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Glacial activity affects landscape evolution in some parts of mountainous Greece. This paper deals with the southern part of Mount Olympus where the geomorphological impacts of Pleistocene glaciations are well presented. It is a preliminary study to demonstrate the landscape that has evolved as a result of glacial activity in these uplands. For this purpose, detailed field work and large-scale geomorphological mapping were performed. A 25-m sediment core was retrieved from the study area on which preliminary lithological and micropalaeontological–palaeobotanical analyses were performed. The intense glacial activity of the southern Mount Olympus area produced a number of landscape changes. Three cirques were identified in the uplands whose evolution has led to the formation of various types of moraines (ground, lateral, medial and terminal) down to an altitude of 1677 m. Intense glacio-fluvial activity caused a major reconfiguration of the drainage network in this area and also caused the formation of a lake. The occurrence of a water body in the area is documented by the presence of aquatic vegetation in parts of a 25-m core retrieved from this former lake basin. In recent times, the lake overtopped the fluvial deposits that bounded it, incising them and leading to the emptying of the lake.

Key words: *cirques, moraines, glacio-fluvial activity, glacial lakes*

Introduction

Large parts of the northern European landscape were covered by ice sheets during Quaternary glacial periods (Ehlers *et al.* 2016). Middle Pleistocene glacial and periglacial activity were widespread in the mountainous regions of the Mediterranean basin such as the Pyrenees, the Italian Apennines and the Pindus Mountains of Greece (Fernandez Mosquera *et al.* 2000; Kotarba *et al.* 2001; Giraudi 2003; Woodward *et al.* 2004; Hughes *et al.* 2006b). Glacial and periglacial features such as cirques (Bathrellos *et al.* 2014 2015), oversteepened slopes, glacial lakes and moraines, can be observed in many Mediterranean mountains. Glaciated mountains exerted a powerful influence on sediment supply and water discharge for Mediterranean river systems at lower elevations (Hughes *et al.* 2006a; Hughes and Woodward 2008 2009).

Glacial activity can be characterised as a main factor of landscape changes in some parts of mountainous Greece (Bathrellos *et al.* 2014 2015; Pope *et al.* 2015). This has been demonstrated in the Voidomatis River basin of northwestern Greece, where thick outwash gravels are an important part of the landscape of the basin (Woodward *et al.* 1995 2008). Mount Olympus was extensively glaciated during the Pleistocene and the geomorphological impacts of glaciations are well preserved. So, the glacial and periglacial processes affected the erosional and depositional regime of the mountain and across the adjacent piedmont (Smith *et al.* 1997 2006; Styllas *et al.* 2016).

In this study the geomorphological impacts of glaciations in the southern part of Mount Olympus are presented. It is a preliminary approach to illustrate the landscape changes, and especially the depositional environments in

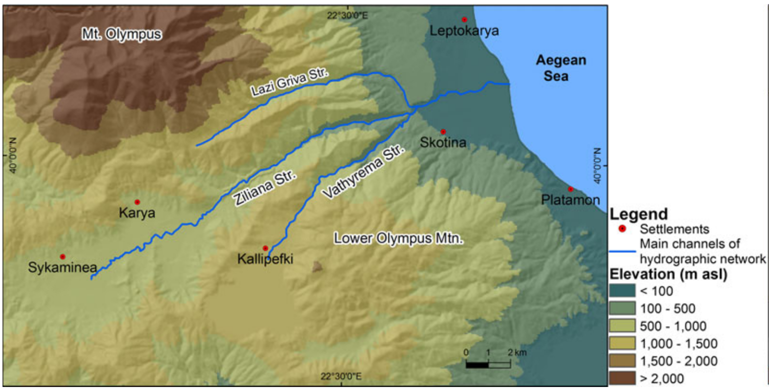

Figure 1 Location map of the southern part of Mount Olympus with the main channels of the Ziliana River hydrographic network

hydrographic networks at lower elevations, caused by glacial activity in the uplands. The study involved detailed field work, large-scale geomorphological mapping and preliminary sedimentological and micropalaeontological–palaeobotanical analyses from a long sediment core record to get some initial results for the evolution of this area in recent times.

Study area

Mount Olympus is located in the eastern part of central Greece (Figure 1) and is the highest mountain of the country (2917 m). The drainage basin of Ziliana stream is located at the southern end of the Olympus massif and includes the drainage basins of the Lazi Griva, Ziliana and Vathyrema, having a total drainage area of 141 km^2 (Figure 2). These streams flow separately in a general SW to NE direction and immediately after their exit from the mountain they join and reach the Aegean Sea as a single main channel, the Ziliana.

The study area involves the upper reaches of the Ziliana, where the most important tributary, the Kokkinochoma, flows from north to south. The relief of the drainage basin is mainly mountainous at its northern end, reaching an elevation of 2670 m (Figure 2).

The geologic formations of Mount Olympus and Ambelakia–Kriovrisi–Kallipefki Units, together with the Pelagonian zone, make up the geological structure of the study area. The Olympus Unit formations outcropping in the study area are Cretaceous grey, medium to thick-

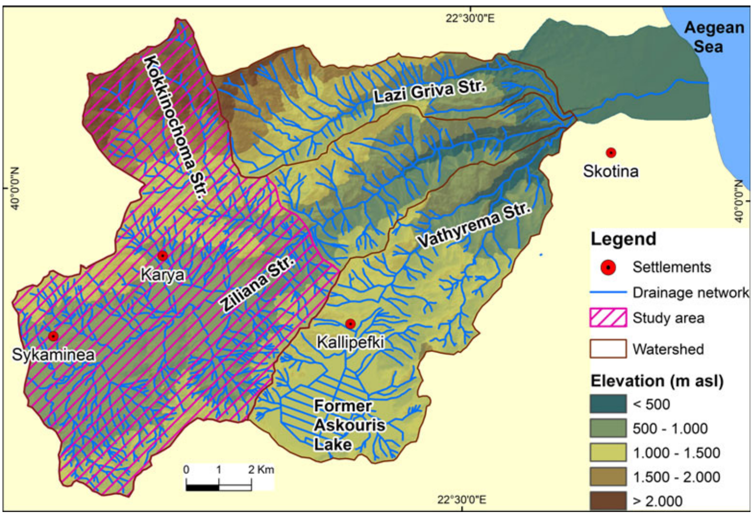

Figure 2 Study area and the drainage networks of the three important streams, along with elevations

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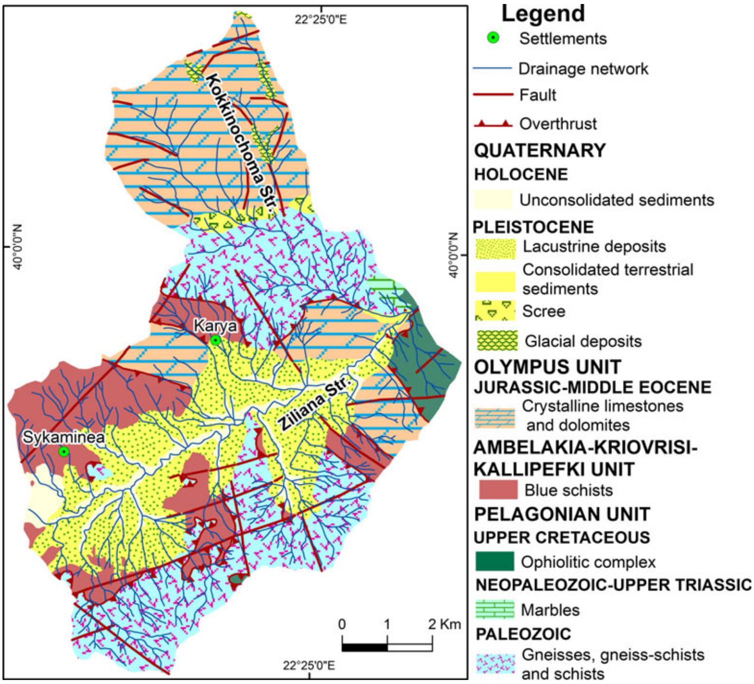

Figure 3 Simplified geological map of the study area (based on geological maps published by IGME 1985)

bedded crystalline limestones with dolomitic intercalations. The Ambelakia–Kriovrisi–Kallipefki Unit rocks comprise blue schists with metabasalt intercalations and marble beds. The overthrust Pelagonian zone formations include Palaeozoic gneisses, gneiss-schists and schists overlain by Neopalaeozoic–Upper Triassic marbles and the dismembered Upper Cretaceous ophiolitic complex consisting of serpentinites (IGME 1985).

The Quaternary sediments consist of Upper Pleistocene lacustrine deposits with peripheral alluvial cones, consolidated terrestrial deposits, scree and

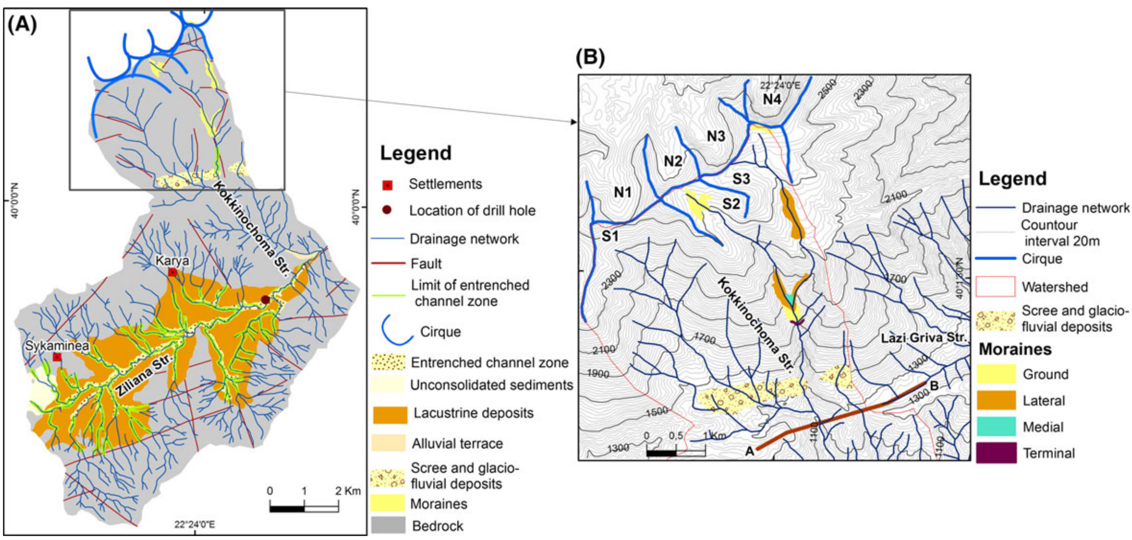

Figure 4 (A) Simplified geomorphological map of the study area. (B) Simplified geomorphological map of the northern part of the study area. Line A–B refers to the cross-sectional profile of Kokkinochoma valley

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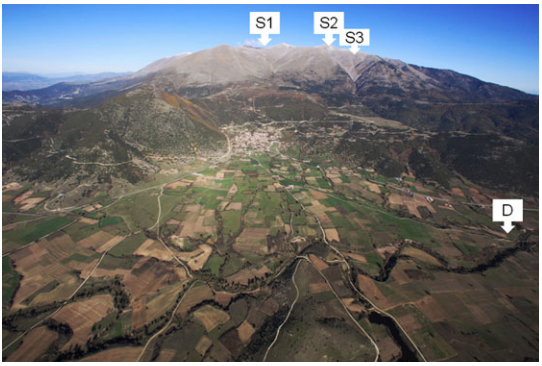

Figure 5 Oblique aerial photograph of the study area showing the glacial lake in the foreground and the three south-facing cirques (S1, S2, S3) in the background. Drill hole (D) is in the far right. The village in the middle of the photo is Karya
Source: Photograph by Matsouka Penelope

glacio-fluvial deposits and glacial deposits. Holocene unconsolidated deposits are also present in the study area (Figure 3).

The Olympus massif was exposed by a tectonic window that occurred between the Oligocene and Late Miocene, during the last stage of the Alpine orogenesis (Schermer 1993; Mountrakis 2006; Vergely and Mercier 1990). Uplift of the mountain mass was facilitated by Pliocene and Quaternary normal faulting. Nance (2010) has studied the eastern flank of Mount Olympus for the Late Pleistocene and suggests rates of uplift of 1.3 mm/year in the last 210 ka and 1.6 mm/year in the last 125 ka.

Materials and methods

The following sources and data were used in the context of the current research:

- Topographic maps and diagrams of the Hellenic Military Geographical Service at scales of 1:50 000 and 1:5000.
- The geological maps of Greece at a scale of 1:50 000, Sheets Kontariotissa–Litochoro and Gonnoi, of the Institute of Geology and Mineral Exploration (IGME 1985).
- Air photos at a scale 1:15 000 (1965).
- The detailed fieldwork of this study was carried out during 2011–13.
- A sediment core was retrieved with the use of rotary BOYLES BROSS BBS drilling equipment.
- A spatial database was created, and ArcGIS 10 software was used to process the collected data.

Geomorphological mapping was undertaken at a scale of 1:5000 in the upper reaches of Ziliana stream. It determined elements such as streams, cirques, glacier deposits, alluvial cones, a gorge and lacustrine deposits. In order to present the landscape changes due to fluvial and glacial activity in the southern part of Mount Olympus, some morphometric parameters of the cirques such as area, altitudes of apex and lip, width, length, amplitude, the length–width and the width–amplitude ratios and orientation of each cirque were calculated. The particle size measurement of the tills was accomplished with the use of a caliper. Additionally, morphological profiles of the streams were produced.

The 25-m long sediment core OLK-1 was retrieved from the middle to lower parts of the lacustrine deposits (Figure 4A). The core was described sedimentologically, but no chronological framework of the deposits was established. A total of 15 sediment samples were collected, mainly from the fine grain deposits and from different depths (Figure 9) and lithological units along the core, in order to investigate the possible presence of

Table 1 Area (in^2), apex, lip and amplitude of cirques in south Olympus mountain (in metres) length–width (L/W) and width–amplitude (W/A) ratios along with orientation (O). The length is the distance from the apex of the cirque headwall to the lip, the width is the distance between the opposite margins of a cirque perpendicular to the length, the amplitude (A) is the difference between the elevations of the apex and lip. The length–width (L/W) ratio expresses the cirque elongation and the width–amplitude ratio (W/A) is a measure of cirque incision

Name	Area	Apex	Lip	Amplitude	Width	Length	L/W	W/A	O
N1	0.76	2680	2360	320	707	734	1.04	2.21	N
N2	0.71	2680	2420	260	776	793	1.02	2.98	N
N3	1.14	2700	2340	360	971	1046	1.08	2.70	NW
N4	0.69	2700	2300	400	779	503	0.65	1.95	N
S1	1.10	2680	2380	300	2203	358	0.16	7.34	SE
S2	0.75	2680	2400	280	912	808	0.89	3.26	SE
S3	1.04	2680	2500	180	750	792	1.06	4.17	ESE

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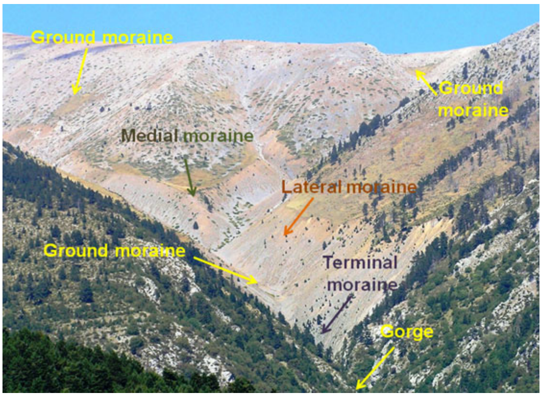

Figure 6 Panoramic view of two glaciated valleys with cirques and moraines, looking north

palaeontological–palaeobotanical material. From each sample, 20 g was wet sieved using a 125 μm sieve and dried at 60°C. The entire residue was analysed under a Leica MZ16 stereoscope and all microfossils were collected and studied.

Results

In total, seven cirques in the study area were observed. As presented in Figure 4(A, B), four of them (N1, N2, N3, N4) are oriented northwards and three southwards (S1, S2, S3) (Figure 5). The south Olympus cirques are formed on crystalline limestones and dolomites.

A comparison of morphometric parameters, ratios and orientation are presented in Table 1 for the four northern and three southern cirques of the study area. The area values range from 0.69 to 1.14 km^2. The apex elevations range from 2680 to 2700 m and are the highest observed in Greece. The lip values vary from 2300 to 2500 m. Regarding amplitudes, the mean values (M) are higher in the four northern cirques (M = 335 m) than the three southern ones (M = 253 m). In the case of width of the cirques, the values range from 707 to 2203

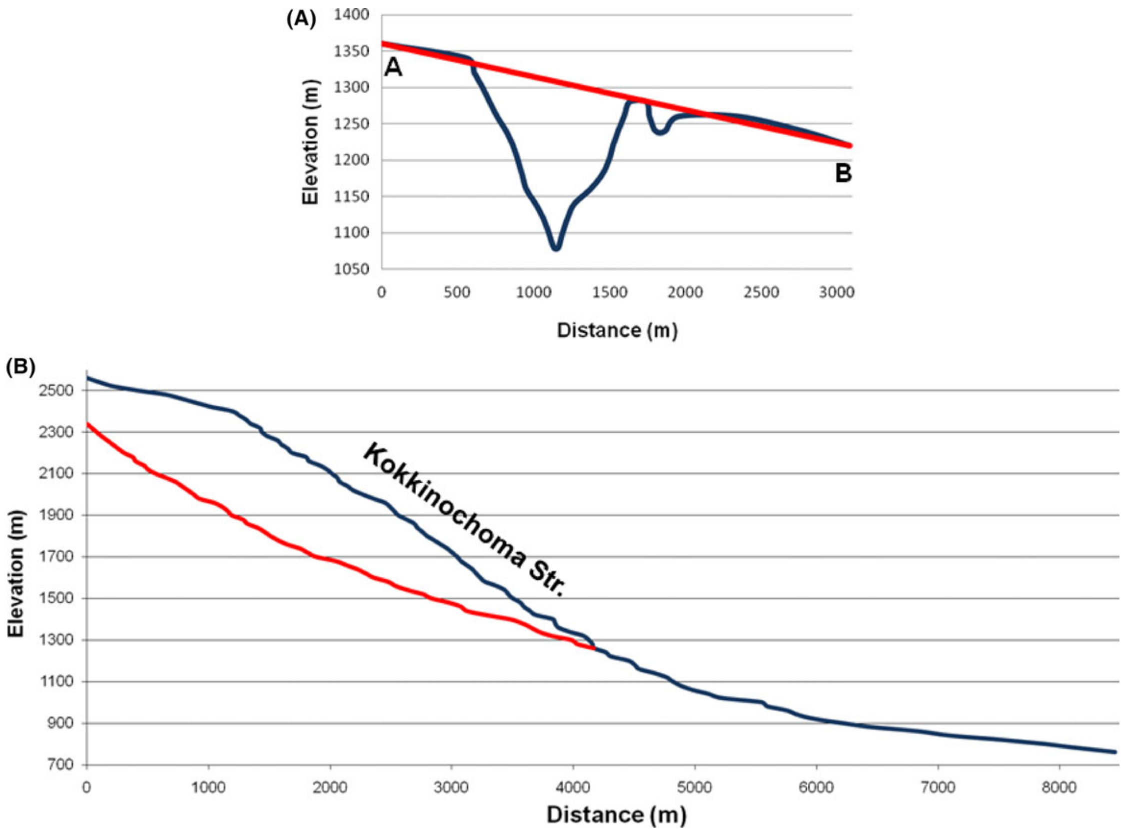

Figure 7 (A) Cross section of Kokkinochoma valley. The red line depicts the former surface of Lazi Griva stream and the blue line the 240 m downcutting. (B) Longitudinal profile of Kokkinochoma stream and its main tributary (red line). The latter seems to be the continuation of the upper section of the Lazi Griva with Kokkinochoma as its tributary in the past

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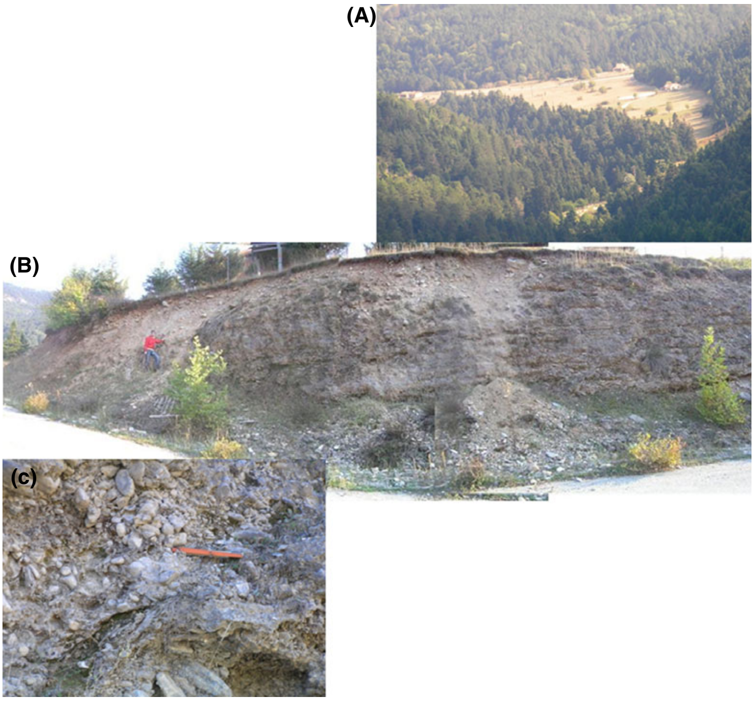

Figure 8 (A) Oblique photo of Kokkinochoma alluvial cone at the confluence with Ziliana stream. (B) Road-cut of the Kokkinochoma alluvial cone just before its confluence with Ziliana stream. (C) Close-up of the alluvial deposits of the Kokkinochoma cone at the road-cut

m. In terms of length of the cirques, the higher values are observed in the north. The length–width (L/W) ratios are relatively higher in the north than in the south, while the northern width–amplitude (W/A) ratios are significantly lower than those in the south.

Moraines are observed in the upstream parts of the Kokkinochoma (Figures 4 and 6). These are remnants of more extensive, partly consolidated moraines formed during the Middle–Late Pleistocene glaciations. The types of moraines present in the study area are: ground, lateral, medial and terminal. The highest ground moraines are located at the two tributaries of the Kokkinochoma at elevations 2640–2660 m and 2500–2590 m. There is also another at 1690–1910 m. Two lateral moraines extend at elevations of 2335–2460 m and 1780–2140 m. A medial moraine is at 1835–1920 m. Finally, there is a terminal moraine at 1677–1765 m (Figures 4B and 6). In most cases, the particle size of the tills is unsorted and heterogeneous, with the larger elements reaching 30 cm in size. The finer matrix decreases significantly from the upper ground moraines to the lower ones. Remnants of well-cemented scree and glacio-fluvial deposits at elevations ranging from 1230 to 1475 m at the base of the cirque were also observed (Figure 4A, B).

A type of stream derangement seems to have occurred in the upper reaches of the Lazi Griva and Kokkinochoma. In Figure 7A, a cross section of the Kokkinochoma valley parallel to Lazi Griva shows a downcutting of 240 m. The longitudinal profile of Kokkinochoma from the cirque to the confluence with the Ziliana exhibits a normal concave-shaped curve (Figure 7B).

At the confluence of Kokkinochoma and Ziliana streams, there is an 18–20 m originally alluvial cone and today a terrace has formed (Figure 8A, B). It is well-cemented, composed primarily of limestone materials ranging from sands to gravels and cobbles not larger than 25 cm (Figure 8C). The deposits lack well-defined stratification and are not affected at all by weathering.

The upper part of core OLK-1 is characterised by low energy, fine grained, mainly muddy, deposits interrupted by several sandy layers, while the intermediate part consists mainly of silty and the lower part of high-energy sandy deposits. Several horizons rich in organics were recorded throughout the core, with the most distinct ones at 5.12 m, 5.30 m, 13.48 m, 15.90 m and 20.65 m. Charcoal fragments were found throughout the fine grain deposits, visible with naked eye in the first 2.30 m

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Table 2 Core OLK-1 lithology description

Depth (m)	Lithology
0.00–0.70	Grey silt with charred coal and root remains
0.70–0.90	Brown mud
0.90–1.24	Sand with coarse pebbles
1.24–2.30	Brown to dark brown mud with peds, charred coal and root remains
2.30–2.55	Fine white/grey/light olive brown/olive yellow laminations
2.55–3.00	Dark grey mud
3.00–3.26	Sand with coarse pebbles
3.26–4.00	Dark grey mud
4.00–4.30	Sand with coarse pebbles
4.30–5.08	Yellow brownish gradually turning to olive brown mud
5.08–5.38	Fine alternations of organic rich mud and fine sand horizons. Organic rich layers observed at 5.12 m and 5.30 m
5.38–6.30	Sand with coarse pebbles
6.30–7.30	Yellow brownish gradually turning to dark greyish brown mud interrupted by a fine sand horizon at 7.00 m depth
7.30–9.00	Sand with pebbles
9.00–11.30	Dark grey silt. A fine sand layer is observed between 9.50 and 9.80 m
11.30–12.00	Sand with coarse pebbles
12.00–12.40	Coarse sand with pebbles
12.40–12.80	Sand with coarse pebbles
12.80–13.80	Dark grey silts alternated with fine sand horizons. An organic rich layer observed at 13.48 m
13.80–15.20	Sands interrupted by a silty horizon at 14.55–14.65 m
15.20–16.65	Dark grey silts alternated with fine sand horizons between 15.30 and 15.55 m and at 16.45m. An organic rich layer observed at 15.90 m
16.65–17.30	Fine sand
17.30–18.00	Dark grey silt
18.00–20.00	Fine sand
20.00–20.65	Dark grey silt. An organic rich layer observed at the base of the layer
20.65–25.00	Fine sand

of the core, but also present as microscopic charcoal in the rest of the deposits. Detailed lithology of the core is provided in Table 2 and featured in Figure 9.

The microscopic study of the microfossils samples revealed no evidence of calcareous micro-fossils, such as ostracods or molluscs. On the contrary, the samples were rich in microscopic charcoal, as stated above and in the interval levels 5.08–5.38 m, 13.30–13.60 m and 15.80–15.95 m. The occurrence of several *Carex* sperms has been recorded. *Carex* is a common plant in wetland and lakeshore environments in Greece and could be connected to wet meadows (Grigoriadis *et al.* 2005) or telmatic conditions (Christanis 1994). They generally avoid drier meadow zones because they cannot survive the very dry conditions in summer (Grigoriadis *et al.* 2005; Lenssen *et al.* 1999). A detailed micropalaeontological study of the entire sediment core is planned, including a study of siliceous microfossils such as diatoms. All of the above indicates the presence of a glacial mountain lake or marsh during the Late Quaternary (Figure 10).

The existing drainage network of the Ziliana stream has eroded the lacustrine sediments vertically down to about 20 m immediately upstream from the natural dam of Kokkinochoma (Figure 11). In the area of the drilling site (N 39° 58′ 29″, E 22° 25′ 24″), the downcutting is about 17 m.

Discussion

The areas of all seven cirques tend to be rather large and are located at the highest elevations (apex and lip) in relation to other cirques of Greece. Regarding amplitudes, the mean value (M = 300 m) is lower than those of other European areas and Epirus. For example the mean amplitude of 206 cirques from the Central Pyrenees is 364 (García-Ruiz *et al.* 2000), and for 432 cirques from the western Alps is 355 m (Federici and Spagnolo 2004). In Epirus, the mean value for 23 limestone cirques is 396 (Hughes *et al.* 2007). It is worth mentioning that even among the seven cirques in the study area there is a significant difference in their development between the northern four (M = 335 m) and the southern three (M = 253). This can be easily explained by the position of the cirques located in the windward side and those found in the leeward.

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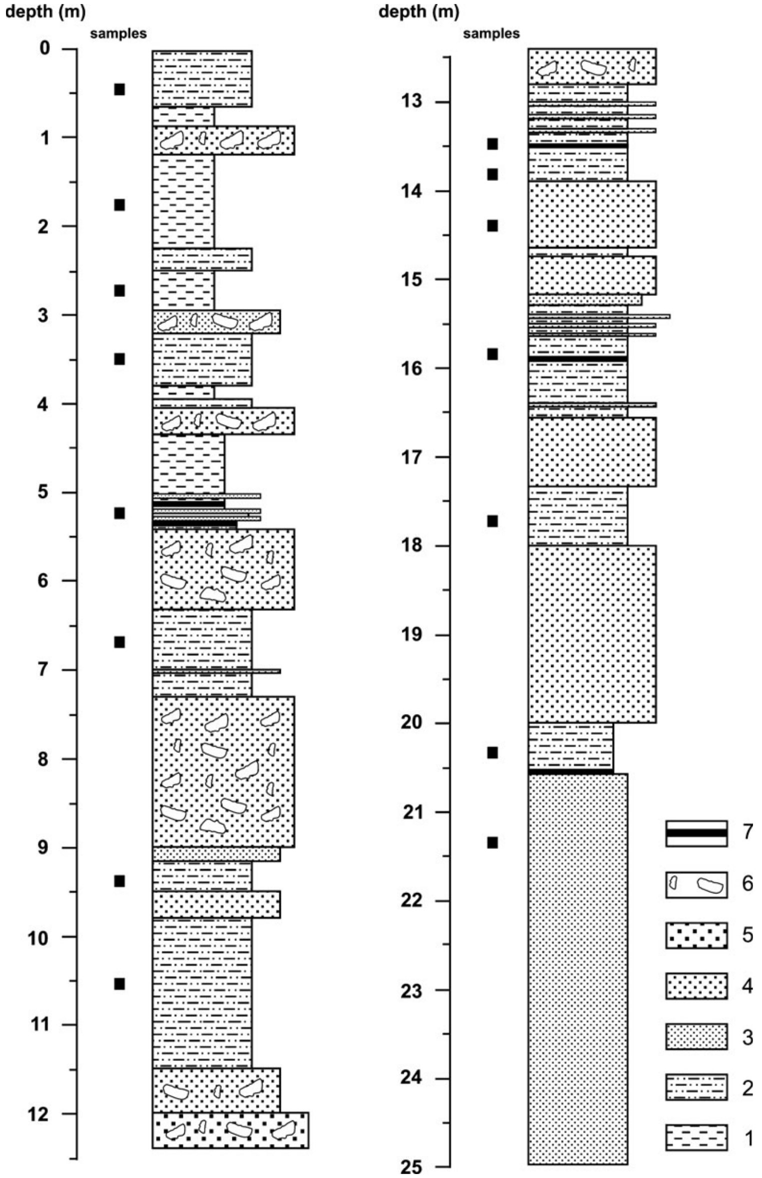

Figure 9 Lithology of core OLK-1: (1) mud, (2) silt, (3) silty sand, (4) fine sand, (5) sand, (6) pebbles, (7) organics horizons. The exact levels of the micropalaeontological samples are indicated

An extreme case of width value (2203 m) is observed in S1 cirque (Table 1), giving the impression that it might not be a cirque after all or is an older one that remained inactive during the last glaciation. The presence of remnants of well-cemented glacio-fluvial deposits at an elevation ranging from 1230 to 1475 m at the base of the cirque indicates the existence of a cirque glacier probably from a former glaciation.

The W/A ratio means that incision in the north is much more advanced than in the south and probably the northern cirques are products of multiple repeated older glaciations. However, the tectonic uplift of Mount Olympus was calculated to be 1.3 mm/year over the last 250 000 years (Smith *et al.* 1997; Nance 2010). If this rate holds true for MIS 12 (*c.*350 000 years), then the total uplift of Mount Olympus should be *c.*455 m. This is a significant elevation difference for cirque formation. Therefore, the weaker south-facing cirques were not only the product of the biggest and coldest Middle Pleistocene glaciations, but also of the more recent one.

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Figure 10 Panoramic view of the former lake

Figure 11 Intense downcutting of the lacustrine deposits forming an erosional scarp of at least 17 m

A study published by Smith *et al.* (1997) on the Quaternary glacial history of Mount Olympus concluded that there were three glacial periods in the northern parts of the mountain (MIS 8, 6 and 4). Similarly, Hughes *et al.* (2006a) and Woodward *et al.* (2008) have recognised three glacial periods in the northern Pindus Mountains extending back to MIS 12.

The moraines of S2, S3 cirques reach down to 1677 m altitude. These are located much higher than the wetter parts of Epirus (Mount Tymphi), where moraines reach down to 850 m altitude on similar south-facing slopes (Hughes *et al.* 2006b). If Olympus moraines were placed in the colder climate of MIS 12, they should have been deposited *c*.455 m lower due to the tectonic activity of the area. It is worth mentioning that just downstream from the terminal moraines there is a deep gorge (Figure 6), which probably blocked the movement of moraines down the valley to lower elevations.

Regarding the tills, the percentage of coarser materials remains at the same level in lower elevations as the finer material is washed downstream in larger amounts.

The stream disorder of Lazi Griva and Kokkinochoma streams indicates that the upper reaches of Lazi Griva were cut off by Kokkinochoma stream following intense glacio-fluvial activity during the end of a glacial period when rapid melting of the glaciers occurred. The intense downcutting of about 240 m of Kokkkinochoma stream indicates that this catchment rearrangement happened during glacial periods MIS 6 or even 8. The extensive alluvial fan formed at the exit of Mount Olympus by Lazi Griva stopped evolving in the Middle to Late Pleistocene (Psilovikos 1981; Skilodimou *et al.* 2014), which coincides well with the results of this study.

The aforementioned alluvial cone of Kokkinochoma at the confluence with Ziliana stream resulted in the damming of the stream and the formation of a lake; in recent times the cone eroded leading to the lake emptying.

The occurrence of a water body in the area is documented by the presence of aquatic vegetation, e.g. water sedges sperms in the core samples. Further detailed paleobotanical–palynological analysis of the deposits would shed light on the exact palaeoenvironmental conditions of the area during this period.

Conclusions

The southern Mount Olympus area has undergone intense glacial activity leading to landscape changes. The evolution of three cirques has led to the formation of various types of moraines (ground, lateral, medial and terminal) down to 1677 m.

Further downstream, the intense glacio-fluvial activity of Kokkinochoma stream resulted in the severing of the upstream part of Lazi Griva stream. There followed the transportation of glacio-fluvial sediments down to the Ziliana stream, which eventually blocked the main stream and formed a glacial lake.

The stratigraphical analysis of a 25-m core in the middle to lower parts of the glacial lake proved that the upper part of the core is characterised by fine grained, mainly muddy, deposits interrupted by several sandy layers, while the intermediate part consists mainly of silty deposits and the lower part of sandy deposits. The

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occurrence of a water body in the area is documented by the presence of aquatic vegetation.

In recent times the lake broke through the fluvial deposits of Kokkinochoma stream, eroding them and leading to the lake emptying. The study is continuing with an emphasis on more detailed analysis of the lacustrine deposits, including absolute dating and better understanding of the landscape evolution of the study area.

Acknowledgments

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