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THE SIGNIFICANCE OF TECTONISM IN THE GLACIATIONS OF GREECE

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1. INTRODUCTION

In the Mediterranean region, glaciers extended throughout the high mountains during the Pleistocene Epoch (Hughes and Woodward, 2009). Many researchers reported several areas with evidence of Pleistocene glacial activity in upland Hellas (Mistardis, 1952; Messerli 1967; Palmentola et al., 1990; Nemec and Postma, 1993; Smith et al., 1997; Woodward et al., 2004; Hughes et al., 2006). In Greece, Middle to Late Pleistocene mountain glaciations appear to have been quite extensive, along the mountain range of Pindus, on Mt. Olympus and in the highlands of Peloponnesus (Bathrellos et al., 2014). This study focuses on the Middle to Late Pleistocene glaciations based on the examination of cirque formations and their elevation changes due to vertical tectonism, in certain parts of Greece, namely, Mt. Olympus, Peloponnesus and Crete.

2. STUDY AREA

Greece is characterized by mountain chains, most of them trending from NNW to SSE, and many summits have altitudes higher than 2000 m (Fig 1). Most of them are located along the Pindus range, the isolated Mount Olympus, and a few peaks in Peloponnesus and Crete. The study covers the administrative units of Greece which are Macedonia, Epirus, Thessaly, Sterea Hellas, Peloponnesus and Crete (**Fig. 1**).

Greece has a characteristic Mediterranean climate with relatively cold and wet winters and hot and dry summers. The annual precipitation of mountainous Greece ranges from 1000 mm to 2000 mm while the average temperature ranges from 10oC to 15oC (Proutsos et al., 2010). Climatic conditions during the LGM were -8oC colder than present (Bush and Philander, 1999) and mean annual precipitation was c. 2300±200mm in the high mountains of Pindus (Hughes et al., 2006).

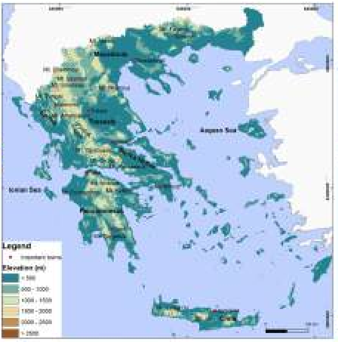

FIGURE 1: Map with elevation classes and important mountains of Greece.

3. DATA AND METHODS

The data collected for this study include 36 topographic maps (scale 1:50,000) published by the Hellenic Army Geographical Service (H.A.G.S.), along with 31 geological maps of Greece at scales 1:500,000 and 1:50,000 published by the Institute of Geology and Mineral Exploration (IGME). They were used to identify the location of cirques and their geologic composition.

An initial spatial database of these glacial forms was created including their location and mean elevation. Some of the glaciated sites have been taken from previous literature and others were recorded from topographic maps, air photos and field work. ArcGIS 10 software was used to process the glaciated sites. A map depicting the glaciated areas of Greek regions was compiled with over 230 cirques. A cirque's top, lip and margins of each location were mapped. So altitudes of apex and lip and mean altitude of each cirque ([apex+lip]/2), were calculated (**Fig. 2**).

FIGURE 2: Measurement of morphometric variables of a cirque on Mount Parnassus.

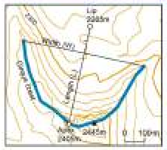

FIGURE 3: Spatial distribution of cirques in the six study regions of Greece.

4. RESULTS

A total number of 227 inactive cirques was recorded (**Fig. 3**) with limestone as the dominant lithology. The area of lithological formations which participate in the structure of cirques was calculated as follows: 82.6 km2 of the total area (94.9 km2) is composed of limestones, 6.6 km2 by flysch, 4.7 km2 by ophiolites and rarely volcano-sedimentary formations, 0.9 km2 by marbles, phyllites, and schists. Since the vast majority of cirque areas are occupied by limestones (87% of the total area), further statistical analysis was performed only on them. **Table 1** summarizes the mean values together with minimum and maximum figures of all the morphometric parameters of cirques formed on limestones. This means that the other lithologies do not significantly affect the mean values of the various parameters used in this study.

Figure 4 depicts the number of cirques on limestones in the six regions of Greece. The number of cirques decreases, as one moves from north to south. **Figure 5** represents the geographical position of each cirque in comparison with its area in each study region. There is a parabolic relation between the two parameters where the small cirque areas are distributed everywhere from south to north, while the large areas increase significantly along the same Y (latitude) meters, in the north.

The relation between mean elevations and number of cirques is shown in **Figure 6**. Interestingly, the six regions are separated in two groups namely: Macedonia and Crete are at higher mean elevations, while Epirus, Sterea Hellas, Thessaly and Peloponnesus are at lower elevations. However, in Peloponnesus a much steeper increase in mean elevations is observed. The higher figures may be the result of the rapid Quaternary uplift of northern Peloponnesus (Armijo et al., 1996) as compared to the southern part.

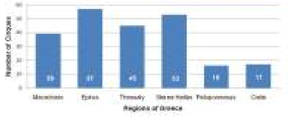

FIGURE 4: Bar graph depicting the number of limestone cirques in the six study regions of Greece.

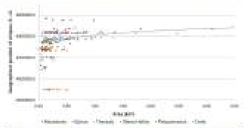

FIGURE 5: Geographical position of each limestone cirque related to its area in each study region. All values are fit in an estimated logarithmic model.

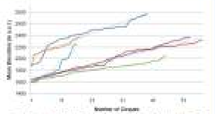

FIGURE 6: Line graph illustrating the mean elevation of limestone cirques in the six study regions of Greece.

5. DISCUSSION

Cirques occur at altitudes varying from 2770 to 1600 m.a.s.l. In general, as one moves to the south, in the case of Pindus range and its extension in the Peloponnesus and Crete, the number of cirques decreases (**Table 1**).

In the decrease of the number of cirques from north to south (**Fig. 4**) we can maintain that although mean cirque elevations stay about the same (1850-2200 m.a.s.l.) the areal extent of glaciations in the six regions varies from north to south. The latitudinal decrease of the cirques is also affected by temperature increases and precipitation reduction. The high cirque area diversification observed in the north (**Fig. 5**) is owed to the more severe climatic conditions present during the glacial periods.

In Greece, there are no straightforward studies related to the role of uplift and evolution of cirques in various glacial periods. Uplift has no doubt taken place, but it is not easy to be sure about precise values and it is spatially very variable across Greece. Concerning the distribution of the mean elevations of cirques in the six regions (**Fig. 6**), one should take into consideration the tectonic activity of each study area. Especially in the areas of Mount Olympus, Peloponnesus and Crete this process is in the form of uplift. For example, the uplift of Mount Olympus was calculated to be 1.3 mm/y in the last 250,000 y (Smith et al., 1997), so the respective mean elevations of cirques at that time (MIS 8) should have been about 325 m lower than those measured in the field today.

Additionally, a mean uplift rate of about 1.5 mm/y over the last 350,000 y was estimated for the central part of northern Peloponnesus (Armijo et al., 1996). So, the relevant mean elevations of the cirques in this area (MIS 10) should have been around 525 m lower than measured today. Since the mean elevation of these cirques (n=10) is 1940 m today and 350,000 y ago was around 1415 m, a significant number of them were most probably formed during the last glacial period (LGM). In the case of Mt.Taygetos, the mean uplift rate was calculated at 0.55 mm/y during the Middle Pleistocene (Mariolakos et al., 1994). Thus, the mean elevations of the cirques in this area (MIS 10) should have been around 190m lower than today. Therefore, the evolution of the cirques of northern from those of southern Peloponnesus is clearly significantly different in time.

In central and western Crete the mean uplift rate was 1-1.2 mm/y during the last 1Ma (Roberts et al., 2013). So, in the last 250,000 y the mean elevations of cirques at that time (MIS 8) should have been about 300m lower than those today. Although these figures are almost the same of Mt. Olympus, one should not forget that the mean elevations of the cirques of the latter are about 230m higher than those of Crete. More importantly, the geographic location of Mt Olympus is much farther to the north than Crete so the preservation of mountain glaciers is much harder in the south.

TABLE 1: Morphometric parameters (maximun, minimum and mean value) of cirques formed on limestones: area (in Km^2), altitudes of apex and Lip, mean altitude in meters.

Macedonia: 39 cirques				
	Area	Apex	Lip	Mean altitude
Max	3.1	2900	2700	2770
Min	0.1	2040	1620	1880
Mean	0.6	2559	2277	2418
Sum	21.7			
Epirus: 57 cirques				
Max	2.5	2420	2240	2320
Min	0.1	1700	1500	1600
Mean	0.4	2161	1853	2007
Sum	24.8			
Thessaly: 45 cirques				
Max	3.5	2280	1940	2060
Min	0.1	1700	1500	1620
Mean	0.5	1964	1663	1813
Sum	21.9			
Sterea Hellas: 53 cirques				
Max	0.6	2480	2300	2370
Min	0.06	1700	1600	1650
Mean	0.2	2083	1899	1991
Sum	9.6			
Peloponnesus: 16 cirques				
Max	0.3	2280	2220	2250
Min	0.04	1700	1600	1650
Mean	0.1	1931	1779	1855
Sum	2.3			
Crete: 17 cirques				
Max	0.5	2440	2320	2360
Min	0.10	1920	1820	1870
Mean	0.2	2275	2096	2186
Sum	4.2			

6. CONCLUSIONS

- In Greece, a total number of 227 inactive cirques was recorded covering an area of 84.5 km^2 with limestone as the dominant underlying lithology.
- As one moves to the south, the number of cirques decreases. Cirques occur at altitudes varying from 2770 to 1600 m.a.s.l. Thus, favorable conditions for glacier formation are more likely at altitudes higher than 1600 m.a.s.l.
- The uplift of Mount Olympus, Peloponnesus and Crete has increased the mean elevation of the cirques in every following ice age. So, in older times many cirques were a few hundred meters lower than the more recent glacial period. In northern Peloponnesus for example, mountain peaks with a mean uplift rate of 1.5 mm/y, were about 500 m lower than present during MIS10.

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