

International Workshop on Geosciences in Active Areas (WGAAL 2023)
16-20 October 2023, Arrecife-Lanzarote, Canary Islands, Spain

José Arnoso Sampedro

Emilio J. Vélez Herranz

Editors

INTERNATIONAL WORKSHOP GEOSCIENCES IN ACTIVE AREAS (WGAAL2023)

Proceedings



WGAAL2023

International Workshop on Geosciences in Active Areas (WGAAL2023)

PROCEEDINGS

16 – 20 October 2023

Arrecife. Lanzarote, Canary Islands, Spain

The contents of this publication have been evaluated by the Scientific Committee

© **Scientific Editors:** José Arnoso Sampedro / Emilio J. Vélez Herranz

© **Texts:** The authors

© **Publisher:** Servicio de Publicaciones del Cabildo de Lanzarote

ISBN: 978-84-128033-6-5

DOI:

Proceedings of the International Workshop on Geosciences in Active Areas (WGAAL2023) © 2024 is licensed under CC BY-NC-ND 4.0. To view a copy of this license, visit

<https://creativecommons.org/licenses/by-nc-nd/4.0/>

Credits: cover photography taken at 2021 La Palma eruption by José Arnoso

INTRODUCTION

It was our pleasure to welcome you in Arrecife de Lanzarote, Canary Islands, Spain for the International Workshop on Geosciences in Active Areas (WGAAAL 2023). The aim of this workshop was to gather scientists from a wide range of Earth's science disciplines (geophysics, geodesy, geology, seismology, volcanology, etc) to show our findings, engage in discussions, and share our insights into various geoscience research fields in different active areas of our planet.

Three main topics were gathered in three sessions: Space and ground-based geodetic and geophysical techniques in Earth Sciences (S1), Potential fields, geophysical exploration and georesources in active areas (S2) and Geomorphology, geomicrobiology, petrology and geological heritage in volcanic areas (S3).

56 registered participants belonging to 19 Institutions from 9 different countries attended the workshop. During 4 days a total of 51 contributions spanning most of the thematic subjects of geosciences applied to the study of active areas were presented. The workshop was organized in four morning sessions for oral presentations, which included two invited conferences, and two afternoon sessions for poster presentations. Also, two field trips were scheduled to visit the scientific facilities of the Geosciences Laboratory of Lanzarote, managed by the Institute of Geosciences (IGEO, CSIC-UCM) of Madrid and the Insular Council of Lanzarote (Canary Islands, Spain). The facilities of the laboratory are located in the most representative touristic places in Lanzarote, the Cueva de los Verdes - Jameos del Agua sites, and the National Park of Timanfaya.

This workshop provided the opportunity of sharing experiences among researchers at different stages of their scientific career. The format and organization of the workshop has led to a stimulating scientific debate and a better understanding of interdisciplinary fields of geosciences. We are strongly convinced that multidisciplinary approach is the golden and only way to face the challenges of understanding active areas of the Earth. Also, field trips and demonstrations of scientific instrumentation provided new insights and exchanges of knowledge for understanding volcanic phenomena and geohazards.

In addition to this peer-reviewed proceedings, and considering the high quality of the contributions, a Pure and Applied Geophysics (PAGEOPH) Topical Issue has been organized to be published in 2024 (<https://link.springer.com/collections/cibgaeheic>).

We strongly acknowledge the support of the Cabildo de Lanzarote and the Institute of Geosciences (CSIC-UCM) of Madrid, and the time and effort devoted by the members of the Scientific Committee to review the papers. We want to express our gratitude to the International Union of Geodesy and Geophysics (IUGG), the International Associations of Geodesy (IAG) and Volcanology and Chemistry of the Earth's Interior (IAVCEI) by their scientific support. We are especially grateful to the invited speakers, Carla Braitenberg from the University of Trieste, Italy, and Andreas Klügel from the University of Bremen, as well as to all the authors for their contributions.

We hope that you had a memorable and fruitful time during this workshop in Lanzarote, and expect that such a positive experience could be repeated in future editions.

Madrid, May 2024

Jose Arnoso Sampedro and Emilio J. Vélez Herranz
Co-chairmen of the WGAAAL2023

WORKSHOP COMMITTEES

Workshop Co-Chairs

José Arnoso Sampedro. Emilio J. Vélez Herranz

Scientific Committee

Arnoso, José. Spain - Chair
Benavent, Maite. Spain
Blanco-Montenegro, Isabel. Spain
Casillas, Ramón. Spain
Del Negro, Ciro. Italy
Fernández, José. Spain
Fraile-Nuez, Eugenio. Spain
Gómez-Ortiz, David. Spain
Martín-Crespo, Tomás. Spain

Montesinos, Fuensanta G. Spain
Montgomery-Brown, Emily. USA
Nunes, João Carlos. Portugal
Palano, Mimmo. Italy
Riccardi, Umberto. Italy
Rosat, Severine. France
Sigmundsson, Freysteinn. Iceland
Tizzani, Pietro. Italy
Tiampo, Kristy F. USA

Local Organising Committee

Arnoso, José (IGEO-CSIC) – Chair
Arranz, Jaime (HoV)
Brandón, Rainero (CIL)
Vélez, Emilio (IGEO-CSIC) – Chair

Local Organisers



INSTITUTO DE GEOCIENCIAS (CSIC-UCM)

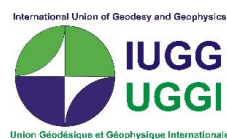


CASA DE LOS VOLCANES – CABILDO DE LANZAROTE

Sponsored



Supported



CONTENTS

Extended abstracts

The Geosciences Laboratory of Lanzarote, by <i>José Arnoso, Emilio J. Vélez, Fuensanta G. Montesinos, Maite Benavent</i>	7
Silica sinters from hydrothermal hot springs in active volcanic areas as tool for astrobiological exploration, by <i>Blanca. Martínez-Benítez, J. Javier Alvaro</i>	15
Slope instability mapping and ground deformation at Colli Albani Hills Volcano (Italy), by <i>Claudia Spinetti, Marina Bisson, Lisa Beccaro, Laura Coloni, Alessandro Galvani, Roberto Giarnardi, Vincenzo Sepe, Cristiano Tolomei</i>	21
A new inversion method for InSAR and GNSS ground deformation data: some examples in Geodynamics and Engineering, by <i>Sen Du, Zhongbo Hu, Joaquín Escayo, Antonio G. Camacho, Juan F. Prieto, P. García-Cerezo, S. Rodríguez, D. Davoise, José Fernández</i>	26
Establishing the surface deformation in the Sofia valley by means of SAR data, by <i>Hristo Nikolov, Mila Atanasova-Zlatareva</i>	34
Study of the coseismic deformations in the Balkan Peninsula area from SAR data, by <i>Mila Atanasova-Zlatareva, Hristo Nikolov, Valentina Protopopova-Kakar</i>	40
Tapping different depth sources and temperature – oxygen fugacity variations throughout the 2021 eruption at La Palma, Canary Islands, Spain: insights from mineral chemistry of spinels, by <i>Cristina de Ignacio, Tomás Martín-Crespo, David Gómez-Ortiz, Silvia Martín-Velázquez, Elena Real, José Arnoso, Fuensanta G. Montesinos</i>	48
Relative gravity networks in the Canary Islands: an effective tool to study volcanic processes in El Hierro and La Palma, by <i>F. G. Montesinos, J. Arnoso, M. Benavent, E. Vélez, D. Gómez-Ortiz, S. Sainz-Maza, I. Blanco-Montenegro, U. Riccardi</i>	53
The role of stand-alone devices for seismological investigation in volcanic and hydrothermal areas, by <i>Paola Cusano, Danilo Galluzzo, Lucia Nardone, Guido Gaudiosi, Simona Morabito</i>	60

Abstracts

Invited conferences

Hunga Tonga, Fani Maoré and other sea mount eruptions: possible observation through future satellite gravity sensors including quantum technology and inclined pair satellite formations, by <i>Carla Braitenberg & Alberto Pastorutti</i>	64
Magma plumbing during the latest eruptions of the Canary and Cape Verde Islands, by <i>Andreas Klügel</i>	65

Session 1. Space and ground based geodetic and geophysical techniques in Earth Sciences

O-030 La Palma volcanic unrest 2009-2023, by <i>José Fernández, J. Escayo, KF. Tiampo, AG. Camacho, JF. Prieto, M. Palano, Z. Hu, SV. Samsonov, E. Ancochea</i>	66
O-006 Source of the recent unrest at Campi Flegrei caldera: preliminary results from the analyses of GNSS and gravity data, by <i>Tommaso Pivetta, U. Riccardi, E. Rivalta, S. Carlino, M. Nikkhoo, F. Maccaferri, M A. Di Vito, P. De Martino</i>	67
O-004 Exploring the significance of the spatial field from integrated DInSAR+GNSS time series for machine learning and volcano early warning applications, by <i>Brianna Corsa; K. Tiampo, C. Meertens, K. Anderson, A. Ellis, PJ. González, J. Fernández Torres, F. Sigmundsson</i>	68
O-046 Slope Instability Mapping of Colli Albani Hills (Italy), by <i>C. Spinetti, L. Colini, M. Bisson, C. Tolomei, L. Beccaro, R. Gianardi</i>	69
O-036 Crustal Monitoring at the Continental Level: the EUREF EPN and GB/WGs Activities, by <i>Joaquín Zurutuza and EUREF Governing Board</i>	70

O-053	Volcano deformation monitoring in Canary Islands (Spain): The case of 2021 La Palma Eruption, by F. Quirós, L. García-Cañada, J. Pereda de Pablo, E. González-Alonso, H. Lamorda, A. Fernández-García, A. J. Molina-Arias, J. Dominguez Valbuena, F. Prieto, L. Sáez Gabarrón	71
O-049	Long term changes and peculiar variations in sea level observed in the Lanzarote Geosciences Laboratory, by Maite Benavent, J. Arnoso, EJ. Vélez, FG. Montesinos, U. Tammamaro, U. Riccardi	72
O-050	Stress-strain models for the Teide-Pico Viejo Complex (Tenerife Island) from GNSS observations, by Manuel Berrocoso, B. Rosado, A. de Gil	73
O-035	Reference frame transitions and their impact on frame realizations, by Joaquín Zurutuza, M. Pertile, M. Bertocco, A. Caporali	74
O-034	The Central European GPS Geodynamical Reference Network (CEGRN), by Joaquín Zurutuza, M. Pertile, O. Khoda, M. Bertocco, A. Caporali	75
O-039	Volcano-tectonic activity of Deception Island from GNSS-GPS observations: 1998-1999, and 2012-2015 volcanic crisis, by Belén Rosado, A. Fernández-Ros, M. Berrocoso	76
O-056	InSar observation in Geodynamics and Engineering: some examples and challenges, by Sen Du, Z. Hu, J. Escayo, AG. Camacho, JF Prieto, P. García-Cerezo, S. Rodríguez, D. Davoise, J. Fernández	77

Session 2. Potential fields, geophysical exploration and georesources in active areas

O-005	Relating temporal variations of the geomagnetic field with volcanic activity at La Palma (Canary Islands): volcanomagnetic signals of the 2021 eruptive process, by Isabel Blanco-Montenegro, José Arnoso, Nieves Sánchez, Fuensanta G. Montesinos, Iacopo Nicolosi, Emilio Vélez and Maite Benavent	78
O-002	Contributions of Growth inversion methodology to volcano gravimetry on Tenerife (Canary Islands), by J. Bódi; P. Vajda; A.G. Camacho, J. Fernández.....	79
O-047	Reliable measurements with FG5/X gravimeters in laboratory and field conditions, by Vojtech Pálinkáš, P. Křen, M. Vaľko, J. Kostecký	80
O-025	Dynamics of the Neapolitan Volcanoes inferred from tiltmeter and seismic data analysis, by Falanga, Aquino, Cusano, De Lauro, Petrosino, Ricco	81
O-017	New paleointensity determinations using Tsunakawa-Shaw, Thellier-Coe and multispecimen methods on a lava flow from the most recent volcanic activity in Cumbre Vieja 2021 (La Palma, Canary Islands), by Eva Vernet, M. Calvo-Rathert, EM. Sánchez-Moreno, Y. Yamamoto, J. Parés, A Carrancho, MF. Bógalo, V. Soler	82
O-055	An improved correlation analysis of potential fields to infer the seamounts magnetization in the Tyrrhenian region, by A. Barone, M. Milano, M. Fedi	83
O-023	The Western High Atlas (Adassil) earthquake of 8 September 2023 (Mw=6.8): pre-earthquake neotectonic observations, by Fida Medina.....	84

Session 3. Geomorphology, geomicrobiology, petrology and geological heritage in volcanic areas

O-031	Revisiting the Timanfaya eruption (1730-1736): evidence and typologies of syn-eruptive instability in single-genetic volcanoes (Lanzarote, Canary Islands), by Carmen Romero, I. Galindo, N. Sánchez, E. Martín-González, J. Vegas	85
O-021	First assessment of marine soundscape alterations during the formation of a new lava delta from a sub-aerial volcanic eruption: the case of Cumbre Vieja volcano (La Palma), by Jesús Alcázar-Treviño, G. Lara, M. Bou, S. Buchan), F. Domínguez-Yanes, E. Fraile-Nuez	86
O-051	A new methodological approach to map and analyse the spatial distribution of ballistic projectiles: the case study of 3 rd July, 2019 paroxysm at Stromboli, by Marina Bisson, C. Spinetti, R. Gianardi, K. Strehlow, E. De Beni, P. Landi	87
O-019	Linking silica sinters from hydrothermal hot springs in active volcanic areas to life on Mars, by J. Javier Álvaro, B. Martínez-Benítez	88

O-024	Experimental evidence of hydrothermal vent fluids fueling microbes at the Tagoro submarine volcano (Canary Islands), by <i>C. Pérez-Barrancos, E. Fraile-Nuez, J.P. Martín-Díaz, A. González-Vega, J. Escáñez-Pérez, M.I. Díaz-Durán, C. Presas-Navarro, J.M. Arrieta</i>	89
O-016	Characteristics of the hydrothermal active area at Tagoro submarine volcano (El Hierro, Canary Islands): venting distribution and fluid, heat and nutrient output quantification, by <i>Juan Pablo Martín-Díaz, A. González-Vega, T. Barreyre, B. Cornide-López, J. Escáñez-Pérez, C. Presas-Navarro, J. María Arrieta, JA. Lozano, E. Fraile-Nuez</i>	90
O-041	Geoheritage inventory update of the UNESCO Global Geopark of Lanzarote and Chinijo islands: contribution from basic science (Canary Islands), by <i>Juana Vegas, I. Galindo, C. Romero, E. Martín-González, G. Lozano, M. González-Roquero, E. Mateo, N. Sánchez</i>	91
O-010	Lava-ocean interaction during the 2021 Cumbre Vieja eruption (La Palma, Canary Islands): physical-chemical and biological anomalies in the water column, by <i>Alba González-Vega, JP. Martín-Díaz, JT. Vázquez, M. Gómez-Ballesteros, O. Sánchez-Guillamón, JA. Lozano, JM. Arrieta, I. Ferrera, E. Huertas, C. Presas-Navarro, E. Fraile-Nuez</i>	92
O-037	Record of temperatures and cooling path of mafic-ultramafic intrusions from Sal Island, Cape Verde archipelago, by <i>María García Rodríguez, C. de Ignacio San José, D. Orejana García, J. Mata, R. Caldeira</i>	93
O-018	The challenge of protecting a new volcano in the Canary Islands, by <i>Juana Vegas, G. Lozano, D. Sanz-Mangas, N. Ferrer-Valero, N. Sánchez, I. Galindo</i>	94

Poster Session

P-007	Exploring Vertical Gravity Gradients at Campi Flegrei, by <i>P. Zahorec, J. Papco, E. Nogova, P. Vajda</i>	95
P-040	Gravimetric networks in the Canary Islands: an effective tool to study the last eruptions in El Hierro and La Palma, by <i>F. G. Montesinos, J. Arnos, M. Benavent, EJ. Vélez, D. Gómez-Ortiz, S. Sainz-Maza, I. Blanco-Montenegro, U. Riccardi</i>	96
P-043	The impact of new volcanic landscapes on gravity field: El Hierro and La Palma case studies, by <i>Sergio Sainz-Maza, FG. Montesinos, J. Arnos</i>	97
P-045	Subsidence and thermo-fluid-dynamics modelling at Timanfaya volcanic area (Lanzarote, Canary Islands), by <i>Umberto Tammara, V. Romano, J. Arnos, M. Benavent, U. Riccardi, F.G. Montesinos, EJ. Vélez, M. Meo</i>	98
P-038	The present-day surface deformation of the Canary Archipelago, by <i>Mimmo Palano, J. Escayo, JF. Prieto, KF. Tiampo, J. Fernández</i>	99
P-009	Researching the surface deformations in the Sofia valley by means of data from SAR, by <i>Hristo Nikolov, M. Atanasova-Zlatareva</i>	100
P-011	Study of the coseismic deformations in the balkan peninsula area from SAR data, by <i>Mila Atanasova-Zlatareva; H. Nikolov; V. Protopopova-Kakar</i>	101
P-022	2021 Vulcano island unrest by InSAR satellite data, by <i>Marco Polcari, C. Tolomei, M. Palano, C. Spinetti</i>	102
P-052	The Casamicciola seismogenetic fault system responsible for the 2017 earthquake at Ischia Island (Italy): geological, seismological and geophysical constraints, by <i>Rosa Nappi, Rosella Nave (1), S. Porfido, V. Siniscalchi, G. Alessio, E. Paganini, AS. Frago, G. Gropelli, G. Norini, M. Pischituta, V. Sapia, V. Materni, V. Paoletti, D. D'Antonio, L. Vezzoli, A M. Michetti</i>	103
P-015	Pyroclastic density currents at basaltic volcanoes: the 10 February 2022 event at Etna volcano (Italy), by <i>P. Del Carlo, B. Behncke, F. Zuccarello, D. Andronico, A. Cappello, F. Ciancitto, A. Di Roberto, G. Ganci, L. Guichard, M. De Micheli Vitturi, T. Esposti Ongaro</i>	104
P-020	Post-emplacement dynamics of Mt. Etna Volcano lava flows during the Christmas 2018 eruption unveiled by optical and radar satellite data, by <i>Lisa Beccaro, C. Tolomei, C. Spinetti, M. Albano</i>	105
P-026	Seismological investigation at Mefite d'Ansanto CO2 emission field, by <i>Paola Cusano, S. Morabito, L. Nardone, S. Petrosino</i>	106

P-028	Tapping different depth sources and temperature – oxygen fugacity variations throughout the 2021 eruption at La Palma, Canary Islands, Spain: insights from mineral chemistry of spinels, by <i>Cristina de Ignacio, T. Martín-Crespo, D. Gomez-Ortiz, S. Martín-Velázquez, E. Real, J. Arnosó, FG. Montesinos</i>	107
P-029	Vents opening susceptibility map of the Colli Albani long-dormant volcano, by <i>Marina Bisson, R. Isaia, R. Nave, A. Pensa, G. Giordano</i>	108
P-044	Local Earthquake Tomography provides new insights on the active degassing system of the Lipari-Vulcano complex (Aeolian Islands, Italy), by <i>C. Totarom, M. Aloisi, C. Ferlito, B. Orecchio, D. Presti, S. Scolaro</i>	109
P-027	Lava flows reaching the submarine platform and slope during the 2021 eruption of Cumbre Vieja Volcano (La Palma, Canary Islands): A petrological and geomorphological study, by <i>Jose Antonio Lozano Rodríguez, R. Casillas, AM. Álvarez-Valero, JT. Vázquez, M. Gómez-Ballesteros, M. García, O. Sánchez-Guillamón, B. Arrese, J. Arrieta, C. Presas-Navarro, JP. Martín-Díaz, A. González-Vega, Á. Brenes, E. Fraile-Nuez</i>	110
P-054	Eruptive column monitoring of the 2021 La Palma eruption, by <i>F. Quirós, J. Pereda de Pablo, A. J. Molina-Arias, L. Sáez Gabarrón, A. Felpeto, S. Meletlidis</i>	111
P-014	Probable effects of coastal erosion and flooding on the geoheritage of the Lanzarote Island in the 21 st Century, by <i>Nicolás Ferrer, J. Vegas, E. Martín-González, J. Lario, C. Romero, I. Galindo, G. Lozano, N. Sánchez</i>	112
P-012	Geodynamics of the Gibraltar Arc. A time series study of the Spanish Navy Observatory stations, by <i>David Rodríguez Collantes, MC. de Lacy Pérez de los Cobos, A. Blanco Hernández, M. Sánchez Piedra, M. Catalán Morollón</i>	113
P-008	Neoalpine tectonics and volcanism in the Western Carpathians, by <i>Vladimír Bezák; J. Vozár; L. Ondrášová</i>	114
P-048	The role of stand-alone devices for seismological investigation in volcanic and hydrothermal áreas, by <i>Paola Cusano, D. Galluzzo, L. Nardone, G. Gaudiosi, S. Morabito</i>	115
P-032	Characterization of volcanic deposits from Cerro Gordo Martian terrestrial analogue by means of susceptibility measurements, petrographic analysis and mineral chemistry, by <i>Emma Losantos Guillén, JL. Mesa Uña, JS. Oliveira, ÓG. Monasterio, M. Díaz Michelena</i>	116

The Geosciences Laboratory of Lanzarote

José Arnoso^{1,3}, Emilio J. Vélez^{1,3}, Fuensanta G. Montesinos^{2,3}, Maite Benavent^{2,3}

¹Instituto de Geociencias (IGEO), CSIC-UCM. Madrid, Spain (jose.arnoso@csic.es)

²Facultad de Ciencias Matemáticas, Universidad Complutense de Madrid, Spain

³Grupo de Investigación 'Geodesia'. Universidad Complutense de Madrid, Spain

Key words: *Geodynamics; Volcano; Surface deformation; Gravity changes; Mass distribution; Canary Islands*

ABSTRACT

The Geosciences Laboratory of Lanzarote was established in 1986 with the aim of investigating geodynamic activity on Lanzarote Island (Canary Islands, Spain) and promoting programs in geodetic and geophysical research to study active areas of the Earth. The laboratory is under agreement between the Institute of Geosciences (Spanish Council for Scientific Research and Complutense University of Madrid) and the Council of Lanzarote Island. The main technical facilities of the laboratory are located to the NE and SW of the island, in the protected areas of Malpaís de La Corona and Timanfaya National Park, respectively. The laboratory exhibits outstanding conditions, provides scientific equipment for observing and analysing geodetic and geophysical parameters in a volcanically active area, and offers an excellent natural environment for developing new geoscience research methods. We describe the scientific facilities offered by this laboratory together with examples that highlight the research activities implemented thus far.

I. INTRODUCTION

The Geosciences Laboratory of Lanzarote (LGL) depends on the Institute of Geosciences (IGEO, CSIC-UCM) of Madrid and the Insular Council of Lanzarote (Canary Islands, Spain). It was created in 1986 owing to the agreement between the Council of Lanzarote and the former Institute of Astronomy and Geodesy (CSIC-UCM) to apply geodetic and geophysical techniques in the study of active areas of the Earth. The laboratory focuses on investigating geodynamic activity on Lanzarote Island, developing mathematical methodologies for analysing and interpreting results from geodetic and geophysical observations, and encompasses facilities for developing ground-based observation equipment and techniques (Vieira *et al.*, 1991; Arnoso *et al.*, 2001a; Arnoso *et al.*, 2001b; Arnoso *et al.*, 2011).

Lanzarote and Fuerteventura are the oldest islands of the Canary Islands archipelago, at approximately 20 Ma old. All the islands form independent volcanic edifices, except for Lanzarote and Fuerteventura, which share an NNE-trending submarine ridge.

Current studies conducted in the laboratory aim to address the mass distribution in the Earth system, surface deformation, oceanic and atmospheric disturbance effects on ground-based observations and long-term observations to accurately detect geodetic phenomena. Since the laboratory is located on a volcanic island, the relevant research also involves the study of geodetic and geophysical parameters allowing the interpretation of volcanic signals during periods of quiescence.

The LGL meets the optimal conditions for observing and analysing geodetic and geophysical parameters in a volcanic active area. The laboratory currently provides ground-based instruments to observe gravity changes, Earth surface deformations and sea-level variations in a continuous operating mode. These instruments are located at different observation sites along the island. Two main installations are located inside the lava tunnel of La Corona volcano (to the NE of the island) and right above the largest heat flow anomaly on the island (to the SW) in the Timanfaya volcanic area (TVA). In addition, geodetic and gravimetric networks designed for local and regional episodic surveys are available.

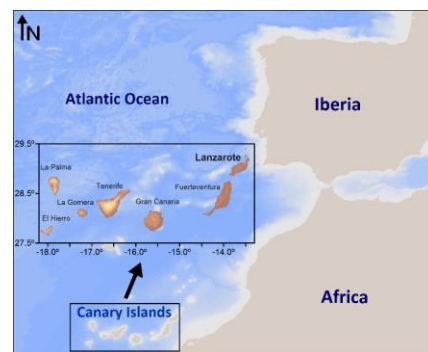


Figure 1: Geographic location of Lanzarote Island to the northeast of the Canary Islands archipelago.

The following sections show the main features of the laboratory and examples of the most recent research activities performed.

II. THE LABORATORY AT THE “CUEVA DE LOS VERDES” AND “JAMEOS DEL AGUA” SITES

The laboratory facilities to the northeast of Lanzarote are located in the interior of the lava tube of the La Corona volcano, which erupted approximately 21 ka ago (Carracedo and Troll, 2016). The lava tube emerges from the volcano, spans 6 km until it reaches the coastline and enters the ocean for approximately 1.8 km (Fig. 2). Part of the laboratory is located in the so-called Cueva de Los Verdes (cave of the Greens), while another part is located at the intersection of the lava tube with the ocean, at the location known as Jameos del Agua (locally, the term “jameo” indicates an opening produced by a collapse in the roof of the lava tube).



Figure 2: From top to bottom, google earth map showing the location of the Cueva de Los Verdes and Jameos del Agua sites (rectangle in the inset) along the lava tube of La Corona volcano, in Lanzarote. Several pictures taken inside the CV-LGL showing the observational facilities and some scientific instruments installed: (left) water-tube tiltmeters, extensometer; (centre) horizontal pendulums; (right) tiltmeter, vertical pendulum, broadband seismometers.

The Cueva de Los Verdes laboratory (hereafter referred to as the CV-LGL) is equipped with permanent scientific instruments (Fig. 2) to collect continuous ground-based observations for studying geodynamic phenomena related to subsurface mass

distributions in the Earth system and surface displacements. These instruments provide long-term measurements for detecting geodetic phenomena accurately and for modelling ocean and atmospheric disturbance effects on the observed signals.

It is widely accepted that slow and small-gravity variations (e.g., from 1 to 10 μGal , with $1 \mu\text{Gal} = 10^{-8} \text{ ms}^{-2}$) could be produced because of the disturbance of the elasto-gravitational equilibrium of the Earth (Riccardi *et al.*, 2011). Thus, high-precision gravity measurements can be used to investigate the elastic properties of the Earth's crust and its dynamics in volcanic areas. To detect gravity signals related to volcanic activity, the most accurate corrections for the effects that perturb gravity measurements must be considered. One of these perturbation effects in Lanzarote is produced by the weight of ocean tides, which generates a periodic load referred to as ocean tide loading (OTL). This effect deforms the Earth's surface and causes gravity variations that may reach up to 15% of the observed tidal signal in Lanzarote (Arnosó *et al.*, 2001b). With the use of data from the LGL, Arnosó *et al.* (2023) reported that the OTL gravity variations range from 8 to 10 μGal in Lanzarote, and the OTL vertical displacement was the greatest in the archipelago, exceeding 2.9 cm (Fig. 3). This study also focused on the mostly elastic relationship between the weight of ocean tides and the resulting surface displacement and gravity changes and certain anelastic effects in the asthenosphere below the archipelago. In fact, the residuals of the GPS-vertical displacements obtained for the Lanzarote and Fuerteventura islands (up to 2 mm) fit better when adjusting the elastic properties of the layers beneath the Moho boundary to depths of approximately 220–300 km by reducing the S-wave velocity in the eastern archipelago. Therefore, the upper mantle materials beneath Lanzarote and Fuerteventura could be less stiff than those beneath the other islands, which is compatible with the low-velocity pockets observed beneath the lithosphere of the archipelago (Miller *et al.*, 2015).

Another relevant purpose of the laboratory is to improve data processing through addressing the estimation and elimination of disturbance signals (e.g., atmospheric disturbances), modelling of the residual drift to study nontidal variations and obtaining anomalous data during processing (Venedikov *et al.*, 2003; 2006).

The above cited disturbances (atmospheric, oceanic and drift) in the laboratory data (gravity, tilt, GNSS displacements, sea level, etc.) should be modelled and carefully removed, together with other known signals (e.g., Earth and ocean tides), to obtain high-quality data for studying other signals, for instance, of volcanic origin. Sea-level monitoring is particularly interesting under the observation conditions of the LGL (Fig. 4), specifically in the lakes situated within the

volcanic tube at the Jameos del Agua site (hereafter referred to as the JA-LGL site). The sea level measured at the JA-LGL site is relative to a fixed, land-based benchmark that is locally tied to a permanent GNSS station, namely, the LACV station (Fig. 4). Therefore, the GNSS station controls the stability of the benchmark and provides accurate information on vertical land movements that can cause relative sea-level changes (Benavent *et al.* 2024).

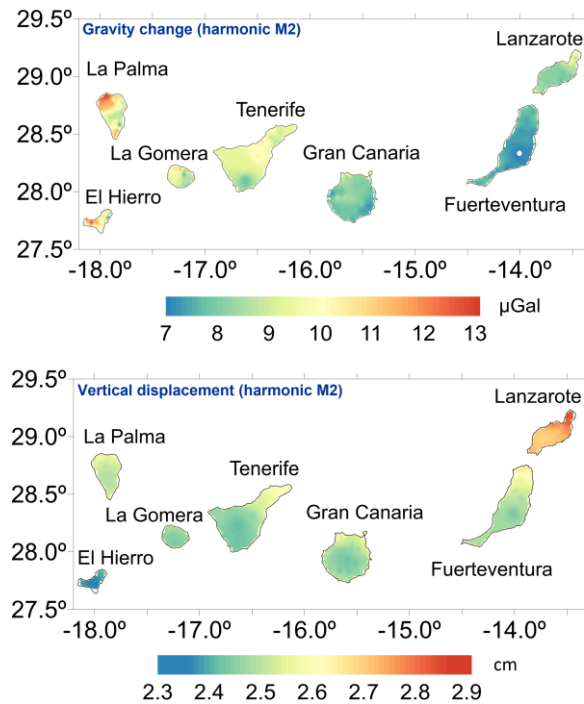


Figure 3: Amplitudes of the OTL prediction for gravity (up) and vertical displacement (down) for harmonic M2 across the Canary Islands (modified from Arnoso *et al.*, 2023).



Figure 4: Pictures of the Large Lake (left) and the permanent GNSS station (right), named LACV, at JA-LGL site.

In this regard, the research conducted at the JA-LGL site contributes to the study of the mass distribution in the Earth system, surface displacements, and oceanic and atmospheric disturbance effects, and, together with the CV-LGL, helps to provide long-term observations for detecting geodetic phenomena accurately.

Fig. 5 shows the sea level, after removing ocean tides and air pressure effects on tidal frequencies, as

measured by pressure gauges at the JA-LGL site since 2005. Following the modelling scheme proposed by Venedikov *et al.* (2006), the sea-level fluctuations shown in Fig. 5 were decomposed into periodic seasonal variations, a polynomial trend and a linear regression trend using the sea-water temperature recorded at this location. The removal of these modelled tidal and nontidal components provides a residual sea-level signal that can be compared with the observed GNSS-vertical displacement measured at the LACV station (Fig. 5), which is situated just above the tide gauge position. It is important to ensure that projections of regional relative sea-level changes account for unpredictable vertical ground movements.

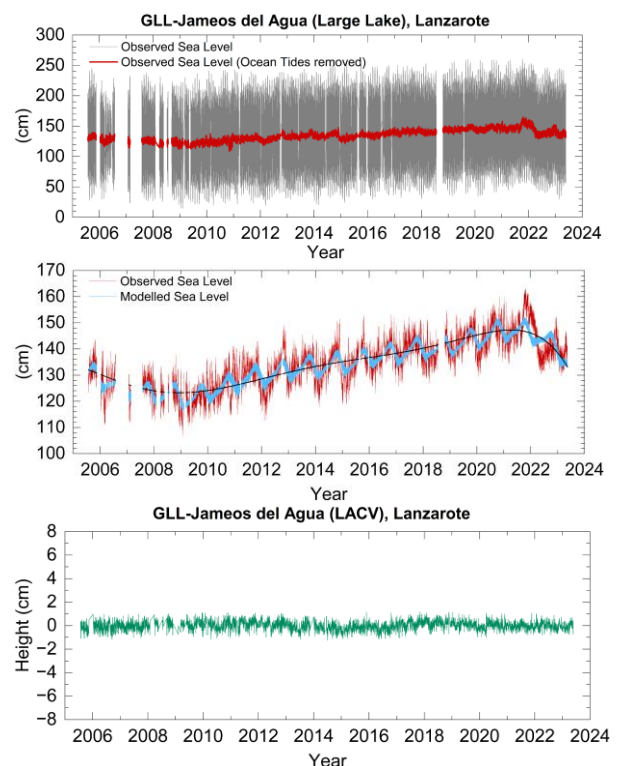


Figure 5: From top to bottom, time series of the air pressure corrected sea-level (red curve) after removing ocean tides (grey curve) at the Large Lake of JA-LGL. Same curve for sea-level but including modelled tidal (blue) and not-tidal components (black). Time series of the observed GNSS vertical displacement (green curve) at LACV station of JA-LGL.

In addition, laboratory instruments can record the effects of different natural phenomena that occur at medium or great distances from the island. Fig. 6 shows the spikes in the air pressure and sea-level signals recorded by pressure gauges operating at the JA-LGL site as a consequence of the 2022 Hunga Tonga volcanic eruption, which occurred approximately 18000 km away from Lanzarote. The submarine volcano Hunga Tonga, located in the southern Pacific, erupted on January 15 (04:10 UTC), 2022, and produced a plume that reached an elevation of 58 km in the troposphere and globally propagated

shockwaves in the atmosphere that were captured by barometric stations around the globe (Li, 2022).

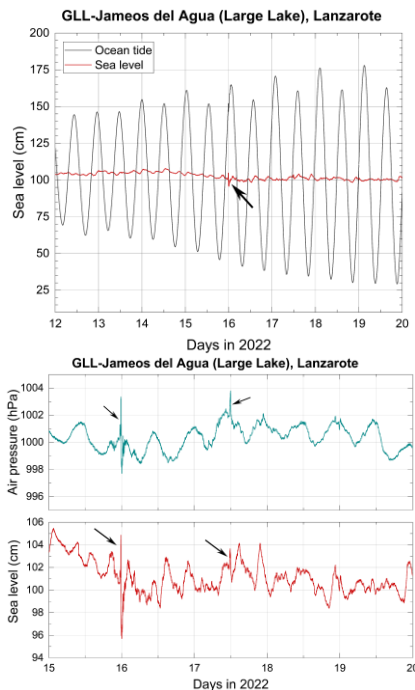


Figure 6: From top to bottom, time series of the sea-level observed (red curve) after removing ocean tides (grey curve) at the Large Lake of JA-LGL site in Lanzarote. Detailed time series of the air pressure (green curve) and the sea-level (red curve) variations. The black arrows point to air pressure disturbances and induced sea-level fluctuations as produced by the global propagating shockwaves following the 2022 Hunga Tonga eruption.

The spikes in Fig. 6 recorded on January 15 at 23:40 UTC exhibit amplitudes of 4.7 hPa (air pressure) and 8.8 cm (sea level) and correspond to the first shockwave detected 19.5 hours after the eruption, which agrees well with the global distribution of the shockwave arrival time computed by Li (2022). These oscillations in the curves clearly account for the response of the ocean surface to the air pressure disturbance generated by the tsunami triggered by the violent explosion produced by the Hunga Tonga eruption (e.g., Omira *et al.*, 2022; Ren *et al.*, 2023). In fact, the Hunga Tonga eruption pushed volcanic products into the atmosphere that produced acoustic gravity waves travelling at the velocity of sound.

III. THE LABORATORY IN THE “TIMANFAYA” VOLCANIC AREA

The LGL also has research facilities in the Timanfaya volcanic area (locally, the term “Timanfaya” means the Fire Mountains), which is located to the southwest of Lanzarote (Fig. 7). This area arises from the volcanic eruptions that occurred between 1730 and 1736 and the eruption that occurred in 1824. The first eruption was the largest historical eruption on the Canary Islands, covering an area of approximately 200 km²

and producing approximately 3 km³ of lava with numerous volcanic cones aligned along an eruptive fissure of 14.5 km in length, large lava flows, volcanic tubes and other underground structures (Carracedo *et al.*, 1990; 1992). The 1824 eruption produced three new volcanoes aligned along the same direction. The volcanic area of Timanfaya is an ideal natural environment for studying volcanic phenomena and associated eruptive processes.

The laboratory of Timanfaya (hereafter referred to as the TIM-LGL) is equipped with permanent scientific instruments to address continuous ground-based observations dedicated to geodynamic research in areas of active volcanism (Figs. 7 and 8). The geodetic and geophysical parameters recorded there can be used to study geophysical signals of volcanic origin during periods of quiescence.

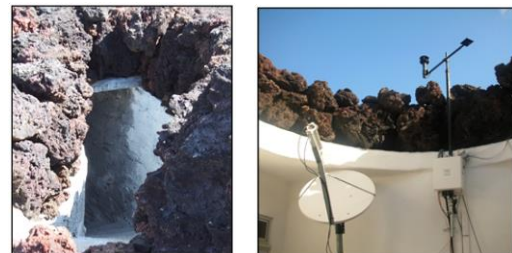
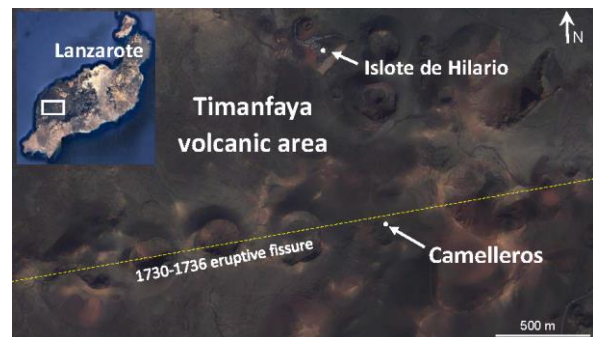


Figure 7: From top to bottom, google earth map showing the location of the laboratory at the TVA (rectangle in the inset), in Lanzarote. Several pictures taken inside the TIM-LGL showing the observational facilities and some scientific instruments installed: (left) water tube tiltmeter; (center) water-tube tiltmeter, extensometer; (right) gravimeter, vertical pendulums, seismometer.

Most related research has focused on monitoring precursory signals of volcanic activity based on analyses of Earth surface deformation processes and gravity variations. Additionally, the study of thermal anomalies and ground subsidence in the Timanfaya area contributes to a greater understanding of the

dynamics of eruptive processes and, in turn, provides interesting information on volcanic hazards in this area.

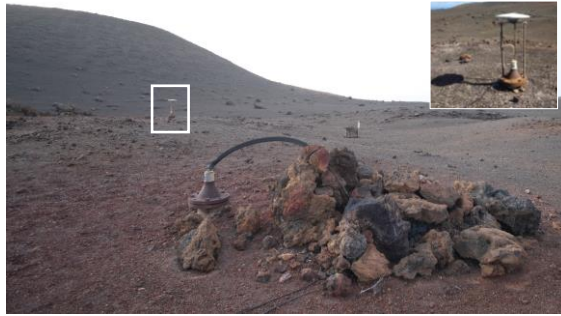


Figure 8: Temperature-depth profile in a geothermal well and the permanent GNSS station CAME (squared area) in TIM-LGL to study the geothermal system in the TVA.

Various studies based on TIM-LGL data have attempted to identify the sources that best explain the observed surface deformation related to the existing geothermal system in the TVA (Riccardi *et al.*, 2018; Tammaro *et al.* 2023). With the use of InSAR analysis, Purcell *et al.* (2022) reported that lava flows from the 1730–1736 eruption exhibit continued subsidence rates of up to ~6 mm/year. In this regard, GNSS displacements measured at the TIM-LGL confirmed considerable ground subsidence rates, although they differed according to the location of the stations within the Timanfaya area (Riccardi *et al.*, 2018). The most recent GNSS analysis at very short wavelengths, with the use of GNSS data from the TIM-LGL, reported subsidence rates of ~9.7 mm/year at the HILA station (in the vicinity of the Islote de Hilario visitor centre) and ~4.3 mm/year at the CAME station (at the Camelleros site), almost 1 km to the south (Figs. 7 and 8, respectively). In addition, strain analysis derived from the GNSS velocity field revealed a compressive strain regime along the island, except for the Timanfaya area, which exhibits tensile strain and the largest strain magnitudes. The observed compression indicates an overall NW trend except for the Timanfaya area, which indicates the opposite trend (ENE). In that area, the predominant tensile strain trends NW. The Timanfaya area clearly shows crustal dilatation from a dominant WNW direction (Fig. 9).

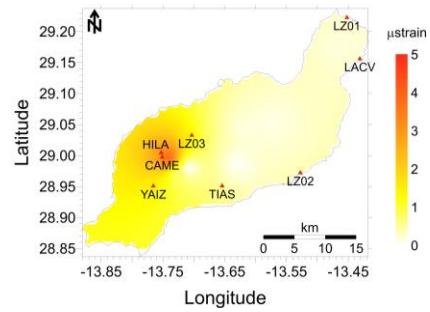
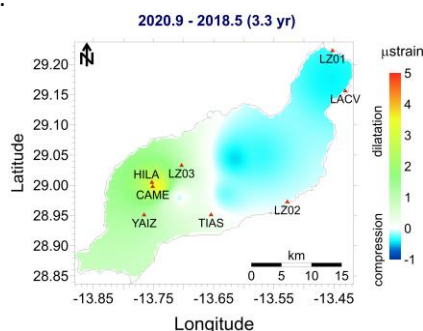


Figure 9. Maps of the 2D distribution of the areal strain (top) and maximum shear strain (bottom) as computed from GNSS data in Lanzarote (red triangles indicates the location of GNSS stations used: HILA, CAME and LACV from LGL; LZ01, LZ02, LZ03 from Spanish IGN; YAIZ and TIAS from GRAFCAN-Canary Islands Government).

The source of thermal anomalies in the TVA lies in an intrusive magma body situated at a depth of approximately 4 km, which fed the 1730–1736 eruption, which was undergoing a cooling process but still had a very high temperature. The geothermal system consists of subsurface zones with very low fluid contents (a type of hot dry rock anomaly). The thermal anomalies were confined either in fracture-related alignments or along the rims of craters, and the recorded temperature reached a maximum of 605°C (Araña *et al.*, 1984; Carracedo and Troll, 2016). Araña *et al.* (1984) suggested that thermal energy is transported through fractures by magmatic volatiles and/or water vapour stemming from a deep-seated 3–4 km water table. To improve the knowledge of these surface thermal anomalies through research conducted at the TM-LGL, Tammaro *et al.* (2023; 2024) considered the unsteady state in the equations governing thermo-fluid dynamics, which were previously studied by Díez-Gil *et al.* (1987). Under suitable initial and boundary conditions, the time needed to reach steady-state conditions was calculated together with the modelled surface displacements in the study area. Considering the deformation measured by the GNSS, tiltmeters and extensometers at the TIM-LGL, new geodetic and geophysical constraints are expected for studying subsidence in the Timanfaya volcanic area.

To characterize the shallower part of the thermal anomaly areas in Timanfaya, Gómez Ortiz *et al.* (2019) combined geophysical prospecting techniques to conduct an analysis and joint interpretation of ground penetrating radar (GPR), magnetic prospecting and electromagnetic induction (EMI) data to model the changes in dielectric properties, magnetic anomalies and the distribution of the apparent resistivity in subsoil layers. This methodology, which avoids the ambiguity inherent in the use of a single prospective technique, provided the best results to date for identifying the location of high ground temperature zones (Fig. 10) in the hot dry rock geothermal system,

using nondestructive methods in an area that requires increased protection, as is the case for the TVA. This study was preceded by other geophysical explorations based on gravity, GPR and electromagnetic induction surveys to determine subsurface structures in Timanfaya. Among the different results reported, new hidden lava tubes were identified in recent lava flows in this volcanic area (Fig. 11) through modelling of density contrast structures, changes in dielectric properties and the subsoil distribution of the apparent resistivity (Montesinos *et al.*, 2013; Gómez-Ortiz *et al.*, 2014; Solla *et al.*, 2015).

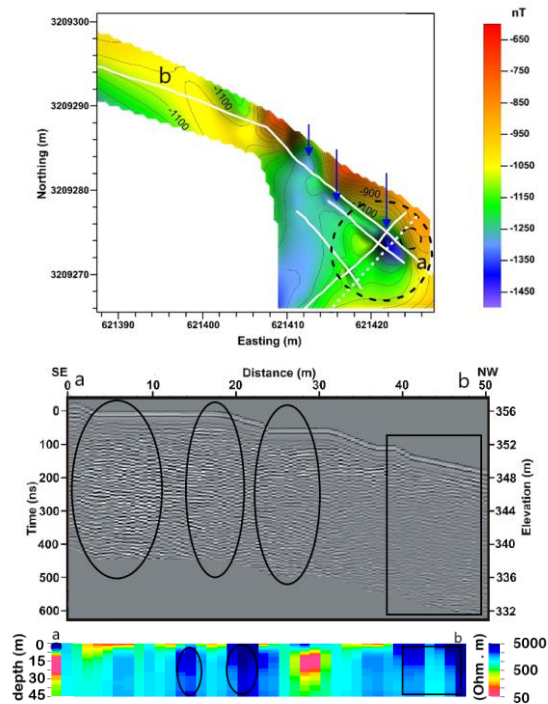


Figure 10. Magnetic anomaly map (top) retrieved from different survey profiles (white lines) in a selected surface thermal anomaly area (dashed black circle) in Timanfaya. The blue arrows indicate magnetic lows suggesting high temperatures beneath the surface. For the profile a-b, the respective GPR (middle) and resistivity (bottom) models.

Circled areas of high resistivity values and high GPR strength signal indicate thermal anomaly areas detected using the three prospecting methods. Same as for the squared areas in GPR and resistivity models, although these were not covered by the magnetic survey (Gómez-Ortiz *et al.*, 2019).

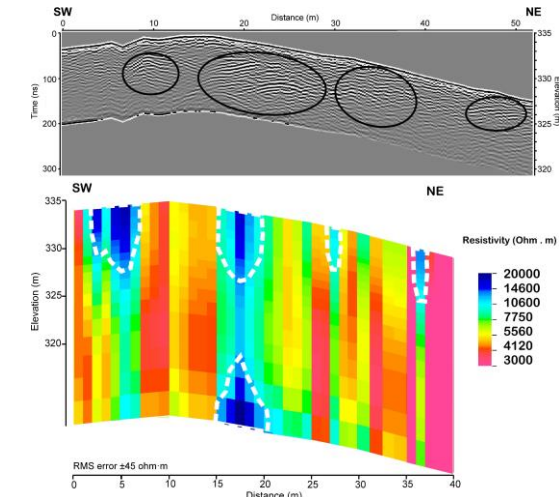
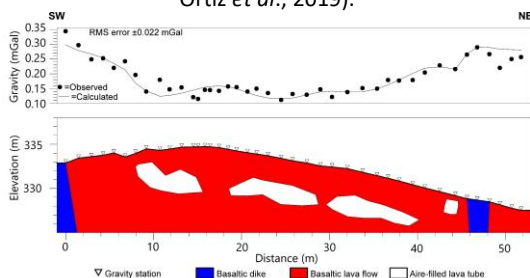


Figure 11. Forward gravity model (top) along a 50 m long profile selected in the thermal anomaly area in Timanfaya. For the same profile, the respective GPR (middle) and resistivity (bottom) models. The figures show the location of lava tubes and basaltic dikes (circled in the respective figures) as determined from the individual geophysical techniques (as per Gómez-Ortiz *et al.*, 2014).

IV. CONCLUSIONS

The Geosciences Laboratory of Lanzarote is a permanent scientific facility that provides ground and space-based observations devoted to investigating geodynamic activity on Lanzarote Island. The laboratory also provides facilities for developing geodetic and geophysical observation techniques and equipment. Most ground-based equipment comprises prototypes specifically developed for the observation conditions at the main laboratory sites (Cueva de Los Verdes, Jameos del Agua and Timanfaya volcanic area).

The continuous ground and space-based laboratory observations can be used to study surface displacements and subsurface mass distributions in the Earth system. The quality of long-term series enables the accurate detection of geodetic phenomena and the modelling of ocean and atmospheric disturbance effects. Such series also contribute to monitoring volcanic activity, studying surface deformation associated with thermal anomalies, and even verifying the heat transmission model and circulation of the residual heat flow remaining from the last eruption occurring in Lanzarote.

Other research conducted by the LGL highlighted the Earth's crustal structure on a regional scale and at different depths through the application of gravimetric, magnetic and microseismic sounding methods. A more recent milestone is the identification and characterization of shallower subsurface volcanic structures (e.g., basaltic dikes and volcanic tunnels not visible at the surface), as the natural conditions in the volcanic area of Timanfaya

facilitate the verification of geophysical exploration methods (microgravimetry, ground penetrating radar, and geomagnetic and electromagnetic induction techniques). For instance, for the first time, the response to electromagnetic waves considering heat sources has been established in terms of depth and geometry in thermal anomaly areas.

Finally, one of the most important assets of the Geosciences Laboratory is its location on the island of Lanzarote, which is a natural geoscience laboratory. This enables cooperation among the international scientific community, thereby contributing to the advancement in research and the resolution of challenges in geosciences in active areas of the planet.

V. ACKNOWLEDGEMENTS

The development of the Geosciences Laboratory of Lanzarote has been made possible thanks to the institutional collaboration between the Institute of Geosciences, IGEO (CSIC-UCM) and the Cabildo Insular de Lanzarote. We would like to highlight the invaluable collaboration of Jaime Arranz and Orlando Hernández, from the Casa de Los Volcanes (Cabildo de Lanzarote), for their permanent technical support and their help during the field surveys. We would also like to thank the staff of the Timanfaya National Park for their support at all times. This work has been supported by grant PID2019-104726GB-I00/AEI/10.13039/501100011033 funded by the Spanish Research Agency. Also, the University Complutense of Madrid (grants Financiación Grupos 2021, UCM 2022-GRFN14/22).

References

- Araña, V., Díez-Gil, J., Ortiz, R., Yuguero, J. (1984). Convection of geothermal fluids in the Timanfaya volcanic area (Lanzarote, Canary Islands). *Bulletin of Volcanology*, 47, 667–677.
- Arnoso, J., Fernández, J., and Vieira, R., (2001a). Interpretation of tidal gravity anomalies in Lanzarote, Canary Islands. *Journal of Geodynamics*, Vol 31, pp. 341–354, doi: 10.1016/S0264-3707(01)00003-5.
- Arnoso, J., Vieira, R., Vélez, E., Cai, W., Tan, S., Jiang, J. and Venedikov, A.P., (2001b). Monitoring tidal and non-tidal variations in Lanzarote Island (Spain). *Journal of the Geodetic Society of Japan*. Vol 47, No 1, pp. 456–462.
- Arnoso, J., Benavent, M., Bos, M.S., Montesinos, F.G., and Vieira, R., (2011). Verifying the body tide at the Canary Islands using tidal gravimetry observations. *Journal of Geodynamics*, Vol 51, pp. 358–365. doi: 10.1016/j.jog.2010.10.004.
- Arnoso, J., Bos, M.S., Benavent, M., Penna, N.T., Sainz-Maza, S., (2023). Anelastic response of the Earth's crust underneath the Canary Islands revealed from ocean tide loading observations. *Geophysical Journal International*, 235-1, 273–286, doi: doi.org/10.1093/gji/ggad205.
- Benavent, M., Arnoso, J., Vélez, E.J., Montesinos, F.G., Tammamo, U., Riccardi, U. (2024). Long term changes and peculiar variations in sea-level observed in the Lanzarote Geosciences Laboratory. *Pure and Applied Geophysics (submitted)*.
- Carracedo, J. C., Rodríguez Badiola, E., Soler, V. (1990). Aspectos volcánicos y estructurales, evolución petrológica e implicaciones en riesgo volcánico de la erupción de 1730 en Lanzarote, Islas Canarias. *Estudios Geológicos*, 46: 25–55.
- Carracedo, J.C., Rodríguez Badiola, E.R., Soler, V. (1992). The 1730–1736 eruption of Lanzarote: an unusually long, high magnitude fissural basaltic eruption in the recent volcanism of the Canary Islands. *Journal of Volcanology and Geothermal Research*, 53, 239–250.
- Carracedo, J.C., Troll, V. (2016). The Geology of Canary Islands. Elsevier, Amsterdam (621 pp.).
- Díez-Gil, J.L., Araña, V., Ortiz, R., Yuguero, J. (1987). Stationary convection model for heat transport by means of geothermal fluids in post eruptive systems. *Geothermics* 15, 77–87.
- Gómez-Ortiz, D., Montesinos, F.G., Martín-Crespo, T., Solla, M., Arnoso, J., Vélez, E. (2014). Combination of geophysical prospecting techniques into areas of high protection value: Identification of shallow volcanic structures. *Journal of Applied Geophysics*, 109, 15–26, doi: 10.1016/J.JAPPGEO.2014.07.009.
- Gómez-Ortiz, D., Blanco-Montenegro, I., Arnoso, J., Martín-Crespo, T., Solla, M., Montesinos, F.G., Vélez, E., Sánchez, N. (2019). Imaging Thermal Anomalies in Hot Dry Rock Geothermal Systems from Near-Surface Geophysical Modelling, *Remote Sensing* 11(6) 675, doi:10.3390/rs11060675.
- Li, C. (2022). Global shockwaves of the Hunga Tonga-Hunga Ha'apai volcano eruption measured at ground stations, *iScience*, 25(11), 105356, doi: 10.1016/j.isci.2022.105356.
- Miller, M.S., O'Driscoll, L.J., Butcher, A.J. & Thomas, C. (2015). Imaging Canary Island hotspot material beneath the lithosphere of Morocco and southern Spain, *Earth and Planetary Science Letters* 431, 186–194.
- Montesinos, F.G., Arnoso, J., Vélez, E., Benavent, M. (2013). Characterization of the crustal structure of Timanfaya volcanic area (Lanzarote, Spain) through gravity study. International Association of Geodesy Scientific Assembly. Potsdam, Germany, pp. 1–6.
- Omira, R., Ramalho, R.S., Kim, J. *et al* (2022). Global Tonga tsunami explained by a fast-moving atmospheric source. *Nature* 609, 734–740, doi: 10.1038/s41586-022-04926-4.
- Purcell, V., Reddin, E., Ebmeier, S., González, P. J., Watson, A., Morishita, Y., Elliott, J. (2022). Nearly three centuries of lava flow subsidence at Timanfaya, Lanzarote. *Geochemistry, Geophysics, Geosystems*, 23, e2022GC010576, doi: 10.1029/2022GC010576.
- Ren, Z., Higuera, P., Liu, P. L.-F. (2023). On tsunami waves induced by atmospheric pressure shock waves after the 2022 Hunga Tonga-Hunga Ha'apai volcano eruption. *Journal of Geophysical Research: Oceans*, 128, e2022JC019166, doi:10.1029/2022JC019166.
- Riccardi, U., Rosat, S. and Hinderer, J. (2011). Comparison of the Micro-g LaCoste gPhone-054 spring gravimeter and the GWR-C026 superconducting gravimeter in Strasbourg (France) using a 300-day time series. *Metrologia*, Vol 48, pp. 28–39.

- Riccardi, U.; Arnoso, J.; Benavent, M.; Velez, E.; Tammaro, U.; Montesinos, F.G. (2018). Exploring deformation scenarios in Timanfaya volcanic area (Lanzarote, Canary Islands) from GNSS and ground based geodetic observations. *Journal of Volcanology and Geothermal Research*, 357, 14–24. doi: 10.1016/j.jvolgeores.2018.04.009.
- Solla, M., Montesinos, FG., Gómez-Ortiz, D., Martín-Crespo, T., Arnoso, J., Vélez, E. (2015). Characterization of volcanic structures using ground penetrating radar and additional inverse modelling: Multidisciplinary geophysical investigation in the Timanfaya National Park (Spain). IEEE Xplore Abstract. Advanced Ground Penetrating Radar (IWAGPR), 2015 8th International Workshop, doi: 10.1109/IWAGPR.2015.7292641.
- Tammaro, U, Romano, V., Arnoso, J., Benavent, M., Riccardi, U., Montesinos, FG., Velez, EJ., Meo, M. (2023). Unsteady thermo-fluid-dynamics modelling of Timanfaya volcanic area (Lanzarote, Canary Islands) and present-day ground deformation. EGU General Assembly 2023. doi:10.5194/egusphere-egu23-16329.
- Tammaro, U., Romano, V., Arnoso, J., Benavent, M., Riccardi, U., Montesinos, F.G., Vélez, E., Meo, M. (2024). Subsidence and thermo-fluid-dynamics modelling at Timanfaya volcanic area (Lanzarote, Canary Islands), *Pure and Applied Geophysics (submitted)*.
- Venedikov, A., Arnoso, J. & Vieira, R., (2003). VAV: A program for tidal data processing. *Computer & Geosciences*, Vol 29, No 4, pp. 487-502. doi: 10.1016/S0098-3004(03)00019-0.
- Venedikov, A.P., Arnoso, J., Cai, W., Vieira, R., Tan, S. and Vélez, EJ., (2006). Separation of the long-term thermal effects from the strain measurements in the Geodynamics Laboratory of Lanzarote. *Journal of Geodynamics*, Vol 41, pp. 213-220. doi: 10.1016/j.jog.2005.08.029.
- Vieira, R., Van Ruymbeke, M., Fernández, J., Arnoso, J., and Toro, C., (1991). The Lanzarote underground laboratory. *Cahiers du Centre Européen de Géodynamique et de Séismologie*, Vol 4, pp. 71-86.

Silica sinters from hydrothermal hot springs in active volcanic areas as a tool for astrobiological exploration

Blanca Martínez-Benítez^{1,2} and J. Javier Álvaro²

¹Facultad de Ciencias Geológicas (UCM), Departamento GEODESPAL, C. de José Antonio Novais, 12, 28040 Madrid, Spain (blanca.m@igeo.ucm-csic.es)

²Instituto de Geociencias (CSIC-UCM), Dr. Severo Ochoa 7, 28040 Madrid, Spain (jj.alvaro@csic.es)

Key words: *Opal-A; Permineralization; Microbes; Biomarkers; Sinter apron; Hydrothermalism; Mars*

ABSTRACT

The discovery of hydrated polyforms of silica on Mars, reported by the Martian Rover Spirit, opens new opportunities to different proxies for the study of ancient life on Mars based on Earth analogues. Precipitation of opal-A nano- and micro-spheres currently takes place in hydrothermal vents with strong links to volcanic activity, known as “sinter apron complexes”. These comprise near neutral, alkali-chloride waters that are oversaturated in silica breaching the surface through geothermal vents, leading to the formation of hot springs and the precipitation of amorphous opal-A. These environments have a great importance in the geological record because the first evidences of life in our planet are hosted in Archaean cherts. Modern-day sinter apron complexes can offer unique insights into the formation of microbial-bearing deposits. In this work, we discuss the results of two campaigns that took place in the Icelandic geothermal fields of Krýsuvík, Hveragerði and Hveravellir, where the sinter microfacies distribution, strongly related to the dominant microbial communities, and the composition and preferred habitat of the microbial assemblages, were analyzed. The affinity of the organic matter has been established by a combination of scanning electron microscopic (SEM) photography and lipid biomarker analysis. The combination of these techniques, alongside paleoenvironmental reconstruction based on the distribution of facies associations, fabrics and textures along streams and ponds, may represent a tool for the astrobiological exploration on ancient Mars.

1. INTRODUCTION

It is currently believed that, due to the low amounts of liquid water, the surface of Mars does not fit with Earth habitability models. As such, much of the search for Martian life has been focused on the preservation of subglacial lakes (Orosei *et al.*, 2018). However, it is possible that the Martian surface sustained life in the distant past, 3.8 billion years ago. At that time, Mars would have recorded higher surface temperatures, a denser atmosphere and vast oceans and rivers (Nazari-Sharabian *et al.*, 2020) where microorganisms may have flourished.

Since 2007, the Mars Rover Spirit and subsequent missions have revealed the existence of a significant amount of hydrated silica on Mars. Hydrated silica is a general term used to refer to both amorphous and crystalline forms of Si-OH minerals (Rogers *et al.*, 2023). Several different theories have been postulated to explain the presence of hydrated silica on the red planet, including direct precipitation in lacustrine and hydrothermal environments, diagenetic and sedimentary processes and the fluid alteration of volcanic rocks (Tarnas *et al.*, 2019).

In order to correctly separate geothermal environments from other forms of silica, scientists employ two different methods: (i) the use of Visible and Near Infrared Reflectance spectroscopy (VNIR), which is capable of identifying opal-A, the main

component of hydrothermal sinter (Álvaro *et al.*, 2021), from other silica phases based on its absorption features (Sun & Milliken, 2018); and (ii) the use of comparative geomorphology with Earth's hot springs and geothermal fields (Rogers *et al.*, 2023; Ruff *et al.*, 2020).

Some localities where presumed silica sinters have been found are: the Melas basin in the Valles Marineris (Rogers *et al.*, 2023); the Home Plate in Columbia Hills (Squyres *et al.*, 2008); and the Nili Patera (Skok *et al.*, 2010). The Valles Marineris is a 4000 km long canyon located in the Tharsis region (Peulvast *et al.*, 2001), whose tectonic origin is still the subject of debate. Some authors support rift system interpretations, similar to the African Rift Valley (Witbeck *et al.*, 1991), while others argue for a strike-slip model with a strong left component (Yin, 2012) mimicking the Dead Sea. The Melas basin (Figure 1a), located on the southern wall of the Melas Chasma, contains a number of silica mounds that have been interpreted as spring deposits, based on their similar morphology to terraces and spring pools (Rogers *et al.*, 2023), similar to those found in the Krýsuvík geothermal field (Álvaro *et al.*, 2021). The spectra data of these deposits most resembles opal-A. The Home Plate (Figure 1b) is a volcanic landmark located in the Columbia Hills of the Gusev crater (Squyres *et al.*, 2008). It is surrounded by silica outcrops and regolith

that have been identified as opal-A based on the use of Thermal Infrared (TIR) spectra, while its geomorphology resembles that of El Tatio geyser field, in Chile, and Roosevelt Springs in USA (Ruff *et al.*, 2020). Finally, the use of Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) has detected the presence of silica deposits on the slopes surrounding the Nili Patera caldera (Figure 1c), where the hydrothermal system is fed by volcanic activity (Skok *et al.*, 2010), similar to different volcanic fields of Iceland.

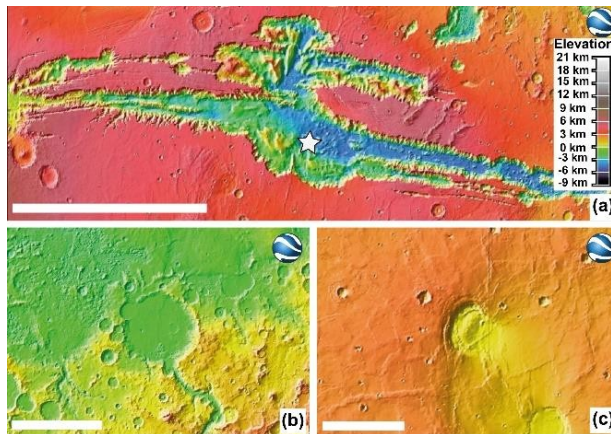


Figure 1. Photographs of the different Martian areas where hydrothermally induced hydrated silica has been detected. (a): Valles Marineris with position of the Melas Basin (see star); scale bar= 900 km; (b): Home Plate, Columbia Hills of Gustav crater; scale bar= 200 km; (c): Nili Patera; scale bar= 100 km; all photographs taken from Google Earth.

The presence of hydrated siliceous polymorphs induced by hydrothermal activity is significant due to the preservation, on Earth analogues, of distinct microbially induced signatures, even in rocks as old as the Archaean, due to silicification process linked to hydrothermal activity (Westall *et al.*, 2015), and the rapid precipitation of opal-A in hot springs, entombing the organic matter and preventing its degradation (Cady *et al.*, 2003).

Examples of this phenomenon can be found in the Palaeoarchaeon Strelley Pool Formation of the Pilbara Craton, Australia (Sugitani *et al.*, 2015), the Palaeoproterozoic Gunflint Chert of Ontario, Canada (González-Flores *et al.*, 2022), and the Devonian Rhynie Chert in Scotland (Edwards *et al.*, 2017). Furthermore, sinter composition and microtextures are strongly dependent on the microbial community that inhabit these waters (Cady & Farmer, 1996), a useful clue when direct biomarker analysis or morphological interpretation is not yet possible, as is the case on Martian sinters. All these factors contribute to making the study of sinter deposits a vital piece for the understanding of ancient life on Mars.

In order to better understanding Mars's sinter complexes, a detailed analysis of their Earth analogues is necessary. Many hydrothermal systems on Earth are

linked to the existence of hotspots, which play an important part both in continental rifts (Golonka & Bocharova, 2000) and intra-plate geologically active areas (Pirajno, 2004). The latter include oceanic island chains like Hawaii (Wilson, 1963), Cape Verde (Courtney & White 1986) and the Canary Islands (Negredo *et al.*, 2022). Hotspots are also responsible for intraplate continental volcanics, strongly linked to the formation of geothermal fields, such as Yellowstone (Courtillet *et al.*, 2003).

The selection of Iceland is based on a combination of geophysical features: the Mid-Atlantic Ridge and a deep hotspot (Dyment *et al.*, 2007), being a clear example of the “on ridge” hotspot interaction (Wolfe *et al.*, 1997). This peculiarity of Iceland would explain its frequent magmatism, tectonic events, and intense geothermal activity (Hardarson *et al.*, 2015).

II. GEOLOGICAL AND GEOGRAPHIC CONTEXT

Based on its volcanic and seismic activity, Iceland has been subdivided into different tectonostratigraphic zones (Figure 2): the Western, Eastern, Northern and Mid-Iceland Volcanic Zones (WVZ, EVZ, NVZ, MIVZ) the South Iceland Seismic Zone (SISZ) and the Reykjanes Ridge and Peninsula (RR, RP) (Hardarson *et al.*, 2015).

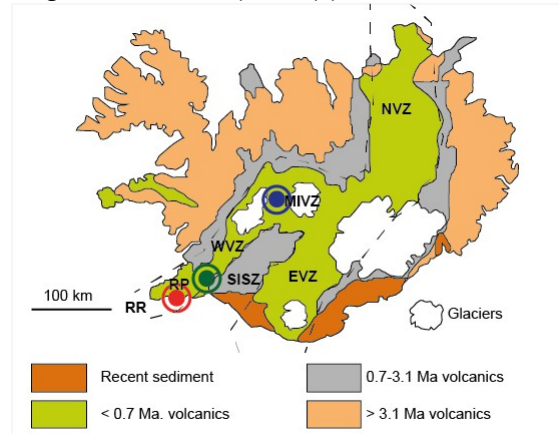


Figure 2. Simplified geological map of Iceland modified from Jóhannesson & Sæmundsson (1998), with tectonic divisions incorporated from Hardarson *et al.*, (2015). The three geothermal fields mentioned in this study are indicated: Krýsuvík (red), Hveragerði (green) and Hveravellir (blue). RR= Reykjanes Ridge; RP= Reykjanes Peninsula; WVZ= Western Volcanic Zone; MIVZ= Mid-Iceland Volcanic Zone; EVZ= Eastern Volcanic Zone; NVZ= Northern Volcanic Zone; SISZ= South Iceland Seismic Zone.

Three geothermal fields were selected for this study, Krýsuvík, Hveragerði and Hveravellir (Figure 2). The Krýsuvík geothermal field is located on the Reykjanes Peninsula and has a total extension of 40 km² (Sæmundsson, 1992). The Hveragerði geothermal field is found in the Western Volcanic Zone, in the Southern Lowlands (Hardarson *et al.*, 2015), inside the Hengill triple volcanic junction (Walker, 1992). And the Hveravellir geothermal area is nestled between the Langjökull and Hofsjökull glaciers (to the west and east

of the field, respectively), within the Mid-Iceland Volcanic Zone. All of them share common geomorphological features, such as steam fumaroles, hot springs, and mud pots. Water vapor plays a very important role within the systems, as the water composition is the result of the alteration of the volcanosedimentary basement (Markússon & Stefánsson, 2011). Each field is characterized by different ranges of temperature, pH, silica content (in ppm), and the additional chemical components in solution (Table 1).

Table 1: Main parameters of the hydrothermal waters in the three studied fields; data taken from Ármannsson *et al.* (2005), Tobler *et al.*, (2008); Williams *et al.*, (2021); Álvaro *et al.* (2021) and Daba (2008).

	Krýsuvík	Hveragerði	Hveravellir
T (°C)	75-60	100-20	97
pH	1.7-7.7	9.05	8.2-8.6
Si (ppm)	700-200	304	641-321
Other main components	SO ₄ ⁻² , Fe, Al	Na, Cl, SO ₄ ⁻²	Cl, SO ₄ ⁻² , Na

III. SINTER APRON COMPLEXES

Sinters or siliceous hot spring deposits are formed when the Earth's surface and the water table intersect, allowing geothermal fluids with close to neutral pH, alkali chloride composition and high silica content to be expelled (Hamilton *et al.*, 2019). As the fluids flow away from the geothermal vents, the water temperature drops from values >100°C to ambient, increasing silica insolubility and leading to the precipitation of hydrated amorphous silica, known as opal-A (Lynne *et al.*, 2019).

The trigger mechanisms for opal-A precipitation are mostly abiotic, such as the previously mentioned rapid cooling of the waters as they move away from the vent (Tobler *et al.*, 2008), evaporate concentration due to boiling or the acidification of the waters at fluid interfaces (Weed, 1889). However, living organisms can play a part in opal-A precipitation by acting as nucleation sites (Konhauser & Ferris, 1996).

The microbial communities living in the streams and pools of a sinter apron complex play a significant role in determining the resulting sinter composition and texture, alongside fluid composition, flow rate and volume (Cady & Farmer, 1996). As the fluid temperature and composition changes in a gradient from the vents to the outer areas of the sinter complex, the inhabiting microbial associations also change. That is why the analysis of sinter facies can be used as a tool for paleoenvironmental reconstruction in the geological record.

A. Parts of the sinter apron complex and facies

A sinter apron complex can be subdivided into several different areas, each with its own characteristic

facies and dominant micro-organisms (Cady & Farmer, 1996):

- (I) The geothermal vent or vent pool (Figure 3a), where the hydrothermal fluids breach the surface at temperatures between 100°C-70°C or in some areas >100°C. Silica precipitation occurs directly from the water column, creating accumulations of geyserite (Channing, 2017).
- (II) The sinter, subdivided into the proximal (100°C-65°C), middle (65°C-45°C) and distal (<45°C) apron. The high variety of organisms that populate this area results in significant diversity of facies and deposits, many of them linked to cyanobacterial presence (Figure 3b), such as the palisade textures of the distal apron (Figure 3c) (Hamilton *et al.*, 2019).
- (III) The geothermal wetland extends several kilometers around the apron complex. The cooler (ambient) waters allow the establishment of a complex ecosystem that includes higher plants and micro/macrobenthos (Channing, 2017). These can include disarticulated plant debris, such as the leaves of vascular plants or the gametophytes of bryophytes accumulating on streams and pools. The silica precipitation generates plant-sinter agglomerates (Figure 3d).

B. Life in the sinter apron

The characterization of microbial life is possible because the microbes living in streams and pools with a constant flow of silica are silicified before degradation (Schultze-Lam *et al.*, 1995), which preserves the microbial ultrastructure in great detail. Álvaro *et al.* (2021) reported in Krýsuvík the presence of cyanobacteriomorphs, bacilli and coccoid bacteriomorphs, and possibly iron oxidizing bacteria. Silicified filamentous cyanobacteriomorphs and coccoid bacteriomorphs are also reported from the Hveragerði geothermal field (Figure 4a). SEM analysis allows the identification of microbial morphologies (morphotypes), but not of their taxonomic affinities. This can be achieved by using lipid biomarker analysis.

The identification of distinct biosignatures, such as archaeol, diacyl glycerol diethers and fatty acids, in Krýsuvík supports the influence of archaea, thermophilic bacteria, cyanobacteria, sulfate reducing bacteria and methanogenic archaea (Álvaro *et al.*, 2021). Previous studies of the biosignatures of living microbial mats (Robinson & Eglinton, 1990) in Hveragerði and Hveravellir have identified n-heptadecanes, different branched alkanes, hexadecanol, phytol and fatty acids, indicative of the presence of cyanobacteria and bacteria.

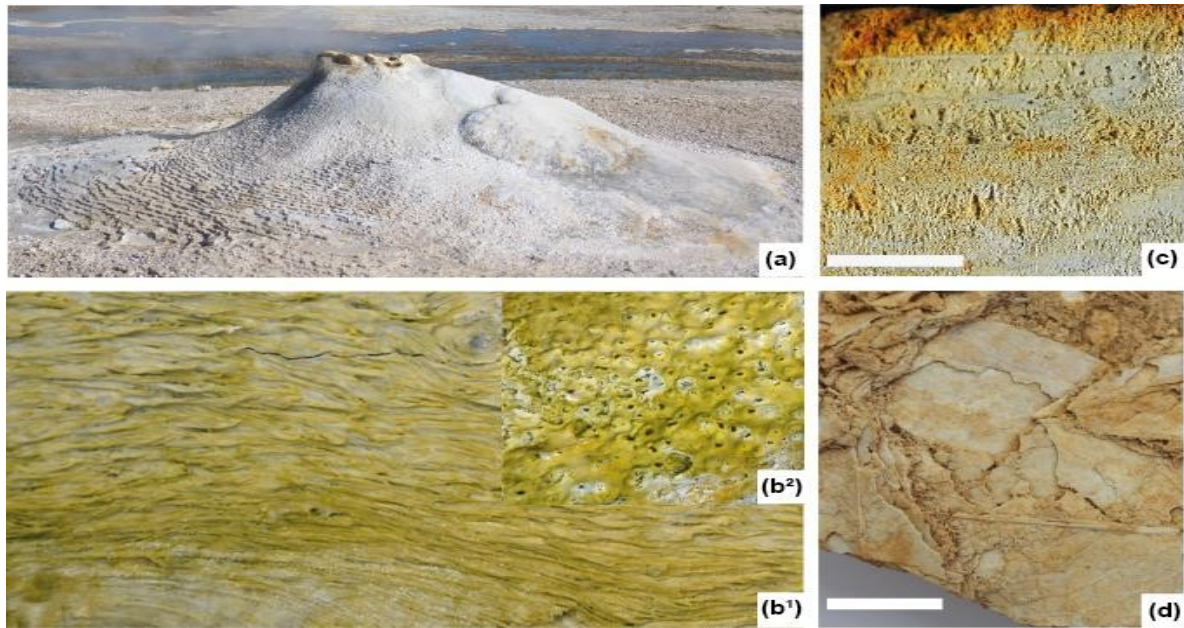


Figure 3. Field photographs taken from the studied geothermal fields of Iceland. (a): Hydrothermal vent with superposed chemical geyserite, Hveravellir; (b): microbial mats not yet silicified with a close-up (b2) of a bubble mat, Hveravellir; (c): silicified microbial mat from Krýsuvík, scale bar= 1 cm; (d): silicified plant matter from Hveragerði, scale bar= 1 cm.

Archaeas and thermophilic bacteria develop under extreme conditions (high temperature and acidic pH) in the geothermal vents (Channing, 2017); cyanobacteria and sulfate reducing bacteria are common in streams and pools, where they form microbial mats, and the dominant lifeform in the distal apron and the geothermal wetlands are cyanobacteria (Lynne & Campbell, 2003; Álvaro *et al.*, 2021).

Sinter apron complexes also favour the preservation of plant debris (Figure 4b), thanks to the permineralization process. Permineralization begins when silica precipitates in the cell walls of the organism (Leo & Barghoorn, 1976) entombing the original organic matter and allowing the preservation of exquisite anatomical and cellular detail (Mustoe, 2017).

Gradual permineralization even occurs simultaneously under tissue degradation, leading to extraordinary preservation patterns (Mustoe 2015). In the Hveragerði sinter, numerous disarticulated parts of bryophytes are identifiable, such as gametophyte stems, as well as disarticulated leaves, some of them exhibiting the midrib.

IV. CONCLUSIONS

As our knowledge of Martian geology and hydrothermal environments grows, the study of Earth's analogue sinter apron complexes, both actual and fossil, has become an invaluable tool for the search of life on ancient Mars.

Most of the research rock material sampled in Mars consists of photographic evidence and spectral analysis, whereas the petrological and (bio)geochemical analysis of the analogous rocks still remains the primary method for palaeoenvironmental reconstruction. The combined analysis of chemical precipitates and microbial permineralization in silica sinters can serve as a proxy for future analysis of Martian hydrothermal areas. In the future, once Martian sinter samples become accessible to the scientific community, our ability to identify and classify microbial life based on external morphology and biomarker analysis will play a more significant, even vital, scientific role.

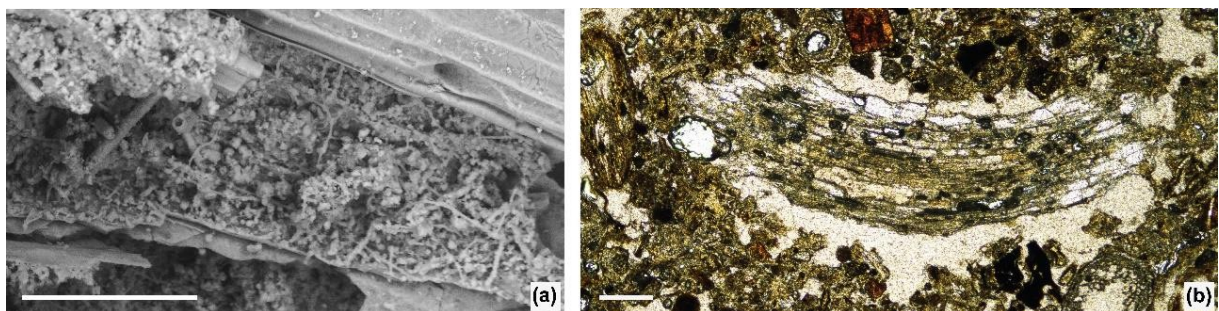


Figure 4. Examples of silicified plant debris preserved in Hveragerði. (a): SEM photograph of a meshwork composed of filamentous cyanobacteriomorphs; scale bar= 100 µm; (b): Thin section photomicrographs of a bryophytic gametophyte stem, cut in longitudinal section, tentatively identified as belonging to the Family Sphagnaceae; scale bar= 200 µm.

V. ACKNOWLEDGEMENTS

The authors appreciate the revisions made by the WGAAL 2023 editing team, and the work of the organizing committee. This study was supported by the Spanish Project PID2021-125585NB-I00, financed by the MCIN/AEI and FEDER.

References

- Álvaro, J.J., Sánchez-Román, M., Nierop, K.G.J. and Peterse, F., (2021). Multiscale microbial preservation and biogeochemical signals in a modern hot-spring siliceous sinter rich in CO₂ emissions, Krýsuvík Geothermal Field, Iceland. *Minerals* 11, 263.
- Ármansson, H., Fridriksson, T. and Kristjánsson, B.R., (2005). CO₂ emissions from geothermal power plants and natural geothermal activity in Iceland. *Geothermics* 34, pp. 286–296.
- Cady, S.L. and Farmer, J.D., (1996). Fossilization processes in siliceous thermal springs: Trends in preservation along thermal gradients, in: *Ciba Foundation Symposium 202 – Evolution of Hydrothermal Ecosystems on Earth (and Mars?)*. John Wiley & Sons, Ltd, pp. 150–173.
- Cady, S.L., Farmer, J.D., Grotzinger, J.P., Schopf, J.W. and Steele, A., (2003). Morphological biosignatures and the search for life on Mars. *Astrobiology* 3, pp. 351–368.
- Channing, A., (2017). A review of active hot-spring analogues of Rhynie: environments, habitats and ecosystems. *Philosophical Transactions of the Royal Society B: Biological Sciences* 373, 20160490.
- Courtillot, V., Davaille, A., Besse, J. and Stock, J., (2003). Three distinct types of hotspots in the Earth's mantle. *Earth and Planetary Science Letters* 205, pp. 295–308.
- Courtney, R.C. and White, R.S., (1986). Anomalous heat flow and geoid across the Cape Verde Rise: evidence for dynamic support from a thermal plume in the mantle. *Geophysical Journal International* 87, pp. 815–867.
- Dyment, J., Lin, J. and Baker, E.T., (2007). Ridge-hotspot interactions: what mid-ocean ridges tell us about deep Earth processes. *Oceanography* 20, pp.102–115.
- Edwards, D., Kenrick, P. and Dolan, L., (2017). History and contemporary significance of the Rhynie cherts—our earliest preserved terrestrial ecosystem. *Philosophical Transactions of the Royal Society B: Biological Sciences* 373, 20160489.
- Golonka, J. and Bocharova, N.Y. (2000). Hot spot activity and the break-up of Pangea. *Palaeogeography, Palaeoclimatology, Palaeoecology* 161, pp. 49-69.
- González-Flores, A.I., Jin, J., Osinski, G.R. and Tsujita, C.J., (2022). Acritarch-like microorganisms from the 1.9 Ga Gunflint Chert, Canada. *Astrobiology* 22, pp. 568–578.
- Hamilton, A., Campbell, K., Guido, D.M., (2019). Atlas of siliceous hot spring deposits (sinter) and other silicified surface manifestations in epithermal environments. *Institute of Geological and Nuclear Sciences (Report) Limited*.
- Hardarson B., B.S., Kristinsson, S.G., Karlsdóttir, R. and Einarsson, G.M., (2015). Geothermal implications of rift zone mini-grabens-geological and geophysical structure of the Reykjafell mini-graben, Hengill geothermal field, SW Iceland: *Transactions – Geothermal Resources Council* 39, p. 537
- Jóhannesson, H. and Sæmundsson, K., (1998). Geological map of Iceland, 1: 500,000. Tectonics. Icelandic Institute of Natural History, Reykjavik.
- Konhäuser, K.O. and Ferris, F.G., (1996). Diversity of iron and silica precipitation by microbial mats in hydrothermal waters, Iceland: Implications for Precambrian iron formations. *Geology* 24, pp. 323–326.
- Leo, R.F. and Barghoorn, E.S., (1976). Silicification of wood. *Botanical Museum Leaflets*, Harvard University 25, pp. 1–47.
- Lynne, B.Y. and Campbell, K.A., (2003). Diagenetic transformations (opal-A to quartz) of low- and mid-temperature microbial textures in siliceous hot-spring deposits, Taupo Volcanic Zone, New Zealand. *Canadian Journal of Earth Sciences* 40, pp. 1679–1696.
- Lynne, B.Y., Boudreau, A., Smith, I.J. and Smith, G.J., (2019). Silica accumulation rates for siliceous sinter at Orakei Korako geothermal field, Taupo Volcanic Zone, New Zealand. *Geothermics* 78, pp. 50–61.
- Markússon, S.H. and Stefánsson, A., (2011). Geothermal surface alteration of basalts, Krýsuvík Iceland—Alteration mineralogy, water chemistry and the effects of acid supply on the alteration process. *Journal of Volcanology and Geothermal Research* 206, pp. 46–59.
- Mustoe, G.E., (2015). Late Tertiary petrified wood from Nevada, USA: Evidence of multiple silicification pathways. *Geosciences* 5, pp. 286–309.
- Mustoe, G.E., (2017). Wood petrification: A new view of permineralization and replacement. *Geosciences* 7, pp. 1–17.
- Nazari-Sharabian, M., Aghababaei, M., Karakouzian, M. and Karami, M., (2020). Water on Mars—A literature review. *Galaxies* 8, pp.40.
- Negredo, A. M., van Hunen, J., Rodríguez-González, J. and Fulla, J., (2022). On the origin of the Canary Islands: insights from mantle convection modelling. *Earth and Planetary Science Letters* 584, 117506.
- Orosei, R., Lauro, S.E., Pettinelli, E., Cicchetti, A., Coradini, M., Cosciotti, B., Di Paolo, F., Flamini, E., Mattei, E., Pajola, M., Soldovieri, F., Cartacci, M., Cassenti, F., Frigeri, A., Giuppi, S., Martufi, R., Masdea, A., Mitri, G., Nenna, C., Noschese, R., Restano, M. and Seu, R., (2018). Radar evidence of subglacial liquid water on Mars. *Science* 361, pp. 490–493.
- Peulvast, J.-P., Mège, D., Chiciak, J., Costard, F. and Masson, P.L., (2001). Morphology, evolution and tectonics of Valles Marineris wallslopes (Mars). *Geomorphology* 37, pp. 329–352.
- Pirajno, F., (2004). Hotspots and mantle plumes: global intraplate tectonics, magmatism and ore deposits. *Mineralogy and Petrology* 82, pp. 183–216.
- Robinson, N. and Eglinton, G., (1990). Lipid chemistry of Icelandic hot spring microbial mats. *Organic Geochemistry* 15, pp. 291–298.
- Rogers, E.R., Qualizza, B.R., Heidenreich, J.R., Dawson, H.G. and Horgan, B.H.N., (2023). Silica-bearing mounds and strata in the Southwest Melas Basin, Valles Marineris, Mars: Evidence for a hydrothermal origin. *Journal of Geophysical Research: Planets* 128, e2023JE007881.

- Ruff, S. W., Campbell, K. A., Van Kranendonk, M. J., Rice, M. S. and Farmer, J.D., (2020). The case for ancient hot springs in Gusev crater, Mars. *Astrobiology* 20, pp. 475–499.
- Sæmundsson, K., (1992). Geology of the Thingvallavatn Area. *Oikos* 64, pp. 40–68.
- Schultze-Lam, S., Ferris, F.G., Konhauser, K.O. and Wiese, R.G., (1995). In situ silicification of an Icelandic hot spring microbial mat: implications for microfossil formation. *Canadian Journal of Earth Sciences* 32, pp. 2021–2026.
- Skok, J.R., Mustard, J.F., Ehlmann, B.L., Milliken, R.E. and Murchie, S.L., (2010). Silica deposits in the Nili Patera caldera on the Syrtis Major volcanic complex on Mars. *Nature Geosciences* 3, pp. 838–841.
- Squyres, S.W., Arvidson, R.E., Ruff, S., Gellert, R., Morris, R.V., Ming, D.W., Crumpler, L., Farmer, J.D., Marais, D.J.D., Yen, A., McLennan, S.M., Calvin, W., Bell, J.F., Clark, B.C., Wang, A., McCoy, T.J., Schmidt, M.E. and de Souza, P.A., (2008). Detection of silica-rich deposits on Mars. *Science* 320, pp. 1063–1067.
- Sugitani, K., Mimura, K., Takeuchi, M., Yamaguchi, T., Suzuki, K., Senda, R., Asahara, Y., Wallis, S. and Van Kranendonk, M.J., (2015). A Paleoproterozoic coastal hydrothermal field inhabited by diverse microbial communities: the Strelley Pool Formation, Pilbara Craton, Western Australia. *Geobiology* 13, pp. 522–545.
- Sun, V.Z. and Milliken, R.E., (2018). Distinct geologic settings of opal-A and more crystalline hydrated silica on Mars. *Geophysical Research Letters* 45 (19), pp. 10–221.
- Tarnas, J. D., Mustard, J. F., Lin, H., Goudge, T. A., Amador, E. S., Bramble, M. S., Kremer, C. H., Zhang, X., Itoh, Y. and Parente, M., (2019). Orbital identification of hydrated silica in Jezero crater, Mars. *Geophysical Research Letters* 46 (22), pp. 12771–12782.
- Tobler, D.J., Stefánsson, A. and Benning, L.G., (2008). In-situ grown silica sinters in Icelandic geothermal areas. *Geobiology* 6, pp. 481–502.
- Walker, C., (1992.) The volcanic history and geochemical evolution of the Hveragerði Region, S. W. Iceland. Doctoral, Durham University, 403p.
- Weed, W.H., (1889). The Vegetation of hot springs: *The American Naturalist* 23, pp. 394–400.
- Westall, F., Foucher, F., Bost, N., Bertrand, M., Loizeau, D., Vago, J.L., Kminek, G., Gaboyer, F., Campbell, K.A., Bréhéret, J.G., Gautret, P. and Cockell, C.S., (2015). Biosignatures on Mars: what, where, and how? Implications for the search for Martian life. *Astrobiology* 15, pp. 998–1029.
- Williams, A.J., Craft, K.L., Millan, M., Johnson, S.S., Knudson, C.A., Juarez Rivera, M., McAdam, A.C., Tobler, D. and Skok, J.R., (2021). Fatty acid preservation in modern and relict hot-spring deposits in Iceland, with implications for organics detection on Mars. *Astrobiology* 21, pp. 60–82.
- Wilson, J.T., (1963). A possible origin of the Hawaiian islands. *Canadian Journal of Physics* 41, pp. 863–870.
- Witbeck, N.E., Tanaka, K.L. and Scott, D.H., (1991). Geologic map of the Valles Marineris region, Mars (No. 2010), IMAP. U.S. Geological Survey.
- Wolfe, C.J., Bjarnason, I., VanDecar, J.C. and Solomon, S.C., (1997). Seismic structure of the Iceland mantle plume. *Nature* 385, pp. 245–247.
- Yin, A., (2012). Structural analysis of the Valles Marineris fault zone: possible evidence for large-scale strike-slip faulting on Mars. *Lithosphere* 4, pp.286–330.

Slope Instability Mapping and Ground Deformation at Colli Albani Hills Volcano (Italy)

Claudia Spinetti¹, Marina Bisson², Lisa Beccaro¹, Laura Colini¹, Alessandro Galvani, Roberto Gianardi², Vincenzo Sepe¹, Cristiano Tolomei¹

¹Istituto Nazionale di Geofisica e Vulcanologia, ONT, Via di Vigna Murata 605, 00143 Roma, Italy

(Claudia.Spinetti@ingv.it, Lisa.Beccaro@ingv.it, Laura.Colini@ingv.it, Alessandro.Galvani@ingv.it, Vincenzo.Sepe@ingv.it, Cristiano.Tolomei@ingv.it)

²Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Via Cesare Battisti 53, 56125 Pisa, Italy

(Marina.Bisson@ingv.it, Roberto.Gianardi@ingv.it)

Key words: Colli Albani Hills; landslides; slope instability; ground deformation; InSAR

ABSTRACT

Colli Albani Hills is a complex volcanic calderic system in a state of quiescence located 20 km SE of Rome (Italy). It is affected by seismic swarms, manifests gaseous emissions and ground deformations. Its volcanic activity dates back to about 600 ky with evidence of pyroclastic flows, lahars, lava fields and ash fallout deposits. Given the high population density of the area, the volcanic system is included in the list of Italian areas exposed to volcanic risk. According to historical data, all the volcanic complex is affected by landslides of different typologies, however the most frequent events result to be the sliding movements, in particular, the debris flows. In this work, the slope instability and the ground deformation of Colli Albani Hills (CA) is investigated and mapped. In order to obtain a debris flow susceptibility map, instability predisposing parameters are identified, calculated and combined in a heuristic approach. Such parameters include morphometry derived from Digital Elevation Model, Geo-lithology and Land Use. The elaborations, performed in GIS environment, provide as output a map that classifies the CA area according to different debris flow susceptibility degrees. Moreover, investigations have been carried out on the ground deformations by analyzing InSAR data from ESA Sentinel-1 (C-Band) satellite. Mean ground velocity maps and the relative displacement time series have been obtained over a time period from 2015 to 2022. Finally, InSAR results have been compared with the GNSS network data highlighting a quite overall stable areas of CA, except in the Genzano di Roma locality where a ground deformation is still present.

I. INTRODUCTION

Colli Albani Hills (CA) is a quiescent volcanic complex located 20 km SE of Rome (Italy). The CA is the southern volcano in the region of Lazio (Figure 1). It consists of a major volcanic edifice (Tuscolano-Artemisio) with a horseshoe-shaped caldera, an intracaldera central edifice (Monte delle Faete, 956 m a.s.l.), minor intracaldera and circum-caldera scoria cones and maars (Giordano *et al.*, 2010). Volcanic activity starts in the period of approximately 600 k years ago with evidence of the occurrence of pyroclastic flow events, lahars, lava fields and ash fallout deposits (Giordano *et al.*, 2006). Its eruptive activity, unlike the other volcanic districts of Lazio region, was characterized by well-clustered cycles, regularly spaced in time. The average recurrence is 45 ky, and with a shorter interval of 30 ky during the last 100 ky, independently from the eruptive style and energy (Marra *et al.*, 2016). Although the last volcanic activity is dated back about 20 ky (De Rita *et al.*, 1995), the volcano edifice still continuing to be subject to seismic swarms, gaseous emissions and ground deformations.

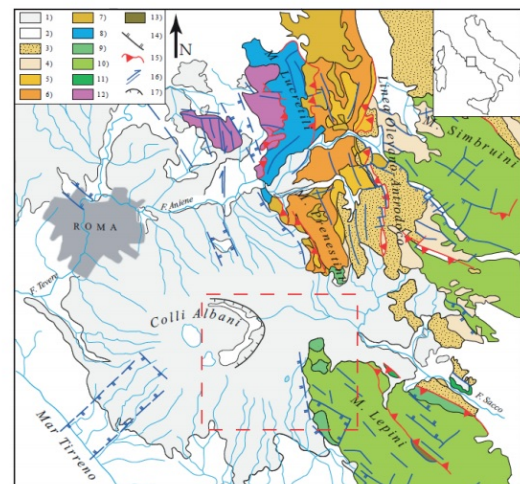


Figure 1. Colli Albani Hills location. Deposits: 1) and 2) post-orogenic; 3) sin-orogenic; 4) pre-orogenic; 5), 6), 7) and 8) platform-basin transition domain. Platform: 9), 10) and 11) carbonate; 12) and 13) paleo-carbonate. 14) normal faults; 15) thrust; 16) strike-slip faults; 17) caldera rim (from Giordano *et al.*, 2010).

Seismic activity has been known since Roman times and in modern times, the most significant swarm occurred between 1989 and 1990 on the western side of the caldera (Funiciello *et al.*, 2003). Further back in time, around 3000 'shallow earthquakes' were recorded between 1700 and 1975 (Feuillet *et al.*, 2004).

Studies on degassing manifestations identify the volcanic North-West side as the sector mainly affected by strong gas emission from the soil, high pCO₂ values in groundwater and high Rn activity (Chiodini and Frondini, 2001). The emitted gases from the soil are CO₂ (up to 98 vol%) and H₂S (1-2 vol%) and are released into the atmosphere from several restricted areas (Carapezza *et al.*, 2012).

Ground deformations are characterized by continuous uplift detected through leveling, GPS and synthetic aperture radar interferometry (InSAR) techniques. An uplift of 30 cm in 43 years was measured from leveling surveys taken during 1950 – 1993 along a line crossing the zone of maximum elevation of the western flank of the caldera (Anzidei *et al.*, 2010). The analysis of permanent scatters from SAR images of the ERS1-2 satellites highlights a deformation field of 2.6 mm/year in the satellite's line of sight in the period 1993-2000 (Salvi *et al.*, 2004). GPS data from continuous monitoring stations indicate that both horizontal and vertical deformations are consistent with a shallow magmatic source (Trasatti *et al.*, 2018).

A multitude of literature works has been addressed to landslide studies concerning the Albano lake, where several events are recorded every year (Patera and Fabbri, 2022). However, all the volcanic complex is affected by a series of landslides (Figure 2) as recorded by the IFFI catalogue (ISPRA, 2006). Almost all the CA municipalities are affected by landslides. The most frequent events are the sliding movements and most of them are debris flows, as highlighted in Figure 2.

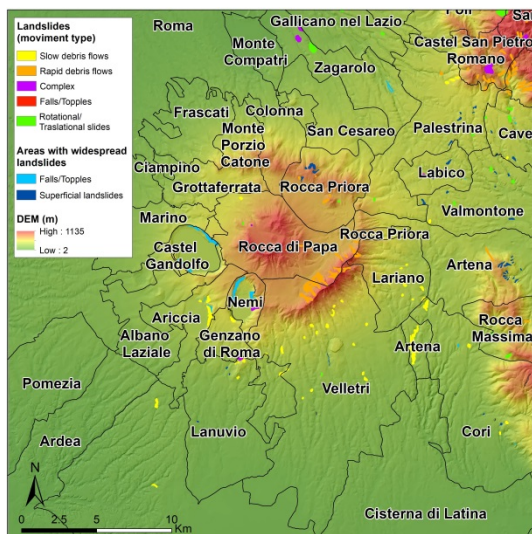


Figure 2. Historical landslides affected Colli Albani Hills volcanic complex (source from ISPRA 2006).

In this work, the slope instability of Colli Albani Hills is investigated and mapped through a debris flow susceptibility index. Moreover, the current ground deformation of the volcanic complex is investigated by using InSAR technique applied to ESA Sentinel-1 data.

II. DATASET AND METHOD

The heuristic approach, here applied, analyzes and relates parameters recognized in literature as significant predisposing factors to landslides generation (Bisson *et al.*, 2014, Bennie *et al.*, 2006, Bovis and Jakob 1999, Calcaterra *et al.*, 2000, De Riso *et al.* 1999, Mejià-Navarro *et al.* 1994, Spinetti *et al.*, 2019). The parameters, listed in Table 1, are represented by geo-spatial (WGS 84 UTM N33 system) raster dataset covering the entire extent of the Colli Albani Hills with a spatial resolution of 10 m.

The morphometric parameters Slope, Relative Relief and Aspect have been derived from the 10 m spatial resolution Digital Elevation Model (DEM) obtained by raster cartography (Tarquini *et al.*, 2007). The Lithology comes from the geo-portal (ISPRA, 2006) and consists in polygonal features that have been grouped in 6 different lithology types (Table 1). The Land Cover parameter was used to determine the type of surface and its influence with respect to the triggering of debris flows.

The parameters, as controlling the Debris Flows triggering, are weighted and ranked based on landslide literature data (mentioned above). The DFI index (*Debris Flows susceptibility index*) has been defined and calculated cell by cell using the following model equation:

$$DFI = \sum_{j=1}^m \sum_{i=1}^n (p_i * w_{ij}) \quad (1)$$

where i = represents the parameter and j its class;
 p_i = primary weight (the weight assigned to each parameter);
 w_{ij} = the relative class weight (the weight assigned to each class defined for each parameter).

The weights values are ranked on a scale from 1 to 10 for both p_i and w_{ij} assuming value 1 for the lowest influence and value 10 for the highest one. Assigned weights are in Table 1.

The parameters are calculated and then combined in GIS environment through the defined equation (1) which calculates in each area of 100 m² the Index of Susceptibility DFI.

Table 1 Predisposing factors to landslides generation (parameters of equation 1)

Parameter	Class	p_i	w_{ij}
Slope (S)	$S < 15^\circ$	1	10
	$15^\circ < S < 25^\circ$	4	
	$25^\circ < S < 35^\circ$	9	
	$S > 35^\circ$	10	
Aspect	S, SE, SW, E	8	5
	N, NE, NW, W	4	
Curvature (C)	flat	0	8
	$-1.5 < C < 0.5$	5	
	$-40 < C < -1.5$	10	
	convex	10	
Lithology	Lakes, Lava flow and Travertine;	0	9
	Breccia, Limestone and Tuffs;	1	
	Calcarenes, Marls and Filling soils;	3	
	Pozzolane, Scorie and Lapilli;	8	
	Colluvium, Elluvium, Cinerites and Red lands;	9	
	Gravel, sand and clay;	10	
Land Use	Industrial areas, commercial areas, communication and urbanized networks and artificial green areas;	3	7
	Permanent crops, stable meadows and heterogeneous agricultural areas;	4	
	Wooded areas;	5	
	Mining areas, landfills and construction sites;	6	
	Vegetated, shrubby and herbaceous areas	8	

The resulting source areas of the Debris Flows are shown in Figure 3, where the map of susceptibility is classified according to 5 degrees of Debris Flows susceptibility.

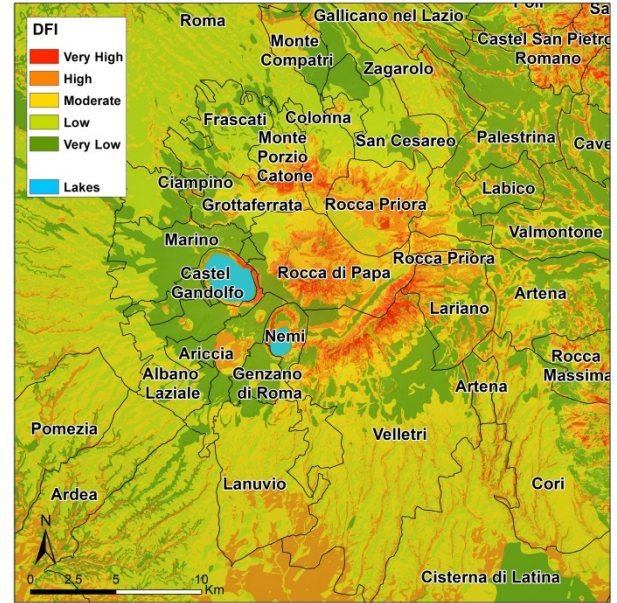


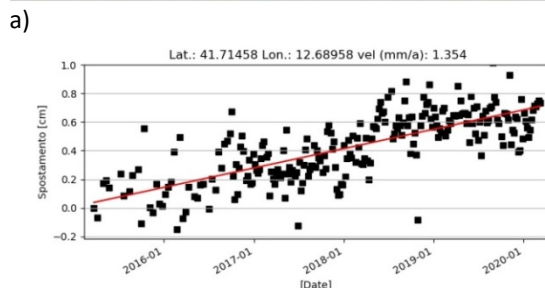
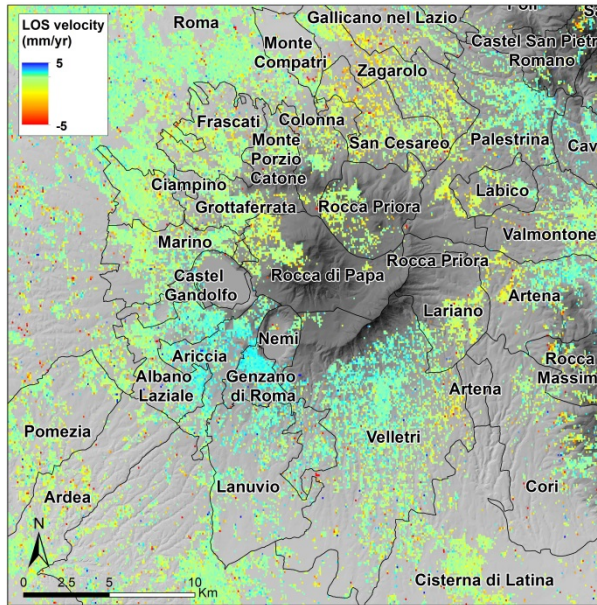
Figure 3. Debris Flows susceptibility map of the Colli Albani Hills volcanic complex.

III. INSAR ANALYSIS

Several datasets of SAR images acquired by the Copernicus Sentinel-1 constellation operated by the European Space Agency (ESA) were selected. The Sentinel-1 images were acquired in TOPSAR mode with a ground swath of 230x200 km along both ascending and descending orbits. The multi-temporal interferometry technique 'Small Baseline Subset' (SBAS, Berardino *et al.*, 2002) was applied to process the images and producing as output the mean ground velocity map and the displacement time series for each pixel of the map in the time range of the processed image dataset. The maps obtained have a ground resolution of 90 m and are georeferenced in the UTM reference system in lat/lon coordinates (decimal degrees) and show the mean ground velocity in the sensor's line of sight. The SBAS technique allows the processing of large quantities of images to generate interferometric pairs in order to preserve the temporal coherence and therefore the final spatial coverage as much as possible. In detail, four datasets of Sentinel-1 images were processed, two along the ascending orbit and two along the descending orbit covering different time intervals.

The processing has been produced 97 ascending images in the period 08/01/2019 - 29/03/2022 for 274 interferograms and 239 descending acquisitions (24/03/2015-09/03/2020) resulting in 693 interferometric pairs.

The images processed by means of the GeoExploitation Platform from ESA, provides the mean ground velocity map result (Figure 4).



b)
Figure 4. Mean ground velocity maps result from Sentinel-1 processing; a) descending orbit; b) ground deformation time series in Genzano di Roma.

In the Figure 4 mean ground velocity maps shows a quite overall stable areas of CA, except in the Genzano di Roma municipality where is still present a ground deformation in the period 2015-2020 with an inflation trend rate of about +1.4 mm/year.

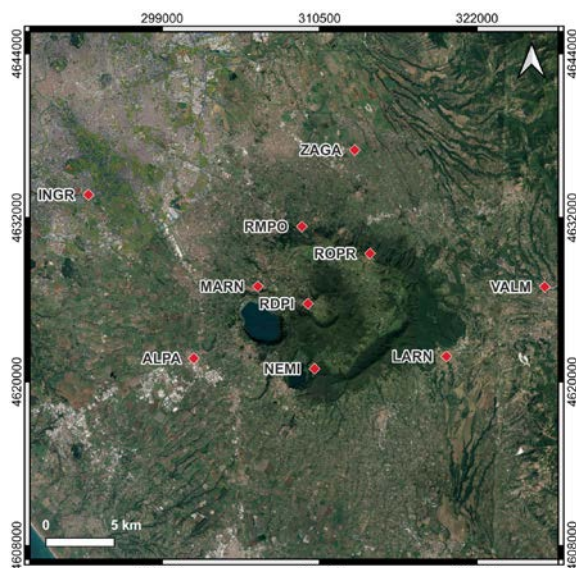


Figure 5. GNSS Colli Albani Hills RING network sites (except ZAGA and VALM discrete points of measurement).

A comparison of LoS velocities has been performed between GNSS data coming from the RING network (Figure 5) and mean velocities from Sentinel-1 descending track (light blue diamonds in Figure 6) and ascending track (red diamonds in Figure 6).

The GNSS mean velocities (from January 2016 to July 2022) were reprojected on Sentinel-1 descending LoS (blue triangles in Figure 6) in the period 24/03/2015-09/03/2020 and ascending LoS (orange triangles in Figure 6) in the period 08/01/2019 - 29/03/2022.

Comparison between Sentinel-1 and GNSS LoS velocities shows a general good agreement (almost all the considered GNSS station with ± 2 mm/year of errors) and considering that the observed period is slightly different.

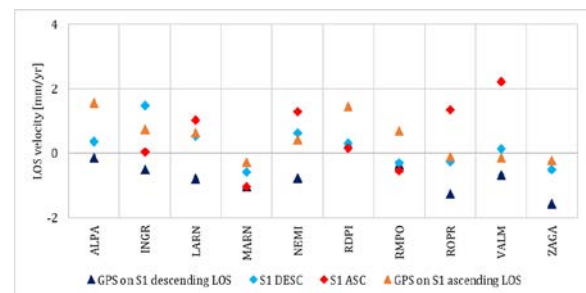


Figure 6. Comparison between GPS and Sentinel-1.

IV. CONCLUSIONS

The landslide susceptibility model and parameters has been obtained in terms of morphometric parameters, lithology and land use considering the debris flow the most typologies of landslide affecting Colli Albani Hills volcanic complex.

The Debris Flow susceptibility map obtained highlights that most of the sloping areas are at high susceptibility and correspond as source areas of slope instability.

InSAR analysis from 2015-2020 shows a ground deformation localized in the southern flank in the Genzano di Roma locality, while all the other municipalities result in quite stable areas. The rate of the inflation trend is about +1.4 mm/year obtained by Sentinel-1 data.

Comparison between Sentinel-1 and GNSS shows a general good agreement between the considered errors even if the observed period is slightly different.

V. ACKNOWLEDGEMENTS

This work was funded by Istituto Nazionale di Geofisica e Vulcanologia SIMCA Project (BRL 2022-2024). The European Space Agency (ESA) is acknowledged for providing the Sentinel-1 data.

References

- Anzidei, M., F. Riguzzi, and S. Stramondo (2010). Current geodetic deformation of the Colli Albani volcano: a review. Funicello, R. and Giordano, G. (eds) *The Colli Albani Volcano. Special Publication of IAVCEI*, Geological Society, London, Vol. 3, pp. 299-310.
- Bennie, J., M.O. Hill, R. Baxter and B. Huntley (2006). Influence of slope and aspect on longterm vegetation change in British chalk grasslands. *Journal of Ecology*, Vol. 94, No. 2, pp. 355-368.
- Berardino, P., G. Fornaro, R. Lanari and E. Sansosti (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on geoscience and remote sensing*, Vol. 40, No. 11, pp. 2375-2383.
- Bisson, M., C. Spinetti and R. Sulpizio (2014). Volcaniclastic flow hazard zonation in the Sub-Apennine Vesuvian area using GIS and remote sensing. *Geosphere*, Vol. 10, No. 6, pp. 1419-1431.
- Bovis, M. J. and M. Jakob (1999). The role of debris supply conditions in predicting debris flow activity. *Earth surface processes and landforms*, Vol. 24, No. 11, pp. 1039-1054.
- Calcaterra, D., M. Parise, B. Palma and L. Pelella (2000). Multiple debris-flows in volcaniclastic materials mantling carbonate slopes. In: *Debris-flow hazards mitigation: mechanics, prediction, and assessment*. Wiczeorek GF, Naeser ND (eds) Balkema, Rotterdam, pp. 99-107
- Carapezza, M.L., F. Barberi, M. Ranaldi, T. Ricci, L. Tarchini, J. Barrancos, and K. Weber (2012). Hazardous gas emissions from the flanks of the quiescent Colli Albani volcano (Rome, Italy). *Applied geochemistry*, Vol. 27, No. 9, pp. 1767-1782.
- Chiodini, G. and F. Frondini (2001). Carbon dioxide degassing from the Alban Hills volcanic region, Central Italy. *Chemical Geology*, Vol. 177, No. 1-2, pp. 67-83.
- De Riso, R., P. Budetta, D. Calcaterra and A. Santo (1999). Le colate rapide in terreni piroclastici del territorio campa-no. In: *Atti Convegno Previsione e prevenzione di movimenti franosi rapidi*, Trento, pp. 17-19.
- De Rita, D., C. Faccenna, R. Funicello and C. Rosa (1995), Stratigraphy and volcano tectonics. In: *The Volcano of the Alban Hills*, R. Trigila (ed), Tipogr. SGS, Rome, pp. 33 – 71.
- Feuillet, N., C. Nostro, C. Chiarabba and M. Cocco (2004). Coupling between earthquake swarms and volcanic unrest at the Alban Hills Volcano (central Italy) modeled through elastic stress transfer. *Journal of Geophysical Research: Solid Earth*, Vol. 109, No. B2.
- Funicello, R., G. Giordano and D. De Rita (2003). The Albano maar lake (Colli Albani Volcano, Italy): recent volcanic activity and evidence of pre-Roman Age catastrophic lahar events. *Journal of Volcanology and Geothermal Research*, Vol. 123, No. 1-2, pp. 43-61.
- Giordano, G., A.A. De Benedetti, A. Diana, G. Diano, F. Gaudioso, F. Marasco and R. Funicello (2006). The Colli Albani mafic caldera (Roma, Italy): stratigraphy, structure and petrology. *Journal of Volcanology and Geothermal Research*, Vol. 155, No. 1-2, pp. 49-80.
- Giordano, G., M. Mattei and R. Funicello (2010). Geological map of the Colli Albani volcano. In: *The Colli Albani volcano*. Special Publication of IAVCEI. Vol. 3. Geological Society London, London.
- ISPRA, (2006). Progetto IFFI. In: *Inventario dei Fenomeni Franosi in Italia*. <https://idrogeo.isprambiente.it/>
- Marra, F., M. Gaeta, B. Giaccio, B.R. Jicha, D.M. Palladino, M. Polcari, G. Sottili, J. Taddeucci, F. Florindo and S. Stramondo (2016). Assessing the volcanic hazard for Rome: 40Ar/39Ar and In- SAR constraints on the most recent eruptive activity and present-day uplift at Colli Albani Volcanic District. *Geophysical Research Letter*, Vol. 43, No. 13, pp. 6898–6906.
- Mejía-Navarro, M., E.E. Wohl, and S.D. Oaks (1994). Geological hazards, vulnerability, and risk assessment using GIS: model for Glenwood Springs, Colorado. In *Geomorphology and Natural Hazards*, Elsevier, pp. 331-354.
- Patera, A. and A. Fabbri (2022). Can We Assess Landslide Hazards In The Volcanic Crater Of Lake Albano, Rome, Italy?. *Risk Analysis, Hazard Mitigation and Safety and Security Engineering XIII*, Vol. 214, No. 3.
- Salvi, S., S. Atzori, C. Tolomei, J. Allievi, A. Ferretti, F. Rocca, C. Prati, S. Stramondo, and N. Feuillet (2004). Inflation rate of the Colli Albani volcanic complex retrieved by the permanent scatterers SAR interferometry technique, *Geophysical Research Letters*, Vol. 31, No. L12606, doi:10.1029/2004GL020253.
- Spinetti, C., Bisson, M., Tolomei, C., Colini, L., Galvani, A., Moro, M., and Sepe, V. (2019). Landslide susceptibility mapping by remote sensing and geomorphological data: Case studies on the Sorrentina Peninsula (Southern Italy). *GIScience & Remote Sensing*, Vol. 56, No. 6, pp. 940-965.
- Tarquini, S., Isola, I., Favalli, M., Mazzarini, F., Bisson, M., Pareschi, M.T., and Boschi, E., (2007). TINITALY/01: A new Triangular Irregular Network of Italy. *Annals of Geophysics*, Vol. 50, No. 3, pp. 407–425.
- Trasatti, E., Marra, F., Polcari, M., Etiope, G., Ciotoli, G., Darrah, T. H., (2018). Coeval uplift and subsidence reveal magma recharging near Rome (Italy). *Geochemistry, Geophysics, Geosystems*, Vol. 19, pp. 1484–1498. Doi:10.1029/2017GC007303

A new inversion method for InSAR and GNSS ground deformation data: some examples in Geodynamics and Engineering

Sen Du¹, Zhongbo Hu¹, Joaquin Escayo¹, Antonio G. Camacho¹, Juan F. Prieto², P. García-Cerezo³, S. Rodríguez⁴, D. Davoise⁴, José Fernández¹

¹Instituto de Geociencias (CSIC, UCM), Calle del Doctor Severo Ochoa, 7. 28040-Madrid, Spain, (dusen@ucm.es, zhongbo.hu@csic.es, jescayo@ucm.es, a.g.camacho@igeo.ucm-csic.es, jft@mat.ucm.es)

²ETS de Ingenieros en Topografía, Geodesia y Cartografía, Universidad Politécnica de Madrid, 28031-Madrid, Spain, (juanf.prieto@upm.es)

³MITERD, Subdirección General de Protección de las Aguas y Gestión de Riesgos, Dirección General del Agua. Plaza San Juan de la Cruz, 10. 28071-Madrid, Spain, (PGCerezo@miteco.es)

⁴Atalaya Mining. La Dehesa s/n. 21660 Minas de Riotinto. Huelva, Spain, (susana.rodriguez@atalayamining.com, diego.davoise@atalayamining.com)

Key words: *InSAR; GNSS; Geodynamics; volcano; Earthquake; Groundwater*

ABSTRACT

Developments in InSAR (Interferometric Synthetic Aperture Radar) and GNSS (Global Navigation Satellite System) during the past decades have provided high-resolution ground deformation data with dense spatio-temporal coverage. This large new dataset offers comprehensive insights into the deformation field and its time-evolution. Here we introduce a new interpretation methodology for InSAR and GNSS deformation results, which employs a combination of 3-D arbitrary sources for pressure and dislocations (including strike-slip, dip-slip, and tensile) simultaneously. The last generation InSAR observation techniques and this new interpretation modeling for geodynamics and engineering are applied to study earthquake, volcanic activity and groundwater extraction associated surface deformation. The results show that the combination of both tools can retrieve the characteristics of the sources correctly and accurately, therefore their use can have an important role in the assessment of volcanic and seismic hazards and in studying their implication on infrastructure and urban development planning, as well as for assessment of potential hazards associated with groundwater extraction and water reservoir exploitation management.

1. INTRODUCTION

Interferometric Synthetic Aperture Radar (InSAR) is a cutting-edge remote sensing technology that has revolutionized our ability to monitor and measure ground deformations, topographic changes, and a wide range of natural and anthropogenic phenomena with remarkable precision, it harnesses the power of radar waves emitted from spaceborne or airborne platforms to create highly detailed and accurate maps of surface displacements.

Compared with traditional deformation monitoring methods, such as leveling, GNSS and total stations, InSAR technology offers significant advantages in terms of coverage, precision, safety, cost-effectiveness, and data acquisition speed. Its remote sensing capabilities and ability to monitor large areas make InSAR an invaluable tool for a wide range of applications, from geology and environmental monitoring to infrastructure management and hazard mitigation (see e.g., Tomás et al., 2014).

On the other side, surface deformation can be a direct consequence of geodynamic activity. Therefore interpretation tools are needed to link observed deformation and causative sources. Normally, regular

geometries (point sources, disks, prolate or oblate ellipsoids, etc.) are assumed at the initial stages (e.g., Lisowski, 2007) and the resulting inversion is carried out in a linear context. InSAR techniques have resulted in the estimation of 1D to 3D deformation field with a dense spatio-temporal coverage never previously obtained. Consequently, high resolution-high precision measurements of ground deformation, with extensive coverage, are available allowing to study complex ground deformation fields in geodynamic areas.

Here we introduce a new inversion process aimed at the determination of the 3D geometry and the location of the causative sources by inverting ground deformations due to pressure, mass and/or dislocation anomalies embedded into an elastic medium. This is a more general inversion method that estimates non-subjective models of the observed deformation process within an almost entirely automatic framework.

Four cases are used in this paper to verify the proposed inversion model: A) Tracking magmatic intrusion at Mount Etna (Italy); B) surface deformation in Lorca (Spain) due to groundwater; C) 2014 Napa earthquake, Mw 6.0, California, US; D) 2021 volcano eruption in La Palma, Canary Islands, Spain. And we finish with a mining area stability study.

II. METHODS

A. Advanced time series InSAR process

Three different InSAR processing software are applied in these cases. For Mount Etna and Napa earthquakes, Gamma software (Wegmuller and Werner, 1997) is applied with RADARSAT-2 images. For the mining and groundwater examples we applied the SUBSIDENCE-GUI interferometric software based on the Coherent Pixels Technique (CPT) developed at the Polytechnic University of Catalonia (UPC) and DARES (Blanco, 2008; Bru, 2018). Sentinel-1 data of La Palma area was processed with both Gamma and the open source software combination of ISCE+MintPy (Roseu, 2012; Yunjun, 2019).

B. Interpretation tool

The current version of the interpretation methodology is an improved version of the ones based on previous works by Camacho et al. (2011), Cannavò et al. (2015), Camacho et al. (2020) and Fernández et al. (2021) and described in detail by Fernández et al. (2022).

The methodology inverts simultaneously ascending and descending sequential LOS displacement data from InSAR, assuming the possible existence of offset values in the data sets. 3-D arbitrary sources for pressure and dislocations (strike-slip, dip-slip, and tensile) sources are adjusted without any a priori hypotheses on the source nature, shape or location. The approach automatically assigns a source type, magnitude values (in MPa, for pressure and cm, for dislocations), position and orientation (angles of dislocation planes). The inversion approach is nonlinear and is based on an exploratory method within the model space. This exploration becomes feasible due to the incorporation of a variable scale factor. The approach commences with a 3D grid covering the entire subsurface volume, which is further divided into small prismatic cells. Through a step-by-step growth process, specific cells are successively filled with an adjusted type of deformation source and intensity values. Importantly, this approach does not necessitate planar, exact, or homogeneously distributed data.

Originally the interpretation methodology (Camacho et al., 2020) considered a dataset referred to a specific epoch. The new version (Fernández et al., 2022) can carry out a time series analysis. See the Methods section by Fernández et al. (2022) for more details.

III. APPLICATION RESULT

The combination of InSAR and the interpretation tool (in its different versions) has been applied to diverse and complementary cases. These test-cases show the applicability of their combination for the geodetic monitoring of geodynamic activity and anthropogenic hazards using slightly different approaches. We describe the application test cases in the following subsections.

A. Magmatic intrusion tracking of Mount Etna in May 2008 and from January 2009 to June 2013

Cannavò et al. (2015) simulated the evolution of magmatic sources and their location in real time for the pre-eruptive period of May 2008, at Mount Etna (Italy) without any a priori assumption on the source geometry (Camacho et al., 2018; Camacho and Fernández, 2019). They seek to delimit the area with the highest likelihood of being the location of an opening fissure or vent for the impending eruption. They apply the software PAF (Camacho et al., 2011; Cannavò et al., 2015; Camacho et al., 2018) to model volcanic sources and track their evolution in time. The approach (Camacho et al., 2018) involves an inversion of ground deformation which enables the rapid estimation of the location, size, and evolution of magma sources with free geometry. Firstly, the proposed inversion methodology (Camacho et al., 2018) is applied to analyze the inflation phase preceding the 13 May 2008 eruption. The time evolution is obtained of the magmatic source for the period 1 January 2007 to 12 May 2008 by considering 15 day-intervals (Fig. 1). It is found that during June and July 2007, the system was subject to recharging episodes characterized by an ascending high-pressure body. The modeled body ascended from about 10 km to a level of about 2–3 km depth.

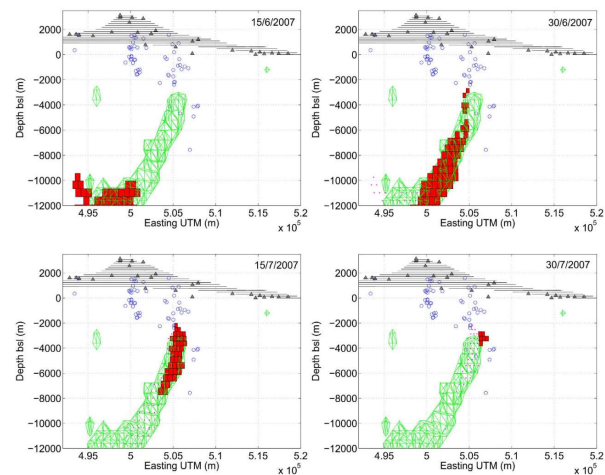


Figure 1. Model for the inflation phase. Cumulated magmatic body (in green) modelled for the period 1 January 2007 to 12 May 2008 and time evolution (in red) for some sub-periods. Blue circles correspond to location of the earthquakes during the considered periods (Cannavò, 2015)

High-speed GPS data from Mount Etna was applied to simulate a real-time monitoring scenario. It successfully reconstructs the three-dimensional distribution and dynamic changes of the magma source before and after the eruption on May 13, 2008. These findings are consistent with previous research results (see e.g., Aloisi, 2009; Bonaccorso, 2011).

Another example is conducted in the same research area with 38 ascending and 59 descending RADARSAT-

2 Standard-3 (S3) images spanning the January 2009 - June 2013 period. The deformation retrieved from the SAR images is interpreted using a new improved version of the interpretation methodology, adding to pressure different kind of dislocations as possible causative sources (Camacho et al., 2020). Fig. 2 shows some isolated source structures (pressure and tensile cells) related to the magmatic plumbing system of Mt. Etna. These appear to be composed of two stepped pressurized reservoirs located at depths of approximately 3-11 km below sea level, and a shallower SSW elongated dike structure at a mean depth of 1.5 km. These plumbing structures are located below the western slope of the volcano edifice. The deeper reservoirs are located progressively more SSW, suggesting an ancient location of the eruptive system. Their overall shape and position correspond to the crustal volume where a number of inflating/deflating sources, feeding the volcanic activity during 2009-2013, have been inferred by GNSS-based models.

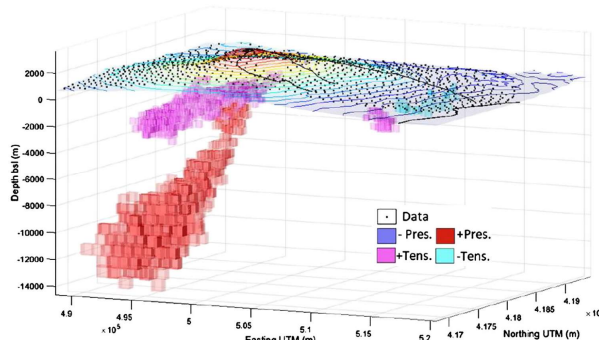


Figure 2. Perspective 3D view of the source elements corresponding to the plumbing system: increasing pressure cells (large deep reservoir with mean depth ~11 km bsl, SW of Etna, and shallow small reservoir with mean depth 3 km bsl. NW of Etna and along the elongation of the deep reservoir), and expanding tensile cells (at levels 1 km and 2 km bsl, with elongated pattern SW-NW). Black lines correspond to Etna summit, Pernicana Fault and Valle del Bove limit (Camacho, 2020).

B. Surface displacement produced by groundwater extraction: Lorca area, Spain

Land subsidence associated with overexploitation of aquifers is a hazard that affects large areas worldwide. The Lorca area, in southeast Spain, has one of the highest subsidence rates in Europe produced by a long-term aquifer exploitation. Up to 2018, studies carried out in this area assumed that the deformation retrieved from InSAR interferometry corresponded only to vertical displacement. Fernández et al. (2018) showed, for the first time, the two and three-dimensional displacement field over the area using InSAR and Global Navigation Satellite System (GNSS) observations. In Fig.3 we present the results obtained from the InSAR processing using CPT technique for the period November 2015–February 2017. Both geometries, ascending and descending, have been processed using

a multilook window of 3×13 pixels (azimuth $\times$ range) which generates a square pixel of about 60×60 meters in ground resolution. Coherence method has been used for pixel selection.

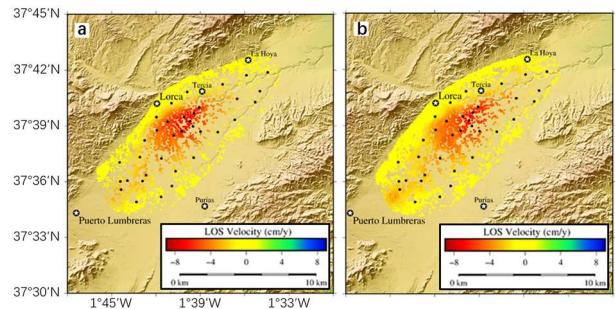


Figure 3. (a) Line of Sight (LOS) velocity values obtained for the ascending orbit. (b) LOS velocity values for the descending orbit. Black dots locate the GNSS stations. (Fernandez, 2018)

Four different data sets (Cases) of surface displacement covering the period from November 2015 to February 2017 were considered and inverted using the methodology by Camacho et al. (2018). The obtained results allowed to study the consequences of neglecting horizontal displacements on the interpretation and to evaluate the consequences and implications for operative monitoring at a global scale. The cases described here are the following:

- (A) LOS A-DInSAR results obtained for descending orbit images, assuming 100% as vertical displacement.
- (B) Purely LOS A-DInSAR results obtained for descending orbit images.
- (C) Purely LOS A-DInSAR results obtained for ascending and descending orbit images.
- (D) Purely LOS A-DInSAR results obtained for ascending and descending orbit images together with the 3D displacements determined using the GNSS survey results.

Case A is one-dimensional (1D), B and C are 2D (indirectly by combining Up-Down and E-W in the measured LOS), and D is a combination of 2D and 3D data (2D + 3D data). Each case was inverted allowing to estimate the volume changes of the water table (volume and geometry) assuming a given pressure change value. A summary of the results is provided in Fig. 4.

The results of 1D results, are ~24% greater in intensity/volume than those of (ii) (2D and 2D + 3D results), indicating that using only one component of the displacement field and assuming that displacements are only vertical significantly overestimates the volume of water extracted during the study period (on the order of tens of hm³). This can have an important effect on predictions of future volume variations and surface displacements.

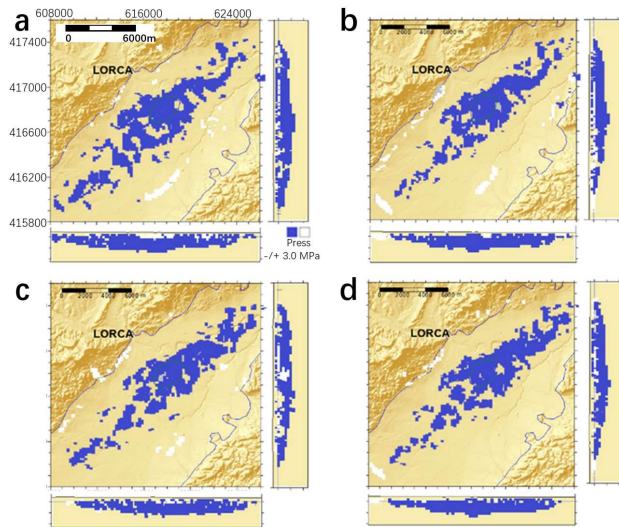


Figure 4. Representation of the inversion results obtained for the 1D, 2D and 2D + 3D considered data sets. (a) case A described in the text; (b) case B described in the text; (c) case C described in the text, and (d) case D described in the text (Fernandez, 2018).

C. Napa Earthquake, California, on August 31st 2014

In this test-case, a single pair of SAR images was exploited in order to detect and measure the co-seismic displacement caused by the Napa earthquake. The pre- and post-earthquake images were acquired on August 7th 2014 and on August 31st 2014, As portrayed in Fig.5, the resulting differential interferogram shows interferometric fringes allowing the detection of a significant surface displacement caused by the earthquake.

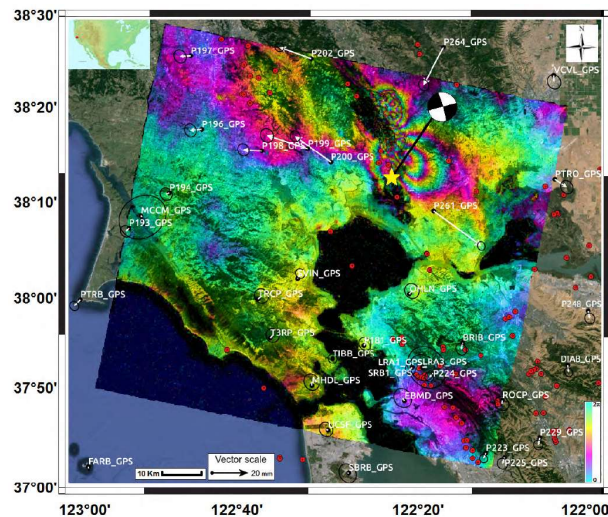


Figure 5. Interferogram of the 2014 Mw 6.0 Napa Valley, California, earthquake (Polcari, 2016).

This deformation field is inverted with the interpretation methodology described by Camacho et al. (2020). It can be seen from Fig.6 that slip in the central section is predominantly strike-slip and shallow. The dislocation source is approximately 3 km in depth, in accordance with the results of other geodetic, or joint geodetic and seismic, inversions of this event (Barnhart

et al., 2015; Dreger et al., 2015; Floyd et al., 2016; Melgar et al., 2015). To the south, the strike slip motion deepens to approximately 5 km, with a small thrust component that continues deeper. This again is similar to other geodetic inversions, but with greater dips and more spatially distributed (Barnhart et al., 2015; Floyd et al., 2016). To the north, the model changes again. The strike-slip motion again deepens and a notable area of negative dip-slip motion occurs at depths of 5-9 km, also modelled by Floyd et al. (2016).

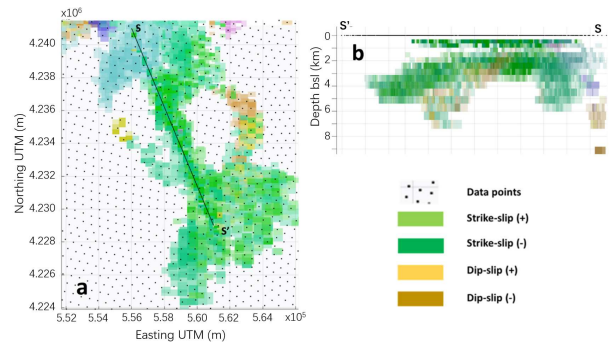


Figure 6. (a) Plan view from the top. All dislocation sources are projected and the primary (average) fault, SS', is also represented. (b) Same as panel a, but in an elevation view NWSE, SS'. Purple sources are tensile sources that appear to adjust outlier data, but which are not actual sources (Camacho, 2020).

D. 2021 La Palma volcanic unrest: onset detection and characterisation of pre-syn-post-eruptive phases

Fernández et al. (2021; 2022) used satellite radar observations and advanced interpretation techniques to detect the onset of volcanic activity on La Palma (Canary Islands) before the September 19th, 2021 and the eruption. The study attributes surface deformation to the injection of deep magma and/or the rise and pressurization of shallow fluids, as well as to sources of displacement associated with pressure sources and possible fractures and faulting. These phenomena may be related to the process of magma rising from depth along the sloping boundary between the northern volcanic complex and the southern volcanic ridge. The study also analyzed surface deformation in relation to seismic activity, gas and geochemical anomalies, and its consistency with the island's three-dimensional density structure.

The study of the period from 2006-2020 points out that La Palma was in the early stages of volcanic unrest in 2009-2010 and it continues up to 2020 and could, or not, erupt in the coming months, years or decades. The study also highlights the importance of continuing to monitor the evolution of volcanic activity, especially the evolution of displacement sources related to the stability of the southern volcanic ridge.

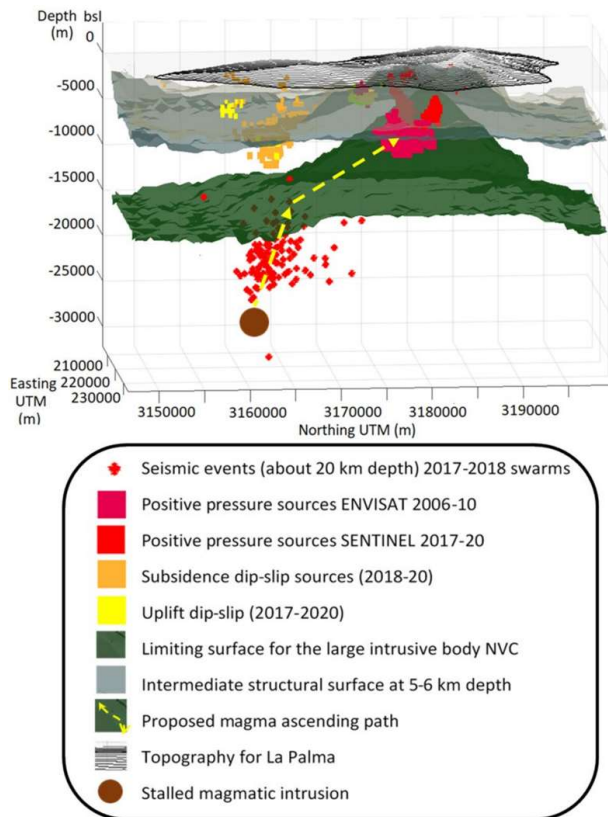


Figure 7. The figure shows the two main surfaces obtained in the 3D gravimetric crustal model (green and grey surfaces), the modeled positive pressure sources for the periods 2006–2010 and 2017–2020, the modeled dip-slip sources in 2019–2020, and the location of seismic events. The possible path followed by the magma from depth (yellow line) before, and probably after the seismic swarms in 2017 and 2018 which may have opened new fractures. (Fernández, 2021)

A conceptual model for the unrest evolution that incorporates these results is presented in Fig. 7. This is the first time that an initial phase of volcanic unrest in the Canary Islands is detected using geodetic methods. The evolution is studied, years after its inception, observing the changing spatial and temporal nature of activity at very high spatial resolutions and over long time periods. While these may be small and nuanced, but they give an insights into the dynamic nature of the volcano.

The shallow magmatic intrusion evolution of La Palma is studied for a better understanding of the pre-, co- and post-eruption phases in 2021, with InSAR and an improved interpretation methodology (Fernández, 2022). Three-dimensional deformation sources of surface displacement are modeled, including pressure and fault slip sources, as well as their time evolution. The results were discussed considering the obtained three-dimensional density model of the island.

The inversion results of LOS displacements and their time evolution are shown in Fig. 8 and 9. Fig. 8 shows the stage before the eruption. It can be seen that the most relevant feature of this period is the appearance and growth of a magmatic intrusion, shown mainly by a source of positive pressure of increasing intensity. More

than a month before the eruption, incipient positive dip-slip sources activated at a depth of about 3 km, suggesting a brittle response of the shallow crust to the rising of magma.

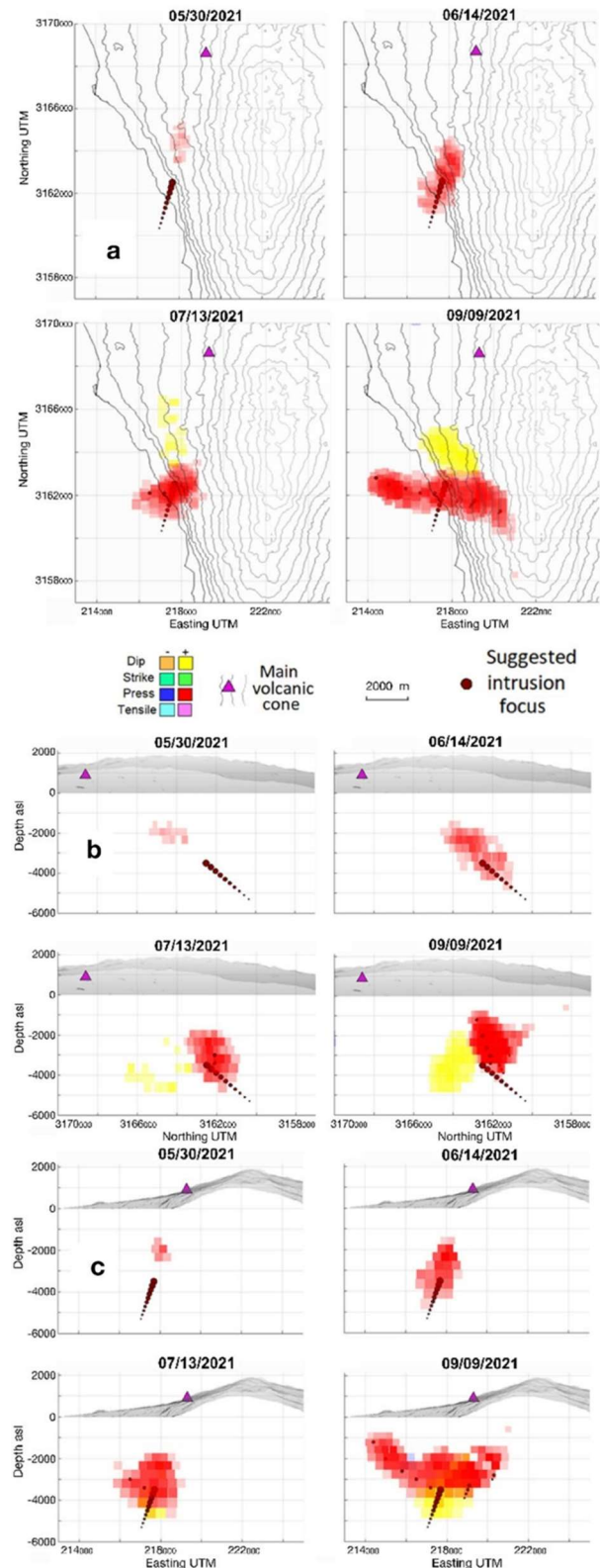


Figure 8. Time evolution of the modeled sources for 01/01/2021–09/13/2021. (a) Horizontal, (b) vertical N-S and (c) vertical W-E projections of the sources obtained for different epochs. The different plots show the time evolution of the different sources obtained from inversion of Sentinel-

1 ascending and descending LOS displacement. Purple triangle shows the location of the main volcanic vent during the 2021 La Palma eruption. Red dots indicate the provenance of the deep magma feed in the detected shallow reservoir from the geodetic modeling. All coordinates and depths are in meters (Fernández, 2022).

As of July 2021, an increase in intensity is detected in the deepest zone of the pressure source, as a consequence of the large inflow of magma. The positive dip-slip sources also are associated with an elevation of the limiting block with the fault/main fracture zone. The modelled increase in pressure/volume in the shallow hydrothermal system is related to the fast influx of deeper magma. Fig. 9 shows a large magma intrusion just before the eruption onset. The magma reached the surface arising along the northernmost branch and led to the formation of the eruptive fissure. This event occurred contemporaneously with a strong fracturing process, as suggested by the strike-slip sources located in a wide depth range, going from the surface to 6 km, probably associated with the seismic swarm. The most superficial negative dip-slip sources (≤ 0.5 km bsl) highlight the path followed by the eruptive fissure at the surface.

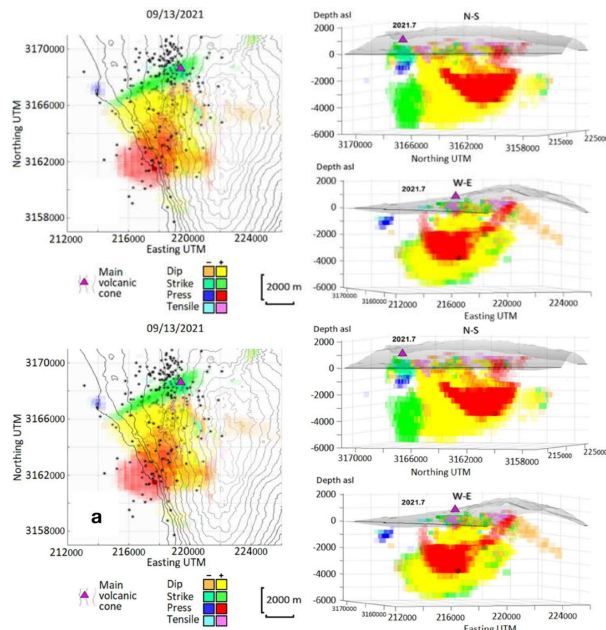


Figure 9. Time evolution of the modelled sources for 09/13/2021–09/20/2021 period, with the horizontal and vertical N-S and W-E projections. Black stars represent the seismicity in that period (Fernández, 2022).

E. Other areas

Besides the earthquake, volcano and groundwater extraction, some other research studies have been carried out in other active areas including mining areas and national natural parks. Here we exhibit some preliminary InSAR LOS deformation of a mining area, Riotinto in Huelva, Spain, in Fig. 10. ERS-1&2, ENVISAT and Sentinel-1 data are applied to show the improvement of satellite baseline, revisit time, image

quality control and their influence on the final deformation result. It is remarkable the spectacular improvement in coverage of the results obtained from ERS to Sentinel-1. Within the region of interest, we could determine 3586 velocity values for the ERS constellation, 5507 values for ENVISAT, and 14,091 values for Sentinel-1. In the case of ERS and ENVISAT, the gap in data coverage could be explained by the large baselines. When the temporal or spatial baselines between two images are too far apart, signal decorrelation may be locally high, and the results from these areas are eliminated during the processing by low coherence filtering. The poor coverage of the ERS dataset is especially remarkable, preventing the identification of any deformation pattern in the scene. Compared with ERS, the ENVISAT dataset shows better coverage, and three zones of deformation in tailing area can be identified. Finally, the Sentinel-1 dataset shows dense coverage along the scene providing information from almost all non-dense vegetated areas and water bodies. The very small Sentinel-1 baselines preserve the coherence between images and provide a spectacular improvement in measurement coverage. The deformation areas unveiled by ENVISAT are now well mapped in extension and value.

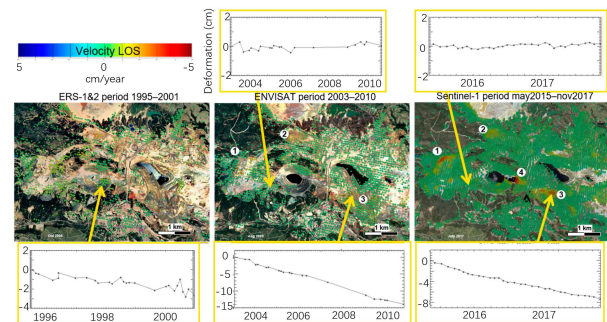


Figure 10. Result for descending orbits. Dots represent mean velocity values (cm/y, in line of sight direction, LOS) of each cell. The graphics show accumulated deformation in stable and unstable points. (Escayo, 2022)

IV. CONCLUSIONS

We have shown that the combined use of InSAR and last-generation interpretation techniques can provide quite real-time information on the causative sources in many geodynamic active areas (e.g., volcanic, seismic) and engineering/anthropogenic (e.g., water extraction, mining) stability monitoring studies. We can obtain information in the number, nature, 3D characteristics, and location of the causative sources of the measured displacements without any a-priori assumption of these parameters. We can also study the time variation of their characteristics and location from very initial stages, what can be extremely useful for hazard studies and helping decision making to avoid, or minimize, crisis situations and their effects. These studies can serve as a useful tool for civil defense purposes as well as for planification of location, and study of the stability, of

infrastructures and also for the planification of urban development.

V. ACKNOWLEDGEMENTS

This work has been supported by grants G2HOTSPOTS (PID2021-122142OB-I00), Defsour-PLUS (PDC2022-133304-I00) and STONE (CPP2021-009072) from the AEI/10.13039/501100011033/Union_Europea_NextGenerationEU/PRTR; and InSAR (20223TE005) from MITERD. This work represents a contribution to CSIC PTI TELEDETEC.

References

- Aloisi, M., Bonaccorso, A., Cannavò, F., Gambino, S., Mattia, M., Puglisi, G., & Boschi, E. (2009). A new dyke intrusion style for the Mount Etna May 2008 eruption modelled through continuous tilt and GPS data. *Terra Nova*, 21(4), 316-321; doi: 10.1111/j.1365-3121.2009.00889.x
- Barnhart, W.D., Murray, J.R., Yun, S.-H., Svarc, J.L., Samsonov, S.B., Fielding, E.J., Brooks, B.A., Milillo, P., (2015). Geodetic Constraints on the 2014 M 6.0 South Napa Earthquake, *Seismological Research Letters*, 86/2A, doi:10.1785/0220140210; doi: 10.1785/0220140210
- Blanco-Sanchez, P., Mallorquí, J. J., Duque, S., & Monells, D. (2008). The coherent pixels technique (CPT): An advanced DInSAR technique for nonlinear deformation monitoring. *Earth Sciences and Mathematics: Volume 1*, 1167-1193; doi: 10.1007/s00024-008-0352-6
- Bonaccorso, A., Bonforte, A., Calvari, S., Del Negro, C., Di Grazia, G., Ganci, G., ... & Boschi, E. (2011). The initial phases of the 2008–2009 Mount Etna eruption: A multidisciplinary approach for hazard assessment. *Journal of Geophysical Research: Solid Earth*, 116(B3) ; doi: 10.1029/2010JB007906
- Bru, G., Escayo, J., Fernández, J., Mallorquí, J. J., Iglesias, R., Sansosti, E., ... & Morales, A. (2018). Suitability assessment of X-band satellite SAR data for geotechnical monitoring of site scale slow moving landslides. *Remote Sensing*, 10(6), 936; doi: 10.3390/rs10060936
- Camacho, A. G., González, P. J., Fernandez, J., & Berrino, G. (2011). Simultaneous inversion of surface deformation and gravity changes by means of extended bodies with a free geometry: Application to deforming calderas. *Journal of Geophysical Research: Solid Earth*, 116(B10) ; doi: 10.1029/2010JB008165
- Camacho, A.G., J. Fernández, F. Cannavó (2018). PAF: A software tool to estimate free-geometry extended bodies of anomalous pressure from surface deformation data. *Computers and Geosciences*, 111, 235-243, doi: 10.1016/j.cageo.2017.11.014.
- Camacho, A.G., Fernández, J. (2019). Modeling 3D free-geometry volumetric sources associated to geological and anthropogenic hazards from space and terrestrial geodetic data. *Remote Sens.*, 11(17), 2042; doi: 10.3390/rs11172042.
- Camacho, A. G., Fernández, J., Samsonov, S. V., Tiampo, K. F., & Palano, M. (2020). 3D multi-source model of elastic volcanic ground deformation. *Earth and Planetary Science Letters*, 547, 116445; doi: 10.1016/j.epsl.2020.116445
- Cannavò, F., Camacho, A. G., González, P. J., Mattia, M., Puglisi, G., & Fernández, J. (2015). Real time tracking of magmatic intrusions by means of ground deformation modeling during volcanic crises. *Scientific reports*, 5(1), 10970; doi: 10.1038/srep10970
- Dreger, D.S., Huang, M.-H., Rodgers, A., Taira, T., Woodell, K., 2015. Kinematic Finite Source Model for the 24 August 2014 South Napa, California, Earthquake from Joint Inversion of Seismic, GPS, and InSAR Data, *Seismological Research Letters*, 86/2A, doi:10.1785/0220140244.
- Escayo, J., Marzan, I., Martí, D., Tornos, F., Farci, A., Schimmel, M., ... & Fernández, J. (2022). Radar Interferometry as a Monitoring Tool for an Active Mining Area Using Sentinel-1 C-Band Data, Case Study of Riotinto Mine. *Remote Sensing*, 14(13), 3061; doi: 10.3390/rs14133061
- Fernandez, J., Prieto, J. F., Escayo, J., Camacho, A. G., Luzón, F., Tiampo, K. F., ... & Mallorquí, J. J. (2018). Modeling the two-and three-dimensional displacement field in Lorca, Spain, subsidence and the global implications. *Scientific reports*, 8(1), 14782; doi: 10.1038/s41598-018-33128-0
- Fernández, J., Escayo, J., Hu, Z., Camacho, A.G., Samsonov, S.V., Prieto, J.F., Tiampo, K.F., Palano, M., Mallorquí, J.J., & Ancochea, E. (2021). Detection of volcanic unrest onset in La Palma, Canary Islands, evolution and implications. *Scientific Reports*, 11(1), 2540; doi:10.1038/s41598-021-82292-3.
- Fernández, J., Escayo, J., Camacho, A.G., Palano, M., Prieto, J.F., Hu, Z., Samsonov, S.V., Tiampo, K.F., Ancochea, E., (2022). Shallow magmatic intrusion evolution below La Palma before and during the 2021 eruption. *Scientific Reports*, 12, 20257; doi: 10.1038/s41598-022-23998-w
- Floyd, M.A., Walters, R.J., Elliott, J.R., Funning, G.J., Svarc, J.L., Murray, J.R., Hooper, A.J., Larsen, Y., Marinkovic, P., Bürgmann, R., Johanson, I.A., Wright, T.J., (2016). Spatial variations in fault friction related to lithology from rupture and afterslip of the 2014 South Napa, California, earthquake, *Geophys. Res. Lett.*, 43, 6808–6816, doi:10.1002/2016GL069428.
- Melgar, D., J. Geng, J., Crowell, B.W., Haase, J.S., Bock, Y., Hammond, W.C., Allen, R.M., (2015), Seismogeodesy of the 2014 Mw6.1 Napa earthquake, California: Rapid response and modeling of fast rupture on a dipping strike-slip fault, *J. Geophys. Res. Solid Earth*, 120, 5013–5033, doi:10.1002/2015JB011921.
- Lisowski, M., (2007). Analytical volcano deformation source models. In: *Volcano Deformation*. Springer Praxis, Chichester, UK, pp.279–304, chap. 8; doi: 10.1007/978-3-540-49302-0_8
- Polcari, M., Palano, M., Fernández, J., Samsonov, S. V., Stramondo, S., & Zerbini, S. (2016). 3D displacement field retrieved by integrating Sentinel-1 InSAR and GPS data: the 2014 South Napa earthquake. *European journal of remote sensing*, 49(1), 1-13; doi: 10.5721/EuJRS20164901
- Rosen, P. A., Gurrola, E., Sacco, G. F., & Zebker, H. (2012, April). The InSAR scientific computing environment. In *EUSAR 2012; 9th European conference on synthetic aperture radar* (pp. 730-733). VDE; doi: 978-3-8007-3404-7
- Tomás, R., Romero, R., Mulas, J., Marturà, J.J., Mallorquí, J.J., López-Sánchez, ... & Blanco, P. (2014). Radar interferometry techniques for the study of ground subsidence phenomena: a review of practical issues through cases in Spain. *Environmental Earth Sciences*, 71-1, 163-181, doi: 10.1007/s12665-013-2422-z

- Wegmuller U., Werner C. (1997) - Gamma SAR processor and interferometry software. In The 3rd ERS symposium on space at the service of our environment, Florence, Italy.
- Yunjun, Z., Fattahi, H., & Amelung, F. (2019). Small baseline InSAR time series analysis: Unwrapping error correction and noise reduction. *Computers & Geosciences*, 133, 104331; doi: 10.1016/j.cageo.2019.104331

Establishing the surface deformations in the Sofia valley by means of SAR data

Hristo Nikolov¹, Mila Atanasova-Zlatareva²

¹Space Research and Technology Institute – Bulgarian Academy of Sciences, Acad. G. Bonchev str., bl. 1, 1113 Sofia, Bulgaria, (hristo@stil.bas.bg)

²National Institute of Geophysics, Geodesy and Geography Institute – Bulgarian Academy of Sciences, Acad. G. Bonchev str., bl. 3, 1113 Sofia, Bulgaria, (mila_at_zl@abv.bg)

Key words: *geodynamic processes, SAR data, active faults, Sofia valley*

ABSTRACT

This paper unveils findings pertaining to the identification of ground deformations in the Sofia Valley (SV), where Sofia city the capital of Bulgaria is located. Those deformations can be attributed to different natural or anthropogenic phenomena, but certainly the seismic events with magnitude larger than 5 could be the major factor as well as other unfavorable geohazard processes such as activation of faults or landslides. The most recent earthquake near the surveyed area of SV was a magnitude 5.8 event on May 22, 2012, followed by several aftershocks. Fortunately no casualties were reported, but the main event was strongly felt in this part of the country destroying partly houses or infrastructural objects. One reliable source of information for continuously monitoring of the said deformations at large scale is the satellite-borne data from synthetic aperture radar (SAR) and for this reason in this study we present results revealing their magnitude for the area of SV. SAR data were processed using persistent scatterer interferometry technique in order to establish the magnitude of the movements along two of the well-known faults located in SV. Since the SAR data are from ERS1/2 and Sentinel-1 the investigated time span stretches from the beginning of nineties of the last century up to 2021. Together with the SAR data other additional data were used such as geological maps and seismological data for historical and instrumentally evidenced earthquakes. The primary conclusion drawn from this research is that regular monitoring of ground motions in the SV through PSInSAR is not only feasible but also essential. Such monitoring proves instrumental in updating risk assessment maps for the region, aiding in better preparation and mitigation strategies.

I. INTRODUCTION

The prevailing understanding among experts is that the manifestation of high-risk geodynamic processes can be attributed to the activity and development of modern active faults. Some of those faults are well-known while others manifest themselves only after strong surface disruptions often leading to earthquakes, landslides etc. For this reason, it is of crucial importance to track ongoing ground motions and register the newly manifested faults. In this way, the current and potential georisk processes triggered by the aforementioned faults could be correctly established, mapped and monitored (Atanasova and Nikolov, 2023). This information has clear contribution to better regional planning, especially in infrastructural engineering and urban development. It needs to be underlined that of paramount importance is its contribution to the development of more robust emergency plans, rooted in scientifically rigorous simulation procedures. This, in turn, leads to the potential for saving human lives.

II. MOTIVATION AND RATIONALE

In this paper, some of the possible sources of information concerning surface deformations at the

territory of Bulgaria as evidenced by the faults established in (Basili *et al.*, 2013; Styron and Pagani, 2020) are examined, as well as information on the epicenters of numerous strong earthquakes that occurred over the past 150 years (Rovida and Antonucci, 2021). In addition to the already identified sources, we explored the potential of utilizing SAR data to monitor small surface deformations in specific areas at regular short time intervals. For that purpose, the choice of spatial resolution for SAR data should be tailored to the size of the studied region, ensuring optimal detection capabilities for the desired deformations. As the study faced limitations in covering the entire territory of Bulgaria, SV was knowingly chosen as the study region (Figure 1). This choice was made considering that according to the national statistics significant portion of the Bulgarian population, around 25% (National statistical institute, 2022), inhabits the SV area (denoted by black line in the inset of Figure 1). The vulnerability of the substantial population residing in SV to the potential impact of a single strong earthquake underscores the imperative to monitor surface deformations, which can serve as precursors to seismic events. In addition to the previously mentioned risk, another significant concern

is the well-documented landslide activity (Bruchev, et al. 2007). According to (Ivanov et al. 2022), a substantial portion of the SV area is also highly susceptible to landslides, a risk that can be attributed to the displacements of faults in this region.

A. Faults zones

As outlined in (D'Agostino *et al.*, 2020), the estimated velocity of the horizontal and vertical displacements along the registered active faults in the territory of Bulgaria is on the order of 2-3 mm/year. As depicted in Figure 1, their distribution across the territory of Bulgaria is uneven, with one contributing factor being the pronounced extensional tectonic processes in the southern part of the country and especially in the southwest part. This assertion is evidenced by geological terrain measurements and confirmed by GNSS data as well. Following the findings in (Nakov *et al.* 2006), it is observed that most of the faults have E-W or NW-SE orientation. The colors of the faults in Figure 1 differ since three independent sources providing their location were used – European Database of Seismogenic Faults (EDSF) in blue (Basili *et al.*, 2013), GEM Global Active Faults Database in green (GEM GAF-DB) (Styron and Pagani, 2020) and Active Faults of Eurasia Database (AFAD) in red (Zelenin *et al.*, 2022)

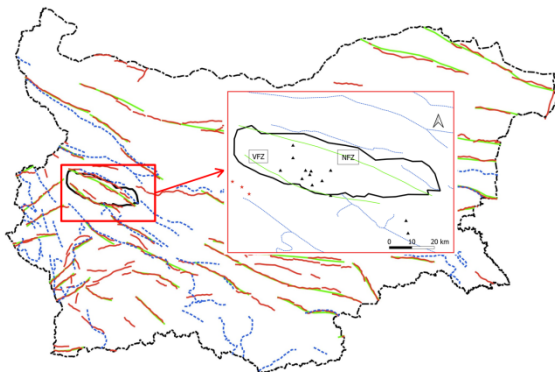


Figure 1. Fault lines as registered by different sources for the territory of Bulgaria and the SV, which is identified by a black line in the region of study (red square).

The inset shown on the same Figure 1 depicts the area of the zone where SV is located (outlined in black colour). From geological point of view, the predominant geodynamic processes in that zone are considered to be extensional ones – towards northeast in the north part of SV, and southwest to the south part (Matova, 2006), (Nakov, 2006).

B. Seismic events

Regarding Bulgaria's seismic activity, from the beginning of the 1990s to 2021, the primary seismic zones are concentrated in Southern Bulgaria, exhibiting a significantly greater density of faults when compared to Northern Bulgaria, as depicted in Figure 2. It is unsurprising that the majority of recorded earthquakes

occur in regions characterized by a higher number of faults. This correlation underscores the importance of understanding fault distribution for effective seismic risk assessment and preparedness measures.

Historically several strong earthquakes with a magnitude exceeding 7 have been evidenced in the said southern regions (see black triangles on Figure 2). The same Figure shows the location of several strong earthquakes having magnitude larger than 5 Mw that were historically evidenced in the studied region of SV (Rovida and Antonucci, 2021) or in its vicinity, during the instrumental period of the seismological research in Bulgaria (European-Mediterranean Seismological Centre, 2023). According to the indicators concerning seismic hazard and exposure reported in (Openquake, 2019) the region of SV is considered as one of the regions with highest risk for Bulgaria.

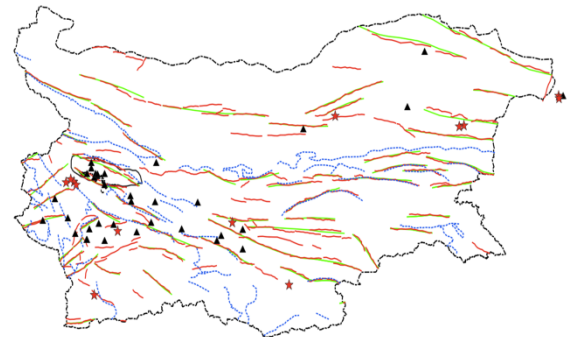


Figure 2. Distribution of evidenced earthquakes in Bulgaria, from the beginning of 1990s to 2021. Information based on Rovida and Antonucci (2021) is indicated with triangles and that based on EMSC (2023) is indicated with red stars.

C. Region of study (ROI)

Sofia City, the capital of Bulgaria, is located in the northern, middle and southern parts of the Sofia graben, known also as SV. As seen on Figure 1 the graben has quasi-ellipsoidal shape with longer axis at NW-SE direction and length of 60 km, while the small axis is at most 25 km long (Shterev, 2004). The zone of the graben is considered to be tectonically active (Bruchev *et al.*, 2007) that underlines the need of its regular monitoring. According to Matova (2006), numerous faults characterized by longitudinal, transverse, or oblique orientations intersect the graben. The longitudinal Vitosha fault zone (VFZ) with orientation NW-SE limits of the graben on south, while the Negushevo fault zone (NFZ) follows the same NW-SE direction both visible as green lines in the inset of Figure 1. Numerous transversal faults with NE-SW as well as several ones with N-S and E-W direction cut the graben and the neighboring horsts. On the one hand, this large number of faults predefines the seismicity in SV to be high, but the larger part of the seismic events is considered as negligible or moderate with Mw magnitudes rarely exceeding 3. On the other hand, it needs to be mentioned that in the last 200 years at least

two historical seismic events larger than 5 Mw were evidenced in SV causing serious damages to houses and other higher buildings. As a result, a new source of geothermal water was reported after one of them (Shterev, 2004).

D. Results from SAR data processing

In this study, we examined the hypothesis that the predominant ground movements in the specified SV region result from activity along the fault lines of VFZ and NFZ (see inset of Figure 1), aligning with the movement direction proposed by geologists and seismologists. We assumed that small, but unidirectional movements could be used as precursor of possible larger ground displacements and provide additional information to the risk maps to be produced for those areas. To detect centimeter scale surface motions, we employed data from two Synthetic Aperture Radar (SAR) missions managed by the European Space Agency (ESA) in order to generate displacement maps for the analyzed Region of Interest (ROI). Due to the study's emphasis on subtle movements, it was essential to acquire time series spanning extended periods for accurate analysis. The initial dataset employed originated from the ERS1/2 satellites, spanning the timeframe from 1992 to 2003, whereas the second dataset utilized data from the Sentinel-1 (S-1) mission, covering the period from 2016 to 2021.

Figure 3 presents a map produced from the wrapped phase of one of the S-1 SAR data products (descending orbit) processed by DInSAR method. As observed, the information in its current form is challenging to interpret. To address this, more extensive time series of SAR data were generated for enhanced clarity and understanding. From these datasets, only points with high information value were extracted and given further consideration.

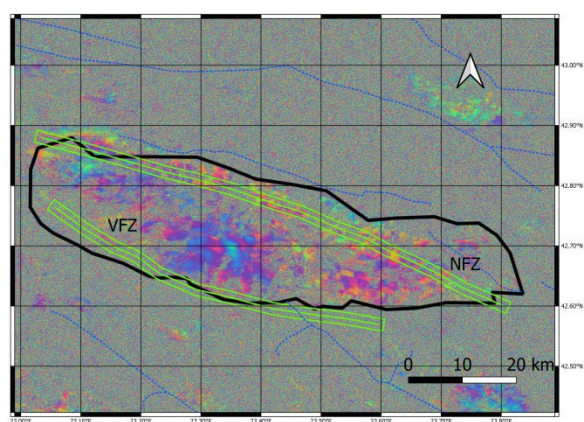


Figure 3. Wrapped phase from S-1 descending orbit. The SV area is indicated by a red line and the polygons around the NFZ and VFZ faults are marked with green lines. Other faults are also indicated (red and green lines).

To evaluate the magnitude of displacements recorded by InSAR along both faults, two polygons of 10 km wide and centered around them were created as vector files. These polygons were then utilized to select only valid points from the raster interferograms. The northern polygon (NFZ) encompasses an area of 152.6 km², whereas the southern one (VFZ) covers 109.3 km².

The results presented in Figure 4 were produced from ERS1/2 data processed as part of ESA TerraFirma project (TerraFirma, 2019). For SV, 45 interferograms were generated, from which surface velocities in the line-of-sight (LoS) of the satellite were derived. As evident from the same Figure, the predominant movements recorded in SV are in a westward direction, indicated by the blue color of the points, while red corresponds to eastward movements. We focused solely on the SV area, excluding mountainous and other densely vegetated regions due to their low coherence values, signifying unreliable information from those points. Although this restriction enhanced the credibility of the obtained information, it resulted in a reduction of points available for subsequent statistical processing.

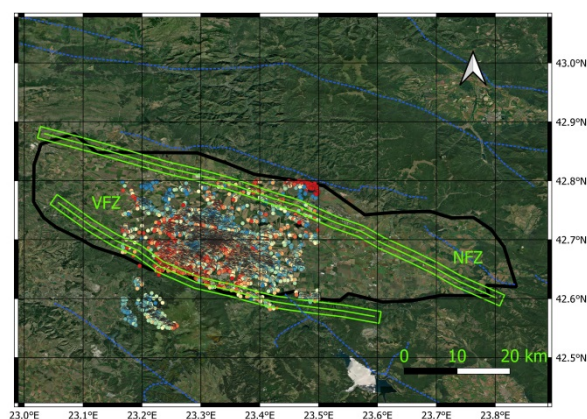


Figure 4. Ground movements in LoS obtained by InSAR processing from pre-Sentinel data.

We selectively extracted data points from the time series of SAR data, focusing solely on those within the specified 10 km polygons along the two major faults under consideration. Thus, two new data sets were formed – for the south fault (VFZ) the number of points is 655, while for the north one (NFZ) there are 971 points.

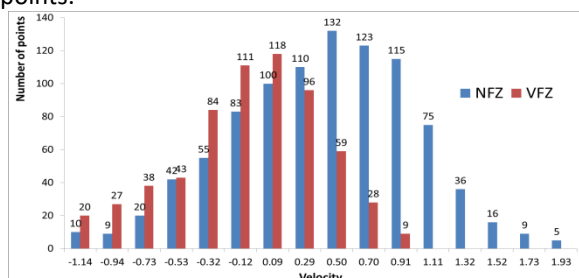


Figure 5. Histogram of the velocity values in LoS from ERS1/2 data.

A coherence threshold of 0.7 was applied to both datasets, with the highest coherence value reaching

0.95. These thresholds ensure the reliability of information obtained from individual data points. Based on the histograms presented in Figure 5 for the mentioned datasets, it is evident that the velocities for the two studied faults are not identical.

The north fault (NFZ) exhibits a higher number of points with positive values, indicating eastward movements, while the south fault displays a greater number of negative values, suggesting westward movement. These findings align with the conclusions in (Matova,2006).

From each of the generated datasets corresponding to VFZ and NFZ, two representative points were extracted to illustrate the variation in movement over the ten-year study period. These points were selected to reflect the lowest and highest values identified within each of the datasets. This demonstrates that the overall movement is neither constant nor uniform across all data points in the sets, as depicted in Figure 6. In the same Figure, it is evident that for the north fault (NFZ), the difference between one of the points with the lowest values and one with the highest values is greater than a similar comparison for the south faults. Over the mentioned time span, no earthquakes with a magnitude exceeding 3 Mw were registered. This lack of notable seismic activity allows us to attribute all observed surface displacements to the tectonic movements of the studied faults. This result suggests that the registered movements along LoS of satellite are similar eastward while NFZ moves westward with velocity almost twice larger than VFZ.

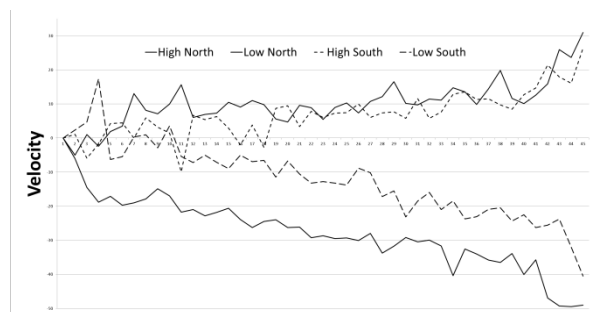


Figure 6. Velocities of two data points from both ERS datasets reflecting the movements in VFZ and NFZ.

For the SV region, we generated two similar datasets containing points derived from the processing of S-1 data products from both types of orbits. This was done to capture the east component of the motion vector as well as its upward component. It is crucial to mention that the size of these two datasets is considerably larger since the revisiting time of S-1 is much shorter than that of ERSs. Given the extensive number of S-1 acquisitions, product pairs were exclusively formed from those displaying high predicted coherence. Following interferometric processing, only points that maintained high coherence values across all interferometric pairs—specifically, 0.6 and above—were further considered. Within the polygons of both faults, the number of

generated points amounted to 2612 for the NFZ and 2127 for the VFZ.

Figure 7 depicts an example of the east component of the displacement vector derived from the S-1 InSAR time series and the black triangles denote significant historical earthquakes. It is seen that most of the large earthquakes are along the VFZ.

Notably, a significantly larger number of high-coherent points is evident compared to those from the ERS acquisitions. This can be attributed to the superior registration capabilities of S-1, including better spatial resolution, a shorter revisiting time and improved orbital positioning. It is important to note the drawback of the S-1 near-polar orbit, which complicates the registration of northward movements (Nannini *et al.*, 2016). Consequently, only the east and up components of the velocity vector were obtained and reported below. It is worth noting that, in addition to the enhanced data acquisition capabilities of the S-1 instrument, significant progress has been made in SAR data processing methods over the last two decades. This advance contributes to increase the reliability of the results following the decomposition of the movement vector, surpassing the outcomes obtained from the ERS missions.

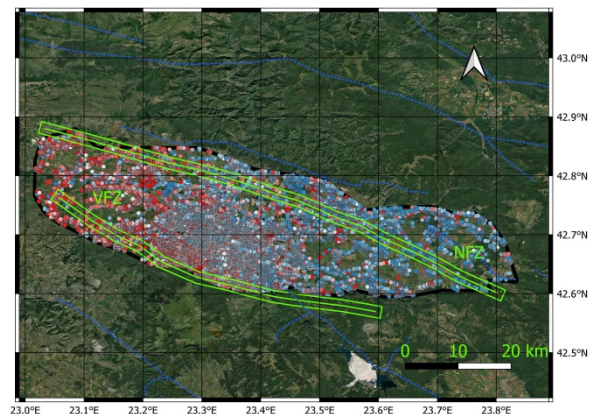


Figure 7. East velocity vector of the displacements derived from S-1 data for the whole ROI of SV. Red colours indicate eastward movement and blue westward.

The histogram of the east component of the surface movement vector, derived from S-1 interferograms, is illustrated in Figure 8. Once again, only points within the formed polygons of VFZ and NFZ were considered. Points falling outside the reported data range on the X-axis were excluded.

This decision was made due to their count being less than 10, which represents less than 0.5% of the entire dataset and likely does not accurately reflect the movement. The removal of points with extreme values was motivated and justified by the absence of significant displacement events in SV, such as earthquakes, recorded by seismologists during the investigated time interval. This lack of substantial seismic activity raises concerns about the reliability of

detecting large displacements at a single point. The reported results for the east component are in agreement with the findings from the previously analyzed ERS1/2 epoch concerning the direction of surface movements along the two faults. It is observed that, while the direction remains consistent, the eastward movements of the north fault are slower when compared to those of the south fault.

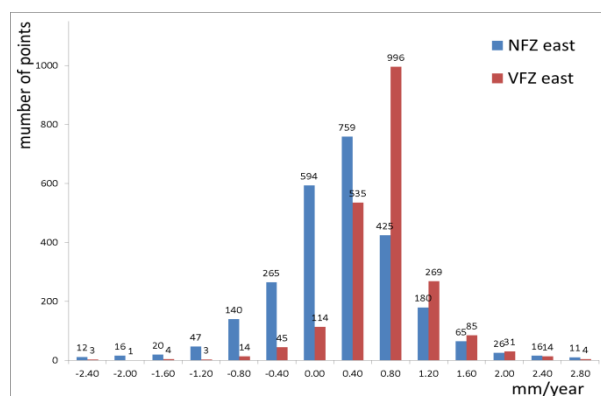


Figure 8. The East component of the displacement vector derived from S-1 data for the VFZ and NFZ faults.

The results for the up component of the decomposed movement vector for the two studied faults are shown in Figure 9. For the area of NFZ the subsidence is more clearly expressed based on the largest number of negative values in up direction. For the VFZ it can be concluded that the displacements that have occurred in up direction are less dynamic since most of the values for the points are in the range between 0 – 1 mm/year.

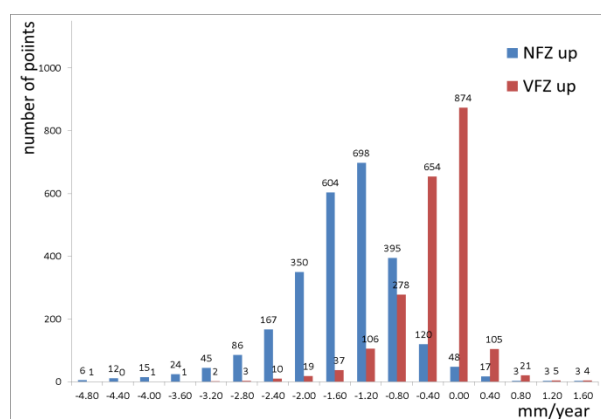


Figure 9. The Up component of the displacement vector derived from S-1 data for the VFZ and NFZ faults.

III. DISCUSSION

In this paper, we presented results from SAR data processing employed to unveil both past and ongoing surface deformations in the SV region. It is essential to highlight that this study is preliminary, focusing on detecting ground motions in the studied SV area through satellite SAR products and their interferometric processing. The research serves a dual purpose – to demonstrate the effectiveness of SAR data for regularly

monitoring active faults in the SV region and to establish time series of SAR data capable of revealing surface movements at a centimeter scale. Therefore, our focus was narrowed to studying only two, albeit the largest and well-pronounced faults in the SV – VFZ and NFZ faults.

The obtained results confirm that the predominant surface motions along these faults are unidirectional over time, such as southeastward for the NFZ. However, it is important to note that the velocities are not constant throughout the entire areas of the fault zones. Moreover, the availability of continuous time series with SAR data could facilitate the assessment of the consequences caused by small and moderate earthquakes, thereby contributing to better mapping after a disaster event.

IV. CONCLUSIONS

The findings presented in this paper unequivocally affirm the capabilities and benefits of detecting and monitoring surface motions within the scrutinized SV region through the utilization of satellite radar instruments processed using the DInSAR method. This valuable information not only corroborates results derived from alternative methods, such as geological terrain investigations and GNSS data obtained from geodetic networks, but it also does so at a significantly reduced cost per unit area. The synergistic integration of these diverse datasets enhances our understanding of the dynamic behavior of the Earth's surface in the studied region, showcasing the pivotal role of advanced satellite technology in geoscientific research.

This study makes a twofold contribution. Firstly, it explicitly highlights the viable means of monitoring surface motions in SV through the utilization of SAR data. Secondly, it validates the imperative to reprocess data from historical SAR missions (ERS1/2 and Envisat) using recently developed innovative methodological advancements in SAR data processing. Thus the length of time series will be extended from 1993 to 2012 and enhancing the quality of the acquired information.

V. ACKNOWLEDGEMENTS

The scientific results are part of the preliminary work on the project: "Study of co-seismic deformations of the earth's crust for the territory of the Balkan Peninsula based on satellite data", financed by "Competition for financial support of basic research projects – 2023" of Bulgaria. Contract No. KP-06-N74/2 from 14.12.2023.

References

- Atanasova M., Nikolov H. (2023). Application of SAR data time series for monitoring of geodynamic processes in the Sofia region. In: *23th International Multidisciplinary Scientific GeoConference SGEM 2023*

- Basili R., Kastelic V., Demircioglu M. B., Garcia Moreno D., Nemser E. S., Petricca P., Sboras S. P., Besana-Ostman G. M., Cabral J., Camelbeeck T., Caputo R., Danciu L., Domac H., Fonseca J., García-Mayordomo J., Giardini D., Glavatovic B., Gulen L., Ince Y., Pavlides S., Sesetyan K., Tarabusi G., Tiberti M. M., Utkucu M., Valensise G., Vanneste K., Vilanova S., Wössner J. (2013). The European Database of Seismogenic Faults (EDSF) compiled in the framework of the Project SHARE. In: <http://diss.rm.ingv.it/share-edsf/>, doi: 10.6092/INGV.IT-SHARE-EDSF.
- Bruchev, I, P. Ivanov, G. Frangov, R. Varbanov, N. Dobrev, B. Berov, R. Nankin, M. Krastanov (2007). The Landslides in Bulgaria – Factors and Distribution. In: *Geologica Balcanica*, vol. 36 (3-4), pp. 3–12, <https://doi.org/10.52321/GeolBalc.36.3-4.3>.
- D'Agostino, N., Métois, M., Koci, R., Duni, L., Kuka, N., Ganas, A., Georgiev, I., Jouanne, F., Kaludjerovic, N., R. Kandic (2020). Active crustal deformation and rotations in the southwestern Balkans from continuous GPS measurements. *Earth and Planetary Science Letters*, Volume 539, 1, Elsevier,
- European-Mediterranean Seismological Centre (EMSC), <https://www.emsc-csem.org/> (visited October 2023)
- Ivanov P., N. Dobrev, B. Berov, A. Frantzova, M. Krastanov, R. Nankin (2022). Landslide risk for the territory of Bulgaria by administrative districts, In: *Geologica Balcanica* vol. 51 (3), pp. 21–28
- Matova M. (2006). About seismotectonic activity of Bulgaria. In: *Reports on Geodesy*.
- Nakov R., V. Kotzev, B.C. Burchfiel, R.W. King (2006). Crustal motion in Bulgaria based on geological and GPS data. In: *Reports on Geodesy*.
- Nannini M., Prats-Iraola, P., Scheiber, R., Yague-Martinez, N., Minati, F. et al. (2016), Sentinel-1 mission: results of the InSARap project. Proceedings of EUSAR 2016: 11th European Conference on Synthetic Aperture Radar, Hamburg, Germany, pp. 1-4.
- National statistical institute of the Republic of Bulgaria (2023). <https://nsi.bg/en/content/2974/population>
- Openquake, (2023), <https://downloads.openquake.org/countryprofiles/BGR.pdf>, (accessed Dec 2023)
- Rovida A., Antonucci A. (2021). EPICA - European PreInstrumental Earthquake CAtalogue, version 1.1 [Data set]. *Istituto Nazionale di Geofisica e Vulcanologia (INGV)*. <https://doi.org/10.13127/epica.1.1>
- Shterev, K.D. (2004). The hydrogeothermal basin of Sofia graben (Bulgaria). *Env Geol* **46**, 651–660.
- Styron, R. and M. Pagani (2020). The GEM Global Active Faults Database.in: *Earthquake Spectra*, vol. 36, no. 1_suppl, Oct. 2020, pp. 160–180, doi:10.1177/8755293020944182
- TerraFirma, (2019). <http://onegeology-geonetwork.brgm.fr/geonetwork3/srv/eng/catalog.search#/search?any=sofia>, (last accessed Sept.2023)
- Zelenin E.A, D.M. Bachmanov, S.T. Garipova, Trifonov V.G., A.I. Kozhurin (2022). The Active Faults of Eurasia Database (AFEAD): the ontology and design behind the continental-scale dataset, In: *Earth System Science Data*,. vol. 14. pp. 4489-4503.

Study of coseismic deformations in the Balkan Peninsula area from SAR data

Mila Atanasova-Zlatareva¹, Hristo Nikolov², Valentina Protopopova-Kakar³

¹National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Acad. G. Bonchev bl.3 Sofia 1113, Bulgaria, (mila_at_zl@abv.bg)

²Space Research and Technology Institute (SRTI) - Bulgarian Academy of Sciences, Acad. G. Bonchev bl.1 Sofia 1113, Bulgaria (hristo@stil.bas.bg)

³Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany (valentina.protopopova-kakar@gfz-potsdam.de)

Key words: co-seismic deformations; SAR; earthquakes; Balkan Peninsula; geohazard maps

ABSTRACT

Earthquakes are a natural disaster that causes damage measured in terms of human lives and infrastructure destruction. The Balkan Peninsula is located in the Alpine-Himalayan seismic zone - the second most active in the world, making it prone to earthquakes. At the beginning of the twentieth century several destructive earthquakes with a magnitude above 7.0 have occurred in Bulgaria, which is *located* on the northern side of the region. Resent stronger shocks have been recorded around the Hellenic Arch and less frequently in the continental part of the region. In recent decades, satellite SAR technologies have made it possible to track surface deformations caused by earthquakes, volcanoes, landslides, etc. The new research technologies could help in a preparation plan to overcome the consequences of future events. In this study, we focused our research on determining the surface deformations after several earthquakes of magnitude gather than 6.0 in the last 5 years along the Hellenic Arch. The presented results from SAR data processing reveal the co-seismic deformations in the region, which are compared and well agree with GNSS data from other studies. The main task is to demonstrate operational readiness, to determine the degree of deformation of the earth's surface, and to prepare displacement maps.

I. INTRODUCTION

The territory of Bulgaria belongs to the relatively dangerous earthquake areas of the Earth. Bulgaria is located near the Mediterranean seismic zone – part of the second most active in the world. At the beginning of the last century, several destructive earthquakes with a magnitude above 7.0 were registered on the territory of our country. Such events cannot be predicted and no territory is immune from the possibility of repeating terrible scenario itself (Solakov D. *et al.*, 2018a). The last stronger earthquake in Bulgaria was in 2012 with a magnitude Mw of 5.6 near the capital Sofia (Solakov D. *et al.*, 2018b).

Earthquakes are a natural disaster that causes damages, measured in human lives and destruction of infrastructure. An important task before the occurrence of such an event is the preparation of a plan to overcome it, based on data from similar, previous events on the territory and nearby lands, agreed with the regional tectonics and possible deformations of the earth's crust. The strongest earthquakes occur most often along tectonic plates boundaries, especially in subduction zones. In the region of Europe, the strongest present earthquakes occur in the subduction zone around the Greek (Hellenic) Arch, less often in the

continental part of the Eurasian plate (Baker C., *et al.*, 1997; Shaw B. & Jackson J. 2010).

Modern SAR satellite technologies allow the observation of the Earth's surface deformation caused by earthquakes, volcanoes, landslides, subsidence due to groundwater extraction and other man-made activities (Fialko Y. & Simons M., 2001; Wright T. *et al.*, 2004; Ganas, A. *et al.*, 2021b; Solari, L. *et al.*, 2017; Ezquerro, P. *et al.*, 2023). In this study, we focused on determining the deformation of the Earth's surface that occurred in the Balkan Peninsula region after 6 earthquakes of magnitude greater than 6.0 and their stronger aftershocks recorded (by NOA, GFZ, USGS, etc.) during the last 5 years along the Greek Arch.

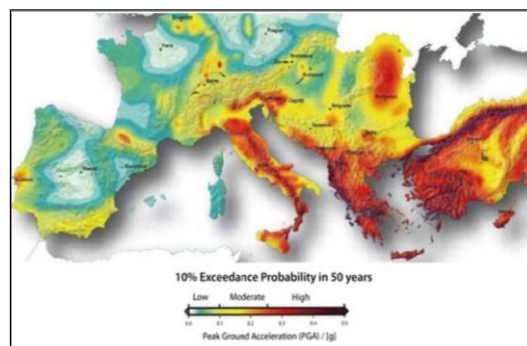


Figure 1. Seismic hazard map of Europe
<https://www.redrisk.com/redeng/EUModel/EUModel.php>

The main task of this study is to demonstrate operational readiness, to determine the magnitude of deformations of the earth's surface, the affected areas and to prepare maps of displacements. Figure 1 presents a seismic hazard map of Europe including the extent of the Mediterranean seismic zone.

Earthquake borderless Risk Model for 44 European countries designed is introduced in the Figure 1, based results and findings about hazard, vulnerability and exposure of the most recent European research projects about earthquake risk analysis and assessment. A hazard Earthquake map is a map that highlights areas affected by, or vulnerable to, a particular hazard. They are used to assess the spatial extent of earthquake hazard. They also provide a great visual assessment of the areas that are most likely to be affected by this specific type of hazard (Giardini, D. *et al.* 2014).

The western border of the Hellenic Arc defines the boundary of a large intracontinental active extensional domain covering the Aegean and the southwestern part of the Balkan Peninsula. Along this boundary a transition from collision in the north to subduction in the south is associated with post-Miocene clockwise rotations (see Figure 2). The D'Agostino N. *et al.* (2020) presents a GPS velocity field, measured by permanent station velocities in Albania, Bulgaria, Kosovo, Montenegro, and Northern Macedonia, that provides insights into previously unresolved aspects on the large-scale dynamics of continental lithosphere and on the relation between long and short-term kinematics.

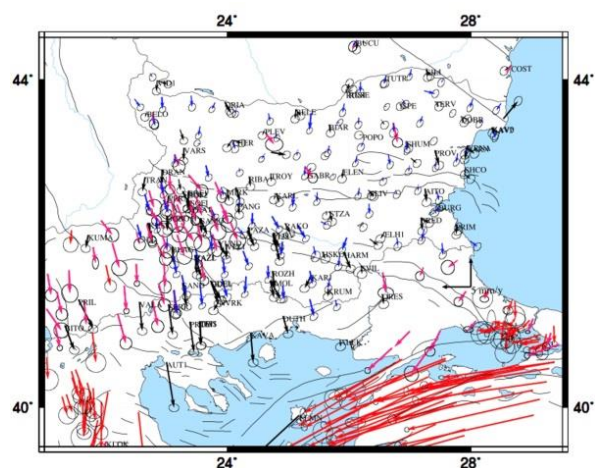


Figure 2. Contemporary crustal motions determined by GNSS measurements - the part Balkan Peninsula and the Eastern Mediterranean. <https://ngic.bg/>

On the Figure 2 present velocities of the points of the Basic class of the State GPS Network of Bulgaria are represented on the graph in blue; Horizontal velocities obtained in NIGGG and in the framework of international cooperation such as EUREF velocities

points in North Macedonia are marked in pink and velocities in Western Turkey and North Greece in red (<https://ngic.bg/>).

II. METHODS AND DATA

DInSAR data obtained from remote sensing of the Earth is a method that can be used to quantify small surface displacements. Using data from the Sentinel-1 and applying DInSAR, the topography of large areas could be mapped, as well as surface displacements could be registered. The basis of the DInSAR method is the use of two images of the phase signal backscattered from the earth's surface, received in the same region at different times and on the basis of which it is possible to accurately measure the relative distances to a specific object. The main data sources used are SAR products from the Sentinel-1 mission satellites. By processing data using the DInSAR method, greater spatial coverage is provided (Hanssen R.F. 2001). Their large territorial coverage allowed production of maps that reveal the extent of disturbances on the Earth's surface

Interferometric pairs were formed in the process of their processing to track the consequences of the event and the obtained information is entirely based on the changes in the phase component of the radar signal reflected from the Earth's surface (Ferretti A. *et al.* 2027). The recorded information in the form of interferometric images (IFIs) made it possible to determine the values of the deformations that appeared.

The thematic processing of the SAR data was performed entirely using the created and freely available software product SNAP (<http://step.esa.int/main/toolboxes/snap/>), while GIS products were used for better visualization and additional analyses.

III. RESULTS OF THE PROCESSING OF THE SAR DATA FOR THE COSEISMIC EVENT

In this section, fragments of obtained IFIs for different earthquakes (see Table 1 and locations Figure 3) from both types of orbits before phase unwrapping are presented, where the phase differences induced by the event are visible.

The interference fringes (Figures 4-6, 8-9) were located on the IFI, showing the areas where deformation processes took place. Each fringe corresponds to a deformation of 28mm and as seen, for the areas near the epicenter, a series of fringes is observed. After applying an IFI phase unwrapping procedure, new images containing information on the absolute values of crustal deformations in a metric system were obtained. The resulting displacements were quantified in the direction of the satellite's line of sight – LoS.

Table 1. Seismic events with a magnitude greater than 6.0 studied for the region of the Mediterranean Seismic Zone

N	Name	Latitude Longitude	Mw	Dates, time/UTC
1	Kos-Bodrum Greece-Turkey	36.96 N 27.45 E	6.6	July 20, 2017
2	Zakynthos Ionian Sea	37.53 N 20.62 E	6.8	October 25, 2018 22:54
3	Durast - Albania	41.38 N 19.47 E	6.4	November 26, 2019
4	Petrinja - Croatia	45.42 N 16.12 E	6.4	December 29, 2020
5	Larissa - Greece	39.76 N 22.21 E	6.3	March 03, 2021
6	Larissa - Greece	39.80 N 22.20 E	6.1	March 04, 2021
7	Turkey-Syria	38.07 N 36.47 E	6.0	February 6, 2023 12:02
8	Turkey-Syria	38.11 N 37.24 E	7.5	February 6, 2023 10:24
9	Turkey-Syria	37.13 N 36.81 E	6.7	February 6, 2023 01:28
10	Turkey-Syria	37.17 N 37.08 E	7.8	February 6, 2023 01:17

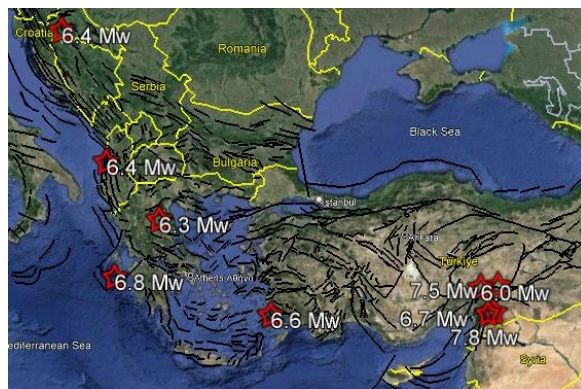


Figure 3. Locations of the epicenters of the studied earthquakes, their magnitudes and the main faults

A. Island of Karaada

On July 20, 2017, an earthquake with Mw 6.6 and a depth of 2 km occurred near the island of Kos. The epicenter of the earthquake was located in the Aegean Sea, about 1 km south of the uninhabited island of Karaada.

The Greek island of Kos and the city of Bodrum in southwestern Turkey were affected. Maps of the displacement were created and the values of the southern sinking of Karaada Island in the LOS direction from descending and ascending orbits were determined (Figure 4), (Atanasova, M. *et al.*, 2019; Ganas, A. *et al.*, 2017).

B. Island Zakynthos

In Nikolov, H. *et al.* (2021) surface deformations were determined based on the prepared interferograms, that occurred after an earthquake on October 25, 2018

located about 45 km southwest of the island of Zakynthos, with Mw 6.8 and a depth of 10 km.

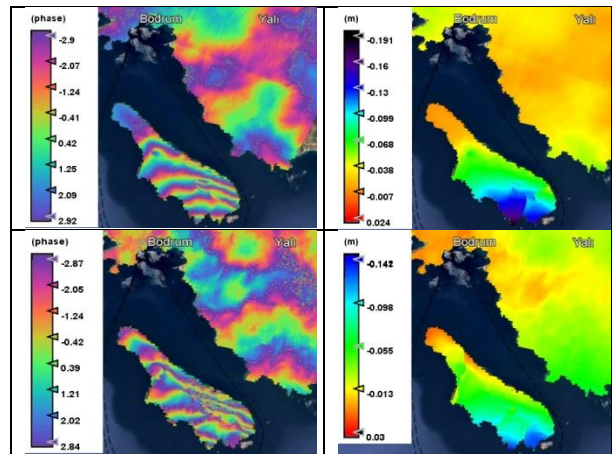


Figure 4. Interferometric images of the Kos - Bodrum earthquake area /Mw 6.6 /, ascending orbit 131, from 12.07-24.07. 2017 and descending orbit 36 from 18.07-30.07.2017; deformation map along the LOS direction

C. Durres- Albania

On November 26, 2019, the most devastating earthquake in the last 40 years in the region occurred in the northwestern part of Albania, which was the second such event in a period of three months, located about 8 km northeast of the port city of Durres. In the Nikolov, H. *et al.* (2020) and Nikolov, H. *et al.* (2021) is presented the processed interferogram of the event from the dates 02.12–19.11.2020 from ascending orbit 175.

D. Petrinja- south-southeast of Zagreb

The devastating earthquake that struck Croatia on December 29, 2020 had a magnitude of 6.4 on the Richter scale. Its epicentre (45.42 N, 16.12 E) is located near the village of Strasnik at a depth of 4 km, 6 km southwest of Petrinja and 65 km south-southeast of Zagreb.

This is the biggest earthquake in Croatia recorded in the last century. An earthquake of similar magnitude occurred in 1880 near Zagreb. Three earthquakes of magnitude 6 and greater have occurred since 1900 to date within 200 kilometers of the epicenter of the December 29, 2020 earthquake. The mainshock and most of the aftershocks are located on the Petrinja Fault, which is well described in the European Seismogenic Fault Database (EDSF). This event was investigated from InSAR data (see Figure 5) supplemented with seismological and geological studies.

E. Larissa- Greece

Surface deformations were determined (Atanasova, M. *et al.*, 2021), after an earthquake Mw 6.3, which occurred on March 3, 2021, 20 km northwest of the Greek city of Larissa, followed by a strong aftershock the next day with a magnitude Mw 6.1. When studying

this type of events, in very rare cases, it is possible to distinguish the deformations of the earth's crust that occurred as a result of only the main earthquake from the subsequent aftershocks. Usually, using the applied method, the total changes of the earth's crust are registered for the period between two passes of the satellites, which for the Sentinel-1 mission (for 2021) is a minimum of 6 days.

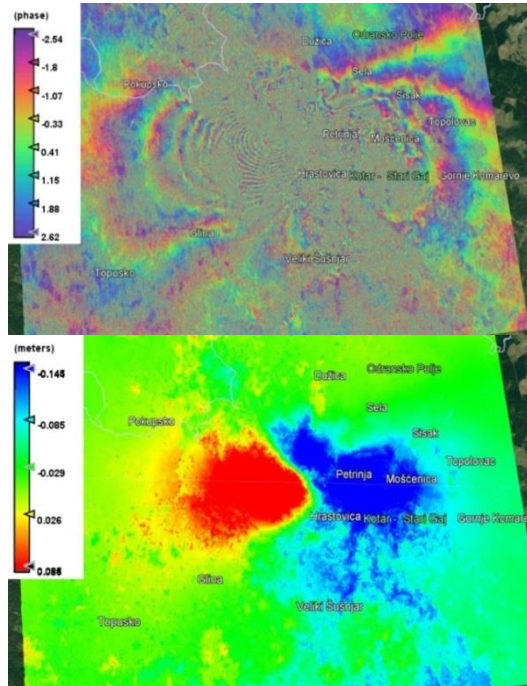
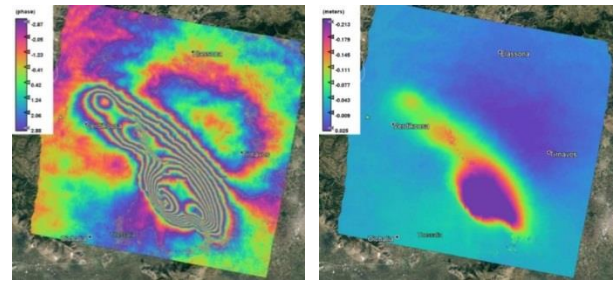


Figure 5. Interferometric image of the Petrinja - Croatia earthquake area on December 29, 2020 ascending orbit and deformation map along the LOS direction (Atanasova, M. 2023)

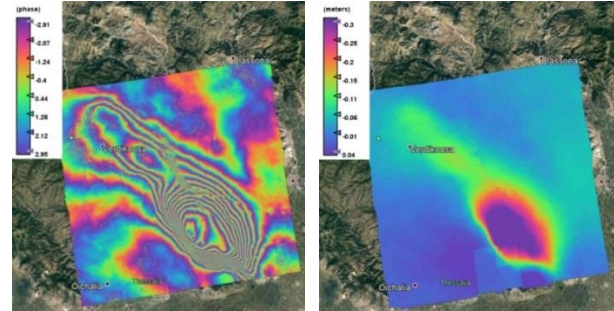
The differences in the values of the occurred displacements of the Earth's crust, determined by the different orbits, confirm the need, when studying deformations, to prepare IFIs from both types of orbits in order to get a better idea of them and to compare them with field measurements or results from other sources (Bignami, C. *et al.*, 2021; Ganas, A. *et al.*, 2021a).

F. Turkey-Syria 2023

The final challenge was to record the deformations of the vast areas, after the two devastating earthquakes of magnitudes Mw 7.8 and Mw 7.5 that struck Turkey on February 6, 2023. The earthquakes occurred along the East Anatolian Fault, west of the city of Gaziantep. The earthquakes were followed by intense aftershocks. This study presents the initial results of interferometric processing of SAR data from the ESA's Sentinel-1 mission, revealing the affected area and magnitude of deformations that occurred after the earthquakes (see Figure 7).



Descending orbits 80 orbit 02-14 March 2021



Ascending orbits 175 orbit 02-14 March

Figure 6. Interferometric images of the area of the Larissa earthquake and maps of the deformations along the LOS direction determined by the two types of orbits

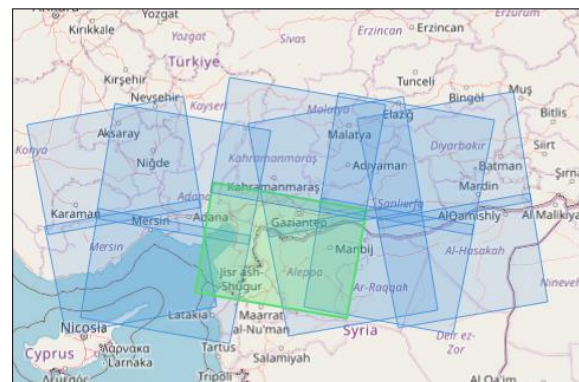


Figure 7. SLC images from Sentinel-1A for area of the Turkey's earthquake - ascending and descending orbits (in green) <https://dataspace.copernicus.eu/browser/>

The produced maps present combined data from several sources, with event epicenters from EMSC and active faults from EDAF, both of which are considered to be the driving forces of these ground motions SAR data used to obtain information showing the actual surface displacements (see Fig 8-9). It should be emphasized that the mentioned information does not reflect the consequences of one seismic event, but the effect of all earthquakes that occurred in the studied region between the dates January 29, 2023 to February 10, 2023 of registration by the SAR instrument (Atanasova, M. *et al.*, 2023; Nikolov, H. & Atanasova, M., 2023)

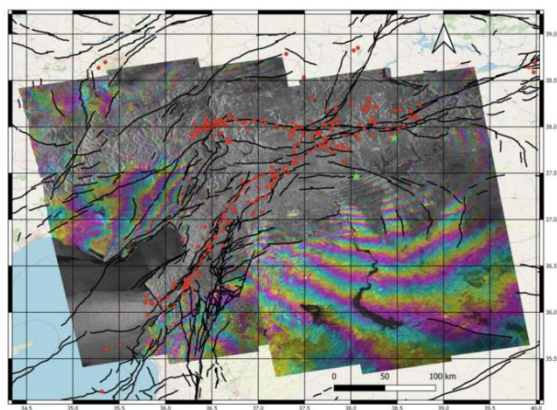


Figure 7. Interferometric images of the area of the Turkey earthquake - ascending orbit, event epicenters from EMSC and active faults from EDAF

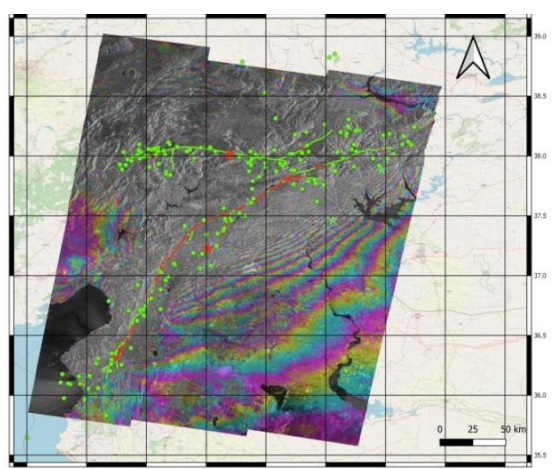


Figure 8. Interferometric images of the area of the Turkey earthquake - descending orbit

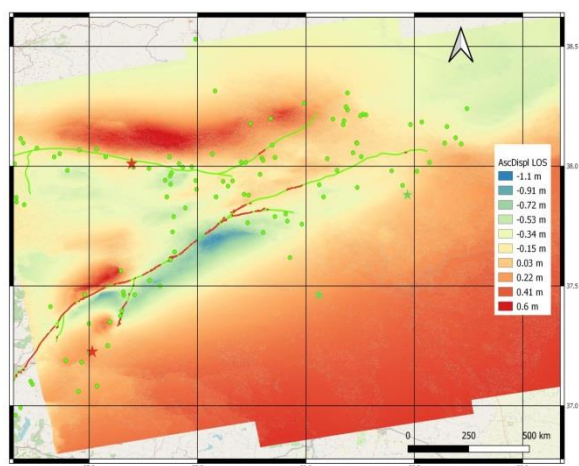


Figure 9. Registered deformations by SARdata from an ascending orbit, earthquake area and epicentres (February 6, 2023), lines - active faults from EDAF

IV. TECTONIC SETTINGS OF THE REGION, SEISMICITY AND DISCUSSION OF THE RESULTS

The southern part of the Balkan Peninsula is outlined by the Hellenic arch, located in the Mediterranean region. The entire area is exposed to a north-south extension that has caused intense deformation and

complex geology. It is bounded to the west by the Dinarides (up to Adriatic Sea), to the east by the Arabian plate, to the north by the Eurasian plate, and to the south by the Hellenic subduction zone (Bonev and Beccaletto 2007; Janssen *et al.* 2009). The current tectonic source in the region is the movement of the African, Arabian, and Eurasian lithospheric plates and Anatolian microplate (McKenzie 1972, 1978; Jackson and McKenzie 1988; McClusky *et al.* 2000). They assume the existence of an Aegean plate that moves at a different speed compared to the Anatolian plate, supplemented by a north-south extension zone in Western Turkey. A tectonic map of the region with the major faults, the epicenters of the studied earthquakes and their focal mechanisms is shown on Figure 10 (western part of the studied area) and Figure 11 (central and eastern part).

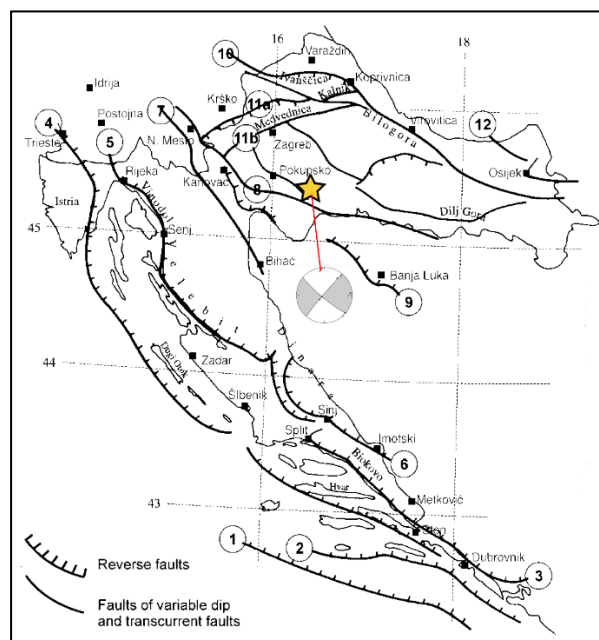


Figure 10. A tectonic map and the active faults in Croatia (western part of the studied area). The epicentre of the the Petrinja - Croatia earthquake (December 29, 2020, N4 in Table 1, 2) is marked with a yellow star and the Focal Mechanism points to the epicentre. 1-Adriatic fault, 2-Dubrovnik fault, 3-Mosor Mt.-Biokovo Mt. fault, 4-Trieste-Dugi Otok Island fault, 5-Rijeka-Velebt Mt. fault, 6-Sini-Imotska fault, 7-Fella-Sava-Cromelj-Bihac fault, 8-Sutern marginal fault of the Pannonian Basin, 9-Banja Luka fault, 10-Periadriatic-Drava fault, 11-Medvednica Mt. fault zone, a-Brezice-Krizevci fault, b-Zagreb fault, 12-Baranja fault. (Modified from Markušić and Herak, 1998)

The fault plain solutions (FPS) data of the studied earthquakes are presented in Table 2. Earthquake N9 occurred only 11 minutes after the main shock, making FPS determination very difficult. All available FPS are presented in Figure 10 (the Petrinja - Croatia earthquake, N4 in Table 1, 2) and Figure 11 (the rest). The fault plains (Strike 1, Dip 1 and Slip 1) of all presented FPS (Table 2) match very well with the

regional tectonics the slip direction of the main faults, and the results obtained from the SAR data.

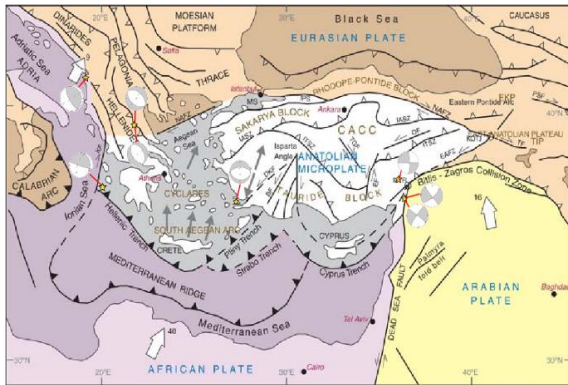


Figure 11. A tectonic map and the active faults in the Aegean zone (central and eastern part of the studied area). The epicentres of remaining earthquakes (Table 1) are marked with a yellow star and the respective Focal Mechanisms point to the epicentres (Table 2). NAFZ - North Anatolian fault zone, MS - Marmara Sea KOTJ – Karliova triple junction, MTR - Maras triple junction, OF - Ovacik fault, TGF - Tuz Golu fault, PSF - Pampak-Sevan fault, TF - Tutak fault, TIP - Turkish-Iranian plateau, DKF – Datca-Kale fault, EAFZ – Eastern Anatolian fault zone, EF – Ecemis fault, EKP – Erzurum-Kars plateau, IASZ – Izmir-Ankara suture zone, IPS – Intra-Pontide structure, KF – Kefalonia fault, MM – Menderes massif, OF – Ovacik fault (modified from Dilek and Altunkaynak 2009)

Table 2. Faults plain solutions (FPS) of the studied earthquakes. All strike, dip and slip angles of the first (1) and second (2) nodal planes are measured in degrees [°]. The numbers (N) are same as in Table 1. GFZ - Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, KOERI - Bogazici University Kandilli Observatory and Earthquake Research Institute Regional Earthquake-Tsunami Monitoring Center.

N	Strike 1	Dip 1	Slip 1	Strike 2	Dip 2	Slip 2	Source
1	98	34	-82	269	55	-94	GFZ
2	107	85	67	5	22	167	GFZ
3	150	72	88	335	17	94	GFZ
4	130	82	177	220	87	7	GFZ
5	130	45	-90	310	44	-89	GFZ
6	146	48	-91	329	41	-88	GFZ
7	216	84	-1	306	88	-174	KOERI
8	89	88	10	359	79	178	GFZ
10	51	75	-4	142	86	-165	GFZ

The Kos-Bodrum earthquake (on July 20 2017, N1 in Table 1, 2) represents purely normal faulting. The fault plane dips to the south, with a surface projection located between Bodrum Peninsula (to the north) and Karaada Island (to the south) and a dip angle of about 34°. This corresponds very well to the InSAR deformations of Kaarada Island (Figure 4).

The Zakintos Island earthquake (on October 25 2018, N2 in Table 1, 2) presents trusts focal mechanism on the

western side of the Hellenic Trench. The surface deformation on Zakintos Island, obtained by the SAR, fit well with the earthquake's focal mechanism.

The Durres - Albania (on November 26 2019, N3 in Table 1, 2) also has a trusts focal mechanism and clear increasing surface deformation southwest of the epicenter to the Adriatic coast.

The Petrinja – Croatia earthquake (on December 29 2020, N4 in Table 1, 2) shows a strike-slip focal mechanism associated with Petrinja fault, part of the Sutern fault zone. The surface deformation shows a clear left lateral horizontal movement in the northwest-southeast direction of the fault.

The Larissa-Greece main shock and the stronger aftershock (on March 3 and March 4 2021, N5 and N6 in Table 1, 2 respectively), present a purely normal faulting, striking along the Hellenides. The obtained InSAR results fit very well with the regional tectonic and both earthquakes focal mechanisms, showing sinking deformation south-western of the fault.

The earthquakes in Turkey-Syria border region (on February 6 2023, N7, N8 and N10 in Table 1, 2) represent left lateral strike-slip faulting typical of the East Anatolian Fault Zone. The obtained interferograms present very complex deformation that are result of the both main shocks and the stronger aftershocks.

V. CONCLUSIONS

From the presented results after processing the SAR data using the InSAR method, it can be concluded that they are an additional source of information about the deformations of the earth's crust that have occurred due to earthquakes. The good compliance between InSAR maps, FPS and regional tectonics shows that the SAR method is reliable and very useful source of information. Their advantage is that this information is obtained for large areas and in a relatively short time after the event, which supports the preparation of maps to overcome its consequences and update the preparation plans in future strong events in same area. The processing methodology applied by the authors made it possible to obtain IFIs that visually represent the displacements around the epicentres.

VI. ACKNOWLEDGEMENTS

Acknowledgments: The scientific results are part of the work on the project: "National Geoinformation Center (NGIC)", financed by the National Roadmap for Scientific Infrastructure 2020-2027 of Bulgaria. Contract No. D01-164/28.07.2022 and the project: "Study of co-seismic deformations of the earth's crust for the territory of the Balkan Peninsula based on satellite data", financed by "Competition for financial support of basic research projects – 2023" of Bulgaria. Contract No. KP-06-N74/2 from 14.12.2023r.

References

- Atanasova, M., Nikolov, H., Protopopova, V. (2019). DInSAR in displacement detection after seismic events. Proceeding 10th Congress of Balkan Geophysical Society, 18-22 September, Albena Resort, Bulgaria, EAGE, 2019, DOI: 10.3997/2214-4609.201902642, 1-4.
- Atanasova, M., Nikolov, H., Oynakov, E. (2021). CO-SEISMIC SURFACE DISPLACEMENTS AFTER THE EARTHQUAKES IN LARISSA, 3 MARCH 2021, DERIVED BY DINSAR. Proceedings of 21th International Multidisciplinary Scientific GeoConference SGEM 2021, Volume: 21, Book number: 2.1, International Multidisciplinary Scientific Geoconference, ISBN:1314-2704, ISSN:978-619-7603-22-4, DOI:10.5593/sgem2021/2.1/s10.64, 521-528.
- Atanasova, M., Nikolov, H. (2022). A STUDY OF SEISMIC DISPLACEMENTS IN THE BALKANS FROM SATELLITE DATA, Proceeding XXX INTERNATIONAL SYMPOSIUM ON MODERN TECHNOLOGIES, EDUCATION AND PROFESSIONAL PRACTICE IN GEODESY AND RELATED FIELDS, Sofia, 02 – 04 November, ISSN:2367-6051, 1-11.
- Atanasova, M., Raykova, P., Nikolov, H. (2023). Determining the Deformations of the Earth's Surface after the Earthquakes in Turkey-Syria of 06 February 2023 - Initial Results. *Comptes rendus de l'Académie bulgare des Sciences*, 76, 4, Bulgarian Academy of Sciences, ISSN:1310–1331, DOI: 10.7546/CRABS.2023.04.07, 554-562.
- Atanasova, M. (2023). Determination of coseismic deformations in the Balkan Peninsula region from SAR data. XI National Geophysical Conference, 9th June, DOI:10.48368/BGS-2023.1.N12 (in bulgarian).
- Bignami, C., Antonioli, A., Atzori, S., Kiratzi, A., Polcari, M., Svighas, N., Tolomei, C., (2021) Mapping InSAR deformation of low and moderate earthquakes, *Procedia Computer Science*, Volume 181, 2021, Pages 214-219.
- Baker, C., Hatzfeld, D., Lyon-Caen, H., Papadimitriou, E., Rigo, A., (1997) Earthquake mechanisms of the Adriatic Sea and Western Greece: implications for the oceanic subduction/continental collision transition. *Geophysical Journal International*, 1997, 131 (3), pp.559 - 594. [ff10.1111/j.1365-246X.1997.tb06600.x](https://doi.org/10.1111/j.1365-246X.1997.tb06600.x).
- Bonev, N., Beccaletto, L. (2007). From syn-to post-orogenic tertiary extension in the north Aegean region: constraints on the kinematics in the eastern Rhodope–Thrace, Bulgaria–Greece and the Biga Peninsula, NW Turkey. *Geol. Soc. Lond. Spec. Publ.* 291:113–142.
- D'Agostino, N., Métois, M., Koci, R., Duni, L., Kuka, N., Ganas, A., Georgiev, I., Jouanne, F., Kaludjerovic, N., Kandic, R., (2020). Active crustal deformation and rotations in the southwestern Balkans from continuous GPS measurements. *Earth and Planetary Science Letters*, Volume 539, 1, Elsevier, ISSN:0012-821X, DOI:10.1016/j.epsl.2020.116246.
- Dilek, Y., Altunkaynak, S. (2009). Geochemical and temporal evolution of Cenozoic magmatism in western Turkey: mantle response to collision, slab breakoff, and lithospheric tearing in an orogenic belt. *Geol. Soc. Lond. Spec. Publ.* 311:213–233.
- Ezquerro, P., Bru, G., Galindo, I., Monserrat, O., García-Davalillo, J.C., Sanchez, N., Montoya, I., Palama, R., Mateos, R.M., Perez-Lopez, R., Gonzalez-Alonso, E., Grandin, R., Guardiola-Albert, C., Lopez-Vinillas, J., Fernandez-Merodo, J.A., Herrera, G., Bejar-Pizarro, M., (2023) Analysis of SAR-derived products to support emergency management during volcanic crisis: La Palma case study, *Remote Sensing of Environment*, Volume 295, 1 September 2023, 113668.
- Ferretti, A., Monti-Guarnieri, A., Prati, C., Rocca, F., Massonnet, D. (2007) *InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation [TM-19]*, ESA Publications, Noordwijk, The Netherlands, 2007.
- Fialko, Y., Simons, M., (2001) The complete (3-D) surface displacement field in the epicentral area of the 1999 Mw7.1 Hector Mine earthquake, California, from space geodetic observations. *GEOPHYSICAL RESEARCH LETTERS*, VOL. 28, NO. 16, PAGES 3063-3066, AUGUST 15, 2001.
- Ganas, A., Elias, P., Valkaniotis, S., Briole, P., Kapetanidis, V., Kassaras, I., Barberopoulou, A., Argyrakakis, P., Chouliaras, G., Moshou, A. (2017) Co-seismic deformation and preliminary fault model of the July 20, 2017 M6.6 Kos earthquake, Aegean Sea, DOI: 10.13140/RG.2.2.33057.30564.
- Ganas, A., Valkaniotis, S., Tsironi, V., Karasante, I., Elias, P., Kapetanidis, V., Kassaras, I., Papathanassiou, G. and Briole, P. 2021a. The March 2021 seismic sequence in Larisa - Damasi, Thessaly (central Greece), its seismotectonic characteristics and geodynamic effects. *Zenodo*. <http://doi.org/10.5281/zenodo.4617264>.
- Ganas, A., Elias, P., Briole, P., Valkaniotis, S., Escartin, J., Tsironi, V., Karasante, I., Kosma, C., 2021b. Co-seismic and post-seismic deformation, field observations and fault model of the 30 October 2020 Mw = 7.0 Samos earthquake, Aegean Sea. *Acta Geophys.* <https://doi.org/10.1007/s11600-021-00599-1>.
- Giardini, D., Woessner, J., Danciu, L., (2014) Mapping Europe's Seismic Hazard. *EOS*, 95(29): 261-262.
- Hanssen, R.F., (2001) *Radar interferometry: data interpretation and error analysis*. Dordrecht, Netherlands: Kluwer Academic Publishers; 2001.
- Jackson, J. and McKenzie, D. P. (1988). The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East, *Geophysical Journal*, 93, 45–73.
- Janssen, C., Bohnhoff, M., Vapnik, Y., Görgün, E., Bulut, F., Plessen, B., Pohl, D., Aktar, M., Okay, A., Dresen, G. (2009). Tectonic evolution of the Ganos segment of the North Anatolian Fault (NW Turkey). *J. Struct. Geol.* 31:11–28.
- McClusky, S., Balassanian, S., Barka, A., Demir, C., Ergintav, S., Georgiev, I., Gurcan, O., Hamburger, O., Hurst, K., Kahle, H., Kastens, K., Kekelidze, G., King, R., Kotsev, V., Lenk, O., Mahmoud, S., Moshin, A., Nadariya, M., Ouzounis, A., Paradissis, D., Peter, Y., Prilepin, M., Peilinger, R., Sanli, I., Seeger, H., Tealeb, A., Toksoz, M., Veis, G. (2000). Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus, *Journal of Geophysical Research: Solid Earth*, Vol. 105, No. B3, 5695-5719.
- McKenzie, D.P. (1972). Active tectonics of the Mediterranean region. *Geophys. J. R. Astron. Soc.* 30:109–185.
- McKenzie, D.P. (1978). Active tectonics of the Alpine–Himalayan belt: the Aegean Sea and surrounding regions. *Geophys. J. R. Astron. Soc.* 55:217–254.

- Markušić, S., Herak, M. (1998). Seismic Zoning of Croatia. *Natural Hazards* 18, 269–285. DOI:10.1023/A:1026484815539.
- Nikolov, H., Protopopova, V., Atanasova, M. (2020). Studying seismic events via satellite interferometry. *Proceedings Volume 11524, Eighth International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2020)*; Paphos, Cyprus, 15241B, 11524, SPIE 2020, *Proceedings of SPIE - The International Society for Optical Engineering*, 2020, 11524, 115241B, ISBN:978-151063857-0, ISSN:0277786X, DOI:10.1117/12.2570676, 1-16.
- Nikolov, H., Atanasova, M., Protopopova, V., (2021). Application of satellite SAR data to detect deformations of the Earth's crust after earthquakes. *Proceedings of 2nd National Workshop with International Participation on COPERNICUS, Space Research and Technology Institute - Bulgarian Academy of Sciences (SRTI-BAS), Sofia, Bulgaria* ISBN:978-619-7490-09-1, DOI:10.5281/zenodo.6497513, 25-37
<https://zenodo.org/record/6497513#.YvpMD31Bmx>
- Nikolov, H., & Atanasova, M. (2023). Co-seismic ground motions following the Turkey-Syria earthquakes recorded from SAR data. *XI National Geophysical Conference, 9th June* DOI:10.48368/BGS-2023.1.N11.
- Solakov, D. S. Simeonova, P. Raykova, I. Aleksandrova (2018a). EMPIRICAL RELATIONS CONVERTING M_d AND M_p MAGNITUDES APPLIED IN BULGARIAN SEISMOLOGICAL ROUTINE PRACTICE TO MOMENT MAGNITUDE. *Comptes rendus de l'Académie bulgare des Sciences*, 71, 8, DOI:10.7546/CRABS.2018.08.09, 1076-1085, <http://www.proceedings.bas.bg/>.
- Solakov, D., Simeonova, S., Raykova, P., Aleksandrova, I (2018b). Seismological analysis of the low frequencies M_w 5.6 earthquake in Sofia Seismogenic zone. *Procc. 9th International INQUA Meeting on Paleoseismology, Active Tectonics and Archeoseismology, PATA*, 267-270.
- Solari, L., Barra, A., Herrera, G., Bianchini S., Monserrat, O., Béjar-Pizarro, M., Crosetto, M., Sarroo, R., Moretti S., (2017): Fast detection of ground motions on vulnerable elements using Sentinel-1 InSAR data, *Geomatics, Natural Hazards and Risk*, DOI: 10.1080/19475705.2017.1413013.
- Shaw, B., and Jackson, J., (2010) Earthquake mechanisms and active tectonics of the Hellenic subduction zone *Geophys. J. Int.* (2010) 181, 966–984 doi: 10.1111/j.1365-246X.2010.04551.x.
- Wright, T., Parsons, B., Zhong Lu (2004) Toward mapping surface deformation in three dimensions using InSAR, *GEOPHYSICAL RESEARCH LETTERS*, VOL. 31, L01607, doi:10.1029/2003GL018827, 2004.

Tapping different depth sources and temperature – oxygen fugacity variations throughout the 2021 eruption at La Palma, Canary Islands, Spain: insights from mineral chemistry of spinels

Cristina de Ignacio¹, Tomás Martín-Crespo², David Gómez-Ortiz², Silvia Martín-Velázquez², Elena Real¹, José Arnoso^{3,5}, Fuensanta G. Montesinos^{4,5}

¹Dpt. Mineralogía y Petrología, Facultad CC. Geológicas, Universidad Complutense de Madrid, C/José Antonio Novais, 2, 28040, Madrid, (cris@geo.ucm.es; elenreal@ucm.es)

²Dpt. Biología, Geología, Física y Química inorgánica, ESCET. Universidad Rey Juan Carlos, C/Tulipán s/n, 28933. Móstoles, Madrid, (tomas.martin@urjc.es; david.gomez@urjc.es; silvia.martin@urjc.es)

³Instituto de Geociencias (CSIC-UCM), C/Doctor Severo Ochoa, 7, 28040 Madrid, (jose.arnoso@csic.es)

⁴Sección Departamental Astronomía y Geodesia, Facultad CC. Matemáticas, UCM, Plaza de Ciencias, 3, 28040 Madrid, (fuensant@ucm.es)

⁵Grupo de Investigación UCM- 'Geodesia'

Key words: spinel; lava flows; temperature; depth; La Palma

ABSTRACT

Spinel as a mineral group are complex in both structure and possible cation substitutions. Their general formula AB_2O_4 hosts both trivalent (Cr^{3+} , Al^{3+} , Fe^{3+}), divalent (Mg^{2+} , Fe^{2+}) and tetravalent (Ti^{4+}) cations, which comprise from refractory, high temperature (and/or pressure) elements to typical rock-forming ones in mafic systems. In this way, the magnesium number in spinels, defined as molar $Mg/(Mg + \text{total iron})$ has proved to be strongly dependent on crystallization temperature, thus providing the base for a recent geothermometer. In addition, the occurrence of both ferric and ferrous iron in spinel structures allows estimation of oxygen fugacity conditions. Compositional variation in spinel group minerals is also influenced from their usual co-crystallization with early ferromagnesian silicates and, therefore, is a good tracer of progressive magma fractionation processes. Representative samples from the 2021 Tajogaite eruption at La Palma (Canary Islands) were selected for this study. Electron probe microanalysis of spinel inclusions in olivine, clinopyroxene (phenocrysts, microphenocrysts and groundmass crystals), as well as oxide grains (groundmass) were used: 1) to track initial interactions between the main magma pulses and shallow felsic magma chambers; 2) to detect subsequent recharge processes involving the injection of deeper, very primitive magma pulses during the main phase of the eruption and 3) to recognize differentiation geochemical patterns linked to polybaric fractional crystallization. All these processes resemble those described for other Macaronesian islands (Madeira) and could reflect overall similar features of the shield stage of intraplate, ocean island building.

I. INTRODUCTION

The Sept-Dec 2021 eruption in Tajogaite (La Palma, Canary Islands, Spain) built a tephrite-basanite scoria cone with associated lava flows, which were sampled from the beginning to the ending of the eruptive process. In this study, electron probe microanalysis (EPMA) of spinel-group minerals as inclusions in olivine (OL) and clinopyroxene (CPX; diopside) macro-, meso- and microcrysts (Figure 1), along with single groundmass crystals have allowed us recognizing changes in the depth of contributing magma pulses to the eruptive process. Additionally, these analyses have shed light on interactions between more primitive, basanite liquids and differentiated (tephritic-phonotephritic) already existing shallow reservoirs.

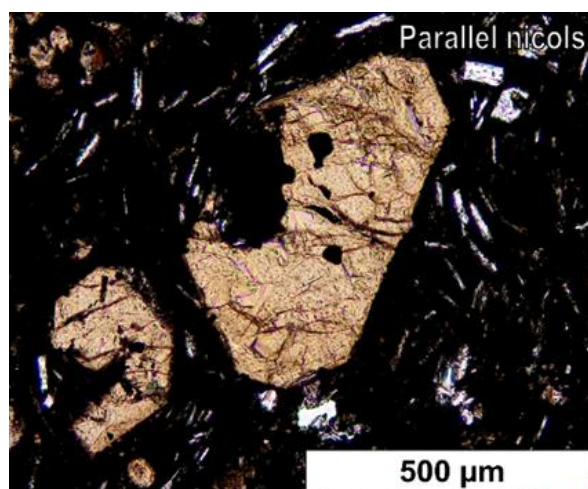


Figure 1. Euhedral to subhedral spinel inclusions in clinopyroxene macrocryst from the Tajogaite basanites.

II. APPROACH AND RESULTS

Spinel group mineral compositions admit trivalent, divalent, and tetravalent cation substitutions. The incorporation of some of these cations is strongly temperature (T) dependent, providing good geothermometers (e.g., $XMg = Mg/(Mg + \text{total iron})$ on

an atoms per formula unit (a.p.f.u.) basis (Canil & Lacourse, 2020).

In turn, the presence of significant Al^{3+} and/or Cr^{3+} is typical of very high T, (>1200°C) and/or high pressure, early-crystallized spinels. Plots of trivalent cation contents in spinels from lavas of the different stages of the 2021 eruption show a significant variation (Figure 2):

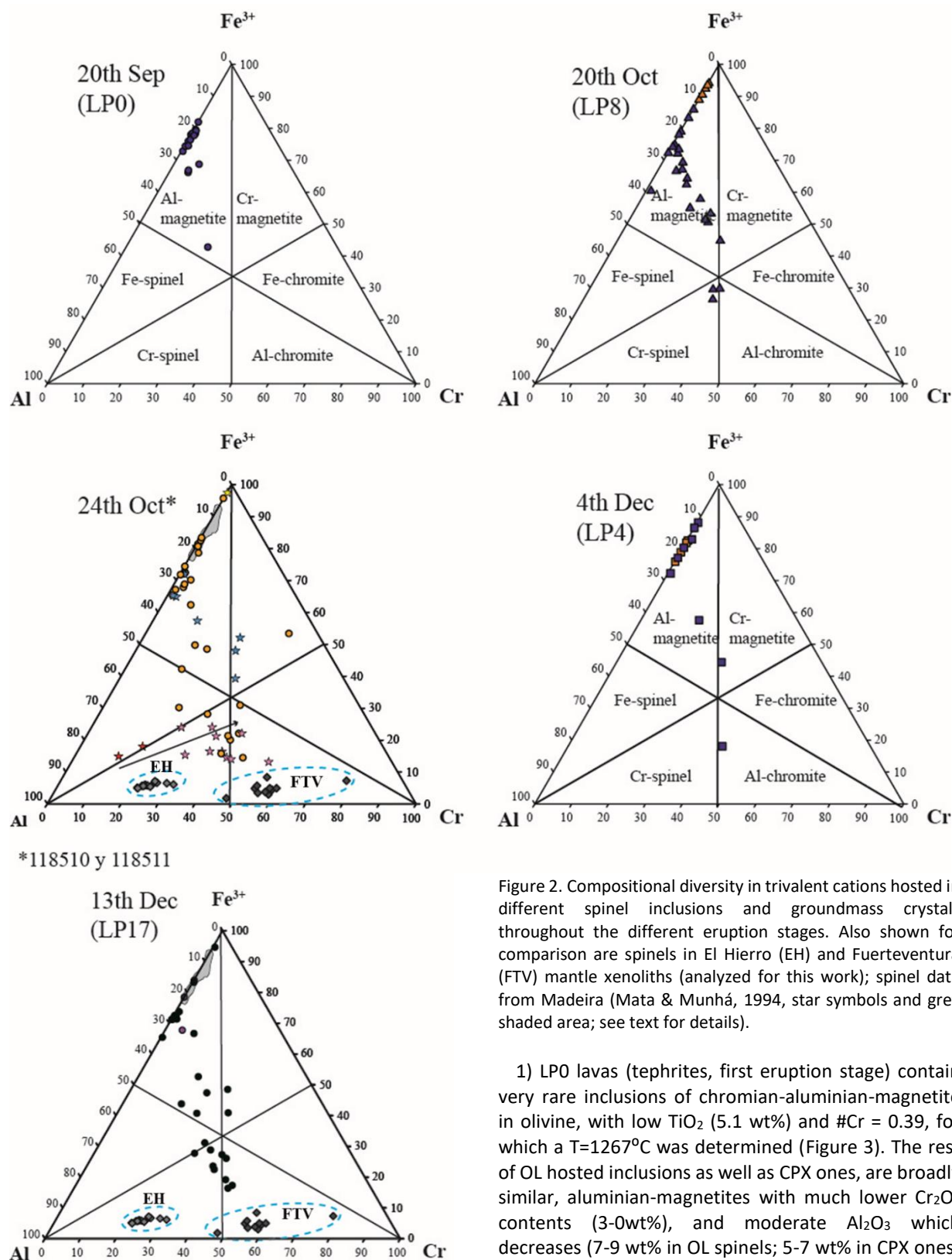


Figure 2. Compositional diversity in trivalent cations hosted in different spinel inclusions and groundmass crystals throughout the different eruption stages. Also shown for comparison are spinels in El Hierro (EH) and Fuerteventura (FTV) mantle xenoliths (analyzed for this work); spinel data from Madeira (Mata & Munhá, 1994, star symbols and grey shaded area; see text for details).

1) LP0 lavas (tephrites, first eruption stage) contain very rare inclusions of chromian-aluminian-magnetite in olivine, with low TiO_2 (5.1 wt%) and $\#Cr = 0.39$, for which a $T=1267^\circ C$ was determined (Figure 3). The rest of OL hosted inclusions as well as CPX ones, are broadly similar, aluminian-magnetites with much lower Cr_2O_3 contents (3-0wt%), and moderate Al_2O_3 which decreases (7-9 wt% in OL spinels; 5-7 wt% in CPX ones)

with temperature, from 1179 to 1056°C. TiO₂ contents on the contrary are progressively higher, from 13-15 wt% in OL hosted magnetites to 9.5-16.8 wt% in CPX ones and 16-20wt% in groundmass magnetites.

2) Samples from mid-late October represented by LP8, 118510 and 118511 (orange filled circles in Figures 2 and 3) show an interesting increase in Cr-Al rich oxides with respect to those of the Mt-Usp series (i.e., Fe-Ti compositions). Some of the analyzed inclusions in OL are classified as spinel *sensu stricto* and are ternary solid solutions containing 23-24 wt% Cr₂O₃, 17-18 wt% Al₂O₃ and 10-11 wt% MgO. Estimated crystallization temperatures for these oxides yielded very high values, >1300°C, out of the calibration range of the Canil & Lacourse (2020) geothermometer, in accordance with their richness in highly refractory elements (Figure 3). In fact, they plot very close to the field of fertile (El Hierro, EH) and refractory (Fuerteventura, FTV) spinels in mantle xenoliths (grey diamonds in Figure 2), that were also analyzed for this work. The rest of OL inclusions exhibit a range in #Cr from 0.51 to 0.10, with a strong decreasing trend in this element from cores to rims.

these oxides are 4.2-5.5 wt%, similar to those in LP0 oxides (Figure 2).

Finally, in the last month of the eruption there is initially a sharp decrease in Al-Cr rich oxides (LP4 lavas in Figure 2), although a few OL inclusions or tiny groundmass spinels still show high #Cr (51) and #Mg (55) and yield T around 1200°C or higher. However, most oxides are again magnetite with moderate Al and yielding from 1165 down to 1033-984°C, which are similar to groundmass CPX-plagioclase calculated equilibrium crystallization temperatures (Real, 2022), whereas in the final day of the eruption (LP17 lavas in Figure 2) another increase in Al-Cr rich spinels is apparent.

III. INTERPRETATION

Comparison of compositional features with similar spinel inclusions in silica-undersaturated mafic lavas from Madeira (Mata & Munhá, 1994) reveals that La Palma Cr-Al rich spinels are similar to Type II chromian spinels from Madeira (red and pink filled stars on 24th October plot, Figure 2), derived from fragmentation of high pressure (around 20 km depth, Moho) ultramafic

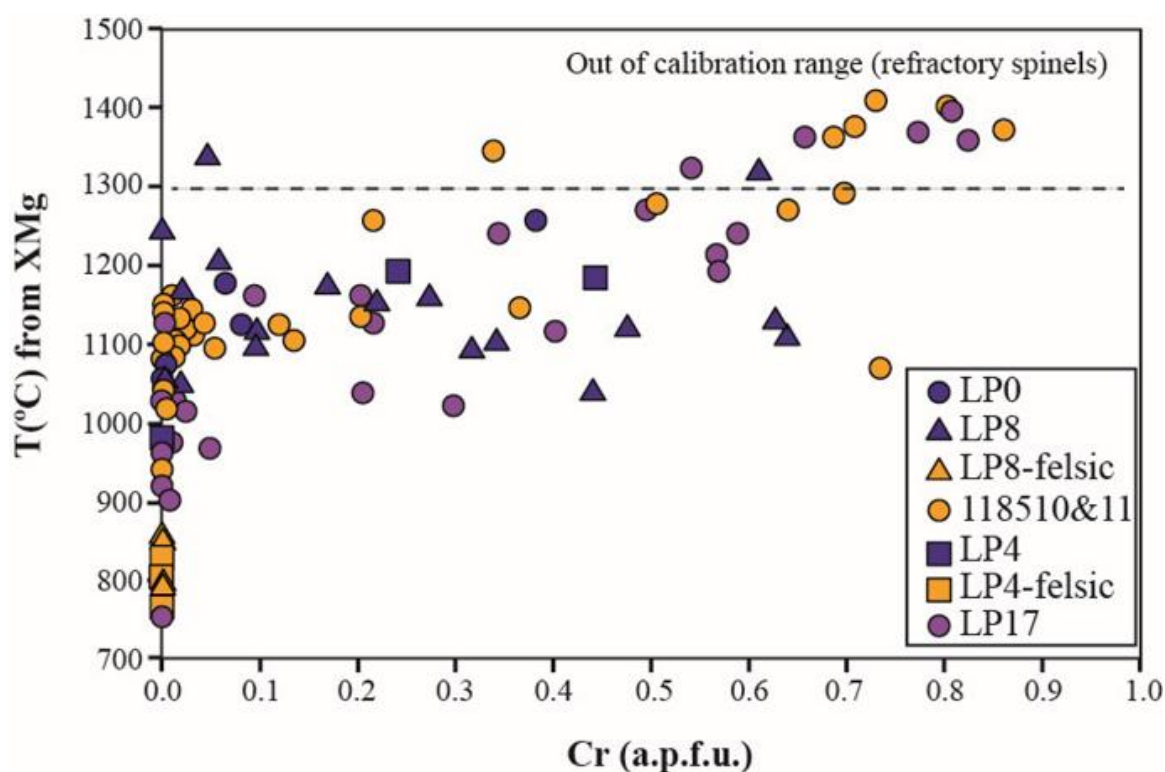


Figure 3. Crystallization temperatures of spinels obtained after Canil & Lacourse (2020) geothermometer, and their correlation with chromium contents (see text for explanation and interpretation of different spinel compositions).

In addition, LP8 lavas contain felsic, phonolite nodules, with its own kind of Fe-Ti oxides, which correspond to very pure magnetite, showing < 10% Al-component and lacking chromium. TiO₂ contents in

cumulate xenoliths. They exhibit an Al-Cr substitution trend (black arrow on same plot) interpreted as due to polybaric crystallization (Mata & Munhá, 1994). These spinels from La Palma are also not only hosted by highly magnesian (up to Fo₈₅₋₈₆) OL, as in Madeira, but also by reversely zoned olivine mesocrysts, and some of the groundmass crystals, which is interpreted as a record of mixing episodes between very deep, primitive magma batches and magmas already experiencing fractional crystallization in ascent. Some of the Type III olivine

hosted inclusions in Madeira (grey shaded area on 24th October and 13th December plots) exhibit compositions transitional from Cr-Ti magnetites to typical solid solutions of the ulvöspinel-magnetite type. The latter ones (similar to Type III spinels from Madeira, grey shaded area in Figure 2) are very abundant both in clinopyroxene macro-, meso- and microcrysts and in scattered crystals in the groundmass of the Tajogaite lavas, recording crystallization Ts from roughly 1100 to 980°C, with the typical Ti-Fe³⁺ enrichment trend described for alkaline basalt spinels by Barnes & Roeder (2001). Finally, Madeira Type IV spinels (high Mn and Fe³⁺, yellow star on 24th October plot) are similar to spinels analyzed in the felsic nodules of LP8 and LP4 lavas, which are a record of interaction of successive magma batches with shallow, more differentiated, magma reservoirs.

The abrupt change in spinel compositions, from dominantly aluminian magnetite to chromium-rich spinels, observed by the 20th October, matches the reported progressive increase in whole-rock MgO, Ni and Cr of lavas from 19th September (first eruption day) to 18th October (Day *et al.*, 2022; Sandoval-Velasquez *et al.*, 2023). It reflects a major change in whole-rock compositions from tephrite to basanite, probably in relation with the documented first collapse (25th September) of the pyroclastic cone (Romero *et al.*, 2022). However, whole-rock major element and trace elements contents remained more or less stable from 18th October (day 30 of eruption) to the end of eruptive activity. From different isotope ratios a roughly homogeneous mantle source with contributions from two components (depleted asthenospheric source and HIMU-type enriched source) has been proposed to feed the eruption (Day *et al.*, 2022). Nevertheless, these authors report an interesting shift in Os isotope ratios, to the most un-radiogenic values ever measured for La Palma, in lava from day 42 (30th October), which is six days later than our recorded most refractory spinels occurrence in samples 118510 and 118511 (Figure 2). These spinels plot near the field for Fuerteventura refractory mantle spinels and could indicate that magmatic pulses at this stage were derived from low partial melting of deep pyroxenitic veins in the mantle, as in Day *et al.* (2022). Also, in accordance with this idea Sandoval-Velasquez *et al.* (2023) reported a significant increase in noble gases (He and radiogenic Ar), CO₂ and N₂ concentrations after 15th October and until early November, which is also interpreted as linked to a deeper provenance of melts.

Our calculated temperatures (Figure 3) are on the same range of olivine-melt (1217-1237 and 1178-1156 °C) and clinopyroxene-melt (1175-1110 and 1023-969 °C) data (Sandoval-Velasquez *et al.*, 2023). Pressures determined by these authors by fluid inclusion barometry show two distinct entrapment populations at 22.5 to 29 and 13.0 to 16.5 km depth for samples

taken on 5th October and 6th November, again matching the simultaneous occurrence of refractory (deep) spinels *sensu stricto* and more common ('shallower') aluminian magnetites in our LP8, 118510 and 118511 samples (Figure 2). González-García *et al.* (2023) also determined two different, though slightly deeper, pressure intervals from fluid inclusion barometry, corresponding to 25-30 and 16-23 km depth.

Comparison between petrological data and seismicity distribution throughout the eruption has also been tackled in the already quoted works (Day *et al.*, 2022; Sandoval-Velasquez *et al.*, 2023; González-García *et al.*, 2023). It can be summarized as follows: the onset of eruptions marked by a fast shallowing of seismicity from 10-12 km to the surface in seven days (11th to 19th September; D'Auria *et al.*, 2023; <https://www.ign.es/web/ign/portal/sis-catalogo-terremotos>), followed by a drastic decrease at the end of September, in accordance with the already mentioned first edifice collapse and change in geochemistry of lavas. From the 1st October on, seismicity records become deeper and show two distinct clusters, whose depth intervals differ depending on the velocity model used to relocate earthquakes. The shallower one ranges from 10 to 14 km depth (<https://www.ign.es/web/ign/portal/sis-catalogo-terremotos>), whereas the deeper one is set at 20-25 km (D'Auria *et al.*, 2023) or 33-39 km (del Fresno *et al.*, 2023). The stagnation level located at 10 to 14 km depth (Moho, oceanic crust – mantle boundary) is also characterized by a tabular, gravity anomaly that has been interpreted as a sill, connected throughout the crust with a probably complex network of vertical or tilted dykes and additional sills making up the feeder system of the Tajogaite eruption (Montesinos *et al.*, 2023). These authors defined another stagnation level for magmas at 6-7 km depth, corresponding to the rheological contrast zone between the old oceanic crust and the submarine volcanic edifice representing the initial growth stage of the island. This is an interesting zone for possible generation of felsic magmas such as those sampled as enclaves in LP8 and LP4 lavas, whose magnetites yield the lowest crystallization temperatures of all studied spinel group minerals in this work (Figure 3).

IV. CONCLUSIONS

The Tajogaite eruption products show a tight compositional range, but detailed petrographic and mineral chemistry studies can provide useful insights into the workings of the subvolcanic to deep feeder system. Spinel-group minerals, both as inclusions and as individual groundmass crystals, show a diversity of compositions that can be correlated with processes of interaction between deeper, more primitive magma batches and more differentiated shallow reservoirs, in

patterns that could reflect common processes in Atlantic Ocean islands.

V. ACKNOWLEDGEMENTS

This research is supported by the project PID2019-104726GB-I00/AEI/10.13039/501100011033 (funded by the Spanish Research Agency), the Spanish Ministry of Science and Innovation (RD 1078/2021, funding for research activities of the CSIC-PIE project CSIC-LAPALMA-07) and by the special funding for GIGGA research group activities focused on the 2021 La Palma eruption (Universidad Rey Juan Carlos).

Vieja ridge eruption (Canary Islands): products and dynamics controlling edifice growth and collapse. *Journal of Volcanology and Geothermal Research*, 431: 107642

Sandoval-Velasquez, A., Rizzo, A.L., Casetta, F., Nftalos, T., Aiuppa, A., Alonso, M., Padrón, E., Pankhurst, M.J., Mundl-Petermeier, A., Zanon, V., Pérez, N.M. (2023). The noble gas signature of the 2021 Tajogaite eruption (La Palma, Canary Islands). *Journal of Volcanology and Geothermal Research*, 443: 107928

References

- Barnes, S.J., and Roeder, P.L. (2001). The range of spinel compositions in terrestrial mafic and ultramafic rocks. *Journal of Petrology*, 42, 2279-2302.
- Canil, D., and Lacourse, T. (2020). Geothermometry using minor and trace elements in igneous and hydrothermal magnetite. *Chemical Geology*, 541, 119576.
- D'Auria, L., Koulakov, I., Prudencio, J., Cabrera-Pérez, I., Ibáñez, J.M., Barrancos, J., García-Hernández, R., Martínez van Dorth, D., Padilla, G.D., Przeor, M., Ortega, V., Hernández, P., Pérez, N.M. (2022): Rapid magma ascent beneath La Palma revealed by seismic tomography. *Scientific Reports*, 12, 17654.
- Day, J.M.D., Troll, V.R., Aulinas, M., Deegan, F.M., Geiger, H., Carracedo, J.C., Gisbert Pinto, G., Pérez-Torrado, F.J. (2022): Mantle source characteristics and magmatic processes during the 2021 La Palma eruption. *Earth and Planetary Science Letters*, 597, 117793
- del Fresno, C., Cesca, S., Klügel, A., Domínguez Cerdeña, I., Díaz-Suárez, E.A., Dahm, T., García-Cañada, L., Meletlidis, S., Milkereit, C., Valenzuela-Malebrán, C., López-Díaz, R., López, C. (2023): Magmatic plumbing and dynamic evolution of the 2021 La Palma eruption. *Nature Communications*, 14, 358.
- González-García, D., Boulesteix, T., Klügel, A., Holz, F. (2023). Bubble-enhanced basanite-tephrite mixing in the early stages of the Cumbre Vieja 2021 eruption, La Palma, Canary Islands. *Scientific Reports*, 13: 14839
- Mata, J., and Munhá, J. (1994). Madeira Island alkaline lava spinels: petrogenetic implications. *Mineralogy and Petrology*, 81, 85-111.
- Montesinos, F.G., Sainz-Maza, S., Gómez-Ortiz, D., Arnoso, J., Blanco-Montenegro, I., Benavent, M., Vélez, E., Sánchez, N., Martín-Crespo, T. (2023): Insights into the Magmatic Feeding System of the 2021 Eruption at Cumbre Vieja (La Palma, Canary Islands) Inferred from Gravity Data Modeling. *Remote Sensing*, 15, 1936.
- Real, E. (2022). Mineral chemistry and thermometry of the October-2021 lava flows of Cumbre Vieja eruption (La Palma). Ms. Sc., Universidad Complutense de Madrid, Spain, 47 p.
- Romero, J.E., Burton, M., Cáceres, F., Taddeucci, J., Civico, R., Ricci, T., Pankhurst, M.J., Hernández, P.A., Bonadonna, C., Llewellyn, E.W., Pistolesi, M., Polacci, M., Solana, C., D'Auria, L., Arzilli, F., Andronico, D., Rodríguez, F., Asensio-Ramos, M., Martín-Lorenzo, A., Hayer, C., Scarlato, P., Pérez, N.M. (2022). The initial phase of the 2021 Cumbre

Relative Gravity networks in the Canary Islands: an effective tool to study volcanic processes in El Hierro and La Palma

F.G. Montesinos^{1,7}, J. Arnoso^{2,7}, M. Benavent^{1,7}, E. Vélez^{2,7},
D. Gómez-Ortiz^{3,8}, S. Sainz-Maza^{4,7}, I. Blanco-Montenegro^{5,7}, U. Riccardi^{6,7}

¹Facultad de CC. Matemáticas, Universidad Complutense de Madrid (UCM), Madrid, Spain (fuensant@ucm.es)

² Instituto de Geociencias (IGEO, CSIC-UCM), Madrid, Spain.

³ Dept. Biología y Geología, Física y Química Inorgánica, ESCET, URJC, Móstoles, Madrid, Spain.

⁴ Observatorio Geofísico Central, Instituto Geográfico Nacional (IGN), Madrid, Spain.

⁵ Dept. de Física, Escuela Politécnica Superior, UBU, Burgos, Spain.

⁶ Dpto. di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR), UNINA, Naples, Italy.

⁷ Research Group 'Geodesia', UCM, Spain.

⁸ Research Group 'Geofísica y Geoquímica Ambiental', Universidad Rey Juan Carlos, Spain.

Key words: *gravity networks, Canary Islands, magmatic process, volcanic events, gravity modelling*

ABSTRACT

The observation of temporal gravity changes can provide valuable insights into magmatic processes associated to volcanic crises. Time gravity changes can be sensitive to mass transport and density variations in the subsoil, as well as to vertical ground deformation. Hence, time-lapse gravity and geodetic measurements, jointly collected on networks, are a reliable tool for monitoring volcanic activity and for hazard assessment and risk mitigation programs. In order to detect possible precursors of volcanic activity in the Canary Islands archipelago, we established some gravity networks in several islands. In particular, we focused in El Hierro and La Palma, where the last eruptions started in October 2011 and September 2021, respectively. These are the first studies on gravity networks carried out in this archipelago. For El Hierro, the relative gravity network was established in 2003 and re-observed in 2004, 2008 and during the ongoing eruption in November 2021. Repeated gravity surveys were conducted in the time span 2012-2023 to study some of the magmatic intrusions, which did not result in a new eruption. The observed gravity changes between all these surveys may reflect the processes of magma displacement and its ascent to the surface. Similarly, the gravity network designed for La Palma was repeatedly surveyed from 2021 to 2023, before, during and after the 2021 volcanic eruption, providing us with an image of the magmatic feeding system of this eruption, and the spatio-temporal path of magma ascent from the mantle to the surface.

1. INTRODUCTION

Volcanoes may commonly show physical signs before erupting, such as an increase of seismicity, surface deformation around the volcano or changes in the geothermal systems and gas emissions. This precursory activity is typically associated with magma ascent or accumulation at depth and can also result in a magmatic intrusion that never reaches the Earth's surface. To study all these elements involved in volcanic or eruptive processes and to detect changes in the magmatic system, monitoring based on multiparametric networks is a good option. In this framework, gravimetry allows studying volcanic processes through spatio-temporal gravity changes (e.g., Berrino and Ricciardi, 2020). Episodic gravity surveys carried out at different stages of volcanic reactivation can help in imaging the mass redistribution involved in the process. Therefore, a suitable gravity network combined with additional information, like ground displacement or seismic data, can provide valuable insights into magma recharge

processes in the shallowest magmatic systems. Furthermore, it can serve as a tool for forecasting eruptions and improving our understanding of volcanic processes. (e.g. Poland *et al.*, 2019; Dalfsen and Poland, 2023). Looking for precursors of volcanic activity, we have established several gravity networks in the Canary Islands archipelago (Spain). The volcanic eruption and magmatic intrusions that occurred in El Hierro between 2011 and 2014, as well as the 2021 eruption in La Palma provided an excellent opportunity to apply time-lapse gravimetry on several gravity datasets acquired before, during and after those volcanic processes. These are the first relative gravity networks that were designed and re-observed at the Canary Islands with the aim of analysing and monitoring the eruptive and volcanic activity in the archipelago (e.g., Montesinos *et al.*, 2023). The relative gravity network in El Hierro island was established in 2003 and has been re-observed in successive surveys to date. Similarly, the gravity network covering the Cumbre Vieja volcano in La Palma Island was exploited to detect mass/density changes

related to the 2021 eruption through several surveys conducted before, during and after the eruption, from 2021 to 2023.

These gravity data have the capability of quantifying magma accumulation or drainage through the detection of mass variations, although the process does not necessarily cause ground deformation or seismicity. Therefore, gravity and ground deformation data represent a powerful tool for improving our knowledge of volcanic processes and eruption forecasting (de Zeeuw-van Dalfsen and Poland, 2023). The gravity changes discussed here in relation to the volcanic processes on the islands of El Hierro and La Palma confirm the feasibility of this methodology for volcano monitoring.

II. METHODOLOGY

The observation procedure used in the relative gravity surveys on El Hierro and La Palma networks was similar, looking for enough repeatability to ensure the necessary accuracy to detect gravity changes linked to volcanic processes. During each survey, approximately 25% of the stations were re-measured, with a selected base station occupied at least twice a day. The repeated observations were used to control the instrumental drift of the spring gravimeter and the possible jumps or offsets during the observation process. Each gravity station was occupied for 30 minutes, logging data every minute, with standard deviations of the individual readings in the range (0.01, 0.08) mGal ($1 \text{ Gal} = 10^{-2} \text{ ms}^{-2}$) (CG5 gravimeter). The absolute gravity stations owned by the Spanish National Geographic Institute (IGN) in these islands were also considered to refer the relative gravity values to the absolute ones. The geographic coordinates of all stations were obtained by differential GNSS calculation, attaining an average error associated with the height values of nearly 2.6 cm. This can lead a gravity error of nearly 0.008 mGal (8 μGal).

Observed gravity data were reduced by the height of the instrument over the benchmark and then corrected for atmospheric effects and Earth tides using the models provided by Arnosó *et al.*, (2011; 2023). In addition, an instrumental linear drift was estimated for all observations in each survey. Once the external/instrumental effects were corrected, the gravity value for each station was estimated by least squares for each survey. The difference between the gravity values obtained for the same site at different epochs, corresponds to gravity changes that could be associated with density/mass changes or vertical ground deformation. To obtain the gravity changes due solely to the redistribution of volcanic mass in the subsurface, several effects have to be corrected: groundwater variations, new topography (e.g., the emitted lava flows and the new volcanic edifice) and changes in the station height.

As for the contribution of the groundwater to gravity variations (e.g., Kennedy *et al.*, 2016), this information

is usually not available and the correction cannot be made. However, it is reasonable to assume a very small gravity effect when surveys are carried out in the same season or when there is little rain during the survey. The new topography generated by an eruption changes the local gravity field. To quantify this effect, appropriate digital terrain models are needed for the beginning and the end of the eruption. For instance, these datasets are available through the Copernicus European program database (www.copernicus.eu/en). Then, the topographic effects on the gravity values deriving from the difference between these models was calculated and removed from the observed gravity changes in the case of La Palma (e.g., Montesinos *et al.*, 2023).

To account for the free-air correction (FAC), an average value of $-308.6 \mu\text{Gal/m}$ is commonly applied. The height changes between different epochs were determined from GNSS measurements collected during the gravity surveys. Moreover, the GNSS results can be compared with data available from permanent GNSS stations that are close to the gravity benchmarks, or with InSAR information.

Once these corrections are performed, the residual gravity difference between two surveys can be studied in terms of subsurface density/mass changes.

III. GRAVITY NETWORK AT EL HIERRO

A. The 2011-2014 El Hierro volcanic unrest

The El Hierro unrest initiated with seismic activity on July 17th, 2011. Between October 2011 and March 2012 an eruption occurred on the southern submarine flank of the island (Figure 1), at a distance of approximately 4 km from the coast.

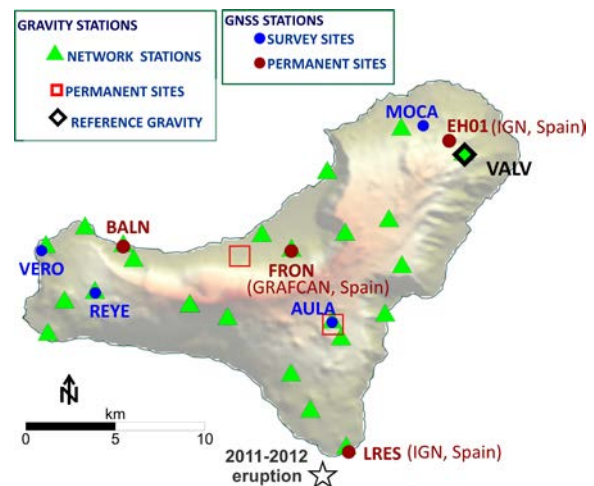


Figure 1. Gravity network and GNSS stations in El Hierro. The white star locates the 2011-2012 submarine eruption.

The seismic activity during the first two months of the unrest period started to the northwestern offshore of the island, at a depth of 10-15 km. It was associated to the primary intrusion of magma coming from a reservoir located at a depth of about 25 km, leading to

the formation of a shallow magma reservoir at the Moho boundary (14 km depth) (Martí *et al.*, 2013; López *et al.*, 2012). Both magma chambers would be connected by a vertical conduit. After this first intrusion episode, magma migrated laterally 20 km towards the South accompanied by a surface uplift of about 4 cm. This lateral migration ended with a submarine eruption that gave rise to a volcanic edifice located 300 m deep, with a base diameter of 700 m and the crater located at about 80 m (b.s.l.).

Besides the intense seismicity and a relatively slow deformation, as detected in FRON site (Figure 1), this eruption was preceded by a 45 μGal decrease as detected by a permanent gravity station installed on the island (Figure 1). Also, during the first days of eruption, the gravity records changed from 10 to -90 μGal , with negligible vertical displacements (Sainz-Maza *et al.*, 2014). During the first two months of the eruption the GPS data revealed a slight ground subsidence (Figure 2).

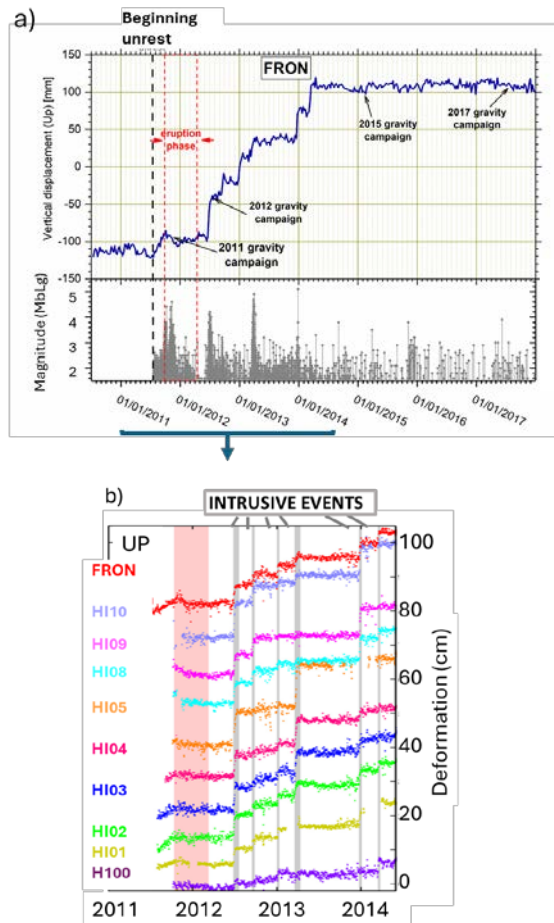


Figure 2. a) Estimates of daily solutions for vertical displacement at FRON GNSS site (Arnosó *et al.*, 2023) b) Evolution of the vertical ground surface deformation from the GPS stations of the IGN (as per Domínguez Cerdeña *et al.*, 2018)

After the end of the eruption, up to six magmatic intrusions were detected, from June 2012 to March 2014, associated to intense seismic swarms and ~22 cm

of ground uplift. (Figure 3). These intrusions did not produce a new eruption, and magma remained stored in the lower Crust and upper Mantle depths. The two largest intrusions occurred in June-July 2012 and March-April 2013 (e.g., Benito-Saz *et al.*, 2019, Domínguez Cerdeña *et al.*, 2018). These post eruptive intrusions released more energy and caused greater surface deformation than the unrest preceding the 2011-2012 eruption and the eruption itself. In fact, the deformation velocities reached up to 2 cm/day, arriving to 22 cm of uplift in the central and western part of the island (e.g., Klügel *et al.*, 2015; Lamolda *et al.*, 2017; Arnoso *et al.*, 2023; Domínguez Cerdeña *et al.*, 2018) (Figures 2 and 3).

From 2015 to 2019 the seismic activity became less intense, and the ground deformation was of lower magnitude, remaining a slight uplift trend ([1 cm, 6.5 cm]) in the central and NE of the island and a slight subsidence ([0.8 cm, 3 cm]) in the NE and W rifts (Arnosó *et al.*, 2023). From 2019 to 2021 an average ground subsidence of 8 mm was reported (Arnosó *et al.*, 2023).

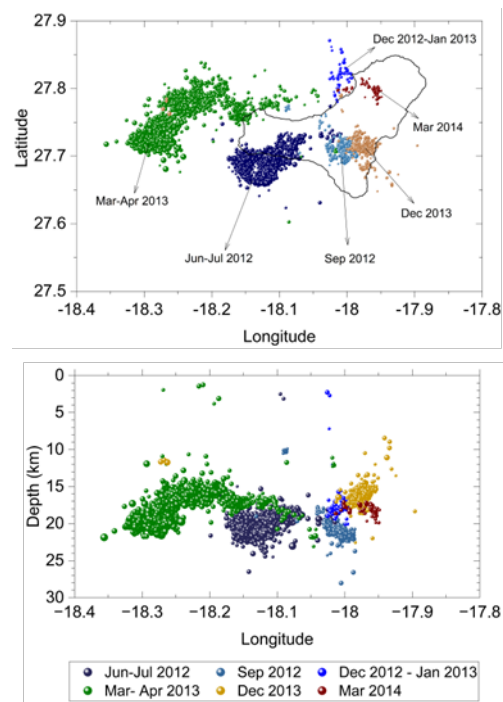


Figure 3. Post-eruptive earthquakes from 2012 to 2014 in El Hierro, and distribution (according to colour scale) of the six respective magmatic intrusions.

B. Gravity network surveys

In 2003, a network with 23 relative gravity stations was established covering a wide area of El Hierro Island (Figure 1) with locations using the geodetic infrastructure of the island and easily identifiable benchmarks.

Gravity measurements were repeated during years 2004 and 2008 and no significant gravity changes were observed. These surveys were performed using the

Lacoste Romberg models G-933 and Graviton EG-1194 gravimeters. In November 2011, during the eruption ongoing, the gravity network was measured again. Since then, periodic measurements have been carried out to study the evolution of the volcanic process: in July 2012; February and November 2015; July 2017; July 2018; October 2019; and May 2023. In all those cases, the Scintrex model CG5 gravimeter was used. The performance of the gravimeters in use were monitored by working in continuous operating mode in the laboratory and performing gravity calibration lines during the periods between surveys.

The gravity station of Valverde, located to the NE of the island (VALV in Figure 1), was selected as a reference station to compare the gravity changes between different surveys. By applying the process described in Section II, a least-squares adjustment of the all-repeated observations resulted in the gravity values obtained in the network stations for each epoch. The average value of the root-mean-square error (rmse) of all surveys was estimated to be 15 μGal .

C. Gravity changes between surveys

The gravity studies performed with this gravity network at El Hierro Island show gravity changes between surveys, which can be related to the volcanic process for the period 2011-2012 and during the post eruptive activity (paper in preparation). In those cases, a strong correlation was detected between the gravity variations and the occurrence of several intrusions and displacements of magma deduced from seismic data. Here, we show an example of these gravity changes detected between the post eruptive period of 2015 and 2017 (Figure 4), where no correction for terrain deformation or the effect of new topography or water table was applied. As the campaigns were always conducted in the same seasons, we assumed that the subsurface water changes were negligible. Furthermore, the GNSS displacements measured at the gravity network show that there were no significant changes in the height of the stations during the survey period. However, ground deformation was detected by the permanent GNSS stations on the island during the complete volcanic process. Thus, gravity changes should be mainly related to underground mass changes, although undetectable ground deformation would be able to produce some small effect on these results. It must be noted that the effect of the new volcano topography is negligible in this case, due to the distance from the volcano edifice to the gravity stations.

The seismic events recorded during this period (November 2015- December 2017) (Figure 4) show that the area of highest seismic activity is the western half of the island, just where the gravity changes were detected. These changes could be related to magma displacements at depth and subsurface mass redistribution that could produce this seismic response.

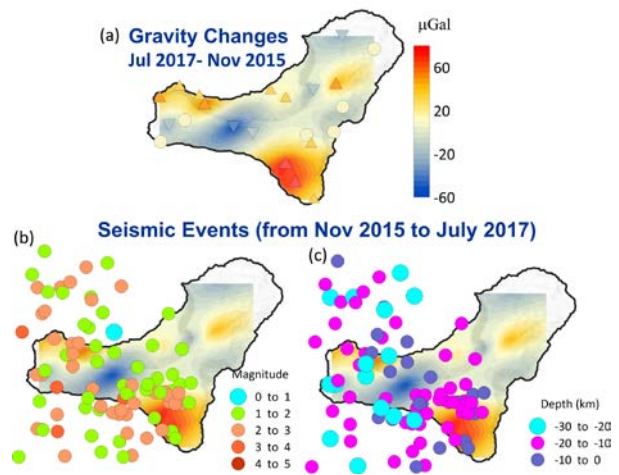


Figure 4. (a) Gravity changes detected on El Hierro between November 2015 and July 2017. Coloured dots show the epicentres of the earthquakes, recorded during this period by the Spanish IGN, represented in function of their magnitude (b) and depth (c).

The interpretation of gravity changes is conditioned by the distribution of observed data in each survey, and some variation may not be evidenced between them due to the lack of data.

IV. GRAVITY NETWORK AT LA PALMA

A. The 2021 volcanic eruption in La Palma

The 2021 eruption at the Cumbre Vieja rift lasted 85 days from September 19th to December 13th, becoming the longest historical eruption in La Palma. The elongated fissure eruption with N133°E orientation built a volcanic cone with a maximum height of 200 m above the preexisting topography, reaching up to 1,121 m a.s.l. The lava emerged from six major craters and up to 9 minor vents. The final estimated erupted lava volume was approximately $34 \times 10^6 \text{ m}^3$, covering an area of 12 km^2 (e.g., Lozano *et al.*, 2021).

Several studies have pointed to deformation patterns prior to the 2021 eruption, with seismic swarms occurred between October 2017 and August 2021. The earthquakes, with an approximate East-West trend, were located at depths of between 14 and 30 km b.s.l. Based on InSAR observations, some deformation patterns were detected probably between 2009 and 2010, and also 3.5 months before the eruption onset (Fernández *et al.*, 2022). The seismic swarm which started on September 11th, 2021, was shallower than the previous seismic activity. After a quick upward migration of the hypocenters from 10-12 km up to 2-3 km and then to the surface, a volcanic eruption started on September 19th in the western flank of Cumbre Vieja (Figure 6). The eruption was also preceded by a ground uplift of approximately 30 cm in the vicinity of the eruptive center, as detected by InSAR (Kyriou and Nikolakopoulos, 2022).

Studying the spatio-temporal evolution of the earthquake hypocenters is the most reliable way of

inferring magma location and allows the real-time position of magma to be tracked at depth. Gravity data, ground deformation, geochemical changes and petrology studies can contribute to a complete account of the process. Based on these data, the feeding system model proposed by Montesinos *et al.*, (2023) reveals the presence of several interconnected sills and dikes during the 2021 La Palma eruption. This model includes a deep (~12 km b.s.l.) large sill-like body located at the Moho, serving as magma reservoir, as well as three minor sills positioned at depths of ~6 km, ~2 km, and ~1 km below the surface acting as shallow magma storage zones. Also, Montesinos *et al.*, (2023) conducted an analysis of the surface deformation linked to the magma plumbing system.

B. Gravity network surveys

31 stations have been selected from the gravity survey conducted in July 2021 to establish a control network to monitor the volcanic activity in Cumbre Vieja volcano (Figure 5). During the 2021 eruption, the gravity network was measured again in October, although some of the stations were inaccessible due to lava flows or ash fall deposits produced by the ongoing volcanic process, and only 15 stations of the initial network could be recovered. After the end of the eruption, several new gravity surveys were conducted. Here, we report the results from January 2022 and October 2022.

All gravity surveys were carried out using a Scintrex CG5 gravimeter, and the gravity stations were located by GNSS differential positioning. The information obtained from these surveys was completed with data from several GNSS permanent stations (Montesinos *et al.*, 2023). The absolute gravity station PALM_EVIR (Spanish IGN), which is located to the north of the study area (Figure 5), was selected as reference station.

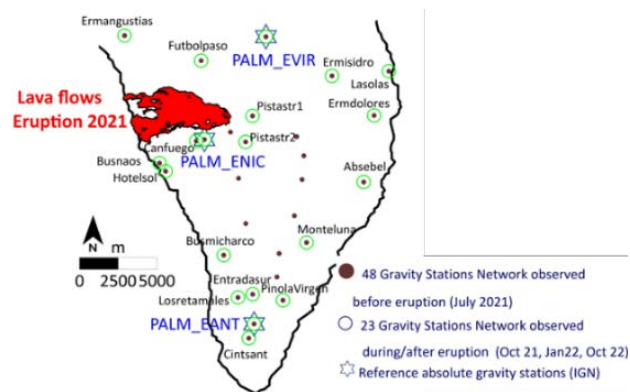


Figure 5. Detailed map of the study area in Cumbre Vieja, La Palma, showing the stations of the gravity network.

All gravity observations were processed according to the established methodology, providing the gravity values at each station of the network for each survey. The average rmse of all surveys was estimated to be 19

μGal, determined by the harsh observation conditions during the eruptive process.

C. Gravity changes between surveys

The gravity changes obtained between different surveys were corrected by the gravimetric effect due to surface deformation during the time elapsed between surveys (FAC), and the gravitational attraction of the new topography (the emitted lava flows and the new volcanic edifice). After this correction, we assure that the observed gravity changes could be associated with the re-distribution of subsurface masses.

The height changes between surveys were calculated from GNSS measurements made during each gravity survey and the available data from the permanent GNSS stations closest to the gravity benchmarks. Assuming the nominal free-air gradient $-308.6 \mu\text{Gal/m}$, the FAC, which correspond to the surface deformation among July 21, October 21, January 22 and October 22, ranges from $+54 \mu\text{Gal}$ to $-45 \mu\text{Gal}$ to the West and East, respectively, of the emission center and decreases with distance to the eruption zone.

To quantify the effect of the new topography generated by the 2021 eruption, we used the elevation differences of the digital terrain model (DTM) for the beginning (October 2nd, 2021) and the end of the eruption (January 1st, 2022) over the DTM before the eruption. These DTMs are available through the Copernicus European program database (www.copernicus.eu/en), from the Spanish Geological Survey (IGME- CSIC) and GRAFCAN (Cartographical Service of Canary Islands Government; www.grafcan.es/red-de-estaciones). Assuming a density of $3,000 \text{ kg/m}^3$ for the terrain masses, which was obtained from the analysis of several lava samples (Montesinos *et al.*, 2023), the correction values range from $-28 \mu\text{Gal}$ to $112 \mu\text{Gal}$.

Considering these corrections, Figure 6 shows the gravity changes calculated between the different surveys conducted in the La Palma gravity network. These changes were presumably produced by the redistribution of mass related to the 2021 eruptive process and indicate a mass increase in the eruption zone during the eruptive process compared with the pre-eruptive situation (July 2021).

There appears that an initial accumulation of magma took place at depth to the South of Cumbre Vieja, which did not cause remarkable deformation on the surface. This magma would have moved beneath the ridge of Cumbre Vieja, storing into a deeper sill, and then migrated from there towards the eruptive center through a system of dikes and sills (October 2021-July 2021).

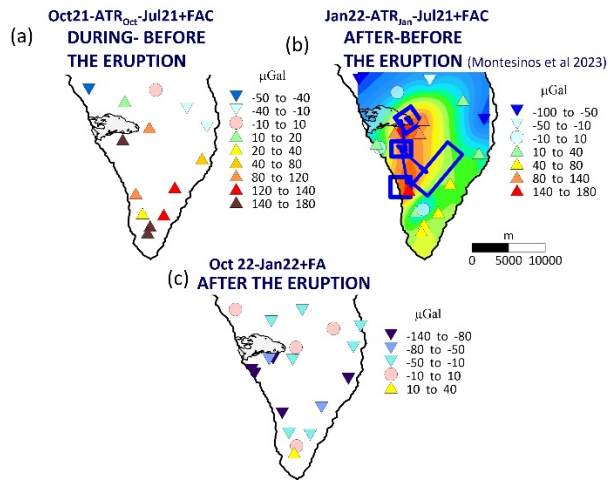


Figure 6. Gravity changes between different periods during and after (a); after and before (b); and after (c) the 2021 eruption. In (b) the magmatic plumbing system obtained by Montesinos *et al.*, (2023) from gravity data is also shown.

The crustal magma plumbing system of the 2021 eruption in La Palma estimated from gravity, GNSS and seismic data by Montesinos *et al.*, (2023) is consistent with the gravity changes observed between January 2022 and July 2021 (after – before eruption). The gravity changes observed between October 2021 and July 2021 (during-before eruption) revealed two zones of increasing gravity values with the highest variation found to the South of Cumbre Vieja. This would correspond to the initial accumulation of magma at the beginning of the eruption that subsequently moved towards the sill located at 12 km of depth (Montesinos *et al.*, 2023), to continue its path through the rest of dykes and sills to the eruptive fissure, where a second high gravity value was detected.

V. CONCLUSIONS

The observation of gravity networks at active volcanic regions constitutes a reliable tool for volcano monitoring and eruption forecasting. Among the different relative gravity networks designed by our research group in the Canary Islands, we show some results from the gravity surveys conducted at El Hierro and La Palma islands, where the last eruptions of the archipelago took place, in 2011 and 2021, respectively. These changes were significantly correlated with the intrusion and migration of magma in the framework of these recent volcanic processes. Our results demonstrate the potential of gravity networks for the study of volcanic processes and associated magmatic systems.

VI. ACKNOWLEDGEMENTS

This research is supported by the project PID2019-104726GB-I00/AEI/10.13039/501100011033 funded by the Spanish Research Agency. Also, the University Complutense of Madrid (grants Financiación Grupos 2021, UCM 2022-GRFN14/22) and the Spanish Ministry

of Science and Innovation (RD 1078/2021, funding for research activities of the CSIC-PIE project CSIC-LAPALMA-07) supported this research.

References

- Arnosó, J.; Benavent, M.; Bos, M.S.; Montesinos, F.G. and Vieira, R. (2011). Verifying the body tide at the Canary Islands using tidal gravimetry observations, *J. Geodyn.*, 51, 5, pp. 358-365, ISSN 0264-3707, doi: 10.1016/j.jog.2010.10.004.
- Arnosó, J., Riccardi, U., Tammara, U., Benavent, M., Montesinos, F.G. and Vélez, E. (2023). 2D strain rate and ground deformation modelling from continuous and survey mode GNSS data in El Hierro, Canary Islands 5th Joint International Symposium on Deformation Monitoring (JISDM), 20-22 June 2022, Valencia, Spain (7 pp) DOI: <http://doi.org/10.4995/JISDM2022.2022.13632>
- Berrino G. and Ricciardi G. (2020). Repeated absolute gravity measurements on a dense network at Campi Flegrei – a reliable tool for volcano monitoring, *Advances in Geosciences*. 52: 41-54
- Benito-Saz, M. A., Sigmundsson, F., Chaco, M., Hooper, A. and Parks, M. (2019). Magma Flow Rates and Temporal Evolution of the 2012–2014 Post-Eruptive Intrusions at El Hierro, Canary Islands. *Journal of Geophysical Research - Solid Earth*. <https://doi.org/10.1029/2019JB018219>.
- de Zeeuw-van Dalsen, E. and Poland, M. P. (2023). Microgravity as a tool for eruption forecasting. *Journal of Volcanology and Geothermal Research*, 107910. <https://doi.org/10.1016/j.jvolgeores.2023.107910>.
- Domínguez-Cerdeña, I., García-Cañada, L., Benito-Saz, M.A., Del Fresno, C., Lamolda, H., Pereda de Pablo, J. and Sánchez-Sanz, C. (2018). On the relation between ground surface deformation and seismicity during 2012–2014 successive magmatic intrusions at El Hierro Island, *Tectonophysics*, 744, pp. 422-437
- Fernández, J., Escayo, J., Camacho, A.G., Palano, M., Prieto, J.F., Hu, Z., Sergey V., Samsonov, Tiampo, K. and Ancochea, E., (2022). Shallow magmatic intrusion evolution below La Palma before and during the 2021 eruption. *Sci. Rep. UK*, 12, 20257. <https://doi.org/10.1038/s41598-022-23998-w>.
- Kennedy, J., Ferré, T. P. and Creutzfeldt, B. (2016). Time-lapse gravity data for monitoring and modeling artificial recharge through a thick unsaturated zone. *Water Resources Research*, 52(9), 7244-7261. <https://doi.org/10.1002/2016WR018770>.
- Klügel, A., Longpré, M. A., García-Cañada, L. and Stix, J. (2015). Deep intrusions, lateral magma transport and related uplift at ocean island volcanoes. *Earth and Planetary Science Letters*, 431, 140-149. <http://dx.doi.org/10.1016/j.epsl.2015.09.031>
- Kyriou, A and Nikolakopoulos, K.G. (2022). Lava Mapping Using Sentinel-1 Data after the Occurrence of a Volcanic Eruption—The Case of Cumbre Vieja Eruption on La Palma, Canary Islands, Spain. *Sensors*, 22, 8768. <https://doi.org/10.3390/s2228768>.
- Lamolda, H., Felpeto, A. and Bethencourt, A. (2017). Time lag between deformation and seismicity along monogenetic volcanic unrest periods: The case of El Hierro Island (Canary Islands). *Geophysical Research Letters*, 44(13), 6771-6777. doi:10.1002/2017GL074494.

- López, C., et al., (2012). Monitoring the volcanic unrest of El Hierro (Canary Islands) before the onset of the 2011–2012 submarine eruption. *Geophys. Res. Lett.* 39, L13303. <http://dx.doi.org/10.1029/2012GL051846>.
- Lozano, G., García, J.C., Lorenzo, C., Hernández, M., Cabrera, A., Díaz, E., Camuñas, C., Mediato, J.F., López, J., Pérez, R., and URGE-IGME Team (2021). Mapa de Evolución de la Lava entre el 24-11-2021 y el 14-12-2021. Available online: info.igme.es/eventos/la-palma/delimitacion-lava/211214_Evolucion-lava.pdf (accessed on 14 December 2021).
- Martí, J., Pinel, V., López, C., Geyer, A., Abella, R., Tárraga, M., Blanco, M.J., Castro, A. and Rodríguez, C. (2013). Causes and mechanisms of the 2011–2012 El Hierro (Canary Islands) submarine eruption. *J. Geophys. Res.* 118, 1–17.
- Montesinos, F.G., Sainz-Maza, S., Gómez-Ortiz, D., Arnoso, J., Blanco-Montenegro, I., Benavent, M., Vélez, E., Sánchez, N. and Martín-Crespo, T. (2023). Insights into the Magmatic Feeding System of the 2021, Eruption at Cumbre Vieja (La Palma, Canary Islands) Inferred from Gravity Data Modeling. *Remote Sens.* 15, 1936
- Sainz-Maza, S., Arnoso, J., Montesinos, F.G. and Martí, J. (2014). Volcanic signatures in time gravity variations during the volcanic unrest on El Hierro (Canary Islands), *Journal of Geophysical Research (Solid earth)* 119, 5033–5051, doi:10.1002/2013JB010795

The role of stand-alone devices for seismological investigation in volcanic and hydrothermal areas

Paola Cusano¹, Danilo Galluzzo¹, Lucia Nardone¹, Guido Gaudiosi¹, Simona Morabito¹

¹Sezione di Napoli 'Osservatorio Vesuviano', INGV, Naples, Italy, (paola.cusano@ingv.it; danilo.galluzzo@ingv.it; lucia.nardone@ingv.it; guido.gaudiosi@ingv.it; simona.morabito@ingv.it)

Key words: *stand-alone temporary devices; volcanic-hydrothermal areas; seismic signals; seismic array; meteorological station.*

ABSTRACT

In some areas of notable scientific interest, the impossibility of using telemetry stations and the need to ensure data continuity unequivocally imply the use of stand-alone instrumentation. Here we present some examples of seismological studies where the use of stand-alone temporary devices led to interesting results. In details, we show the case of the active volcanic area of Mt. Vesuvius (Italy), and of Mefite D'Ansanto (Italy) CO₂ emission area. The use of high-quality data recorded by temporary broadband seismic stations at Mt. Vesuvius, allowed to estimate the source parameters of the local seismicity in 2018-2020. These stations are located close to the crater area, their instrumental response is well known and the sites are unaffected by dramatic local amplification. Tectonic, cold CO₂ emissions of Mefite D'Ansanto were inspected in 2021 by using two array configurations, designed to explore the seismic noise associated to fluid emissions. The favorable location and the adopted geometries, let us to track the wavefield sourced by Mefite emissions, to characterize the associated spectral properties and to formulate some hypothesis on the endogenous source. The investigations on the seismic noise at Mefite evidenced a clear link among the noise amplitude temporal pattern and the meteorological parameters. In 2022 we installed a meteorological station close to the vents, equipped with an anemometer, a rain collector, a temperature and a humidity sensor. It operated for a dry-wet season cycle. Research activities performed on these data are funded by INGV-Strategic Department project FURTHER and *Ricerca Libera* project LAST.

1. INTRODUCTION

Volcanic and hydrothermal areas are frequently impervious environments and sometimes present inaccessible sectors. Often the local morphology is irregular with the presence of escarpments, canyons, solidified lava flow bodies, acid lakes, etc. Sometimes these zones are scarcely inhabited and the UMTS connection, frequently used to telemeter scientific data to acquisition centers, is not available.

Nevertheless, given the high risk level that exists in these environments, the use of performant monitoring instruments is necessary to carry out high level scientific research.

Mt. Vesuvius is a stratovolcano 1281 m high and 10 km wide, which is part of the Somma-Vesuvius volcanic complex (Figure 1) in the Campanian Plain (southern Italy). Even if it is in a quiescent state, it is one of the most dangerous volcanoes on Earth, being located inside the densely urbanized area of Naples (Italy, Figure 1). Since its past eruptions have destroyed towns and impacted thousands of victims (Doronzo *et al.*, 2022), currently it is one of the most monitored volcanoes in the world, with a wide and modern multidisciplinary monitoring system (Ricco *et al.*, 2021). This volcano hosts a National Naturalistic Park in which wide areas are covered by woods. Due to the morphology of the volcano and the presence of

vegetation, some locations, which are strategic for the seismic monitoring, are not ideal to telemeter data. For this reason, in these locations some stand-alone seismic stations have been deployed by the Mobile Seismic Network of Osservatorio Vesuviano (INGV, Italy).

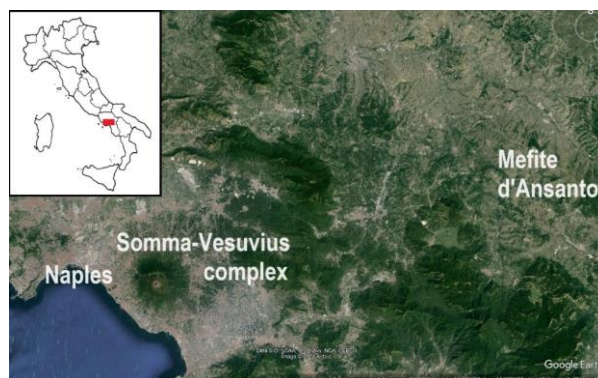


Figure 1. Sector of Italian territory, highlighted in red in the up-left corner map, in which the study areas are located. (Data SIO, NOAA, U.S. Navy. NGA, GEBCO Image © 2024 Airbus – Acquisition image data 09/14/2022. Google Earth).

Mefite D'Ansanto (southern Italy, Figure 1) hosts the largest non-volcanic CO₂ emissions on Earth (Chiodini *et al.*, 2010). It is set at the northern tip of

the Irpinia fault system that is associated with the destructive MS 6.9, 1980 Irpinia earthquake. The Mefite cold CO₂ escapes from the upper mantle and Chiodini *et al.* (2010) found that, under low-wind conditions, the gas flows along a narrow natural channel, producing a persistent invisible and lethal gas river. The area surrounding the main emissions is morphologically complex and made up of cultivated fields, and a long-term monitoring system is hard to manage. Moreover, the corrosive and toxic gases destroy the vegetation in the areas directly in contact.

In this paper we present a review of three studies, two of which have been already published and the other one is still in progress, that represent typical situations in which permanent instruments are difficult to manage or data telemetering is not trivial, with the final goal of evidencing the importance of the use of high-level instrument also in unfavorable local conditions.

II. STAND-ALONE TEMPORARY INSTRUMENTS

A. Broad band seismic stations at Mt. Vesuvius

The Osservatorio Vesuviano (OV), branch of INGV, manages the Permanent and the Mobile Seismic networks of Mt. Vesuvius (Italy, Figure 2).

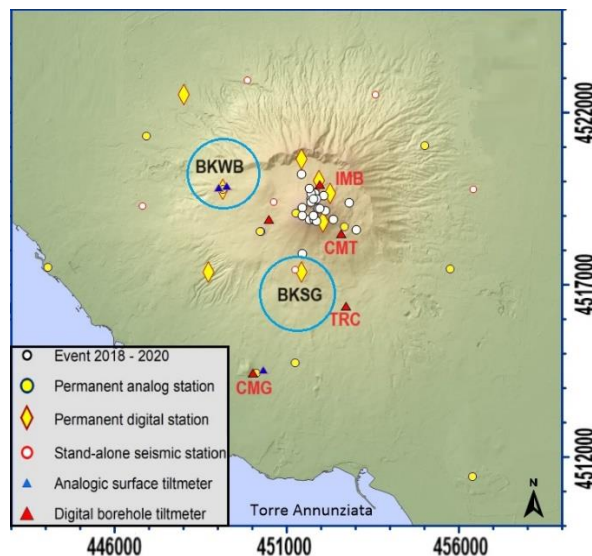


Figure 2. (After Cusano *et al.*, 2022) (A) OV-INGV seismic and tilt monitoring networks at Mt. Vesuvius and location of the earthquakes with MD ≥ 2.0 (white circles) for the years 2018-2020 (courtesy of E. Bellucci Sessa). The two considered mobile stations are highlighted by blue circles. The coordinates are expressed in UTM.

The Mobile Network consists of some temporary three-component digital broadband, stand-alone stations, which store the data locally. Seismological analyses were carried out for the years 2018-2020 (Cusano *et al.*, 2022) by using the earthquakes located in the crater area with a duration magnitude MD ≥ 2.0 , which ensured a favorable signal-to-noise ratio. To estimate the source parameters, a classical approach

was applied to the signals recorded by two mobile digital, stand-alone, broadband stations, BKWB and BKSG (Figure 2). The two considered stations are equipped with Guralp CMG-40T velocimeter, have a very stable operation over the studied period and their site responses are well known. The very high-quality signals recorded by the two stations were used to estimate the source dimensions and the net slip on the fault (Figure 3).

For each earthquake, the theoretical soil inclination was calculated starting from the estimated source parameters (Figure 3) and compared with the soil inclination measured by the tiltmeters (Figure 2). It was the first time for Mt. Vesuvius that the co-seismic soil inclination due to an earthquake and the soil inclination measured by a tiltmeter have been directly compared. The estimated and measured values resulted well in agreement in intensity and direction (see figure 5 in Cusano *et al.*, 2022). This outcome opens a new prospective on the link between soil tilt and ground velocity caused by earthquakes, that can have interesting consequences on the monitoring.

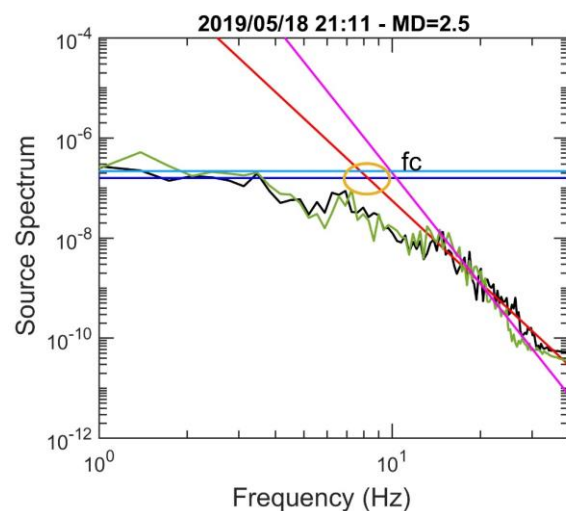


Figure 3. (after Cusano *et al.*, 2022, figure 3b) Example of source spectrum. For BKWB (black spectrum), the linear interpolation of the low-frequency level is in dark blue, and the high-frequency pattern interpolation is in red. For BKSG (green spectrum), the low-frequency level is light blue, and the high-frequency pattern is magenta. The corner frequencies (fc) are highlighted by a golden oval.

A. Mefite D'Ansanto CO₂ emissions

AME - Seismic array

In hydrothermal and volcanic environments, a frequent practice aimed to improve the signal-to-noise ratio and to track sources of non-impulsive signals is to arrange seismic stations in arrays (Schweitzer *et al.*, 2012). In particular, arrays are used to investigate the seismic noise wavefield and several techniques have been developed to exploit their properties. The application of array analysis (Capon,

1969) at Mefite d'Ansanto site permitted to link the seismic signal to the hydrothermal activity (Morabito *et al.*, 2023; La Rocca *et al.*, 2023). AME (MEfite seismic Array) was employed close Mefite CO₂ emission main vents (Mefite Lake, Figure 4) in the framework of FURTHER, INGV project (<https://progetti.ingv.it/en/further>). The array was composed of seven 1-Hz stations arranged in two configurations. The first one was designed to correctly explore the 1.8–5 Hz frequency band and Rayleigh wave phase velocities in the 480–800 m/s range, while the second one 2.8–8 Hz frequency band and velocities in the 400–630 m/s range. As can be seen from Figure 5, after about 20:00 UTC, the signal becomes correlated, with backazimuth values in a narrow range centered at about 160°, which corresponds to the Mefite emission field (Figure 4). This signal shows very low amplitude and, hence, it is overcome by anthropogenic noise during the daytime. Thanks to seismic array usage, La Rocca *et al.* (2023) could attribute the signal around 3 Hz to a persistent source linked to Mefite emissions.

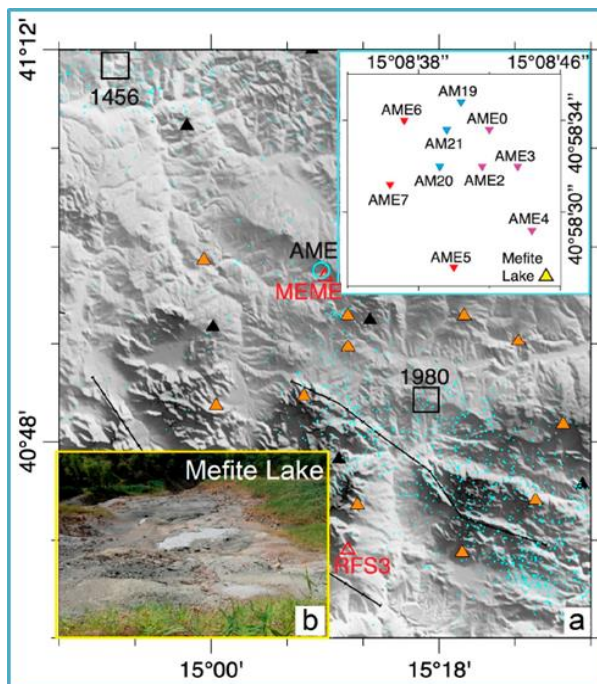


Figure 4. (Morabito *et al.*, 2023, figure 2) (a) Northern Irpinia region (Italy). The two black squares mark the location of the most destructive earthquakes occurred in the represented area, one in 1456 (magnitude 6.1) and the other in 1980 (magnitude 6.9). Orange and black triangles show the locations of the Irpinia and IV seismic networks, respectively. The open cyan circle indicates the location of the AME array whose station deployment is shown in the inset at the top right. A first array configurations (the purple and the red triangles) operated in 8 June-24 August 2021; a second (the purple and the blue triangles) operated in 24 August-28 September 2021. A red triangle shows the position of MEME station. The yellow triangle shows the position of "Mefite Lake". (b) A picture of the Mefite main degassing vents (Mefite Lake).

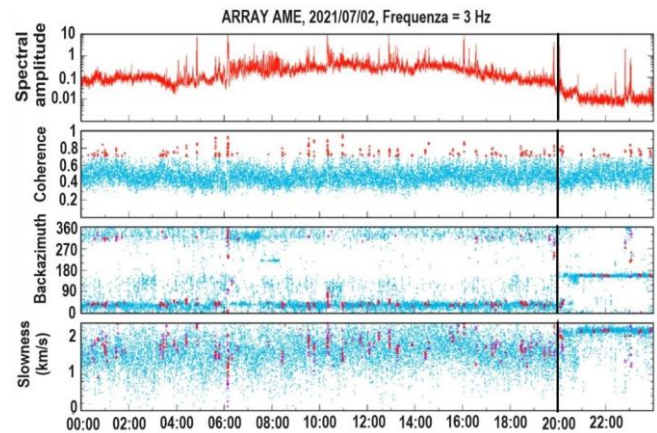


Figure 5. (Morabito *et al.*, 2023, figure 10) Example of Array analysis at 3Hz frequency for one day of seismic data recorded by AME. From top to bottom, the plots show spectral amplitude, coherence, backazimuth and slowness. The results corresponding to windows with coherence greater than 0.7 are shown by red and magenta symbols for the beamforming and the high resolution techniques, respectively. The black vertical lines mark 20:00 UTC.

MEME - Meteorological station

From the comparison among the RMS of the background seismic noise recorded by AME and meteorological parameters (Montemarano regional station, 11 km far from Mefite, www.agricoltura.regione.campania.it/meteo/agrome-teo.htm, last access 30 April 2022) a link is evident (Figure 6).

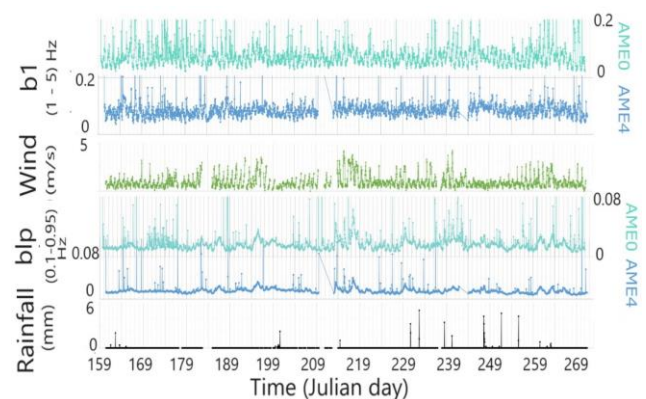


Figure 6. From the top, the first two graphs show the RMS pattern at AME0 (cyan) and AME4 (blue) in b1 frequency band (1-5 Hz). In the third graph the velocity (m/s) of wind is reported (green). The fourth and fifth graphs show the b1p (0.1-0.95 Hz) RMS pattern for AME0 and AME4. The horizontal axis, in Julian day, starts from 9 Jun 2021 (159) and ends on 30 Sep of 2021 (273). The rainfall amount is shown in the last graph.

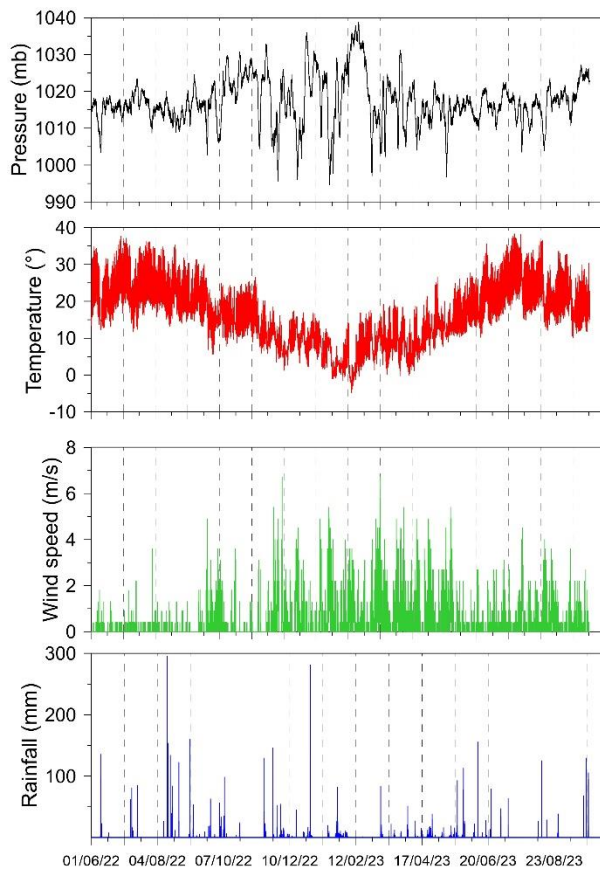


Figure 7. Meteorological data acquired by MEME. From top to bottom: air pressure, air temperature, wind speed and rainfall.

To investigate this link, on 26 May 2022 we installed a meteorological station, MEME (MEfite MEteorological), at about 100 m from the emission vents. It is a Davis Vantage Pro2 Station which will acquire data until the end of FURTHER (October 2024), covering more than 2 dry-wet cycles. MEME locally acquires air temperature, air pressure, speed and direction of wind, rainfall and air moisture. In Figure 7 we show the data acquired until the end of September 2023. The data will be compared with the other time series recorded in area (background seismic noise, CO₂ flux, deformation, etc.) and could help to give important information of the emission source dynamics over long-term periods, after correcting for the seasonal cycle (365 days), as well as over short-term time intervals.

III. CONCLUSION

We presented some studies carried out in volcanic/hydrothermal environments, in which some locations, difficult to be explored by using permanent instruments which could be prohibitive for a long-term remote data transmission, have been investigated thanks to stand-alone devices. In all the three case studies, we showed how the use of suitable and modern instruments permitted to carry out sophisticated analyses which shed light on different phenomena occurring in such adverse environments.

IV. ACKNOWLEDGEMENTS

Research activities performed on the data reported in the text are funded by INGV-Strategic Department project FURTHER and *Ricerca Libera* project LAST.

References

- Capon, J. (1969). High-resolution frequency–wavenumber. *Proc. IEEE* 1969, 57, 1408–1418.
- Chiodini, G., D. Granieri, R. Avino, S. Caliro, A. Costa, C. Minopoli, G. Vilardo (2010). Non-volcanic CO₂ Earth degassing: Case of Mefite d’Ansanto (southern Apennines), Italy. *Geophys. Res. Lett.*, L11303.
- Cusano, P., C. Ricco, I. Aquino, S. Petrosino S. (2022). A First Step towards the Definition of a Link between Ground Tilt and Earthquakes at Mt. Vesuvius (Italy). *Appl. Sci.*, 12, 12261. <https://doi.org/10.3390/app122312261>.
- Doranzo, D. M., M. A. Di Vito, I. Arienzo, M. Bini, B. Calusi, M. Cerminara, S. Corradini, S. de Vita, B. Giaccio, L. Gurlioli, G. Mannella, G. P. Ricciardi, I. Rucco, D. Sparice, M. Todesco, E. Trasatti, G. Zanchetta (2022). The 79 CE eruption of Vesuvius: A lesson from the past and the need of a multidisciplinary approach for developments in volcanology. *Earth-Science Reviews*, 231, 104072. <https://doi.org/10.1016/j.earscirev.2022.104072>.
- La Rocca, M., D. Galluzzo, L. Nardone, G. Gaudiosi, F. Di Luccio (2023). Hydrothermal Seismic Tremor in a Wide Frequency Band: The Nonvolcanic CO₂ Degassing Site of Mefite d’Ansanto, Italy. *Bull. Seismol. Soc. Am.*, 113, 1102–1114. <https://doi.org/10.1785/0120220243>.
- Morabito, S., P. Cusano, D. Galluzzo, G. Gaudiosi, L. Nardone, P. Del Gaudio, A. Gervasi, M. La Rocca, G. Milano, S. Petrosino, L. Zuccarello, R. Manzo, C. Buonocunto, F. Di Luccio (2023). One-Year Seismic Survey of the Tectonic CO₂-Rich Site of Mefite d’Ansanto (Southern Italy): Preliminary Insights in the Seismic NoiseWavefield. *Sensors*, 23, 1630. <https://doi.org/10.3390/s23031630>.
- Ricco, C., S. Petrosino, I. Aquino, P. Cusano, P. Madonia. (2021). Tracking the recent dynamics of Mt. Vesuvius from joint investigations of ground deformation, seismicity and geofluid circulation. *Sci. Rep.*, 11, 965. <https://doi.org/10.1038/s41598-020-79636-w>.
- Schweitzer, J., J. Fyen, S. Mykkeltveit, S.J. Gibbons, M. Pirli, D. Kühn, T. Kværna. (2012) Seismic Arrays. In *New Manual of Seismological Observatory Practice 2 (NMSOP-2)*; P. Bormann Ed., Deutsches GeoForschungsZentrum GFZ: Potsdam, Germany, 2012; pp. 1–80. https://doi.org/10.2312/GFZ.NMSOP_r1_ch9.

Hunga Tonga, Fani Maoré and other seamount eruptions: possible observation through future satellite gravity sensors including quantum technology and inclined pair satellite formations

Carla Braitenberg and Alberto Pastorutti

Dipartimento di Matematica e Geoscienze, Università di Trieste, Trieste, Italy (berg@units.it)

ABSTRACT

The changing shape of the Hunga Tonga Hunga Ha'apai (HTHH) islands is well documented over the years starting with the volcanic unrests of 2014/2015 up to the dramatic pre-eruption changes during 2021/2022. Optical and SAR imaging show the changes above the ocean surface, but what happens below the sea surface remains undetected, except a ship cruise is sent to the remote site. The Fani Maoré submarine volcano remained concealed below the sea surface, but the volcanic eruption of 2018-2021 produced a new seamount 800 m tall, not detectable from above sea surface. This shows that submarine volcanic eruptions are a challenge and probably are greatly uncharted. The gravity field observations are a means to detect hidden mass changes, but the noise levels must be below the gravity signal generated by the mass variations. Here we give a review on a collection of seamount eruptions, with an estimate of the mass changes, based on the documentation of volume changes. The uncertainties on the density of the erupted mass are discussed, as they enter the mass estimates. The gravity signal is then matched against the performances of the ongoing GRACE-FO mission, and the future gravity missions, with Quantum Technology sensors and constellations with double pair satellites, leading to a significant lowering of the sensitivity. We estimate that mass changes of 12 Gt could be detected, which correspond to the seasonal mass change of Lake Victoria.

The research is supported by PNRR MUR project PE0000023-NQSTI and Sub-Contract to ESA Contract No. 4000138395/22/NL/SD Quantum Space Gravimetry for monitoring Earth's Mass Transport processes. We thank Technical University Munich and Politecnico di Milano for the satellite noise estimates.

Reference:

Pivetta, T., Braitenberg, C., & Pastorutti, A. (2022). Sensitivity to Mass Changes of Lakes, Subsurface Hydrology and Glaciers of the Quantum Technology Gravity Gradients and Time Observations of Satellite MOCAST+. *Remote Sensing*, 14(17), 4278. <https://doi.org/10.3390/rs14174278>

Magma plumbing during the latest eruptions of the Canary and Cape Verde Islands

Andreas Klügel

Universität Bremen, Faculty of Geosciences, Klagenfurter Str. 2-4, 28334 Bremen, Germany (akluegel@uni-bremen.de)

ABSTRACT

The latest eruptions of the Canary and Cape Verde Islands, monitored by modern instrumentation, occurred on El Hierro (2011–2012), Fogo (2014–2015), and La Palma (2021). They erupted alkali basaltic lavas stored at similar mantle depths, but differed in terms of precursory activity and magma transport. The submarine El Hierro eruption began after >10 weeks of seismic activity with ~10,000 events, accompanied by island-wide surface deformation. About 0.33 km³ of lava (bulk volume) were erupted during 147 days, followed by six seismic swarms within two years, during which further surface deformation and voluminous intrusion of magma occurred. The Fogo eruption began after only one week of shallow seismic activity with <300 events, and local surface deformation just hours before the vent opened. During 77 days it produced 0.044 km³ of lava. The La Palma eruption was preceded by a few weak seismic swarms over four years, followed by stronger and shallower seismicity, as well as considerable surface deformation, during eight days before the vent opened. Around 0.2 km³ of lava were erupted during 85 days, accompanied by intense syn-eruptive seismicity at two depth levels. The combination of instrumental observations with results from petrological-geochemical investigations of erupted products results in unusually clear pictures of magma plumbing. Mineral-melt barometry of erupted products indicates pre-eruptive storage of the magmas in the mantle at around 15–25 km depth for El Hierro, 21 km (tephrites) and 16 km (early phonotephrites) for Fogo, and 16–26 km (basanites) and 14–23 km (early tephrites) for La Palma. These depths are similar to barometric results obtained for earlier eruptions on these islands. A complex multi-stage ascent of the magmas is common. Reservoirs in the uppermost mantle are episodically recharged from deeper levels. During ascent to the surface, the magmas migrate through a prominent magma accumulation zone in the lowermost oceanic crust, where remnants from earlier eruptions are picked up. The eruptions are controlled principally by deep-seated processes and by the thermal state of the crust, which in turn depends on eruption frequency and eruption rates.

Session 1. Space and ground based geodetic and geophysical techniques in Earth Sciences

O-030	La Palma volcanic unrest 2009-2023
	<u>José Fernández</u> ¹ , Joaquin Escayo ¹ , Kristy F. Tiampo ² , Antonio G. Camacho ¹ , Juan F. Prieto ³ , Mimmo Palano ⁴ , Zhongbo Hu ¹ , Sergey V. Samsonov ⁵ , Eumenio Ancochea ⁶
	¹ Instituto de Geociencias (CSIC, UCM). Calle del Doctor Severo Ochoa, nº 7. Ciudad Universitaria. 28040-Madrid, Spain (ift@mat.ucm.es) ² Cooperative Institute for Research in Environmental Sciences (CIRES), 216UCB, University of Colorado at Boulder, Boulder, CO, 80309, USA ³ ETS de Ingenieros en Topografía, Geodesia y Cartografía, Universidad Politécnica de Madrid, 28031-Madrid, Spain ⁴ Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo - Sezione di Catania, Piazza Roma 2, 95125 Catania, Italy ⁵ Canada Centre for Mapping and Earth Observation, Natural Resources Canada, 560 Rochester Street, Ottawa, ON K1A 0E4, Canada ⁶ Departamento de Mineralogía y Petrología, Fac. CC. Geológicas, Universidad Complutense de Madrid, 28040 Madrid, Spain

ABSTRACT

La Palma island, one of the highest potential risks in the Canary Islands archipelago, started a volcanic unrest in 2009-2010 which culminated in its largest historical eruption starting in September 19, 2021. Subsequent to the end of this eruption in December 13, 2021, up to May 2023, there were more than 2,000 seismic events, primarily at depths ≤ 20 km. We study this volcanic unrest up to 2023 using Interferometric Synthetic Aperture Radar (InSAR) and a new interpretation methodology, comparing achieved results with the crustal structure and the recent volcanic activity in the island.

O-006	Source of the recent unrest at Campi Flegrei caldera: preliminary results from the analyses of GNSS and gravity data
	<u>Tommaso Pivetta</u> ¹ , Umberto Riccardi ^{2,3} , Eleonora Rivalta ^{4,5} , Stefano Carlino ¹ , Mehdi Nikkhoo ⁴ , Francesco Maccaferri ¹ , Mauro Antonio Di Vito ¹ , Prospero De Martino ¹
	¹ INGV, Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, Osservatorio Vesuviano, Italy (tommaso.pivetta@ingv.it) ² Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR), Università "Federico II" di Napoli, Italy ³ Research group "Geodesia", Universidad Complutense de Madrid, Spain ⁴ GFZ, Deutsches GeoForschungsZentrum, Potsdam, Germany ⁵ Dipartimento di Fisica e Astronomia, Università Alma Mater Studiorum di Bologna, Bologna, Italy

ABSTRACT

The Campi Flegrei caldera, located in the western sector of Naples, is experiencing since 2005 a long-term unrest episode with continuous uplift, escalating seismicity and increased hydrothermal activity. The caldera is monitored by the geodetic infrastructure of the INGV- OV, which includes a network of 25 continuously operating GNSS stations, and more than 30 gravimetric benchmarks, that are surveyed by relative gravity measurements at least twice per year. Geodetic observations collected since 2005 have revealed an increasing uplift rate reaching 10 cm/yr at the center of the caldera, and a rate of gravity decrease of more than 30 $\mu\text{Gal/yr}$. We present a joint analysis of gravity and GNSS datasets to investigate the source location, volume and pressure changes, and the apparent density of the fluid intrusion associated with the source. We employ a recent formulation of the deformation and gravity changes induced by a triaxial ellipsoidal source to model both uplift and gravity changes recorded between 2005 and 2022. To properly interpret the apparent density of the intrusion we account for the compressibility of the fluids within the source and of the surrounding rocks. We show the importance of combining gravity and GNSS observations to reduce the ambiguity in the interpretation of the source of the unrest. Accounting for gravity variations helps constraining the intrusion density, which has clear implications in defining the type of unrest, whether hydrothermal, magmatic, or a combination thereof.

O-004	Exploring the significance of the spatial field from integrated DInSAR+GNSS time series for machine learning and volcano early warning applications
	<u>Brianna Corsa</u> ¹ , Kristy Tiampo ² , Charles Meertens ³ , Kyle Anderson ⁴ , Andrea Ellis ⁵ , Pablo González ⁶ , Jose Fernández Torres ⁷ , Freysteinn Sigmundsson ⁸
	¹ National Science Foundation (EAR-PF) (Brianna.Corsa@colorado.edu) ² University of Colorado Boulder ³ USGS California Volcano Observatory ⁴ USGS Hawaiian Volcano Observatory ⁵ Spanish National Research Council (IPNA-CSIC) ⁶ Spanish National Research Council (IGEO-CSIC) ⁷ University of Iceland

ABSTRACT

The greatest challenges in the field of volcanic observation research involve how to prepare for, or when and where to anticipate, eruptive or high-magnitude events. To better understand magmatic structure and eruptive behavior, and to improve hazard early warning systems, we present the development of a standard workflow in which machine learning approaches are used to model geodetic deformation data. By integrating multi-band Synthetic Aperture Radar (SAR), Global Navigation Satellite Systems (GNSS), and high-resolution Digital Elevation Model (DEM) data collected over Hawaii and La Palma, we generate a novel, high-resolution, three-dimensional (east, north, up) time series containing surface deformation measurements with improved precision. Advanced numerical and physical models will use the satellite observations to invert for subsurface structures, locate volcanic source geometries, resolve magmatic transport behavior over local to regional scales, and generate synthetic training data. Machine learning algorithms will be trained to detect anomalous motions, or gradients, between remote sensing images and time series for volcanic monitoring and forecasting applications. Plotted time series will be streamed through Long-Term-Short-Term Memory (LSTM) algorithms to predict the next, most-likely position of a ground point. Convolutional Neural Network (CNN) image classification algorithms will be trained using cumulative ground deformation maps, which involve dual spatiotemporal components. These methods will determine how interacting surface signals may be used to evaluate volcanic unrest, how topographic change from neighboring pixels affects the ways in which machine learning algorithms consume or process knowledge, and how efficient and reliable they are at forecasting various phases of an eruption.

O-046	Slope Instability Mapping of Colli Albani Hills (Italy)
	<u>C. Spinetti</u> , L. Colini, M. Bisson, C. Tolomei, L. Beccaro, R. Gianardi
	Istituto Nazionale di Geofisica e Vulcanologia (claudia.spinetti@ingv.it)

ABSTRACT

Colli Albani Hills is a quiescent volcanic complex located 20 km SE of Rome, it is subject to seismic swarms and manifests gaseous emissions and soil deformations. Volcanic activity dates back to about 600 ky with evidence of pyroclastic flows, lahars, lava fields and ash fallout deposits. Given the high population density of the area, CA is included in the list of Italian areas exposed to volcanic risk. In this work, the slope instability of Colli Albani Hills (CA) is investigated and mapped. Ground deformations are obtained by using InSAR data acquired in ascending and descending orbit from Sentinel-1 (C-Band) sensor and processed with Persistent Scatterers (PS) and/or Small Baseline Subset (SBAS) techniques to obtain the mean ground velocity maps and the relative displacement time series over a long time period from 2015 to 2022. Both maps are derived in the East-West and Up component for the surface displacement. In the ground deformations areas the instability predisposing parameters, as the morphometric parameters derived from high spatial resolution Digital Elevation Model, are derived and combined in an heuristic approach. Elaborations are performed in GIS environment and provide as output the map showing the classification of CA area according to different landslides susceptibility degrees.

O-036	Crustal Monitoring at the Continental Level: the EUREF EPN and GB/WGs Activities
	<u>J. Zurutuza</u> ^{1,2} , EUREF Governing Board
	¹ University of Padova (Italy) (jzurutuza@gmail.com) ² ARANZADI Sciences Society (Spain)

ABSTRACT

Monitoring crustal deformations by GNSS observations demand a very systematic, thorough and constant work over time. This statement becomes even more relevant in networks that span over large areas and when the deformations to be monitored are at the level of the observational accuracies as in Europe, where, except for tectonic/volcanic active areas, the EURASIA ETRS89 intraplate deformations are in the nanostrain/yr (1 nanostrain = 10^{-9}) or even less for most areas. EUREF, created in 1995, is a sub-commission of the International Association of Geodesy (Sub- commission for Europe, sub-commission 1.3a of Commission 1 of the IAG), originally to realize and densify the ITRF/ETRS89 frames over Europe. For this initial goal, EUREF created the EUREF Permanent Network (EPN) that is being densified (EPND) and supports other GNSS networks (e.g. CEGRN, MoU signed in 2011 in Chisinau, Moldova or EPOS). EUREF provides, through its Data Centers, seamless access to EPN data and EPN/EPND reference frame realizations that allow producing other products besides positions and velocities that can be used to derive additional geophysical products, such as deformation fields. EUREF provides support to the GNSS community, maintains several repositories to keep all the data (GNSS observations, navigation files, IGS-style logsheets,...). On top of these actions, EUREF monitors permanently the EPN and maintains several guidelines that have become GNSS processing and network densification standards. The EUREF GB is the responsible for EUREF. In this presentation we summarize the EUREF GB (Governing Board) activities and EUREF active Working Groups in the scope of the EPN and EPND networks that lead to a very dense velocity field over all Europe with +2500 high-quality permanent sites over different European countries.

O-053	Volcano deformation monitoring in Canary Islands (Spain): The case of 2021 La Palma Eruption
	F. Quirós ¹ , L. García-Cañada ² , J. Pereda de Pablo ¹ , E. González-Alonso ² , H. Lamolda ² , A. Fernández-García ² , A. J. Molina-Arias ¹ , J. Domínguez Valbuena ² , F. Prieto ² , Sáez Gabarrón L. ¹
	¹ Centro Geofísico de Canarias, Instituto Geográfico Nacional, Santa Cruz de Tenerife, Spain (fquiros@mitma.es) ² Observatorio Geofísico Central, Instituto Geográfico Nacional, Madrid, Spain

ABSTRACT

Surface deformation is one of the most important parameters in volcano monitoring. Land movements, due to volcanic processes, can occur at several spatial and temporal scales and the measurement of these possible deformations must be done using different geodetic techniques. Although space methods, such as GNSS and InSAR, are increasingly used in recent years, classical geodetic techniques are yet especially useful in some specific areas. They can complement space geodetic results and provide more information that can be useful precursors of active volcanoes. Each type of data has different characteristics, such as deformation components or spatial and temporal coverage, so each technique has its advantages and disadvantages. In addition, deformation results are integrated with other monitoring techniques, seismic, geochemical and geomagnetic, to have a global vision about what is happening before, during, and after eruptions. The IGN's deformation monitoring system was operational during the phases prior to La Palma eruption in 2021 and during its development for almost three months until the end of the eruption, detecting the deformations areas and their spatiotemporal evolution. In this work we present the strategy for monitoring ground deformations carried out during the phases before, during and after the eruption of La Palma in 2021, with the aim of obtaining results with the maximum frequency and spatial coverage. Together with deformation and seismic data, the results obtained, help us to understand and constrain the volcanic plumbing system of La Palma during 2021 eruption.

O-049	Long term changes and peculiar variations in sea level observed in the Lanzarote Geosciences Laboratory
	<u>M. Benavent</u> ^{1,5} , J. Arnoso ^{2,5} , EJ. Vélez ^{2,5} , FG. Montesinos ^{1,5} , U. Tammaro ³ , U. Riccardi ^{4,5}
	¹ Facultad de CC. Matemáticas, Universidad Complutense de Madrid (mbena@ucm.es) ² Instituto de Geociencias (IGEO), CSIC-UCM ³ Istituto Nazionale di Geofisica e Vulcanologia, Napoli ⁴ Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR), Università "Federico II" di Napoli ⁵ Research Group 'Geodesia', Universidad Complutense de Madrid

ABSTRACT

The Lanzarote Geosciences Laboratory is a scientific-technical facility where, among other multidisciplinary activities, studies of sea level changes and vertical movements of the crust are carried out since 1986. During the last 30 years, sea level variations have been recorded in a lake formed in the intersection of the volcanic tunnel of La Corona volcano and the Atlantic Ocean, at the northeast coast of Lanzarote. From the analysis of this data set, after tide correction and other effects (interannual and seasonal variability, dynamic atmospheric effect, etc.), we have estimated the linear long-term rate of change of the sea level to be 1.490 ± 0.004 cm/yr between the period 2005-2023. The further modelling of these data was done using a regression approach, where a linear relation with sea water temperature, periodic components and low degree polynomials were considered. In order to compare the sea level values with possible surface displacements, a GNSS station with permanent record was established in the year 2005, near the tide gauge location. We present the analysis of the sea level change and vertical displacements time series, studying long-term trends and correlations between them to identify possible volcano-tectonic signals.

O-050	Stress-strain models for the Teide-Pico Viejo Complex (Tenerife Island) from GNSS observations
	Manuel Berrocoso, <u>Belén Rosado</u> , Amós de Gil
	Laboratorio de Astronomía, Geodesia y Cartografía, Departamento de Matemáticas, Facultad de Ciencias, Universidad de Cádiz, Cádiz, Spain (belen.rosado@uca.es)

ABSTRACT

Tenerife is the largest and highest island of the Canaries. The central part of the island consists of a volcanic complex which includes the Las Cañadas edifice and the Teide-Pico Viejo Complex. In the last 300 years, six effusive eruptions have been reported, with the last occurring in 1909. An unusual increase in seismic events was detected in 2004. Before that, epicenters only clustered in an offshore area southeast of Tenerife, associated with regional tectonic stresses. After the 2004 reawakening, seismic activity in Tenerife decreased. After the 2004 unrest in Tenerife, GNSS geodetic benchmarks were designed and established to obtain a geodynamic model for Tenerife Island in the context of the Nubian Plate. In addition, GNSS geodetic marks were established to densify the geodynamic model and to obtain a volcanic deformation model of the Teide-Pico Viejo Complex. Another objective of this network was to establish the geodesic structure for the volcanic monitoring of the activity of this volcanic complex. This network, called the TEGETEIDE network, was set up in 2005 and was re-observed until 2013. This work focuses on the study of the volcano-tectonic activity of Tenerife, obtained from GNSS-GPS observations from the TEGETEIDE network. The displacement models are presented in order to explain the observed island displacement pattern in the geodynamic context of the Nubian plate and the geodynamic model of the Teide-Pico Viejo volcanic complex. Moreover, a comparative study of the models obtained from the continuous GNSS stations that are currently established on the island is carried out.

O-035	Reference frame transitions and their impact on frame realizations
	<u>J. Zurutuza</u> , M. Pertile, M. Bertocco, A. Caporali
	University of Padova (Italy) (jjurutuza@gmail.com)

ABSTRACT

When dealing with GNSS solutions over time, one of the issues, that can imply introducing discontinuities in the time series, is related to reference frame switches. The International Terrestrial Reference Frame (ITRF) reference frames are updated from time to time and after the publication of each ITRFxxxx, a new counterpart IGSxx (based on GNSS solutions only) realization follows. The IGS realizations include a set of positions and velocities at a certain epoch, as well as ITRFxx-consistent antenna offset and phase center variation file in standard ANTEX format (IGSxx.ATX). GNSS observations are computed using different standards and antenna offsets related to the different reference frames that may change when a new one is introduced. In some cases, like in the IGB08->IGS14 datum switch (2017/01/29), the IGS provides latitude-dependent models that allow computing the position offsets due to the switch from igs08.atx to igs14.atx. Applying these models, the solutions can be combined and the reference frame transition is smoothed and no discontinuity is needed at the switch date. Starting GPSW 2238 (2022/11/27), the IGS20 is introduced by the IGS as the new reference frame for its products and, besides this frame switch, other conventions are implemented: a new antenna PCV model (igs20.atx), and the usage of long filenames for IGS products are the most relevant. Because the aim of all GNSS solutions is to be aligned to the IGS products, the standards to compute GNSS observations must tightly follow the IGS20, which implies some changes in the processing recommendations of, for example, EUREF. In this presentation, we show the impact in the time series of different EPN and EPND sites, which can be as large as (all EPND sites with IGB14 solutions computed individual absolute antenna calibration values: DNEU refers to the IGS20 coordinates minus IGB14 for the North, East and Up components respectively): AND2: LEIAR20 LEIM, DNEU = -2.42; -0.92 ; 5.09 mm / OSUN: TRM57971.00 NONE, DNEU = -9.67; 8.34; -8.70 mm / JACA: LEIAR25.R3 LEIT, DNEU = 1.68; 0.01; -6.07 mm / ZFRA: LEIAR25.R3 LEIT, DNEU = 2.50; 2.22; -6.72 mm.

O-034	The Central European GPS Geodynamical Reference Network (CEGRN)
	J. Zurutuza ¹ , M. Pertile ¹ , O. Khoda ² , M. Bertocco ¹ , A. Caporali ¹
	¹ University of Padova (Italy) (jjurutuza@gmail.com) ² Main Astronomical Observatory (Ukraine)

ABSTRACT

The Central European GPS Geodynamic Research Network (CEGRN) consortium has its origin in the framework of the project called CERGOP (Central European Research on Geodynamics Project) that started in 1994. The CERGOP consisted originally of 11 countries of Central Europe. In 1998, 3 more countries joined this initiative and, altogether, agreed to organize the CEGRN consortium to operate, maintain and develop the Central European GPS Geodynamic Reference Network (CEGRN network). In 2011 a Memorandum of Understanding between the EUREF (www.euref.eu) and the CEGRN based on the ETRS89 implementation and densification was signed at the 2011 EUREF Symposium of Chisinau, Moldova (EUREF Symposium 2011). The main objective of the CEGRN network is the monitoring of crustal surface deformations by GNSS, analysis from measurements of regularly scheduled campaigns: one week of data every two years, usually in mid-June. The CEGRN partners provide either GNSS observations to be processed by the CEGRN Analysis Center (University of Padova, Italy, and Main Astronomical Observatory of Kiev, Ukraine) or post-computed solutions (in standard SINEX format). The daily/weekly data are stacked and a cumulative solution, providing positions and velocities is computed. The main study areas cover the Adriatic Microplate, the Balkan and Dinarides, the Carpathian Arc, the Eastern Alps and the Pannonian Basin, being all of them active tectonic zones. The CEGRN dataset, published in 2019, comprises 1229 sites with both positions and velocities: the mean positions and velocities of common EPN Class A (release C1890) and CEGRN stations differ by 0.0 ± 1.1 , 0.5 ± 1.0 and 0.1 ± 2.7 mm for the coordinates and 0.06 ± 0.13 , -0.07 ± 0.12 , 0.38 ± 0.28 mm/yr for the velocities respectively for the North, East and Up components at epoch 2010.0. In this presentation we show the CEGRN status and the future plans.

O-039	Volcano-tectonic activity of Deception Island from GNSS-GPS observations: 1998-1999, and 2012-2015 volcanic crisis
	<u>Belén Rosado</u> , Alberto Fernández-Ros, Manuel Berrocoso
	Laboratorio de Astronomía, Geodesia y Cartografía, Departamento de Matemáticas, Facultad de Ciencias, Universidad de Cádiz, Cádiz, Spain (belen.rosado@uca.es)

ABSTRACT

Deception Island, in the South Shetland Islands, is one of the most active volcanoes in Antarctica, with recent eruptions in 1967, 1969 and 1970. Monitoring of Deception Island's tectonic and volcanic behavior through GPS observations has been carried out from 1991 until 2023. For this purpose, a geodetic network was deployed: the REGID network. Currently, this network consists of 15 geodetic benchmarks located around Port Foster, Deception's inner bay open to the sea. Two additional geodetic benchmarks were installed outside Deception Island to be used as reference benchmarks for the differential positioning strategy. Since 1991-1992, geodetic ground-displacement velocities between the successive austral summer Antarctic campaigns are computed and analyzed. Inflation-uplift, deflation- subsidence and transitional processes are detected. This work focuses on the study of the geodynamic activity of Deception Island from 1991 to 2023, analyzing in detail two phases of volcanic unrest that occurred during that period: from 1998 to 1999 and from 2012 to 2015. These results are correlated with seismic activity, soil temperature and seawater temperature. The results show that the correlation between the inflation processes, identified by ground displacement of the network geodetic benchmarks, the increase in seismicity and the increment of soil and seawater temperature makes the transitional phases potential precursors of Deception Island's volcanic unrest periods.

O-056	InSAR observation in Geodynamics and Engineering: some examples and challenges
	<u>Sen Du</u> ¹ , Zhongbo Hu ¹ , Joaquin Escayo ¹ , Antonio G. Camacho ¹ , Juan F. Prieto ² , P. García-Cerezo ³ , S. Rodríguez ⁴ , D. Davoise ⁴ , José Fernández ¹
	¹ Instituto de Geociencias (CSIC, UCM), Calle del Doctor Severo Ochoa, 7. 28040-Madrid, Spain (dusen@ucm.es) ² ETS de Ingenieros en Topografía, Geodesia y Cartografía, Universidad Politécnica de Madrid, 28031-Madrid, Spain ³ MITERD, Subdirección General de Protección de las Aguas y Gestión de Riesgos, Dirección General del Agua. Plaza San Juan de la Cruz, 10. 28071-Madrid, Spain ⁴ Atalaya Mining. La Dehesa s/n. 21660 Minas de Riotinto. Huelva, Spain

ABSTRACT

Developments in InSAR (Interferometric Synthetic Aperture Radar) and GNSS (Global Navigation Satellite System) during last decades have provided high-resolution ground deformation data with dense spatio-temporal coverage. This large new dataset offers comprehensive insights into the deformation field and its time-evolution. These new data sets cannot be fully exploited using classical approach for interpretation to produce accurate assessments of the processes occurring in active areas. Normally these classical approaches assume a priori geometries (e.g., point sources, disks, prolate or oblate spheroids, etc.) and nature of the source, and invert separately for the different sources when more than one is considered. Also, many time-series deformations in active regions are characterized by complicated patterns of ground deformation resulting from multiple natural and anthropogenic sources. In response to these challenges, we consider a new interpretation methodology which employs a combination of 3-D arbitrary sources for pressure and dislocations (including strike-slip, dip-slip, and tensile) simultaneously. This approach is distinctive in that it dispenses with any a priori hypotheses regarding the deformation source's number, nature, shape or location. Instead, this approach provides deformation sources as 3D cell aggregations for which the inversion process automatically assigns a source type, magnitude values (MPa for pressure and cm for dislocations), position and orientation (angles of dislocation planes). We apply last generation InSAR observation techniques and this new interpretation modeling for Geodynamics and Engineering studies (e.g., to volcanoes, earthquakes, mining activity, critical facilities, water extraction) showing the obtained results and a discussion of the improvements with respect to classical approaches.

Session 2. Potential fields, geophysical exploration and georesources in active areas

O-005	Relating temporal variations of the geomagnetic field with volcanic activity at La Palma (Canary Islands): volcanomagnetic signals of the 2021 eruptive process.
	<u>Isabel Blanco-Montenegro</u> ^{1,2} , José Arnoso ^{3,2} , Nieves Sánchez ⁴ , Fuensanta G. Montesinos ^{5,2} , Iacopo Nicolosi ⁶ , Emilio Vélez ^{3,2} , Maite Benavent ^{5,2}
	¹ Departamento de Física, Escuela Politécnica Superior, Universidad de Burgos, Spain (iblanco@ubu.es) ² Research Group 'Geodesia', Universidad Complutense de Madrid, Spain ³ Instituto de Geociencias IGEO (CSIC-UCM), Madrid, Spain ⁴ Instituto Geológico y Minero de España (IGME-CSIC), Las Palmas de Gran Canaria, Spain ⁵ Facultad de Ciencias Matemáticas, Universidad Complutense de Madrid, Spain ⁶ Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

ABSTRACT

After almost 50 years of quiescence, the Cumbre Vieja rift at La Palma underwent a reactivation process that culminated in a volcanic eruption from September 19 to December 13, 2021, preceded by a seismic swarm that started just eight days before the eruption onset. Seismic unrest started in October 2017 and comprised ten seismic swarms in five years, with the last one in August 2021. In July 2021, a magnetic station (CFU) was deployed in Cumbre Vieja, 2 km away from the site where the eruptive vents would open two months later. In September 2021, a second magnetic station (SAN) was installed near the southern end of the Cumbre Vieja rift. Both stations are still in operation today and acquire the total geomagnetic field intensity (F) with a sampling rate of 1 measurement/minute with two Overhauser magnetometers. Recently, a new magnetometer was deployed in a third location in the Cumbre Vieja area. We present the results of the analysis of the geomagnetic data acquired by all these instruments from the beginning of the series until today. Our data revealed a magnetic signal at CFU station by mid-August, one month before the eruption onset. During the eruption, the SAN magnetic station registered a magnetic signal in the second half of October. We analysed possible correlations with other physical parameters and concluded that these signals are the result of changes in the magnetization of rocks beneath the volcanic edifice related with volcanic activity.

O-002	Contributions of Growth inversion methodology to volcano gravimetry on Tenerife (Canary Islands)
	<u>J. Bódi</u> ¹ , P. Vajda ¹ , A.G. Camacho ² , J. Fernández ²
	¹ Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, P.O. Box 106, SK-840 05 Bratislava, Slovakia (jozefbodi@gmail.com) ² Instituto de Geociencias (CSIC, UCM), C/Doctor Severo Ochoa, 7, 28040 Madrid, Spain

ABSTRACT

We revisit the gravimetric imprint of the volcanic unrest of 2004–2005 on Tenerife (Canary Islands). We revise the interpretation of the observed spatiotemporal (time-lapse) gravity changes accompanying the unrest by applying the Growth inversion approach based on model exploration and free geometry growing source bodies. We interpret the Growth solution, our new gravimetric model of the unrest, in the context of structural controls within the central volcanic complex (CVC) of the island, based on the subsurface density model obtained from new Growth inversion of complete Bouguer anomalies (CBAs). The gravimetric picture of the unrest indicates a stalled magma intrusion risen along the Boca Tauce basaltic body boundary, followed by upward and lateral migration of volcanic fluids reaching the aquifer and the SW end of the caldera wall. In addition we perform Growth inversions of synthetic gravity data of simulated sources to better understand how Growth would detect and image such presumed sources. We simulate a hypothetical Teide summit conduit (thin shallow vertical cylinder), a presumed phonolitic magma chamber below Teide (flat horizontal ellipsoid), and a central phonolitic plumbing system as indicated by seismic interpretation of Koulakov et al. (JGR Solid Earth, 2023, doi 10.1029/2022JB025798). Synthetic gravity data are used in the inversion as noise-free mesh data, noise-free benchmark data, and noisy benchmark data to analyze the effect of the benchmark sparsity and spatial distribution, as well as the signal-to-noise ratio of the input gravity data, on the reproducibility of such sources.

O-047	Reliable measurements with FG5/X gravimeters in laboratory and field conditions
	<u>V. Pálinskáš</u> , P. Křen, M. Vaľko, J. Kostecký
	VÚGTK, v.v.i., Ústecká 98, 25066 Zdiby, Czech Republic; Czech Metrology Institute, Okružní 31, 63800 Brno, Czech Republic (vojtech.palinkas@pecny.cz)

ABSTRACT

FG5 and FG5X (FG5/X) gravimeters are the most accurate commercially available absolute gravimeters used especially in geosciences and metrology. The gravimeters are designed to be primarily used indoor, however, in the past they have also been successfully operated outdoor in field conditions. It opens a possibility for more wide collocation of absolute measurements with another techniques (e.g. GNSS, InSAR), and by this way to utilize the main benefit of this absolute technique, which is traceable to SI units and clearly related to conventional global models of atmosphere, tidal system and reference pole. To utilize correctly the results from FG5/X gravimeters, it is necessary to well understood the difference between the stability and uncertainty of measurements. While the stability of results could be achieved at the level of 1 μGal ($1\text{E-}8 \text{ m/s}^2$) within less than 2 hours, due to error contributions from key error sources (e.g. laser diffraction, signal distortion and dispersion, Coriolis effect, recoil effects), the uncertainty of measurements will be above 2 μGal , practically independently on the length of observations but significantly depending on the approach how the key error sources are handled and taken into account. Based on large number of repeated absolute measurements carried out during 20 years, we are demonstrating the ability to detect subtle effects with amplitudes of a few microgal, methods to improve the accuracy of measurements and finally also an approach for the evaluation of quality of measurements carried out under different conditions.

O-025	Dynamics of the Neapolitan Volcanoes inferred from tiltmeter and seismic data analysis
	<u>Falanga</u> ¹ , Aquino ² , Cusano ² , De Lauro ¹ , Petrosino ² , Ricco ²
	¹ Dipartimento di Ingegneria dell'Informazione ed Elettrica e Matematica applicata/DIEM, Università degli Studi di Salerno, Fisciano, Italy (mfalanga@unisa.it) ² Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli – Osservatorio Vesuviano, Naples, Italy

ABSTRACT

We analyse ground tilt and seismic activity at the Neapolitan Volcanoes: Campi Flegrei, Ischia and Vesuvius (Southern Italy). Due to the high seismic and volcanic risk for the population living there, the volcanic areas are continuously monitored by borehole tiltmeter and seismic networks, whose development and improvement over time have enabled high-quality data collection. Focusing on the time interval 2015–2022, our most important results concern the observations of relationships between seismic activity and ground tilt anomalies. In particular: 1) At Campi Flegrei, the study of the tiltmetric pattern recorded since 2015 indicates a change in the dynamics of the caldera from the second part of the year 2020, in agreement with other geophysical observations, such as changes in the seismicity rate, ground temperatures of the fumarolic field, gravimetric and geochemical parameters. 2) At Ischia, the ground tilt pattern shows a well-defined polarization direction toward the NNW; the tilting directions turned clockwise towards the NNE in concomitance with the $M_d = 4.0$ earthquake occurred on August 21 2017. 3) At Vesuvius, the exploited link between local volcano-tectonic earthquakes and co-seismic ground tilt, using seismicity from 2018-2020, allows the estimate of the source parameters and calculating the associated static displacement. In all three cases, the joint analyses of the seismic and tiltmeter signals represent a powerful tool to better understand the volcanic dynamics and to discriminate between endogenous and exogenous sources. In addition, the techniques of analysis that we present have potential applicability to other volcanic systems.

O-017	New paleointensity determinations using Tsunakawa-Shaw, Thellier-Coe and multispecimen methods on a lava flow from the most recent volcanic activity in Cumbre Vieja 2021 (La Palma, Canary Islands)
	<u>Eva Vernet</u> ¹ , Manuel Calvo-Rathert ¹ , Elisa M. Sánchez-Moreno ¹ , Yuhji Yamamoto ² , Josep Parés ³ , Ángel Carrancho ⁴ , María-Felicidad Bógalo ¹ , Vicente Soler ²
	¹ Departamento de Física, EPS, Universidad de Burgos, Av. Cantabria, s/n, 09006 Burgos, Spain (evernet@ubu.es) ² Center for Advanced Marine Core Research, Kochi University, B200 Monobe, Nankoku, Kochi, 783-8502, Japan ³ Geochronology & Geology, CENIEH, Paseo Sierra de Atapuerca 3, 09002 Burgos, Spain ⁴ Departamento de Historia, Área de Prehistoria, Geografía y Comunicación, Universidad de Burgos, 09001 Burgos, Spain

ABSTRACT

The latest volcanic activity occurred on the island of La Palma between September and December 2021 (Canary Islands) presents a valuable opportunity to understand better how volcanic rocks record geomagnetic field intensity. During a paleomagnetic campaign after the volcanic event of Cumbre Vieja, a 2 meter thick lava flow was sampled along a transect obtaining 27 samples from the bottom to the top of the lava flow. This outcrop was recently created by the construction of a new road at the West part of the island, replacing the previous one. It is known that the date of emplacement of the sampled lava-flow was on 4th December 2021. In addition, samples from a lava flow solidified under water during the same volcanic event have been added to the paleointensity experiments. The aim of this study is to analyze possible changes on the paleointensity results along the transect and to compare the reliability of different paleointensity methods on recent volcanic rocks. Paleointensity experiments using Tsunakawa-Shaw method were performed at the Kochi Core Center in Japan, while Thellier-Coe and multispecimen methods have been applied at the Laboratory of Paleomagnetism in the University of Burgos. Several rock magnetic experiments have been performed at the University of Burgos, the Kochi Core Center in Japan and the CENIEH research center in Burgos; such as FORCs, magnetization vs temperature and susceptibility vs temperature curves, isothermal remanent magnetization (IRM) and hysteresis loops.

O-055	An improved correlation analysis of potential fields to infer the seamounts magnetization in the Tyrrhenian region
	A. Barone ¹ , M. Milano ² , <u>M. Fedi</u> ²
	¹ Istituto per il Rilevamento Elettromagnetico dell'Ambiente, Consiglio Nazionale delle Ricerche, Napoli, Italy ² Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università degli Studi di Napoli Federico II, Naples, Italy (fedi@unina.it)

ABSTRACT

Potential fields studies offer a non-invasive approach to explore volcanic systems large areas and allow a meaningful modeling of subsurface sources in terms of density and magnetization distributions. In this study, we perform a joint analysis of gravity and magnetic datasets in the Tyrrhenian Sea region, to infer the rock physical parameters of several volcanic seamounts through the Poisson's theorem. We propose a new approach combining the total gradient of the magnetic field with the total gradient of the first-order vertical derivative of the gravity data. This because it does not require the knowledge about the source total-magnetization direction, which is important in volcanic environments due to the strong intensity of remanent magnetization. We first perform realistic synthetic tests by employing a moving-data window approach, to perform a multisource analysis; the best window size is chosen according to these simulations. We, then, analyze the anomalies related to several seamounts and retrieve their magnetization intensity contrast by assuming the average density of the volcanic edifices. Through our moving window analysis, we characterize these volcanic edifices even when they are magnetically inhomogeneous. We show the results of the correlation analysis for the Palinuro, Marsili, Vavilov and Magnaghi seamounts, by which it was possible to infer interesting information about the variability in magnetization for each seamount and also about the effect of demagnetization after hydrothermal alteration processes.

O-023	The Western High Atlas (Adassil) earthquake of 8 September 2023 (Mw=6.8): pre-earthquake neotectonic observations
	Fida Medina
	Moroccan Association of Geosciences, Commission of Natural Hazards, Rabat, Morocco (fidamedina@gmail.com)

ABSTRACT

The Western High Atlas earthquake is the largest earthquake in Morocco to date. It caused 3,000 dead, 5,000 injured and more than 2,000,000 homeless, mostly in rural zones. The preliminary earthquake parameters indicate a reverse fault with a 30x20 km rupture and a maximum displacement of 1.5-2 m along a NNW dipping plane. The focus depth has been determined at 24 km (international agencies) or 10 km (TE Cherkaoui, personal communication). This mostly unexpected event occurred within a mountainous area coinciding with a seismic gap between the Agadir and Central Atlas more seismic areas. However, several tectonic and geomorphological observations carried out since the 1970s show that the Amez Miz to Taroudant transect is undergoing active tectonics expressed by folds and faults that mainly affect the foreland strata (Miocene-Pliocene and Plio-Quaternary), and also some scarce recent sediments within the mountainous areas. Some of the mappable structures are shown in the Neotectonic Map of Morocco. This presentation illustrates several variable-scale neotectonic structures observed by our research teams, that have not been taken into account for assessing the seismic hazard around the Marrakech touristic region.

Session 3. Geomorphology, geomicrobiology, petrology and geological heritage in volcanic areas

O-031	Revisiting the Timanfaya eruption (1730-1736): evidence and typologies of syn-eruptive instability in single-genetic volcanoes (Lanzarote, Canary Islands)
	Carmen Romero ¹ , Inés Galindo ² , Nieves Sánchez ² , Esther Martín-González ³ , <u>Juana Vegas</u> ²
	¹ University of La Laguna, Santa Cruz de Tenerife, Spain ² Institute of Geological and Mining of Spain (IGME-CSIC), Gran Canaria & Madrid, Spain (j.vegas@igme.es) ³ Nature and Archaeology Museum, Santa Cruz de Tenerife, Spain

ABSTRACT

Nine of the twenty-five monogenetic cones recognized in the Timanfaya eruption (1730-1736, on the island of Lanzarote) show syn-genetic collapse processes. Analyzing their morphology and genetic origin, together with the description of these processes documented in historical chronicles, four basic types of instabilities associated with these monogenetic volcanic cones have been identified: 1) intracrater collapses, as in the cases of Montaña de Las Lapas and Montaña Colorada; 2) lateral collapses associated with fractures and faults coeval with the eruption, in the cases of Mazo and Boca del Infierno; 3) collapses due to sudden magma injections that trigger fracturing and partial sliding of the cone, as in Montaña Encantada; 4) hornitos field with vertical collapse and a graven formation by deep magma migration, such as those of Echadero de los Camellos. These type of processes entails a change in the eruptive mechanisms, which evolve to higher explosive volcanic indexes (EVI) directly related to the presence of fissural volcanic processes. In fact, it was the problems caused by the lateral collapse during the eruption of Mazo that the volcanic processes started to be documented and the crisis management of the Timanfaya volcanic emergency went from being a local crisis, to escalate to the regional level and finally become a national emergency in the year 1731 (official bulletins of the time). From that moment on, authorities allowed the evacuation of the population to Fuerteventura and America. The identification of these processes during the La Palma 2021 eruption demonstrates the need for a chronostratigraphic review of the different phases of Timanfaya and other monogenetic eruptions in Canary Islands.

O-021	First assessment of marine soundscape alterations during the formation of a new lava delta from a sub-aerial volcanic eruption: the case of Cumbre Vieja volcano (La Palma)
	<u>Jesús Alcázar-Treviño</u> ^{1,2} , Guillermo Lara ^{3,4} , Manuel Bou ^{3,4} , Susannah Buchan ^{5,6,7} , Francisco Domínguez-Yanes ⁸ , Eugenio Fraile-Nuez ²
	¹ Departamento de Ingeniería Industrial, Escuela Superior de Ingeniería y Tecnología, Universidad de La Laguna, P.O. Box 456, 38200 La Laguna, Spain (jalcazar@ull.edu.es) ² Centro Oceanográfico de Canarias, Instituto Español de Oceanografía (IEO), Consejo Superior de Investigaciones Científicas (CSIC), 38180 Santa Cruz de Tenerife, Spain ³ Instituto Español de Oceanografía (IEO), C.O. Murcia, C/ el Varadero 1, Lo Pagan, 30740 Murcia, Spain ⁴ Unidad Mixta de Investigación IEO (CSIC)-UPV, Tinglados Muelle Frutero, Grau de Gandia, 46370 Valencia, Spain ⁵ Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Raul Bitran 1305, 1700000, La Serena, Chile ⁶ Center for Oceanographic Research COPAS Sur-Austral and COPAS COASTAL, Universidad de Concepción, Casilla 160-C, 4070043, Concepción, Región del Bio, Chile ⁷ Departamento de Oceanografía, Facultad de Ciencias Naturales y Oceanográficas, Universidad de Concepción, Casilla 160-C, 4070043, Concepción, Región del Bio, Chile ⁸ DC Servicios Ambientales, C/ Robayna, 13, 1ºI. 38003 Santa Cruz de Tenerife, Spain

ABSTRACT

Marine soundscapes are made up of natural sounds from the geophony and the biophony and by man-made sounds from the anthrophony. The soundscape can reflect ecosystem state and is susceptible to drastic changes from both natural and anthropogenic events. The sub-aerial volcanic eruption at Cumbre Vieja rift at La Palma (Canary Islands) produced lava flows that reached the sea, forming two lava deltas that changed the geomorphology and physical- chemical seawater characteristics at a local scale in a marine protected area. Here we investigated acoustic recordings from sensors moored in shallow waters near these geological formations, both during and after the eruption. We computed acoustic metrics to study the marine soundscape during the eruption, looking for candidate sounds associated with the high-temperature lava flow that met the cooler seawater. Then, we compared these metrics with those calculated for almost a year after the eruption, exploring the geophony, anthrophony and the possible effects of these in the biophony. Our results show much higher sound levels at low frequencies (<100 Hz) in the recordings during the eruption, even locating impulsive low-frequency sounds (<50 Hz) that could be attributed to this lava-seawater contact. We also detected biological choruses and delphinid vocalizations, which could be influenced by the volcanic eruption. We encourage the continuity of these passive acoustic monitoring efforts combined with other methods to study the recovery of this protected area. Moreover, validation of sounds related to volcanic products reaching the sea could help to safely monitor remote areas susceptible of these drastic events.

O-051	A new methodological approach to map and analyse the spatial distribution of ballistic projectiles: the case study of 3rd July, 2019 paroxysm at Stromboli
	M. Bisson ¹ , C. Spinetti ² , R. Gianardi ¹ , K. Strehlow ^{3,5} , E. De Beni ⁴ , P. Landi ¹
	¹ Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Pisa, Pisa, Italy marina.bisson@ingv.it ² Istituto Nazionale di Geofisica e Vulcanologia - ONT, Roma, Italy ³ GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany ⁴ Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Etneo, Sezione di Catania, Catania, Italy ⁵ Mitiga Solutions SL, Barcelona, Spain

ABSTRACT

This work presents a new methodological approach to map and analyse the dispersion of the ballistic projectiles emplaced at Stromboli (Aeolian Archipelago, Italy) during the 3rd July, 2019 paroxysm. The approach is entirely developed on GIS platform and uses, as input data, a very high spatial resolution UAV optical imagery (RGB) acquired within few days from the paroxysm. The first part of the approach is represented by a flow of elaborations applied to the UAV imagery in order to reconstruct the boundary of ballistic spatter clasts as polygons features georeferenced into WGS 84 UTM 33 metric coordinates. The second parts is dedicated to quantify and analyse the spatial distribution of the spatter clasts emplaced on the East flank of the volcano, deriving the total areas of the spatter clasts, the estimation of the related volume, two dispersion parameters analysed moving away from the vent and the main trends of emplacement along the radial directions. The obtained results highlight as the approach presented here can generate in efficient and rapid way, a larger amount of data and information on ballistic deposits with respect to the classic field survey, especially in the areas inaccessible and can provide a useful contribute to volcanic hazard mitigation from ballistic fallout.

O-019	Linking silica sinters from hydrothermal hot springs in active volcanic areas to life on Mars
	<u>J. Javier Álvaro</u> , Blanca Martínez-Benítez
	Instituto de Geociencias (CSIC-UCM), Dr. Severo Ochoa 7, 28040 Madrid, Spain (jj.alvaro@csic.es)

ABSTRACT

Hot springs are the surface manifestation of large hydrothermal systems, and are of major importance for mineral exploration and geothermal energy. Hot waters can be highly supersaturated with respect to a variety of minerals, precipitating travertines (made up of calcium carbonate minerals) and silica sinters. Siliceous sinter deposits are chemical sediments of amorphous silica (opal-A), deposited by near-neutral alkali-chloride waters, derived from deep reservoirs with temperatures $>175^{\circ}\text{C}$. They form as abiotic precipitates of dissolved silica contained in geothermal waters after they have reached the surface. Water evaporation and cooling are the main abiotic drivers of precipitation and consequently of sinter formation. Silica accumulates on all available substrates, including microbes, vascular and non-vascular plants thriving and floating in the thermal fluid discharge of outflow channels and pools. Modern hot springs are analogues for understanding the biogeochemical processes implied in the formation of ancient cherts. In this context, the Precambrian cherts are of extraordinary interest because their microfossils represent some of the earliest records of life on Earth and provide a proxy for the biogeochemical conditions of the early biosphere. Hydrothermal systems are also proposed sites for exobiological investigation of Mars. In fact, NASA's Mars Spirit rover, operational until 2010, made pioneering discoveries identifying rocks on Mars that form in the presence of water, including sinter deposits. Ultimately, collecting sinter samples from Mars and returning them to Earth for microscopic and biogeochemical analysis will provide an answer to the question of whether there was life under these conditions on Mars.

O-024	Experimental evidence of hydrothermal vent fluids fueling microbes at the Tagoro submarine volcano (Canary Islands)
	<u>C. Pérez-Barrancos</u> ^{1,2} , E. Fraile-Nuez ¹ , J.P. Martín-Díaz ^{1,3} , A. González-Vega ^{1,2} , J. Escáñez-Pérez ¹ , M.I. Díaz-Durán ¹ , C. Presas-Navarro ¹ , J.M. Arrieta ¹
	¹ Centro Oceanográfico de Canarias, Instituto Español de Oceanografía (IEO), Consejo Superior de Investigaciones Científicas (CSIC), 38180 Santa Cruz de Tenerife, Spain (claperbar95@gmail.com) ² Universidad de Las Palmas de Gran Canaria (ULPGC), Las Palmas, Spain ³ Universidad de La Laguna (ULL), La Laguna, Spain

ABSTRACT

It is estimated that about 85% of the global volcanic activity occurs underwater and yet, submarine volcanoes remain understudied relative to their subaerial counterparts. Even less is known about the potential effects of submarine volcanoes and associated hydrothermal activity on marine ecosystems. More than a decade later since its eruption, the Tagoro submarine volcano (El Hierro, Canary Islands) continues to release noticeable amounts of reduced compounds and inorganic nutrients into the water column. It is hypothesized that these nutrient inputs may enhance primary production in the area. In the absence of in situ evidence, we developed an experimental approach to assess the effects of diffuse hydrothermal fluids on the abundance and community structure of local microbial communities. The experimental treatment involved mixing different proportions of hydrothermal fluids with non-affected seawater to reproduce dilution levels observed hundreds of meters away from the diffusive flows. The treatments enriched with volcanic products showed increased concentrations of chlorophyll a compared to controls, indicating a thriving response in phototrophic primary production in the presence of hydrothermal fluids. Flow cytometric analyses indicated that picophytoplankton was the most benefited from volcanic inputs, but DNA analysis showed effects on other groups of eukaryotic and prokaryotic organisms. Our results therefore suggest a positive effect of diffusive flows released by Tagoro on planktonic microbial communities, supporting enhanced primary production. Many more submarine volcanoes remain undiscovered in the area and elsewhere in the world, which may contribute significantly to global primary production.

O-016	Characteristics of the hydrothermal active area at Tagoro submarine volcano (El Hierro, Canary Islands): venting distribution and fluid, heat and nutrient output quantification
	<u>Juan Pablo Martin-Diaz</u> ^{1,2} , Alba González-Vega ¹ , Thibaut Barreyre ³ , Bernardo Cornide-López ⁴ , José Escáñez-Pérez ¹ , Carmen Presas-Navarro ¹ , Jesús María Arrieta ¹ , José Antonio Lozano ¹ , Eugenio Fraile-Nuez ¹
	¹ Centro Oceanográfico de Canarias, Instituto Español de Oceanografía (IEO), Consejo Superior de Investigaciones Científicas (CSIC), 38180 Santa Cruz de Tenerife, Spain (juanpablo.martin@ieo.csic.es) ² Universidad de La Laguna (ULL), La Laguna, Spain ³ University of Bergen (UiB), Bergen, Norway ⁴ ACSM Shipping Co SL, Vigo, Spain

ABSTRACT

Tagoro is one of the few submarine volcanoes in the world that has been monitored since its early eruptive stage in 2011 to the present. After over a decade of widespread investigation, we provide an accurate delimitation of the hydrothermal field, as well as an estimate of the ongoing heat output. Six multidisciplinary oceanographic cruises were conducted between 2014 and 2023 to gather a comprehensive dataset of georeferenced video-imagery and in situ measurements of both hydrothermal flow velocities and hydrothermal fluid samples. Our aim was to describe the spatial distribution of venting and estimate the released rates of hydrothermal fluids, heat and nutrients. The results emphasize the complexity of the Tagoro hydrothermal system, which extends from the main crater up to the main cone, covering an area of over 7000 m². This hydrothermal field comprises thousands of small individual vents of varying morphologies, such as crevices and delicate chimney-like vents, unevenly distributed along the dominant diffuse venting surface. Hydrothermal fluid velocities and flow rates at the substratum level show an uneven spatial distribution, ranging from 3.8 - 11.1 cm min⁻¹ and 38.5 - 111.2 L m⁻² min⁻¹, respectively, with heat fluxes exceeding 200 MW for the entire active area. Silicates, nitrates, phosphates and ammonium concentrations show significant enrichments throughout the whole system, with higher concentrations observed near the rim of the main crater.

O-041	Geoheritage inventory update of the UNESCO Global Geopark of Lanzarote and Chinijo islands: contribution from basic science (Canary Islands)
	<u>Juana Vegas</u> ¹ , Inés Galindo ² , Carmen Romero ³ , Esther Martín-González ⁴ , Gonzalo Lozano ¹ , Mar González-Roquero ⁴ , Elena Mateo ⁵ , Nieves Sánchez ¹
	¹ Geological and Mining Institute of Spain (IGME-CSIC), Spain (j.vegas@igme.es) ² Spanish Research Council (CSIC), Spain; (3) University of La Laguna, Santa Cruz de Tenerife, Spain ³ University of La Laguna, Santa Cruz de Tenerife, Spain ⁴ Nature and Archaeology Museum, Santa Cruz de Tenerife, Spain ⁵ Lanzarote and Chinijo islands UGGp, Cabildo de Lanzarote, Spain

ABSTRACT

The UNESCO Global Geopark (UGGp) of Lanzarote and Chinijo Islands was included in the Global Geoparks Network in 2015. The formation and evolution of this UGGp can be understood through 68 geosites, grouped into eight geological frameworks which are representative of the geology and geodiversity of volcanic oceanic islands in a semiarid climate since the Miocene. During these last eight years, the basic science outreach and the new research conducted in this UGGp have motivated the update of its inventory to accommodate 14 new geosites. In this updating phase, the relevance of the geosites has also been modified, increasing from 15 to 18 geosites with international scientific significance. All this has led to a clear increase in the geoheritage value of these geosites. This inventory provides underwater Geosites. Its assessment using a methodology different from that used to evaluate inland geosites has provided a relevant innovation. Not only updating the geosites but parameters such as conservation status and risk of degradation to the current state, they have made possible to achieve a more effective and real management of the territory, allowing to update the geoconservation ratings and the educational and tourist resources of this UGGp.

O-010	Lava-ocean interaction during the 2021 Cumbre Vieja eruption (La Palma, Canary Islands): physical-chemical and biological anomalies in the water column
	<u>Alba González-Vega</u> ^{1,2} , Juan Pablo Martín-Díaz ^{1,3} , Juan-Tomás Vázquez ⁴ , María Gómez-Ballesteros ⁵ , Olga Sánchez-Guillamón ⁴ , José Antonio Lozano ¹ , Jesús M. Arrieta ¹ , Isabel Ferrera ⁴ , Emma Huertas ⁶ , Carmen Presas-Navarro ¹ , Eugenio Fraile-Nuez ¹
	¹ Centro Oceanográfico de Canarias, Instituto Español de Oceanografía (IEO-CSIC) (alba.gonzalez@ieo.csic.es) ² Universidad de Las Palmas de Gran Canaria (ULPGC) ³ Universidad de La Laguna (ULL) ⁴ Centro Oceanográfico de Málaga, Instituto Español de Oceanografía (IEO-CSIC) ⁵ Sede Central de Madrid, Instituto Español de Oceanografía (IEO-CSIC) ⁶ Instituto de Ciencias Marinas de Andalucía (ICMAN-CSIC)

ABSTRACT

On September 19th 2021, a volcanic eruption took place in La Palma (Canary Islands, Spain), in the area known as Cumbre Vieja, lasting for 85 days . On September 28th, the lava flow reached the ocean for the first time at Playa de Los Guirres and started forming the first lava delta. Several lava flows reached the ocean on the following weeks forming different lava deltas, most of which ended up merging into one main delta. Two multidisciplinary oceanographic cruises (VULCANA-0921 and VULCANA-1021) were conducted during the eruption to assess the effects of the lava-ocean interactions on the physical, chemical, and biological properties of the seawater, as well as to map the new geological structures formed underwater. The results show physical and chemical anomalies both in surface and in the water column reaching down to 300 m depth and up to 0.8 km distance from the shoreline, affecting various parameters such as temperature, salinity, turbidity, pH, fluorescence, and oxygen. Moreover, an upwelling effect was observed associated to density anomalies caused by the lava flowing over the seabed. However, no evidence of an upwelling-induced phytoplanktonic bloom was observed; in fact, chlorophyll-a showed a decreasing trend with increasing proximity to the shoreline. This is likely due to the high turbidity levels and shadowing of solar radiation caused by the presence of ashes and hyaloclastites in the seawater.

O-037	Record of temperatures and cooling path of mafic-ultramafic intrusions from Sal Island, Cape Verde archipelago
	<u>María García Rodríguez</u> ¹ , Cristina de Ignacio San José ¹ , David Orejana García ¹ , João Mata ² , Rita Caldeira ³
	¹ Dpt. Mineralogía y Petrología, Facultad CC. Geológicas, Universidad Complutense de Madrid, 28040, Madrid, Spain (magarc40@ucm.es) ² Dpt Geologia, Faculdade de Ciências da Universidade de Lisboa ³ Laboratório Nacional de Energia e Geologia (LNEG), Portugal

ABSTRACT

Sal is the oldest island of the Cape Verde archipelago, with magmatic activity starting around 25 Ma (submarine pillow lavas; Torres et al., 2010). It is the northernmost island of an N-S alignment also including the islands of Boa Vista and Maio, all highly eroded and with intrusive bodies representing the subvolcanic roots of the volcanic edifices exposed. These intrusions form part of the Old Eruptive Complex, cropping out in the central-west part of the island and comprising a pyroxenite-gabbro body and a number of circular/subcircular, pyroxenite-gabbro-foid syenite complexes. There are no detailed studies concerning mineral chemistry and crystallization conditions of these intrusions, which are a first step, together with precise geochronology, in order to correlate them with any of the different volcanic series occurring in Sal. In this work we present an interesting record of compositional variations of spinel group minerals that allow us determining, through selected geothermobarometers (Andersen and Lindsley, 1985; Canil and Lacourse, 2020) the evolutionary path of progressive cooling of the ultramafic-mafic coastal pyroxenites and gabbros. Chromium-rich spinels in cumulus minerals yielded from magmatic crystallization to clearly subsolidus reequilibration temperatures (1275-742 °C). In turn intercumular magnetites yielded 1081-492 °C, reflecting the transition from magmatic to subsolidus to hydrothermal conditions. Corresponding fO₂ values from magnetite-ilmenite exsolution pairs yielded from -13.19 at 840 °C to -16.87 at 641 °C corresponding to $\Delta\text{NNO}-\Delta\text{HM}$ buffers, indicating relatively oxidizing conditions.

O-018	The challenge of protecting a new volcano in the Canary Islands
	<u>Juana Vegas</u> ¹ , Gonzalo Lozano ² , David Sanz-Mangas ² , Nicolás Ferrer-Valero ² , Nieves Sánchez ¹ , Inés Galindo ¹
	¹ Instituto Geológico y Minero de España (IGME-CSIC) (j.vegas@igme.es) ² Instituto de Oceanografía y Cambio Global, Universidad de Las Palmas de Gran Canaria (IOCAG-ULPGC)

ABSTRACT

The archipelago of the Canaries is the European region with the highest number of volcanoes preserved through the declaration of protected natural areas, moreover International programs of UNESCO Global Geoparks and Biosphere Reserves. Volcanoes of high scientific value have recognized through the Spanish Inventory of Sites of Geological Interest (IELIG). These facts may indicate that the Canary Islands are at the forefront of geoheritage recognition and protection. However, the latest eruption on La Palma in 2021 has highlighted the scientific challenge of determining the most valuable volcanic features for protection. More importantly, it has emphasized, the consequences of irreversible damages and impacts to this volcano before it is officially recognised and being legally protected. The damage caused is irreversible and, only 1 year and 10 months after the end of the eruption, many of the most valuable volcanic elements have already been lost forever. In this first phase of the recovery, there has been a lack of ability to acquire funding resources to invest them to develop new and modern infrastructures that can produce exceptional quality tourism experience, which could potentially be unique worldwide. Furthermore, this has also contributed to less new green jobs opportunities that had not been generated. The present work reports the methodology specially designed to identify the Volcanic Elements of Interest (VEI), assess their scientific and touristic value, whose results have allowed to select VEI that should be legally protected to ensure a sustainable socioeconomic development that does not compromise the conservation of the most modern volcano in the Canary Islands.

Poster Session

P-007	Exploring Vertical Gravity Gradients at Campi Flegrei
	Zahorec P. ¹ , Papco J. ² , <u>Nogova E.</u> ^{1,3} , Vajda P. ¹
	¹ Earth Science Institute, Slovak Academy of Sciences (ema.nogova@savba.sk) ² Faculty of Civil Engineering, Slovak University of Technology ³ Faculty of Natural Sciences, Comenius University

ABSTRACT

To better understand the processes inside active volcanoes, measurements of gravity changes, often in areas affected by deformations of the Earth's surface, and related vertical gravity gradients play an important role. On-site measurements of vertical gravity gradients can differ significantly from the often-used theoretical (normal) values. Many authors recommend using the in-situ measured vertical gradients rather than the normal gradient to account for the deep geological contribution to the gradients in the areas affected by vertical deformation. However, in the context of Campi Flegrei caldera, the effect of geological values on the anomalous vertical gravity gradient is usually overestimated, and the effect of topography is underestimated. Through modelling the influence of nearby topography on vertical gravity gradients and subsequent in-situ verification, we show that Campi Flegrei is not a "reasonable flat area," as often described in the literature. The following results demonstrate the significance of vertical gravity gradient for understanding gravity changes in subsurface structures. We are comparing our in situ measurements with theoretical models to identify any discrepancies or deviations from expected values. We show that nearby topography can truly influence vertical gravity gradients, even in seemingly flat areas like Campi Flegrei, and such a topographic contribution to the gradient is usually much greater than the expected geological contribution. This must be carefully considered when using in- situ vertical gravity gradient measurements. We suggest that a more nuanced approach is needed to fully understand the relationship between vertical gravity gradients and subsurface structures in complex geological environments like volcanic calderas.

P-040	Gravimetric networks in the Canary Islands: an effective tool to study the last eruptions in El Hierro and La Palma
	F. G. Montesinos^{1,7}, J. Arnoso^{2,7}, M. Benavent^{1,7}, E. Vélez^{2,7}, D. Gómez-Ortiz^{3,8}, S. Sainz-Maza^{4,7}, I. Blanco-Montenegro^{5,7}, U. Riccardi^{6,7}
	¹ Facultad de CC. Matemáticas, Universidad Complutense de Madrid. Plaza de Ciencias 3, 28040 Madrid, Spain (fuensant@ucm.es) ² Instituto de Geociencias (IGEO), CSIC-UCM. C/ Doctor Severo Ochoa, 7. 28040 Madrid, Spain ³ Dpt. Biología y Geología, Física y Química Inorgánica, ESCET, Universidad Rey Juan Carlos. C/Tulipán s/n, 28933 Móstoles, Madrid, Spain ⁴ Observatorio Geofísico Central (IGN). C/ Alfonso XII, 3. 28014 Madrid, Spain ⁵ Departamento de Física, Escuela Politécnica Superior, Universidad de Burgos. Avda. de Cantabria s/n, 09006 Burgos, Spain ⁶ Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR), University "Federico II" of Naples, Italy ⁷ Research Group 'Geodesia', Universidad Complutense de Madrid, Spain ⁸ Research Group 'Geofísica y Geoquímica Ambiental', Universidad Rey Juan Carlos, Spain

ABSTRACT

The observation of temporal gravity changes can provide valuable insights into the seismic and magmatic processes associated to volcanic crises. Gravity changes can be sensitive to mass transport and density variation in the subsoil, as well as vertical ground deformation. Hence, gravity and geodetic measurements, jointly collected on networks, are essential for monitoring volcanic activity and hazard assessment and risk mitigation programs. The relative gravity network at El Hierro was established in 2003 and re-observed in 2004 and 2008. In October 2011, following the onset of a submarine eruption (Tagoro volcano), which was preceded by nearly 3 months of seismic unrest, the gravity network was measured in November 2011, during the ongoing eruption. The end of this submarine eruption, in March 2012, was followed by six episodes of magmatic intrusion in the following two years, which did not end on a new eruption. Subsequent surveys were conducted during 2012-2023 to study these episodes and the observed gravity changes presumably reveal the process of magma displacement and its ascent to the surface. Similarly, the gravity network at La Palma allowed us to study the magmatic feeding system of the 2021 eruption (Tajogaite volcano). Several gravity surveys conducted before and after the eruption (from 2021 to 2023) provided us with an image of the magmatic system responsible for this last eruption and the spatio-temporal path of magma ascent from the mantle to the surface.

P-043	The impact of new volcanic landscapes on gravity field: El Hierro and La Palma case studies
	S. Sainz-Maza ^{1,4} , <u>F. G. Montesinos</u> ^{2,4} , J. Arnosó ^{3,4}
	¹ Observatorio Geofísico Central (IGN). C/ Alfonso XII, 3. 28014 Madrid, Spain ² Facultad de CC. Matemáticas, Universidad Complutense de Madrid. Plaza de Ciencias 3, 28040 Madrid, Spain (fuensant@ucm.es) ³ Instituto de Geociencias (IGEO), CSIC-UCM. C/ Doctor Severo Ochoa, 7. 28040 Madrid, Spain ⁴ Research Group 'Geodesia', Universidad Complutense de Madrid, Spain

ABSTRACT

Microgravimetry applied to study of volcanoes is a proven tool that is able to detect subsoil masses redistribution during any volcanic event, as long as they are associated to spatiotemporal gravity changes observed on the surface. Instead, the interpretation of the results provided by this technique is influenced by large mass changes, which can be added above the earth surface during an eruptive process (cones, lava flows, etc.). Therefore, the gravity field during volcanic activity periods can be modified by mass redistribution above or under the earth's surface as well as by substantial terrain deformations. Here, we focus our study on the contribution to the gravity field of the volcanism understood as a geological process that shapes the landscapes around the places where it occurs. The preeruptive and posteruptive landscapes reflect, among others, the contribution of episodes of inflation and deflation as well as those due to the creation, modification, and destruction of terrain. We present a modelling of the gravity field perturbation at El Hierro and La Palma (Canary Islands) due to the emergence of new volcanic buildings during 2011-2012 and 2021, respectively. The influence of the products associated to the eruption as lava flows have been also considered. Our results show that while the influence on gravity value of the new submarine edifice built at El Hierro is minimal, the eruption that occurred at La Palma during 2021 particularly produced important gravity changes, which are essential when making corrections in microgravimetry to study volcanic process.

P-045	Subsidence and thermo-fluid-dynamics modelling at Timanfaya volcanic area (Lanzarote, Canary Islands)
	<u>U. Tammaro</u> ¹ , V. Romano ² , J. Arnoso ^{3,7} , M. Benavent ^{4,7} , U. Riccardi ^{5,7} , F.G. Montesinos ^{4,7} , E.J. Vélez ^{3,7} , M. Meo ⁶
	¹ Istituto Nazionale di Geofisica e Vulcanologia, Italy (umberto.tammaro@ingv.it) ² Dipartimento di Ingegneria Industriale, Università di Salerno, Italy ³ Instituto de Geociencias (IGEO), CSIC-UCM. C/ Doctor Severo Ochoa, 7. 28040 Madrid, Spain ⁴ Facultad de CC. Matemáticas, Universidad Complutense de Madrid. Plaza de Ciencias 3, 28040 Madrid, Spain ⁵ Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR), Università "Federico II" di Napoli ⁶ Faculty of Engineering and Physical Sciences, University of Southampton, Southampton, United Kingdom ⁷ Research Group 'Geodesia', Universidad Complutense de Madrid, Spain

ABSTRACT

We report on the analysis of the geodetic strain retrieved from about 6 years of GNSS data collected on a small CORS network of 9 stations, spread over Lanzarote (Canary Islands). This study aims to understand the present-day ground deformations on Lanzarote and its origin, mainly in Timanfaya volcanic area (TVA), where the last eruptive cycle occurred (1730-36). The retrieved strain field reveals a compression along the island, except for the TVA that displays relevant tensile strain. The compression has an overall NW trend, while in TVA the predominant tensile strain trends NW. Furthermore, GNSS data shows a significant subsidence in the area of the strongest geothermal anomaly in TVA. Through a FEM modelling, we examine the possible relation between the subsidence and the geothermal anomaly. First, we produce a thermal model of TVA as an idealized axial-symmetric cylindrical domain with three sub-domains: conduit, the cooling magmatic body and outside area, unaffected by the geothermal processes. As heat transfer mechanisms, we assume conduction and convection in the conduit and pure conduction outside. One can imagine that the water table, which is very close to the magma body, is heated by conduction and then the thermal energy is transferred by convection into the conduit, where a mixture of magmatic gas and water vapor upraises. A mechanical FEM modelling is even produced to test that subsidence in TVA is due to cooling and contraction of a magma body. Finally, the temperature field and deformations are interpreted in light of the known tectonics.

P-038	The present-day surface deformation of the Canary Archipelago
	<u>Palano M.</u> ¹ , Escayo J. ² , Prieto J. F. ³ , Tiampo, K.F. ⁴ , Fernandez J. ²
	¹ Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Catania, Italy mimmo.palano@ingv.it ² Instituto de Geociencias (IGEO), CSIC-UCM. C/ Doctor Severo Ochoa, 7. 28040 Madrid, Spain ³ ETSI Topografía, Geodesia y Cartografía, Universidad Politécnica de Madrid, Ctra. Valencia km 7, Madrid, Spain ⁴ Cooperative Institute for Research in Environmental Sciences (CIRES), 216UCB, University of Colorado at Boulder, Boulder, CO, USA

ABSTRACT

We analysed all raw data acquired by the continuous GNSS stations of the Canary Archipelago and spanning a time span of 12 years. Raw data were processed by using the GAMIT/GLOBK 10.7 software adopting a standard processing setup. To improve the overall configuration of the network and to provide an updated definition of the local reference frame, we introduced into the processing more than 15 continuous GNSS stations mostly located in Western Europe. Resulting time-series and velocity field have been firstly referred to the ITRF2014 reference frame and then rotated into both a Eurasian and a Nubia reference frame. Achieved results as velocity and strain-rate fields well highlight a different crustal deformation pattern between the eastern sector and the western sector, affected by crustal contraction and stretching, respectively. The boundary of the two deforming sectors overlaps with the seismogenic fault system located between Tenerife and Gran Canaria islands.

P-009	Researching the surface deformations in the Sofia valley by means of data from SAR
	<u>Hristo Nikolov</u> ¹ , Mila Atanasova ²
	¹ Space Research and Technology Institute - Bulgarian Academy of Sciences hristo@stil.bas.bg ² National Institute of Geophysics, Geodesy and Geography - Bulgarian Academy of Sciences

ABSTRACT

This paper presents results concerning the detection of the ground deformations in the valley of Sofia, the capital of Bulgaria. Those deformations can be caused by different phenomena, but certainly influence on them could have seismic events with large magnitude above 5 combined with other unfavorable geohazard processes such as faults activation. It needs to be mentioned that in 2012 some 40 km west from Sofia occurred an earthquake with magnitude of 5.8, fortunately causing no casualties, but was strongly felt in this part of the country. The rapid expansion of the urbanized areas in the Sofia valley, and especially by high storey construction of blocks of flats and office buildings, increases the requirements for their regular monitoring with regard to the subsidence or uplift processes. One modern and rapidly developing technique to produce information on the said processes is the DInSAR approach. Here we showcase the usage of this method to create reliable information for the mentioned area by combining data from satellite SAR instruments with GNSS measurements, geological data as well as other additional ones. The information produced by the authors allowed detecting and assessing the ground deformations that lead to better understanding of the past and ongoing geohazard processes. For our research the source for SAR data is the Sentinel-1 mission of launched and maintained by European Space Agency.

P-011	Study of the coseismic deformations in the balkan peninsula area from SAR data
	<u>Mila Atanasova-Zlatareva</u> ¹ , Hristo Nikolov ² , Valentina Protopopova-Kakar ³
	¹ National Institute of Geophysics, Geodesy and Geography (NIGGG)-Bulgarian Academy of Sciences (mila_at_zl@abv.bg) ² Space Research and Technology Institute (SRTI) - Bulgarian Academy of Sciences ³ Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam

ABSTRACT

The Balkan Peninsula is located in the Alpine-Himalayan seismic zone - the second most active in the world, making it prone to earthquakes. At the beginning of the twentieth century several destructive earthquakes with a magnitude above 7.0 have occurred in Bulgaria, which is located on the northern side of the region. Resent stronger shocks have been recorded around the Hellenic arc and less frequently in the continental part of the region. Earthquakes are a natural disaster that causes damage measured in terms of human lives and infrastructure destruction. In recent decades, satellite SAR technologies have made it possible to track surface deformations caused by earthquakes, volcanoes, landslides, etc. The new research technologies could help in a preparation plan to overcome the consequences of future events. In this study, we focused our research on determining the surface deformations after several earthquakes of magnitude gather than 6.5 in the last 5 years along the Hellenic Arch. The presented results from SAR data processing reveal the co-seismic deformations in the region, which are compared and well agree with GNSS data from other studies. The main task is to demonstrate operational readiness, to determine the degree of deformation of the earth's surface, and to prepare displacement maps.

P-022	2021 Vulcano island unrest by InSAR satellite data
	<u>Marco Polcari</u> , Cristiano Tolomei, Mimmo Palano, Claudia Spinetti
	Istituto Nazionale di Geofisica e Vulcanologia (marco.polcari@ingv.it)

ABSTRACT

Starting from July 2021, a set of relevant anomalies in geophysical and geochemical parameters were recorded by the INGV networks at Vulcano island (Aeolian archipelago; southern Italy). In particular, variations of temperatures and gas emissions were recorded in the hydrothermal field at La Fossa Crater (LFC). In addition, significant ground deformation of about 1 cm/month were recorded at IVCR continuous GNSS station located on the northern slope of LFC. In the present work, satellite Synthetic Aperture Radar (SAR) were exploited in order to get a synoptic view of the ground displacement phenomenon occurred during the 2021 Vulcano unrest. Ground deformation velocity maps and displacement time series have been independently obtained by using two multitemporal SAR Interferometry (InSAR) approaches. In particular, the SBAS and IPTA techniques have been applied to two datasets of SAR radar images acquired from May 2021 to January 2022 by Sentinel1-A/B (S1) sensors (TOPSAR mode) operated by the European Space Agency (ESA) along descending and ascending orbits. The availability of both satellite orbits allowed to compute the components of the motion along the Vertical (UP) and the East-West (EW) directions. The results are in agreement with each other, highlighting the same deformation pattern along UP and EW component, consistent with an inflation of LFC. The maximum deformation area is detected along the southern rim of LFC. The good agreement between the SBAS and IPTA outcomes provide a cross-validation of the measurements guaranteeing the reliability of the results. Moreover, achieved results are complementary to the ones obtained by the continuously monitoring GNSS network.

P-052	The Casamicciola seismogenetic fault system responsible for the 2017 earthquake at Ischia Island (Italy): geological, seismological and geophysical constraints
	Nappi Rosa ¹ , Rosella Nave ¹ , Sabina Porfido ² , Valeria Siniscalchi ¹ , Giuliana Alessio ¹ , Elisa Paganini ³ , Argelia Silva Fragoso ³ , Gianluca Groppelli ⁴ , Gianluca Norin ⁴ , Marta Pischiutta ⁵ , Vincenzo Sapia ⁵ , Valerio Materni ⁵ , Valeria Paoletti ⁶ , Donato D'Antonio ⁷ , Luigina Vezzoli ³ , Alessandro Maria Michetti ³
	¹ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli Osservatorio Vesuviano (rosa.nappi@ingv.it) ² Consiglio Nazionale delle Ricerche-ISA ³ UNINSUBRIA ⁴ Consiglio Nazionale delle Ricerche – IGAG ⁵ Istituto Nazionale di Geofisica e Vulcanologia, Roma 1 ⁶ UNINA-Distar ⁷ Geologist

ABSTRACT

In this study we aim to constrain the source characteristics of the Casamicciola active and capable fault system at Ischia Island, to provide insights about the local seismic hazard. On August 21st, 2017, a Md 4.0, shallow (1.5 km), volcano-tectonic earthquake reactivated the Casamicciola capable fault. The primary coseismic deformation observed at surface allowed to constrain its seismogenic source. The August 21st earthquake was caused by the reactivation of the E–W fault system, associated with the holocenic uplift of Mt Epomeo northern flank. The epicentral location of the most relevant earthquakes in the last three centuries, is systematically confined just within a few square kilometers in the Casamicciola area, particularly the strongest occurred in 1796 (I=VIII MCS), 1828 (I=VIII–IX MCS), 1881 (I=IX MCS), and 1883 (I=XI MCS). For constraining the source of the 2017 and of the historical earthquakes, we have investigated the 2 km long, E–W trending Casamicciola Holocene graben, at the base of the Mt Epomeo range front. We have carried out a) a new geomorphic and structural analysis using drone aerial survey by a LiDAR scanner generating a 5-10 cm resolution DTM and by a radiometric thermal camera b) a macroseismic analysis of the historical earthquakes applying the ESI 07 scale c) a geophysical survey of the 2017 earthquake epicentral through Electrical Resistivity Tomography profiles across the Casamicciola graben; d) a geophysical survey using a large-depth LOZA GPR; e) a SAR data analysis; f) directional amplification and polarization analyses to investigate fracture-related stiffness anisotropy.

P-015	Pyroclastic density currents at basaltic volcanoes: the 10 February 2022 event at Etna volcano (Italy)
	<u>P. Del Carlo</u> ¹ , B. Behncke ² , F. Zuccarello ² , D. Andronico ² , A. Cappello ² , F. Ciancitto ² , A. Di Roberto ¹ , G. Ganci ² , L. Guichard ^{2,3} , M. De Micheli Vitturi ¹ , T. Esposti Ongaro ¹
	¹ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa (paola.delcarlo@ingv.it) ² Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etno ³ University Paris Sciences & Lettres

ABSTRACT

At Etna, small-volume pyroclastic density currents (PDCs) have been occurred several times over the last 40 years. In the past, the triggering mechanisms of such events has been attributed to: i) failure and/or sliding of pyroclastic fall deposits emplaced on steep slopes during intense lava fountaining, ii) the gravitational collapse of lava flow fronts, and iii) the interaction/mixing of unstable and unconsolidated deposits making up the flank of the summit cones with hot lava and wet rocks or snow. On late 10 February 2022, Strombolian activity at Etna's South East Crater (SEC) increased to lava fountaining accumulating hot material on the steep slope of the cone the caused three flows of pyroclastic material at 21:40, 22:19 and 22:26. The first two travelled a few hundred meters in the direction of Valle del Bove, while the third one headed south up to ~1.4 km from the source area, reaching Mts. Barbagallo and burning a small tourist shelter. Real-time camera videos and surveys revealed that the last PDC was related to the collapse of a portion of the SEC's south flank, where a deep scar formed. Here we present the preliminary results on the deposit stratigraphy and data obtained from the analysis of the monitoring camera network to reconstruct the triggering mechanisms and flow dynamics of the 10 February 2022 PDC. These results can contribute to understand this complex type of volcanic phenomena on volcanoes fed by basaltic magmas and for their hazard assessment in highly touristic volcanoes as Etna.

P-020	Post-emplacment dynamics of Mt. Etna Volcano lava flows during the Christmas 2018 eruption unveiled by optical and radar satellite data
	Lisa Beccaro, Cristiano Tolomei , Claudia Spinetti, Matteo Albano
	Istituto Nazionale di Geofisica e Vulcanologia (cristiano.tolomei@ingv.it)

ABSTRACT

Lava flows are among the most remarkable products of Mt. Etna volcano (Southern Italy) activity. They are also a major cause of displacement on its volcanic edifice, making their study an issue to be delved deeper due to the impact they could have on the hazard associated with the volcanic activity. Aiming at the characterization of the dynamics of the Mt. Etna volcano lava flows emplaced during the last decade, here we adopted a multidisciplinary approach comprising the processing of optical and radar satellite data through different remote sensing techniques. Long stacks of Synthetic Aperture Radar (SAR) data, acquired during Sentinel-1 satellite mission, were elaborated with the Small Baseline Subset SAR Interferometry technique to study the ground displacements evolution before (January 2016 – December 2018) and after (January 2019 – July 2021) the 24 December 2018 eruption. Sentinel-2 data allowed to identify the lava flows boundaries emplaced during December 2018 and May 2019 eruptions. The subtraction of Digital Elevation Models, generated through the application of stereo radargrammetry technique to high resolution COSMO-SkyMed data, allowed to estimate the topographic changes caused by the lava emplaced during the aforementioned events. Results allowed to establish the influence that the physical mechanisms have on the observed motion, suggesting that thermal contraction of the lava body, viscous compaction of the substrate and downslope sliding induce significant volcanic ground displacements, acting in different time-periods and topographic conditions.

P-026	Seismological investigation at Mefite d'Ansanto CO2 emission field
	<u>Paola Cusano</u> ; Simona Morabito; Lucia Nardone; Simona Petrosino
	Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli - Osservatorio Vesuviano, Naples (paola.cusano@ingv.it)

ABSTRACT

The largest non-volcanic CO₂ emission field on the Earth is located at Mefite d'Ansanto (Italy). The CO₂ isotopic signature reflects a deep origin, whose source is probably the mantle wedge beneath the Apennines along the Tyrrhenian side. The emission site falls at the northern tip of the Irpinia fault system that is associated with the destructive MS = 6.9, 1980 Irpinia earthquake. The gas leakage from this zone is linked to active faulting that characterized the area and determined large historical earthquakes. From 8 June to 28 September 2020 a seismic array (AME, Array Mefite), composed of seven short-period stations, operated close to the Mefite emission field. By using the local seismic noise, we have analyzed the wavefield characteristics, e.g., spectral properties, energy temporal pattern (RMS) and polarization, and estimated site effects. The seismological temporal patterns have been compared with the meteorological parameters, such as temperature and rainfall, to find possible relationships with exogenous factors. We found a well-defined spatial pattern for the spectral components above 5 Hz, which appear clearly linked to the emission field dynamics. On the other hand, the spectral components below 5 Hz result from the overlapping of multiple sources, of both exogenous, such as anthropogenic and meteorological factors, and endogenous nature. Application of the Independent Component Analysis (ICA) technique contributed to discriminate between natural and anthropogenic sources. This research is funded by INGV-Strategic Department project FURTHER.

P-028	Tapping different depth sources and temperature – oxygen fugacity variations throughout the 2021 eruption at La Palma, Canary Islands, Spain: insights from mineral chemistry of spinels
	<u>Cristina de Ignacio</u> ¹ , Tomás Martín-Crespo ^{2,3} , David Gomez-Ortiz ^{2,3} , Silvia Martín-Velázquez ^{2,3} , Elena Real ¹ , José Arnoso ^{4,6} , Fuensanta G. Montesinos ^{5,6}
	¹ Dpt. Mineralogía y Petrología, Facultad CC. Geológicas, Universidad Complutense de Madrid, C/ José Antonio Novais, 2, 28040 Madrid (cris@geo.ucm.es) ² Dpt. Biología y Geología, Física y Química Inorgánica, ESCET, Universidad Rey Juan Carlos, Madrid, Spain ³ Research Group 'Geofísica y Geoquímica Ambiental', Universidad Rey Juan Carlos, Spain ⁴ Instituto de Geociencias (IGEO), CSIC-UCM. Doctor Severo Ochoa, 7. 28040 Madrid, Spain ⁵ Facultad de CC. Matemáticas, Universidad Complutense de Madrid. Plaza de Ciencias 3, 28040 Madrid, Spain ⁶ Research Group 'Geodesia', Universidad Complutense de Madrid, Spain

ABSTRACT

Spinel as a mineral group are complex both in structure and possible cation substitutions. Their general formula AB_2O_4 hosts both trivalent (Cr^{3+} , Al^{3+} , Fe^{3+}), divalent (Mg^{2+} , Fe^{2+}) and tetravalent (Ti^{4+}) cations, which comprise from refractory, high temperature (and/or pressure) elements to typical rock-forming ones in mafic systems. In this way, the magnesium number in spinels, defined as molar $Mg/(Mg + \text{total iron})$ has proved to be strongly dependent on crystallization temperature, thus providing the base for a recent geothermometer (Canil and Lacourse, 2020). In addition, the occurrence of both ferric and ferrous iron in spinel structures allows estimation of oxygen fugacity conditions. Compositional variation in spinel group minerals is also influenced from their usual co-crystallization with early ferromagnesian silicates and therefore is a good tracer of progressive magma fractionation processes. Representative samples from the 2021 Tajogaite eruption at La Palma (Canary Islands) were selected for this study, in which electron probe microanalysis of spinel inclusions in olivine and clinopyroxene phenocrysts, microphenocrysts and groundmass crystals, as well as groundmass oxide grains were used: 1) to track initial interactions between the main magma pulses and shallow felsic magma chambers; 2) to detect subsequent recharge processes involving the injection of deeper, very primitive magma pulses during the main phase of the eruption and 3) to recognize differentiation geochemical patterns linked to polybaric fractional crystallization. All these processes resemble those described for other Macaronesian islands (Madeira; Mata and Munhá, 2004) and could reflect overall similar features of the shield stage of intraplate, ocean island building.

P-029	Vents opening susceptibility map of the Colli Albani long-dormant volcano
	<u>Marina Bisson</u> ¹ , Roberto Isaia ² , Rosella Nave ² , Alessandra Pensa ^{3,4} , Guido Giordano ⁴
	¹ Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Pisa, Italy marina.bisson@ingv.it ² Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy ³ ISPRA – Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma, Italy ⁴ Dipartimento di Scienze, Università degli Studi Roma Tre, Roma, Italy

ABSTRACT

Despite their protracted periods of inactivity, long-dormant volcanoes may be highly hazardous, as their reactivation can be characterised by violent explosive eruptions. An example of such volcanoes is the Colli Albani caldera, onto which deposits Rome Capital City is built, Italy. Its last volcanic activity was characterised by voluminous maar-forming phreatomagmatic eruptions dated between 36-25ka, but the volcano has produced several maar lake overflows during the Holocene till historical times. Presently, Colli Albani is affected by recurrent seismic events, anomalous heat flow, ground uplifts, hydrothermal circulation and gas emissions. For these reasons, the Italian Civil Protection has recently listed Colli Albani among the ten active volcanoes of Italy, but products for the evaluation of its volcanic hazards lacking. This work presents the first study on vent opening susceptibility mapping at Colli Albani. We explore the potential of an available geological dataset for building, through GIS analysis, an index that classifies areas at different vents opening susceptibility (low, moderate and high). Such result highlights as a solid geological mapping is a prerequisite for the volcanic hazard assessment, especially in remote or poorly studied long-dormant volcanoes such as caldera systems where the location of new vents could occur in different volcano sectors.

P-044	Local Earthquake Tomography provides new insights on the active degassing system of the Lipari-Vulcano complex (Aeolian Islands, Italy)
	<u>C. Totaro</u> ¹ , M. Aloisi ² , C. Ferlito ³ , B. Orecchio ¹ , D. Presti ¹ , S. Scolaro ¹
	¹ Department of Mathematical and Computer Science, Physical Sciences and Earth Sciences, University of Messina, Italy (ctotaro@unime.it) ² Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania-Osservatorio Etneo, Italy ³ Department of Biological, Geological and Environmental Sciences, University of Catania, Italy

ABSTRACT

Seismic tomography represents a very powerful and effective tool for looking at depths beneath volcanic systems and to better understand their behavior. In particular, the P-wave and S-wave velocity ratio is a key parameter to discriminate the presence of gas, fluids and melts. Almost 4400 crustal earthquakes occurred in the last thirty years have been collected and the LOTOS software has been used to estimate the first 3D overall model of V_p , V_s and V_p/V_s for the Lipari–Vulcano complex. The investigated system, belonging to the Aeolian island archipelago (southern Tyrrhenian sea), has been characterized both in old and recent times by fumaroles, hydrothermal activity and several episodes of anomalous increases of fumarole temperature and strong degassing. The results of tomographic investigation indicate the presence of two main anomalies of low V_p and low V_p/V_s , clearly depicted up to ~ 8 km depths, related to gas-rich materials beneath the central-northern sector of Vulcano and the western off-shore of Lipari, respectively. The anomaly beneath Vulcano is located in close correspondence with the sectors where fumaroles, hydrothermal activity and active degassing are widely documented. A new, previously undetected, volume of strong gas-concentration has been identified beneath the western Lipari off-shore. The obtained results furnished a picture of the spatial distribution of gas-filled volumes feeding the main degassing activity of the Lipari-Vulcano complex and allowed to highlight the main role played by volcanic gas in the whole system, furnishing invaluable constraints for improved modelling of the volcanic system and of its possible evolution.

P-027	Lava flows reaching the submarine platform and slope during the 2021 eruption of Cumbre Vieja Volcano (La Palma, Canary Islands): A petrological and geomorphological study
	<u>Lozano Rodríguez, Jose Antonio</u> ¹ , Casillas, Ramón ² , Álvarez-Valero, Antonio M. ³ , Vázquez, Juan Tomás ⁴ , Gómez-Ballesteros, María ⁵ , García, Marga ⁶ , Sánchez-Guillamón, Olga ⁴ , Arrese, Beatriz ⁵ , Arrieta, Jesús ¹ , Presas-Navarro, Carmen ¹ , Martín-Díaz, Juan Pablo ¹ , González-Vega, Alba ¹ , Brenes, Álex ⁷ , Fraile-Nuez, Eugenio ¹
	¹ Centro Oceanográfico de Canarias, IEO-CSIC, C/ Farola del mar, 21. Dársena Pesquera. Santa Cruz de Tenerife, España (ja.lozano@ieo.csic.es) ² Universidad de La Laguna. Departamento de Biología Animal, Edafología y Geología. Avenida Astrofísico Francisco Sánchez, s/n. Facultad de Ciencias. San Cristóbal de la Laguna, España ³ Universidad de Salamanca, Departamento de Geología, Plaza de la Merced, Salamanca, España ⁴ Centro Oceanográfico de Málaga, IEO-CSIC, Puerto Pesquero s/n, Fuengirola, España ⁵ Servicios Centrales, IEO-CSIC, C/ Corazón de María, 8, Madrid, España ⁶ Centro Oceanográfico de Cádiz, IEO-CSIC, Puerto Pesquero s/n, Cádiz, España ⁷ Universidad de Las Palmas de Gran Canaria, Campus de Tarifa, 35017. Las Palmas, España

ABSTRACT

On September 19, 2021, a strombolian eruption occurred at the Cumbre Vieja volcano situated on the Canary Island of La Palma, resulting in the expulsion of a substantial amount of lava. Eight days later, the westward lava flows reached the coastline in the area between Punta de la Bombilla and Tzacorte harbor. In order to examine the immediate impacts of the lava activity on submarine geology and ecosystems, the Spanish Institute of Oceanography (IEO-CSIC) conducted five surveys along the coastal regions using the Ramón Margalef and Ángeles Alvariño oceanographic research vessels. High-resolution bathymetric maps were obtained using the multibeam echosounder EM710 while high-definition submarine images and rock samples were collected from the seafloor using a Remotely Operated Underwater Vehicle (ROV LIROPUS) as well as a manned submarine (PISCES VI). These datasets indicated that lava flowed down the shelf and upper slope as block (aa) and pillow lava flows, channeled by small gullies on the upper slope. The research identified significant morphological changes were detected in the subaerial northern and southern lava deltas occupying areas of 5,4 and 43 ha, respectively, as well as in a submarine area of ~30 ha. New volcanic materials have been identified as far as 1.2 km from the original coastline at a depth of around 305 m. Preliminary petrographic studies determined that the eruption initially brought tephrites to the surface, which later evolved into basanites containing olivine, pyroxene, amphibole and plagioclase phenocrysts engulfed in a glassy matrix with a variable number of vesicles. The total volume of lava invading the submarine environment is roughly estimated around 3 Mm³ reaching a maximum thickness of about 40 m along pre-existing gullies of the submarine slope. By integrated multidisciplinary analyses of the water column and ecosystem changes, this study will enhance our understanding of magmatic evolution from depth to eruption. Furthermore, the findings will be valuable for future risk management of eruptive events.

P-054	Eruptive column monitoring of the 2021 La Palma eruption
	<u>F. Quirós</u> ¹ , J. Pereda de Pablo ¹ , A. J. Molina-Arias ¹ , Sáez Gabarrón L. ¹ , A. Felpeto ² , S. Meletlidis ¹
	¹ Centro Geofísico de Canarias, Instituto Geográfico Nacional, Santa Cruz de Tenerife, Spain (fquiros@mitma.es) ² Observatorio Geofísico Central, Instituto Geográfico Nacional, Madrid, Spain

ABSTRACT

The evolution of the eruptive column during an eruption is a parameter that must be constantly monitored, as it can supply us valuable information about the type, development, and dynamics of the eruption, as well as being a fundamental data for aviation safety and public health. To determine the height above sea level that the eruptive column will have at any given time, it is mandatory to measure the planimetric and altimetric coordinates of the lava vent from the very beginning and during the whole eruptive process. Based on this information, atmospheric models can be applied, which allow estimating the dispersion of the pyroclastic material through the different layers of the atmosphere, and its impact on air traffic and are affected by the fine gran material. This information is also crucial to work with numerical models of possible spread of lava flows. The IGN, fulfilling its assigned task of monitoring and transmitting the information of the eruptive column to the pertinent authorities, monitored it by installing surveillance cameras around it that allowed continuous monitoring of the phenomenon. In addition to the determination of the coordinates of the eruptive center, the calibration of the images obtained by the cameras, estimation of the correction by wind direction and control of the measurement system and sending images through mobile devices were also carried out.

P-014	Probable effects of coastal erosion and flooding on the geoheritage of the Lanzarote Island in the 21st Century
	Nicolás Ferrer ¹ , Juana Vegas ² , Esther Martín-González ³ , Javier Lario ⁴ , Carmen Romero ⁵ , Inés Galindo ² , Gonzalo Lozano ² , Nieves Sánchez ²
	¹ Instituto de Oceanografía y Cambio Global, IOCAG, Universidad de Las Palmas de Gran Canarias, ULPGC (nicolas.fvg@ulpgc.es) ² Instituto Geológico y Minero de España, IGME-CSIC ³ Museo de la Naturaleza y Arqueología de Tenerife, Cabildo de Tenerife ⁴ Universidad Nacional Educación a Distancia, UNED ⁵ Universidad de La Laguna, ULL

ABSTRACT

Sea level rise (SLR) is one of the most notable consequences of anthropogenic climate change. SLR will simultaneously lead to an increase in flooded areas and an acceleration of coastal erosion processes. Regionalised projections indicate that mean SLR on the Lanzarote (Canary Islands) could reach ~20 cm by mid-century and ~65 cm by the end of the century. The geological heritage of the island of Lanzarote is unique and includes 48 geosites (LIG, Spanish acronym) on land, of which 21 are located on the coast and 3 of them in the coastal area of the Timanfaya National Park. It is expected that Lanzarote's coastal geosites will be exposed to the potentially destructive effects of coastal erosion and flooding during this century as a result of the SLR. However, no damage estimates exist, so this work presents a first approximation of the combined effects of erosion and coastal flooding during the 21st century on the conservation of coastal geoheritage. For this purpose, two groups of morphodynamic models based on equilibrium profiles are used, applied discriminately according to a classification of the LIG between rocky structures (mainly platforms, cliffs) or sedimentary deposits (mainly beaches). The results provide a quantification of the total and relative potential surface and value loss in the coastal LIG of Lanzarote, taking into account the combined effect of flooding and marine erosion. The results can help to establish damage reduction measures for the geoheritage elements with the highest exposed value and risk of destruction.

P-012	Geodynamics of the Gibraltar Arc. A time series study of the Spanish Navy Observatory stations
	<u>Rodríguez Collantes, David</u> ¹ , De Lacy Pérez de los Cobos, M ^a Clara ² , Blanco Hernández, Abel ¹ , Sánchez Piedra, Manuel ¹ , Catalán Morollón, Manuel ¹
	¹ Royal Institute and Observatory of the Spanish Navy (drodriguez@roa.es) ² San Pablo CEU University

ABSTRACT

The Alboran Sea hosts the extensional basin located in the Alpine orogeny, between the Betic mountain range in the Southeast of the Iberian Peninsula and the Rif in North Africa. This area of geodynamic interest, better known as the Gibraltar Arc, is a North-South convergence zone of diffuse tectonics between the African and Eurasian Plates. The origination of this subsystem dates back to the Lower Miocene, when simultaneous cortical compression and expansion gave rise to the surrounding mountain ranges and the Alboran Basin respectively. This involved the thinning of the continental crust accompanied by an important magmatic phase that reached its maximum in the late Miocene. Currently, the Eurasia-Africa convergence is evolving in a NW-SE direction and one of its main structures is the Alboran Ridge, which extends from the Alhucemas Bay area to the Alboran Island. This area presents dextral WNW-ESE and sinistral NE-SW to NNE-SSW fractures or conjugate faults, which are a clear example of the complex incidence model it represents that makes it possible to accommodate the deformations. The Royal Institute and Observatory of the Spanish Navy (ROA) currently has geodetic stations in different parts of North Africa, some of them in very interesting locations such as the Alhucemas and Velez rocks or the Chafarinas Islands. In order to know and restrict the difficult behavior of this area, we contrast the data of the stations located in Western Mediterranean belonging to ROA, with the models and data to date verifying the performance of the stations located in these remarkable points.

P-008	Neoalpine tectonics and volcanism in the Western Carpathians
	<u>Vladimír Bezák</u> , Ján Vozár, Lenka Ondrášová
	Earth Science Institute of SAS, Bratislava (geofbezv@savba.sk)

ABSTRACT

The Western Carpathians (WECA) belong to the terranes, which under the pressure of the Adriatic plate were pushed mainly during Neogene out from the Alpine area into the eastern gulf of the North Penninic ocean. The bay was arcuately bounded by European Platform (EP). Interaction of WECA with EP was complex. After subduction accompanied by back-arc volcanism, an oblique collision occurred, especially in the western part. Strike-slip tectonics played a dominant role here. The eastern part came into frontal collision with the platform. Later, after the subduction moved to the Eastern Carpathians, the WECA passed to the extensional regime. Then fault tectonics of the basins and ranges type prevailed, accompanied by the ascent of the asthenolite and volcanism. Many faults are still active today, as evidenced by seismic station records. Volcanism lasted from Miocene to Quaternary. In the initial stages, it was rhyolite volcanism, but then andesitic stratovolcanoes played a dominant role. Finally, basalt volcanism took place on deep faults. Rhyolite volcanism produced all types of volcanoclastic rocks: autoclásticos (lava breccias), pyroclásticos (mainly ash fall type, but also pyroclastic flows) and epiclásticos in the marginal zones. Andesite stratovolcanoes reached a height of over 4 km and have a typical structure of alternating lava flows and pyroclásticos, several of them formed a caldera. Lahars and various types of epiclásticos dominate in the peripheral parts farther from the center.

P-048	The role of stand-alone devices for seismological investigation in volcanic and hydrothermal areas
	<u>Paola Cusano</u> , Danilo Galluzzo, Lucia Nardone, Guido Gaudiosi, Simona Morabito
	INGV, Sezione di Napoli - Osservatorio Vesuviano, Naples (paola.cusano@ingv.it)

ABSTRACT

In some areas of notable scientific interest, the impossibility of using telemetry stations and the need to ensure data continuity unequivocally imply the use of stand-alone instrumentation. Here we present some examples of seismological studies where the use of stand-alone temporary devices led to interesting results. In details, we show the case of active volcanic area of Mt. Vesuvius (Italy), and of Mefite D'Ansanto (Italy) CO₂ emission area. The use of high quality data recoded by temporary broadband seismic stations at Mt. Vesuvius, allowed to estimate the source parameters of local seismicity in 2018-2020. These stations are located close to the crater area, their instrumental response is well known and the sites are unaffected by dramatic local amplification. Tectonic, cold CO₂ emissions of Mefite D'Ansanto were inspected in 2021 by using two array configurations, designed to explore the seismic noise associated to fluid emissions. The favorable location and adopted geometries, let us to track the wavefield sourced by Mefite emissions, to characterize the associated spectral properties and to formulate some hypothesis on the endogenous source. The investigations on the seismic noise at Mefite evidenced a clear link among the noise amplitude temporal pattern and the meteorological parameters. In 2022 we installed a meteorological station close to the vents, equipped with an anemometer, a rain collector, a temperature and a humidity sensor. It operated for a dry–wet season cycle. Research activities performed on these data are funded by INGV-Strategic Department project FURTHER and Ricerca Libera project LAST.

P-032	Characterization of volcanic deposits from Cerro Gordo Martian terrestrial analogue by means of susceptibility measurements, petrographic analysis and mineral chemistry
	<u>Emma Losantos Guillén</u> ¹ , José Luis Mesa Uña ¹ , Joana S. Oliveira ² , Óscar G. Monasterio ³ , Marina Díaz Michelena ¹
	¹ Instituto Nacional de Técnica Aeroespacial (INTA), Space Magnetism Area, Torrejón de Ardoz, Spain (emmalosantos@gmail.com) ² Telespazio IK for European Space Agency ESAC, Spain ³ Sanfire MATSA, Aguas Teñidas Mine, Spain

ABSTRACT

The determination of the magnetic susceptibility of regolith and surface rocks can provide valuable information about the composition and structure of rocky bodies of the solar system but still remains an unexplored tool in surface planetary exploration. For this endeavour we propose the NEWTON susceptometer developed by our team. The susceptometer, based on AC - inductive methods, has a real magnetic susceptibility dynamic range covering values of rocks from the Earth, Moon and Mars. In this work we aim to test the suitability of this susceptometer to distinguish between different volcanic deposits and to relate the in-situ real magnetic susceptibility values measured in the field with the type of deposit. We selected the Cerro Gordo volcano (Campo de Calatrava volcanic region, Spain), an intraplate volcano, for its morphological similarities with Martian volcanoes which make it suitable as a terrestrial analogue. The eruptive style of this volcano has varied through time from phreatomagmatic to strombolian and phreatomagmatic again to end with an effusive phase and, therefore, the deposits found in the field (pyroclastic surge deposits, lahar facies, scoria and pyroclastic deposits, a lava flow, tuffs, breccias and spatter deposits) can provide a large range of magnetic susceptibility values. Here we compare the magnetic susceptibility values of different units from this volcanic edifice to results from petrographic and mineral composition analysis.