1. Introduction

Quaternary volcanic activity in the South Aegean Active Volcanic Arc (Figure 1), extends on an arcuate belt starting from Saronikos Gulf in the west, comprising the volcanic centres of Sousaki, Aegina, Methana and Poros, to Milos and Santorini at the centre, and the Kos-Nisyros group at the eastern end (Francalanci, Vougioukalakis, Perini, & Manetti, 2005; Pe-Piper & Piper, 2005). It is the result of the subduction and rapid rollback of the African plate beneath the Aegean microplate (Le Pichon & Angelier, 1979; McKenzie, 1978; Mercier, Sorel, Vergely, & Simeakis, 1989; Pe & Piper, 1972).

Volcanic centres have migrated southwards, from North Greece and Bulgaria (Eocene), through North Aegean (Oligocene–Early Miocene) and Central Aegean (Middle–Late Miocene) to the present day (Pliocene–Quaternary) South Aegean Active Volcanic Arc (Fytikas et al., 1984; Royden & Papandakou, 2011).

Several studies have been focused on volcanic rocks of the Methana peninsula, and the Plio-Quaternary facies of the onshore areas have been adequately described (D’Alessandro, Brusca, Kyriakopoulos, Michas, & Papadakis, 2008; Dietrich, Gaitanakis, Mercoli, & Oberhaensli, 1993; Dietrich, Mercoli, & Oberhaensli, 1988; Dotsika, Poutoukis, & Rac, 2010; Efstathiou, Tzanis, Challas, Lagios, & Stamatakis, 2012; Francalanci et al., 2005; Fytikas, Giuliani, Innocenti, Marinelli, & Mazzuoli, 1976; Fytikas, Innocenti, & Kolios, 1986; Gaitanakis & Dietrich, 1995; Georgalas, 1962; Pe, 1974; Pe-Piper & Piper, 2005, 2013). The Methana peninsula is composed mainly of Late Pliocene–Pleistocene, arc-related andesitic and dacitic volcanic rocks (Fytikas, 1988; Gaitanakis & Dietrich, 1995; Pe, 1974; Pe-Piper & Piper, 2005). Recently, eight volcanic phases (A to H) have been distinguished from Pe-Piper and Piper (2013). The most recent volcanic rocks were reported in Kammeni Hora (or Kameno Vouno), dated at 0.2 ± 0.3 Ma (Matsuda, Senoh, Maruoka, Sato, & Mitropoulos, 1999). A historic eruption producing andesitic lava was described by Strabo at about 230 BC. Post volcanic activity, as manifested by geothermal springs, has been spotted mainly at the eastern and the northern part of the Methana Peninsula (D’Alessandro et al., 2008). According to Pe-Piper and Piper (2013), Pliocene volcanism is mainly emplaced along N-S striking listric faults during E-W extension. The initiation of NE-SW crustal scale strike-slip faults in the early Pleistocene, related to the collision of the Aegean microplate with the Libyan promontory, is linked with explosive volcanism and the least evolved rocks on the Methana Peninsula. Thereafter, volcanism is controlled by E-W striking faults (Pe-Piper & Piper, 2013).

Offshore Methana peninsula knowledge is poor, as it is based on oceanographic missions of the mid-1980s.
(Nomikou, Papanikolaou, Alexandri, Sakellariou, & Rousakis, 2013; Papanikolaou et al., 1989; Pavlakis, Lykoussis, Papanikolaou, & Chronis, 1990). In 2009 and 2011, two oceanographic surveys were primarily focused at the offshore north–north-western part of the Methana peninsula (Figure 1) that displays the most active Upper Quaternary volcanism of the region. Submarine Pausanias Volcanic Field (SPVF) is located in Saronikos Gulf, NW from the Methana Peninsula (Foutrakis & Anastasakis, 2017, 2018), as part of the north-western end of the South Aegean Active Volcanic Arc. This area has been previously reported as Pausanias volcano (Pavlakis et al., 1990). The recovered samples are dacites and their geochemical characteristics show similarity with volcanic rocks from the Methana peninsula (Pavlakis et al., 1990). The region is near the junction of two different Plio-Quaternary tectonic domains within the Aegean plate. A zone of rapid N-S extension with seismically active faults and a zone of E-W extension that has predominated since Pliocene (Jolivet et al., 2013). Tectonic activity is expressed by ENE-WSW normal faults, whereas N-S, NNE-SSW and E-W striking normal faults are also observed (Hatzfeld, 1999; Papanikolaou et al., 1989; Pe-Piper & Piper, 2013). In the adjacent depocentre of Epidavros basin, the deepest region of Saronikos Gulf, more than 380 m (Foutrakis & Anastasakis, 2018) of unconsolidated Plio-Quaternary sediments have accumulated.

The main objective of this study is to provide the first detailed bathymetric map of the SPVF at 1:12,000 scale, through the analysis of high-resolution swath-bathymetric data and the extraction of a Digital Terrain Model (DTM). Moreover, the morphological analysis, with the integration of 2D seismic profiles, will allow to elucidate the sub-bottom outcropping

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**Figure 1.** Simplified map showing the South Aegean Active Volcanic Arc (modified from Pe-Piper & Piper, 2005). Red rectangle outlines Saronikos Gulf. Regional map of Saronikos Gulf (upper left inset) shows Sousaki and Aegina–Methana–Poros volcanic centers. Submarine Pausanias Volcanic Field is indicated by the arrow and the black box. The study area (upper right inset), tracklines for both multibeam and seismic lines (black) and the presented seismic profile (red) are also pointed out. Greek Geodetic Reference System 1987 (GGRS 87) and Transverse Mercator Projection (Greek Grid) is used here and elsewhere in the presented maps.
formations and understand the geological processes that formed the present morphology. Useful information on possibly geo-hazardous processes, taking place not far from densely populated areas, will be also provided.

2. Methods

Multibeam and 2D seismic data have been obtained aboard catamaran RV Oceanus in 2009 and 2010, during two oceanographic surveys in Saronikos Gulf. All the equipment used belongs to the Department of Historical Geology–Palaeontology of the National and Kapodistrian University of Athens.

All data have been geolocated using a Fugro SeaSTAR 8200 HP DGPS system with a SeaSTAR-XP service achieving position accuracy better than 10 cm. Multibeam and seismic profile tracklines are presented in Figure 1.

Swath-bathymetry has been acquired, in accordance with Order 1b of the IHO S44 standards for hydrographic surveys (IHO, 2008). According to these standards, the maximum allowable Total Horizontal Uncertainty is 5 m + 5% of depth, whereas the maximum allowable Total Vertical Uncertainty is \( \sqrt{0.5^2 + (0.013 \times \text{depth})^2} \). A SEABEAM 1180 swath system operating at 180 kHz in areas shallower than 250 m and a SEABEAM 1155 operating at 50 kHz, in waters deeper than 250 m has been used. Both multibeam systems were coupled with a GPS compass Hemisphere Crescent VS101 and a Seatex MRU 5 motion sensor was installed on the vessel. Full coverage of the study area has been achieved except from the nearshore part, shallower than 50 m, where swath-bathymetry is poor. Sound velocity profiles were collected with an Aquamatic-AQSV-1500 sensor. The dedicated software platform Hypack 6.1 has been used for the acquisition of swath-bathymetric data. Data processing was performed at the processing modules of the software, using manual despiking and statistical filtering, in order to minimize the noise component. An \((x, y, z)\) point file has been exported with an average number of 6 points within every 10 m cell. Full coverage has been achieved throughout the survey area, except the 0–50 m depth range as previously indicated. Horizontal accuracy is depth-related and ranges between 7.5 and 25 m (50–400 m depth) while vertical accuracy is 0.65–5 m (50–400 m depth), according to the equations for Order 1b of the IHO S44 standards (IHO, 2008).

Processed data were gridded, using the Inverse Distance Weight (IDW) algorithm, and a detailed 10 m resolution DTM has been created in ArcGIS Software (Figure 2 and Main Map). After using Focal Statistics to smooth the raster, contours have been extracted every 5 m using the relevant GIS tool. In the coastal part (0–50 m), the bathymetric uncertainty is high due to reduced multibeam coverage. A hillshade (Main Map) and a slope distribution map of the study area were computed from the DTM (Figure 3). The slope gradient (Figure 3), which corresponds to the modulus of the first derivative of the sea-bottom surface, has been used in order to manually trace the boundaries of the distinctive volcanic outcrops.

Seismic reflection profiles (2D) were obtained through both channels of a Benthos CAP-6000 platform, using the Chirp II TTV-190 Benthos – Datasonics system operating at 2–7 KHz and the Sparker SIG-2mille. Trigger rate was ranging from 250 ms to 1 s (Figure 1). Processing and interpretation of seismic profiles have been done on Coda Octopus Survey Engine Seismic+ software. A sound velocity of 1520 m/s was used for the water column and 1650 m/s was assumed for the sub-bottom unconsolidated sediments.

3. Results

3.1. Bathymetric map of the SPVF

The DTM of the study area is reported as a color shaded relief map (Figure 2 and Main Map) and along with its first order derivative (Figure 3) revealed a field of six volcanic outcrops, the SPVF, having a sea-floor coverage of about 12 km² and displaying various geomorphological characteristics.

3.2. Bathy-morphological characteristics

The most complex and extensive volcanic outcrop is the VO1 (Figure 3), which rises from 380 to 154 m depth (Figure 2), with a basal perimeter of about 8.7 km. It covers an area of 4.6 km² and has an approximate volume of 0.35 km³. It is NE-SW oriented, with a major axis of 3.2 km and a minor axis of 1.6 km. Its height/width ratio is 0.07–0.14. Alternating, gullies and elongated ridges are aligned along NNE-SSW and E-W directions in its north–north-eastern and western flanks (Figure 3). Slope values are ranging between 5° and 45° (Figure 3), while the south and southeast flanks of VO1 are characterized by high gradients (>20°) with short gullies developed especially at its southern flank.

VO2 is also a complex volcanic outcrop (Figure 3), 2.2 km long and 1.2 km wide, rising from 310 to 150 m depth (Figure 2) that covers an area of about 2.3 km², with a periphery of 6.8 km. The height/width ratio is 0.07–0.13. NNE-SSW trending ridges and gullies are developed in the northern flank which is elongated northwards, with slope values between 5° and 45° (Figure 3). The west, south and east flanks generally show higher slope values (>20°) with shorter gullies.
A smaller volcanic outcrop (Figure 3), VO3, is formed 600 m north of the north-western coast of the Methana peninsula. VO3 rises from 280 to 62 m depth (Figure 2), with a basal circumference of 3.8 km and an elongated shape, 1.3 km long and 0.8 km wide, extending NE-SW. It covers about 1 km² and its height/width ratio is 0.17–0.27. VO3 is characterized by very steep flanks (>20°) at the perimeter and a hummocky terrace on top (Figure 3). VO4 is a steep (>20°) cone (Figure 3), protruding from 260 to 132 m (Figure 2), with a rounded perimeter of 2.5 km covering 0.4 km² approximately, a diameter of 0.9 km and a height/width ratio of 0.14. Further westwards, VO5 is another steep (>20°) cone (Figure 3), that rises from 320 to 190 m depth (Figure 2), having a basal circumference of 3 km, developed over an area of about 0.65 km². Its diameter is 1 km and the height/width ratio is 0.13. VO6 is a smaller very steep (>20°) cone to the southwest (Figure 3), protruding from 360 to 218 m depth (Figure 2), with a periphery of about 2 km, covering an area of 0.3 km². Its diameter is 0.8 km and the height/width ratio is 0.18. At the periphery of the outcrops (Figure 3), low slope values (<5°) are observed with the exception of the northern boundary of the Methana Peninsula where high gradients (>20°) are encountered. Steep slopes are also noticeable along the E-W ridge that is protruding westwards the north-western part of the Methana Peninsula.

### 3.3. Sub-bottom facies

The seismic profile presented in Figure 4 illustrates the overall sub-bottom characteristics of the SPVF. The profile crosses the eastern and southern flanks of VO1 as well as the main parts of VO2, VO3, VO4 and VO6. The southern flank of VO5 is also recognized (Figure 4). Volcanic facies generally present chaotic configurations and dome-shaped external geometries marked by strong diffractions and numerous high amplitude hyperbolas, especially in the upper part of the cones. Deeper sub-bottom reflectors are weakened gradually and pass into reflection free zone (Figure 4). Basinwards, at the surrounding perimeter of the SPVF...
l laterally continuous, parallel reflectors with amplitude and frequency ranging from medium to high are developed. These reflectors are interpreted as unconsolidated sedimentary facies.

3.4. Volcanic outcrop intercomparison

Volcanic outcrops VO1 and VO2 show similar characteristics with complex morphologies, low height/width ratio (0.07–0.14) and the development of gullies alternating with ridges especially at their flanks. This degraded morphology possibly suggests an earlier volcanic emplacement. These outcrops show similar morphological characteristics with the onshore volcanic equivalents of the Methana peninsula, especially the dome-like eroded north-western dacitic volcanoes (Figure 4) that have been attributed to Phase E and dated at 0.6 ± 2 Ma by Pe-Piper and Piper (2013).

Volcanic outcrops VO3–VO6 display comparable sub-cone-shaped morphology with higher height/width ratio (0.13–0.27) and very steep flanks. They display cone-shaped summits, with the exception of VO3 that presents flat-bedded terraces (Figure 4). The absence of extended erosional features at their flanks indicates younger age development. The morphological alignment along an E-W direction and their similarity to the onshore fissure volcanoes of the Methana Peninsula lead us to correlate all VO3–VO6 outcrops to Phase G (Figure 4) land equivalents documented by Pe-Piper and Piper (2013), with an assigned age of 0.32 Ma (Fytikas et al., 1976). The flat-bedded terrace developed on VO3 at 150 ms most likely is the effect of wave erosion during Late Quaternary sea level lowstands, possibly during Marine Isotopic Stages 2 and 6 as this is implied by the recognized prograding clinoforms (Figure 4). The terrace recognized at 100 ms (Figure 4) may represent the Younger Dryas sea level still stand. VO3 proximity to the domes of Mavri Petra Complex on the Methana Peninsula could associate its formation to Late Pleistocene to Holocene volcanic events, coinciding with Phase H (Figure 4) of Pe-Piper and Piper (2013).
4. Conclusions

This paper describes the main bathy-morphological characteristics of the SPVF, presented in a new high-resolution bathymetric map. Six major volcanic outcrops, VO1–VO6, extending across an area of 12 km² have been mapped. VO1 and VO2 show complex mature morphologies attributed to their evolved volcanic emplacement. VO3–VO6 outcrops are presumably younger, morphologically simpler cones. SPVF show similarities to the onshore volcanic centres of the Methana Peninsula and covers an area, much more extensive and considerably closer to the onshore known equivalents, than previously thought. No obvious evidence of destabilization and flank failure/gravity flows has been observed on the steep slopes, as a result of the active tectonic regime. This is probably due to the relatively small elevation and volume of the mapped volcanic outcrops that did not promote mass flow phenomena.

Geolocation information

Northwest of the Methana Peninsula (37.64° N, 23.30° E), Saronikos Gulf, Greece.

Software

Hypack 6.1 was used to process the multibeam data, while Coda Octopus Survey Engine+ 4.3.3 was used for the processing of seismic profiles. ESRI ArcGIS 10 and QGIS 2.18 have been used for the generation of the DTM and all the derived maps. The final editing of the presented images and the Main Map has been done in Inkscape 0.92.

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