SCIENCE

Geology of Ammouliani Island (Northern Greece) – implications for the tectono-magmatic evolution of the Serbo-Macedonian Massif

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Ammouliani Island is located in Northern Greece with its exposed rocks belonging to the Serbo-Macedonian Massif of the Hellenic hinterland. Its geology is of great importance because it lies in an area where a striking change in trend of the orogenic fabric from NW-SE to ENE-WSW occurs. For this purpose, a geological map at a scale of 1:10,000 is presented based upon detailed fieldwork and the interpretation of satellite imagery. In addition, special interest has been paid to the tectonic elements of the map units. This detailed mapping results in the definition of a new unit, the Ammouliani Unit, which is placed between the underlying Kerdilion and the overlying Vertiskos Unit of the Serbo-Macedonian Massif. The main features of the Ammouliani Unit are the predominance of leucosomes and the intense migmatization and strong shearing. Three main folding events (F1, F2 and F3) have been defined in the exposed rocks of the island with the first related to intense migmatization and shearing, whereas the last two are progressive to each other and are related to Mesozoic orogenic processes. In addition, NE-ENE striking shear zones were observed with the Ammouliani granite placed parallel to these. The bending of the orogenic fabric from NW-SE to ENE-WSW is younger than the F2 and F3 folding events and is related to Tertiary orogenic (tectono-magmatic) processes due to the convergence between Apulia and Eurasia and the ongoing retreat of the Hellenic subduction zone.

Keywords: internal Hellenides; Hellenic hinterland; ductile deformation; Chalkidiki

1. Introduction

Ammouliani Island is a small island of about 4.5 km² that is located in Northern Greece, approximately 130 km east of the city of Thessaloniki. The island lies in the inner part of Siggitikos Gulf, between the Sithonia and Athos peninsulas of Chalkidiki. It consists of crystalline rocks that belong to the Serbo-Macedonian Massif (SMM) and it is a part of the hinterland of the Hellenic orogen. The latter was formed from Tertiary Alpine orogenic processes due to the convergence between Apulia and Eurasia plates at the onset of their collision in the Eocene. Recently, an evolutionary model about the hinterland from the Tertiary to the present day has been proposed by Tranos and Lacombe (2014). The SMM trending NW-SE covers the eastern Central Macedonia and Chalkidiki peninsula from the Greek borders in the north to the North Aegean Sea in the south. The western boundary of the SMM is the NW-SE trending fold-and-thrust belt named
Circum-Rhodope Belt Thrust System (CRBTS) (Tranos, Kilias, & Mountrakis, 1999), whereas to the east it tectonically overlies the Rhodope Massif (RhM) along the Strymon Lineament (‘Strimonlinie’ of Kockel & Walther, 1965).

The SMM consists of Paleozoic or older in age meta-sedimentary rocks that have experienced poly-metamorphism and poly-deformation and which have been placed into two units (Kockel, Mollat, & Walther, 1977). The upper Vertiskos Unit that covers the center and west of the SMM and the lower Kerdilion Unit that exposes in the east and SE parts of Chalkidiki peninsula. The Vertiskos Unit is characterized by relatively lower-grade metamorphic rocks than the rocks of Kerdilion Unit and mainly consists of two-mica gneisses, muscovite gneisses, muscovite-garnet gneisses, staurolite- kyanite-garnet gneisses and augen gneisses. The Kerdilion Unit consists of fine- to medium-grained biotite gneisses, biotite-hornblende gneisses, amphibolites and marbles (Sakellariou, 1989, 1993).

The distinction of the SMM in units and the nature of the contacts between these units has recently been an important research subject. Among these efforts are those of Burg, Godfriaux, and Ricou (1995), Himmerkus, Reischmann, and Kostopoulos (2006), and Burg (2012) which made different or new groupings for several rocks in the region covered by the SMM. They also tried to unify several of these rocks with those of the RhM. Kockel et al. (1977), who undertook basic mapping of the SMM in the central part of Macedonia and Chalkidiki mapped the contact between the Kerdilion and Vertiskos Units as a normal contact (i.e., ‘geological boundary’). In contrast, Sakellariou (1989) and Sakellariou and Dürr (1993) argue that it is a tectonic contact reporting that the upper marble horizon of the Kerdilion Unit (named by them as ‘Upper Marble Shear Zone’) comes in to contact with different lithologies of the Vertiskos Unit and is actually an ultra-mylonite thus showing intense shearing. On the other hand, Dinter (1998) and Brun and Sokoutis (2007) considered this boundary as a Tertiary extensional detachment or shear zone, respectively.

Another important feature of the SMM is the large igneous rock bodies that intruded both its units. Kockel et al. (1977) have described four magmatic events, although a more complicated magmatic history is implied based on zircon analysis (see Himmerkus, Reischmann, & Kostopoulos, 2009, 2011). The first magmatic event is a basic-ultrabasic one of Paleozoic (i.e., pre-alpine) age. The second event was also constrained as Paleozoic and was attributed to the Hercynian orogeny giving rise to extensive granitic rocks that have been metamorphosed to plagioclase-microcline gneisses. The third magmatic event gave rise to large granitoids, such as Arnea, Flamouri and Monopigadon, have been dated to Jurassic times (De Wet, Miller, Bickle, & Chapman, 1989) or \(\sim 240\) Ma (Himmmkerus et al., 2009). The last magmatic event dated in Eocene and Early Oligocene times is also acid giving rise to large granitoid bodies such as those of Sithonia, Ouranoupolis, Gregoriou, Ierissos, and Straton and this magmatism is related with Tertiary orogenic processes due to the Apulia-Eurasia convergence (Pe-Piper & Piper, 2002; Tranos & Lacombe, 2014).

Apart from the problem concerning the units, the rocks and their contacts, the intriguing issue is that the orogenic fabric of the SMM, as delineated by the rock contacts and foliation trajectories, changes in trend from NW-SE to ENE-WSW in the south-eastern part of the Chalkidiki peninsula (i.e., the part where the Sithonia and Athos peninsulas come in contact).

Geologically speaking, the island of Ammouliani is very important because (a) it lies in the region where the above-mentioned change or bending of the orogenic fabric occurs, (b) the rocks of the island belonging to the Vertiskos and Kerdilion Units (Kockel et al., 1977; Kockel, Mollat, & Antoniadis, 1978) provide the opportunity for the examination of the contact between these units, and (c) large granitic bodies are exposed in the island intruding the crystalline rocks of the Vertiskos and Kerdilion Units. In addition, no detailed geological map exists so far, apart from basic geological maps at 1:100,000 scale (Kockel et al., 1977).
and the Ierissos sheet at 1:50,000 scale (Kockel et al., 1978) which show significant differences in the grouping of the exposed rocks either into the Vertiskos or Kerdilion Units.

2. Methodology
Geological mapping of the Ammouliani Island was performed at 1:5000 scale (HMGS, 1983). Although, the low relief of the island is ideal for geological mapping, several areas are poorly accessible due to the highly dense bush-type vegetation.

Field mapping was also based on the interpretation of Landsat 7 imagery (http://onearth.jpl.nasa.gov/) and those available through Google Earth. Satellite images, topographic maps at scale 1:5000 and previous geological maps were input as different layers into a geographic information system (GIS) software and were registered to the Greek Grid 87 projection. For the spatial analysis of our data, including those derived from our field mapping and satellite interpretation or previous geological maps, we used digital processing within a GIS. Final map production was performed using graphic design software at a scale of 1:10,000. The reason for using graphic design software is the rich selection of design tools which allow the artistic design of a scientific document.

The geological map of Ammouliani Island also includes: (a) a tectonostratigraphic column and geological cross-sections that were based on field observations, (b) reference maps and information about the coordinate system. More importantly, it includes field photographs and tectonic diagrams of the main structural elements of the rocks in order for someone to be able to better understand the ductile deformation of the island. In particular, a large amount of structural data that were analyzed and plotted using equal-area, lower hemisphere diagrams, provided for the metamorphic rocks with the orientation of the S1 and S2 foliations, lineation (L), F2, F3a and F3b folds, and (for the exposed granite) the granite foliation (FL).

3. Geological map description
Based on our detailed geological mapping, the constructed geological cross sections as well as information from previously published maps we grouped the mapped rocks into three different units. In addition, several thin sections were prepared and examined in order to better determine the mineral composition, texture and deformation of the mapped rocks. The lower unit is the Kerdilion Unit that mainly consists of amphibolites, biotite gneisses and marbles the age of which is considered Paleozoic or older (Himmerkus et al., 2006; Kockel et al., 1977; Sakellariou, 1989). In other parts of the Chalkidiki peninsula, this unit also includes migmatitic gneisses indicating some of migmatization processes (Dimitriadis, 1974). The exposed rocks of the Kerdilion Unit are tectonically overlain by leucocratic rocks which are characterized by a strong migmatization and shearing such as quartzofeldspathic gneisses and anatexites-granitic gneisses. Due to this intense migmatization and shearing the latter rocks were separately grouped in a new unit called the Ammouliani Unit. Above the rocks of the Ammouliani Unit, tectonically monotonous brown colored gneissic rock are placed that show no field evidence for the migmatization processes. These rocks have been grouped in the Vertiskos Unit. Finally, (a) Mesozoic (?) acid intrusions metamorphosed in plagioclase-microcline gneisses, and (b) Tertiary granites intruded into the previous mapping units but without presenting analogous intense deformation.

Several exposures of small thin marbles have also been mapped in the island. They were in contact with the rocks of the Kerdilion Unit, but the most peculiar were those exposed as small lense-shape bodies either within the plagioclase-microcline gneisses or in contact both with the plagioclase-microcline gneisses and the two mica gneisses of the Vertiskos Unit. The size and contacts of the latter could not be precisely defined in the field due to the intense
vegetation. It is interesting to note that thin lenses and layers of marbles have been mapped within the two-mica gneisses of the Vertiskos Unit in the area of Gomati-Develiki (an area of northern Ammouliani Island, SW of Ierissos granite (IG)). These marbles have been placed either in the Kerdilion Unit (Kockel et al., 1977) or in the Vertiskos Unit (Kockel et al., 1978). Further north, in the area south of Volvi Lake, metasediments such as marbles in alternation with graphitic-garnet gneisses metamorphosed under medium-grade conditions have been mapped in the new Nea Madytos Unit by Sakellariou (1989). Himmerkus et al. (2006) included all the above-mentioned exposures and their surrounding rocks in the Athos-Volvi-Gomati melange zone that lies between the Vertiskos and Kerdilion Units. The Nea Madytos Unit has probably suffered a pre-Mesozoic amphibolite facies metamorphism and an Early Cretaceous greenschist facies metamorphism (Papadopoulos, 1982). The most striking feature of these marbles and their surrounding rocks that are mainly two mica gneisses is that they are very strongly folded with tight to isoclinal folds (Sakellariou, 1989; present work). Obviously, the above statements show how hard is to explain in a robust way the real origin of these marbles.

3.1. Geological units and their contact relationship
The mapped rocks will be described from deeper to the higher levels as follows:

3.1.1. Kerdilion unit
Amphibolite – Hornblende gneisses (amph): These rocks are exposed in the central part of the island along with the biotite gneisses. They are fine-grained, green to dark green colored rocks with fibroblastic fabric that at places indicate features of fine-banding. They consist of hornblende, plagioclase, epidote, zoisite, quartz, garnet, rutile with titanite, biotite, apatite and chlorite.

Biotite gneisses (bign): These rocks are exposed in the central part of the island along with the previously described rocks. In particular, they have been found in places to form interbeds with the hornblende gneisses, and to pass out toward biotite-hornblende gneissic lithologies. They are dark gray to dark brown gneisses with lepidoblastic, but in a few cases granoblastic fabric, that are characterized by the paragenesis of quartz, plagioclase, biotite, epidote, garnet, apatite, feldspars and zircon.

Marbles (mr): They are exposed in the central part of the island forming tabular or lenticular interbeds of chartographic map of width up to 50 m with the amphibolite-hornblende gneisses and biotite gneisses. The marbles are medium- to coarse-grained and of white to bluish white color. Their fabric is granoblastic, but without any noticeable internal structure.

3.1.2. Ammouliani unit
In our map, the new Ammouliani Unit has been discriminated and separated from the underlying Kerdilion and overlying Vertiskos Units. The reason for this was that it is characterized by an extensive migmatization-anatexis and intense shearing. More importantly, the rocks grouped in the Ammouliani Unit are predominantly leucocratic and in them the leucosome-melanosome ratio is about 4:1 or 80%–20%. On the contrary, the rocks of the Kerdilion Unit although are also characterized by migmatization, they do not show such an intense shearing and their rocks are predominantly melanocratic with the leucosome-melanosome ratio less than ~1:4 or 20%–80%.

Quartzofeldspathic gneisses (qgn): These rocks are exposed at the northernmost part of Ammouliani Island. Their milky white to light gray colors are related to the relative abundance of quartz and feldspar minerals. Other minerals are muscovite, biotite and garnet. The latter
mineral is sporadically observed in layers the width of which varies from several centimeters up to several decimeters. In places, the quartzofeldspathic gneisses pass into augen gneisses, where they are impregnated with many quartz veins the thickness of which ranges from several centimeters up to two meters. The quartz veins as rule run parallel to the foliation and are intensely deformed forming pinch and swell structures. In places, the quartzofeldspathic gneisses along with biotite gneisses form distinct bands, similar to those formed by a leucosome-melanosome extensive zonal migmatization due to a widespread anatexis. This migmatization is associated with strong shearing that caused a penetrative mylonitic fabric in the exposed rocks.

Anatexites – Granitic gneisses (grgn): These rocks are found in the central-northern part of the island in contact with the quartzofeldspathic gneisses. They are whitish gray to light gray colored granitic gneisses and pegmatoids that, in several places, are characterized by anatectic phenomena forming migmatitic layering along with dark gray biotite granites to biotite gneisses. Their fabric is granoblastic to lepidogranoblastic formed by minerals such as quartz, feldspar, ± muscovite and ± biotite.

3.1.3. Vertiskos unit

Two-mica gneisses (gn2): These rocks are exposed in the central and western part of the island. They are medium-grained monotonous gneisses of brown to light brown color with lepidoblastic fabric and mineralogy that consists of muscovite, biotite, quartz and feldspars.

3.1.4. Igneous rocks

Plagioclase-microcline gneisses (lgn): These rocks are metamorphosed acid magmatic rocks that are exposed in the central part of the island and are of pinkish beige to pinkish white color. Their fabric is lepido- to granoblastic and their mineral constituents that dominate the fabric, apart from the feldspars (microcline and plagioclases), are quartz, muscovite, allanite, sericite, epidote (zoisite-clinozoisite), apatite and zircon. These rocks form sharp contacts without any distinct contact aureole phenomena. They are ambiguously constrained in the Paleozoic by Kockel et al. (1977), but also have similarities with the Mesozoic Arnea granite that was dated to the Jurassic (De Wet et al., 1989) or Triassic (Himmerkus et al., 2009).

Granite (gr): A medium- to coarse-grained granite, the Ammouliani granite, that occupies the southeastern part of the island. It consists of quartz, feldspars, biotite and muscovite. Pegmatite and quartz veins transect the main body. It is considered part of the larger Eocene Ouranoupolis granitoid, with the latter is closely exposed as a large batholith on the Athos peninsula (Kockel et al., 1977; Kilias, Falalakis, & Mountrakis, 1999). Both are possibly connected at depth with other Tertiary granitoids of the SMM such as the Sithonia and Gregoriou granitoids (Tranos, Kilias, & Mountrakis, 1993). We have not observed any contact phenomena. In the country rocks and up to 10 s m away from the contact, leuco-sheets from the granite with thickness of decimeters intrude as sills parallel to the envelope foliation implying the concordant emplacement of the Ammouliani granite. The foliation of the country rocks is intensely flattened and sheared, but this is not observed in the granite.

4. Structural elements

In the field, a main foliation (S1) characterizes the exposed crystalline rocks that strike from ENE-WSW to WNW-ESE. In migmatitic rocks, the S1 foliation occurs as banding or stromatic layering parallel to gneissic foliation that separates the leucosomes from the melanosomes. Within this foliation relict rootless intrafolial folds (F1) are indexes of a strong transposition of a previous
The planes of the S1 foliation show two maximum concentrations at (a) dipD-dipA = 192°–65° and (b) dipD-dipA = 342°–80° which correspond to the limbs of isoclinal upright map-scale folds (F2) whose fold axes plunge at approximately 30° towards WSW (265°). In the hinges of several F2 folds an almost vertical axial foliation (S2) has been observed to strike E-W. In addition, a stretching lineation (L) recorded on the foliation of the crystalline rocks plunges at approximately 40° toward WNW (pl-plA = 252°–38°), i.e., as the fold axes do. In several places the main S1 foliation dipping either to the S or to the N is folded by smaller in size F3 folds that have short limbs up to 1 m long. These F3 folds plunge at medium angles (≏50°–60°), i.e., at higher plunge angles than those of the F2 axes and their axial planes dip at high angles to NW-NNW (dipD-dipA = 325°–70°). It seems that the overall folding in this internal part of the orogen consisting of the E-W trending F2 upright folds and the NE-SW to ENE-WSW trending F3 folds could be interpreted as the result of a progressive folding deformation and rotation of the contemporary fold axes in a way similar with that suggested by Alsop (1992) for north-west Ireland. Similar map-scale folds with the F2 ones have been reported more northwards (in the mainland of the Chalkidiki peninsula) to trend NW-SE and to outline the orogenic fabric. These folds have been also attributed to Mesozoic orogenic processes (Patras, Killias, Chatzidimitriadis and Mountrakis, 1988; Sakellariou, 1989, 1993; Sakellariou & Dürr, 1993).

In addition, some E-W to ENE-WSW trending highly dipping to vertical shear zones of several meters width, that are associated with a mylonitic foliation (Sm) and a left-lateral oblique strike-slip displacements, have been mapped close to some of the contacts between the different map units. NNE-SSW to NE-SW trending, vertical or steeply dipping, left-lateral strike-slip shear zones have been reported to affect both the Eocene Sithonia granitoid (Tranos, 1998; Tranos et al., 1993) and the Gregoriou granitoid in the southernmost part of the Athos peninsula (Georgiadis, Tranos, & Mountrakis, 2007). The ductile deformation of the Tertiary magmatic bodies is also reported by Sakellariou (1993). These shear zones are bracketed in age between the Latest Eocene and the Late Oligocene and have been attributed to a transpressional event driven by the Apulia and Eurasia collisional to late-collisional processes (Georgiadis et al., 2007; Tranos, 1998).

The Ammouliani granite presents at places a week foliation that dips at high angles to the NNW (dipD-dipA = 338°–70°), i.e., parallel to the mylonitic foliation of the envelope. The fact that intense shearing and flattening is observed in the country rocks close to the contact, but not in the granite or its intrusive sills implies that the shearing and flattening of the envelope outlasted the emplacement of the granite.

5. Discussion and conclusions
Detailed geological mapping of Ammouliani Island has allowed us to propose a new unit, the Ammouliani Unit, for the SMM. It is characterized by intense shearing and migmatization and it is placed between the underlying Kerdilion Unit and the overlying Vertiskos Unit of the SMM. Since the Vertiskos and Kerdilion units consists of meta-sediments that are dated as Paleozoic or older, the migmatization and shearing of the Ammouliani Unit, probably in association with the F1 folding is constrained after that age and before both the intrusion of the leucogneisses (lgn) and the F2 folding. A critical issue that needs further research is the precise dating of the leucogneisses to better constrain the deformational events.

The F2 and F3 folding events are progressive ones. The F2 folds are the map-scale folds that either trend NW-SE or E-W in the SMM and are related with the Mesozoic orogenic processes. The latest ductile and semi-ductile deformation of the island outlasted the Eocene Ammouliani granite. It also fits well with the ENE-WSW bending of the orogenic fabric of the
SMM that folds the F2 and F3 folds and is accommodated by the steeply dipping shear zones. This deformation is attributed to the Tertiary tectono-magmatic processes due to the convergence between the Apulia and Eurasia plates and the ongoing retreat of the Hellenic subduction zone to its present day position. In particular, we attribute this bending to the stage of Tertiary escape tectonics that compensated the late-orogenic processes driven by the collision of the Apulia and Eurasia plates as described by Tranos and Lacombe (2014) because such large strike-slip shear zones (e.g., Georgiadis et al., 2007; Tranos, 2009, 2011; Tranos & Lacombe, 2014; Tranos et al., 1999, 2008) and block rotations (Atzemoglou, Kondopoulou, Papamarinopoulos, & Dimitriadis, 1994; Kondopoulou & Westphal, 1986) have been reported in the broader Chalkidiki and Central Macedonia area from the Eocene onwards.

Based on our mapping and the deformation events we have defined, as well as the review of previously published maps, we interpret the peculiar lense-shape exposures of the marbles within the Vertiskos Unit, Ammouliani Island, and the region of Gomati-Develiki to have their origin to the marbles of the Kerdilion Unit. More precisely, the uppermost part of the marbles of the Kerdilion Unit that was in contact with the overlying Vertiskos Unit after isoclinal folding (F1), shearing and transposition that suffered along with the overlying Vertiskos Unit was mainly transposed towards the thin, elongate hinge zones of the isoclinal folds (F1). Eventually, some of these elongate hinge zones were cut off from the main marble body because of the continuous transposition and shearing during the F1 deformational event and also because of the next isoclinal folding (F2). As a result, these marbles are now exposed as thin lense-shape tectonic

![Figure 1](image)

**Figure 1.** Schematic drawings showing, in evolutionary interpretative stages, the Kerdilion marble exposures as tectonic bodies in the two mica gneisses of the Vertiskos Unit. (a) Initial stage of ductile shearing, transposition and shearing of the Vertiskos Unit over the Kerdilion Unit, (b) Formation of isoclinal folds (F1) with the marble material transposed towards the hinge zones of the antiforms, (c) Cut off of the hinge zones of the elongate antiforms due to progressive transposition and shearing between the underlying Kerdilion Unit and the overlying Vertiskos Unit, (d) Progressive folding (F1) (or refolding F2) of the detached hinge zones with the occurrence of elongate lenses of Kerdilion marbles as tectonic bodies in the rocks of the Vertiskos Unit. Explanation: KU: Kerdilion Unit, VU: Vertiskos Unit, gn2: two mica gneiss, mr: marble, bign: biotite gneiss. The one side directed arrow indicates the relative tectonic transport of crustal material.
bodies within the two-mica gneisses of the Vertiskos Unit as shown schematically in Figure 1. This explanation requires the Vertiskos Unit to come into tectonic contact with the underlying Kerdilion Unit during the F1 deformational event and the upper Kerdilion marbles to be very highly strained and to come into contact with different lithological units of the Vertiskos Unit.

Software
Esri ArcGIS and CorelDraw were used for the production of the geological data and their presentation along with data from existing geological maps. In addition, the stereographic projection stereonet diagrams were constructed using StereoNet (Duyester, 1999) and Stereo32 (Röller & Trepmann, 2003).

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