Conference Proceedings Paper

Investigating 2015-2019 deformation patterns at the Methana volcano in Greece using Sentinel-1 MT-InSAR, GNSS/GPS and seismic data

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Abstract: Methana is the westernmost dormant volcanic system belonging to the Hellenic volcanic arc in Greece. Its last historic eruption occurred in ~230 BC, and no alarming signs were observed in recent times. Nevertheless, seismic activity in the Saronic Gulf, geothermal manifestations, and the proximity to densely populated regions (e.g. Athens), provide motivation for a dedicated investigation into present-day deformation patterns. This study exploits Copernicus Sentinel-1 C-band Synthetic Aperture Radar (SAR) images acquired in 2015–2019, processed with a Multi-Temporal Interferometric SAR (MT-InSAR) approach using both persistent and distributed scatterers. Geodetic data from permanent GNSS stations and 2006–2019 GPS benchmark surveying are used as reference to calibrate the MT-InSAR results and validate their accuracy. Combination with geological, seismological and geomorphological data, allows better understanding of the observed ground deformation. The results suggest a complex displacement pattern across the volcano, including local-scale processes, such as settlement in the suburban zones, mass movements and some seasonal fluctuation overlapping with the long-term trend. This geoinformation can feed into the volcano baseline hazard assessment and the monitoring system. Key findings are presented in this short paper, while the full study is published in the journal *Applied Sciences*.

Keywords: SAR; InSAR; ground deformation; Sentinel-1; volcano monitoring; GNSS; seismicity; ground deformation; slope instability; MT-InSAR

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1. Introduction

The Methana peninsula in Greece is the westernmost dormant but geodynamically and hydrothermally active [1], volcanic system belonging to the Hellenic volcanic arc. Its last historic eruption occurred in ~230 BC, and no alarming signs were observed in recent times, so volcanic hazard in Methana is considered “low” [2]. Nevertheless, seismic activity in the Saronic Gulf [3], geothermal manifestations [1], and the proximity to densely populated regions (e.g. Athens), provide motivation for a dedicated investigation into present-day deformation patterns.

In this context, the present study aims to investigate ground stability and motions at the Methana volcano over the last five years, based on multi-temporal interferometric processing of Synthetic

Aperture Radar (SAR) satellite imagery, and integration of deformation estimates with an analysis of regional seismicity and geodetic data from continuous Global Navigation Satellite System (GNSS) monitoring and Global Positioning System (GPS) benchmark surveying.

Satellite Interferometric SAR (InSAR) has been largely exploited to study surface deformation at many volcanic centers of the arc (e.g., [4–8]), proving its effectiveness to provide a spatially distributed estimation of volcanic activity due to magma chamber processes, as well as shallow deformation associated to hydrothermal activity. Despite this abundant literature, to the best of our knowledge, no InSAR investigation has been previously focused on Methana, therefore the present study aims to start filling this knowledge gap.

Key findings from this integrated analysis are presented in this paper. For the detailed analysis and discussion of the results, the reader can refer to the full article published in the journal *Applied Sciences* [9].

2. Experiments

2.1. Seismic Data Analysis

The database of the seismological laboratory of the National and Kapodistrian University of Athens (NKUA; http://dggsl.geol.uoa.gr/en_index.html) was exploited for the analysis of regional seismicity in the 2006–2019 period.

The optimization of epicentres was carried out using the HYPOINVERSE software [10], and the data were divided into two time intervals: (i) January 2006 to August 2019, i.e. the time period covered by the GNSS data; and (ii) March 2015 to August 2019, i.e. the MT-InSAR time span.

2.2. GNSS and GPS Monitoring

Two benchmark stations were established in 2006 in the northern (i.e. station MENO) and southern (MESO) sector of Methana [11], as part of a larger GPS network aiming to study ground deformation in the north-western part of the Hellenic volcanic arc. The stations were re-occupied several times up to December 2019 using Leica receivers (SR9500 and AX1200).

Since August 2019, cGNSS data were available from the MTNA station located in the western part of the peninsula, and part of the GNSS network of the Institute of Geodynamics, National Observatory of Athens (NOA). Horizontal velocity records from two more cGNSS stations were also available from the National Technical University of Athens (NTUA), i.e. station METH installed in 2004 in the southern sector of Methana, and from [12], i.e. station 010A located to the south-east of the peninsula, at Poros. Moreover, a continuous GNSS (cGNSS) station was established in early 2015 at Lygourio (LYGO), as part of the HxGN SmartNet (https://gr.nrtk.eu/), and since then it acts as local reference station. For this reason, the regional velocity vector estimated at LYGO was subtracted from the two local GPS benchmark stations, as well as the two other sites (i.e. METH and 010A), with the aim to better define the local deformation field of the peninsula.

2.3. Satellite MT-InSAR Investigation

A long data stack of 99 SAR images acquired by the Copernicus Sentinel-1 constellation in ascending mode in the period March 2015 – August 2019 was exploited. These data are in Interferometric Wide (IW) swath mode [13], and provide a 250 km large coverage, with pixel resolutions of 5 m and 20 m (single look) in range and azimuth, respectively.

The stack was processed using an advanced Multi-Temporal InSAR (MT-InSAR) approach, an extension of the basic technique of Differential InSAR (DInSAR; e.g. [14]). The method used both Persistent Scatterers (PS) and Distributed Scatterers (DS), in order to enhance the coverage of monitoring targets in sub-urban and rural areas. The GAMMA SAR and Interferometry software and the Interferometric Point Target Analysis (IPTA) method [15] were used for the multi-temporal analysis.

3. Results and Discussion

The seismic data analysis shows that the Saronikos Gulf region is mainly characterized by moderate seismic events and shallow depths, as already discussed in the literature [16]. In 2015–2019 (Figure 1), three significant seismic events occurred in the area: two moderate shallow earthquakes with magnitudes Mw=3.8, and Mw=3.6, and a very deep one (depth=142 km) with magnitude Mw=4.2. A significant seismic swarm was observed NE of Poros Island. The seismic activity in this cluster started in 2016 and continued with few events up to 2019. Additional to the surface seismicity, very deep (80–100 km) sporadic micro events took place on a wider area extending from Methana towards Hydra Island. These deep micro-events may be attributed to the NE-subduction zone of the Ionian oceanic plate that reaches very deep in this area [3,11,17,18].

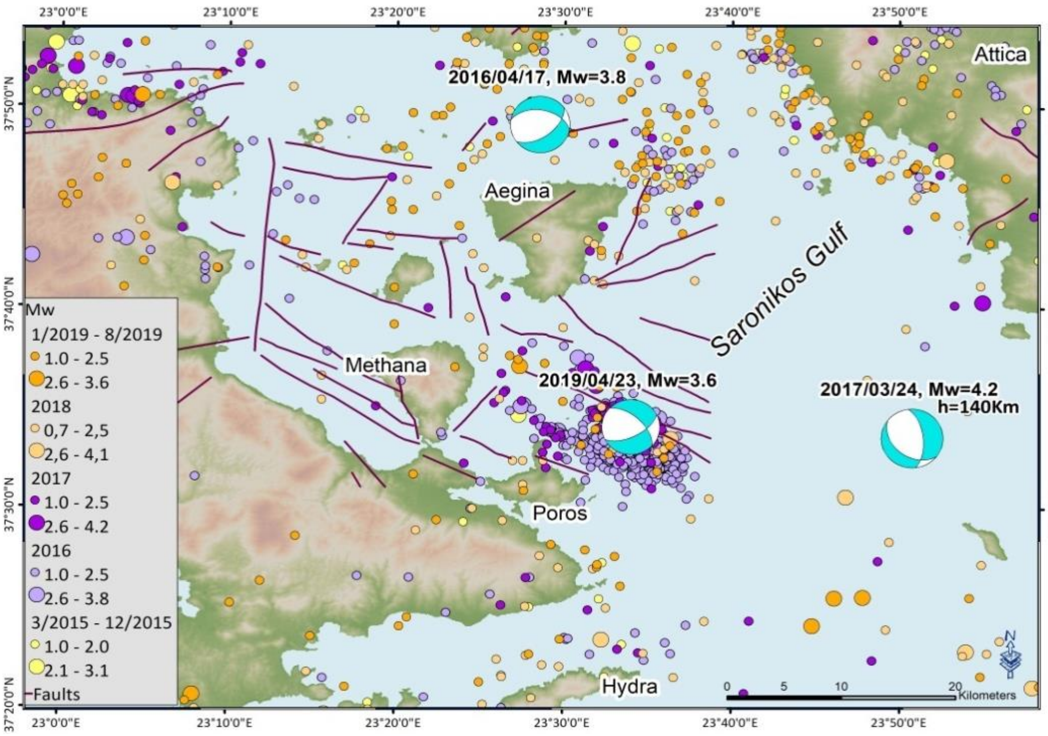

Figure 1. Seismic activity recorded in March 2015–August 2019. Full paper source: [9].

Geodetic monitoring results at the two local benchmark stations MENO and MESO for the period 2006–2019 appeared consistent with the regional velocity field. Although the resulting horizontal velocity vectors are very small (< 1 mm/year) and indicate a uniform deformation of the broader Methana area, a pattern of differential motion can be distinguished (Figure 2). The northern station (i.e. MENO) exhibited westward motion, while the southern sites (i.e. MESO and METH) showed northward motion (though velocity values are small, and errors significant). The more evident differential behaviour is found in the vertical component at the MESO station, which exhibited noticeable subsidence, to correlate with MT-InSAR findings.

The MT-InSAR processing extracted 4769 PS targets and 6234 DS targets (Figure 3), mostly located at low altitudes (up to ~100–150 m a.s.l. for the PS, and up to ~350–400 m a.s.l. for the DS), where there are urban settlements, and also on geological formations which exhibit high coherence, such as volcanoclasts. The uncertainty observed in the estimated Line-Of-Sight (LOS) velocity V_{LOS} is 2.8 mm/year on average for the PS dataset, and 2.6 mm/year for the DS dataset. These values provide an indication of the precision of the MT-InSAR results, and also suggest that the ±3.0 mm/year V_{LOS} interval can be considered as the velocity range indicating stability (green points in Figure 3).

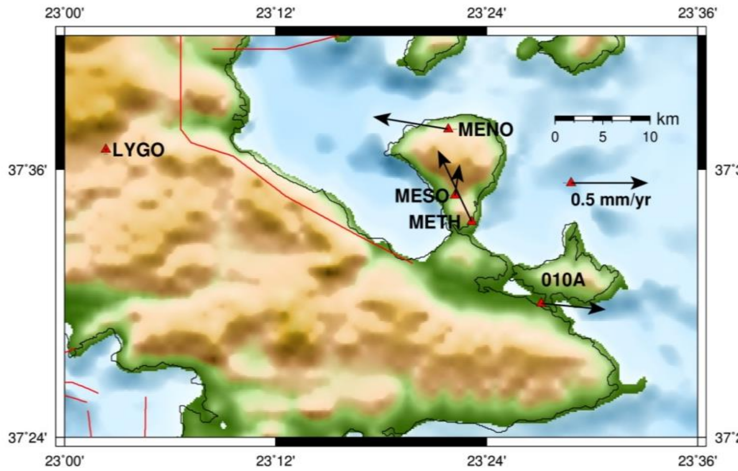

Figure 2. Local horizontal velocity field 2006–2019 calculated with respect to the LYGO cGNSS site in the broader area of Methana peninsula. Full paper source: [9].

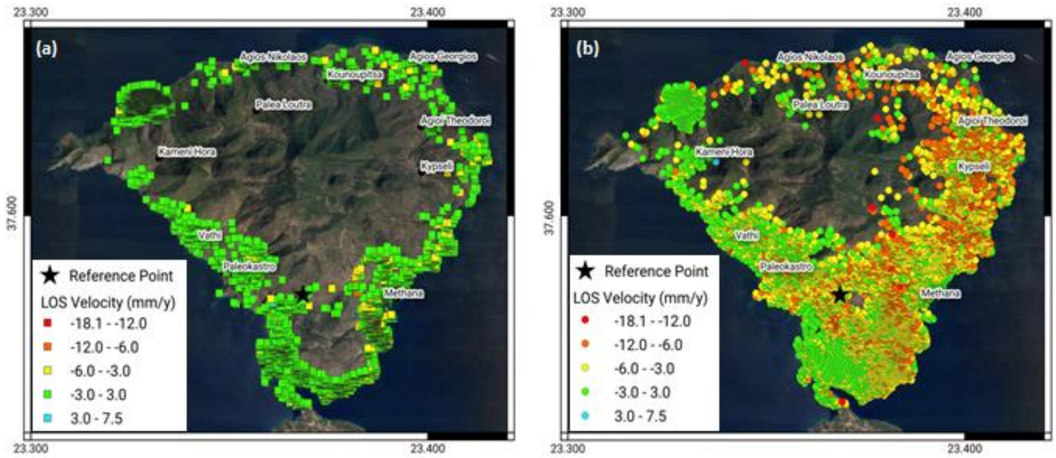

Figure 3. Line-of-sight (LOS) deformation velocity in 2015–2019 from the Multi-Temporal Interferometric Synthetic Aperture Radar (MT-InSAR) analysis for the (**a**) Persistent Scatterers (PS) and (**b**) Distributed Scatterers (DS) datasets, overlapped onto satellite optical imagery (© 2020 TerraMetrics, © 2020 Google). Full paper source: [9].

The accuracy of the MT-InSAR results was also estimated at the GPS benchmark stations MESO and MENO, after conversion of their local velocity values to the LOS direction using a frame of reference transformation (full details available in the full paper [9]).

After calibration, the maximum V_{LOS} observed was -18.1 mm/year away from the sensor (i.e. negative values). PS and DS moving faster are located on the eastern flank of the peninsula and, considering the LOS geometry, these could plausibly indicate occurrence of downslope mass movements and slope instability in rugged terrain and volcanic landforms that are recognized as prone to landsliding and rock-falls [19]. These concentrate on the volcanic ranges and gully erosion landforms above the urban settlements of Methana, Kipseli, Agii Teodori and Agios Georgios.

The northern portion of Methana town is built onto alluvium, and it seems slightly more stable (V_{LOS} = -1.8 mm/year) than the central zone of the town (built onto volcanoclastics), which is moving away from the satellite at -2.5 mm/year. Overall, it appears that the majority of the urban area footprint is not affected by significant deformation, while somehow greater rates are found in the sub-urban zones, as revealed by the DS targets.

No significant deformation pattern is found across the sparsely-vegetated outcrops at Mavri Petra. However, evidence of seasonal deformation can be detected in the time-series, with amplitude of approximately 5 mm, and periodicity of 1 year.

4. Conclusions

2015–2019 observations from the MT-InSAR and GNSS/GPS analysis are compatible with the anticipated “low” volcanic activity of Methana. The overall spatial distribution of the PS deformation values does not shape into a deformation field that could be reliably attributed to a typical volcanic inflation/deflation dynamic of the whole Methana, as found in the literature for other active volcanic areas. On the other side, the DS dataset may suggest the presence of deformation patterns along the eastern flank, though only in some cases these associate with specific landforms (e.g. narrow valleys, erosion gullies, superficial slides). No strong seismic events (Mw>4) or intense seismicity was recorded in the peninsula. Moreover, neither the location, the depth nor the magnitude of seismic events occurred in the vicinity could be directly associated with the observed ground deformation.

The interpreted low level of activity is clearly the initial baseline above which further investigations need to be conducted to improve our understanding of the long-term deformation behavior of the peninsula and the potential risk for the densily populated areas in its proximity.

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