Geomorphology of the Pieria Mtns, Northern Greece

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1. Introduction

Landscapes continually evolve and processes such as deposition, erosion and tectonics have a major influence in shaping them (Tucker & Hancock, 2010). Geomorphological mapping is an important tool for both long-term and short-term landscape reconstruction (Karymbalis, Papanastassiou, Gaki-Papanastassiou, Tsanakas, & Maroukian, 2013) and an indispensable technique for geomorphological studies (Karymbalis, Gaki-Papanastassiou, Tsanakas, & Ferentinou, 2016). The present study is an attempt to comprehend and interpret the geomorphological factors that contributed to the landscape formation and evolution of the broader area of Pieria Mtns in Northern Greece.

2. Study area

The study area is a geographical region where different geomorphic environments meet. It is bounded by Aliakmonas river to the West and North, by Mount Olympus to the South and by the western coast of Thermaikos Gulf to the East. It covers an area of approximately 1600 km², which is drained by numerous well developed ephemeral streams having an almost W–E direction of flow, draining into the Gulf of Thermaikos (Figure 1). The relief is divided mainly into three units according to their topography, geology and age. The first unit (A) comprises the Pieria Mtns (2913 m) and part of Mount Olympus (2918 m) and covers almost 40% of the study area. The second unit (B), is a hilly terrain with elevations not exceeding 500 m covering almost another 40% of the study area, and finally, the third unit (C – 20% of the study area), does not exceed 200 m in elevation at its southernmost part, and extends eastwards from unit B to the western coast of Thermaikos Gulf.

In terms of Geology (Figure 2), Pieria Mtns. and Mount Olympus consists of Pre Alpine volcano-sedimentary, metamorphic and igneous rocks along with the contact of the Pelagonian and Almopia geotectonic zones (Mountarakis, 1985). The lowland part extends from Pieria Mtns., eastwards to Thermaikos Gulf and it consists of 1000–1500 m thick Neogene and Quaternary formations. The latter are specifically, undivided Neogene lacustrine formations, Mio-Pliocene marine, lacustrine and deltaic formations, Pleistocene lacustrine and continental deposits and Holocene alluvial and coastal sediments (Sylvestrou, 2002).

The study area has been affected by tectonic activity by ‘en echelon’ faults located at the WSW boundaries, while normal NE–SW dislocation faults have affected the area southwards of Moschopotamos (Papachristou, Arvanitis, & Kolios, 2017). Normal faults at the northeastern part of the area, follow NE–SW, ENE–WSW, NW–SE and E–W directions. Moreover, Quaternary formations at Makrigyalos area have been dislocated by NE–SW and NNE–SSE faults (Sylvestrou, 2002), while Faugères (1977) identified a NE–SW normal fault at Methoni area that has affected the Quaternary sediment layers during the Holocene.

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ABSTRACT
The present study is an attempt to comprehend and interpret the geomorphological factors that contributed to the landscape formation and evolution of the broader area of Pieria Mtns in Northern Greece. Detailed geomorphological mapping was performed utilizing both automated GIS oriented and traditional geomorphological techniques. In order to scientifically determine the formation and evolution of present day landscape, topography, geology, tectonics and climatic status were taken into consideration. The broader area of Pieria Mtns is a landscape with heterogeneous geomorphological environments. The geomorphological formation and evolution is the result of primarily active tectonics, and exogenic processes from Lower Miocene until present. The combined methodology of GIS oriented and traditional geomorphological mapping was proved to be scientifically accurate although time consuming. Detailed field work was considered mandatory in order to validate the GIS derivatives, and interpret the genesis of the landforms.

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Figure 1. Location map of the study area depicting landscape units A, B and C categorized according to the topography, geology and age.

Figure 2. Lithological map of the broader Pieria Mtns. Late Miocene river courses of Former Aliakmonas River are indicated with green and blue dashed arrows.
No site-specific climatic data are available for the study area, and therefore the statistics for the Katerini weather station (located at N 40° 15.426’ and E 22° 29.745’ elev.: 37 m) were used to describe the climate. Katerini has a long term average annual rainfall of 592.6 mm occurring mainly between November and February. On average, the maximum summer temperature in the area is recorded in July (29.3°C) and the minimum in January (~1.2°C). In general, the cold, wet winters and hot, dry summers with an average temperature of 12.9°C imply a typical Mediterranean climate (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006).

Thermaikos Gulf is a microtidal marine environment with semi-diurnal constituents $M_2$ and $S_2$ rarely exceeding 10 and 7 cm and major diurnal tidal constituents ($K_1$ and $S_1$) of small amplitudes 2.7 and 1.7 cm, respectively (Tsimplis, Proctor, & Flather, 1995). Surface water circulation over the inner shelf of the Thermaikos Gulf is mainly influenced by the prevailing wind conditions (Poulos, Chronis, Collins, and Lykousis (2000)). Water moves to the South along the western coastline of the Gulf under N–NW winds, as opposed to the S–SW winds that drive the circulation in the opposite direction (Ganoulis, 1987). During the presence of a persistent northerly wind, general surficial flow throughout the whole embayment is towards the South (Poulos et al., 2000). Wave activity is strongly influenced by the wind regime. High waves of long wavelength are originating from southerly directions as they are associated to the most important in terms of magnitude southerly winds and the longest fetches (~170 km), respectively (Poulos et al., 2000).

3. Data and methods

Geomorphological maps serve as integral tools of geosciences, supporting more effective geomorphological studies (Smith, Paron, & Griffiths, 2011). Hence, the geomorphological mapping of the compounded in terms of landscape and geology Pieria Mtns area, was considered mandatory, in order to better decode the complexity of processes that formed the present day relief.

The geomorphological study of the broader Pieria Mtns was performed at various scales (1:250.000, 1:50.000 and 1:5:000) applying both GIS oriented, and traditional field geomorphological techniques. Field survey was carried out during the time period between January 2009 and September 2016.

The analog data that was used during the geomorphological mapping include:

- Topographic maps obtained from the Hellenic Military Geographical Service (HMGS) at scales: 1:250.000 sheet Thessaloniki (HMGS, 1971)
- 1:50.000 sheets Alexandria, Katerini, Kolindros, Kontariotissa, Litohoro, Livadi, Plati, Velvendos (HMGS, 1983)
- 1:5.000 Sheets 430301-08, 431301-08, 431401-08, 432301-08, 433301-08 (HMGS, 1979)

Geological maps obtained from the Institute of Geology and Mineral Exploration of Greece at a scale of 1:50.000, sheets Alexandrea, Katerini, Kolindros, Kontariotissa, Litohoro, Livadi, Plati, Velvendos (IGME, 1987).

One series of vertical, single lens aerial photographs in selected locations (scale 1:42,000) taken in 1945, obtained from the Hellenic Military Geographical Service (HMGS, 1945).

The digital data include:

- Google Earth imagery: Google earth V 7.1.2.2041. (10/7/2013). Katerini, Digital Globe 2014. http://www.earth.google.com [15 January 2014].
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model Version 2 (GDEM V2), METI – NASA, October 2011, (cell size 30 m).
- SRTM 90 m Digital Elevation Data (Ver. 4), CGIAR Consortium for Spatial Information, August 2008.

Geomorphological mapping of this region was mainly based on GIS analysis, but also combined with traditional field geomorphological mapping techniques. This combined methodology is preferred in the literature in order to eliminate disadvantages of fully automated or fully traditional mapping techniques (Miccadei, Orrù, Piacentini, Mascioli, & Puliga, 2012; Perego, Zerboni, & Cremaschi, 2011; Zerboni, Perego, & Cremaschi, 2015). The geomorphological mapping was performed at three phases (Figure 3):

(a) Collection and preparation of literature and data, determination of the appropriate methodology and mapping protocols and organization of available data into a (GIS) geodatabase,
(b) Field survey in preselected areas where landform identification was impossible utilizing Remote Sensing data. Delimitation of landform with GPS.
(c) Comparative description of field notes with Remote sensing data. Production and evaluation of a preliminary morphological sketch. Production of the final Geomorphological map.

In particular, analog topographic and geological maps were digitized and were imported as layers (lithology, tectonic contacts, contours, coastline, drainage network, etc.) into the GIS spatial geodatabase. Then, secondary layers were produced implementing GIS techniques which include: A Digital Elevation
Model utilizing 20 m, and 4 m interval contour lines, along with elevation points and the drainage network, a hill-shade map, a slope-aspect map, a range map and a map of morphological discontinuities of slopes. The aforementioned secondary layers were used as land surface parameters in the production of a preliminary morphological sketch of the study area, depicting elementary morphological features. At that point, we were able to identify large scale landforms such as alluvial fans and cones, mass wasting forms, planation surfaces, brakes of slope, glacial landforms, etc. The preliminary output of the morphological sketch was then evaluated using remote sensing data. The produced elementary morphological patterns were validated with field observations and finally, the geomorphological map was produced. The legend was structured on six levels of information while geomorphology was grouped in nine categories according to the operative causes of landforms.

4. Results

The geomorphic configuration of the broader area of Pieria Mt is the outcome of the interaction of endogenic and exogenic processes during the geological past. Based on the controlling factors that shaped the present relief, the study area can be divided into three distinct landscape units (A–C, Figure 1), dominated by similar processes, and consisting of a variety of characteristic geographical features. Landscape unit A corresponds to the mountainous relief of Pieria Mt and part of Mount Olympus, comprising of Alpine rocks with elevations exceeding 2900 m. Landscape unit B corresponds to the hilly terrain of Neogene formations with elevations not exceeding 780 m. Landscape unit C is the low lying alluvial plain of the study area.

4.1. Landscape unit A

The mountainous relief of unit A ranges in elevation from 500 to 2190 m. In terms of morphology, it is dominated by intense downcutting and distinct ridge crests which is characteristic of the transition from a young to a mature stage of landscape evolution (Davis, 1899). Intense downcutting, observed by the majority of drainage networks in this unit, is the result of the tectonic uplift of the area (Smith & Nance, 2006). The southern part of Pieria Mt consists of gneiss, schists, amphibolites and limestones of the Pelagonian geotectonic zone as well as ophiolites of the Almopia zone. The ephemeral streams that drain the southern Pieria Mt (Kakolakos, Mavroneri and Petriotikos) constitute tributaries of Mavroneri drainage network and have developed almost parallel to each other in a dendritic pattern Main Map. The distinct elongation of Livadiotikos stream towards the Southeast could be attributed to a tectonic contact. Intense incision and V-shaped valleys are dominant features of this unit, as opposed to the less incised streams of unit B, which could be attributed to the difference in lithology. However, Petriotikos stream has developed a wider cross-sectional channel profile and a more gentle longitudinal profile in its upper reaches (Agios Dimitrios settlement). Furthermore, fluvi-torrential deposits in the form of extensive fluvial terraces have been observed along the main channel of Petriotikos stream in the same region Main Map. The latter could be attributed to the tectonic action of a local NNE–SSW trending normal fault cutting across the main channel.
Figure 4 depicts a local bedrock exposure and a stream flow shift due to a recent activation of the fault. Multiple activations of the fault resulted to a more gentle longitudinal profile of the main channel of Petriotikos, which further caused the deposition of fluvio-torrential sediments and the formation of fluvial terraces.

East of Petriotikos stream, two drainage networks of Xirolaki and Papa Aloni have developed their main channels in an almost S–N direction of flow, draining the northern part of Mount Olympus. This is the most mountainous part of the study area and is dominated by steep slopes and intense incision with distinct ridge crests, characteristic of a youthful to maturity stage of development (Tsanakas et al., 2016). Tectonic uplift of Mount Olympus (Smith & Nance, 2006) during the Quaternary, forced the drainage networks to incise into bedrock forming steep slopes and V-shaped valleys. According to Godfriaux (1968), Mount Olympus consists of Mesozoic to lower Cenozoic carbonate rocks of the Pelagonian zone, overthrust onto the younger rocks of Gavrovo–Tripoli massif. Hence, the geological configuration of Mount Olympus is the combined result of active tectonics and exogenic processes that eroded the Pelagonian cap and exposed the Gavrovo–Tripoli massif, in the form of a tectonic window.

The upper parts of Xirolaki and Papa Aloni catchments appear to be morphologically and genetically different than the adjacent drainage networks of the Pieria Mtns. Amphitheater-like features with precipitous walls (glacial cirques) at elevations greater than 2600 m (Xirolaki) and 2500 m (Papa Aloni), imply the presence of glaciers within the geological past, indicating climatic control in the landscape configuration of Mount Olympus (Smith & Nance, 2006). In addition, an elongated flat surface consisting of consolidated angular sediments has been identified at an elevation of 700 m in the drainage basin of Xirolaki stream Main Map. This feature corresponds to a terminal moraine which was formed by the accumulation of glacial debris, originating from a past glacier and marking its maximum advance inside the valley (Figure 5).

The deposition of fluvial sediments transported by Xirolaki and Papa Aloni streams, resulted to the formation of two relatively extended well shaped alluvial fans of Pleistocene age, north of Mount Olympus, both consisting of consolidated, medium-sized, well-rounded pebbles (Figure 6).

Despite the fact that these fans belong to the hilly terrain of unit B, their formation is controlled by the depositional processes originating from Mount Olympus. The Papa Aloni alluvial fan is less extended than the Xirolaki fan. It has been formed by fluvial sediments originating from the northern part of Mount Olympus. Its elevation ranges from 250 to 340 m and it is considered to be inactive. The surface of Xirolaki alluvial fan appears a morphological discontinuity (Figure 7), attributed to the recent tectonic activity of an E–W trending normal fault, cutting the fan. The combined activity of the normal fault vertical movements during the Pleistocene, along with the formation of the terminal moraine at the stream outlet (Elos), resulted to a local
blocking of its course. Consequently, the stream was forced to change its course to the west and cease the supply of Xirolaki fan with fluvial sediments.

4.2. Landscape unit B

Thermaikos Gulf has been the receiving basin of 300 m thickness sediments from lower Miocene until present (Lalechos & Savoyat, 1977). Faugères (1977) has distinguished this basin into separate grabens, one of them corresponding to the present Katerini plain. Unit B extends east of Pieria Mtns, from the deltaic plain of Aliakmonas R. to the North, to Mount Olympus to the South, covering an area of approximately 500 km². The hilly terrain of this unit has been developed almost entirely on Neogene formations and Quaternary deposits mostly in the form of alluvial fans and cones. Both lithology and the formation and evolution of the relatively young drainage networks of this unit, combined with a series of geomorphic markers, give insight of a very interesting evolution during the pre-Quaternary period.

A series of geomorphic – landscape markers within unit B have been recognized and studied in detail. The Northern part of the unit is drained by five ephemeral streams (Krasopouli, Kerasies, Gerakari, Smixi and Traganas), which have been developed on Upper Miocene Marls, Clays, Sandstones and Conglomerates in a radial pattern suggesting the existence of a fan-shaped feature. The topographic section of Figure 8, enhances the idea of a fan surface dipping to the East. Furthermore, the Neogene formations spread eastwards from Pieria Mtns, and they dip in the form of an extensive fan, covering an area of approximately 291 km² having an apex west of Ryakia at an elevation of 340 m. Additionally, the composition and size of this large fluvio-torrential fan, points to a large river with high discharge rates and sediment yields. Moreover, the presence of a wind gap (770 m) in the southern part of Pieria Mtns, indicates an older channel outlet located at a higher elevation than the large deltaic fan. Last but not least, Neogene lacustrine remnants in the western part of Pieria Mtns, indicate the existence of a Neogene lake when the area was a few hundred meters lower than present elevations.

All of the above, indicate the existence of two river mouths of Mio-Pliocene age, contributing to the Neogene paleogeographic reconstruction of the study area. Aliakmonas river is the longest river flowing in Greek territory along its whole length of 297 km. It originates from Pindos Mtns, flows to the southeast, makes a sudden right angle turn to the northeast and debouches into Thermaikos Gulf. In its last segment, it flows through the extensive deltaic plain of Thessaloniki formed by the alluvial deposits of Axios, Aliakmonas, Loudias and Gallikos rivers (Figure 9).

Aliakmonas river drained into a lake, that existed in Meteora region in Thessaly in early Miocene times.
By the end of Miocene, Aliakmonas river at its southernmost point was forced to turn to the northeast following the emptying of the large inland lake and the ensuing uplift of Thessaly (Ferriere et al., 2011). As a result, Aliakmonas found an outlet in this region, first at the site of Moshopotamos where it deposited coarse fluvial material (fanglomerates) at the boundary of the present high and low Pieria Mtns; and then further north, near Ryakia village, in the form of an extensive deltaic fan, flowing into a large lake. The subsequent uplift of the broader Pieria Mtns, compelled the river to follow its present course. The Pliocene lake was superseded by the Aegean Sea in Plio-Pleistocene times.

4.3. Landscape unit C

The low-lying landscape unit C is the morphological continuation of the hilly terrain of unit B towards the western coast of Thermaikos Gulf and does not exceed 40–50 m in elevation Main Map. Its geomorphological
evolution has been mainly affected by interrelated terrestrial and marine processes during the Quaternary. The broader Katerini area comprises an extended alluvial plain as a result of fluvial sedimentation during the Holocene. The coastal part of landscape unit C can be distinguished into two parts. The first and southernmost one is a coastal lowland plain of low relief (slopes <1%), accommodated by a NNE–SSW oriented, extended sandy beach at a total length of approximately 25 km. The second, northernmost one, extends between Cape Atherida and Methoni Bay and is characterized by the presence of 20–30 m coastal cliffs, consisting of Plio-Pleistocene formations (Faugères, 1977). The monotonous lowland – beach topography of the first part is interrupted by the presence of a lagoon, located at Cape Atherida. According to Tsanakas (2017), the beginning of the formation of the lagoon can be safely put around the sixth millennium BP with the formation of a barrier spit which extended towards the NNE and finally confined the lagoon. The combined action of two longshore drifts (N–S and S–N) lead to the formation of two generations of beach ridges with WNW–ESE and SSW–NNE orientations.

Human interference along the southern part of the coastal zone depicted a major impact in its recent geomorphic configuration. The construction of a port for small fishing vessels mooring at Paralia settlement in the early 1970s, resulted to the norward longshore drift blocking and the consequent sedimentation equilibrium disturbance, north of the port. Comparative visual interpretation of 1969, 1987 and 2000 aerial photographs, indicated a mean coastal retreat of 36 mm/yr at Paralia settlement.

The general topography of the northern part of landscape unit C is dominated by distinct relatively flat, gently inclined surfaces, bounded by steeper ascending slopes, corresponding to wave-cut abrasion platforms, in the form of uplifted marine terraces (Figure 10).

In particular, 21 elevated surfaces (5–110 m asl) have been identified and mapped at a scale of 1:5.000 along the coastal zone between Methoni Bay and Alykes lagoon. These terraces were further grouped into five categories, A (5 m), B (24–36 m), C (52–56 m), D (64–72 m) and E (100–110 m), according to their elevation. In the absence of absolute datings, since no cap-rock formation was found at any location, it was impossible to draw conclusions for the time constrain of their genesis. However, it is generally accepted that the presence of marine terraces certainly indicates tectonic uplift within the Late Pleistocene (Papanastassiou, Cundy, Gaki–Armijo, Meyer, King, Rigo & Papanastassiou, 1996; Papanastassiou et al., 2014). Estimation however of a precise uplift rate lies beyond the available data and the methodology applied in the
present study. Uplifted beachrock formations located at the same area at ≅0.2 m asl, further enhances recent tectonic uplift of this region.

5. Conclusions

The present contribution is an attempt for an integrated geomorphological study of an extended study area of approximately 1600 km². In order to scientifically determine the formation and evolution of present-day landscape, all those factors that shape the relief were taken into account: topography, geology, tectonics and climatic status. The broader area of Pieria Mtns is a landscape where heterogeneous geomorphological environments meet. The geomorphological formation and evolution of these environments is the result of primarily active tectonics, allowing subordinately the activation/de-activation (and accelerating/decreasing the intensity) of exogenic processes from Lower Miocene until present. The combined methodology of GIS oriented and traditional geomorphological mapping was proved to be scientifically accurate although time-consuming. In the general concept of a geomorphological study, detailed field work was considered mandatory not only to validate the GIS derivatives, but also to effectively interpret the genesis of the landforms.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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