Late Pleistocene ELA trend in the Eastern Carpathians

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Reconstruction of the former equilibrium line altitude (ELA) of mountain glaciers is useful paleoclimate tool. The spatial distribution of ELA provides information concerning the summer temperature and annual precipitation and could be used to infer the pattern of moisture advection and orographically induced precipitation in the past (Allen et al., 2008; Cuffey and Paterson, 2010; Rea et al., 2020). In the Eastern Carpathians of Ukraine and Romania the legacy of Late Pleistocene glaciation is preserved in several isolated mountain massifs standing above 1600-1800 m (Fig. 1). This area acts as a regional orographic barrier for North Atlantic Westerlies that travel preferentially from the northwest and continental pressure system from the east (Micu et al., 2015). Therefore, this region may document the magnitude and extent of the zonal atmospheric circulation across the interior of the continent during glacial maxima as the Last Glacial Maximum (LGM). Despite a long glacial research history dating back to late 19th century (Paul and Tietze, 1876), this region represents one of the least explored areas in terms of glacial geomorphology in Europe mostly due to a lack of comprehensive mapping of ice-marginal landforms in a poorly accessible and densely forested area.

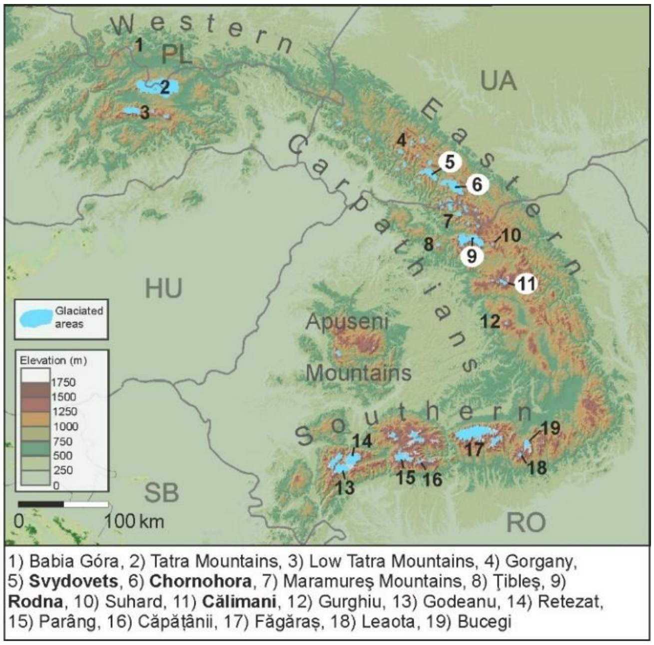

Figure 1 Location of the Eastern Carpathians with marked selected mountains in the Carpathians where evidence of glaciation has been identified. White circles mark the mountain massifs discussed in the text.

The new geomorphological mapping campaign established in the Ukraine and Romanian part of the eastern Carpathians (Kłapyta et al., 2021a, b) provides an opportunity to reveal the pattern of regional ELAs during the maximal extent of the Late Pleistocene glaciation which have probably formed during the global LGM (26-19 ka). Based on geomorphological data, we reconstructed the extent and ice-surface geometry, and determined the ELA using the Area-Altitude-Balance-Ratio method for 90 palaeoglaciers in the Svydovets (1883 m asl), Chornohora (2061 m asl), Rodna (2303 m asl) and Călimani Mountains (2100 m asl), representing the highest mountain massifs in the Eastern Carpathians (Fig. 1).
Our data show an increase in the ELA rise towards SE from 1400 m asl to 1516 m asl. in the Svydovets and Chornohora massifs, respectively, through 1697 m asl in the Rodna Mountains and up to 1869 m asl in the Călimani Mountains. The reconstructed ELA trend mimics the present-day precipitation pattern in the region, with the highest precipitation levels documented in the Ukrainian Carpathians and the lowest in the SE part of the Eastern Carpathians. The distribution of ELA is closely related to the trend of the cirque floor (Mîndrescu et al., 2010; Kłapyta et al., 2021) which shows a rising tendency from the Ukrainian Carpathians (1548 m asl), through the Maramureş Mountains (1591 m asl) and Rodna (1749 m asl) up to 1804 m asl in the Călimani Mountains (Mîndrescu and Evans, 2014; Mîndrescu 2016; Kłapyta et al., 2021b).
The positive SE cirque and ELA gradients were controlled by preferential winds and moisture transport from the northwest, which, due to orographically induced precipitation, produced the largest amounts of precipitation that fed glaciers across the Svydovets and Chornohora massifs and moisture starvation farther south in the Rodna and Călimani mountains, where ice accumulations were reduced to the highest elevation. This suggests that the dominant W-NW precipitation regime during the LGM was similar to present-day conditions, but may have become strengthened in full glacial conditions. Such a pattern of atmospheric circulation during the LGM in the Eastern Carpathians is in agreement with cirque distribution in the Romanian Carpathians (Mîndrescu et al., 2010) and aeolian evidence (i.e. Pleistocene dunes, yardangs, loess features) found around the Carpathians (Sebe et al., 2011; Różycki, 1967).
Taking the ELAs, cirque floor altitudes and mountain hypsometry we also quantitatively discussed the glaciation style in the Eastern Carpathians. We found that the style of glaciation is largely controlled by the relation between the height of the mountain range with respect to the former ELA (Kłapyta et al., 2021b). The higher summits rise above ELA, the more symmetrical glaciation (N-S slope glacier distribution) are developed and commonly larger and complex cirques on various aspects are formed (Evans, 1977). Our data show that the cirque glaciation with strong asymmetry is initiated when mountain ranges stand at least 100 m above the ELA. Such asymmetric style of glaciation dominate in the Eastern Carpathians with only single exception of mountain ridges rising 300 m above the LGM ELA. The example is the main ridge of Chornohora between Mount Hoverla and Pip Ivan, which raised highest above the LGM ELA (324 m) and therefore has experienced the strongest glacier modification (Kłapyta et al., 2021b) (Fig. 2).
This is expressed by quite a symmetrical glacier development on both NE and SW slopes (Fig. 2A) and the presence of a large number of cirques, including complexes of inner and outer cirques (Fig. 2C) and a presence of typical valley glaciers with a length of 5-6 km. Although the mountain ridge of Chornohora is 110 m lower compared to the Rodna Mountains, the ELA descended there ~50 m lower below the mountain ridge compared to the Rodna Mountains. Because of that Chornohora was the most glaciated massif in the Eastern Carpathians. Compared to the Rodna Mountains, the Chornohora massif had the largest glaciers (2.51 vs. 1.13 km^2) and a greater total glaciation area (51.6 vs. 45.2 km^2) in addition to a similar mountain area of mountains (approx. 900 km^2). Furthermore, the Chornohora had the largest and the longest glaciers in the entire region. The Prut valley glacier was the largest valley

glacier in the Eastern Carpathians with 11.3 km^2 of area and a length of 6.6 km with front descending to 1045 m asl (Fig. 2).

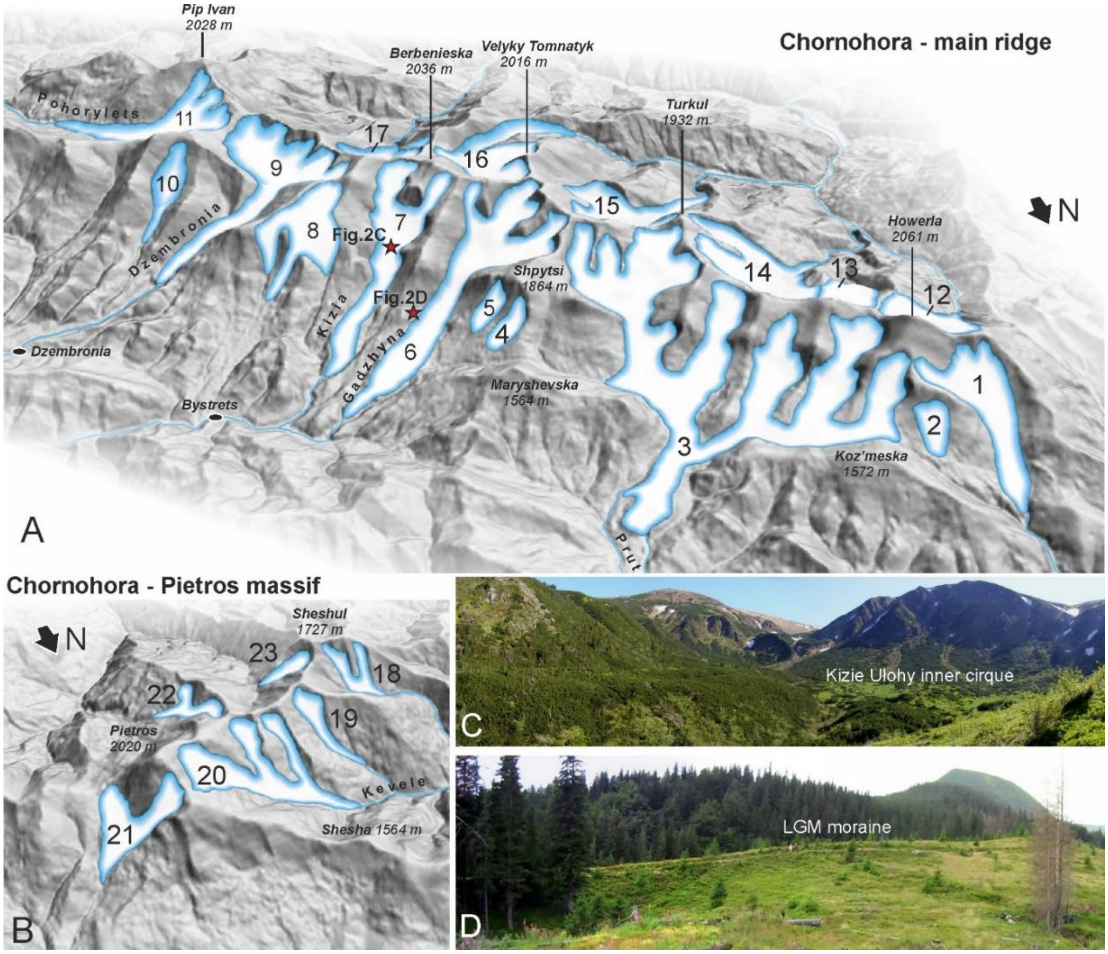

Figure 2 Glacier distribution in the Chornohora massif during the LGM advance according to Kłapyta et al. (2021b). Numbers refer to glacier symbols. Asteriks mark the location of Figs. 2C and D. A – The main ridge of Chornohora between Mt. Hoverla and Pip Ivan. B – Mt. Pietros massif. C – Example of compound glacial cirque in the Kizia valley. D – Prominent right lateral moraine in the Gadzhyna valley.

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