Glacial cirque morphometry of Rila and Pirin Mountains (Bulgaria)

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I. Introduction

Glacial cirques are typical landforms of formerly glaciated high mountains, which also play an important role in paleoclimate reconstruction. In Bulgaria, the **Rila** (Musala 2925 m) and **Pirin** (Vihren 2914 m) Mountains were the only largely glaciated ranges during the Pleistocene glaciations. A comprehensive quantitative geomorphometric analysis of glacial cirques enables to reconstruct the paleoenvironmental conditions that led to their formation (*Barr and Spagnolo, 2015*).

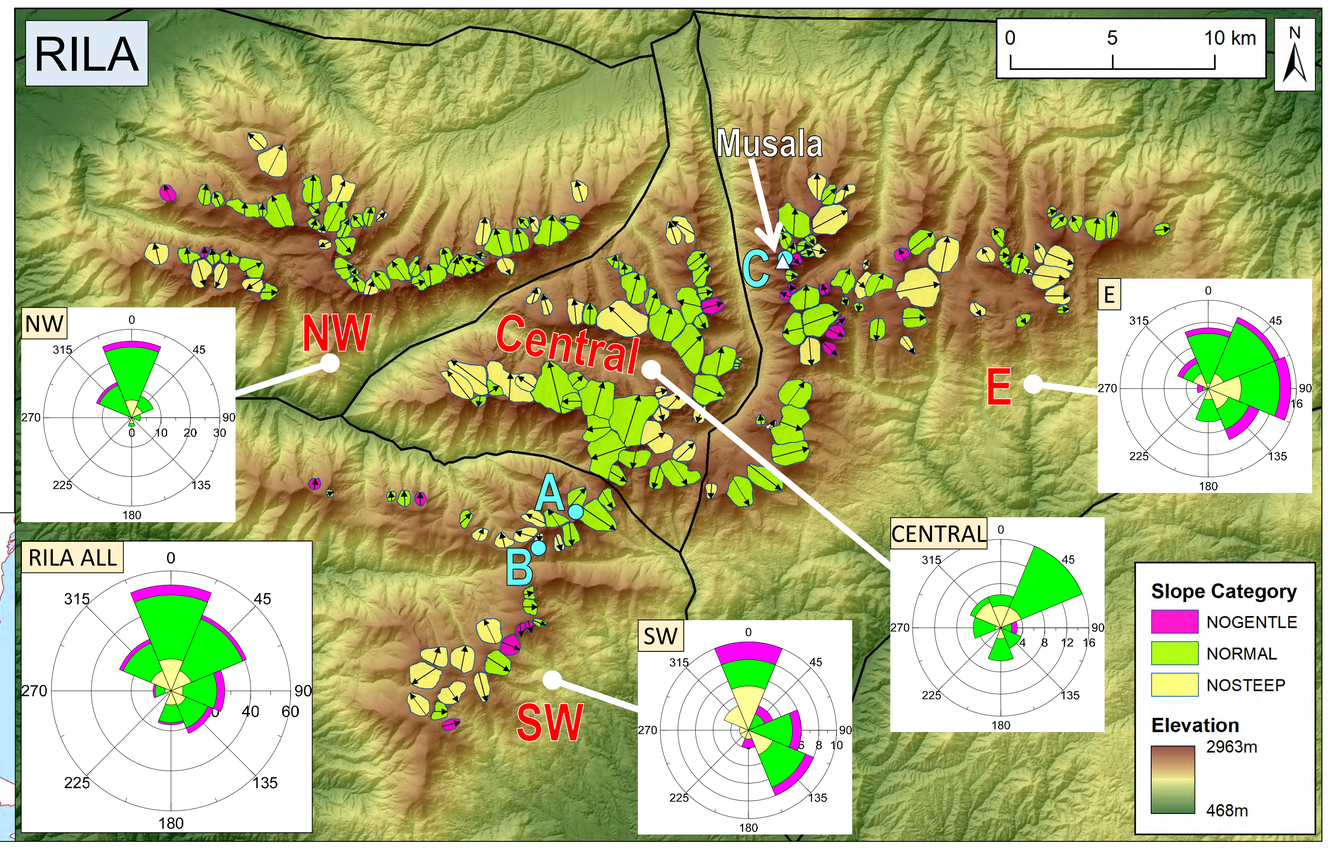
Main objectives of the study:

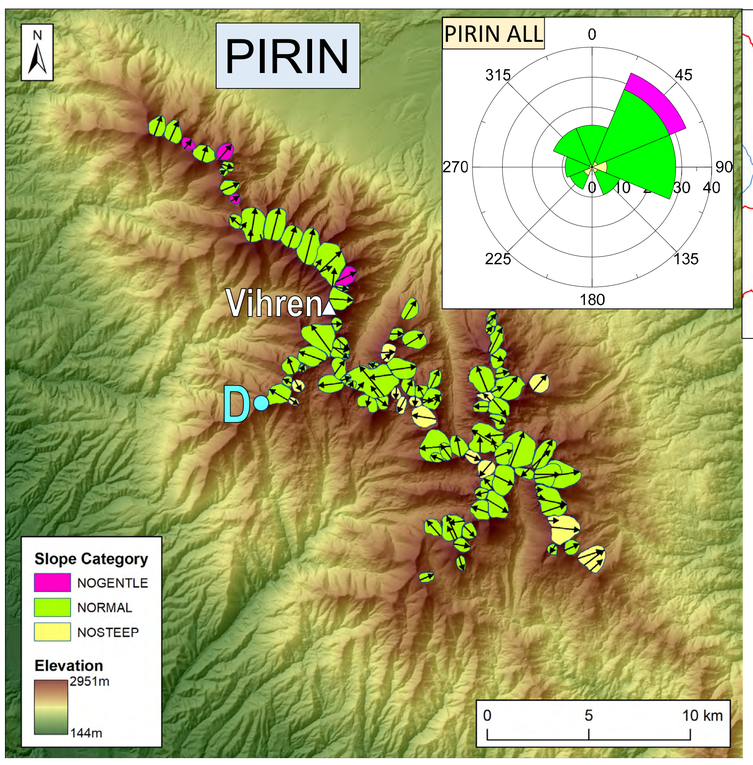
- ❖ Test the GIS cirque morphometry tool ACME2 (developed by *Li et al. 2024*)
- ❖ Analyse the distribution of cirques with different size and shape parameters
- ❖ Find spatial relationship between size and shape characteristics related to aspect and elevation.
- ❖ Infer paleoenvironmental conditions from the spatial pattern of the cirques.

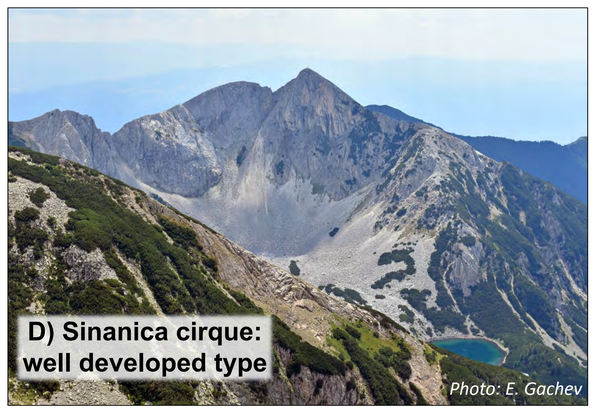
II. Study Area

Rila Mountain has a dome shape and its relief is dominated by relics of **planation surfaces** at about 2400–2600 m a. s. l. (*Kuhlemann et al. 2013*). The mountain is dissected into four main parts: Eastern, Central, Northwestern and Southwestern Rila. The main building rocks are intrusive and metamorphic silicate rocks. ***Pirin Mountain*** consists of one main ridge with orientation NNE-SSW with several transverse branches. It has a more diverse geology than Rila with granitic intrusions and metamorphic rocks. **Marbles** occupy considerable areas, especially in the northern part, giving home to a well-developed **glacio-karstic relief** *(Gachev 2017).*

In the Pleistocene glacials, both mountains were glaciated. **Valley glaciers** were present in both mountains (the longest in Rila: 22km; in Pirin: 13km), and some **ice caps** also existed in Rila. The maximum ice extent was 430 km^2 in Rila and cca. half of it in Pirin. The present climate is temperate mountain climate with some Mediterranean influence, especially in Pirin (1000-1100 mm annual precipitation in the top region).







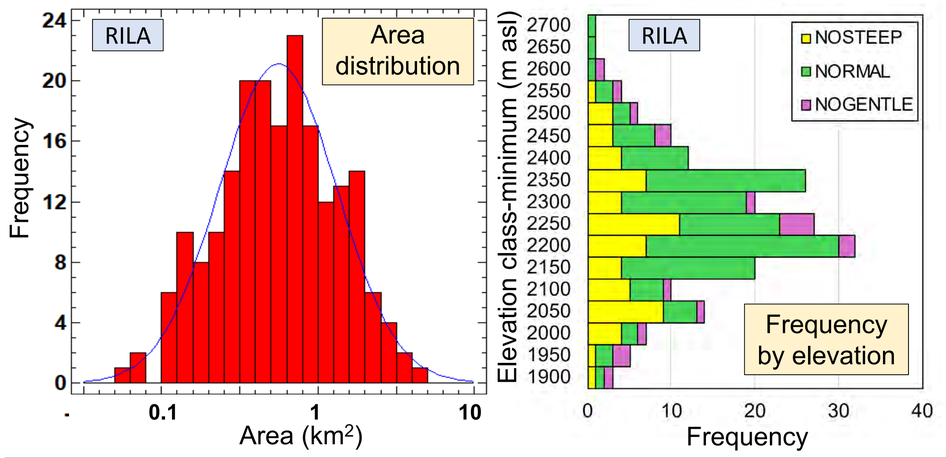
III. Methodology

Cirques were manually delineated using different DTM-based GIS layers: elevation, slope categories, contour lines, hillshades, aerial and satellite imagery. The horizontal resolution of the used DTM is 10 m.

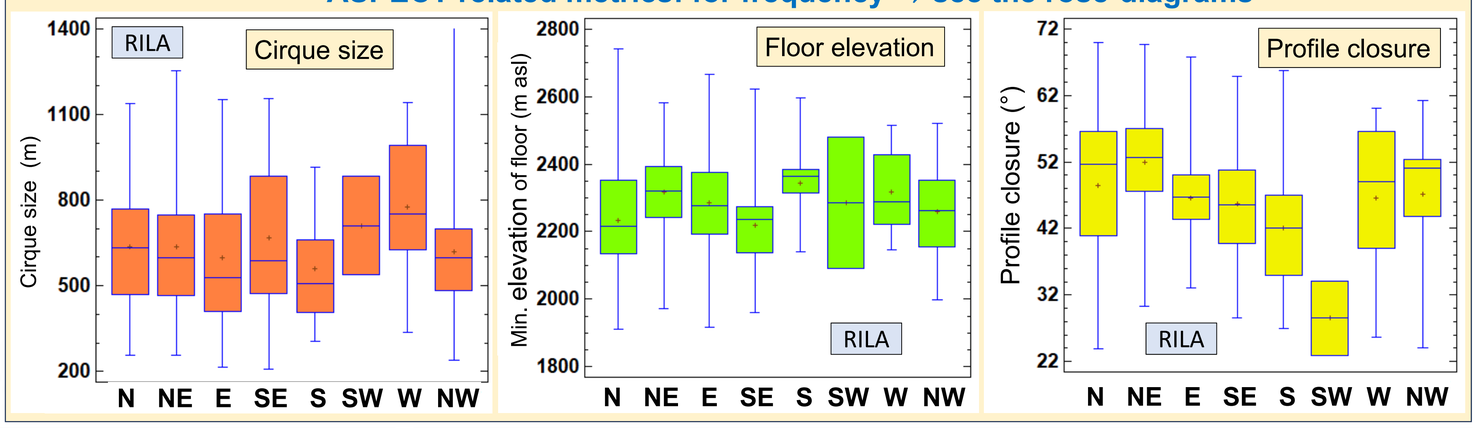
ACME2 tool (*Li et al. 2024*) was used to calculate a wide range of morphometric parameters (area, length, width, height; elevation statistics, slope statistics, axis length and direction among many others.)

Cirque size = $\sqrt[3]{L \times W \times H}$, **Profile closure** = MaxSlope – MinSlope (including all pixels)

Slope categories: **NOSTEEP** = Proportion of slopes less than 20° < 15%,
NOGENTLE = Proportion of slopes greater than 33° < 15%,
NORMAL = none of the above



ASPECT related metrics: for frequency → see the rose-diagrams



IV. Results

- ❖ Several types of cirques were identified from **embryonic to well developed**. “NORMAL” includes typical cirques with steep headwalls and flat bottom (Rila: 59%; Pirin: 82%), “NOSTEEP” includes flat and shallow cirques (Rila: 32%; Pirin: 13%), “NOGENTLE” includes cirques without flat floor (Rila: 9%, Pirin: 5%). Both “NOSTEEP” and “NOGENTLE” are “poorly developed”. These are much more frequent in Rila than in Pirin.
- ❖ The size distribution of the cirques is **lognormal** for both mountains probably due to their growth by multiplicative processes (cf. *Mitzenmacher 2004*). Rila cirques are 23% larger in area than Pirin cirques.
- ❖ The **number of cirques** is the largest towards the N and NE in most parts of the Rila, NE and E for Pirin.
- ❖ Meanwhile, the **size of cirques** is the largest towards W and SW (Rila), W and NW (Pirin).
- ❖ The **floor elevation** has a cca. 100 m north-south difference in Rila, but otherwise its relation with aspect is complicated, influenced by several factors (e.g. size, development of cirques). The same for Pirin.
- ❖ The **profile closure** characterizes in some way cirque development. The highest values are typical of N, NE, NW, W aspects (in Rila and Pirin alike). This refers to more developed cirques in these directions, i.e. larger ice accumulations on these sides of the ridges.
- ❖ The ACME2 tool is highly useful in cirque morphometry. However, we found errors in some slope parameters.

V. Conclusions

Cirque directions are clearly influenced by the **strike of the major ridges**, which is demonstrated by the rose diagrams of the different parts (NW, SW, Central, E) of Rila Mt.

Cirque evolution is in connection with the **large planation surfaces** present especially in Rila Mt. The large but shallow (“poorly developed”) W, SW cirques are carved in the planation surfaces, whereas the E, NE, N cirques are connected to the steep ridges.

The large number of N and NE exposed cirques are in accordance with the significant lack of direct sunshine on these sides indicative of open sky conditions during the glaciations. Further on, it may also point to **snow-redistribution** by wind to the luv side of the ridges.

Cirque development parameters show that northerly and westerly exposed cirques are the most developed suggesting that the Pleistocene glaciation pattern in the Rila and Pirin Mts was dominated by the **continental setting of the range**: limited cloudiness enabled the aspect dominated cirque development, and also probably the significance of westerly winds in snow accumulation and thus cirque development.

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