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The Geomorphological and Geological Structure of the Samaria Gorge, Crete, Greece—Geological Models Comprehensive Review and the Link with the Geomorphological Evolution

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Abstract: The Samaria Gorge is a dominant geomorphological and geological structure on Crete Island and it is one of the national parks established in Greece. Due to the complex tectonics and the stratigraphic ambiguities imprinted in the geological formations of the area, a comprehensive review of the geological models referring to the geological evolution of the area is essential in order to clarify its geomorphological evolution. In particular, the study area is geologically structured by the Gigilos formation, the Plattenkalk series and the Trypali unit. Regarding lithology, the Gigilos formation predominantly includes phyllites and slates, while the Plattenkalk series and the Trypali unit are mainly structured by metacarbonate rocks; the Plattenkalk series metacarbonate rocks include cherts, while the corresponding ones of the Trypali unit do not. Furthermore, the wider region was subjected to compressional tectonics, resulting in folding occurrences and intense faulting, accompanied by high dip angles of the formations, causing similar differentiations in the relief. Significant lithological differentiations are documented among them, which are further analyzed in relation to stratigraphy, the tectonics, and the erosion rate that changes, due to differentiations of the lithological composition. In addition, the existing hydrological conditions are decisive for further geomorphological evolution.

Keywords: geomorphological and geological features; Samaria Gorge; White Mountains; Crete; Greece

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1. Introduction

The western part of Crete is predominantly structured by Plattenkalk Group geological formations, which belong to the Hellenides foreland [1]. However, the stratigraphically lowest formations of this group are additionally documented in Central Crete, where the bed inversion occurred [2]. This complicated geological structure, which significantly affects geomorphological evolution, resulted in proposing three different geological models for the wider area [3–7], while the need for implementing cutting-edge techniques was generated, in order to display them accurately; this is achieved by implementing three-dimensional (3D) geological modeling [8,9].

Three-dimensional geological modeling was initiated in the early 60s as a tool for improving mining excavation. In particular, the 3D fixed block model was an initial application, performed for tectonically deformed stratified deposit excavation [10,11], as well as the gridded seam model, which was implemented on tectonically undisturbed ore deposits [12]. Regarding geological simulation, Houlding [13] proposed boundary representation, which is based on geological mapping data recorded during fieldwork; these are imprinted in an artificial environment and subjected to geometrical rules, while representative geological cross-sections and preexisting legends of geological formations are necessary for 3D geological composition.

Considering both the proposed geological models and the 3D geological modeling principles, the objective of this paper is to review the proposed geological models of the Samaria area, in order to link the geological regime, geological formation properties (lithology, tectonics and stratigraphy) and the drainage network to the geomorphological evolution.

2. Geology of Crete Island

Crete Island is located just over the active subduction zone of the African plate beneath the Eurasian one ([14] and references therein), resulting in the gradual uplift of the entirety of Crete [15]), characterized by complicated active tectonics. The Alpine tectonostratigraphic regime indicates complexity as the various units and lithological formations covering the island are controlled by compressional tectonics, such as folding, thrust sheets etc. [16]. In particular, the major tectonic units of Crete (stratigraphically from the lower to the upper one) are the following [17–23]: (i) Plattenkalk Group (parautochthonous), (ii) Phyllite Nappe, (iii) Tripolis Nappe, (iv) Pindos Nappe and (v) Uppermost Nappe (Figure 1).

Various lithological formations, composing these nappes, tectonically overlie different parts of the parautochthonous formations of the Plattenkalk Group, which is predominantly structured by HP/LT-affected metamorphic rocks [18,24]. Furthermore, the Ravdoucha (slate-carbonate) beds tectonically overlie the dynamometamorphic sequence in different sites of Western Crete, constituting the lower part of the Tripolis unit, whilst the upper part includes the carbonate sequence and flysch (Figure 1). The Tripolis unit is approximately aged between the Middle and Upper Triassic, while the corresponding age of the overlying Pindos (or Olonos-Pindos) unit ranges between the Upper Triassic and the Middle Palaeocene [25–29].

It is worth mentioning that the Tripolis and Pindos geotectonic zones, which are part of the External Hellenides, tectonically underlie the allochthonous Internal Hellenides nappes, and they are characterized as the "Uppermost unit"; this unit constitutes complicated lithofacies, a tectonic complex consisting of a nappes pile [2].

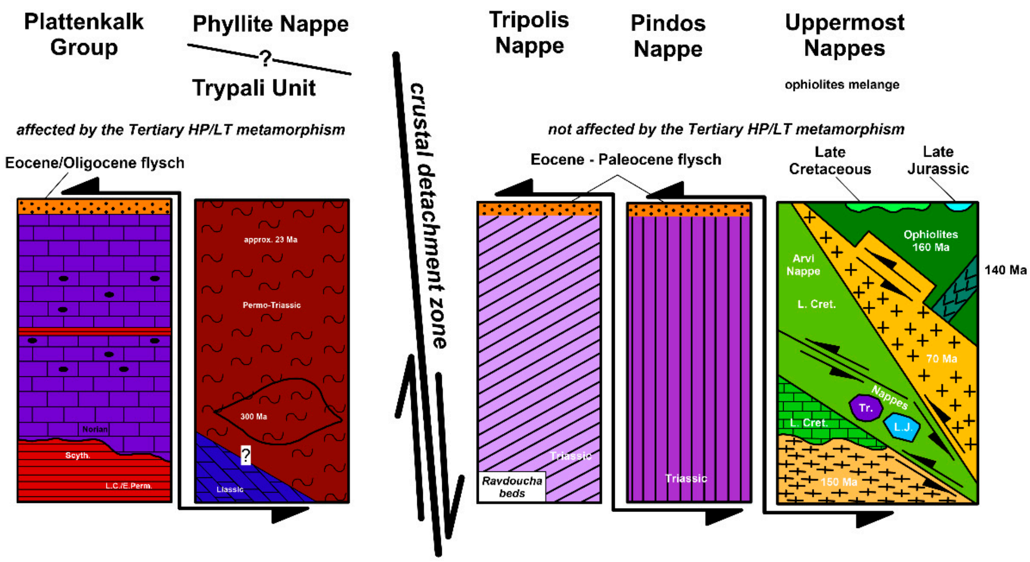
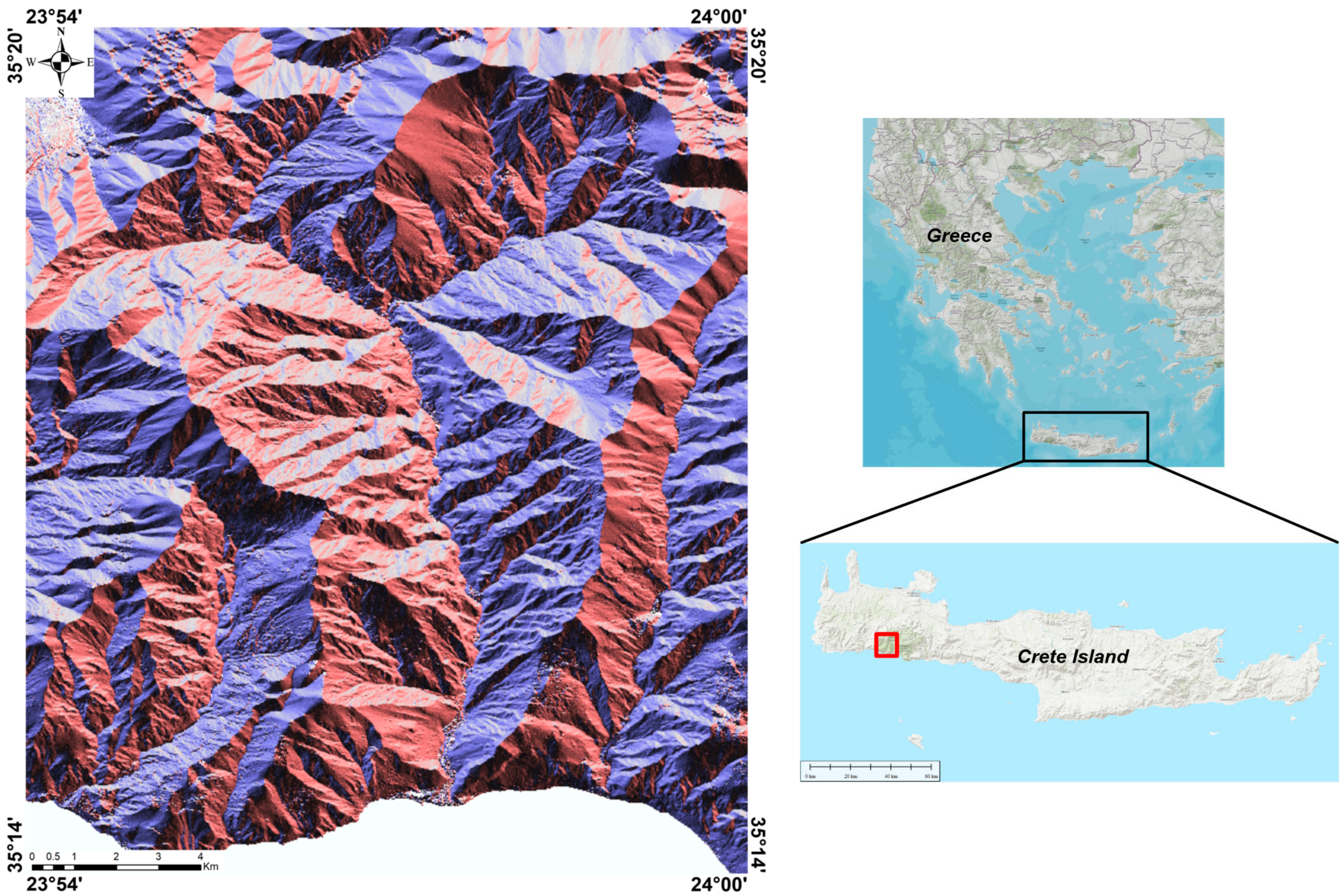


Figure 1. Tectonic emplacement of the tectonostratigraphic units and nappes of Crete (modified from Seidel et al. [23]).

In particular, these different nappes are as follows (from the uppermost to the lowermost): (i) ophiolites nappe (serpentinized peridotites, gabbros, diorites, dolerites and diabases) of Lower Jurassic–Upper Cretaceous age. The vast majority of ophiolites are exposed at the central part of Crete and they are placed at the top of the Uppermost unit [30], extending in areas that vary from a few hundred square meters to several square kilometers, (ii) Asterousia nappe (meta-silt, mica, chlorite, epidotite gneisses and schists, amphibolites and marbles) of Lower Jurassic–Upper Cretaceous age, (iii) Vatos nappe (dark siltstones, limestone beds and sandstones alternations) of Upper Jurassic age, (iv) Arvi nappe (basalts and pillow lavas) of Upper Cretaceous age. Eventually, the Alpine formations which extend in different Crete regions underlie the Neogene and Quaternary units of various thicknesses; these formations are associated with the post-orogenetic processes that occurred in the area. The uppermost Quaternary formations, affecting the geomorphological evolution of the area, unconformably overlie the Neogene formations or the pre-Neogene bedrock [31,32]. They consist of loose or compact terrestrial formations (Pleistocene or more recent), documented as colluvial deposits or alluvial fans.

The Samaria Gorge is located in the White Mountains mass in the southwestern part of Crete (Figure 2), being one of the National Parks of Greece (established in 1962). It is considered as one of the most significant geomorphological structures in the Mediterranean region, and it extends in an N–S direction for approximately 13 km. The global recognition of the Samaria Gorge is documented by numerous international distinctions: (1) UNESCO Man and the Biosphere Reserve, (2) European Diploma of Protected Areas, awarded by the Council of Europe, (3) European Biogenetic Reserve of the Council of Europe, (4) Important Bird Areas by the Birdlife International and (5) NATURA 2000 protected area, under code GR4340014 (Zone of Special Protection: ZSP), and it is considered as one of the most significant geotopes of Greece. Furthermore, the wider area of the White Mountains belongs to the Natura 2000 European Network of Protected Areas, under code GR4340008H, and it is certified as a Place of Universal Importance (PUI).



(a) (b)

Figure 2. (**a**) Digital Elevation Model (DEM) of Samaria Gorge; (**b**) Location of Samaria Gorge in Greece.

The Samaria Gorge is also characterized by complicated tectonics, affecting the geological and geomorphological features of the area. It represents the geological profile of the region, highlighting the Plattenkalk Group geological formations (Figure 3), which is the lower parautochthonous group of all the sequences, structuring the White Mountains' core, as well as the major mountain masses of Crete (Mt Talea, Mt Psiloritis, Mt Lasithiotika etc.).

It is worth noting that the lower tectonic units, such as the Fodele (including the Galinos beds) and Sisses beds [1] are lacking in the study area.

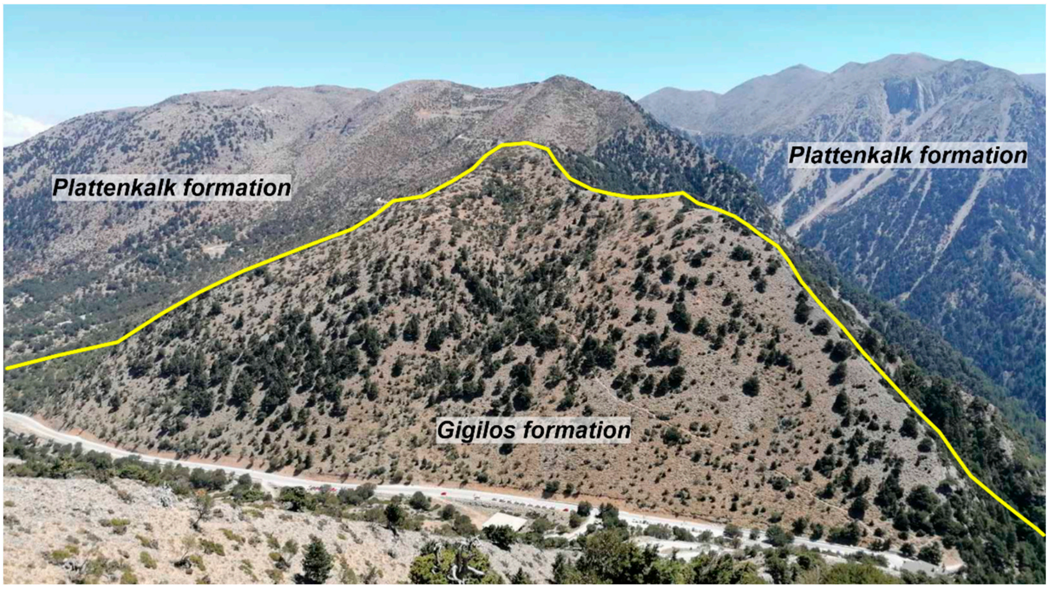


Figure 3. Contact (yellow line) between the Gigilos and Plattenkalk formations.

Regarding the geological formations of the Plattenkalk Group, they are geomorphologically associated with the sharp topographic relief of the area, as well as with the steep slopes that are presented. Moreover, the drainage network density, and mainly the river crossing the gorge, contributes decisively to the geomorphological configuration of the area. The erosion caused by the river flow is directly related to precipitation; the increased winter precipitation is expressed by significant water flow quantities, recorded in the winter period between May and October. On the contrary, the limited precipitation from June to September (summer period) results in lower flow water quantities and hence a lower erosion rate.

Concerning the northern part of the Samaria Gorge, a different geological formation (Gigilos formation) is documented, which outcrops as a tectonic window structure, while a smoother relief is observed; despite the numerous drainage network branches, the main river, mentioned above, is absent. Considering the elevation variety and the drainage network, the Samaria river catchment area shows significant differentiations between the northern and the southern part, related both to the shape and extension. In addition, dense forest is documented in the northern part of the study area, related to the aforementioned factors [33]. Particularly, nine distinct land ecotopes have been identified in the Samaria Gorge, including 162 plant species, while 36 of them are protected and characterized as endangered [34].

3. Geology of the Study Area

The Samaria Gorge area is geologically structured by Neogene–Quaternary geological formations, as well as by Alpine bedrock. The geological and topographical complexity of the study area has been highlighted by various researchers, who contributed to the theoretical background establishment. In these proposals, the following geological formations/terms are referred to:

The "Plattenkalk" term, which was initially introduced by Chalikiopoulos [35], describes a thin- to medium-bedded crystalline limestone sequence, including chert intercalations or/and nodules, located in Eastern Crete. Numerous geological studies, performed in the Peloponnese and Crete regions, consider that this sequence is predominantly exhumated as a tectonic window throughout these regions. On the contrary, Creutzburg [36] applied a different terminology, introducing the "Madara-Kalke" term in order to describe a thick complex of white to dark recrystallized limestones («mächtiger Komplex»), bedded in the lower part and unsorted in the upper part. The Triassic age was questioned as it underlies the Permian "Phyllites-Quartzites" unit.

Regarding the Western Crete region, the "underlying system of the Plattenkalk" term was introduced by Tataris and Christodoulou [3] to describe a system of approximately 300 m in thickness that consists of phyllites, dolomites, microbreccia limestones, cherts and clays, while numerous Upper Triassic occurrences (with Ostrea, Myophoria and probably Halobia) are documented within the dark, thin-bedded limestones.

In the geological map of Crete (1:200,000 scale) constructed by Creutzburg et al. [37], the aforementioned beds are defined as the "Gigilos formation", which underlies the Plattenkalk" formation. On the contrary, Fytrolakis [38] proposed the existence of a tectonic unconformity between the Gigilos beds and the Plattenkalk formation; the gradual stratigraphic transition is the potential between the two formations, and the estimated age of the Gigilos formation is Liasian–Doggerian. Furthermore, apart from the common clastic sediment alternations (clays, calc-phyllites, sandstones, microbreccia limestones), an additional formation was identified, which resembles flysch and consists of clays with a thin gypsum layer, thin-bedded sandstones and thin-bedded, clastic limestones.

Therefore, according to various researchers [17,31,38–41], the generally accepted geological model highlights an anticlinic megastructure occurrence, which considers Mt Gigilos as the core [6,7]. It should be emphasized that the Trypali unit dolomitic limestones are documented southwest of the Samaria Gorge, while the corresponding underlying system of the Plattenkalk Group is not. The Trypali dolomitic limestones tectonically overlie the Plattenkalk formation, while the in-between contact is accompanied by a tectonic breccia, locally exceeding 2 m thick.

In particular, the Trypali unit and Plattenkalk Group constituting the bedrock of the wider area of Samaria Gorge show different lithological characteristics; intensively brecciated, strongly karstified, predominantly carbonate formations dominate in the Trypali unit, characterized by their cellular texture, resembling rauhwackes. The Plattenkalk Formation consists of thin-bedded marbles, including chert intercalations and/or nodules, while the underlying Gigilos Formation rocks consist of alternations of metaclastic and metacarbonate rocks with cherts.

4. Data and Methodology

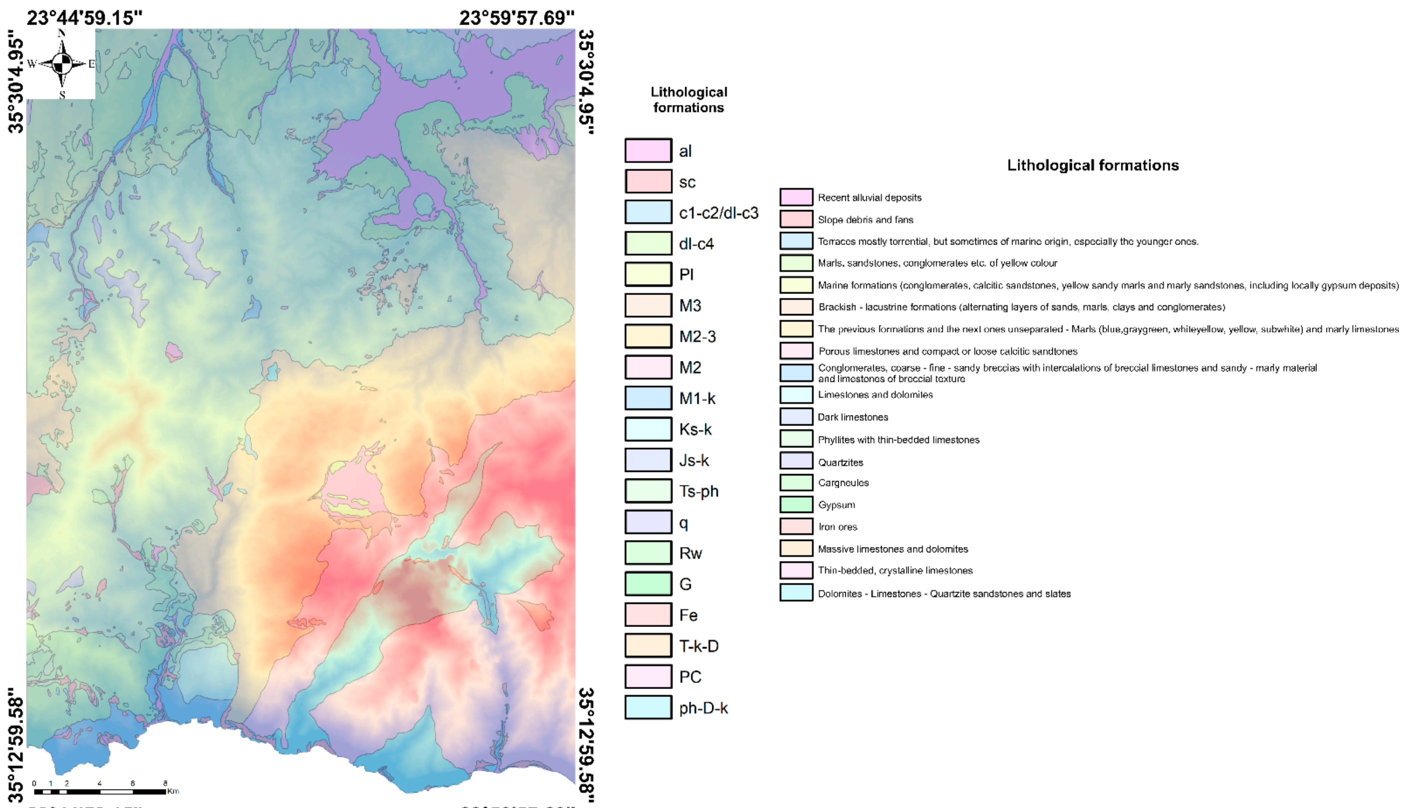
The 3D geological model construction was performed by applying software packages, which are widely implemented in geosciences. In particular, the presentation of the first and the second models was carried out using the ArcGIS 10.6.1 software package, while the third one was performed by the SURPAC2000 software package. The methodological process of geological models in the ArcGIS 10.6.1 software package includes the georeferencing of the original geological maps [3,4] and the existing formations' digitalization; moreover, a colored legend was extracted based on the age of each formation. Then, a detailed digital elevation model (DEM) of the study area was implemented, resulting in the three-dimensional configuration of geological formations; for this purpose, the ArcScene application (extension of ArcGIS 10.6.1 software) was applied. Regarding the corresponding process in the SURPAC2000 software package, the principles of digitalization are identical to the ArcGIS 10.6.1 software package ones, while limited technical differentiations are documented.

5. Results—Discussion

5.1. Geological Models Review

Based on the various approaches concerning the geology of the Samaria Gorge, and the theoretical background improvement, different geological models were proposed, highlighting the geological regime of the wider area. Particularly, three geological models have been proposed by: (a) Tataris and Christodoulou [3,4]—1st model, (b) Pavlaki and Perleros [5]—2nd model, (c) Manutsoglu et al. [6,7]—3rd model.

Regarding the 1st model [3,4] shown in Figure 4, the underlying bed system of Plattenkalk (after Chalikiopoulos [35]) is characterized by the following lithological formations (stratigraphically from the upper to the lower one): (a) Phyllites, (b) Gray–white grayish, massive carbonates with sparse chert nodules, (c) Gray limestones with a cellular texture (in some locations), (d) Thin-bedded limestones with marl intercalations, (e) Dark, massive limestones with chert nodules and phyllite intercalations, (f) Calcitic phyllites and dark, crystalline limestones alternations, (g) Crystalline limestones, (h) Calcitic phyllites and dark, crystalline limestone alternations and (i) Calcitic phyllites. According to this model, the Plattenkalk system consists of thin-bedded, crystalline limestones, including nodules and/or thin chert intercalations and thin phyllite intercalations. These limestones are locally documented in a thick-bedded form, without chert occurrences, maintaining the crystallization. Moreover, the transition of these formations to calcitic phyllites is observed. The formations system, overlying Plattenkalk, includes a lower sequence of limestones and dolomites (Madara-Kalke), and an upper sequence consisting of phyllites, quartzites, rauhwackes, gypsum, limestones, eruptive formations and iron ores.



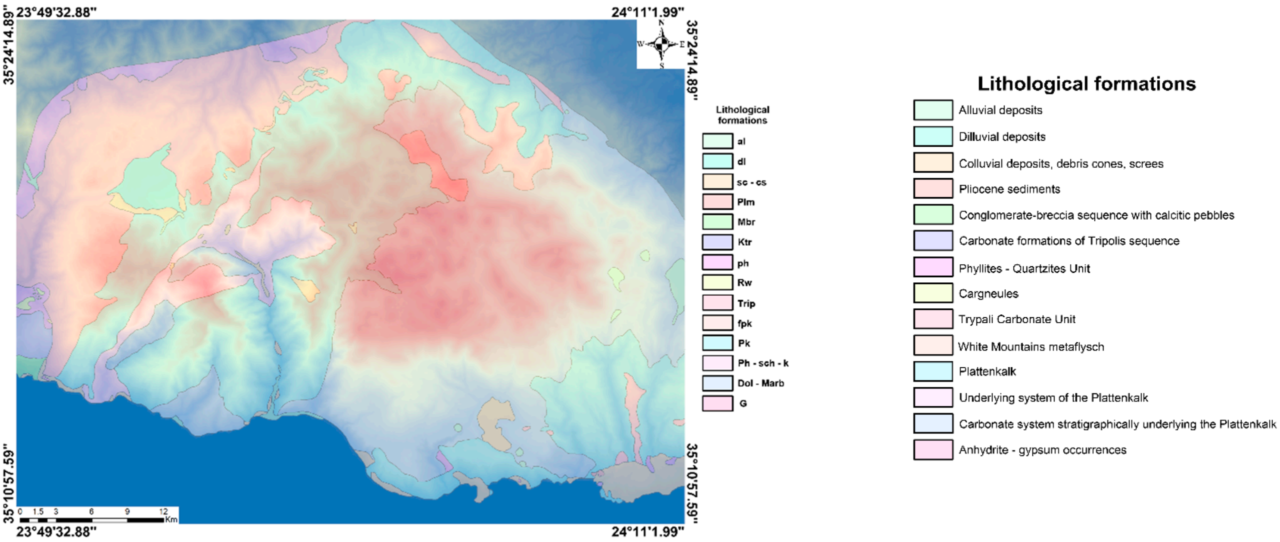
(**a**) (**b**)

Figure 4. The geological model for the wider Samaria Gorge modified from Tataris and Christodoulou [3]—1st geological model: (**a**) Lithological map of the study area; (**b**) Description of the geological formations.

According to Pavlaki and Perleros [5], the 2nd model (shown in Figure 5) suggests that the underlying system of the Plattenkalk includes: (a) Thin-bedded alternations of clay phyllites and (meta)sandstones with low-grade metamorphism, marls, as well as sparse thin-bedded limestones and chert occurrences. This sequence is also known as "Gigilos beds"; (b) A carbonate system, subjected to different tectonic phases of folding and uplift. It is characterized by significant thickness in the greatest part of the White Mountains region, and it is divided into (a) White-grayish–whitish marbles, locally cracked, showing karstic features, (b) Stromatolitic dolomites and (c) Black dolomites, showing a cellular texture, strongly cracked with karstic features.

Regarding the Plattenkalk series, the upper members consist of thick-bedded carbonate formations, alternating with green, calcitic phyllites, while brown-black slates are locally documented (White Mountains metaflysch). The lower members consist of thin-bedded and strongly recrystallized gray-black limestones and dolomites, forming beds with thin chert intercalations and nodules.

Finally, the overlying Trypali unit, strongly karstified and tectonically affected, includes (meta)carbonate formations, which locally show a conglomerate-breccia formation. In particular, the upper horizons consist of coarse carbonate conglomerate-breccia formations and recrystallized limestones–dolomitic limestones, while the corresponding lower ones include strongly recrystallized, white-grayish, thick-bedded and cracked limestones, as well as dark dolomites.



(**a**) (**b**)

Figure 5. The 2nd geological model for the wider Samaria area (modified from Pavlaki and Perleros, 2015 [5]): (**a**) Lithological map of the study area; (**b**) Description of the geological formations.

According to Manutsoglu et al. [6,7], the 3rd model (Figure 6), which considers the study of Soujon et al. [40], the Plattenkalk Group of the White Mountains, consists of the “Mavri” and the “Aloides” formations, which include the following lithologies (from the upper to the lower): (a) Carbonate breccia, (b) Dolomitic marbles with chert nodules, (c) Chert-clay-carbonate sequence, (d) Thin-bedded calcitic marbles with chert intercalations and nodules, (e) Medium-bedded to thin-bedded calcitic marbles with chert nodules and layers and (f) Thin-bedded marbles with red/green calc-silt horizons and cherts. In addition, the upper part includes marls and calc-schists (Kalavros formation), which are considered the White Mountains metaflysch. Eventually, the Trypali unit overlies the Plattenkalk Group sequence.

Considering the aforementioned viewpoints, we correlated the geological-lithological formations of the models highlighting the similarities and differences between them. The results are summarized in Table 1.

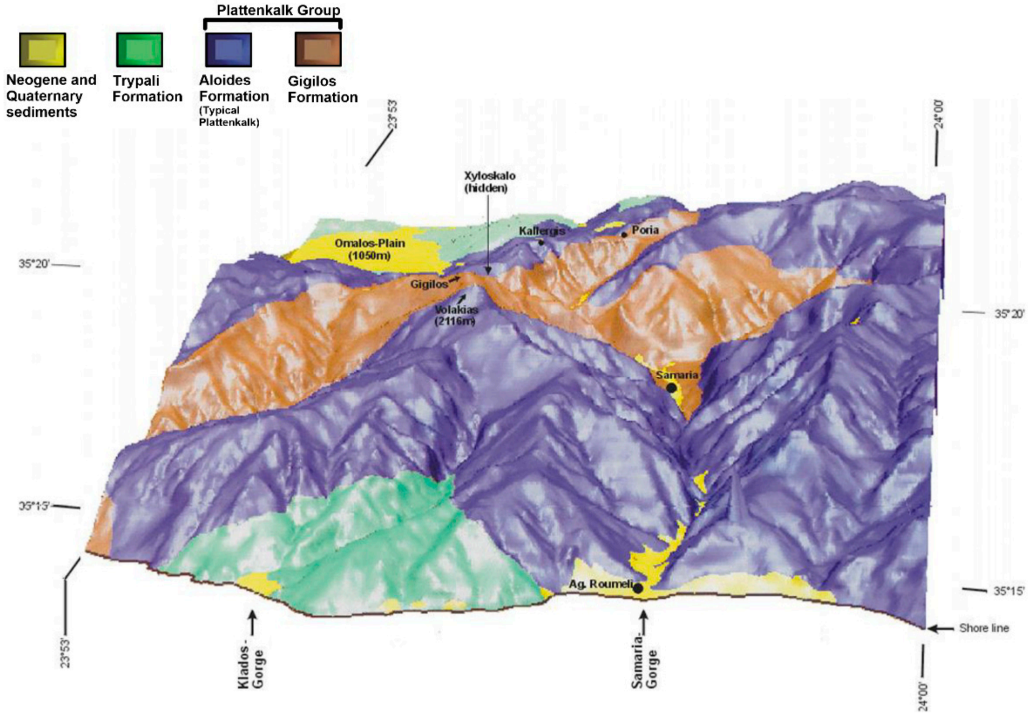


Figure 6. The 3rd geological model for the wider region of Samaria Gorge (modified from Manutsoglu et al., 1999; 2001 [6,7]).

Table 1. Correlation of the proposed geological models for the wider Samaria Gorge area.

1st Model (by Tataris and Christodoulou [3,4])	2nd Model (by Pavlaki and Perleros [5])	3rd Model (by Manutsoglu et al. [6,7])
Formations system, overlying Plattenkalk: a. Upper sequence b. Lower sequence—Madara-Kalke (limestones and dolomites)	Trypali unit	Trypali formation
Plattenkalk system: crystalline, light gray–dark gray limestones with phyllite intercalations. Thin-bedded with chert intercalations and nodules. The uppermost horizons are thick-bedded without cherts, changing locally into calcitic phyllites.	White Mountains metaflysch: Thick-bedded carbonate formations with intercalations of green, calcitic phyllites	Aloides formation
	Plattenkalk: (detailed lithological description in the text)	
Underlying bed system of Plattenkalk: phyllites, dolomites, limestones, quartz sandstones and slates. These formations are documented in the Klados and Trypiti Gorges, as well as within the Gigilos and Poria areas.	System underlying the Plattenkalk: division into metacarbonate and metaclastic formations (detailed lithological description in the text)	Gigilos (Mavri) formation

5.2. Geomorphological Evolution of Samaria Gorge

Sea-level change is a significant factor affecting the geomorphological evolution of a region. In particular, numerous and various sea-level changes have occurred throughout the Mediterranean Sea since the Middle Pleistocene, due to climate change ([42] and references therein), and therefore Crete Island was correspondingly affected.

Especially, the Samaria Gorge's geomorphological evolution is based on the combination of lithology, stratigraphy, tectonics, karstic processes and erosion, resulting in an intense topographic relief configuration, as well as in the formation of a surface and underground drainage network. In general, the Samaria Gorge structure is part of the Samaria River catchment area (Figure 7), composed of geological formations with different vulnerabilities.

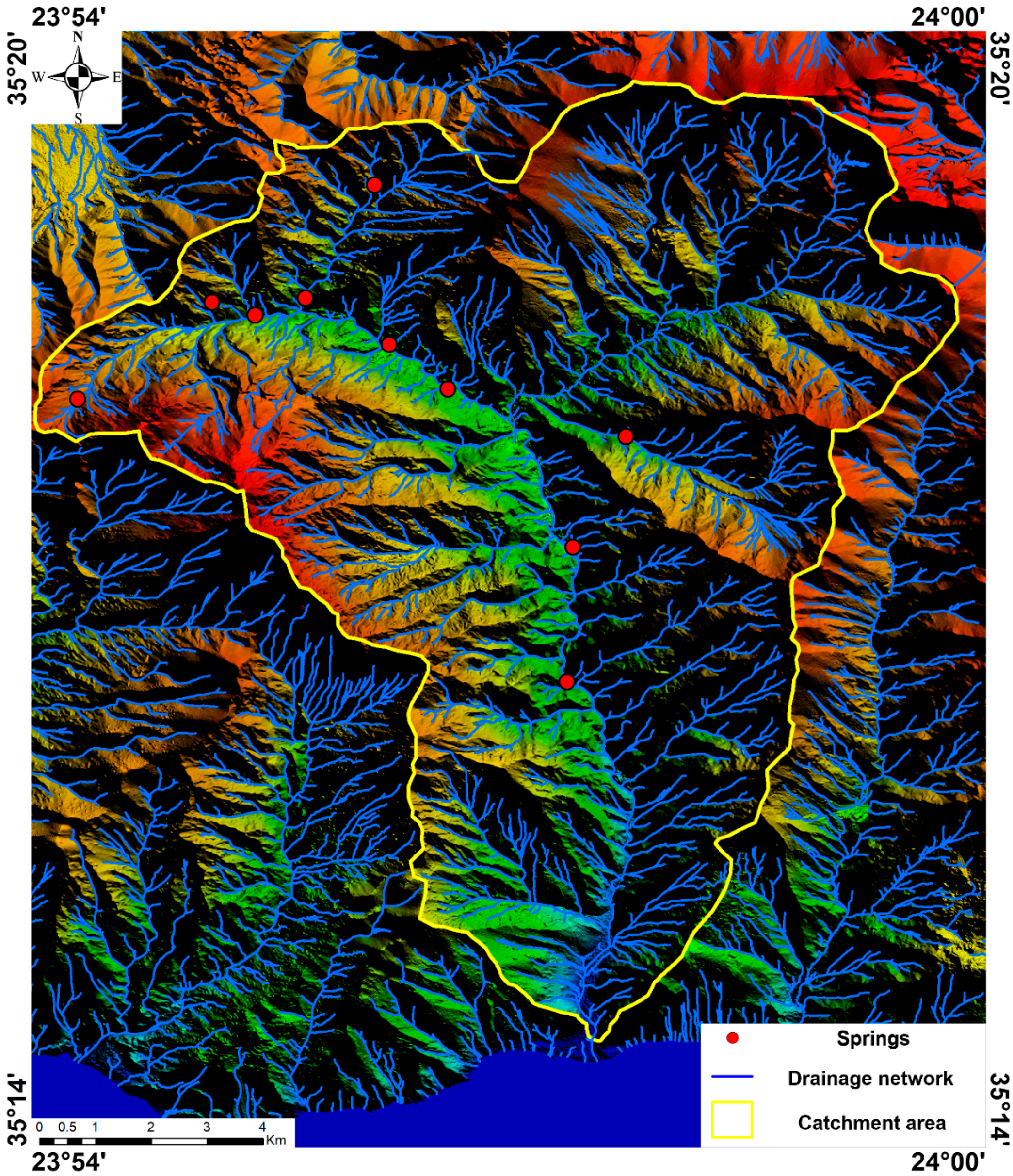


Figure 7. Catchment area of Samaria River, including the drainage network and springs outlets.

Particularly, post-Alpine formations (recent alluvial deposits, slope debris and fans, terraces and Quaternary formations) aged between the Quaternary to the present (Figure 8) affect the geomorphological evolution of the area. Specifically:

Recent alluvial deposits, slope debris and fans include sand, dune or torrent depositions formed in different depositional environments. Slope debris and fans are additionally documented, forming variable debris cones. In particular, the slope debris is derived from the older formations weathering, resulting in rock fragment occurrences, which are displaced by gravity, forming loose and compact sediments. Alluvial fans differ from slope debris due to the different clastic parts' distribution, while they display sorting and layering. Furthermore, alluvial fans significantly contribute to different geomorphological evolutions depending on the climate environment [43,44].

Terrace formations have predominantly been formed at the exit of Samaria Gorge, as well as the adjacent gorges, while they have been interpreted as an index of the marine environment; the estimated thickness ranges between one and several meters. The material of their formation derived from alluvial deposits and fans, while the intense tectonic activity, which uplifts the wider area, results in the formation of beach rocks, which are also uplifted, forming terraces.

The Quaternary formations are divided into Lower and Upper parts. Particularly, the Lower Quaternary formations include marls, sandstones and conglomerates, while the Upper Quaternary ones are characterized by torrential origin and consist of sandy marls, clays, sandstones and conglomerates, with considerable thickness. Similarly to the terraces, they are affected by significant tectonic activity.

Figure 8. Representative post-Alpine formations of various thicknesses, documented throughout the Samaria Gorge area.

Furthermore, the Gigilos formation (northern part of the Samaria Gorge), which is part of the Alpine formations, is susceptible to erosion, as, in this formation, phyllites and slates with smooth dip angles are predominantly included (Figure 9a). In particular, the minerals composing these formations, such as moscovite, kaolinite, montmorillonite and illite, are prone to erosional processes. Therefore, these lithological properties affect the catchment area shape, which is significantly widened in the northern part. On the contrary, the Plattenkalk (metacarbonate formations with chert intercalations consisting of calcite/dolomite and cryptocrystalline silicon dioxide, respectively) formation is characterized by steep slopes along the southern part of Samaria Gorge (Figure 9b), resulting in the narrowing of the catchment area throughout this part. Moreover, it should be mentioned that the low (25°–35°) and high angles (75°–85°) of slopes which are observed in the Gigilos and Plattenkalk formations, respectively, resulted from local erosion activity. Moreover, remarkable karstic features are documented, especially in the southern part of the Samaria Gorge (Figure 10).

Regarding groundwater permeability, the Gigilos formation is considered impermeable, as the watertight horizons of chert and schists restrict the downward movement of the water. Therefore, the limited infiltration and the high surface drainage result in a high runoff coefficient, affecting the geomorphological relief. Moreover, the lithological alternation between the metaclastic and metacarbonate rocks, as well as the extended fracture, favors the formation of low-capacity aquifers, represented by low-discharge value springs. However, some of these springs, located within the Gigilos beds, show significant discharge values, such as the Mytatouli (5.9 m^3/h) and Potistiria (5.3 m^3/h) springs [45]. It is worth mentioning that the transmissibility of the Gigilos formation is significantly lower than the corresponding one of the Trypali unit. Regarding the Plattenkalk series, it consists of several hundreds of meters of crystalline limestone and dolomite, while it is interbedded with watertight horizons of chert and schists. These horizons restrict the downward movement of the water and strongly influence its movement and concentration in the overlying carbonate formation of the Trypali unit. The transmissibility of the Trypali carbonate formations ranges between 0.1 to 1 m^2/sec, which is equivalent to permeability between 10^{-3} and 10^{-2} m/sec [46].


(a)


(b)

Figure 9. The main lithological formations outcropping in the Samaria Gorge: (**a**) Gigilos formation, consisting of phyllites and slates. The slopes are characterized by smooth dip angles; (**b**) Plattenkalk formation, consisting of recrystallized limestones with chert intercalations, showing steep slopes.

Figure 10. Extensive karst features predominantly observed in the southern part of Samaria Gorge.

6. Conclusions

Considering the models relating to geological processes and their relationship with geomorphological features, the following concluding remarks arise for the Samaria Gorge area:

1. The entire region is a part of a megastructure, with the core of Mt Gigilos, consisting of unsorted, dolomitic stromatolite limestones. On either side of the mountain, the dip direction of the formations is differentiated, maintaining the same NNE–SSW striking, indicating that Mt Gigilos is a tectonic window.
2. Although the proposed models are detailed and provide different aspects of the geological regime of the study area, we conclude that the 3rd model is more accurate as the Trypali unit's occurrence at the southwestern part of Samaria Gorge suggested; this is verified by field observations.
3. According to the field observations, this megastructure dips in the NE direction, resulting in the geological formations' intense erosion rate. Therefore, the geological formations' inclination, which is directly associated with tectonic processes, occurred in the area, controlling the geomorphological evolution of the region.
4. The lithology constitution, combined with the tectonic evidence, is a significant factor affecting the geomorphological relief. In particular, the phyllite and slate formations (Gigilos formation) with medium dip angles are characterized by smooth relief. On the contrary, the metacarbonate formations of the Plattenkalk Group, accompanied by high (up to vertical) dip angles, show sharp slopes on both sides of the river that crosses the Samaria Gorge and form slopes with heights of up to 300 m in some locations.
5. Overall, the Samaria Gorge constitutes a typical catchment area, in which the surface runoff is favored in the northern part, due to the lithological formations, while the underground one is favored in the southern part, respectively.

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