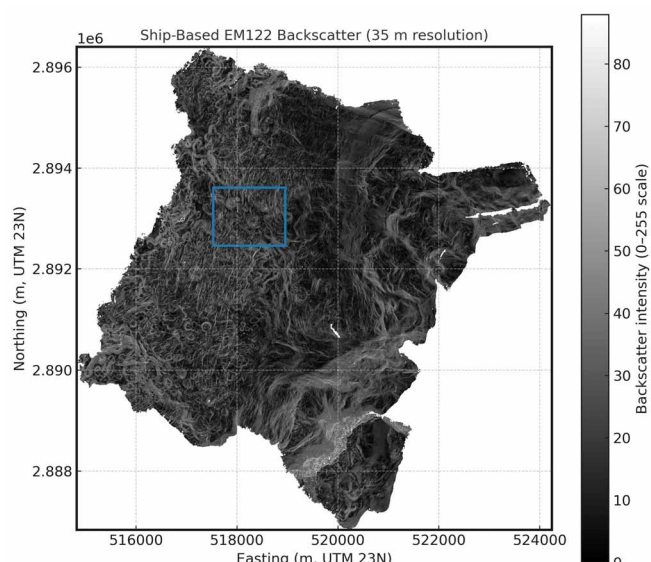


Figure 4 EM122 backscatter intensity map of the TAG hydrothermal field at 35 m resolution, covering a 2.5 × 2.5 km area centered around 26°08'N, 44°50'W. The blue rectangle outlines the geochemical sampling zone shown in Figure 3 and corresponds to the Three Mounds Area in Figures 1 and 2. Brighter pixels (>-15 dB) represent high-reflectivity surfaces such as exposed sulphides and basaltic ridges, while darker zones (<-25 dB) indicate sediment cover or altered substrate. The map provides acoustic validation of geophysical and geochemical features.

Conclusion

This study highlights the value of integrating bathymetric, magnetic, and geochemical datasets to characterize sulphide mound morphology, composition, and relative age in the TAG hydrothermal field. Correlations among elevation, magnetic intensity, and trace metal concentrations support interpretations of hydrothermal evolution and deposit zonation. The results underscore the potential of such systems as sources of critical metals like cobalt and gold, relevant for green technologies. This multidisciplinary approach enables early-stage resource assessment while informing environmental baselines in deep-sea settings. Overall, the workflow contributes to responsible exploration strategies for seafloor massive sulphide systems.

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Active Tectonics and Earthquake Potential of the East Anatolian Fault Zone

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Introduction to East Anatolian Fault

The East Anatolian Fault Zone (EAFZ) is a ~600 km-long left-lateral strike-slip fault accommodating Anatolia–Arabia plate convergence. Its complex geometry and variable slip rates result in heterogeneous seismicity, leading to segmentation into Palu, Pütürge, Erkenek, Pazarcık, Amanos, and Karliova [Duman and Emre, 2013; Karabulut et al., 2023]. GNSS data indicate ~6 mm/yr aseismic creep along the Palu segment [Kurt et al., 2023]. The NE Sivrice–Pütürge segment shows weak interseismic coupling and elevated seismicity. Interseismic coupling quantifies fault locking between earthquakes: weakly coupled zones accommodate slip via creep, while strongly coupled zones accumulate elastic strain. This weakly coupled section experienced aseismic creep during the interseismic period [Konca et al., 2021, Figure 1].

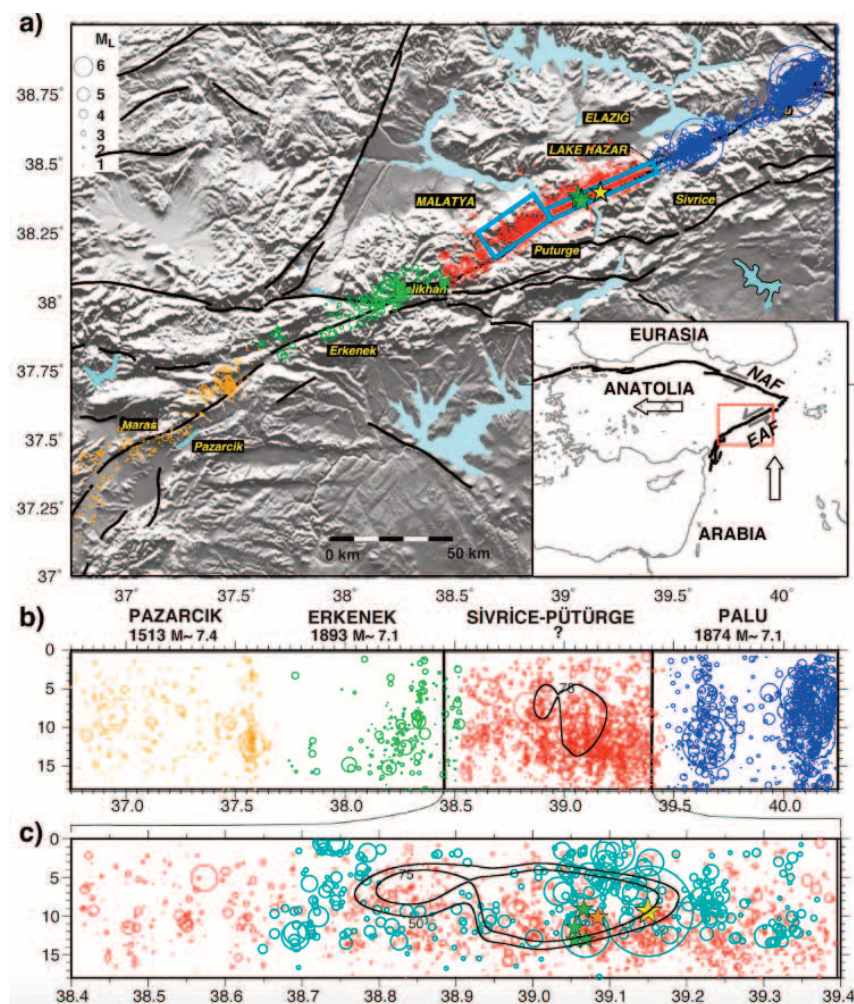


Figure 1 Interseismic seismicity along the segments of the East Anatolian Fault [Konca et al., 2021].

2020 Mw 6.8 Sivrice Earthquake

The seismic potential of the region was underscored by the Mw 6.8 Sivrice earthquake on 24 January 2020, which ruptured approximately 45 km of the northeastern section of the Pütürge segment [Pousse-Beltran et al., 2020; Konca et al., 2021]. The southwestern portion, previously characterized as a seismic gap, remained unruptured, suggesting persistent seismic hazard along this section [Duman and Emre, 2013]. Geodetic observations from GNSS and InSAR indicate the presence of shallow aseismic creep preceding the event, which may have impeded rupture propagation to the surface [Çakır et al., 2023; Figure2]. The Pütürge segment continues to exhibit high seismic potential, with the southwestern part expected to host future events of Mw ~ 6.7–7.0, consistent with an estimated recurrence interval of ~150 years [Güvercin et al., 2022].

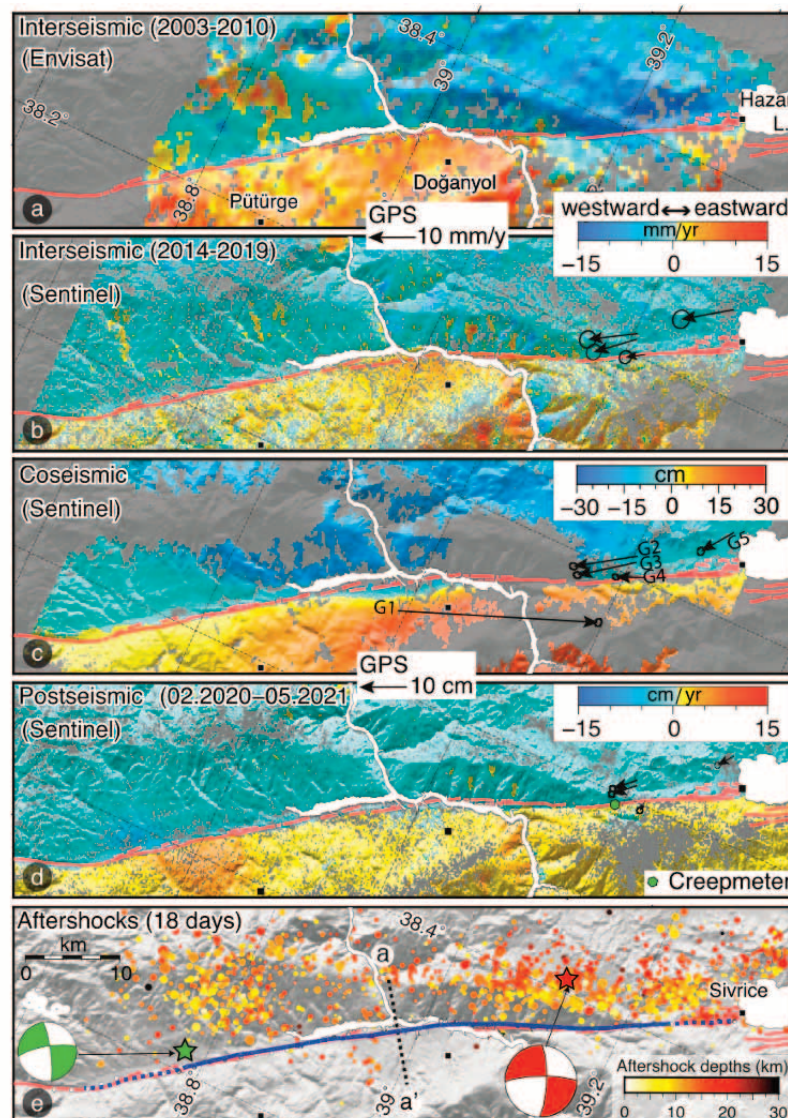


Figure 2 InSAR and GPS measurements during the earthquake cycle, and distribution of the first 18 days of aftershocks [Çakır et al., 2023].

While studies continued on the Pütürge segment, where a seismic gap was presumed to remain, two devastating earthquakes occurred on February 6, 2023 (Mw 7.8 and Mw 7.6). Following these events on the EAF, the southern region was also incorporated into the analysis using geodetic and seismological data [Ergintav et al., 2024; Figure 3].

2023 Kahramanmaraş Earthquake Sequence

The 2023 Kahramanmaraş Earthquake Sequence comprises two major strike-slip events (Mw 7.8 and Mw 7.6) that occurred on 6 February 2023 in southeastern Türkiye. The first ruptured the southern East Anatolian Fault Zone (EAFZ), followed nine hours later by rupture on a nearby splay fault. Together, they produced over 300 km of surface rupture across a previously identified seismic gap, indicating the release of long-accumulated tectonic stress. Geodetic observations (InSAR, GNSS) revealed heterogeneous slip across multiple strands, highlighting complex fault interactions and cascading rupture. The sequence underscores the high seismic potential of the EAFZ and the need to reassess its future hazard [Karabulut et al., 2023].

According to Figure 3, these devastating earthquakes have affected both the near and far fields. Due to the region's active tectonic setting, it should continue to be investigated through high-precision observations. Monitoring both the coseismic and postseismic behavior of earthquakes is crucial for understanding the underlying tectonic structure.

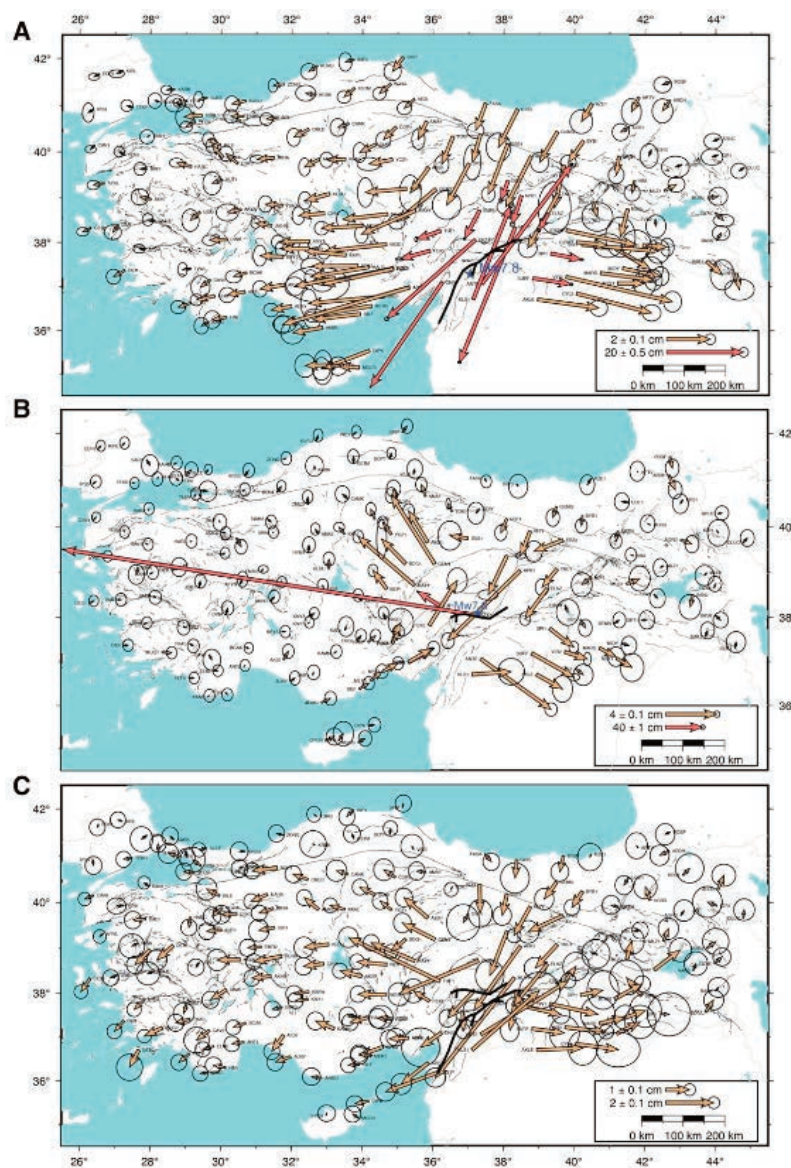


Figure 3 Panels (A) and (B) show co-seismic displacements for the 2023 Pazarçık (Mw 7.8) and Elbistan (Mw 7.6) earthquakes, with 95% confidence ellipses and two color scales for vector magnitudes. Black lines indicate rupture traces; blue stars mark epicenters. Thin black lines denote active faults [Emre et al., 2013]. Panel (C) shows cumulative post-seismic displacement, reaching ~0.33 m [Ergintav et al., 2024].

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Advancing Rapid and Precise Seismic Event Detection and Localization with DAS: Evaluating the Source-Scanning Algorithm Approach

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The Source-Scanning Algorithm (SSA), originally proposed by Kao and Shan [2004; 2007], offers a fully automated method for detecting and locating seismic events without the need for traditional phase picking. By leveraging theoretical arrival times from a velocity model and assuming a point-source origin, SSA stacks observed waveforms across a predefined spatial grid. The locations yielding the highest stacking amplitudes, measured in “brightness” units, are interpreted as the most probable hypocenters. Over the years, SSA and its derivatives have proven robust when applied to continuous seismic data, even in scenarios characterized by poor station coverage, high noise levels, or complex source processes. One example of this is SSA2py [Fountoulakis and Evangelidis, 2024], a high-performance Python implementation of SSA designed to efficiently handle large-scale waveform datasets.

In parallel, Distributed Acoustic Sensing (DAS) has emerged as a transformative technology in seismology. Utilizing existing fiber-optic cables, DAS enables the deployment of dense, large-aperture arrays by turning each meter of fiber into a virtual seismic sensor. This method provides high spatial and temporal resolution over extensive distances, offering continuous seismic monitoring in regions that are otherwise inaccessible, such as offshore environments, where installing conventional seismic instruments is challenging. With proper preprocessing, DAS-measured strain rates can be transformed into particle motion, making it possible to apply established seismic analysis techniques. However, DAS data present unique complications, including azimuthal ambiguity stemming from cable orientation and geometry.

In this study, we explore the viability of applying SSA to DAS datasets from Greece (Preveza and Rhodes cables) for the purpose of seismic event localization. Our evaluation involves both synthetic and real-world DAS recordings from geographically diverse and seismically active regions, including offshore and onshore cases. Through this analysis, we aim to systematically assess the performance, limitations, and strengths of the SSA when applied to continuous DAS data. We also address key technical challenges such as data volume and computational load, the selection of suitable characteristic functions, synchronization with local seismic networks, the fidelity of the velocity models used, and the implementation of necessary time corrections.

Our findings demonstrate that SSA is capable of detecting and locating seismic events in DAS data quickly and reliably, even in the absence of explicit phase information (Figure 1). This reinforces its potential as a powerful tool for continuous seismic monitoring in DAS-based systems. Ultimately, our work highlights the synergy between SSA and DAS, pointing toward a promising direction for real-time, high-resolution earthquake monitoring across a wide range of environments.

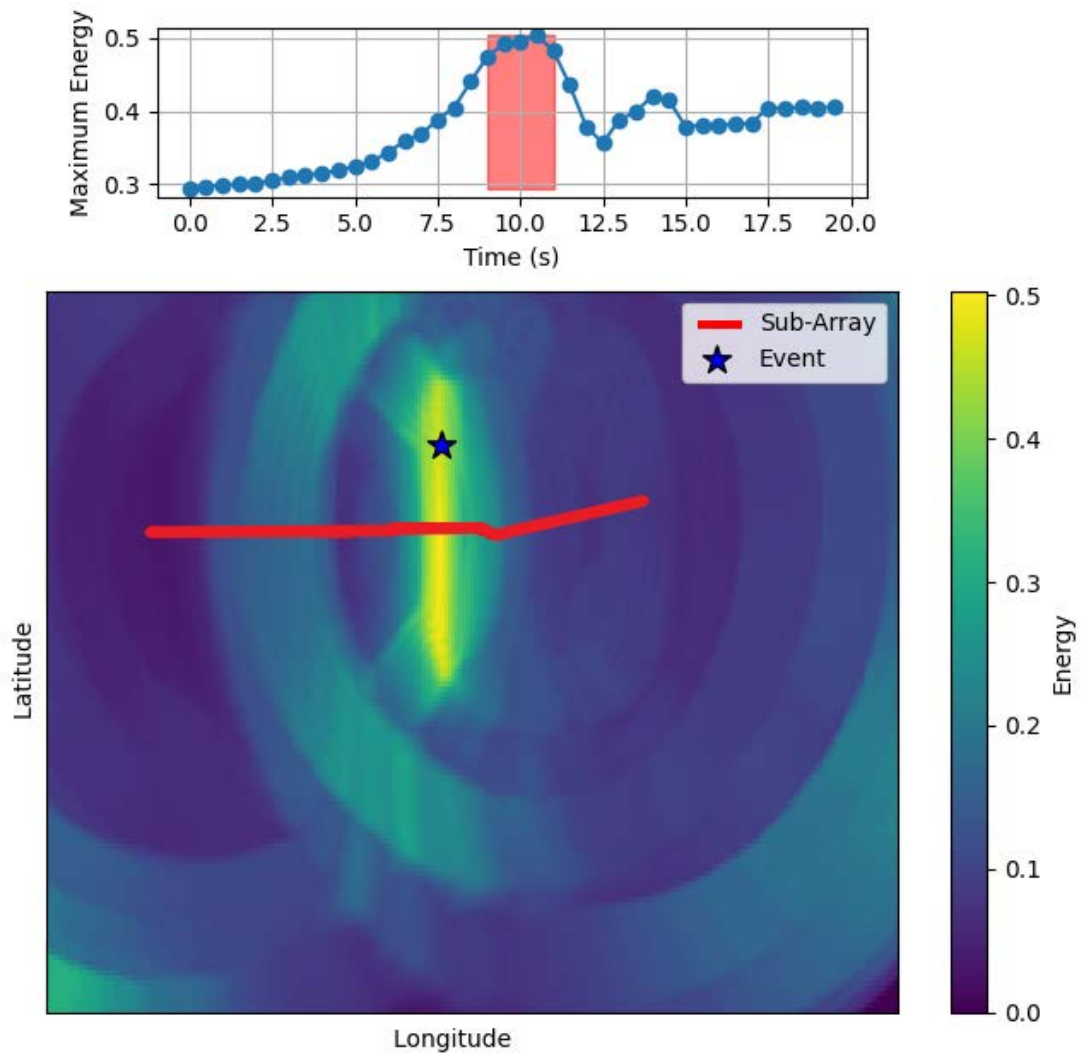


Figure 1 Backprojection results using SSA and DAS data for a seismic event from the Preveza cable. Top: Time series of maximum backprojection energy (or brightness as called in SSA method), with the red shaded region indicating the time window selected to plot. Bottom: Backprojection brightness map. The red line marks the cable used, and the blue star denotes the estimated event location corresponding to peak brightness. The color scale represents the normalized brightness energy.

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Advancing Seismic Source Tracking with Six-Component Rotational Seismology

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Rotational seismology, an emerging branch of observational seismology, extends traditional ground motion analysis by including rotational degrees of freedom alongside the conventional three translational components. This six-component (6C) approach enables a more comprehensive observation of seismic wavefields, resulting in enhanced source characterization, wave-type decomposition, and directionality estimation. Recent advances in instrumentation, particularly the development of field-deployable fiber-optic gyroscopes like the BlueSeis-3A, have enabled the collection of high-quality rotational data in both controlled experiments and natural seismic settings. This body of work summarizes three interconnected studies [Izgi et al., 2021; Izgi et al., 2025a; Izgi et al., 2025b] that together demonstrate the potential of 6C seismology for enhancing seismic source tracking and improving azimuthal accuracy through sensor validation, method development, and wavefield classification.

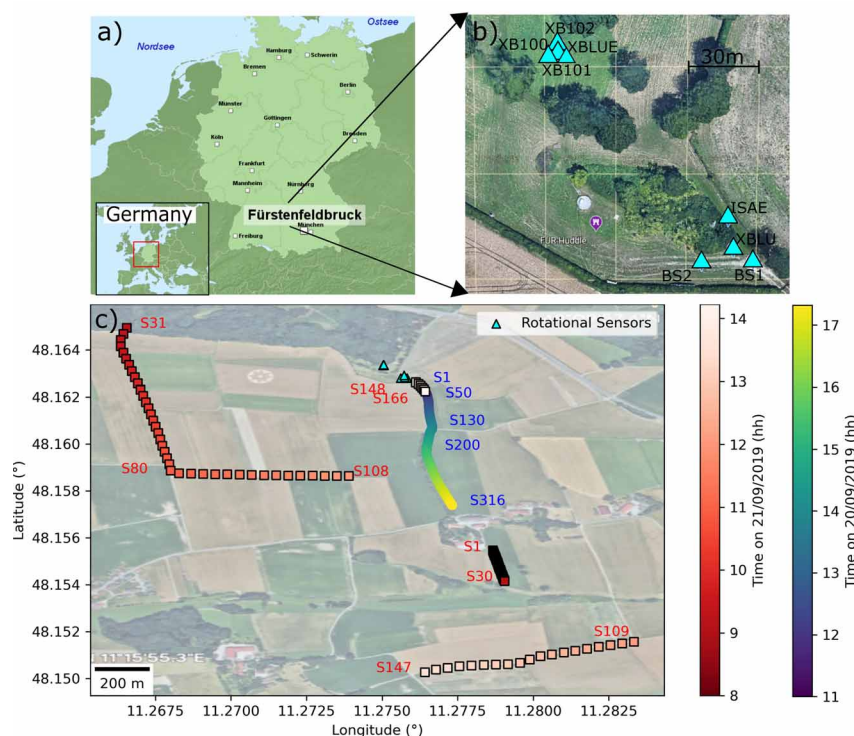


Figure 1 Overview of the study area and locations of the sweeps and rotational sensors. a) Location of the study site in Germany. b) Overview of the sensor network in Fürstenfeldbruck. Sensors distributed into two clusters are shown as cyan triangles. c) On 20 September 2019 from 11:00:00 to 17:30:00 UTC the trucks migration is shown by the color change from blueish to yellow. Similarly, on 21 November 2019 from 08:00:00 to 14:30:00 UTC from red to whitish colors. Labels mark some representative sweep numbers.

Izgi et al. [2021], investigated a comprehensive performance evaluation of six BlueSeis-3A rotational sensors and three Trillium Horizon 120s seismometers co-located in a concrete bunker in Fürstfeldbruck, Germany. The aim was to assess the stability, noise characteristics, and coherence of rotational data under controlled conditions. Power spectral density analyses revealed stable self-noise levels between 0.5 and 40 Hz, consistent with the manufacturer's specifications. All deviation values ranged from 15 to 25 nrad/s at 1-second averaging. During a local ML 3.4 earthquake, cross-correlation between rotational and translational recordings produced correlation coefficients averaging 0.64 to 0.67. Back azimuth (BAz) estimates derived from horizontal rotational components closely matched theoretical values, and derived phase velocities ranged from 0.49 to 0.63 km/s. These findings confirmed the sensors' reliability and suitability for field deployment.

Izgi et al. [2025a], applied 6C seismology to an active-source experiment involving five explosive shots at distances between 50 and 1070 meters from the sensor clusters. Eight BlueSeis-3A rotational sensors and a set of broadband seismometers recorded the events. Back azimuth estimates were computed using only horizontal rotational data and compared with estimates based on translational components. The results demonstrated that rotational-only BAz estimates achieved an average deviation of 10.2° from theoretical values. Translational estimates from co-located bunker seismometers deviated by only 1.8°, but this deviation increased to 29.4° for clustered configurations due to scattering and wavefield complexity. The rotational measurements, however, remained robust across sensor configurations, indicating their resilience and utility in complex wavefields where traditional approaches often degrade.

Izgi et al. [2025b], extended the application of 6C data to a dynamic vibroseis experiment conducted over two days. A vibroseis truck performed 480 sweeps across 160 locations, generating frequency-controlled signals in the 7 to 120 Hz range. Using a dual-cluster setup of eight rotational and six translational sensors, the study implemented a polarization-based BAz estimation method using sliding 0.71-second windows and orthogonal distance regression. A wave-type fingerprinting algorithm based on support vector machines was employed to classify wavefields into P, SV, SH, Rayleigh, or noise categories, using synthetic training data derived from modeled 6C polarization patterns.

By filtering to retain only SV-type windows and discarding those with low linearity or SNR, the mean BAz deviation was reduced from nearly 48.6° to under 2.2°. SV/SH amplitude ratios further indicated frequency-dependent scattering effects: SV components dominated at low frequencies, while SH contributions increased at higher frequencies due to structural heterogeneity. This approach allowed accurate source tracking even in low-SNR conditions and at longer propagation distances (>400 m), where wavefield mixing would otherwise obscure directionality.

Together, these studies present a compelling case for incorporating rotational seismology into routine observational workflows. We demonstrate that 6C data significantly improve back azimuth estimation, enhance source classification capabilities, and allow for real-time tracking of both static and dynamic sources. The successful validation of BlueSeis-3A sensors, the development of adaptive processing techniques, and the application of machine-learning-based wave-type classification suggest that 6C seismology is poised to play a central role in future seismic monitoring, particularly in structurally complex or noise-prone environments.

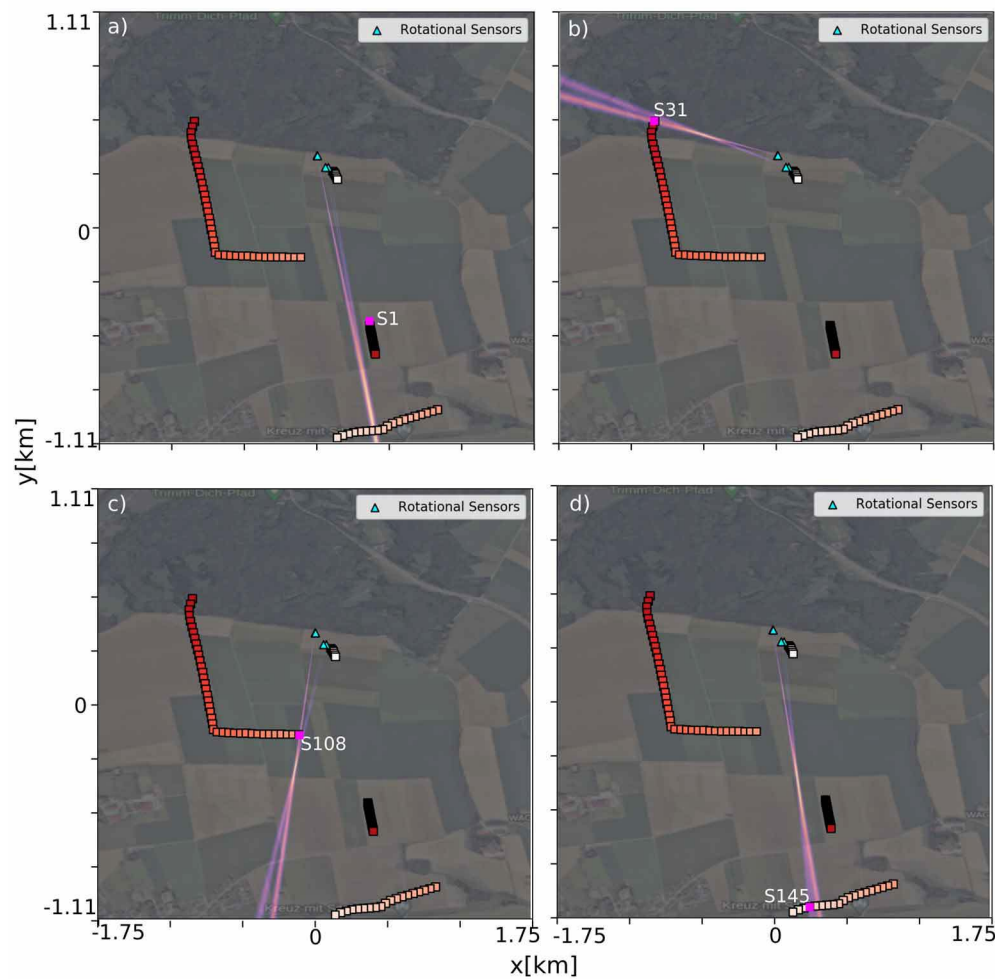


Figure 2 Directional projections showing back azimuths corrected for 180° ambiguity on 21 November 2019, derived from the horizontal components of the five rotational sensors. We used rotational sensor back azimuth estimates for each time window, shown with purple colors as projections. Subplots (a, b, c, and d) show the projections at different locations of the truck. Colors from red to white represent sweep locations, cyan triangles show the rotational sensors, and magenta squares mark the true sweep locations. The brightness of the projections increases when more projections intersect at a point on the map. Latitude and longitude of the study area are converted to meters.

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3D fully coupled simulations of earthquake-tsunami generation and controlled wave tank experiments for submarine distributed acoustic sensing of acoustic and gravity waves

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Distributed Acoustic Sensing (DAS) transforms fiber-optic cables into a dense array of geophysical sensors [e.g., Hartog, 2017; Lindsey and Martin, 2021; Masoudi and Newson, 2016]. Previous efforts applied DAS to offshore cable sections, to, for example, track whale migration [Rørstadbotnen et al., 2023] or to investigate the interplay between ocean waves and the seafloor [Romanowicz et al., 2023]. DAS was recently shown to be sensitive enough to capture tsunami signals [Becerill et al., 2025; Toneyawa and Araki, 2024; Xiao et al., 2024], and first transfer functions between DAS measurements and nearshore surface gravity waves have been developed [Glover et al., 2024; Meulé et al., 2024]. However, a detailed investigation in a controlled environment using different fiber-optic cables and a broad frequency band is still lacking. In this presentation, we focus on the physical mechanisms by which DAS records seismo-acoustic and gravity wave signals in two parts: (1) numerical models of fully coupled earthquake-tsunami generation, with (2) controlled wave tank laboratory experiments.

First, we study synthetic submarine cables in the presence of a propagating tsunami and determine some of the fundamental contributions to the recording of a strain signal (Figure 1) [Becerril et al., 2025]. We find that the combined hydrostatic effects outweigh any signals from seafloor shear and temperature fluctuations in deep water. Supported by fully coupled numerical simulations combining an idealized megathrust earthquake on a shallowly dipping thrust fault with non-linear tsunami generation across a compressible ocean layer using SeisSol [Gabriel et al., 2025]. We retrieve the tsunami signal from synthetic receivers emulating DAS cables using appropriate filtering. The preferred cable orientation for detection is aligned with the direction of wave propagation. However, submarine earthquakes can excite unexpectedly large acoustic waves propagating through the water column in addition to the slower propagating ocean gravity (that is, tsunami) waves [e.g., Kozdon and Dunham, 2014; Kutschera et al., 2024; Yamamoto, 1982], requiring more work to untangle the different wave types, especially in shallow water.

In the second part, we aim to experimentally identify optimal fiber-optic cable types and interrogation strategies for the detection of both acoustic and gravity waves to pave the way for future large-scale fiber-optic designs along shorelines and in other marine settings. We will show preliminary results from a controlled wave tank experiment using the 36-meter-long Scripps Ocean-Atmosphere Research Simulator (SOARS; Figure 2a) [e.g., Moore et al., 2025] and a slightly smaller 33-meter-long glass channel (Figure 2b). Different single-mode fiber-optical cables (e.g., 250 μm , 900 μm , 3 mm, 5 mm, and a 1.73 cm thick optomechanical UNOLS cable representative for ocean deployment) are placed on the bottom of the respective wave tank and probed with a DAS

interrogator at gauge lengths down to 1.27 m and a high dynamic range mode, designed for very low frequencies. A wave paddle generates left-to-right propagating waves with user-defined periods and wave heights, while four co-located hydrophones and a modified pressure sensor allow for calibration and a comparison with the DAS recordings [e.g., Chien et al., 2025]. First 3D numerical simulations with SeisSol for the glass channel, using a traveling planar wave of 1 s period and 10 cm amplitude, indicate that longitudinal strain varies with wave height (Figure 2c). These experiments will provide a means to evaluate the dominant mechanisms by which ocean-bottom fiber-optic sensing detects acoustic, gravity, and infragravity waves [e.g., Liu et al., 2025; Williams et al., 2022].

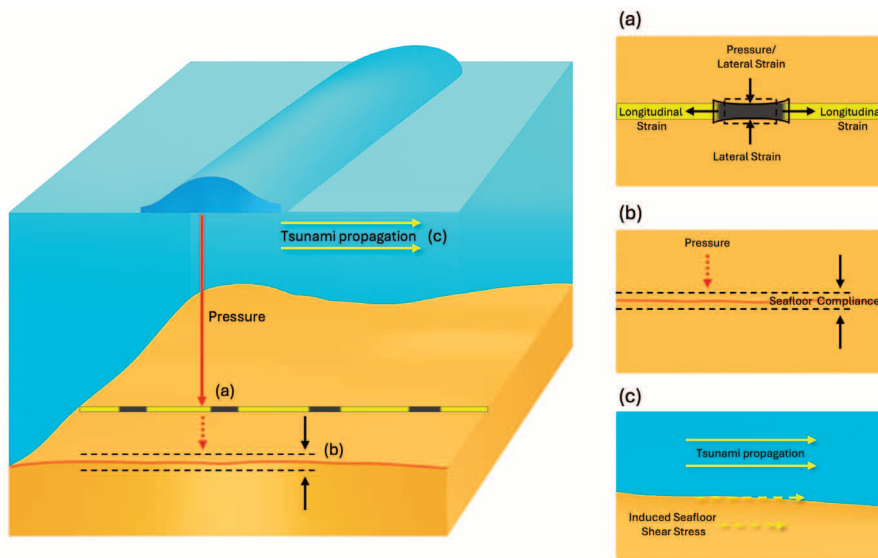


Figure 1 Illustration adapted from Becerril et al. [2025], showing how a passing wave affects strain recorded on a fiber-optic cable at the seafloor. The hydrostatic pressure effects include (a) the longitudinal elongation of the cable due to the Poisson effect and (b) the elastic deformation of the seafloor (i.e., compliance effect) due to the water pressure perturbation of a wave. (c) A smaller contribution is expected due to the horizontal propagation of the tsunami, inducing seafloor shear stress.

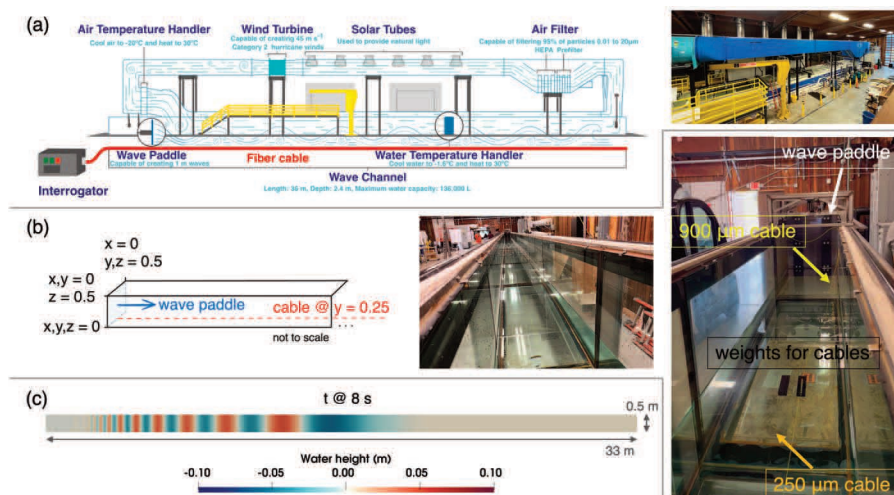


Figure 2 (a) Schematic of the Scripps Ocean-Atmosphere Research Simulator (SOARS) wind-wave channel, adapted from Moore et al. [2025], with a fiber-optical cable (red) placed at the bottom of the wave tank. (b) Sketch and images of the 33 m long and 0.5 m wide glass channel, with a normal water depth of 0.5 m. (c) Preliminary simulation for a 3D model of the glass channel, with an incoming ~10 cm amplitude wave from the location of the wave paddle on the left side, not to scale. Densely spaced synthetic receivers (for x in [0, 33] m and along $y = 0.25$ m) placed at the bottom and at the water surface record longitudinal strain and water height, respectively.

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Insights from the 2025 Myanmar Earthquake: A Preliminary Investigation of Coseismic Vertical Displacement Using Sentinel-1 Imagery

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Background and Research Objectives

On March 28, 2025, a powerful earthquake with a moment magnitude (M_w) of 7.9 struck central Myanmar at a shallow depth of 10 km, causing widespread impacts that extended as far as Bangkok, Thailand; Yunnan Province in China; and Vietnam. The mainshock was followed by 468 aftershocks recorded through April 12, 2025. Mandalay, Myanmar's second-largest city, located just 16 km east of the epicenter, suffered the most severe damage, resulting in 3,354 confirmed fatalities, 4,508 injuries, and 202 people reported missing. This earthquake is considered the most destructive in Myanmar since the 1912 event, with a maximum Modified Mercalli Intensity (MMI) of IX (Violent). The rupture occurred along the dextral (right-lateral) strike-slip Sagaing Fault, an active tectonic boundary between the Indian and Sunda Plates, known for producing numerous large earthquakes ($M_w \geq 7.0$), including the significant 1912 event [Cai et al., 2025]. This study presents a preliminary investigation of vertical displacement associated with the earthquake, focusing on the areas around the epicenter near Sagaing and Mandalay, using Sentinel-1 satellite imagery.

Geological Setting

Myanmar is located at the southeastern extension of the Mediterranean-Himalayan seismic belt and lies within the interaction zone of the Indian, Eurasian, and Sunda plates. This tectonic interaction has resulted in the formation of several active faults, most notably the Sagaing Fault. The Sagaing Fault is the most active and longest tectonic structure in Myanmar, extending approximately 1,400 km from the northern mountains of Myanmar to the Gulf of Martaban in the south. It serves as the principal boundary between the Indian and Sunda Plates [Kundu & Gahalaut, 2012]. The fault passes through major cities, including Yangon, Naypyidaw, and Mandalay, posing a significant disaster risk to millions of residents. It accommodates the shear component resulting from the oblique subduction of the Indian Plate beneath the Eurasian Plate, which is moving northeastward at a rate of 4–5 cm per year [Pailoplee & Nimnate, 2022]. This movement causes significant tectonic stress accumulation along the Sunda Plate boundary. Since 1900, at least ten earthquakes with magnitudes greater than 7 have occurred within a 300 km radius of the 2025 earthquake's epicenter, including major events in 1912 (M_w 7.9), 1946 (M_w 7.6), and 2009 (M_w 7.5). Focal mechanism analyses indicate a dominance of strike-slip and thrust faulting, consistent with the dual role of the Sagaing Fault in accommodating both lateral shear and tectonic compression [Min et al., 2022].

Method

This study utilized Sentinel-1 imagery from both ascending and descending orbits, acquired before and after the earthquake event from the Copernicus Open Access Hub. Specifically,

ascending images from March 23 and April 4, 2025, and descending images from 22 March and 3 April 2025 were processed. The Interferometric Synthetic Aperture Radar (InSAR) technique [Aslan et al., 2018] was applied to each image pair (ascending and descending) to generate LOS (Line of Sight) displacement maps using the ESA Sentinel Application Platform (SNAP 8.0) [1]. Subsequently, geometric decomposition was performed by combining LOS displacements from both viewing geometries to derive estimates of vertical and quasi-east-west (E-W) ground surface displacement. This approach enables a more accurate assessment of vertical land deformation associated with the 2025 Myanmar earthquake by isolating the vertical displacement component from radar measurements. The full InSAR processing workflow included the co-registration, TOPS splitting, orbit correction, interferogram generation, coherence estimation, phase filtering, phase-to-displacement conversion, geocoding, terrain correction, and geometric decomposition (Figure 1).

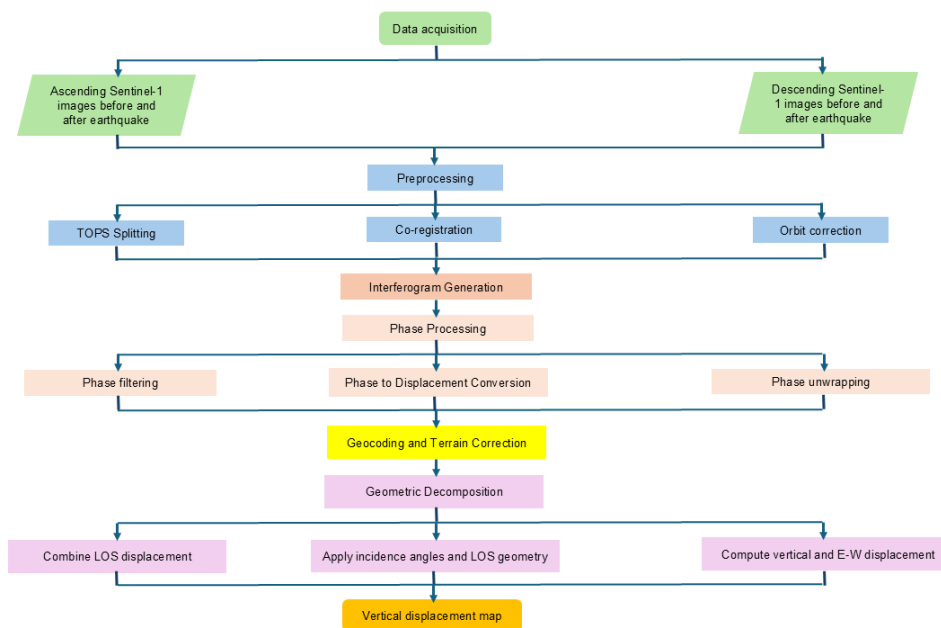


Figure 1 Flow chart of vertical deformation analysis from Sentinel-1 image using SNAP 8.0 software.

Results and Analysis

Preliminary findings indicate that vertical deformation patterns observed after the earthquake around the fault rupture area show subsidence of up to 0.6 meters, particularly in Mandalay (Figures 2A and 2B), which is located near the earthquake's epicenter-southeastern Mandalay, and along the Sagaing Fault. In contrast, subsidence in northern, western, and southern Sagaing is relatively lower, ranging between 0.2 to 0.3 meters, compared to Mandalay and eastern Sagaing. A similar pattern is also identified in northern and western parts of Shan (North), where the level of subsidence is lower than that in Mandalay (Figure 2A). In southern Mandalay, a subsidence of nearly 0.4 meters was observed (Figure 2B). The significant subsidence along the Sagaing Fault and in Mandalay (Figure 3), combined with horizontal ground movement, has led to severe structural damage to surface infrastructure, including the Shwe Sar Yan Pagoda in southeastern Mandalay—one of Myanmar's most renowned and historic pagodas. Satellite imagery and field data collected after the earthquake further confirm that both public infrastructure and residential areas in this region suffered the most severe impacts [Rajaram et al., 2025]. Damage was not limited to Myanmar alone; the effects extended as far as Bangkok, where a building approximately 130 meters tall collapsed, resulting in dozens of fatalities.

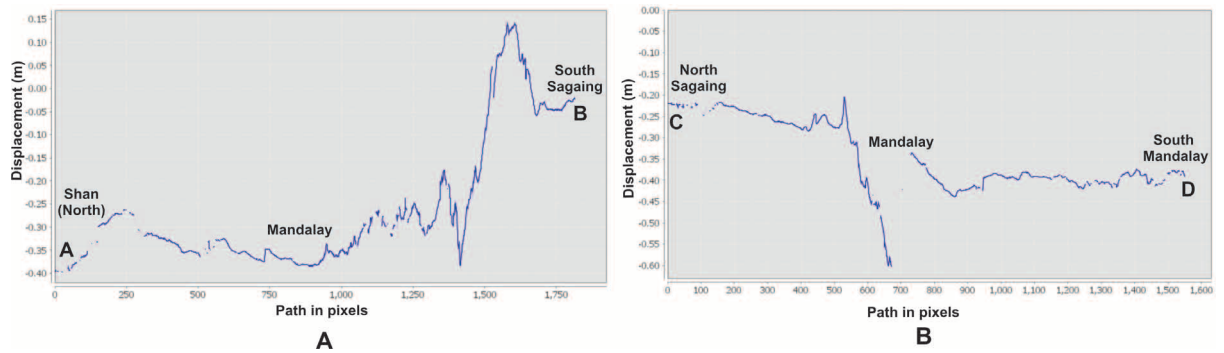


Figure 2 A. Subsidence in Mandalay exhibits greater displacement compared to Shan (North) and southern Sagaing. B. In Mandalay, subsidence becomes increasingly significant with proximity to the earthquake's epicenter.

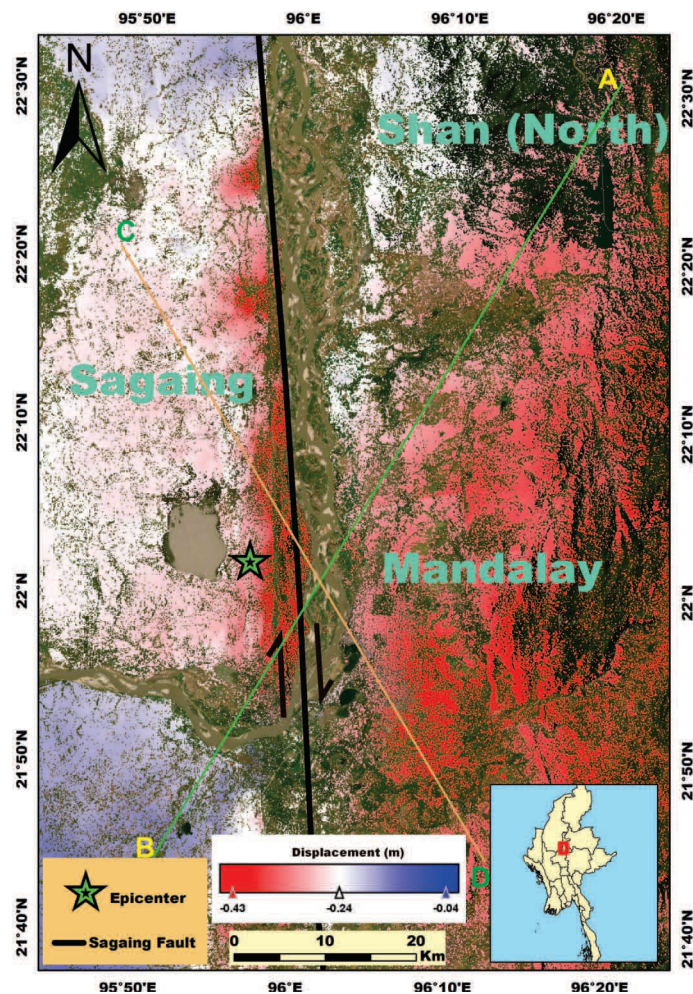


Figure 3 The spatial distribution of subsidence near the Sagaing Fault and the earthquake's epicenter (star) indicates that Mandalay experienced substantially greater subsidence than other regions, including Shan (North) and much of Sagaing. Lines A-B (green) and C-D (brown) represent the cross section of Figures 2A and 2B.

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Sitography

- [1] <https://step.esa.int/main/download/snap-download/>

Mapping ocean-bottom dynamics with Φ -OTDR DAS

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Rayleigh-based Distributed Acoustic Sensing (DAS or Φ -OTDR) measures strain, temperature, and pressure by analysing laser light back-scattering on discrete lengths of fibre, over long ranges (e.g., [Waagaard et al., (2021)]). To improve the signal-to-noise ratio (SNR), multiple consecutive channels can be combined into gauge lengths (GL). However, Φ -OTDR is inherently cross-sensitive to strain, temperature, and pressure [Waagaard et al., (2021); Lu et al., (2017)]. Apparent strain (ϵ_{ap}) at each channel depends on the actual strain (ϵ), temperature changes (ΔT), and pressure (p):

$$\epsilon_{ap} = \underbrace{g(\theta, GL)C(t_a)a(t_a)\epsilon}_{\text{Strain term}} + \underbrace{\alpha\beta\Delta t}_{\text{Temperature term}} + \underbrace{J(t_p)(p_s + p_T)}_{\text{Pressure term}} \quad (1)$$

Strain response depends on azimuthal sensitivity and geometric low-pass filtering $g(\theta, GL)$ introduced by the linear sensing element, ground coupling $C(t_a)$, and ageing $a(t_a)$. Temperature response depends on the thermal expansion (α) thermal response (β) coefficients for a ΔT temperature change [Hocker (1979); Hartog. (2017); Sinnett et al., (2020)]. Hydrostatic pressure variations due to changes in sea-surface level deform the cable not only through Poisson's effect [Becerril et al., (2024)], but also via the compliance of the seafloor and a creep compliance term (J). This term reflects the overall stiffness of the sensing system, encompassing the fibre, cladding, gel, casing, armouring, and the surrounding seafloor at each section of the cable. The non-Newtonian behaviour of the gel and other viscoelastic components is also accounted for. Pressure-response time (t_p) is related to each pressure event to describe the time-dependent strain response due to viscoelasticity.

Rapid strain events (e.g., earthquakes, surface waves) produce direct strain signals, while temperature changes have a slower response [Peláez Quiñones et al., (2023); Sinnett et al., (2020); Fernandez-Ruiz et al., (2022)]. Pressure from shoaling of ocean surface waves have periods longer than a few seconds [e.g. Longuet-Higgins, M. S. (1950); Lindsey et al. (2019)], but increasing depths introduce a low-pass filtering in the pressure field that decays linearly with depth [Becerril et al., (2024); Sladen et al., (2019)]. Tides induce long-wavelength, low-frequency variations. This distinction means that different frequency components can be isolated to analyse how various physical phenomena influence the response of the sensing fibre. Low-pass filtering (e.g., 30 min) helps isolate temperature and tidal effects by filtering impulsive strain events and ocean wave pressure changes, thus Eq. (1) can be simplified as Eq. (2):

$$F(\epsilon_{ap}) = \alpha\beta\Delta t + J(t_p)p_T \quad (2)$$

Direct temperature measurements are not possible [Sinnott et al., (2020); Ide et al., (2021)], as there is no in-situ calibration, but temperature differentials can be mapped across time and space on the filtered data. It becomes possible to follow the movements of water at different temperatures. To further enhance the signal, we analyse the SNR of the average apparent strain on each GL. A simple median filter correction [Duncan & Beresford (1995)] is also applied.

The dataset used in this work was collected at GeoLab, a collaborative initiative designed for the research community, involving FCT, FCCN, ARDITI, EllaLink, EMACOM, and GEANT. It utilizes a ~56 km dedicated dark fibre on the Madeira branch of the EllaLink cable for seismology, oceanography, and biology research, supporting the Oceanic Observatory of Madeira (OOM) with seabed observations and providing a bottom-up view of the Madeira basin.

The cable can be divided into three main overlapping domains according to the mixing regime of water masses (see coloured bands under Figure 1a). Down to a depth of ~1000 m, ocean waves shoaling dominate the signal. Deeper, the influence of internal waves becomes visible. At depths between ~1500 m and ~3000 m, internal tides are identifiable and dominate at depths greater than ~2000 m. Internal tides are a result of the interaction between tides and accentuated topography, especially in places where steep topography and strong buoyancy stratification combine to trigger internal oscillations, as observed around Madeira's slopes. They are identified by their semidiurnal period, and exhibit similar patterns to those in the Canary Islands, where a DAS dataset was recorded on a comparable bathymetric profile to the GeoLab fibre [Peláez Quiñones et al., (2023); Williams et al., (2023); González-Herráez (2024)]. In the deep basin, diffusion patterns are observable. At the beginning of the time series, a temperature perturbation is visible at ~50 km cable distance. It slowly migrates westwards until, at ~30 h, it splits into two distinct branches. The eastern branch remains approximately in the same position, oscillating with an amplitude of ~1 km and a period matching the tide. Temperature variations (Figure 1a) become weaker with depth. Tidal influence prevails shallower than 1800 m, with stronger signals on the island slope. In the deep basin, the semi-diurnal pattern loses symmetry, which may indicate that the temperature fluctuations are linked to mesoscale events associated with the meandering of the Azores current [Käse & Siedler (1982); Frazão et al., (2021)], or the dissipation of mesoscale eddies. Up to 1800 m depth, internal tides, internal waves, and other oceanographic phenomena dominate a more complex regime.

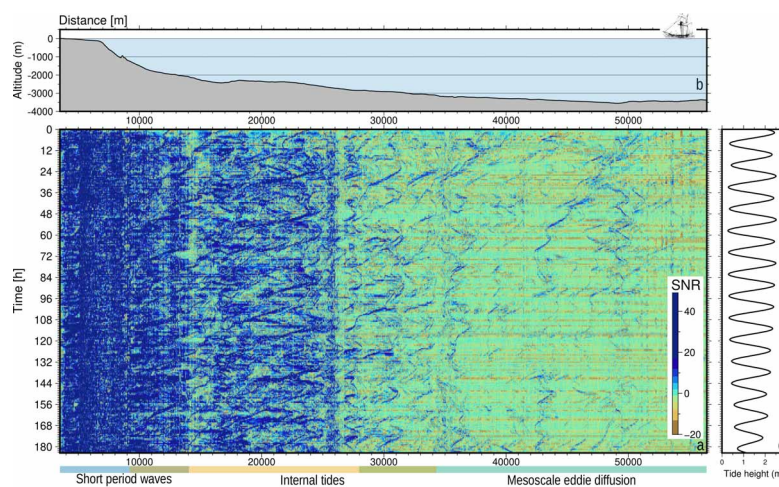


Figure 1 Global SNR map. a) Median-corrected SNR for the entire dataset, calculated as the mean μ divided by the standard deviation σ in 30-minute windows for each individual GL. At each time window, the median value of all channels is subtracted to each channel. The extension of the different domains is marked with coloured bands. b) Depth profile along the cable track, source [GEBCO Compilation Group (2023)]. c) Tide heights modelled for Funchal.

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Multi-Scale Fibre-Optic Sensing Experiments for Subsurface Monitoring

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Introduction

High-resolution distributed fibre-optic sensing (DFOS) offers a crucial advantage by enabling data acquisition with significantly higher spatial resolution and, in many cases, a broader frequency bandwidth than conventional sensors, while maintaining accuracy across multiple spatial and temporal scales. This enables the early detection of subsurface integrity problems and induced seismicity across various scales, thereby enhancing operational safety, reducing costs, and fostering public trust in geothermal and energy storage projects. Yet the detailed character and fidelity of its signals remain poorly quantified and are frequently overlooked.

This work presents a comprehensive, multi-scale experimental campaign designed to quantify the limitations of DFOS and establish validated protocols that bridge the gap between laboratory studies and field applications. Within the framework of EPOS-eNLarge, by integrating facilities and expertise from Utrecht University, TU Delft, the TNO Rijswijk Centre for Sustainable Geo-Energy (RCSG), and field sites (the Groningen gas field or the Delft geothermal site), we aim to develop robust methodologies for subsurface DFOS deployment.

Methodology and Experimental Framework

To create reliable strategies for deploying DFOS in the subsurface, we plan to conduct a series of experiments across variable spatial scales, ranging from millimetres to centimetres, decimetres, and metres, followed by field data validation (Figure 1).

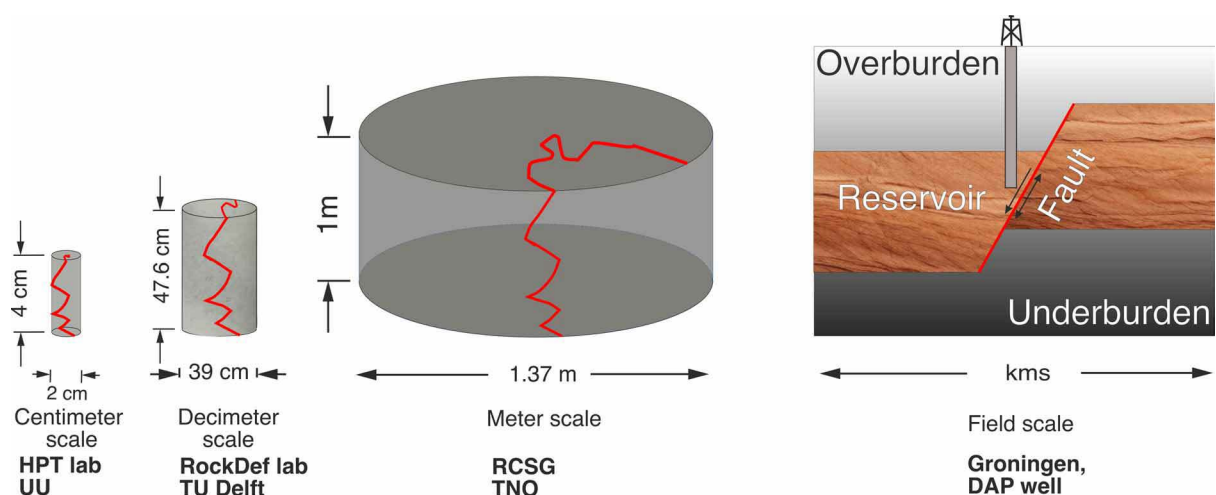


Figure 1 Schematic of cross-scale experiments, illustrating variable spatial scales ranging from millimetres to centimetres, decimetres, and metres.

At Utrecht University's HPT laboratory, high-resolution distributed strain sensing (DSS) tests will be conducted on rock cores (heights 20-80 mm; diameters 10-40 mm) under controlled pressure-temperature conditions to capture the evolution of strain during rock deformation. Cylindrical specimens, instrumented with fibre-optic cables of varied coupling and orientation, will be loaded uniaxially in a standard frame until failure (Figure 2a). A laser vibrometer will be employed alongside the DSS setup to monitor surface vibrations during deformation and failure, enabling cross-comparison with distributed strain measurements and providing insights into the acoustic energy associated with micro-fracturing events. The aims are to characterise fracture initiation and propagation, strain localisation, and the fidelity of the recorded DSS signals.

Building upon earlier experiments, at the TU Delft Rock Deformation laboratory, we plan to deploy fibres with multiple orientations on ≈ 0.5 m rock blocks and induce fracture opening in the borehole simulator setup (Figure 2b). In this setup, we will record slow-deformation signals with DSS and attempt to capture acoustic-energy outbursts using distributed acoustic sensing (DAS). With these tests, we will assess static–dynamic response calibration and acoustic-event localisation and will benchmark DSS measurements against DAS.

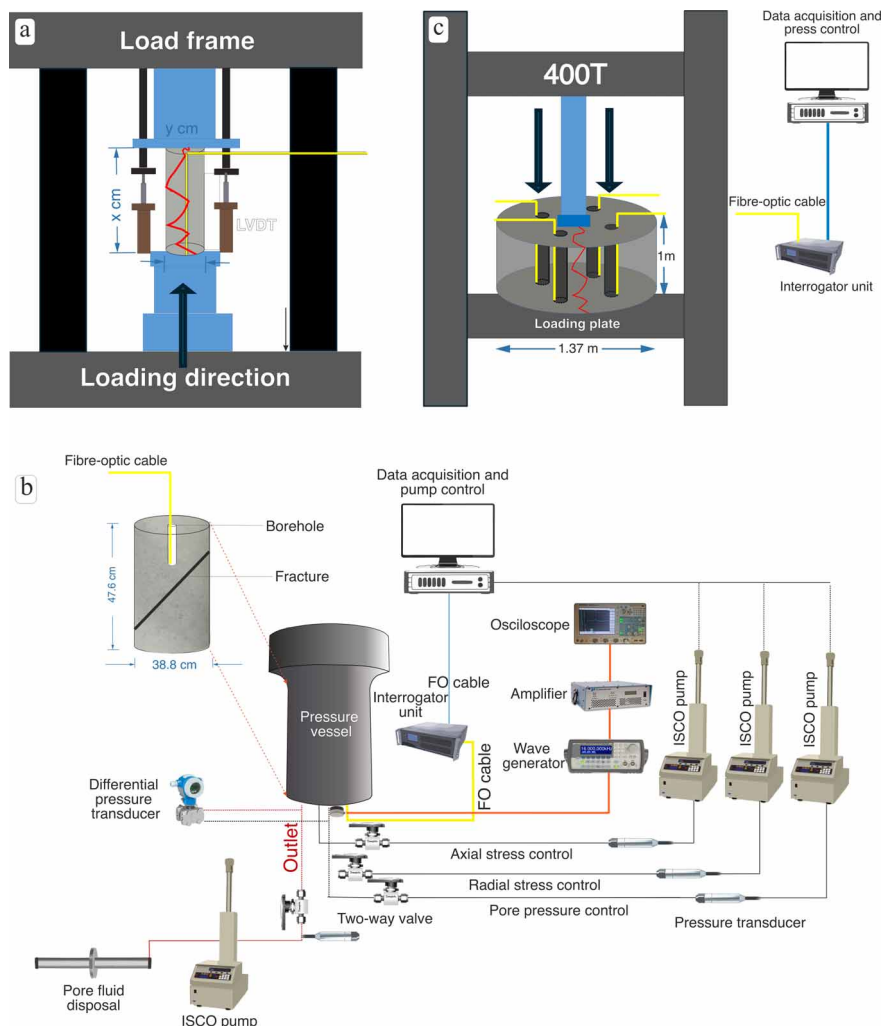


Figure 2 (a) Experimental setup at HPT lab (Utrecht University) for measuring strain variations during uniaxial loading of a cylindrical rock sample using Distributed Strain Sensing (DSS). (b) The laboratory setup at Rockdef Lab (TU Delft) for DFOS measurements at elevated stress conditions. (c) Illustrative setup at RCSG (TNO) for mounting the cement block in a 400-ton hydraulic press for a monotonic uniaxial compression test, with continuous acquisition of load, displacement, and other sensor data until failure.

To bridge the gap between lab-scale and field-scale deployments, we propose scaling up a small setup to a meter-scale experiment inside the 400-ton uniaxial press at the RCSG. A homogeneous or layered cement sample (1.37 m in diameter and 1.0 m in height, exact dimensions to be confirmed) (Figure 2c) will be used for this test. Multiple small wells will be created either by drilling or as a result of the casting process. Each borehole will be instrumented with fibre optic cables for DSS and DAS for complementary measurement points for data verification purposes. A 400-ton hydraulic press will be used for the uniaxial compression test, with continuous acquisition of load, displacement and other sensor data until failure. During the continuous load-to-failure run, the DSS recordings will resolve millimetre-scale strain localisation and quasi-static strain. At the same time, the DAS measurements capture the kilohertz acoustic-emission bursts associated with rapid crack propagation. This will enable us to create a seamless strain history at every measurement point, allowing for direct comparison with co-located conventional sensors.

Lastly, field data will be used to validate lab-derived observations and assess the long-term performance of DFOS in operational environments. We will use field data from the Groningen gas field and/or TU Delft's DAP research boreholes.

Expected Outcomes

This multi-scale experimental approach will provide distributed-strain measurements, enabling the systematic evaluation of millimetre-scale strain build-up and localisation that precede rupture, facilitating the location of micro-events, and allowing for the testing of moment-tensor inversion using DAS data. Results will be compared with traditional geophone-based methods to assess the performance of DAS-only localisation. Additionally, with these experiments, we will address the scaling challenge of translating measurements made with a sensor spacing of 0.25 cm in the lab to field-scale deployments, with data recording at 1–2-meter intervals at a gauge length of a few meters.

The expected outcomes of this work include validated DSS/DAS transfer functions under varying stress, temperature, and coupling conditions; benchmarks for DAS-only event localisation and moment tensor inversion; and quantitative relationships between strain evolution, acoustic emissions, and failure modes.

Conclusions

This work presents the first fully integrated lab-to-field workflow for fibre-optic sensing in subsurface applications. Through rigorous validation of DFOS technologies across various spatial scales and sensor types, we establish a robust foundation for interpreting DAS/DSS data, develop scalable sensor deployment strategies, and deliver field-ready benchmarks and calibration protocols. These contributions enable safer and more reliable monitoring of subsurface operations, ultimately supporting and accelerating the energy transition.

Acknowledgements

The authors gratefully acknowledge support from the Netherlands Organisation for Scientific Research (NWO) through the research program National Roadmap for Large Scale Research Facilities (project EPOS-eNLarge).

Developing a Hierarchical System for Stromboli's Paroxysmal Events: Insights from Deformation and Seismic Data

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Introduction

Explosive volcanic eruptions pose a significant threat, making Early Detection (ED) systems crucial for public safety [Gregg et al., 2015]. However, the complex dynamics of volcanic activity often hinder accurate prediction and identification of reliable precursors. Stromboli volcano, located in Italy's Aeolian Archipelago, exemplifies this challenge; its rare but powerful paroxysmal eruptions can have substantial impacts on the island, because of the generation high eruption columns, widespread pyroclastic dispersion, and hazardous phenomena like tsunamis and wildfires [Turchi et al., 2020]. Despite the difficulty in predicting these events [Vicarò et al., 2021], Stromboli's paroxysms are consistently preceded by significant inflation of volcanic edifice [Giudicepietro et al., 2020; Ripepe et al., 2021].

Leveraging this, the Università di Firenze – Laboratorio di Geofisica Sperimentale (UNIFI - LGS) implemented an inclinometer-based ED system in 2019. This system successfully detected the July 11, 2024, paroxysmal eruption with a 2.6-minute lead time. Although similar deformation anomalies have also been observed in other types of geophysical data [e.g., Giudicepietro et al., 2020; Viccarò et al., 2021], the current system relies exclusively on a single sensor, introducing an additional risk factor related to the absence of redundant data system. This work therefore proposes a new hierarchical detection system. This system will integrate multiple independent ED units, processing 18 years of seismic and deformation data from the Istituto Nazionale di Geofisica e Vulcanologia (INGV) permanent monitoring network (Figure 1). This multi-level approach aims to provide a more robust and flexible strategy for managing volcanic crises at Stromboli, ultimately improving risk management in emergency scenarios.

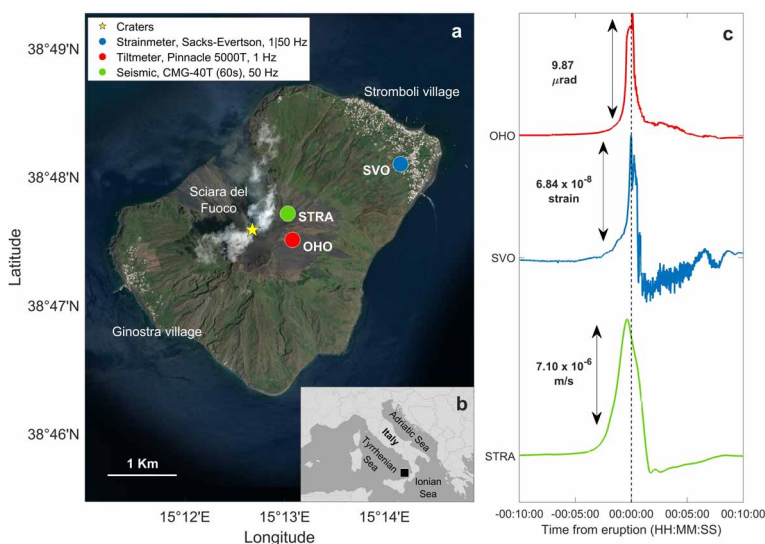


Figure 1 a) Stromboli Island (from Earthstar Geographics®), showing the positions of the tiltmeter (OHO, red), strainmeter (SVO, blue), and velocimeter (STRA, green). b) Area of the Mediterranean Sea, indicating the location of Stromboli Island (from Earthstar Geographics®). c) Seismic and deformation data illustrating the inflation of the volcano edifice during the paroxysm of July 2024 (dotted line).

Deformation and seismic data

The current ED system has been implemented using OHO inclinometer data (radial component; Figure 1a) from 2006 to 2019. This study adapts this system to INGV's network by analyzing SVO borehole dilatometer data and N-S component of STRA seismic station (Figure 1a). Both OHO and SVO have long acquisition histories encompassing four paroxysmal events (March 2007, July 2019, August 2019, July 2024), while STRA data suitable for ED development are only available from 2017. Significant amplitude changes in ground deformation and velocity signals are observed about 10 minutes before paroxysms (Figure 1c), such as the July 11, 2024, event. These pre-eruptive changes can be exploited for multiple ED systems using the UNIFILGS approach.

Implementing ED systems at Stromboli

The current ED system is based on a physical model linking the inflation rate of the volcanic edifice to magma ascent dynamics through an exponential relationship [Ripepe et al., 2021]. A reference recognition pattern (Template) can be extracted from this model to implement real-time pattern-matching techniques. The system continuously compares this template against real-time deformation data using a customized fitting function. An alert is triggered for 30 minutes when both the fit value and the peak-to-peak amplitude of the observed signals exceed predefined thresholds.

In this study, this algorithm was evaluated through a pseudo real time simulation on the full historical dataset (2006 - 2024) including the July 11, 2024, paroxysm. At the same time, it was adapted to develop two additional ED systems based on STRA and SVO data. While outlier removal and linear interpolation of data gaps are identical for each ED system, the length of the window analysis and the preprocessing are tailored for each data type. Examples of the output from the ED systems for OHO, SVO, and STRA during the July 11, 2024, paroxysm, are shown in Figure 2.

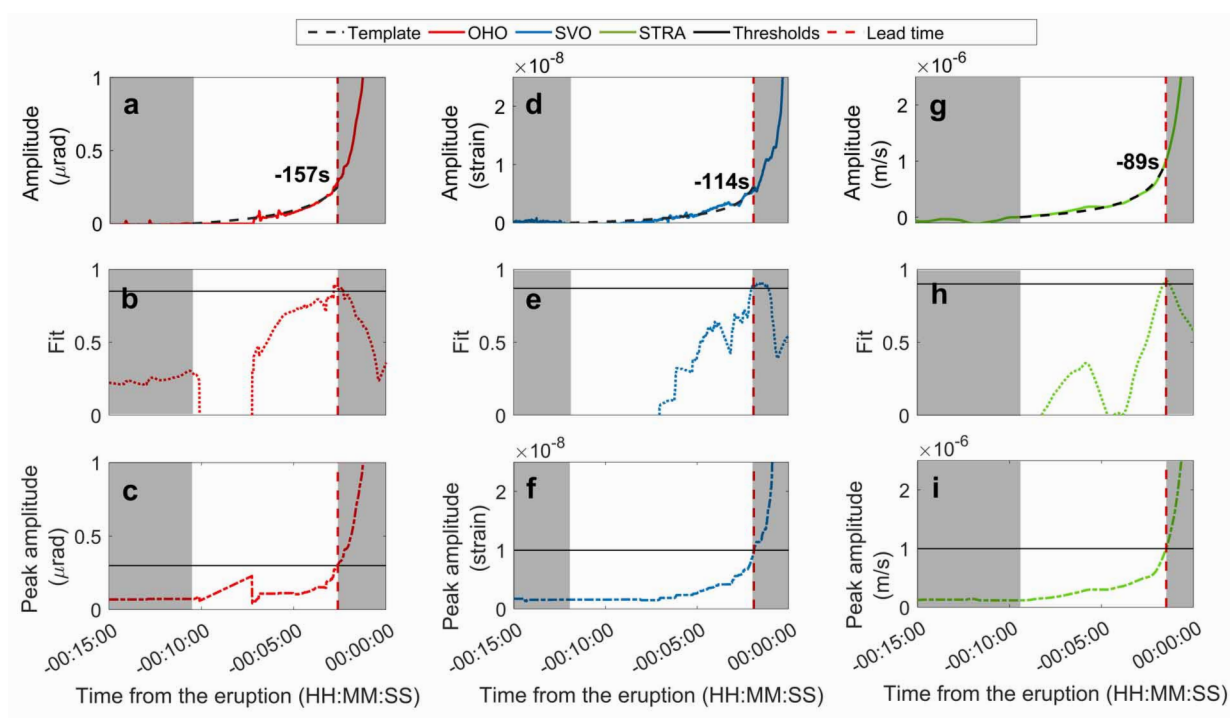


Figure 2 Examples of output of the ED system obtained 10 minutes before the onset of the paroxysm of 11 July 2024, at 12:08:53 UTC for OHO (a, b, c), SVO (d, e, f), and STRA (g, h, i).

Evaluation of the performances

A sensitivity analysis was conducted to identify optimal parameters (template, fit, and peak amplitude thresholds) required to achieve 100% detection success while minimizing the number of false alerts. These values were determined using 3D search grids and Multi-Criteria Decision Making [Thakkar, 2021] on pseudo-real-time simulations for all available datasets. In these cases, the selection criterion was based on identifying parameter combinations that exhibit a 100% True Positive Rate (TPR), 0% False Discovery Rate (FDR), and the maximum average Lead Time (LT). To assess the overall performance, Monte Carlo Cross Validation (MCCV) was applied to each ED system with over 10,000 iterations [Xu et al., 2004]. For each iteration, the algorithm was trained on a subset (training set) and validated on remaining data (testing set), ensuring at least one target event in the testing set. This yielded statistical distributions of TPR, FDR, and LT, providing a more robust measure of reliability.

Results and discussion

Analysis of deformation and seismic data reveals consistent pre-eruptive patterns (Figure 1), indicating overpressure caused by the accumulation and ascent of magmatic fluid [Ripepe et al., 2021]. These events, recorded by tiltmeters, dilatometers, and seismic sensors, are significantly larger and longer than those from major and ordinary explosions [Giudicepietro et al., 2020; Ripepe et al., 2021; Viccaro et al., 2021].

Each individual ED system achieved 100% detection of paroxysmal events with zero false alarms during 2006-2024 period. Their primary distinction lies in average Lead Time (LT): ~3.3 minutes for OHO, and ~1.4 minutes for both SVO and STRA.

MCCV evaluation allows objective comparison of these systems [Xu et al., 2004]. The OHO-based system consistently outperformed others, achieving ~98% of TPR and 3.3 minutes of mean LT, due to its high signal-to-noise ratio and proximity to the source [Genco and Ripepe, 2010]. The SVO-based system showed slightly lower performance (~87% TPR, 1.4 minutes LT) due to environmental noise and signal decay [Giudicepietro et al., 2020]. The STRA system had the lowest performance (~75% TPR, 1.4 minutes LT) influenced by a smaller dataset and lower sensitivity [Genco and Ripepe, 2010; Giudicepietro et al., 2020]. All systems reported similar FDRs (~20-35%).

Given varied performances, the three units can form a hierarchical ED system where the best-performing available unit controls alerts. This approach significantly improves alert management during sensor failures and leverages reliable predictive capabilities. This hierarchical framework may provide a robust solution crucial for volcanic crisis management at Stromboli.

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3D Insights into Volcanic Dome Collapse: The Hidden Influence of Hydrothermal Alteration

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Volcanic lava domes are inherently unstable structures that form when lava is too viscous to flow freely and accumulates around the vent. Dome instability arises from their incremental growth, varying extrusion rates, and diverse material properties. Thus, volcanic domes are an important source of geohazard, with frequent collapses generating landslides, destructive pyroclastic density currents, and debris avalanches. Such collapse events pose serious risks to nearby towns and infrastructure and can also influence the volcano's eruptive dynamics [Harnett and Heap, 2021].

During dome growth and following emplacement, stability is further affected by the circulation of hot hydrothermal fluids within the subsurface. Interaction between hydrothermal fluids and volcanic rock alters the rock's physical and chemical properties, often leading to rock weakening, and influencing both dome morphology and structural integrity. Hydrothermal alteration is commonly concentrated in zones of high fluid flow, such as fractures and areas of elevated permeability within the dome [Heap et al., 2021a].

In this study, we focus on the case of La Soufrière de Guadeloupe in the Eastern Caribbean to investigate how hydrothermal alteration affects dome stability and how it influences the magnitude of collapse volumes and associated runout distances. The internal structure of the La Soufrière de Guadeloupe dome has been mapped using geophysical methods [Rosas-Carbajal et al., 2016; 2017] to obtain rock density variation within the dome. We correlate the density contrasts with mechanical parameters provided by Heap et al., [2021b] to obtain a 3D strength map of the volcano (Figure 1). We then input this data into large-scale 3D models that employ the particle-based Discrete Element Method [Cundall and Strack, 1979]. The DEM simulates an assembly of individual particles upon which Newton's laws of motion are calculated. Particles behave as rigid bodies and interact via interparticle contacts, with associated forces and moments updated per particle per model time step.

We first present 3D models that combine morphological, geophysical, and mechanical data to investigate various post-emplacement dome stability scenarios. We model rock weakening by hydrothermal alteration by generating altered zones within the dome. Our results show that increased alteration-induced weakening (i.e., to 50% or 10% of the original rock strength) leads to greater displacements and causes dome destabilisation within an altered zone and downslope.

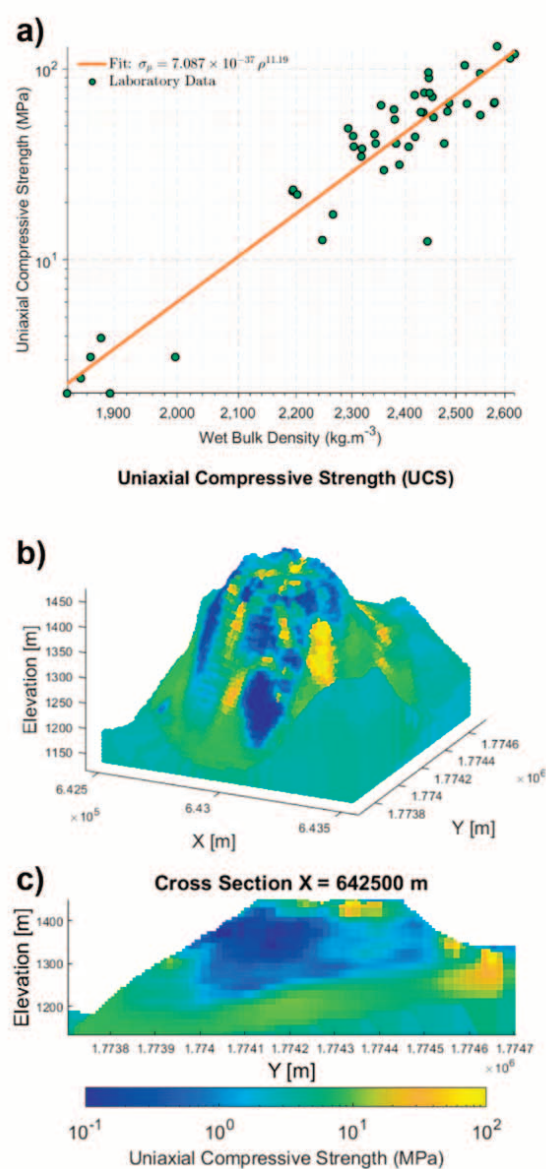


Figure 1 Strength distribution (UCS) within the La Soufrière de Guadeloupe dome where (a) shows a log-log plot of UCS as a function of density (data from Heap et al., [2021b]), (b) shows an overall view of the dome in 3D and (c) shows a cross section through the x-axis.

Additionally, we vary the spatial extent - the thickness (150 m or 50 m) and location - of the altered zones. Models with a shallower (50 m) altered zone still generated displacements up to 400 m into the subsurface. We model finite shear strain for these alteration scenarios and find evidence of rotational failure planes, slumping, and disaggregation within and in the areas surrounding the altered zones.

By quantifying collapse volumes generated by alteration-related deformation, we estimate potential debris flow runout distances. We use VolcFlow software (MATLAB) to input our collapse volumes and generate debris avalanches based on each model. The minimum collapse volume modelled ($0.092 \times 10^6 \text{ m}^3$) and therefore runout distance (391 m), is generated by the model with the smallest altered zone and weakened to 50% strength (Figure 2). The maximum collapse volume ($17.19 \times 10^6 \text{ m}^3$) and runout distance (exceeding 8 km) is generated by the model with the largest alteration zone that is weakened to 10% strength (Figure 2). The

modelling results clearly demonstrate that greater degrees of alteration and larger altered zones significantly increase both collapse volume and runout distance.

Our model incorporates rare data that allows us to design a fully comprehensive, heterogeneous simulation of the internal dome structure. We include individual density values for each discrete element and uniaxial compressive strength (UCS) and Young's modulus values for over 5 million interparticle contacts. Therefore, we show that incorporating mechanical heterogeneity is crucial for accurate hazard modelling as homogeneous models can both over- and underestimate collapse potential and hazard extent.

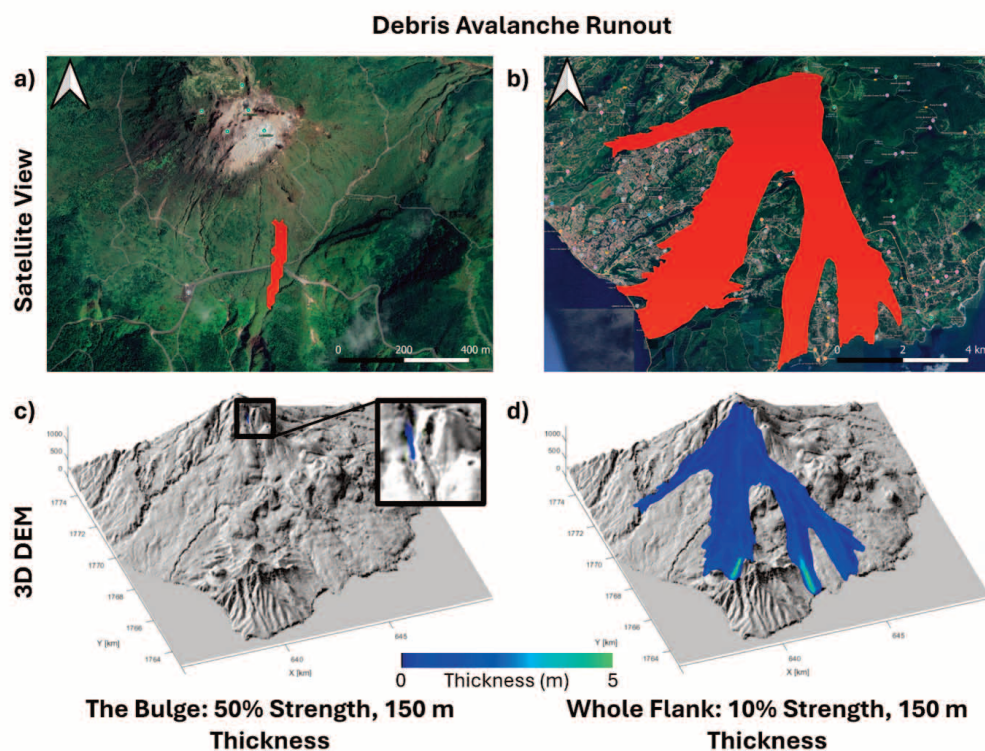


Figure 2 Models showing the runout distances from the (a) and (c) model with the minimum, and (b) and (d) model with the maximum debris avalanche volumes generated in VolcFlow, from collapse volumes generated in PFC. (a) and (b) show the runout on a hybrid satellite and terrain map, whilst (c) and (d) show the runout on the 3D DTM at $t = 100$ seconds. Basemap Data: Google, Landsat / Copernicus / ©2025 TerraMetrics / ©2025 Airbus / ©2025 Maxar Technologies / IBCAO.

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Integrating InSAR and Environmental Seismic Intensity (ESI2007) for Earthquake Impact Assessment in the Aegean Region

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The study of earthquake impacts on the environment is important for understanding seismic hazards and reducing associated risks. Remote sensing technologies—especially data derived from Sentinel-1 satellite imagery—enable precise detection of Line of Sight (LoS) ground deformation and fault line mapping. The Environmental Seismic Intensity Scale (ESI 2007) serves as a reliable tool for systematically assessing earthquake-induced environmental impacts, offering high spatial accuracy and consistency [Michetti et al., 2007]. This study aims to highlight the synergy between satellite-based techniques and field-based macroseismic observations in assessing seismic hazards and disaster potential by analysing recent seismic events in the Aegean region, focusing on the Kozani-Grevena 1995, Lesvos 2017 and Samos 2020 earthquakes. On May 13, 1995, a strong earthquake of magnitude Mw 6.5 struck the Kozani-Grevena region in northern Greece. The event was generated by normal faulting along the previously unknown Palaeochori Fault. [Pavlidis et al., 1995]. The earthquake triggered environmental effects, including ground cracks, uplifts, subsidence, landslides, rockfalls and liquefaction [Hatzfeld et al., 1995]. On June 12, 2017, a Mw 6.3 earthquake occurred offshore southeastern Lesvos Island, in the North Aegean Sea. The rupture was associated with a SW-dipping normal fault striking NW-SE [Papadimitriou et al., 2017; Chatzipetros et al., 2013]. The earthquake caused one fatality, many injuries, and severely damaged the village of Vrisa. Slope failures, ground cracks, coastal subsidence, and a small tsunami at the port of Plomari were reported [Lekkas et al., 2017]. The Mw 7.0 Samos earthquake occurred on October 30, 2020, rupturing an offshore normal fault in the North Aegean Trough and it was associated with co-seismic uplift, landslides, liquefaction, and tsunami generation [Ganas et al., 2021; Mavroulis et al., 2021].

Methodology

This study employs a combined methodological approach that integrates advanced remote sensing and field-based techniques to assess ground deformation and related environmental impacts resulting from seismic activity. Utilizing Sentinel-1 Synthetic Aperture Radar (SAR) imagery [1], we apply interferometric processing to detect co-seismic ground deformation, while the ESI2007 provides a consistent framework for classifying earthquake environmental effects (EEEs). We processed the Sentinel-1 SAR data from Samos ascending (Figure 1a) and descending (Figure 1b) and Lesvos (Figure 1c) and descending (Figure 1d), orbital acquisition geometries to extract co-seismic deformation using differential InSAR (DInSAR). The workflow included image co-registration, removal of topographic signals via Shuttle Radar Topography Mission (SRTM) data, and phase unwrapping performed through the SNAP Desktop software [2]. The resulting LoS displacements were integrated into a GIS framework [3] and compared with published and field-verified EEEs to map the spatial distribution of intensity values according to the ESI 2007 scale. The analysis includes the production of isoseismal maps using the kriging method of geostatistical interpolation. Where available, correlation analysis

between measured ground displacement and ESI intensity levels was performed to explore potential thresholds of environmental impact. The Kozani-Grevena earthquake, lacking InSAR coverage, was analyzed using field data for isoseismal mapping only.

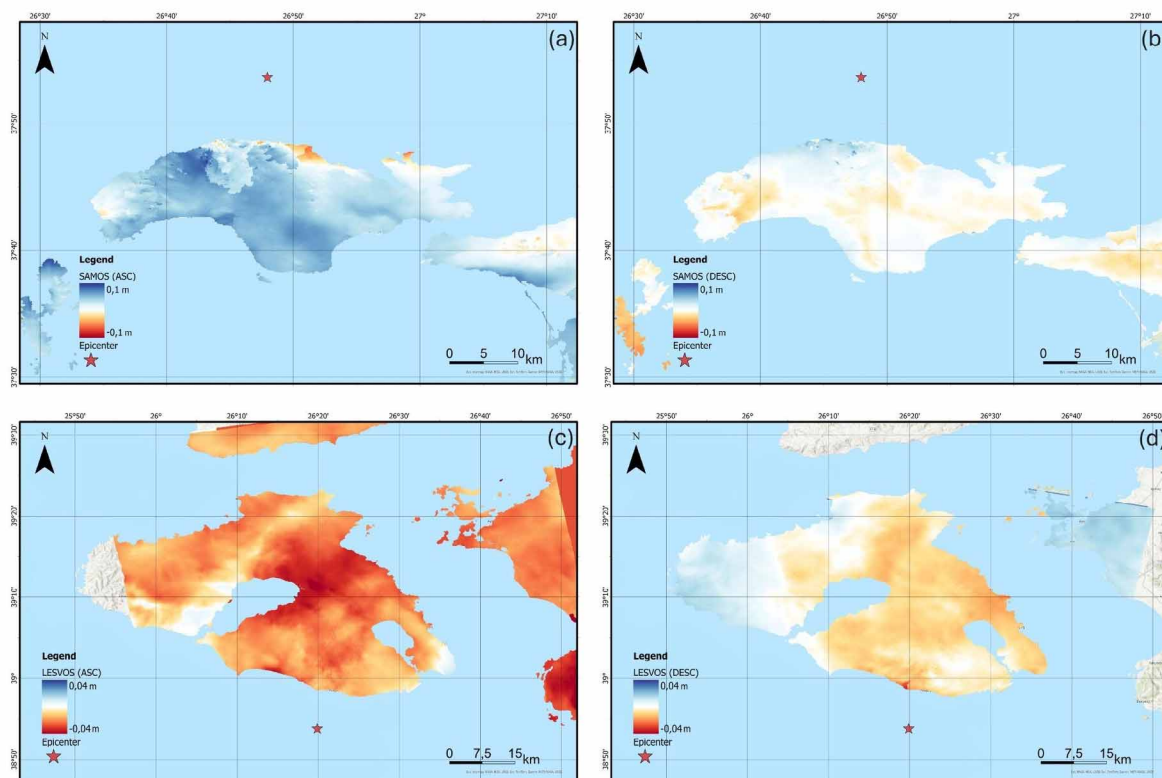


Figure 1 Maps show the LoS ground displacement in meters after the Samos earthquake by interferometric processing of Sentinel-1 post-event data for ascending (a) and descending (b) orbital acquisition geometry. Maps show the LoS ground displacement in meters after the Lesvos earthquake by interferometric processing of Sentinel-1 post-event data for ascending (c) and descending (d) orbital acquisition geometry. Positive LoS values correspond to motion towards the satellite, whereas negative LoS values correspond to motion away from the satellite.



Figure 2 Isoseismal map of the Samos (a), Lesvos (b) and Kozani-Grevena (c) earthquake, using field survey data. The epicenter of each seismic event is indicated by a red star.

Results and Conclusions

Co-seismic deformation patterns obtained from Sentinel-1 SAR data provided high-resolution insights into vertical and horizontal ground line-of-sight (LOS) displacements associated with the Lesvos and Samos earthquakes. It is worth mentioning that the application of the Environmental Seismic Intensity (ESI 2007) scale allowed us to identify and classify the

earthquake environmental effects. It is important to mention that the ESI-derived intensity values, ranging from IV to IX, are broadly in agreement with previously published studies [Lekkas et al., 2017; Papanikolaou & Melaki, 2017; Mavroulis et al., 2021]. The spatial distribution of these seismic intensities was visualized via isoseismal maps for the Samos (Figure 2a), Lesvos (Figure 2b) Kozani-Grevena (Figure 2c) events, revealing zones of increased environmental impact. However, a noteworthy observation emerged that the regions of maximum ground displacement, as detected by InSAR, did not always coincide with areas of peak seismic environmental intensity and, the epicenter does not necessarily correspond to the zone of greatest environmental impact, highlighting the need for spatially distributed observations when assessing seismic intensity. In conclusion, this integrated approach shows the growing potential of geospatial technologies when combined with in-situ observations and historical data archives which contributes to the improvement of seismic hazard models and supports the development of more effective disaster risk reduction strategies.

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Sitography

- [1] www.copernicus.eu
- [2] <https://step.esa.int/main/toolboxes/snap/>
- [3] <https://www.arcgis.com/index.html>

Environmental and Weather Monitoring with Distributed Acoustic Sensing in Large-Scale Research Infrastructure

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The sensitivity of research facilities such as, particle accelerators, gravitational wave detectors underground laboratories, among others; are influenced by ambient seismic and anthropogenic noise. While human-made noise can sometimes be mitigated through careful site planning and engineering controls, naturally occurring environmental and seismic disturbances such as earthquakes, microseisms, or tides, cannot be eliminated. One effective strategy to suppress the impact of these noises is through post-processing noise cancellation [Harms, 2019], using witness sensor array that record these disturbances in parallel with the experiment. The data recorded by the witnesses sensors can then be used to estimate and subtract the noise from the experimental data, improving the clarity and sensitivity of the final measurements.

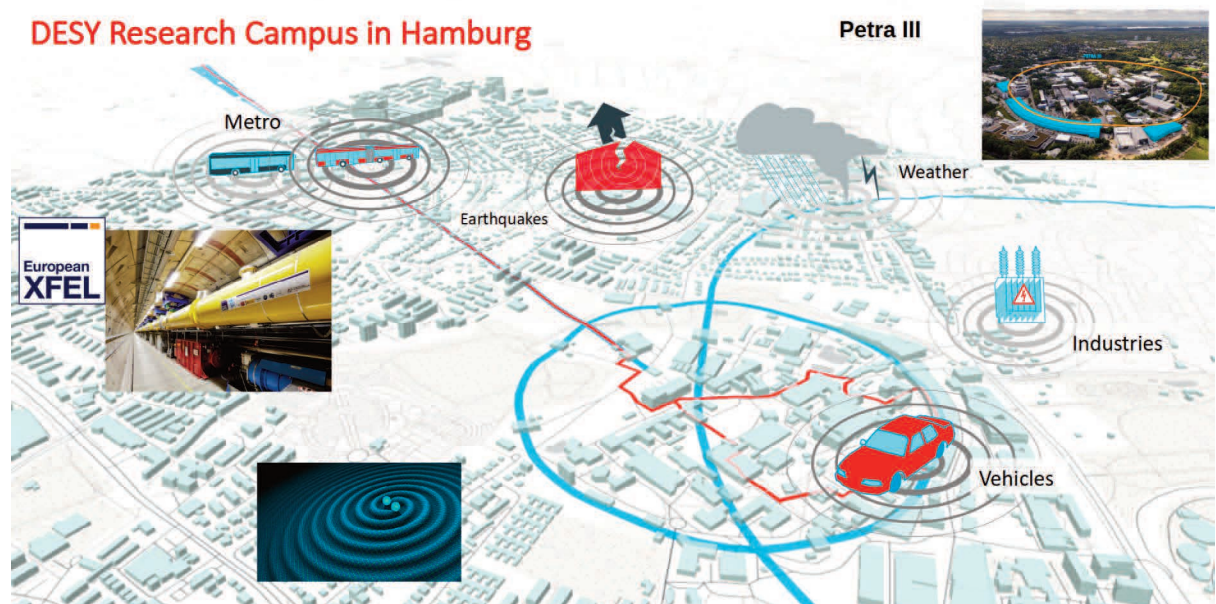


Figure 1 Map of the DESY campus showing 20 km of DAS fiber deployed as a continuous array of witness sensors for monitoring seismic and environmental noise. The system captures both natural and anthropogenic sources, including vehicle traffic from metros, buses, and personal cars. The DESY site hosts several major research facilities, such as gravitational wave detection experiments, the X-ray Free Electron Laser (XFEL), and PETRA.

Traditionally, witness sensors such as seismometers, geophones, tiltmeters, and several other environmental monitoring sensors have been used around these facilities. However, next-generation large-scale infrastructures—such as third-generation gravitational wave detectors—will span vast areas. For instance, the Einstein Telescope will have arms that each extend 10 kilometers in length. In such scenarios, deploying a sufficient number of spatially discrete, point-based sensors becomes both challenging and cost-prohibitive. A promising solution to these challenges is the use of Distributed Acoustic Sensing (DAS) [Hartog, 2017], which converts standard optical fibers into dense arrays of virtual sensors capable of detecting seismic and environmental disturbances continuously along the fiber path. DAS offers several advantages compared to traditional seismic sensors: it provides high spatial resolution over long distances, reduces infrastructure cost, and can be deployed in already-existing fiber networks.

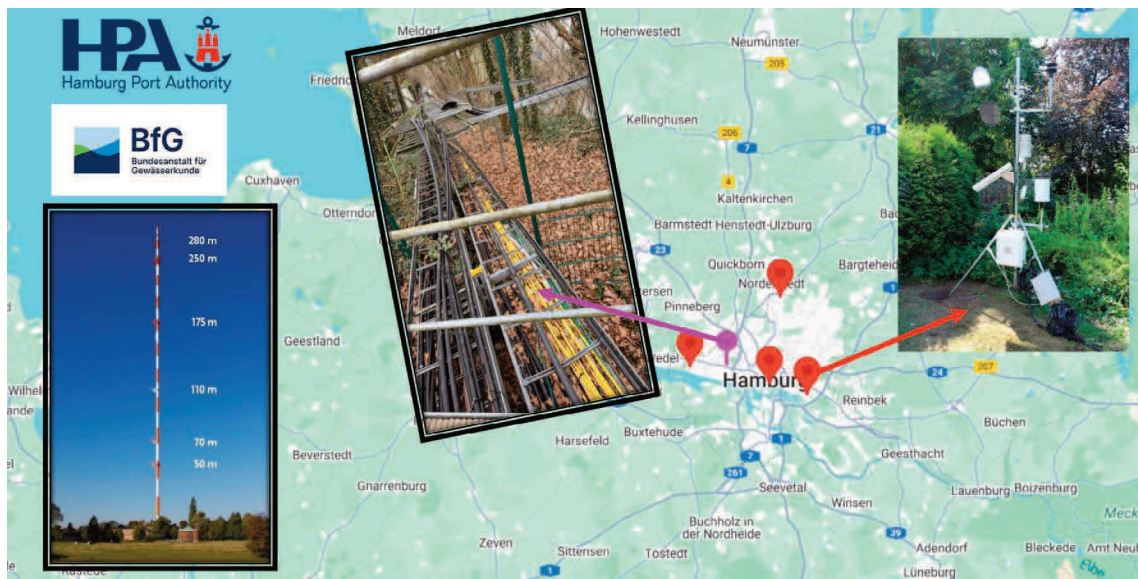


Figure 2 Image showing a section of the DAS fiber installed in an open-air cable track, alongside a map of Hamburg, Germany, highlighting locations where environmental sensors—such as anemometers, thermometers, hygrometers, and barometers—have been installed. Data from the DAS system were compared with these reference sensors to evaluate its capability for detecting and monitoring environmental changes.

At the DESY research campus in Hamburg, in collaboration with the WAVE initiative [1], we have installed and tested a 20-km dark fiber loop that includes sections laid within accelerator tunnels and outdoor environments. Using this DAS system, we continuously monitor a wide range of environmental phenomena including earthquakes, microseisms, thunderstorms, vehicular and other anthropogenic sources. Furthermore, a portion of the fiber is deployed in open-air cable tracks, allowing us to measure environmental parameters such as temperature fluctuations, wind activity, humidity and pressure effects—without dedicated environmental sensors.

This work presents recent findings from the WAVE seismic network, with a focus on the performance of DAS for environmental monitoring. We first evaluate the sensitivity of DAS to seismic signals by comparing its output to that of conventional seismic instruments, including geophones and broadband seismometers. As DAS usually records strain-rate along the optical fiber, we introduce a method to convert its output into ground motion quantities—specifically velocity and acceleration—enabling direct comparison with traditional sensors. We

use the semblance method [Niedell et al., 1971], which estimates local slowness thereby giving accurate strain-rate-to-velocity conversion without the need for external sensor reference data. This method is based on the coherence of seismic wavefronts across DAS channels and ensures the accuracy of conversion.

Secondly, we demonstrate the ability of DAS in detecting environmental changes. DAS responses to atmospheric changes such as temperature and wind were analyzed and compared against standard meteorological sensors, including thermometers and anemometers. The DAS signal exhibited sensitivity to diurnal temperature variations, which showed a strong correlation of 0.8 with measurements from the Hamburg weather station [Deutscher Wetterdienst, 2025]. Similarly, wind-induced vibrations recorded by DAS displayed frequency components similar with those measured by anemometers. Power spectral density (PSD) analyses showed matching features between DAS and wind speed data, confirming DAS's capability to detect wind-related phenomena.

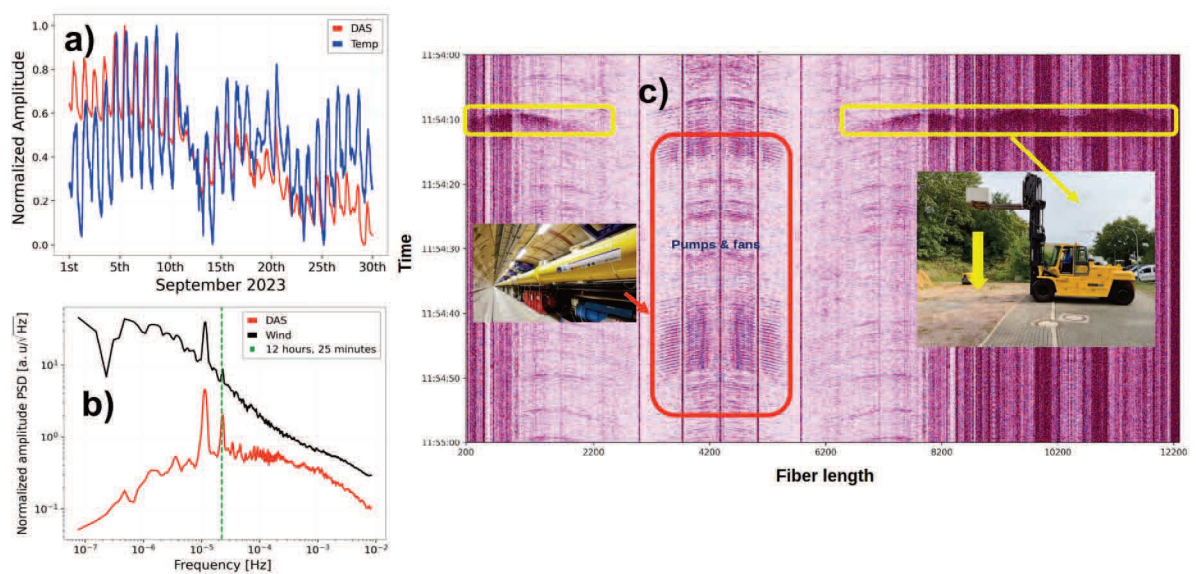


Figure 3 Demonstration of DAS sensitivity to environmental and anthropogenic signals.

- (a) Comparison between DAS output and temperature data from the Hamburg weather station, showing a strong morphological match with a correlation coefficient of 0.8.
- (b) PSD comparison between wind speed data from the weather station and DAS output, revealing matching spectral features that confirm DAS's ability to detect wind-related phenomena.
- (c) Waterfall plot of DAS recordings within the European XFEL tunnel, illustrating narrowband vibrations generated by HVAC systems (pumps and fans), highlighting DAS sensitivity to infrastructure-induced signals. The right panel shows DAS response to controlled stone-drop experiments, further validating its capability to capture localized mechanical events.

Furthermore, beamforming techniques were applied to the DAS array to estimate the angle of arrival of dominant environmental signals. During specific time intervals, these beamformed angles aligned with wind directions obtained from meteorological data, supporting the interpretation that DAS captured wind-induced vibrations. These results proves that DAS can be effectively used not only to detect but also to localize environmental disturbances. Looking forward, we propose leveraging machine learning algorithms to classify and separate overlapping environmental contributions within the DAS signal. Given that DAS is sensitive to a superposition of physical processes—including temperature fluctuations, wind stress, atmospheric pressure changes,

microseismicity, and several other effects—data-driven approaches will be employed to extract distinct spectral and statistical signatures associated with each environmental factor. This will allow for a more understanding of DAS's sensing capabilities and its limitations in environmental monitoring, especially in the low-frequency domain.

Finally, we address the integration of DAS data into noise cancellation frameworks for high-precision experiments. In particular, we consider its role in mitigating Newtonian noise, which arises from local mass-density perturbations and represents a limiting factor in ground-based gravitational wave detectors. We present a case study in which DAS measurements were successfully used to predict and subtract environmental noise from the signal, illustrating the feasibility of using DAS as a cost-effective, densely sampled array for Newtonian noise suppression. These findings supports the potential of DAS as an enabling technology for scalable, high-resolution environmental and seismic monitoring within next-generation scientific infrastructures.

Acknowledgment

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Sitography

- [1] <https://wave-hamburg.eu/>

Integrating Detailed DEMs and Hydroclimatic Data for LSTM-Based Runoff Estimation

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Introduction

Surface runoff is a pivotal hydrological process, directly influencing flood dynamics, agricultural water availability, and sustainable land management. Traditional hydrological models frequently employ simplified terrain representations, which often prove insufficient in capturing the complex spatial variability of runoff, especially in heterogeneous landscapes. Recent advancements in deep learning, particularly Long Short-Term Memory (LSTM) networks, present a robust opportunity to enhance runoff modeling. By integrating high-resolution topographic data with hydroclimatic variables, LSTMs can significantly improve spatio-temporal accuracy. This study aims to develop a novel runoff estimation framework utilizing LSTM models to predict daily runoff values, spatially discretized for Poland's counties (powiaty). The proposed model integrates key hydroclimatic variables—precipitation and evapotranspiration—with detailed Digital Elevation Models (DEMs) to comprehensively capture the influence of topography on runoff generation and routing. Our central hypothesis is that incorporating detailed terrain variables into LSTM-based runoff models will significantly improve predictive accuracy and enhance generalizability across regions with diverse physiographic conditions.

Methods

Hydroclimatic data for this study were acquired through the Hydroclimate Pipeline GitHub repository [1], a custom R-based pipeline designed for scalable data generation and reproducibility. This pipeline automates the downloading, preprocessing, and generation of daily precipitation and evapotranspiration raster datasets for all Polish counties (powiaty), ensuring 100% geographical coverage. Daily evapotranspiration and precipitation data, alongside observed runoff data, were processed to a consistent 30-meter spatial resolution in GeoTIFF format. Evapotranspiration was processed via temporal aggregation, while precipitation and runoff were spatially interpolated using Ordinary Kriging to achieve the target resolution. Data sources included EUMETSAT [2025] for satellite products, synoptic stations from IMGW-PIB Poland [Czernecki et al., 2020; IMGW-PIB, 2025] for ground observations, and ECMWF ERA5-LAND [ECMWF, 2025] datasets accessed via Google Earth Engine.

Detailed DEMs with 30-meter spatial resolution were obtained from the Polish Head Office of Geodesy and Cartography [GUGiK, 2025]. Data preprocessing further involved normalization of all hydroclimatic variables and the extraction of crucial topographic features from the DEMs. These features included slope, aspect, curvature, flow accumulation, and the Topographic Wetness Index (TWI), calculated using Python's rasterio and richdem libraries. The extracted features were then structured into temporal sequences, with a fixed sequence length of 30 days to capture essential monthly hydrological memory for each powiat. These structured feature matrices served as inputs for the LSTM model, implemented using the TensorFlow/Keras framework.

Model Architecture

The proposed LSTM model architecture is structured as follows:

- The model employs a multi-input architecture where dynamic hydroclimatic sequences and static DEM-derived features are processed separately and concatenated prior to the output layer.
- Two stacked LSTM layers, comprising 64 and 32 units respectively, utilizing the ReLU activation function.
- Dropout layers (with a rate of 0.2) applied for regularization, mitigating overfitting.
- A final dense output layer, providing daily runoff estimates for each individual powiat. Model hyperparameters were optimized using a Bayesian search approach, with the objective of minimizing the Mean Squared Error (MSE) between predicted and observed runoff values. The 'observed' runoff for model evaluation was derived from available hydrological stations located within representative catchments, and then spatially extrapolated to non-gauged powiaty using a Thiessen polygon approach.

Results

The integration of detailed topographic features into the LSTM model resulted in a significant and demonstrable improvement in runoff prediction accuracy when compared to baseline models utilizing only precipitation and evapotranspiration. Specifically:

- The average Root Mean Square Error (RMSE) for daily runoff predictions decreased by 18–25% across the validation powiaty.
- The Nash-Sutcliffe Efficiency (NSE) increased substantially, indicating a strong predictive performance and good model fit (Figure 1).

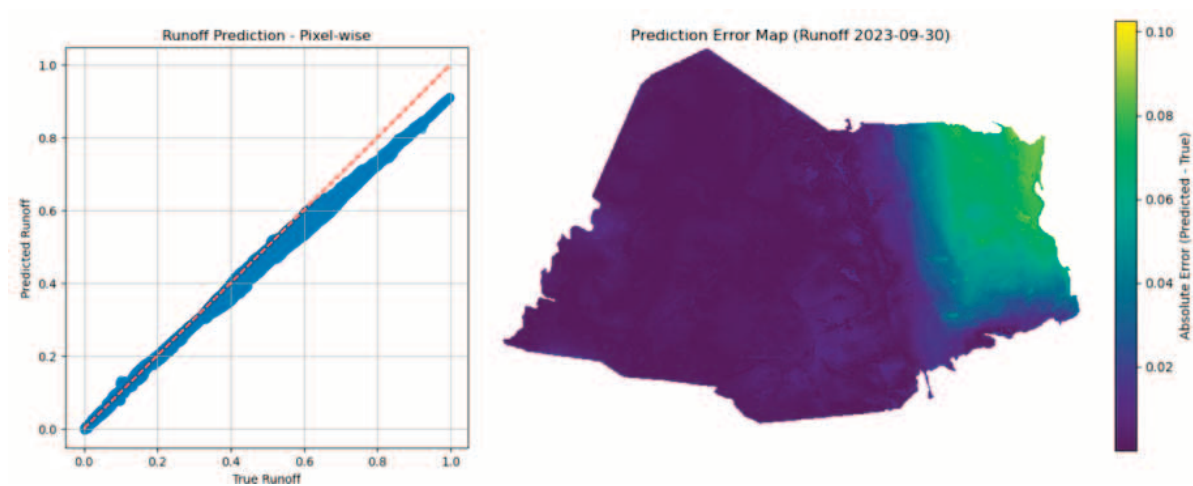


Figure 1 Spatial and Statistical Evaluation of Model Predictions: Scatterplot and Prediction Error Map.

Figure 1 presents two key spatial diagnostics: the left panel displays a pixel-wise scatterplot indicating strong correspondence between predicted and observed values, confirming the model's predictive robustness; the right panel shows the spatial distribution of prediction error, where areas with pronounced terrain variability, particularly in the southern mountainous powiaty of Poland, demonstrate marked improvements in accuracy. These patterns validate our hypothesis that incorporating detailed topographic features enhances model generalization across heterogeneous landscapes, with prediction hotspots aligning with historically flood-prone zones in the Silesian and Lesser Poland voivodeships.

Discussion

This study conclusively demonstrates the feasibility and significant advantages of integrating detailed DEM-derived topographic features and hydroclimatic data, as evapotranspiration, precipitation and runoff, with LSTM networks for daily runoff prediction at the administrative unit (powiat) scale. It critically underscores the importance of incorporating these detailed terrain variables, which are frequently oversimplified or overlooked in conventional large-scale runoff estimation approaches, into modern data-driven hydrological modeling frameworks. The successful application of the Hydroclimate Pipeline GitHub repository proved invaluable, providing a robust, reproducible, and scalable solution for preprocessing hydroclimatic data across all Polish powiaty, thereby enabling rapid model deployment and efficient retraining with updated inputs as required.

Further improvements will explore the inclusion of additional static features crucial for hydrological processes, such as soil infiltration capacity, detailed land use infiltration coefficients, and geological characteristics. Moreover, the implementation of advanced Graph Neural Networks (GNNs) is envisioned to more effectively model the complex spatial dependencies and interactions between neighboring powiaty, potentially leading to even more accurate and spatially coherent runoff predictions.

Conclusion

The developed LSTM-based runoff estimation framework represents a novel and highly terrain-sensitive tool for advancing hydrological forecasting, robust flood risk assessment, and sustainable water resource management practices across Poland. By effectively leveraging detailed Digital Elevation Models in conjunction with comprehensive hydroclimatic data within a sophisticated deep learning architecture, and critically, by automating input preparation through the Hydroclimate Pipeline, this methodology successfully bridges the gap between raw data availability and actionable hydrological intelligence. The framework's modular design and reliance on widely available geospatial and administrative data structures ensure its ready transferability and applicability to other regions facing similar hydrological challenges.

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- [1] <https://github.com/ynramirezy/hydroclimate-pipeline>

Application of Near-Surface Seismic Imaging for Embankment Characterization in Poland

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Introduction

Climate change in the Northern Hemisphere has intensified flood risks due to altered precipitation patterns, extreme weather, and hydrological variability. This puts critical infrastructure like dams and embankments at risk. Damage to embankments may also result from aging, foundation failure, seepage, and internal erosion. Stability assessments and seismic evaluations are crucial to mitigate these risks. Recent studies show the value of three-component (3C) geophones and Distributed Acoustic Sensing (DAS) in near-surface seismic imaging. DAS offers high spatial resolution and continuous monitoring. Roshdy et al., [2025] and Brodic et al., [2023] demonstrate DAS's ability to capture full wave energy effectively. This study investigates seismic methods at the Orzepowice embankment, Poland, utilizing 3C geophones and DAS along the same profile. An active seismic survey in October 2023 employed 3C 4.5Hz geophones and DAS installations with an industrial S-wave source. Stations were spaced every 4 m, and shooting occurred every 2 m (Figure 1). Traditional geophones may lack resolution for detailed analysis, whereas DAS captures dynamic strain along optical fibers, enhancing spatial sampling [Li et al., 2023]. The combined use of P- and S-wave velocities supports assessment of elastic properties and seismic stability.

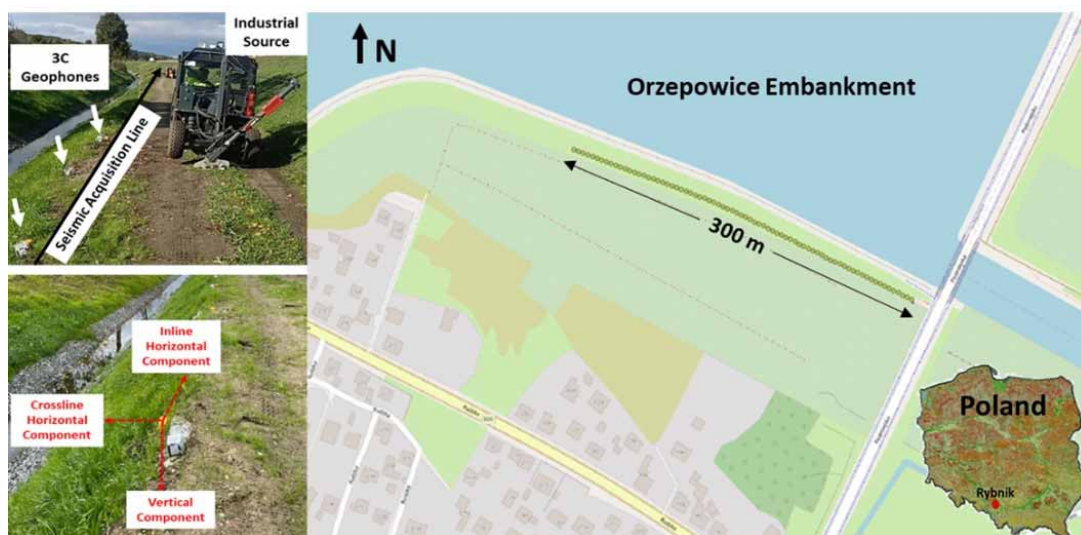


Figure 1 The location map of the study area. Industrial s-wave source and 3c geophone were used.

Data Analysis

3C geophones provide a more comprehensive capture of the seismic wavefield than single-component systems. They enable differentiation between compressional (P) waves and shear (S) waves. P-waves are the fastest, travel through both solids and fluids, and have high signal-

to-noise ratios. S-waves, on the other hand, travel only through solids and are slower, but offer crucial insights into subsurface anisotropy and lithological variations [Marciniak et al., 2024]. DAS technology, which uses standard fiber-optic cables to record seismic data, offers numerous advantages. It is cost-effective, environmentally robust, and highly adaptable—allowing adjustable parameters like gauge length to suit both shallow and deep surveys. DAS operates through Rayleigh backscattering, where local fiber deformation alters the phase of backscattered laser light, which is then interpreted to measure strain [Caudron et al., 2024].

Figure 2 highlights DAS's advantages, including its higher signal-to-noise ratio and enhanced sensitivity to low-frequency signals. Although geophones perform slightly better in the 20–60 Hz range, DAS is superior in capturing low-frequency content. These strengths make DAS a powerful tool for high-resolution subsurface modeling and advanced seismic monitoring.

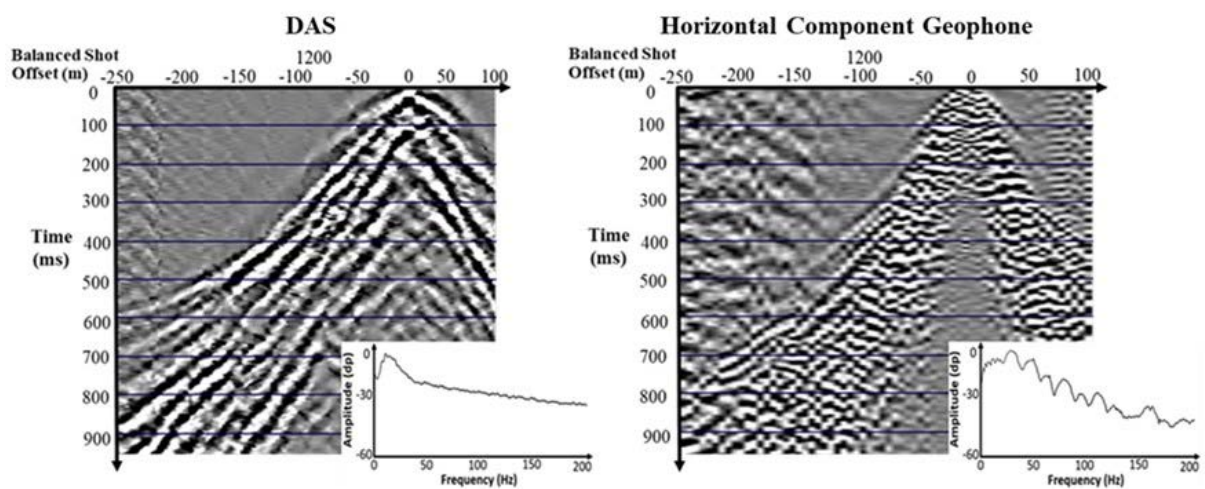


Figure 3 Shot gather comparison: DAS vs. horizontal geophone component using industrial S-wave source.

The seismic data processing began with pre-processing tasks: SEG-Y formatting, bad trace removal, and phase correction. Spherical divergence correction compensated for energy loss due to geometrical spreading, absorption, and transmission effects. Refraction statics compensates for the travel time variations caused by the weathering layer, and residual statics removes the remaining travel time variations [Yilmaz et al., 2001].

During a seismic survey, recorded traces contain both desired signals and unwanted noise. Noise is categorized as either coherent (consistent across traces) or random (inconsistent between traces). Denoising becomes challenging when signal and noise overlap in time, frequency, or velocity domains, making the choice of suppression method and domain crucial. The noise attenuation process began with a low-cut filter (4–6 Hz) to eliminate low-frequency noise. An FK (frequency-wavenumber) filter was then applied by transforming the data into the frequency domain, muting unwanted linear noise, and converting it back to the time domain using an inverse Fourier transform [Roshdy et al., 2022].

Velocity analysis is essential for identifying rock types, correcting amplitudes, migration, and depth conversion. Its main goal is to determine the velocity that flattens reflection hyperbolas for optimal stacking results. Deconvolution enhances vertical resolution by sharpening the seismic wavelet. Migration improves horizontal resolution by repositioning reflections to their true spatial and temporal locations [Onajite et al., 2014].

Figure 3 shows the comparison of the initial image and final image for seismic data processing for three components of geophones.

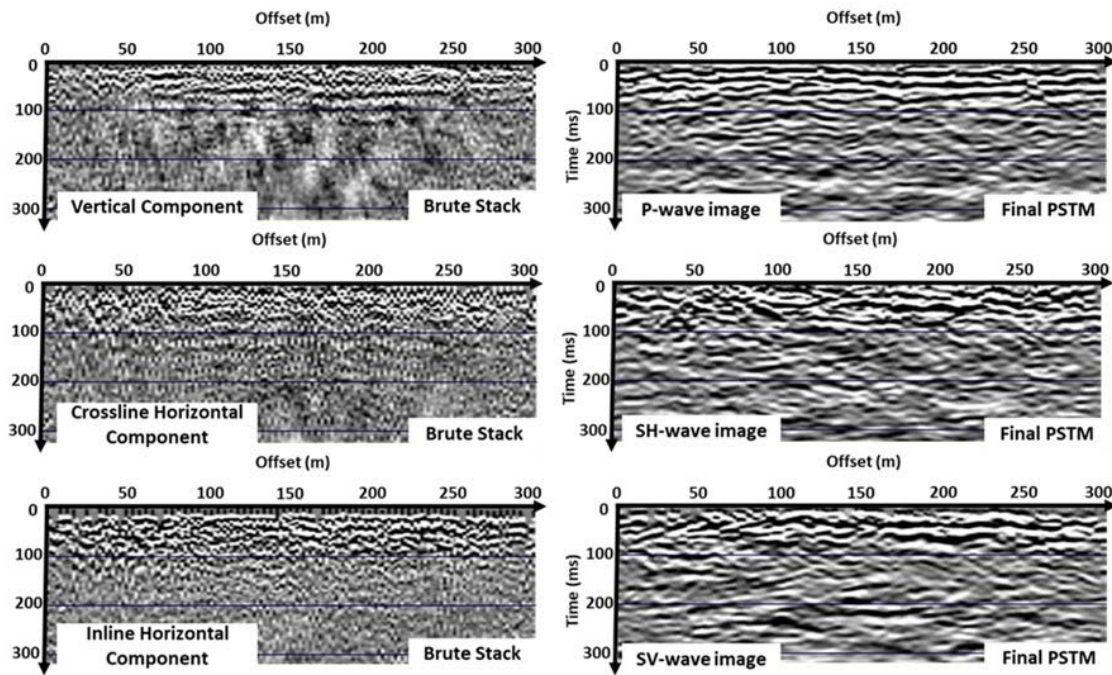


Figure 3 Comparison between brute stack and final PSTM for each component of the geophone.

Conclusion

Three-component (3C) active seismic data demonstrate that compressional (P) waves are most distinctly recorded in the vertical geophone component, while shear (S) waves are strongly observed in the horizontal components (inline and crossline). This separation enables a clearer interpretation of different wave modes. For improved S-wave imaging, tau-p filtering has proven to significantly enhance data quality by isolating coherent wavefields and reducing noise interference. The integration of both P- and S-wave images enables advanced seismic attribute inversion, offering detailed insights into subsurface properties such as fluid content, pore pressure, stress orientation, lithological changes, and fracture networks. Distributed Acoustic Sensing (DAS) technology transforms a standard fiber optic cable into a dense array of sensors, replacing thousands of conventional geophones. This allows for continuous, high-resolution measurements along the entire fiber length. Compared to traditional 3C seismic, DAS provides superior S-wave resolution and a broader frequency response, especially in lower frequencies, which are critical for advanced imaging techniques such as Full Waveform Inversion. In June 2024, we plan to reprocess seismic data along the same line to perform time-lapse (4D) monitoring and identify changes in the subsurface over time. By combining 3C active seismic with DAS, we aim to enhance our ability to detect localized damage (e.g., cracks), monitor stress evolution, and assess the overall deformation state of the Orzepowice embankment with greater spatial detail and accuracy.

Acknowledgment

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Near-fault Ground Motion Prediction for a Shallow Earthquake in Southeast France

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An Extremely Shallow Earthquake in Southeastern France

Southeastern France is one of the regions with the highest seismic hazard in metropolitan France [Drouet et al., 2020]. In 2019, a very shallow earthquake (Mw 4.9) struck the town of Le Teil [Cornou et al., 2021], broke the surface [Ritz et al., 2020], and produced an estimated maximum intensity of VIII despite its moderate magnitude [Causse et al., 2021]. Moreover, the quake occurred in a moderate seismic hazard area within a stable continental region, with two nuclear power plants (NPPs) located less than 15 km from the epicenter (Figure 1), raising serious concerns about seismic risk management in this area. The economic losses from this event were estimated at €260 million [France Assureurs, 2019]. Some collapsed houses and displaced grave slabs are shown in Figure 1, evidencing the strong ground shaking caused by the mainshock. The amplitude of near-fault ground motions (NFGM), however, remains unknown due to the lack of near-fault strong-motion records—a problem that is also common worldwide, especially for shallow and moderate events. Therefore, the commonly used ground motion models (GMMs) are not well calibrated, and large uncertainty exists in the near-fault area. The bottom-right panel of Figure 1 shows the amplitude of available records and GMM predictions for the Le Teil earthquake as a function of distance. Our simulation target area is indicated with a blue square in the same plot.

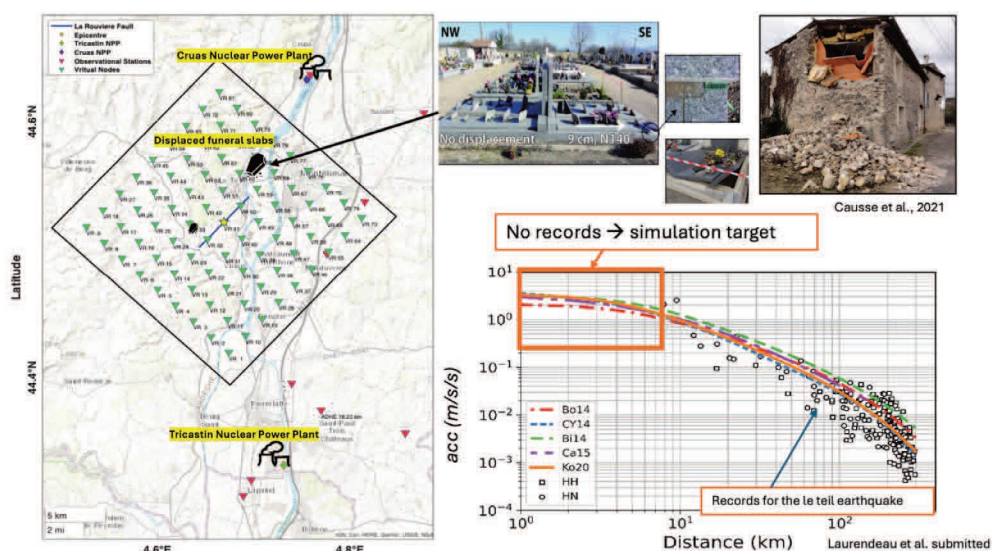


Figure 1 The left panel shows a map of the epicentral area: two nuclear power plants (NPPs) are marked, red triangles indicate observational seismic stations, green triangles represent virtual receivers, the black square outlines the computational mesh boundary, the yellow star marks the epicenter, and the blue line traces the fault. The coffin symbol marks a cemetery where Causse et al. (2021) documented the displacement of funeral slabs immediately after the mainshock. The top-right panel displays photos of a collapsed building and displaced grave slabs. The bottom-right panel presents the amplitude of ground acceleration from available records and ground motion models (GMMs) for the Le Teil earthquake, plotted as a function of distance.

Method and Resources

In nature, stress accumulation and release cause faults to rupture. However, routinely computed data-driven kinematic rupture models are designed to match observations (teleseismic, geodetic) but are not necessarily consistent with the underlying stress conditions. We propose a state-of-the-art physics-based simulation method to assess NFGM. Our proposed physics-based simulation method aims to achieve consistency with the data-driven kinematic model as well as ensuring physical consistency.

We start with a seismologically inferred kinematic rupture model [Godano et al., submitted] and then perform a series of physics-based dynamic rupture simulations. The open-source code SeisSol [Heinecke et al., 2014] is used for dynamic rupture modeling, and the freely available software Gmsh is employed to build the computational mesh. For the computations, we utilize the French high-performance computing (HPC) infrastructure at CCRT (Centre de Calcul Recherche et Technologie du CEA).

First Results and Perspectives

In the bottom right panel of Figure 2, we show a comparison between the original kinematic slip rate history and the dynamic slip rate history (obtained by imposing the kinematic slip rate) on the fault plane. The ‘kinematic-inspired’ dynamic model not only provides higher resolution in space and time but also computes the traction changes associated with fault slip evolution. This ‘kinematic-inspired’ dynamic model is an intermediate step, as no friction law is defined yet. Later, we link the traction changes from this intermediate dynamic model to a widely used linear slip weakening (LSW) friction law [Ida, 1972; Palmer & Rice, 1973; Andrews, 1976] to simulate dynamic rupture and ground motion. As shown in the same Figure, variability in parametrization plays a critical role in modelling NFGM, highlighting the challenges of validation.

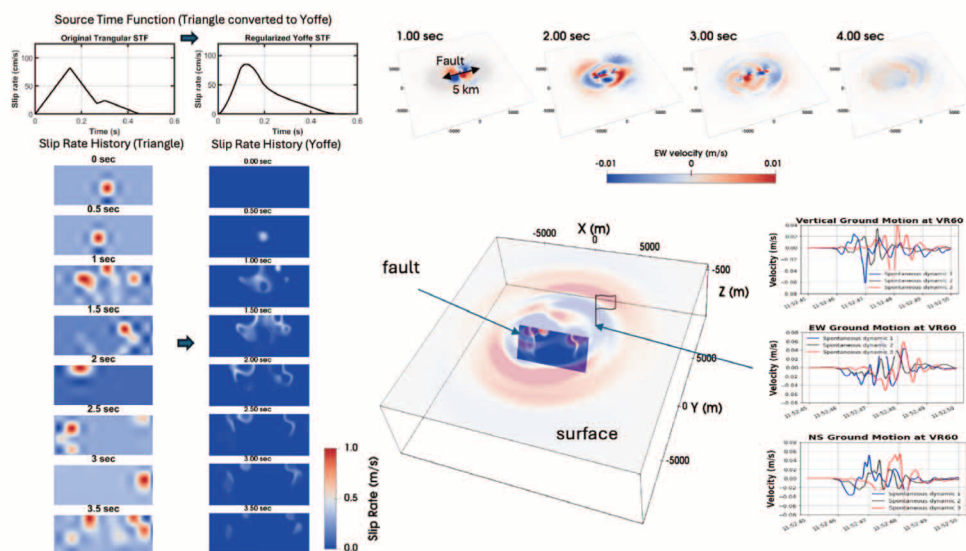


Figure 2 The top right panel presents an example of converting the original kinematic source time function—composed of three overlapping isosceles triangles — into a dynamically compatible regularized Yoffe function, as defined by Tinti et al., (2005). The bottom right panel compares the slip rate histories from the original kinematic model and the newly derived ‘kinematic-inspired’ dynamic model. In the center panel, a snapshot dynamic fault rupture coupled with seismic wave propagation on the surface; the white flag marks the location of a site of interest (one of the cemeteries), where three-component waveforms (velocity) from three different scenarios (different in fracture energy) are displayed in the bottom right panel. The top right panel also includes a sequence of snapshots showing wave propagation at the surface from 1 to 4 seconds; the spatial scale of the fault is indicated in the 1 second frame.

In future work, we propose a novel validation approach using in-situ observations of displaced grave slabs and damaged buildings by the earthquake. These observations provide quantitative measurements of ground acceleration near the fault [Causse et al., 2021]. We envision that this approach will also contribute to the broader validation of NFGM models used in seismic hazard assessments [Valentová et al., 2021].

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Unveiling aseismic fault behavior in an active rift zone using integrated InSAR and GNSS monitoring

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The western Gulf of Corinth (GoC), an actively extending continental rift in central Greece, is an excellent site for investigating crustal deformation and seismotectonic behavior. A key structural element within this rift is the Psathopyrgos fault—an onshore, north-dipping normal fault located near the densely populated city of Patras [Elias & Briole, 2018]. Despite the lack of historically significant surface-rupturing earthquakes over the past four centuries, geophysical observations indicate ongoing deformation and the potential for seismic hazard. This study integrates Sentinel-1 InSAR time-series analysis with continuous Global Navigation Satellite System (GNSS) velocity data from 2016 to 2022 to characterize fault kinematics and assess both interseismic strain accumulation and co-seismic responses. A focal point of the analysis is the subtle deformation signal associated with the Mw 5.3 earthquake of 17 February 2021, which was not clearly visible in conventional co-seismic interferograms [Serpetsidaki et al., 2023; Zahradník et al., 2022].

A time-series approach using the LiCSBAS open-source processing pipeline was employed to analyze Sentinel-1 InSAR data from both ascending and descending orbits [Morishita et al., 2020]. The Network-based Small Baseline Subset (N-SBAS) technique was applied to generate displacement rates in the satellite Line of Sight (LOS). These LOS velocities were subsequently transformed into the Eurasia-fixed reference frame using data from nine permanent GNSS stations within the broader GoC region. Cross-sectional velocity profiles were extracted perpendicular to the fault trace, and linear regression models were used to analyze temporal displacement patterns and isolate co-seismic offsets. To discern long-term trends, the displacement time-series were corrected for the 2021 co-seismic signal, allowing us to isolate interseismic behavior and investigate the potential for shallow creep.

The analysis reveals consistent vertical and horizontal displacement patterns indicative of active faulting. LOS velocity maps exhibit differential motion between the footwall and hanging wall blocks, with maximum displacements approaching ± 7 mm/yr. Decomposition into vertical and east-west components further highlights uplift of the footwall and subsidence of the hanging wall, suggesting tectonically driven deformation. A critical finding is the identification of an approximately 9–10 mm co-seismic displacement offset across the hanging wall following the February 2021 earthquake—detected solely through time-series analysis. This deformation is not apparent in single interferograms, emphasizing the necessity of time-series methods for capturing low-amplitude, distributed fault slip. Even after accounting for the co-seismic signal, a persistent velocity gradient across the fault trace remains, with vertical motion offsets reaching up to 4.5 mm/yr. These observations support the hypothesis of shallow fault creep or aseismic slip on upper fault segments, potentially linked to regional detachment surfaces or fluid migration along fault zones [Duverger et al., 2018].

The Psathopyrgos fault appears to exhibit dual behavior—experiencing both transient co-seismic deformation and continuous aseismic slip. The observed shallow creep may serve as a mechanism for strain accommodation in the absence of frequent large earthquakes, complicating traditional hazard assessments based solely on seismic catalogs. The presence of such aseismic behavior also raises questions about fault coupling at depth and the partitioning of strain between elastic and inelastic mechanisms. Velocity cross-sections strongly support the existence of a creeping fault segment, with velocity discontinuities. The findings align with regional models suggesting a complex fault system that includes low-angle detachment components [Duverger et al., 2018].

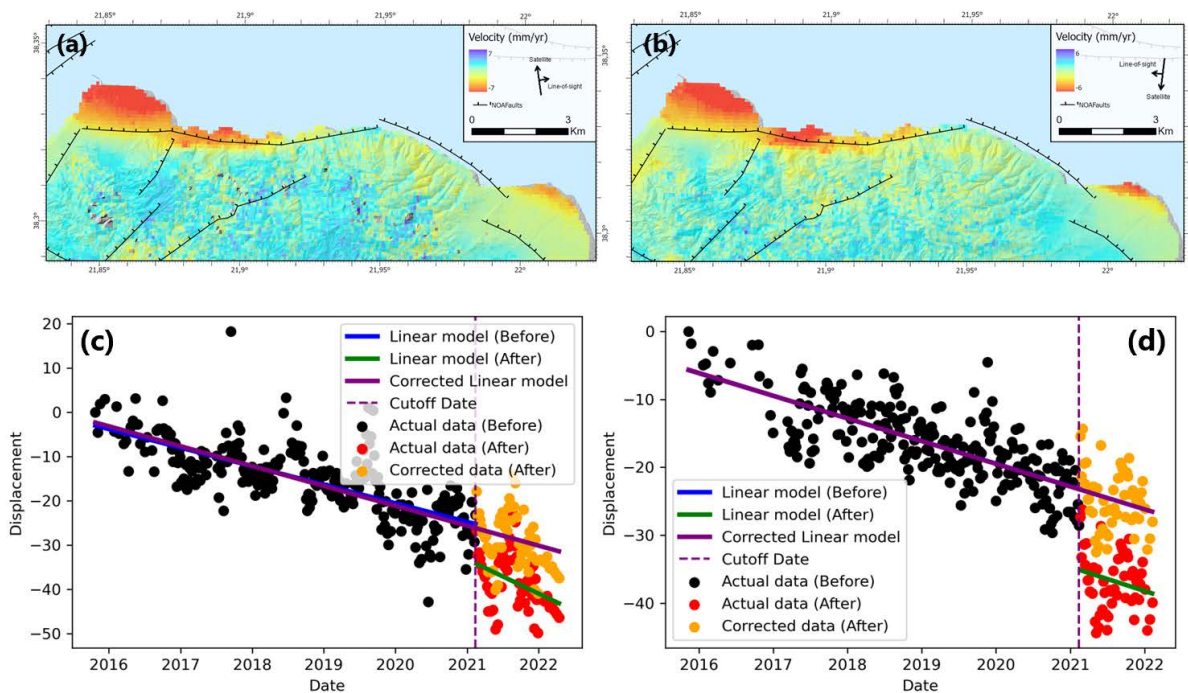


Figure 1 Displacement-rate (mm/yr) maps in LOS (Line of Sight) direction for broader area of Psathopyrgos for S1 ascending (a) and descending (b) track. Pixel size on this map is 100 m. Line with teeth indicates trace of the Psathopyrgos normal fault (north-dipping). (c & d) Graphs that represent the average time-series of the pixels that are located on the western part of the hanging wall of the Psathopyrgos fault. The blue line represents the fit of the linear regression for the time period before the earthquake. The purple line represents the new best fit of the linear model that combines the actual positions before the earthquake (black dots) with the corrected positions after the subtraction of the offset (orange dots). The (c) graph represents the time-series of ascending track, and the (d) graph represents the time-series of descending track.

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Exploring the Capabilities of High-Rate GNSS in Volcanic Scenarios

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Global Navigation Satellite Systems (GNSS) is a relevant technology for deformation monitoring as it offers continuous, high-precision measurements of displacements, providing multiple advantages, in some cases over traditional seismic monitoring approaches, as has been documented for earthquake monitoring. While seismic instruments offer greater sensitivity than high-rate GNSS, their recordings are more susceptible to distortion from sensor clipping and tilting, which can compromise the waveforms when integrated [Xu et al., 2016]. The integration of the GNSS technique with seismic observations also enables the increase of the density of instrument deployment, thus enhancing monitoring network capabilities. However, the exploration of GNSS for seismogeodetic purposes is challenging as the nature of GNSS involves significant noise levels.

In volcanic scenarios, high-rate GNSS data allows to detect rapid volcanic processes and transient phenomena occurring on timescales of seconds to minutes [Puglisi et al., 2005]. These high-frequency observations enable the investigation of dynamic and structural volcanic behavior, particularly processes within shallow plumbing systems that control eruptive activity. Integrating geodetic and seismic observations provides complementary information, where GNSS captures permanent displacement and long-period deformation while seismic instruments record high-frequency oscillatory motion.

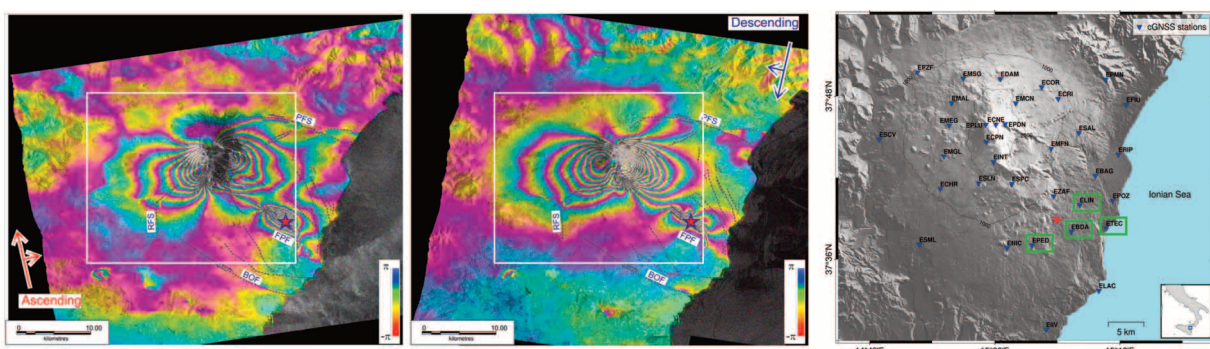


Figure 1 (Left) Ascending and descending interferograms from 22 to 28 December 2018 showing ground displacement related to a dyke intrusion and the 26 December 2018 earthquake, indicated by the red star [Bonforte et al., 2019]. (Right) GNSS network deployed on Etna volcano. The red star marks the 26 December 2018 earthquake. Highlighted stations are shown in Figure 3.

One of the cases to explore the capability of high-rate GNSS for volcanic applications is a major dyke intrusion that occurred on Christmas Eve 2018 at Mount Etna, followed by a Mw 4.9 earthquake two days later on the volcano's eastern flank [Bonforte et al., 2019]. These events caused a significant deformation along the volcano edifice, as observable also through satellite geodetic tools such as Interferometric Synthetic Aperture Radar (InSAR; Figure 1). Processing of 1 Hz GNSS data successfully captured the deformation sequence related with the dyke intrusion recording displacements up to 40 cm in the East GNSS component (Figure 2). Furthermore, as shown in Figure 3, 1 Hz GNSS detected earthquake-related displacements and reveals station sensitivity based on their location relative to the earthquake epicenter.

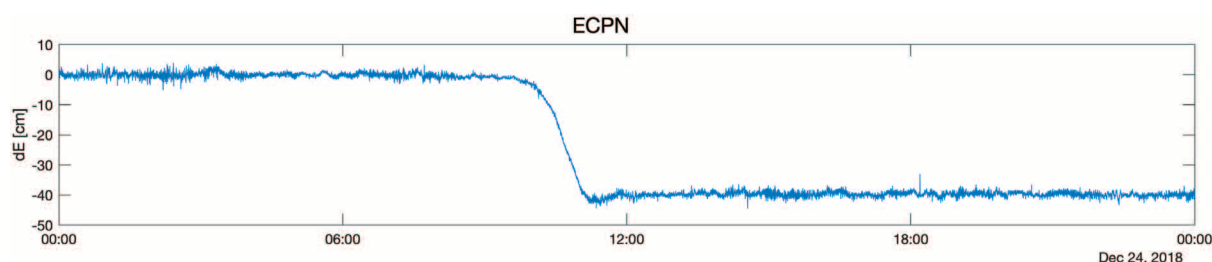


Figure 2 Time series of the East component of GNSS station ECPN, located at the summit of Etna volcano, on 24 December 2018.

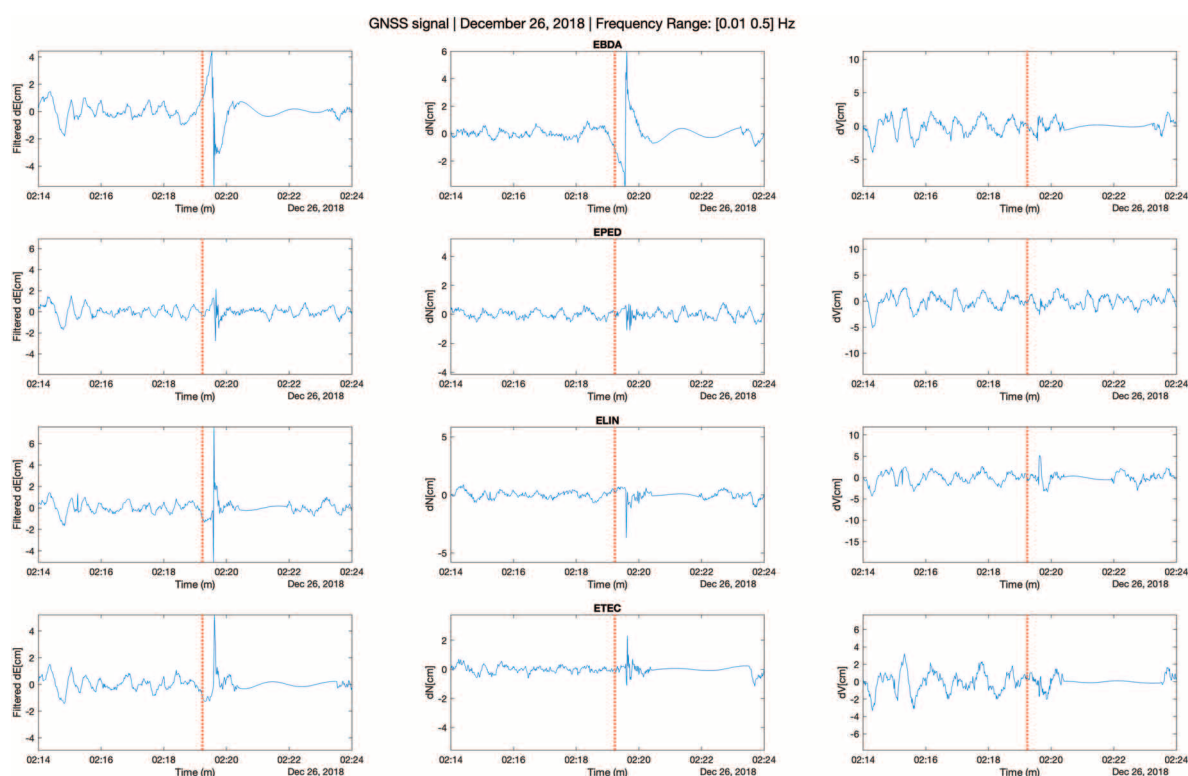


Figure 3 GNSS signals from the stations highlighted in Figure 1, showing the East (left), North (centre), and Vertical (right) components. The red line indicates the occurrence of the 26 December 2018 earthquake.

We also analysed high-rate GNSS data sampled at 50 Hz from three stations deployed around Mt. Etna between July 23 and August 2, 2023. This period was characterized by continuous degassing activity from the summit area, together with the occurrence of two earthquakes (ML 2.5 and ML 3.1) on July 24 at 02:55 and 03:01 UTC, respectively, in the lower Valle del Bove on

Etna's eastern flank at depths of 2–3 km below sea level. Here we report the exploration of using high rate GNSS data to retrieve deformation signals associated with both seismic events and degassing events, characteristic volcanic signatures of Mount Etna. This analysis explores both the Precise Point Positioning (PPP) technique, introduced by Zumberge et al. (1997), and the variometric approach to exploit ultra-high-frequency geodetic observations. While PPP focuses on positioning, the variometric method [Colosimo et al., 2011], estimates displacements by means of velocity integration.

This research systematically investigates the capabilities and limitations of high-rate GNSS for volcanic monitoring and provides a comparison between different processing approaches.

Acknowledgments

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An Extended Italian Dataset for the analysis of the Ground Motion-to-Intensity Conversion Equations (GMICEs)

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We use the latest accelerometric data from the Italian Accelerometric Archive (ITACA) dataset, together with the macroseismic data available from the Database of Italian Macroseismic Data (DBMI15), to obtain a new pairing dataset of ground motion parameters and macroseismic intensities. A set of prior/existing reversible relationships [Gomez-Capera et al., 2020-G20; Oliveti et al., 2022-O22; Zanini et al., 2019-Z19] for the peak ground acceleration (PGA) and peak ground velocity (PGV) are selected for testing/validation analysis. This research assembled 584 pairs of ground-motion records with macroseismic observations corresponding to 97 earthquakes, where the interdistance between recording stations and macroseismic localities is lower than 3 km. The earthquakes in the dataset range in moment magnitude (M_w) from 3.5 to 7.0, corresponding to the macroseismic intensity of III-XI in the European Macroseismic (EMS-98) or the Mercalli-Cancani-Sieberg (MCS) scales. Our analysis focused on the residuals for the intensity and M_w , show for $M_w < 5.0$ events, residuals are compact, but they become more dispersed for $M_w > 5.0$. The O22 model aligns with G20 for PGA and Z19 for PGV. Discrepancies are significant for intensities $> VI$ and $M_w > 5.0$. The dataset/pairing analysis can be used to improve ground motion-to-intensity relationships, to be considered in earthquake engineering applications, improving the accuracy and reliability of seismic assessments.

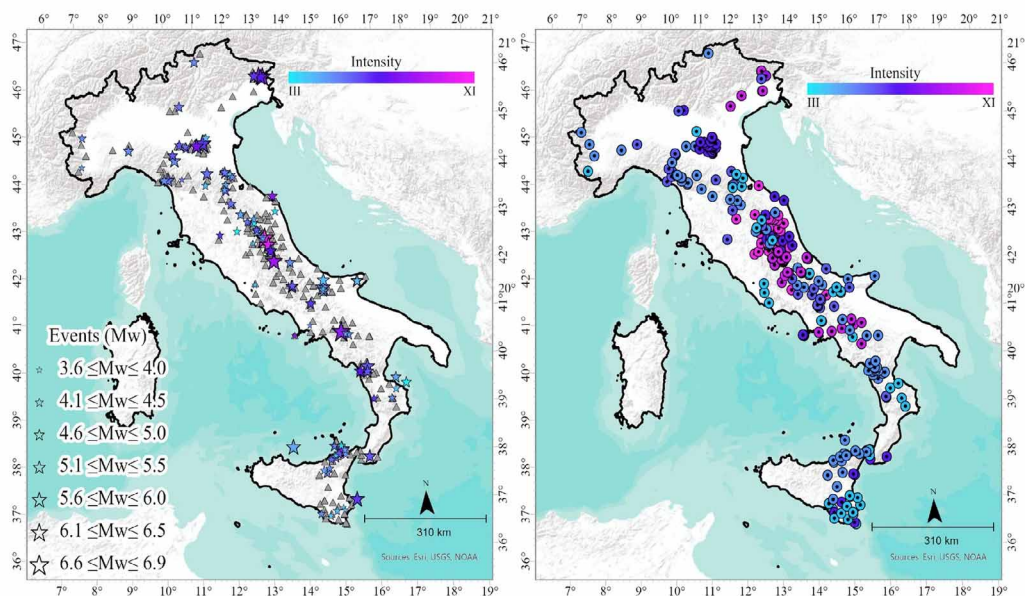


Figure 1 (a) Spatial distribution of recorded events (circles) from acceleration stations in ITACAext (grey triangles) across Italy, used for compiling ground motion parameters and macroseismic intensity. The size of the circles represents the M_w , while the color indicates intensity levels. (b) Spatial distribution of DBMI15 localities (circles) in Italy, used to compile pairs of ground motion parameters and macroseismic intensity. The color of the circles reflects the intensity (I_{maxNum}). The basemap is provided by ESRI and was created using ArcGIS Pro (Esri n.d). For further details, please refer to the text and relevant references.

Datasets

The dataset used in this work are the most recently updated ones in Italy. For our analysis we adopted/used the ITACAext [Lanzano et al., 2024], which is a parametric table of intensity measures and the associated metadata for accessing strong-motion recordings, accelerometric stations information, and the related list of earthquakes for the time span 1972-2022. The macroseismic datasets is the associated DBMI15 [Locati et al., 2019], which makes available intensity data related to earthquakes in the Italian Parametric Catalogue-CPTI15 [Rovida et al., 2020]. The intensity data are expressed in the MCS [Sieberg, A., 1930] or the EMS-98 [Grunthal, 1998] macroseismic scale. Figure 1a and Figure 1b shows the distribution of the DBMI15 and ITACA dataset, respectively.

Methodology

The procedure followed on similar previous studies [Gomez-Capera et al., 2020; Oliveti et al., 2022; Zanini et al., 2019], with the stations having at least one locality within 3 km, taking into account those localities in DBMI15 is adopted. The linking between the coordinates of the localities and of the stations was manually performed in a geographic information system (GIS). The associated dataset resulted in 584 pairs of site PGM-Intensity from 97 Italian earthquakes in the time-window 1976–2022. The pairs correspond to events with M_w from 3.5–6.9 (for magnitude conversation and priorities to M_w , we follow Rovida et al., 2020) and depths of 0 – 35 km. The macroseismicity intensities range between III–XI. Following the recommendation by Musson et al. (2009), the intensities reported as MCS or EMS-98 are both used without conversions.

Results

The paired dataset was assessed by comparing it with recent prior works (G20, O22 and Z19), which were developed using different macroseismic scales and processing criteria. Our analysis focused on residual analysis for PGA and PGV as a function predicted intensity and earthquake magnitude are shown in Figures 2.

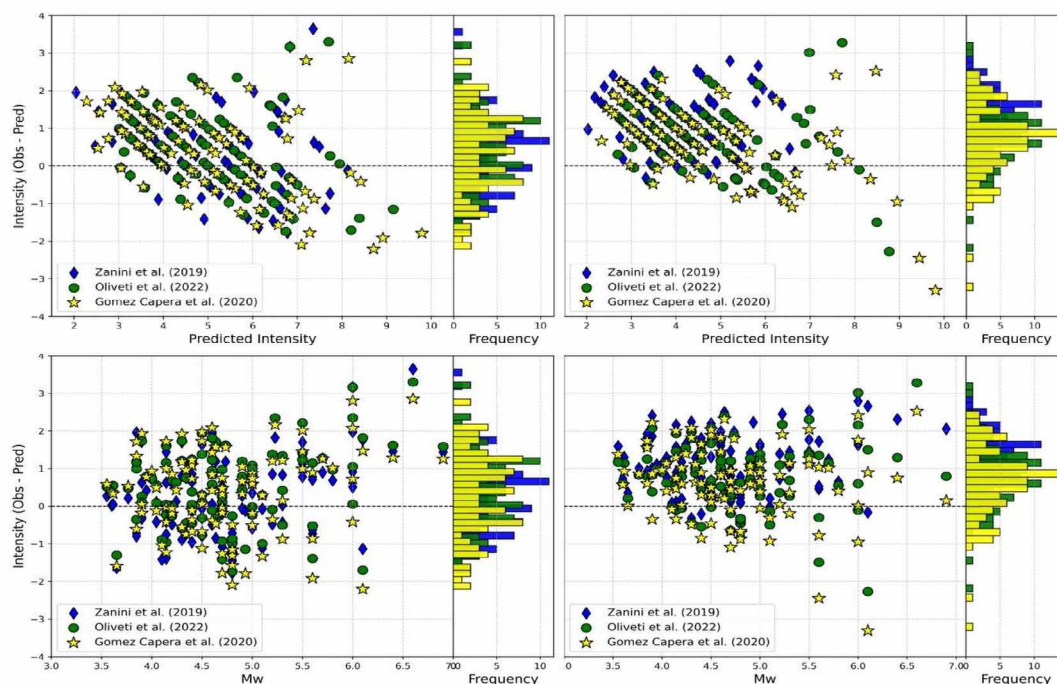


Figure 2 Residuals (observed minus predicted intensity) for intensity predicted from (a) PGA, and (b) PGV. Residuals (observed minus predicted intensity) for M_w from (c) PGA, and (d) PGV. Data represent the selected relationships as listed in the legend (color-coded markers). The subplots (histograms) show the trend of the observations with respect to predicted intensities; color corresponds to the selected relationships.

The positive residual values for the predicted intensities of PGA (Figure 2a) and PGV (Figure 2b) indicate that the models underpredicted the observed intensities, as reflected in the data distribution shown in the histogram subplots. Conversely, negative residual values reveal that the models overpredicted the observed intensities. For PGA (Figure 2a), the residuals are almost evenly distributed within the intensity range of -2 to +2. In contrast, PGV (Figure 2b) exhibits a different pattern, with most residuals concentrated within the intensity range of 0 to +3. This behavior is clearly illustrated in the histogram subplots, where the majority of the data points for all models are greater than zero. The model by Gómez-Capera et al. (2020) (yellow stars) shows better performance compared to other models for both PGA and PGV, as it shows lower levels of underpredicted intensities. The residuals concerning earthquake magnitude (M_w) were analyzed similarly, revealing a consistent trend. Positive residual values for M_w from PGA (Figure 2c) and PGV (Figure 2d) indicate that the models underpredicted the observed intensities. Among these, the Z19 model (blue diamonds) performs better for PGA, with most of the residuals distributed around zero compared to earlier models. Conversely, negative residual values indicate overpredictions, with the G20 model (yellow stars) yielding higher values for both PGA and PGV. For $M_w < 5.0$, the residuals of the selected models have a lower associated variability, but as M_w increases, the residuals become more dispersed around zero (because the data are few) and vary more significantly between models. This trend is also evident in the histogram subplots, where the O22 model shows a pattern similar to the G20 model for PGA and aligns more closely with the Z19 model for PGV. Overall, the residual analysis for predicted intensities (Figure 2a and b) and M_w (Figure 2c and d) from PGA and PGV highlights significant discrepancies for intensities greater than VI and M_w exceeding 5.0, respectively. The dataset/pairing analysis presented here can be applied to propose or update the relationships between ground motion and intensity, contributing to further studies in ground motion-to-intensity conversion. This includes their applicability in different earthquake engineering applications, improving the accuracy and reliability of seismic assessments.

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Travel time tomography of Aluto Volcano in the Main Ethiopian Rift

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Understanding the structure of the crust and subsurface fluid distribution in volcanic systems is critical for geothermal energy development, volcanic hazard monitoring and mineral exploration [Hudson et al., 2023]. Seismic travel time tomography provides high-resolution images of the subsurface by mapping variations in P- and S-wave velocity structures and their ratio (V_p/V_s), offering insights into the internal structure of the volcano [Gauntlett et al., 2023]. In this study, we apply local earthquake travel time tomography at Aluto volcano, located in the central Main Ethiopian Rift (MER), and Ethiopia's first pilot site for geothermal energy development [Gizaw 1993]. We analyse seismic data recorded between January 2012 and January 2014 [Wilks et al., 2017; Wilks et al., 2020], identifying 2,393 local earthquakes mainly along the central part of the caldera and the Wonji Fault Belt (WFB) [Yemane et al., 2025] using non-linear location methods [Lomax et al., 2000]. We selected events with low spatial errors and a signal-to-noise ratio threshold of three or higher for the 3D travel time tomography. By resolving P- and S-wave velocity variations, as well as V_p/V_s anomalies [Bogiatzis et al., 2022], we aim to delineate zones of fluid saturation and structural heterogeneity. We compute the complete model resolution matrix using direct sparse methods, enabling us to assess the reliability of the tomographic model.

The results of this study are compared with previous studies on the attenuation and conductivity structure of Aluto, collectively providing new insights into the magmatic-hydrothermal system of the Aluto volcano. This study will help to refine geothermal exploration strategies and enhance our understanding of subsurface processes beneath the volcano.

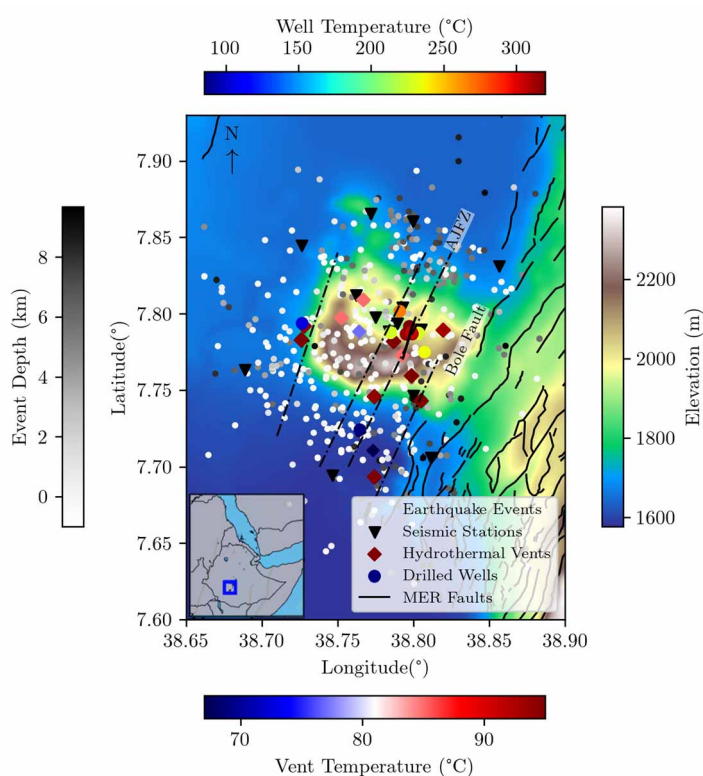


Figure 1 Seismic events at Aluto caldera and its surroundings used for travel-time tomography, colour-coded by depth. Seismic stations are shown as black inverted triangles, hydrothermal vents as diamonds coloured by vent temperature, and geothermal wells as circles, also colour-coded by temperature. Black solid lines denote faults of the Main Ethiopian Rift, while black dashed lines indicate the Artu Jawa Fault Zone (AJFZ).

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Detection of Slow Slip Events in Strainmeter Data Using Deep Learning and Their Link to Deep Slip Transients

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Slow slip events (SSEs) are transient aseismic fault slips that release accumulated tectonic stress without generating abrupt ground shaking or impulsive seismic signals. Although long-duration SSEs can be detected in subduction zones using geodetic networks, short-duration SSEs lasting minutes to hours remain challenging to identify due to their subtle strain signatures and contamination by environmental and instrumental noise. This difficulty is especially pronounced in transform fault systems like the San Andreas Fault, where deformation signals are small.

Borehole strainmeters (BSMs) provide highly sensitive, continuous measurements of crustal strain with fine temporal resolution, making them well suited for detecting short-duration SSEs. However, SSE detection is complicated by the small amplitude of these events, which can be easily masked by environmental influences such as tides, atmospheric pressure variations, and instrumental noise, as well as by other transient signals and background variability in the data. Traditional SSE identification based on manual inspection or simple thresholding is time-consuming, subjective, and often ineffective under these conditions. To overcome these challenges, we present a fully automated deep learning-based algorithm for detecting short-duration SSEs in continuous strainmeter records.

Our method consists of four main steps. First, we preprocess raw strainmeter data using EarthScopeStrainTools to remove long-term trends, tidal effects, and barometric pressure influences. Second, we apply the continuous Morlet wavelet transform to the data to enhance transient features associated with SSEs, producing daily wavelet spectra. Third, we employ AutoencoderZ [Zali et al., 2024; Zali et al., 2025], a neural network-based autoencoder, to perform nonlinear dimensionality reduction and extract informative latent features from the wavelet spectra. Fourth, we apply clustering to the extracted features to identify SSEs as a distinct cluster, separating them from other signals and noise. See workflow in Figure 1 [1].

We applied this workflow to eight years (2009–2016) of 1 Hz continuous strainmeter recording from three stations (B073, B075, B076) near Parkfield, California. We successfully detected SSEs across all three strainmeter stations, with several events consistently observed at multiple stations, verified against a manual catalog, and further corroborated by nearby creepmeter observations. At the reference station B073, our algorithm automatically detected 90% of the 71 SSEs identified in the manual catalog and additionally discovered 21 previously undocumented SSEs, 14 of which are supported by creepmeter data. To our knowledge, this represents the first fully unsupervised machine learning detection of SSEs based solely on strainmeter data.

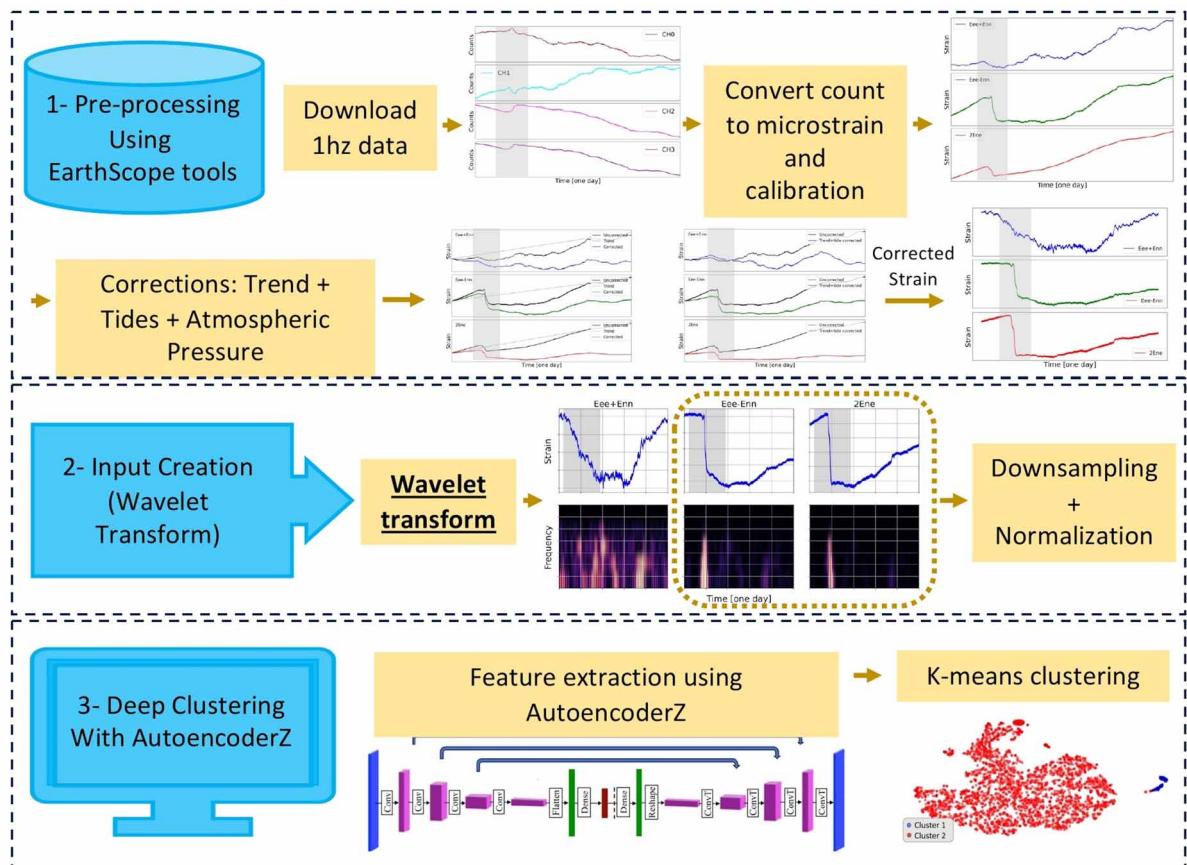


Figure 1 Flowchart of our SSE detection algorithm for strainmeter data. The workflow consists of three primary stages: (1) preprocessing of strainmeter time series, (2) wavelet transforms to capture transient features, and (3) unsupervised learning and clustering using AutoencoderZ.

Using this SSE catalog, we explored the temporal relationship with previously documented low-frequency earthquakes (LFEs) catalogue [Shelly, 2017] within 10 km of B073. LFEs occurring shallower than 20 km show a statistically significant increase in rate during and immediately after SSEs, suggesting that aseismic slip modulates local seismicity by transiently altering fault stress. Unlike previous studies that inferred SSE timing from LFE bursts, our direct SSE detections enable precise time-resolved correlation, providing stronger evidence for the relationship between aseismic and seismic slip.

This work demonstrates the efficacy of combining advanced signal processing and unsupervised deep learning for extracting subtle tectonic signals from noisy strainmeter data. Our approach is generalizable to other tectonic settings, including subduction zones where SSEs are known to play a key role in fault slip dynamics. The ability to systematically detect short-duration SSEs in different tectonic environments (from continental faults to subduction zones) can enhance our understanding of transient deformation processes and their interactions with seismicity. Expanding SSE detection across these settings is essential for improving models of strain accumulation and release, refining our knowledge of earthquake preparation processes, and advancing seismic hazard assessment globally.

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Sitography

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Enhancing debris flow early warning using machine learning and seismic signals

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Debris flows are a widespread gravity-driven hazard in mountainous regions. These mixtures of water, mud, and solid particles of various sizes can be triggered by shallow landslides, runoff onto unconsolidated soil, in-channel mobilization, dam failure, seismic liquefaction, and rapid snow melting. Due to their high impact force, intense basal-lateral erosion, and long outflow distances, debris flows are one of the most destructive mass movements in the mountain landscapes and pose a threat to residents and property along the main flow path. It is still challenging to ensure the safety of life and property within the debris-flow hazard zone.

Early warning systems (EWSs) offer a cost-effective approach for reducing debris flow hazard. The seismic signal-driven warning systems can issue warning times ranging from several minutes to three hours scale [Lai et al., 2018; Chmiel et al., 2021]. Advances in machine learning present promising opportunities to handling massive seismic datasets. However, the temporal patterns of debris flow signals remain poorly understood and lacks systematic validation. Better characterization of these features is essential to enhance the reliability of EWSs.

In this study, we use the Random Forest and XGBoost models as the benchmark to evaluate whether incorporating temporal patterns of seismic data via a Long Short-Term Memory (LSTM) model can enhance early warning for debris flows. We then apply the trained optimal models to a global debris flow catalog, which we compiled independently, to assess their generalizability. Additionally, we investigate whether the number and types of events used for training affect the model's classification performance. Our results establish a foundation for cost-effective, seismic signal-driven early warning systems for debris flows and other channelized flow hazards.

Data source and debris flow monitoring station

The Illgraben catchment (~ 9.5 km²) near the village of Leuk in southwest Switzerland (Figure 1a) is one of the most active debris flow catchments in the Alps. Debris flows are typically triggered by short-duration convective storms between May and October, with about three to five events occurring annually [McArdell et al., 2007]. Several check dams (CD) have been constructed both to record the arrival time of debris flows and to mitigate related hazards, such as CD29, located at the confluence of the debris flow channel and the Rhône River (Figure 1a). Together with the Swiss Federal Institute for Forest, Snow and Landscape Research, the Swiss Seismological Service at ETH Zurich has deployed a temporary seismic network (Figure 1a), coded as 9S in the International Federation of Digital Seismograph Networks (FDSN), to monitor mass movements in Illgraben. For example, a debris flow event observed on 29 June 2020 is

shown in Figure 1b. We used the open-access dataset from 2017 to 2020 in this study. The raw seismic data are available at <https://doi.org/10.12686/SED/NETWORKS/XP>.

Debris flow warning via multiple seismic stations

With an attention window size of 13 minutes and a global average probability of 0.1, the LSTM model achieved the highest performance. It provided a minimum warning time of 31.9 minutes and a mean warning time of 121.6 minutes for the twelve validation events, compared to the debris flow front first reaching CD29 (Figure 1b). The Random Forest model issued the first warning at 04:38:00 UTC+0 for the 2020-06-29 debris flow, providing an additional 71 minutes of warning time before the flow reached CD29 at 05:49:13. This was approximately 4.5 minutes later than Pre-CD1 warning (04:33:29) and 32 minutes earlier than Post-CD1 warning (05:10:09), respectively. XGBoost issued warnings at 04:42:00. The LSTM model issued the first warning at 04:36:00, the earliest among the three models.

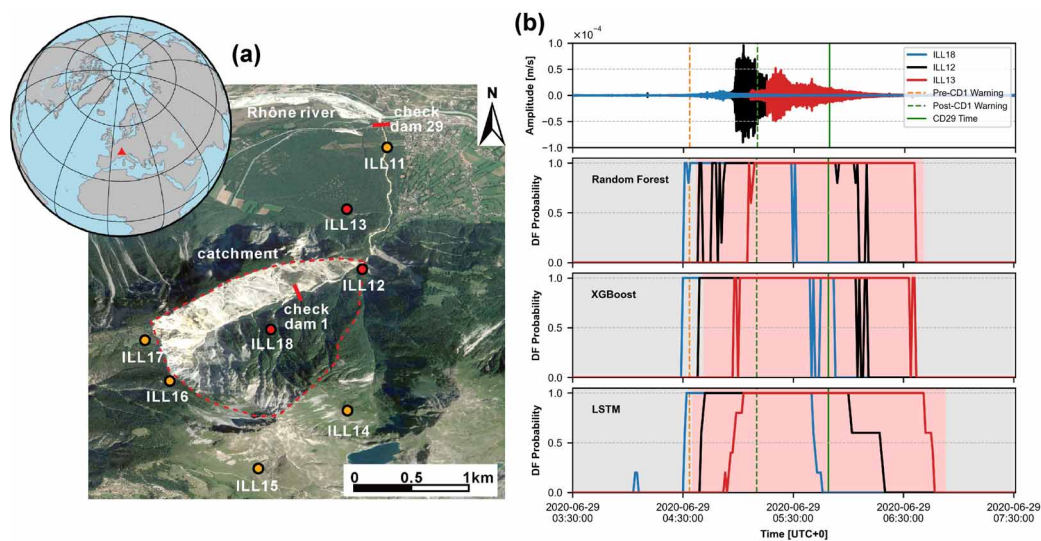


Figure 1 Study area and predicted debris flow probability. (a) Illgraben catchment and distribution of seismic stations. The stations used in this paper are indicated in red. When a debris flow reaches check dam 1 (CD1) or CD29, the time of arrival will be recorded. For example, Pre-CD1 and Post-CD1 indicate the time before and after the debris flow passes CD1. (b) Waveform recorded at three seismic stations and predicted 2020-06-29 debris flow probability.

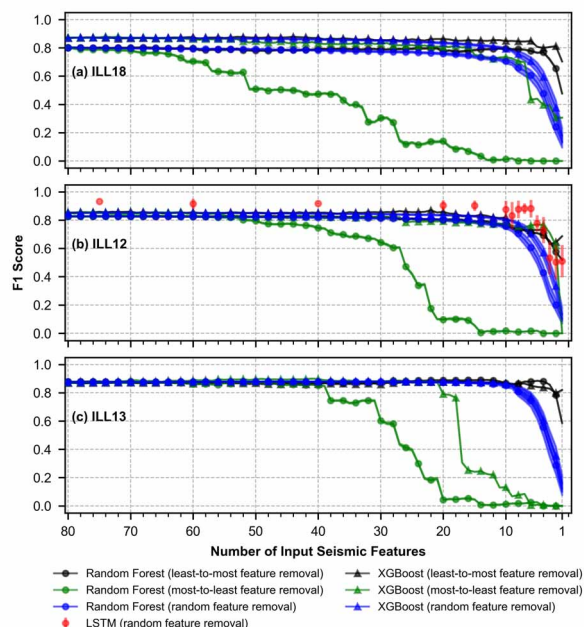


Figure 2 Performance of machine learning models as a function of the number of input seismic features. After training on the 2017–2019 dataset, panels (a)–(c) show testing results from different models using the 2020 dataset.

Impact of seismic feature on machine learning model performance

When we began removing the features with the minimal weight, the results indicate that the majority of seismic features introduced by Provost et al. (2017) and Zhou et al. (2024) do not contribute to training the machine learning model for binary debris flow classification task (Figure 2). For example, only the top ten features without network feature affect the model performance significantly, especially for station ILL12. When we began removing features starting with the maximum weight, the XGBoost model's performance decreased more slowly than that of the Random Forest model. Additionally, there were significant performance differences for the Random Forest model at the station level when features were removed one by one, starting with the most important one. For example, the XGBoost performance remained relatively stable even after removing the top 60 features, and the ILL18 station became more sensitive when most of the highest-weighted features were removed (indicated by triangles in Figure 3.9). Therefore, we argue that machine learning models, such as ensemble models (RF and XGB), is less dependent on the number and even type of input seismic features in the single-station-based binary debris flow classification task.

Performance of the Pre-trained LSTM on global debris flow seismic records

On a global scale, we applied the pre-trained LSTM classifier to 55 events collected from 24 different catchments (Figure 3). Among these, the pre-trained model successfully issued warnings for 40 events. We observed notable differences in model performance between data collected from peer-reviewed papers (IDs 67–86, 17 of the 20 events were detected) and the Exotic Seismic Events Query (IDs 87–121, 17 of the 35 events were detected).

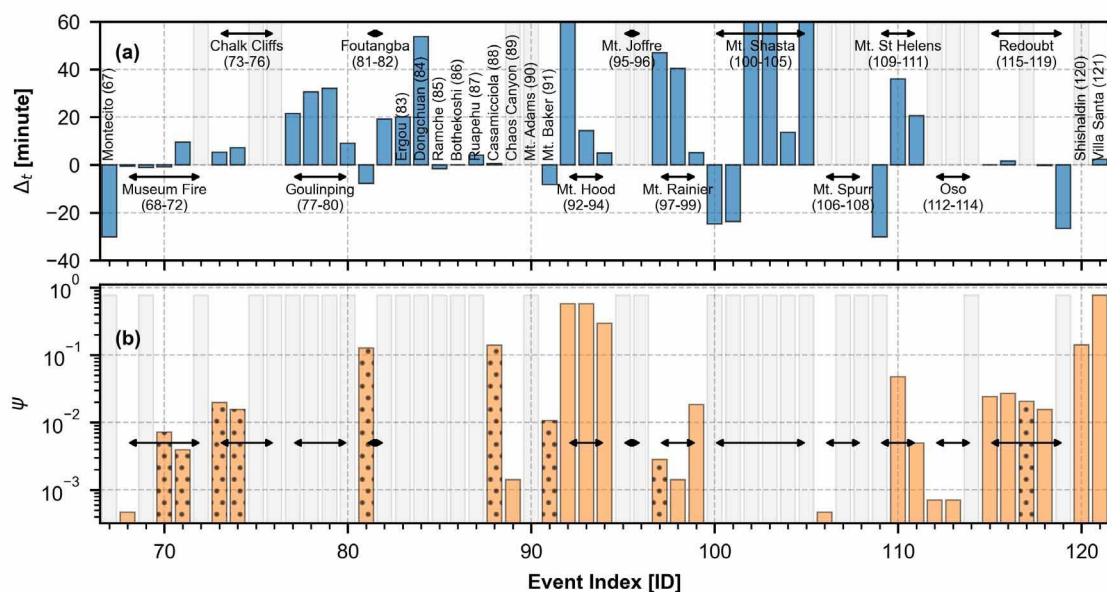


Figure 3 Pre-trained LSTM model performance across global channelized flow events. The raw dataset of IDs 67-121 can be found at Bahavar et al. [2019].

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Integrating DAS into Real-Time Seismic Monitoring

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The southeastern transition zone between the Adriatic microplate and the Dinarides is among the most seismically active regions in Croatia and one of the most tectonically dynamic areas in Europe. Historical records document significant earthquakes that have had profound impacts on the region [Albini and Rovida, 2018]. Given the persistent seismic activity, there is a strong need for improved monitoring and characterization of local fault dynamics.

To support this effort, we deployed a DAS interrogator along a 17-kilometer-long optic fiber, operating in parallel with the existing traditional seismic network.

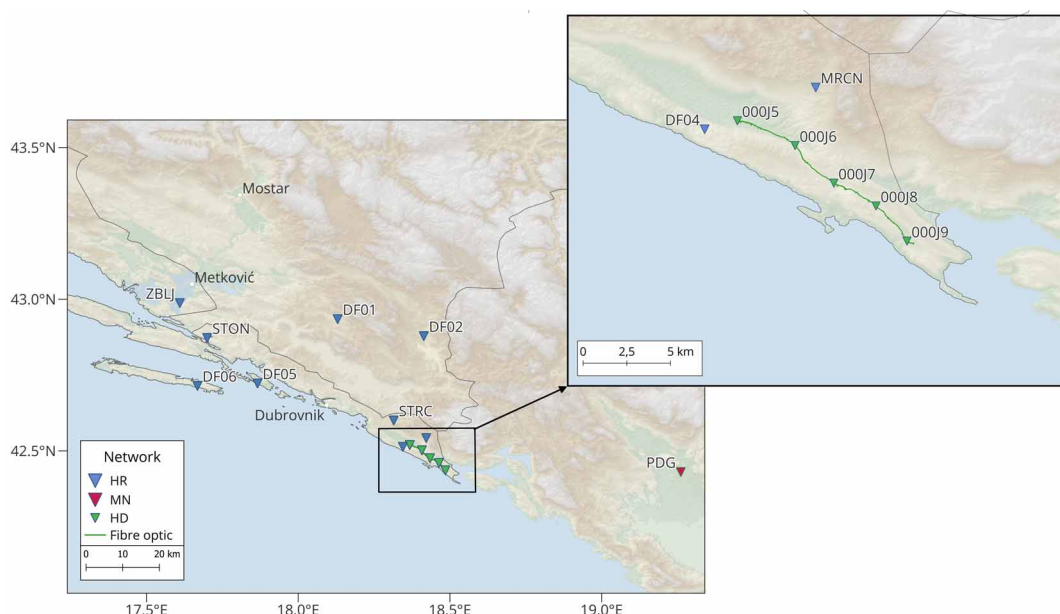


Figure 1 Map of seismic stations used for real-time monitoring. Blue triangles indicate conventional stations [2,3]; green triangles indicate DAS channels.

We implemented a real-time seismic monitoring workflow within SeisComP [1], incorporating both DAS and traditional seismic data, following the approach developed by SED [Massin et. al., 2025]. The first step in the workflow is set-up of data acquisition.

Given the high spatial resolution of DAS data, careful selection of channels used for monitoring is critical, as using all available channels would result in redundancy and high computational demands. Currently, subset of five DAS channels is used (Figure 1), selected at equal intervals along the fibre to ensure spatial coverage, while maintaining efficiency.

The workflow proceeds with automatic phase picking, event location and magnitude estimation. DAS channels are streamed at 100 Hz in SEED compliant channel name HSF [4] as one-component waveforms, limiting detection to P phases. Current implementation only uses P picks in event association across both traditional and DAS data.

We present examples of associated events (Figure 2) and detected phases (Figure 3). DAS channels provide valuable information, enhancing the detection of smaller earthquakes. We discuss initial results, including pick and location accuracy, as well as efforts to fine-tune the workflow parameters. So far, the initial system has detected dozens of local earthquakes, with some earthquakes still being missed, highlighting the importance of continued optimization. In parallel, we are developing a pipeline for regional seismic monitoring and working on integrating additional data. Preliminary results indicate that combining traditional and DAS data improves location accuracy. Increasing the number of channels is likely to enhance detection by providing more picks, while the system is still being refined. We are exploring the use of DAS amplitudes for magnitude estimation.

We discuss the advantages and current limitations of the approach, and outline planned improvements and potential future applications, including its use in early earthquake warning systems and automated earthquake catalogue generation using machine learning methods.

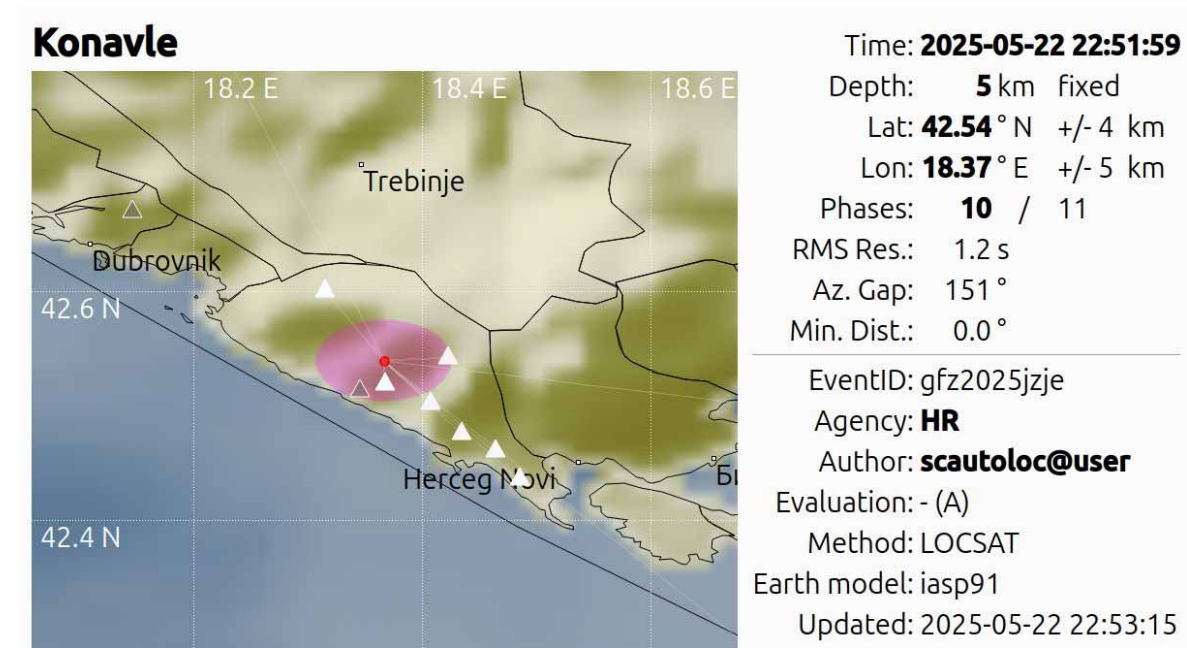


Figure 2 Earthquake recorded on May 22, 2025, shown in SeisComP scolv interface. The red dot marks the epicentre, with the surrounding ellipse representing location uncertainty. Triangles show station locations; origin parameters are displayed on the right.

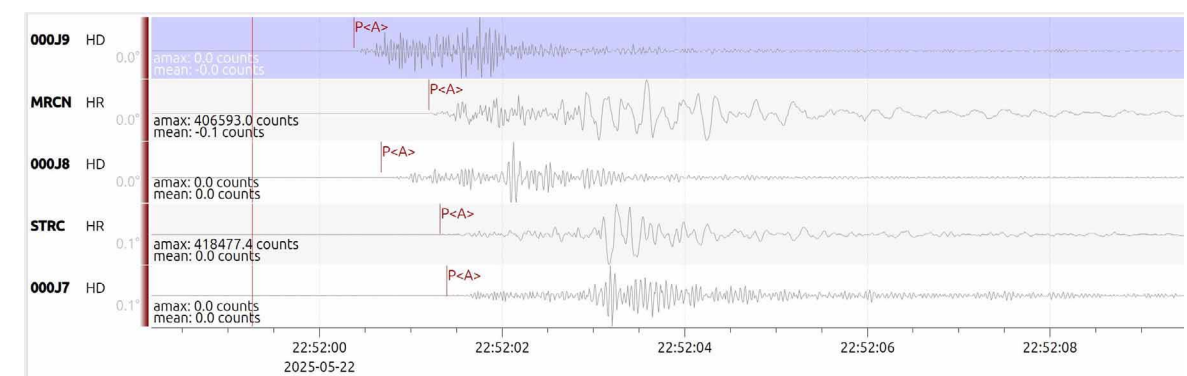


Figure 3 Vertical component waveforms for the May 22, 2025 earthquake. Dark red lines mark P-phase picks; the continuous red line indicates origin time. Stations labeled "000J*" are DAS; others are from the conventional network.

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Sitography

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Mt. Etna Fieldtrip

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Mount Etna is the highest (~3400 m a.s.l.) and largest (~1200 km²) volcano of Europe and one of the most active volcanoes on the Earth.

The morpho-structural setting of Etna volcano results from the complex interaction between a 0,5 Ma long eruptive activity, regional tectonics, flank instability processes, basement morphology and magma dynamics.

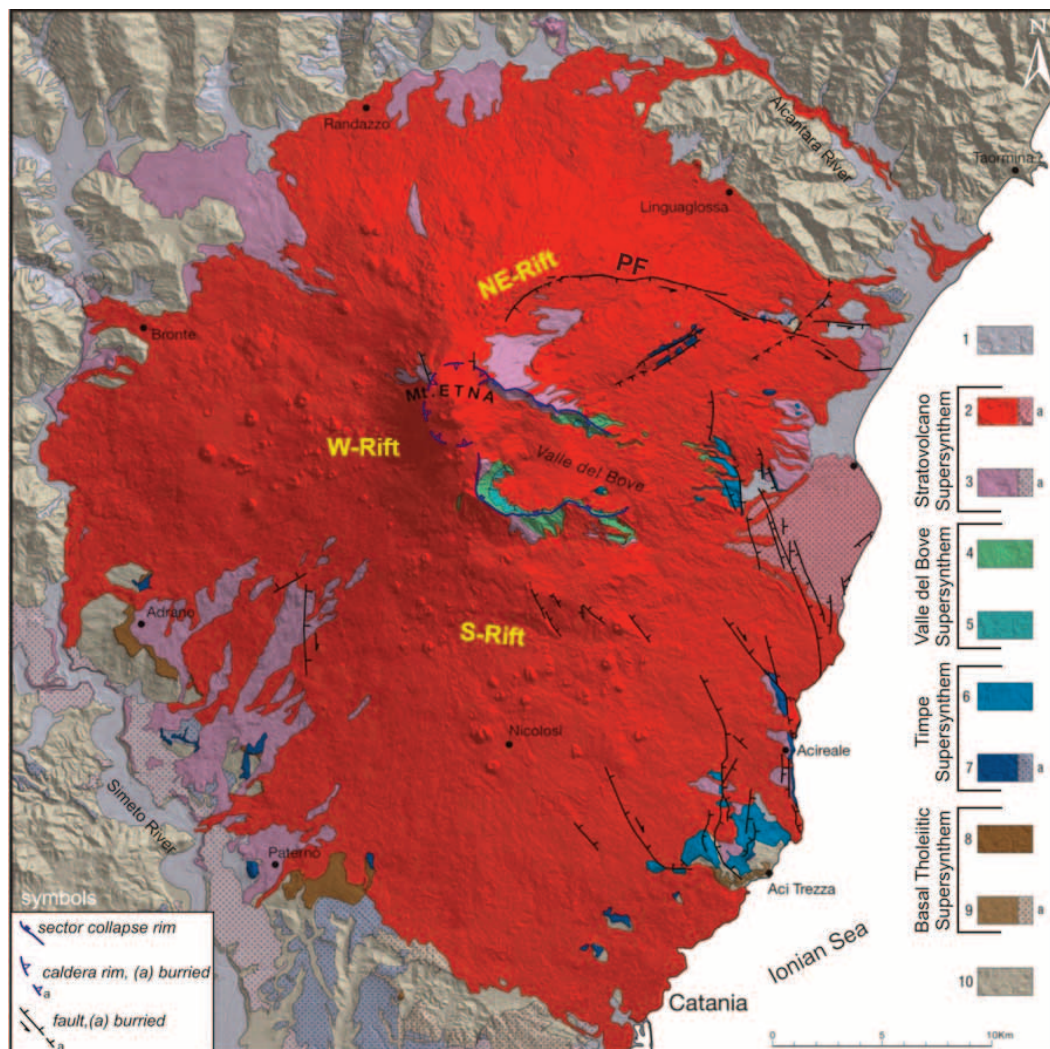


Figure 1 Simplified tectonic and geologic map of Mount Etna (1:250.000 scale) based on the main unconformity-bounded units [Branca et al., 2011a].

Legend: 1, Present and recent covers; 2, Il Piano Synthem (Mongibello volcano) (a, sedimentary deposits); 3, Concazze Synthem (Ellittico volcano) (a, sedimentary deposits); 4, Zappini Synthem (Cuvigghiuni, Salifizio, Giannicola and Monte Cerasa volcanoes); 5, Croce Menza Synthem (Trifoglietto, Rocche and Tarderìa volcanoes); 6, S. Alfio Synthem; 7, Acireale Synthem (a, sedimentary deposits); 8, Adrano Synthem; 9, Aci Trezza Synthem (a, sedimentary deposits); 10, sedimentary and metamorphic basement. PF, Pernicana fault.

Etna stratigraphic sequence

The eruptive history of Etna volcano is synthetically described according to the stratigraphy and geological map (Figure 1) by Branca et al. [2011a, b]. The oldest activity spans from about 580 to 260 ka and corresponds to the Basal Tholeiitic phase characterized by scattered fissure-type tholeiitic volcanism, which represents the northward extension of the Plio-Pleistocene Hyblean volcanism to the Etna region. The second phase (Timpe) started about 220 ka ago when a fissure-type eruptive activity was mainly concentrated in the Ionian coast along the NNW-SSE oriented Timpe fault system. The third phase (Valle del Bove) is marked by a westward shift of the feeding conduits in the area presently occupied by the Valle del Bove depression, where some nested volcanic centres formed. The fourth phase (Stratovolcano) led to the definitive centralization of the main eruptive axes and the construction of the Ellittico stratovolcano, which forms the bulk of the present edifice. Five caldera-forming Plinian eruptions, occurring between 19 and 17 ka, marked the end of Ellittico activity [Coltelli et al., 2000; Del Carlo et al., 2017]. During the Holocene, a persistent basaltic volcanic activity formed the Mongibello volcano, whose products cover about 85% of the Mount Etna area. The morphostructural setting of Etna volcano was strongly influenced by the presence of the wide Valle del Bove formed, about 10 ka ago, as a consequence of slope failures that involved a large portion of the eastern flank [Calvari et al., 2004; Guest et al., 1984].

Etna with its quasi-persistent eruptive activity is a quite dynamic system as witnessed by the rapid morphology changes of the summit area. This last only a century ago hosted a single 250 m high and 500 m wide cone named “Central Crater”. Presently, four craters occur in the summit area, the Voragine and the Bocca Nuova, which lie in the area of the former Central Crater, and the Northeast Crater and Southeast Crater, located on the Central Crater’s cone flanks (Figure 2).

In the last centuries, frequent, quasi-persistent eruptive activity has occurred from both the summit area and the volcano flanks down to elevations of 400 metres a.s.l..

Morphological evolution and eruptive activity of the summit area

The NE Crater was born in 1911 and has represented the highest topographically point (3330 m a.s.l.) of the volcano until 2021. Its growth was accompanied by voluminous outflows of lava and repeated collapses throughout the 1950s. Vigorous growth phases of the cone occurred from 1966 to 1977, with Strombolian activity and lava effusions. In 1977-1981, the crater changed its behaviour, producing a series of short-lived violent explosive eruptions with high lava fountains and voluminous lava flows extending a few km down slope. The most violent eruption occurred in 1986 and ended with the partial destruction of the cone. Another series of paroxysmal eruptions with high lava fountains occurred in 1995-1996, causing a partial filling of the inner crater with subsequent collapses of portions of the cone. During the May 2016 eruption, the crater largely collapsed.

The Voragine formed in 1945 in the NE sector of the previous “Central Crater” at the end of a 15-year long and intense explosive activity alternated with gravitational collapses. During the following decades the crater gradually enlarged due to collapses and/or explosive activity. A powerful explosive eruption occurred in July 1960, and produced heavy tephra fall causing forest fires and considerable damages to farmlands particularly on the volcano’s NE flank. Since its formation, periods of collapses and partial infilling of the crater alternated. In a few cases (e.g. in 1980) magma almost entirely filled the Voragine crater. A remarkable series of four paroxysmal events occurred in December 2015, one of which produced a “pine”-like plume higher than 14 km. After the eruptive activity of n May 2016, the Voragine produced an intense and almost continuous fumarolic activity from a degassing vent located in the eastern sector of the crater (Figure 2). The most recent eruptive activity occurred in the summer of 2024 when, due to the accumulation of material produced during 7 paroxysms, the Voragine became the highest topographically point of Etna (~3400 m a.s.l.).

The Bocca Nuova is the largest among the summit craters being 250x300 m wide and ~100 m deep.

Born in 1968 as a small “pit crater” of the main Voragine crater, Bocca Nuova then enlarged due to the numerous collapses and explosive episodes during the next decades, which have determined the present structure. During the ‘70s, it was the most active among the four summit craters, and fed intense Strombolian eruptions throwing large bombs out of the crater’s rim. One of the most important eruptions occurred in 1999 when the crater supplied an intense Strombolian phase and lava overflows from the western rim that extended up to the middle western slopes of the volcano edifice down to 1750 m a.s.l.. From the beginning of the 21th century, Bocca Nuova morphology has been characterized by two main degassing pit craters. In 2024 Bocca Nuova was completely filled by the lava flows erupted by the Voragine crater.

The SE Crater is the youngest summit crater that was born in 1971 as a “pit crater”; actually its eruptive activity started in 1978. In the last 20 years, SE Crater has been the most active crater, mainly producing paroxysmal events characterized by Strombolian explosions likely evolving in lava fountains, sometimes associated with lava overflows, commonly lasting from a few weeks to months. Indeed, the frequent occurrence of eruptive activity, e.g. 1989 (16 lava fountains), 1998–99 (22 lava fountains), 2000 (64 lava fountains), 2001 (15 lava fountains), 2006–2007 (24 lava fountains), 2011–2013 (45 lava fountains), has fostered the rapid growth and morphology changes of this crater [e.g. Behncke et al., 2006; Andronico and Corsaro, 2011; De Beni et al., 2015]. In 2010, in fact, a “pit crater” feeding high temperature degassing, formed on its eastern flank. In the following years, thanks to the quasi continuous and intense explosive activity, the pit crater rapidly formed a new crater called New SE Crater. From 2020 to 2023 the SE crater produced 62 paroxysms [Proietti et al., 2024]; in this period and until 2024 it was the highest point of the volcano. On June 2nd 2025, the SE produced another paroxysmal event, that developed an eruptive column, a few kilometres high, causing the fallout of pyroclasts (from ash to lapilli) down to the coast, with copious damage to agriculture and the closure of the Catania airport for several days. During this event a sector of the SE cone collapsed and produced a pyroclastic flow confined within the highest part of the Valle del Bove. The last activity of the SE crater occurred between the end of August and the beginning of September 2025 with Strombolian explosions and the emission of lava flows from three vents opened at the base of the crater. During these last years the effusive activity remained confined to the summit area reducing the hazard of lava flow invasion.



Figure 2 Drone image of the summit craters during 2024. VOR = Voragine; BN = Bocca Nuova; NEC = NE Crater; SEC = SE Crater. View is from the north to the south.

Rock and gas composition

Mount Etna exhibits a complex history of magma's evolution. It can be broadly divided into two main stages based on the petrochemical characteristics of its rocks.

The earliest activity of the Basal tholeiitic Phase, approximately from 500 to 260 ka, produced rocks, essentially basalts (Figure 3), belonging to the tholeiitic suite, [Gillot et al., 1994; Le Maitre, 2002; Corsaro and Pompilio, 2004]. This early phase represents a distinct magmatic source and tectonic setting compared to the later, more voluminous activity.

Following this initial phase, the composition of the magma changed radically. From the subsequent volcanic phases (Timpe and the Valle del Bove) up to the present day, Etna has been erupting magmas that belong to the alkali suite. [Le Maitre, 2002; Corsaro and Pompilio, 2004]. The alkali suite is not uniform and includes a wide range of rocks, from the most primitive basalt to the most evolved trachyte (Figure 3). The change from tholeiitic to alkali suite corresponds to a shift in the processes governing magma generation, strongly related to the underlying tectonic movements in the region of Eastern Sicily.

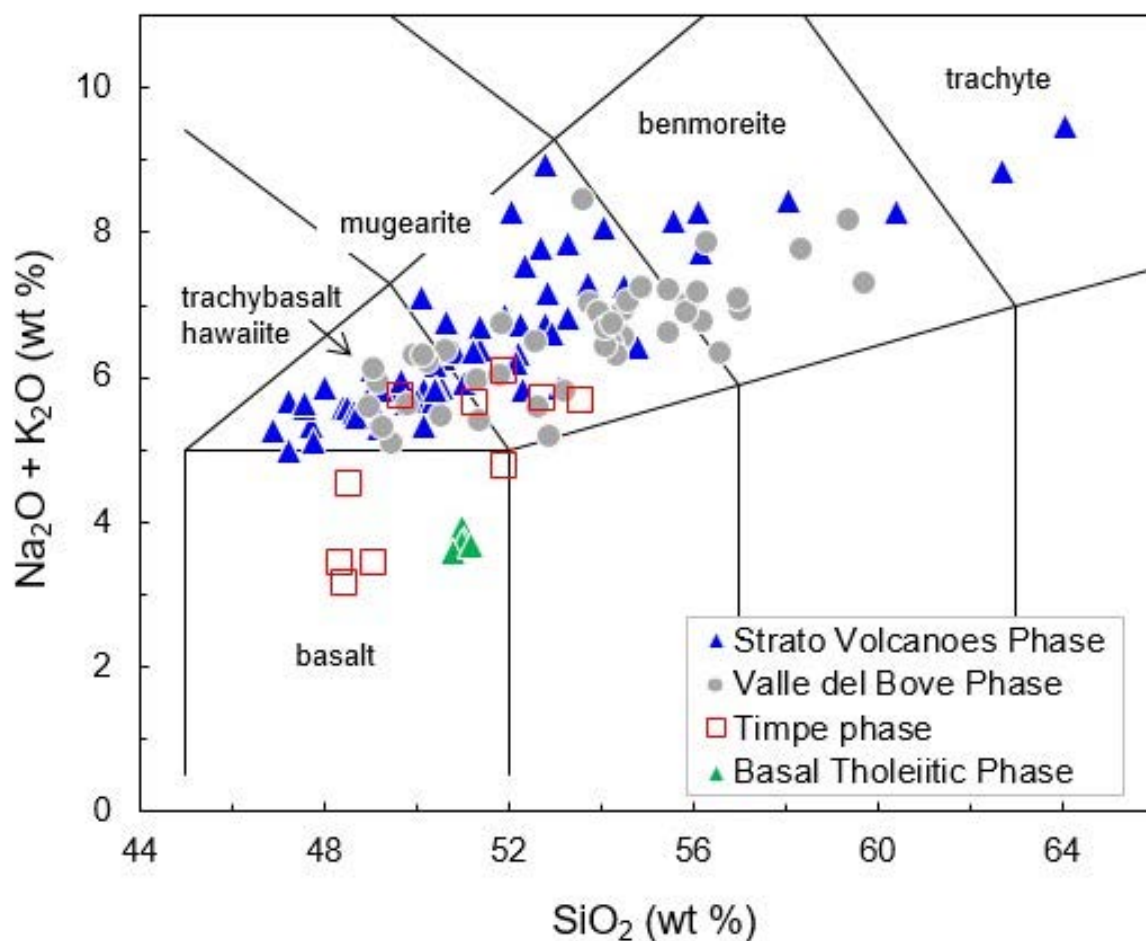


Figure 3 TAS (Total Alkali Silica) classification diagram [Le Maitre, 2002]. Etna rocks range in composition from basalt to trachyte.

Ranking among the strongest persistent volcanic gas emitters worldwide, Mount Etna contributes 10–15% of the global volcanogenic magmatic gas budget [e.g., Allard et al., 1991; Aiuppa et al., 2008]. Its emissions are dominated by H_2O , CO_2 , and SO_2 , with significant amounts of halogen species such as HCl and HF. Etna releases on average ~21,000 tons of

volatiles per day, with H₂O accounting for ~13,000 tons (~70%). During sin-eruptive degassing, H₂O dominates the volatile budget, whereas during passive degassing CO₂ and H₂O contribute roughly equally. SO₂ fluxes range from ~3,000 tons/day, during quiescent periods, up to ~20,000 tons/day during eruptions, while halogen emissions remain significant throughout [e.g., Aiuppa et al., 2008]. Volcanic emissions from Mount Etna have a noticeable but moderate effect on the climate. During explosive eruptions, they slightly cool the atmosphere, with an effect smaller than that of large eruptions like Tambora or Pinatubo. When the volcano is not erupting, its influence on the climate is minimal [Sellito et al., 2023].

Rift zones

Aside from the summit volcanic activity, over time Etna has also fed eruptive activity from its flanks. Based on the areal distribution of the eruptive fissures and scoria cones on the flanks, three main weakness zones (S-, NE- and W-Rift), favouring magma intrusion and eruptions at greater distance from the central volcanic conduits, were identified, (Figure 1). In detail the:

- S-Rift comprises scoria cones and eruptive fissures that had mostly developed over the last 2 ka [Del Carlo and Branca, 1998], which are distributed from the summit area to the S-SE down to elevations of ~600 m a.s.l.. The latest scoria cones of this rift formed during the 2002-2003 eruption [e.g. Spampinato et al., 2008].
- NE-Rift consists of a system of N- to NE-striking sub-parallel eruptive fissures spatter ramparts, scoria cones and pit craters, which are clustered in a narrow area ~2 km wide extending from elevations of 2500 m a.s.l. down to 1700 m a.s.l. [Garduño et al., 1997; Branca et al., 2003]. This rift is affected by a strong-eastward extensional tectonic activity linked to the Pernicana Fault System (PF in Figure 1). The last eruption in this area occurred in 2002, during which numerous cinder cones built up due to the intense explosive activity, and a wide lava flow field emplaced [e.g. Andronico et al., 2005].
- W-Rift includes ~60 scoria cones among which there are some of the largest of the whole Etna volcano [e.g. Mt. Minardo and Mt. Ruvolo]. The latest flank eruption in this rift occurred in 1974 when several eruptive fissures produced two small scoria cones at 1650 m a.s.l. (Monti De Fiore).

Field trip

The Etna field trip itinerary (Figure 4) focuses on the main features of the volcano's northern flank, including the NE-rift and the 2002 "bottoniera", with a view of the summit craters and the Valle del Bove depression.

The trip will start from Piano Provenzana ski area (1800 m a.s.l.). We will reach by 4x4 cars one of the INGV Osservatorio Etneo's multiparametric, summit station (ECNE) and then the Piano delle Concazze area for a viewpoint of the summit craters, the remnants of an ancient volcano "Ellittico" on which the current Etna's edifice has developed and the Valle del Bove depression, followed by the visit of the Pizzi Deneri INGV Volcano Observatory.

Then we will start a downslope walk along the NE-Rift zone, where it will be possible to observe the upper, middle and lower segments of the 2002 eruptive fissure and the vents of the 1809 and 1879 eruptions, before reaching Piano Provenzana again.

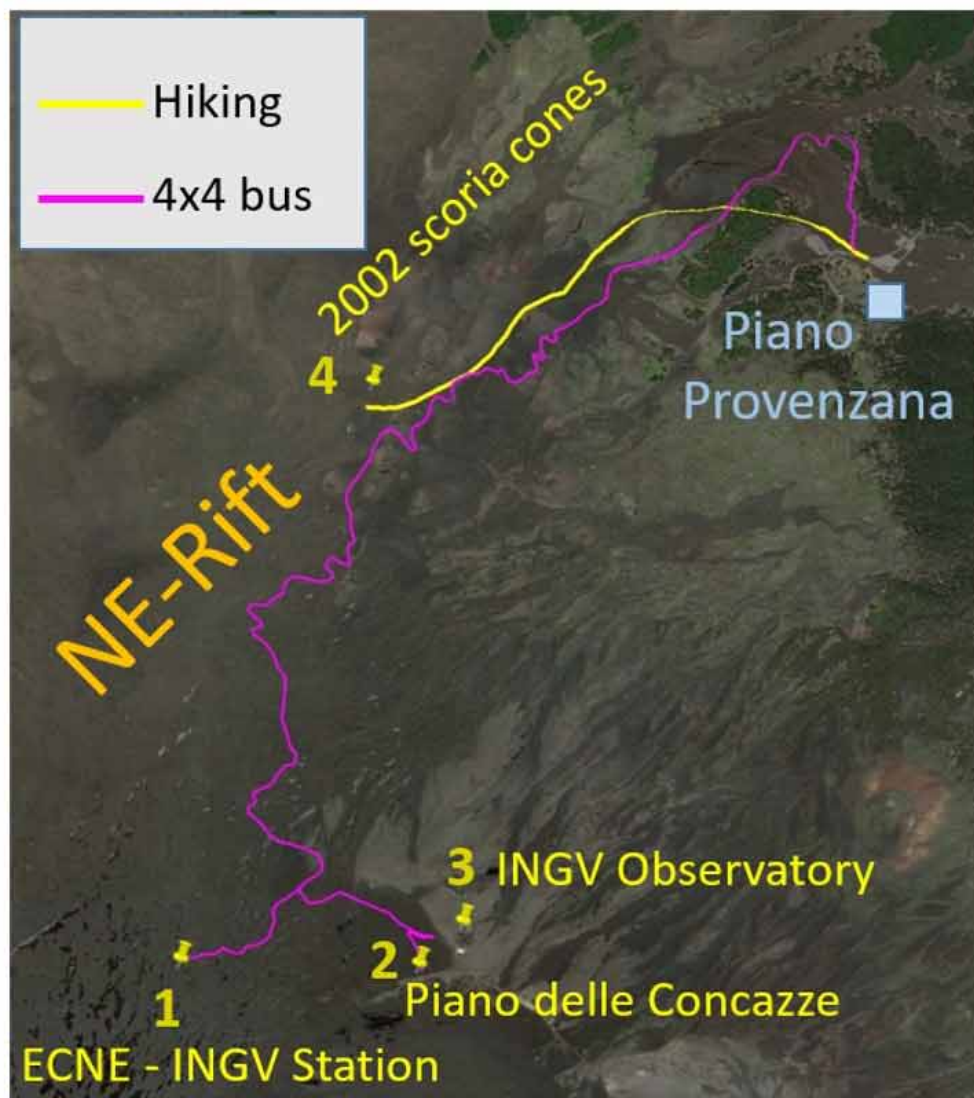
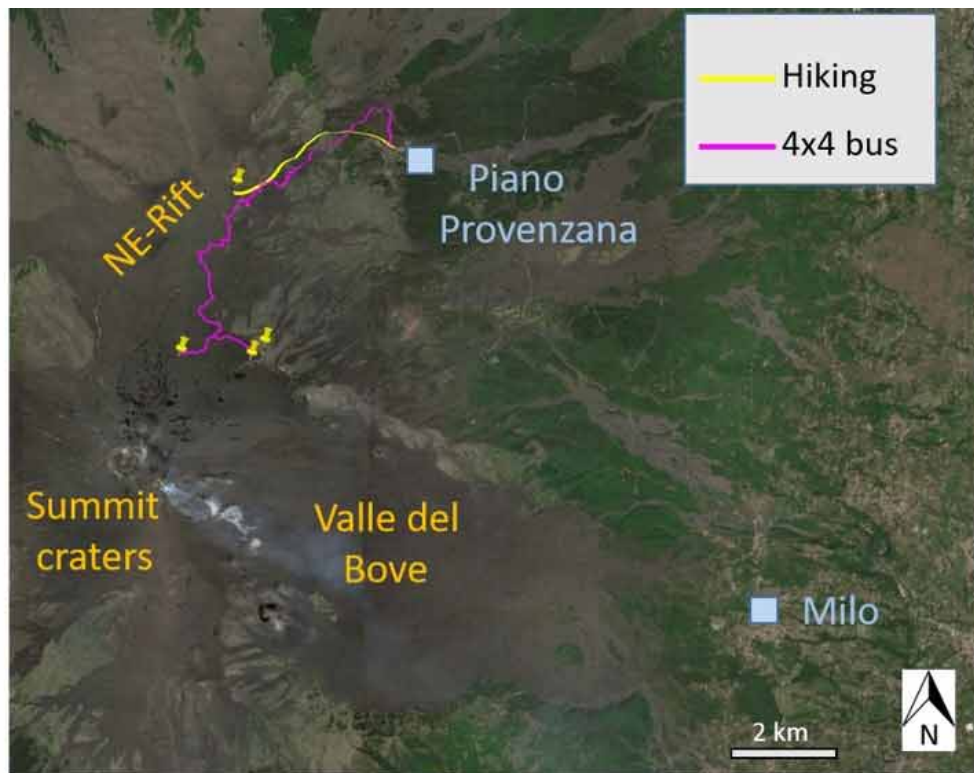


Figure 4 Itinerary and stop points of the field trip on Etna volcano overlapped on a Google Earth map.

Stop 1: INGV multi-parametric station (ECNE)

INGV's monitoring system is based on a multidisciplinary approach, and thus all the studied areas are observed by different kinds of sensors (e.g. seismic, infrasound, GPS, magnetometer, UV scanner, radiometers, etc.), which are often arranged in the same station (multi-parametric station Figure 5). In the case of Etna, there are multi-parametric stations all around the volcano edifice. Indeed, every station is equipped with specific sensors depending on their instrumental characteristics, monitoring aim, and characteristics of the site. Today, we will visit ECNE station (2946 m a.s.l.; Lat.: 37.7653 N° Lon.: 15.0018 E°) that belongs to the summit multi-parametric station network. ECNE is equipped with a:

- GNSS: LEICA GMX902 GNSS receiver; it is able to track the satellites of the GPS, GLONASS and GALILEO constellations; typically, the used sampling rates are 30 secs and 1 sec.
- Infrasound: GRAS 40 AN infrasonic sensor; 50 Hz sampling rate
- Trident_Infra: a Nanometrics Trident digitizer for the GRAS 40 AN infrasonic sensor; mVolt/Count converter: 0.00100000
- Velocimeter: Nanometrics Trillium 40s sensor; 3 components (HHZ, HHN, HHE); 100 Hz sampling rate; V* s/m 1553
- Trident: a Nanometrics Trident digitizer for the velocimeter; mVolt/Count converter: 0.00250000
- Radiometer: Optris CTfast-LT15F radiometer; response time of 6 ms; temperature range -50 to 975 °C; 8–14 μm spectral region; optical resolution of 15:1; 50 Hz sampling rate.



Figure 5 (a) One of the INGV Osservatorio Etno summit multi-parametric stations; (b) the same station seen from inside [modified after Muré et al., 2013].

Stop 2: Piano delle Concazze

Piano delle Concazze is located at about 2800 m a.s.l. and represents one of the best sites to observe the Valle del Bove depression.

Valle del Bove (VDB) is a 7x5 km wide, horseshoe-shaped morpho-structural depression located along the eastern flank of Etna, with up to 1000 m high sub-vertical walls. It is the result of lateral collapses affecting the eastern flank of the volcano since 9-10 ka ago [Malaguti et al., 2023], not directly associated with eruptive activity [Calvari et al., 2004]. At its mouth the debris avalanche deposit related to the collapses [Milo member, Calvari et al., 1998] crops out, whereas its fluvial reworking constitutes the Chiancone member, a fan-shaped volcanoclastic deposit extending along the coast [Calvari and Groppelli, 1996] and offshore [Bousquet et al., 1998; Del Negro and Napoli, 2002; Chiocci et al., 2011]. Along the Valle del Bove collapse walls, lava flows, tephra layers and dikes belonging to the ancient volcanic centres preceding the present Etna volcano (Mongibello volcano, last 15 ka years) are well exposed Figure 6), putting in

evidence spectacular stratigraphic relationships and angular to erosional unconformities. Lava flows and tephra from the Valle del Bove centres are porphyritic, containing phenocrysts of plagioclase, clinopyroxene, olivine and Ti-magnetite. These rocks belong to the Na-alkali suite, with compositions ranging from hawaiites to benmoreites.

The Valle del Bove collapse depression represents the preferred area, where most of the historical lava flows has streamed and piled up. From this viewpoint, the 1991-1993, 2001, 2008-2009, 2018, 2019-2023 lava flow fields are well recognizable (Figure. 1 and 7).

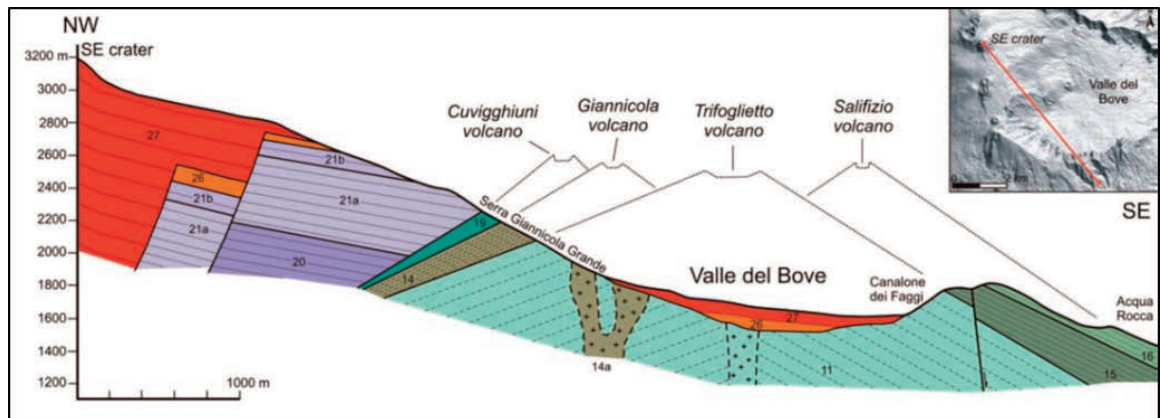


Figure 6 Schematic geologic section from the summit toward SE reconstructing the paleo-morphology of the main volcanic centres of Valle del Bove [Branca et al., 2011b].

At the Piano delle Concazze area the northern rim of the Ellittico caldera is also recognized. This caldera has been formed during a rather short eruptive period dated at 19-17 ka through five Plinian eruptions that ended the activity of the Ellittico volcano [Coltelli et al., 2000; Del Carlo et al., 2017]. A stratigraphic unit made up by layers of pumice lapilli is the evidence of this series of strong explosive eruptions. The sub-horizontal lava flow units of the younger Mongibello volcano filled the Ellittico caldera collapse depression and on-lap the older lava flows truncated by the collapse [Coltelli et al., 1994] producing the stratigraphic unconformity exposed along the collapsed flank of Valle del Bove.

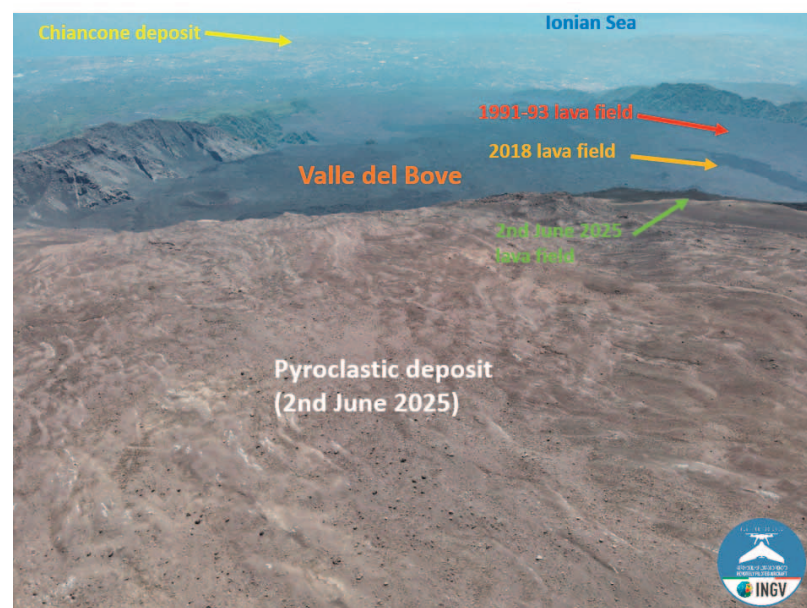


Figure 7 View of the Valle del Bove depression from the NE flank.

Stop 3: Pizzi Deneri INGV Volcanological Observatory

The Pizzi Deneri Volcano Observatory was built in 1977 (Figure 8) on the volcano North flank in a safe position with respect to the hazard of lava flow invasion, in an area corresponding to the morphological relief of Pizzi Deneri (at 2818 m a.s.l.) and representing the rim of an ancient caldera. The observatory currently houses the following monitoring instrumentation: gravimeter, seismic station, GPS, infrasonic sensor, as well as a strain meter in the well and a laser interferometer. The location of the observatory on one of the most active volcanoes in the world represents a worldwide uniqueness due to the only 2 km distance from the summit craters. Since its creation, the national and international scientific community, in collaboration with the INGV researchers, have used the PDVO as a logistical base and advanced laboratory for both research and monitoring activities. In fact, since the beginning, the observatory has had the twofold objective of being the key element of Mount Etna's monitoring system and carrying out breakthrough researchers in a national and international cooperation framework. Thanks to its location and facilities, The Pizzi Deneri observatory hosted several summer schools and was offered for Transnational Accesses in the framework of EC projects. Since 2013, the observatory lies in a protected area of Etna Regional Park which has been declared a World Heritage Site of UNESCO for its notoriety, scientific importance, and cultural and educational value of global significance.



Figure 8 (a) The INGV Osservatorio Etneo Pizzi Deneri Volcano Observatory, please note the altitude and the extreme environmental setting in which it lies; (b) closer view of the Observatory.

Stop 4: the NE-Rift and 2002 scoria cones

The NE-Rift is one of the main zones where magma intrudes into Etna's edifice. It extends for about 7 km from the summit craters down to 1500 m a.s.l., and consists of a system of N to NE-striking sub-parallel eruptive fissures closely spaced in an area up 2 km wide [Garduno et al., 1997; Andronico et al., 2005]. These fissures have produced spatter ramparts and scoria cones during the last 15 ka. In the last 300 years, the eruptive events along the NE-Rift have been characterized by short durations and low volume effusive activities [Branca and Del Carlo, 2005]. The onsets of the eruptions have been commonly preceded by seismic swarms, marking magma intrusion and the opening of several km-long fissure systems that developed from the summit craters down to the NE-Rift zone (e.g., during the 1809, 1879, 1911, 1923, 1947 and 2002 eruptions).

In 2002, the eruption was characterized by the unusual opening of eruptive fissures on both

the NE and S flanks of the volcano [e.g. Andronico et al., 2005; Spampinato et al., 2008] (Figure 9A). A seismic swarm with its epicentre in the summit area began on 26 October 2002. The day after, a set of extensional fractures trending N-S (horizontal displacements between 10 and 50 cm) formed in the Piano delle Concazze area (2800 m a.s.l.). Subsequently, a N-S trending fissure at the base of the NE Crater (3000 m a.s.l.) produced a short-lived explosive event. The downslope propagation of the dike was marked by the opening of an eruptive fissure system at 2470 m a.s.l. that extended along the eastern border of the NE-Rift over a distance of 3.5 km until 1900 m a.s.l. (Figure 9B). The upper portion of the NE rift (2470–2150 m a.s.l.) consisted of a set of dry and eruptive fissures (Figure 52A), striking from N5°E to N20°E in a right en-echelon arrangement producing both explosive and effusive activity. These segments were characterized by spatter ramparts and pit craters of which the volcanic succession of the rift is exposed [Branca et al., 2003].

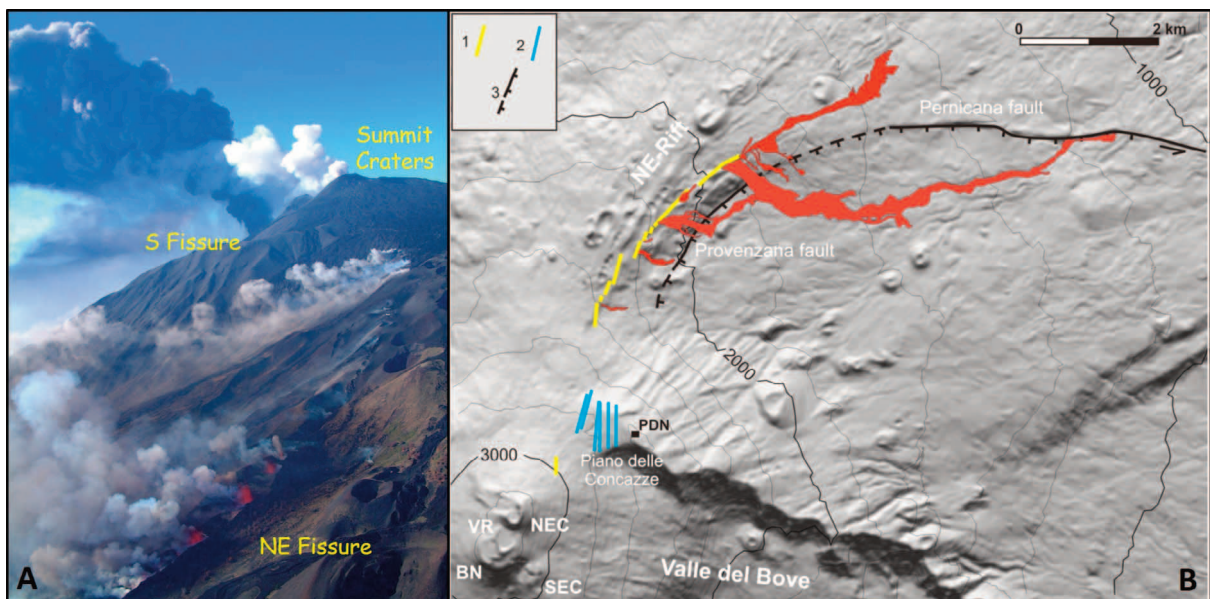


Figure 9 A) Helicopter view of the 2002 eruptive fissure along the NE-Rift. In the background the contemporaneous activity on the southern flank is visible. B) Map showing the fissure system and the lava flow of the 2002 eruption (Branca et al., 2003). VR = Voragine; BN = Bocca Nuova; NEC = NE Crater; SEC = SE Crater. Inset Legend: 1, eruptive fissure; 2, dry fractures; 3, fault.

This eruption was characterized by an extraordinary and continuous explosive activity with abundant ash emission (which reached the coasts of Greece and Libya) causing damage to agriculture and local economy, and discontinuous lava flow output. The eruption involved the opening of eruptive fissures on both the NE and S flanks of the volcano; this last was affected by lava flows and pyroclastic deposits until the beginning of 2003.

It is noteworthy that during the 2002-03 eruption at Etna, two distinct types of magma erupted simultaneously. The (NE fissure emitted a porphyritic, plagioclase-rich trachybasalt that had been stored in the volcano's shallow plumbing system. Conversely, the S fissures produced a volatile-rich, aphyric basalt that ascended directly from the deeper plumbing system bypassing the central conduits. This phenomenon is a defining characteristic of Etna's "eccentric eruptions" (Figure 10).

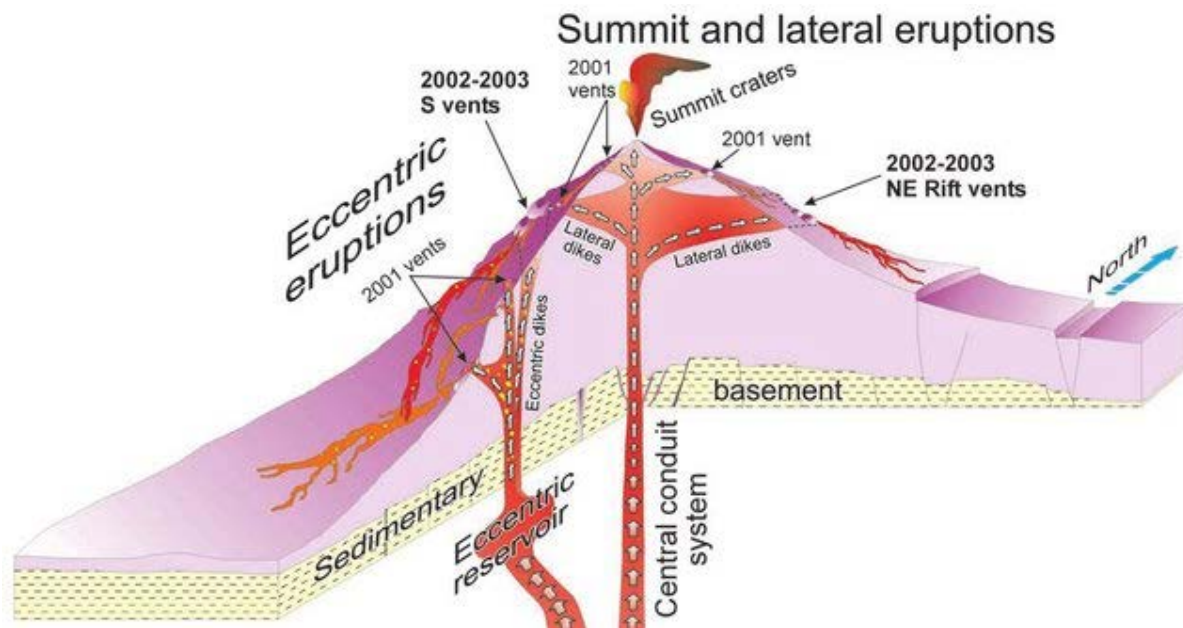


Figure 10 Schematic diagram of the magma feeding system feeding the 2002–03 eruption [Behncke and Neri, 2003; Andronico et al., 2005].

During the downhill it will be possible to also observe the scoria cones related to the 1809 [Geshi and Neri, 2014] and 1879 (Umberto e Margherita craters) eruptions.

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- [1] www.ingv.it
- [2] <https://www.ingv.it/monitoraggio-e-infrastrutture/sorveglianza/servizio-di-sorveglianza-sismica>

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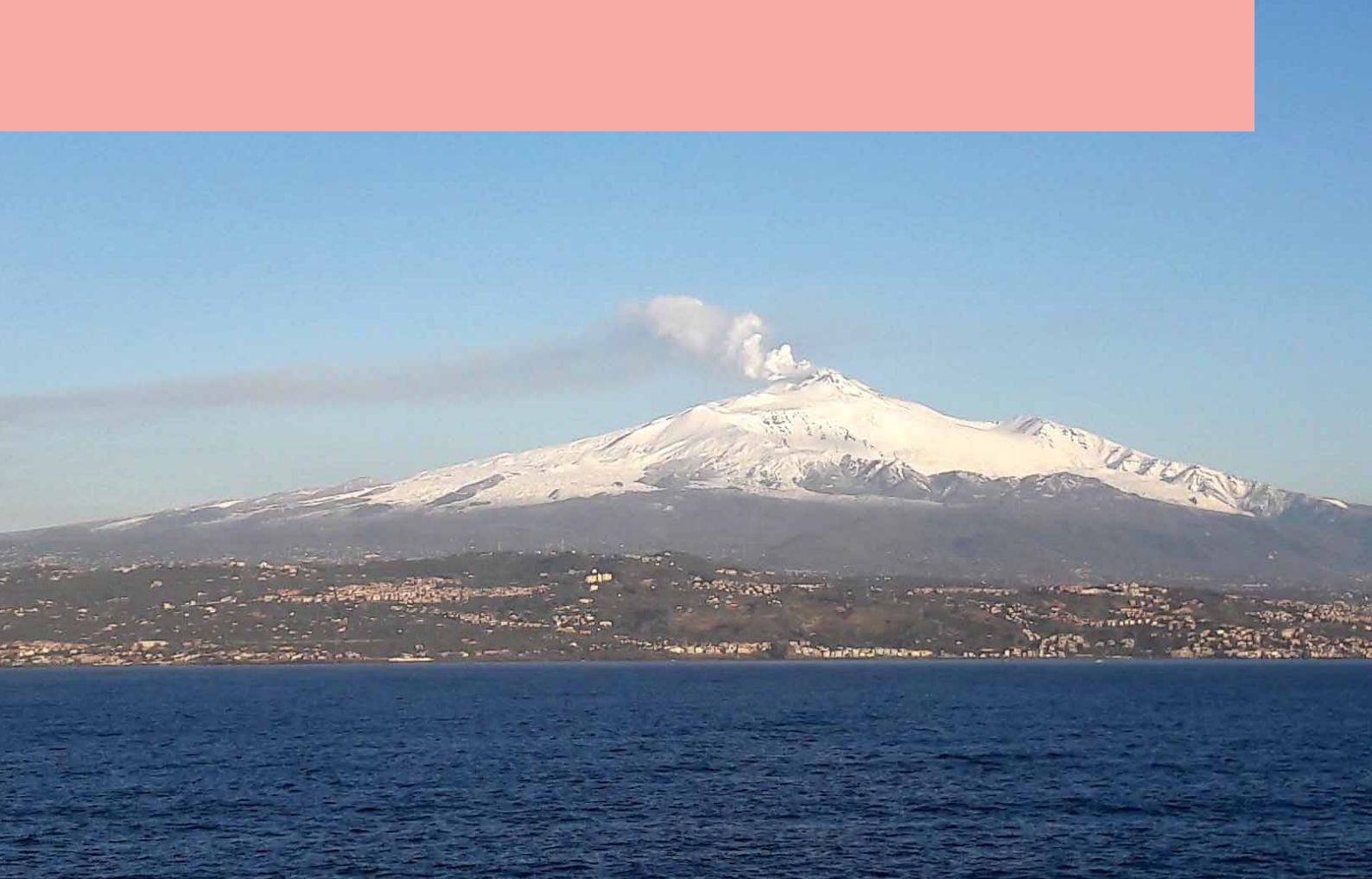
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