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RESEARCH HISTORY ON THE TATRA MOUNTAINS GLACIATIONS

Abstract. In this paper, we provide a brief history of glacial geomorphologic research in the Tatra Mountains with a special focus on glacial chronologies. We provide critical comments on previously published glacial chronologies and identify relevant gaps in knowledge on Tatra mountain glaciations suggesting future challenges and the focus of scientific research. Distinct differences in applied methodologies, presented conceptions, and research paradigms over 160 years of research enable us to distinguish four phases of scientific research on Tatra mountain glaciation (pioneer phase, mapping phase, geochronological phase and meta-analysis phase). These four phases follow the universal sequence of glacial geomorphologic research history defined by P.D. Hughes et al. (2006) and P.D. Hughes and J.C. Woodward (2016) for Mediterranean mountain areas. In the last two phases, the glacial chronology was substantially supported with radiometric dating of landforms and sediments as well as paleobotanical data obtained from intra-moraine sites. The current meta-analysis phase of research provides dating techniques using terrestrial cosmogenic nuclide (TCN) exposure ages and glacier-climate modeling. The present-day TCN dataset for the Tatra Mountains includes 300 individual ages (^{10}Be and ^{36}Cl together). We underscore the fact that this dataset has substantially verified many key issues in the glacier geochronology of the Tatra Mountains. This is particularly true of the Last Glacial Maximum (LGM) – the Lateglacial chronology for which abundant datings are currently available and their number is still increasing. However, it is challenging to evidence the chronology and extent of the most extensive glaciation(s) (MEG).

Keywords: history of research, glaciation, glacial chronology, Tatra Mountains

INTRODUCTION

The Tatra Mountains are the highest massif in the Carpathian arc (Gierlachovsky Štit 2,655 m a.s.l.) and form an outstanding topographic culmination in the centre of the Western Carpathians. Among glaciated mountain ranges in the entire Alpine-Carpathian-Dinaric region, the Tatras are located at the northernmost (49°10'N) position. This unique climatic and topographic setting promoted relatively strong glaciation of the massif during the Pleistocene when compared to other Carpathian ranges (Fig. 1). The Tatras yield some of the best glacial landscapes in the Carpathians, with an abundance of glacial erosional landforms typical of the advanced stage of glacial transformation, including features such as large, deep cirque overdeepenings, overhanging cirque backwalls, aretés, and

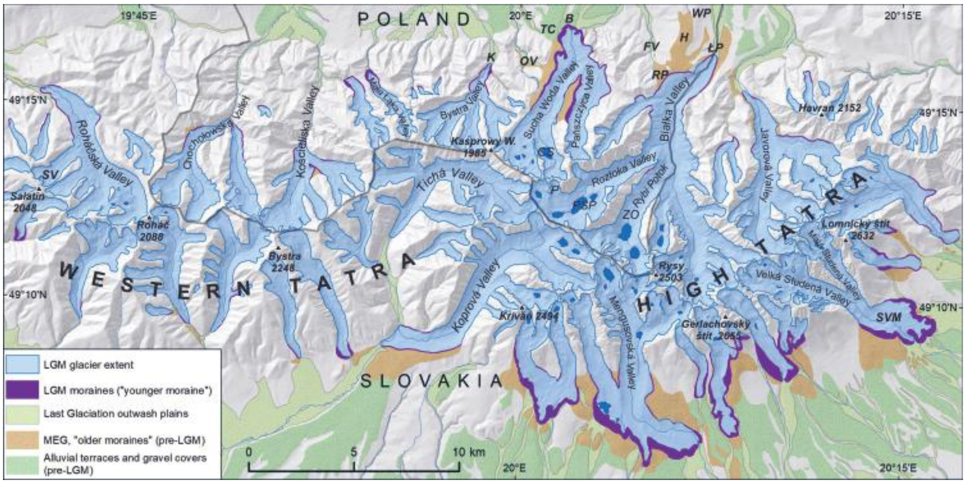

Fig. 1. Last Glaciation (LGM) and older glaciation(s) (pre-LGM) glacial and alluvial sediments in the Tatra Mountains after J. Zasadni and P. Kłapyta (2014), J. Zasadni et al. (2015) and references therein. Locations discussed in the text are shown on the map. SV – Salatínska Valley, K – Kuźnice, OV – Olczyska Valley, TC – Toporowa Cyrhla, B – Brzeziny, CS – Czarny Staw Gąsienicowy lake, FV – Filipka Valley, RP – Rusinowa Polana glade, H – Hurkotne cover, WP – Wierch Poroniec, ŁP – Łysa Polana, PSP – Pięć Stawów Polskich Valley, P – Pusta Valley, ZO – Żabie Oko lake, SVM – Studená Valley morainic amphitheatre.

paleonunataks. Conducive topographic conditions of low-relief southern foreland of the High Tatras promote the preservation of prominent Pleistocene morainic amphitheatres with multi-lobed geometry (Zasadni, Kłapyta 2014; Fig. 1). In contrast, on the northern slopes of the Tatra range, where past glaciers terminated inside the narrow valleys, smaller moraines can be found. Nevertheless, the glacier extents are well-traceable there because of the lithological contrast between Mesozoic bedrock and granite-dominated moraine material.

The Tatra Mountains have unique alpine-type relief which attracted researches for years A long geomorphological studies tradition in the Tatras dates back to the pioneer observations of S. Staszic (1815). It results in relatively better relief examination of the massif in comparison with other Central European mountains (Kotarba, Krzemień 1996). This study is focused on main phases and turning points in glacial geomorphological research. Starting with the work of L. Zejszner (1856), Quaternary glaciations have been studied for over 160 years in the Tatra Mountains. Over that period of time, many different and often contradictory conclusions on the number, timing and extent of glaciations were presented. Previous summaries on this research subject were presented by M. Lukniš (1973), M. Klimaszewski (1988) and more recently by B. Gądek (1998). The last decade, however, has witnessed an important increase in the number of publications and methodological progress in dating and resulting chronological datasets which verified many aspects of our understanding of Pleistocene glaciations of the massif.

We provide a synthetic overview of glacial research history of the Tatra Mountains with a special focus on glacial chronologies and stratigraphy. The main aims of this paper are: (1) to provide the background on the history of glacial research; (2) to examine the current state of knowledge regarding Pleistocene glaciation in the light of previous studies (3) to outline prospects for future studies.

We propose a subdivision of glacial research history in the Tatras on four distinct phases utilizing P.D. Hughes et al. (2006) and P.D. Hughes and J.C. Woodward (2016) scheme for Mediterranean mountains: (1) pioneer phase, (2) mapping phase, (3) geochronological phase and (4) meta-analysis phase. Each phase differs from the other in terms of applied methodology, presented conceptions, and research paradigms. We selected key papers that could be considered as turning points which initiate a new research phase. In most cases, the main concepts and methods presented in these papers were not widely accepted immediately, thus the proposed phases have strongly overlapping boundaries.

PIONEER PHASE (1856–1955)

The pioneer phase was characterized by the collection of initial descriptive information on key glacial features such as moraines, cirques, and U-shaped valleys. Most early geomorphological studies were influenced by the geopolitical framework of the time. The location of the Tatra Mountains in the Austro-Hungarian Empire up to the First World War favoured the exchange of ideas and research in general associated with the University of Vienna.

In the first part of this phase (second half of 19th century), researchers focused on the study and description of traces of glaciation in selected valleys (Zejszner 1856; Sonklar 1857; Fuchs 1863; Stache 1867; Hauer 1869; Alth 1879; Emericzy 1881; Roth 1885, 1888; Deneš 1889; Rehman 1893; Uhlig 1899). In the second part of this phase (first half of 20th century), synthetic studies were presented on the larger part of the Tatra massif with a reconstruction of the number and extent of Quaternary glaciations as well as past snow line altitude estimations (Lucerna 1908; Partsch 1923; Gadomski 1926; Romer 1929; Halicki 1930; Lencewicz 1936; Szaflarski 1937). The most important papers of this phase were published by J. Partsch (1923), A. Gadomski (1926), E. Romer (1929), B. Halicki (1930) and J. Szaflarski (1937). The first schematic glacio-geomorphological maps of the Tatra Mountains were published during the pioneer phase of research (Romer 1929; Halicki 1930; Gadomski 1936; Lencewicz 1936).

The pioneer of glacial studies in the Tatra Mountains was L. Zejszner, one of the most prominent Polish geologists of the second half of the 19th century and the author of the first geological map of the Tatra Mountains (Szaflarski 1972). His earliest unpublished observations of large granitic material in erratic positions on the Mesozoic bedrock in the Białka Valley are from the 1830s. Nevertheless, at that time he did not link this observation with glacial transport. The earliest suggestion of the presence of glacial sediments in the Sucha Woda Valley was published by him in 1849 (Zejszner 1849). Nevertheless, he finally provided convincing proof of glaciation in 1856 (Zejszner 1856) by describing glacial moraines in the Bystra Valley located near the town of Zakopane. Recognition of glacial deposits on the northern Tatra slopes (Poland) was facilitated by local geology. The upper parts of glaciated valleys are formed of crystalline rocks, while lower parts are formed of Mesozoic sedimentary rocks, thus the erratic position of crystalline-rock boulders is easy to note. The first evidence of former glaciation on the southern, granite-dominated slopes of the High Tatras (Slovakia) was presented by K.A. Sonklar (1857), thus very soon after L. Zejszner's discovery.

The studies of L. Zejszner were at the forefront of early glacial research in European mountains. The rapid increase of evidence for mountain glaciation in Europe in the second half of the 19th century followed the establishment of glacial theory in the Alps by L. Agassiz. The theory was publicly presented in 1837 and published in 1840 (Agassiz 1840). First reports of glaciation in the Vosges Range (Leblanc 1838), Black Forest (Schimper 1837) and the Anatolian Mountains in Turkey (Ainsworth 1842) occurred almost simultaneously with the examination of Alpine glaciation. However, most pioneer discoveries associated with the glaciation of European mountains occurred in the 1880s and 1890s (see Hughes, Woodward 2016; Evans 2008). Similarly, in the Eastern Carpathians and the Southern Carpathians, the study of glaciation occurred in 1876 and 1881, respectively (Paul, Tietze 1876; Lehman 1881). Hence, the Tatra Mountains were one of the first mountain massifs outside the Alps, where the legacy of Quaternary glaciation has been recognized in the landscape.

According to early studies (Lucerna 1908; Partsch 1923; Romer 1929), the Tatra Mountains, similarly to the Alps, was covered by an extensive ice cap during the Pleistocene. Subsequent studies (Gadomski 1926; Halicki 1930; Szaflarski 1937), however, demonstrated unequivocally that the glaciation was characterized by valleys and cirque glaciers. The study of maximal glacier extent during the last glaciation enabled the first estimation of Pleistocene snow line altitudes (glacier equilibrium line altitudes – ELA) based on simple H. Höfer's (1879) method (Luc erna 1908; Partsch 1923). F. Vitasek (1924) calculated ELAs for mountain ranges located in former Czechoslovakia from the Bohemian Forest (present-day Czech Rep.) to Chornohora Mts. (present-day Ukraine, Eastern Carpathians). His ELA estimation for Tatras glaciers equalled 1,557 and 1,654 m a.s.l. on the northern and southern slope, respectively. A discussion on the spatial diversity of past climatic conditions in the Tatra Mountains was also initiated at the time. J. Partsch (1882) was the first to notice a strong trend of increasing ELAs from the west to the east.

The earliest researchers (Zejszner 1956; Partsch 1882; Roth 1885) had assumed a single glaciation in the Tatra Mountains. The concept of multiple Tatra glaciations was developed after the publication of A. Penck (1882) in the Alps. F. Deneš (1889) as the first presented a concept of two glaciations in the Tatra Mountains taking a significant difference in till weathering into account along with freshness between moraines of the last glacial cycle and most extensive moraine cover from older glaciations. During the pioneer phase, two to four glaciations were distinguished in the Tatra Mountains. This number was assumed on the basis of the number of fluvioglacial levels (Partsch 1907, 1904; Halicki 1930; Szaflarski 1937) as well as glacio-erosional levels in the studied cirques and valleys (Lucerna 1908; Gadomski 1926). The latter concept was developed after the work of H. Hess (1904) in the Alps and was based on the key assumption that repeated cycles of glacial erosion during subsequent glaciations produce a system of inserted cirques and glacial troughs. This concept was popular during the first part of the pioneer phase; however, it became largely abandoned in the second part of the pioneer phase (Halicki 1930; Szaflarski 1937).

One unique feature of this phase of research was the coexistence of extremely different views on the Most Extensive Glaciation (MEG) during the Pleistocene. Some researchers (Alth 1879; Stache 1867; Rehman 1893; Małkowski 1924, 1928; Romer 1929; Pawłowski 1936) stated that the Tatra glaciers had been much larger and had extended far into the northern and southern forelands of the Tatras. This view was based on interpretation of granitic and quartzite boulders and cobbles as a remnant of glacial deposit. According to E. Romer (1927, 1929), during the maximal glaciation 50 km in length and 25–30 km in width piedmont glacier protruded across the northern Tatra foreland. In order to support such extensive glaciation, E. Romer (1927) argued that the elevation of the Tatra Mountains must have reached 3,500 to 4,000 m a.s.l. during older glaciations. In contrast, other researchers (Lucerna 1908; Partsch 1923; Halicki 1930; Szaflarski 1937) argued that MEG was restricted to the Tatra massif and its closest foreland. This radical revision of earlier views became established in the literature after detailed geological studies on the northern Tatra foreland by B. Halicki (1930). He showed that the presence of well-rounded quarzitic and granitic gravel and blocks of a maximum diameter of 1–1.5 m in the Podhale foreland represents the fluvioglacial accumulation in terraces and extensive outwash fans and that these sediments are not glacial tills. After the paper of B. Halicki (1930), the concept of the widespread extent of piedmont glaciers in the Tatra region during older glaciations was largely abandoned by the scientific community.

The first Tatra glacial stratigraphy was published during the pioneer phase. Because of a lack of geochronological control, a glacial stratigraphy was established based on a tentative correlation with Alpine glacial schemes. The work of R. Lucerna (1908) is a good example of the use of the earliest Alpine morphostratigraphical scheme presented by A. Penck and E. Brückner (1901–1909). Thus, four glaciations (Günz, Mindel, Riss, Würm) and three recessional stages of the Würm glacial period (Bühl, Gschnitz, Daun) were adopted to the glacial record of the Tatra Mountains.

MAPPING PHASE (1955–1979)

The mapping phase of research in the Tatra Mountains was characterized by the use of detailed geomorphologic mapping, an enhancement of glacial stratigraphy and development of first tentative glacial chronology. The beginning of this phase of research we have arbitrarily set at around the year 1955 when many new works were being produced simultaneously after a long break in research activity due to the Second World War. In addition to progress in the quality of research and enhanced precision of cartographic image of glacial landforms, this phase featured also the use of the first biostratigraphic results in the construction of glacial chronologies. They were based on tentative linkages between the moraine sequence with the paleobotanical data obtained outside the Tatra Mountains. Hence, we refer to these schemes as the extra-Tatra biostratigraphy based, in contrast with the next phase of research where the intra-Tatra biostratigraphy and radiometric age were commonly applied in the construction of glacial chronologies.

The progress of mapping was strongly enhanced by the availability of topographic maps and a development methodology for detailed geomorphological mapping (Klimaszewski 1953, 1956; Mazúr and Lukniš 1956). As a result of systematic mapping, glacial landforms and sediments were depicted for many individual glaciated valleys (Ksandr 1954; Lukniš 1955; Košťálik 1958; Jaczynowski 1959; Mičian 1959; Mazúr 1955; Zatko 1961).

Interestingly, in the mapping phase of research, Czech and Slovak scientists from former Czechoslovakia were highly active in research in the present-day Slovak part of the Tatras, among which the most influential person was M. Lukniš. On the contrary, the Polish part of the Tatras was studied mostly by M. Klimaszewski, a famous Polish geomorphologist. These two researchers independently published detailed geomorphological maps for the large part of the Tatras (Fig. 2a, b). M. Lukniš (1968) presented a geomorphologic map of the Slovak part of the High Tatras on a scale of 1: 50,000 (Fig. 2a), while M. Klimaszewski (1985) produced a map of the Polish Tatra Mountains on a scale of 1: 30,000 (Fig. 2b). These maps are undoubtedly the greatest achievement of the mapping phase in Tatra research. For the Polish Tatra Mountains, glacial landform sediments were also shown on 14 sheets of a geologic map on a scale of 1:10,000 (Guzik, Sokołowski 1958–1980) (Fig. 2c). The map series yield an outstanding, detailed, and technically advanced cartographic image of Quaternary landforms and sediments, but largely ignore both stratigraphic and chronological issues. M. Lukniš (1973) and M. Klimaszewski (1988) presented

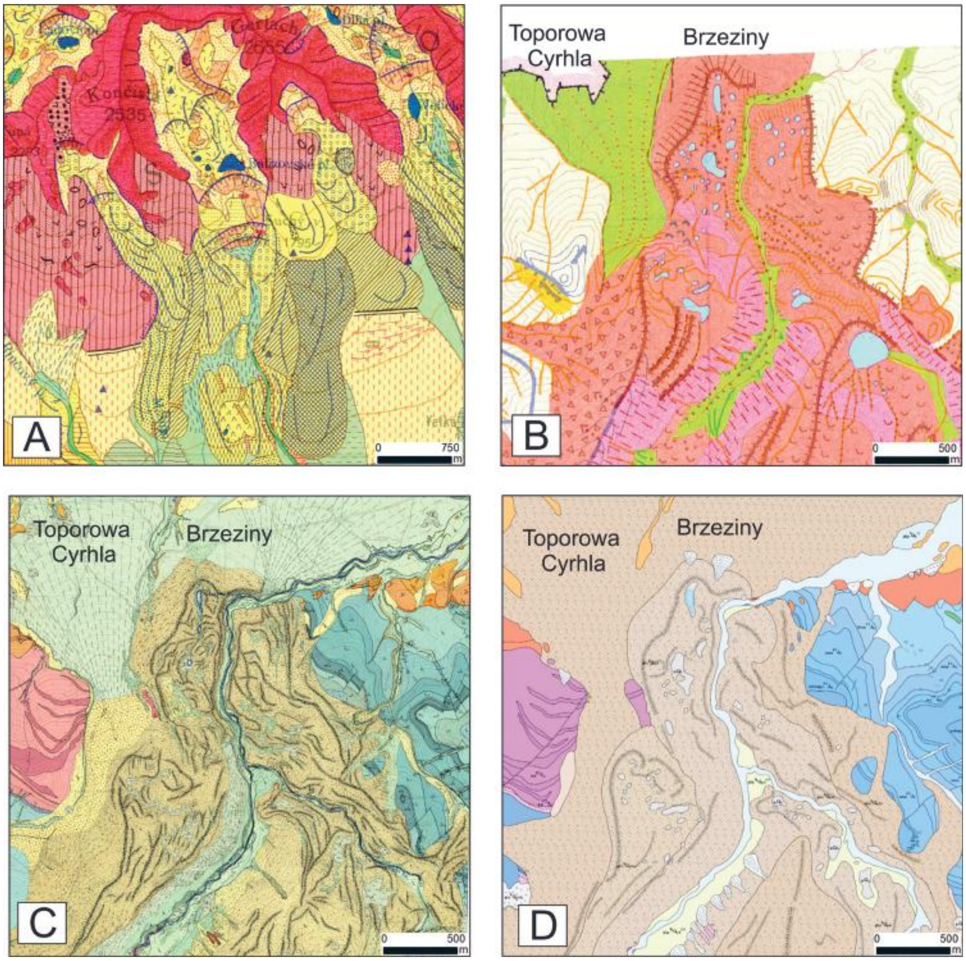

Fig. 2. Geomorphological and geological maps showing glacial landforms and sediments in the Tatra Mountains (selected parts of maps). A – Geomorphological map of the High Tatra Mountains, 1: 50,000, Batizovská valley, (Lukniš 1968, 1973); B – Geomorphological map of the Polish Tatra Mountains, 1: 30,000, terminal moraines in the Sucha Woda Valley, (Klimaszewski 1988); C and D – Detailed Geological Map of the Tatra Mountains 1: 10,000, terminal moraines in the Sucha Woda Valley, C – K. Guzik and S. Sokołowski (1958–1980) and D – K. Piotrowska et al. (2015).

also the most comprehensive and detailed monographs concerning Tatra mountain relief. Notably, different methodological approaches were applied in these fundamental studies: (i) a geologic and morphostratigraphic classification of glacial landforms and sediments (Lukniš 1973), and (ii) genetic-geomorphologic mapping without focusing on the details of glacial chronology (Klimaszewski 1988).

The first glacial chronologies based on data obtained from the vicinity of the Tatra Mountains was proposed by M. Klimaszewski (1961) and M. Lukniš

(1964, 1973). Due to the lack of independent geochronological control of moraine ages directly in the Tatra Mountains, the stratigraphic position of Lateglacial moraines was inferred using a correlation with cold stage intervals recorded in regional pollen proxy data. These were obtained by W. Koperowa (1958, 1962) at the "Na Grelu" peat bog located about 25 km north from the Tatra Mountains in the Podhale Basin at an elevation of 560 m (Koperowa 1958). Pollen-based stratigraphy from this site served the first approximation of Lateglacial paleo--environmental conditions in the vicinity of the Tatra Mountains and represents some of the first biostratigraphic data taken from the Western Carpathians. M. Klimaszewski (1961) and M. Lukniš (1964, 1973) used W. Koperowa's (1958, 1962) pollen-derived position of the timberline and air temperature during the Lateglacial and the Holocene, and estimated past shifts in the climatic snow line (CSL) in the Tatra Mountains – by making the assumption made by M. Hess (1968) that the position of the CSL corresponds to mean annual air temperature of –2 °C. The reconstructed CSL during Older Dryas, Younger Dryas and Holocene stages was then linked to the given moraine elevations.

M. Klimaszewski (1961, 1965, 1967) argued theoretically for the synchronism of the Tatra deglaciation scheme and the Alpine and Scandinavian glacial chronologies; however, he did not propose a specific correlation. M. Klimaszewski (1967) identified 6 recessional stages in the High Tatras and 3 stages in the Western Tatras. According to M. Klimaszewski (1967, 1988), in the Western Tatras glaciers disappeared before the Oldest Dryas, while in the High Tatras, it is likely that they survived right into the Younger Dryas when cirques above 1,800 m could have been filled with ice. He believed that morphological predisposition from preglacial time had had the greatest impact on the pattern of deglaciation, as opposed to climatic conditions. Thus, an active recession occurred in lower valley sections with steep gradients, while areal deglaciation occurred in sections with lower gradients. He adhered to the paradigm that glacier's fronts in the massif should have similar elevations at the same time. Taking this view, he stated that the elevation of frontal moraines could be used as a criterion for moraine correlation. Observation of correlative moraines at different altitude in the Tatras leads him to the conclusion that "deglaciation took place almost simultaneously, although not at the same rate". Analyzing the work of H. Heuberger (1966), he questioned the use of an Alpine methodology based on the differences between the ELA of paleoglaciers (Heuberger 1966; Kerschner 1978) in the Tatra Mountains. He observed that Alpine frontal moraines of the same age are found at different elevations, which was in conflict with his paradigm adopted specifically for the Tatras. In consequence, he argued that the correlation of Tatra moraines with Alpine glacial chronology is impossible (Klimaszewski 1988). This view was later criticized by M. Baumgart-Kotarba and A. Kotarba (2001).

In contrast, M. Lukniš (1959, 1964, 1973) tentatively correlated mapped glacial sequences with contemporary Alpine and Northern European stratigraphy;

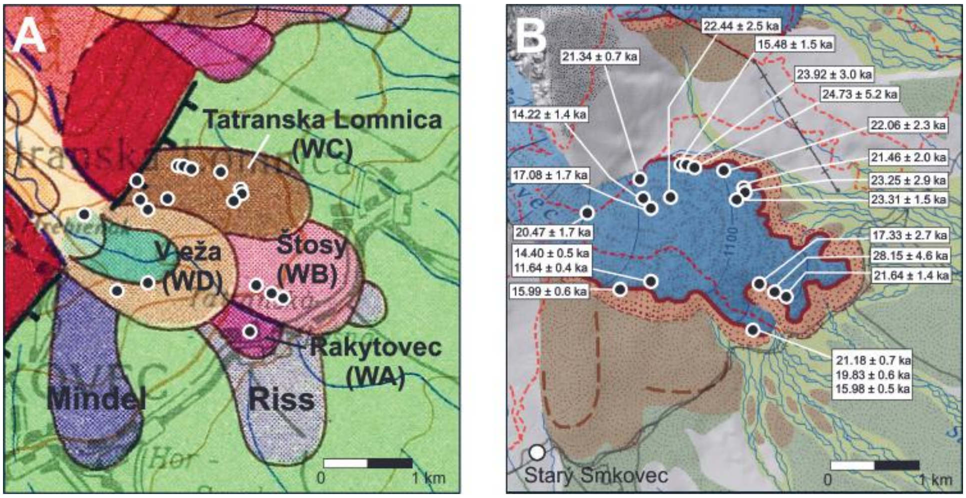

Fig. 3. Studená Valley morainic amphitheatre. A – Stratigraphic framework of fourfold glacial advances (WA-WD) during the Last Glaciation (Würm) proposed by M. Lukniš (1968, 1973). B- results of TCN dating (Engel et al. 2015) indicate that entire morainic amphitheatre was stabilized during the LGM. Background map shows LGM and pre-LGM moraines and alluvial deposits (Zasadni, Kłapyta 2014; Zasadni et al. 2015).

however, this was not supported by any type of geochronological data. This morphostratigraphic scheme has been adopted in all of subsequent Tatra geochronologies (Lindner et al. 1990, 1993; Baumgart-Kotarba, Kotarba 2001; Makos 2015). M. Lukniš (1973) also distinguished moraines and moraine covers for three glaciations (Mindel, Riss, Würm) (Fig. 3a), with the most extensive advance during the penultimate glaciation. He presented subdivision of the Last Glaciation (Würm) into four different stadial of Würmian glaciation: Rakytovec (WA), Štosy (WB), Tatranska Lomnica (WC), and Veža (WD) basing on morphostratigraphy and weathering characteristics of moraine boulders (Fig. 3a). These stadials were assumed to be Early–Late Würm in age (MIS 5d – MIS 2), where the WB stadial (middle Würmian) was the most extensive. M. Lukniš (1964, 1973) defined five recessional stages for the Lateglacial (D1, D2, E1-E3) and assigned the Early Holocene to the youngest moraine deposits ("névé moraine") that cover cirque floors. This classic morphostratigraphic scheme was further extended by R. Halouzka (1977, 1987, 1989) who added two Early Holocene glacial phases, but again without any geochronological control.

GEOCHRONOLOGICAL PHASE (1979–1999)

The onset of the geochronological phase was coeval with the application of radiometric dating to the construction of glacial chronologies, thus this phase could also be called the advanced phase (Hughes et al. 2006). We attribute a shift from the mapping to the geochronological phase to a publication produced by M. Baumgart-Kotarba and A. Kotarba (1979). In this paper, the age of Tatra moraines was established for the first time utilizing intra-Tatra stratigraphic data. Detailed sedimentological and palynological analyses of lacustrine sediments from the Pięć Stawów Polskich Valley (Wicik 1979) yielded evidence of a surprisingly early deglaciation in the high-elevation cirque basins of the High Tatras in the later part of the Oldest Dryas or Bølling/Allerød. Following these results, M. Baumgart-Kotarba and A. Kotarba (1979) correlated prominent, blocky moraines situated in several valleys on the northern side of the High Tatra Mts. (accordingly SW-4, RP-2, BW-6) (Fig. 4a) with the Oldest Dryas biochronozone. They noted that these moraines had formed during a prominent glacier readvance and correlated them with the Alpine Gschnitz stadial and the Gardno Phase in northern Poland (Fig. 4). These new findings were important turning points in the understanding of Tatra deglaciation chronology. They showed that high-elevation moraines in Tatra cirques were much older than previously suspected.

The further construction of the Lateglacial part of the Tatra glacier chronology was enhanced by sediments drilling in several Tatra lakes (Wicik 1984; Kondracki 1986; Baumgart-Kotarba, Kotarba 1993, 1996, 2001) and peat bogs (Obidowicz 1993, 1996; Baumgart-Kotarba et al. 1994) (Fig. 4). As a result, a maximum age of the sediments and their biostratigraphy were obtained for several dozens of sites throughout the entire Tatra mountain range (see Kłapyta et al. 2016, for a summary).

A unique feature of the geochronological phase of research was the coexistence of two different and independent methodological approaches to the construction of glacial chronologies, which could be referred to as the Cracow and Warsaw Schools (Mojski 2005). During this phase of research, fieldwork was focused on the Polish part of the Tatra Mountains – and only Polish researchers were engaged in this effort.

THE CRACOW SCHOOL

The glacial geochronology of the "Cracow School" was constructed as a combination of detailed geomorphologic mapping and substantially supported with the results of radiocarbon dating, palynological and sedimentological analysis of peat bog and lake sedimentary sequences, as well as thermoluminescence (TL), optically stimulated luminescence (OSL), and single-aliquot regeneration (SAR) dating of morainic and underlying mineral deposits. (Fig. 4). The main results of these studies were summarized in papers by M. Baumgart-Kotarba and A. Kotarba (1997, 2001) It is worth noting that these authors questioned and partially rejected the results of TL dating of Tatra moraines presented by the "Warsaw School" led by L. Linder (Fig. 5).

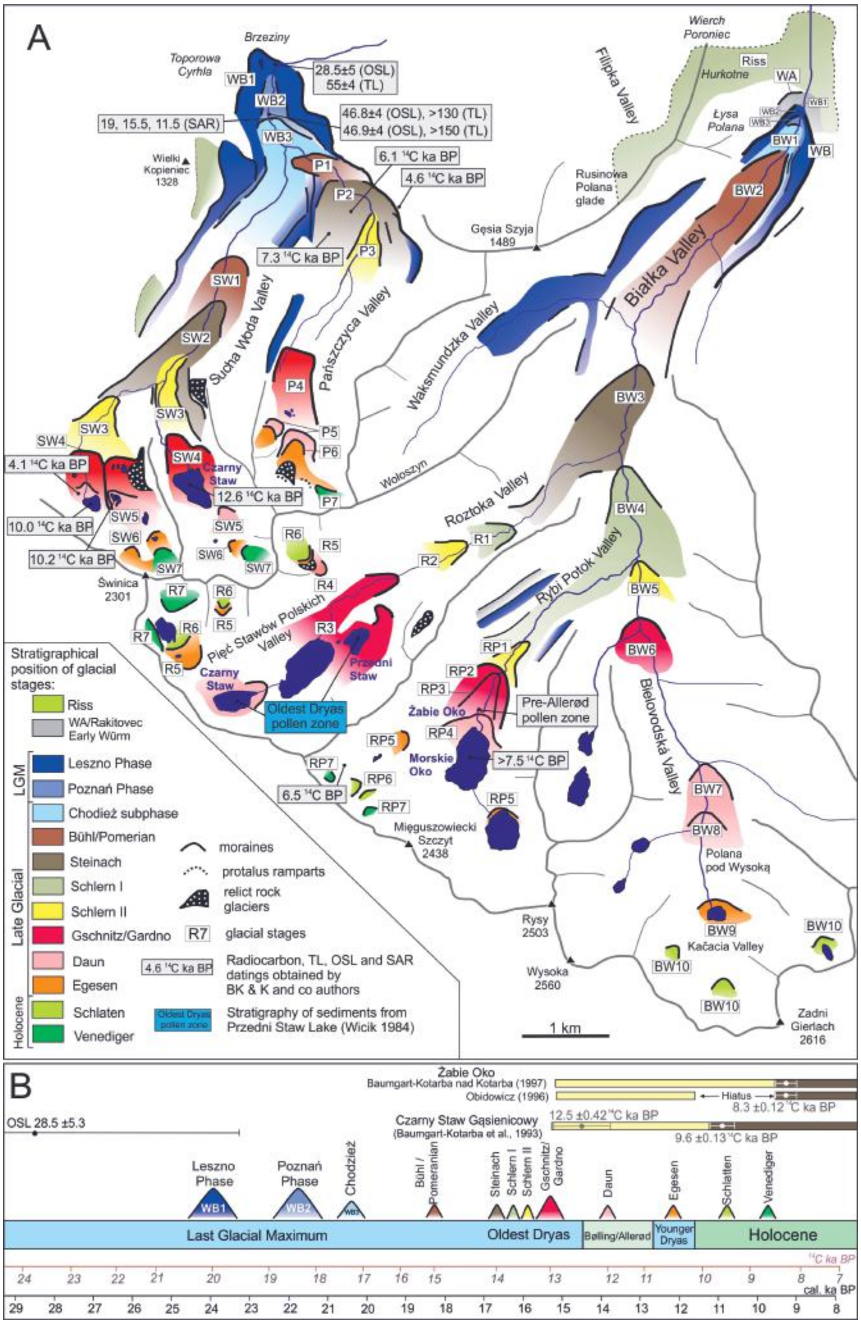

Fig. 4. Glacial chronology of the Polish High Tatra Mountains according to "Cracow school", a compilation based on M. Baumgart-Kotarba and A. Kotarba (1997, 2001) and A. Obidowicz (1996). A – Glacier extent and morphostratigraphic relations during the Würm glaciation in the Sucha Woda and Białka valleys according to M. Baumgart-Kotarba and A. Kotarba (1997, 2001). B- Chronology of glacier advances plotted against radiocarbon and absolute time scales.

According to the Cracow scheme, the MEG had occurred during the penultimate glaciation (Riss), whereas the maximum extent of glaciers during the last glaciation (Würm) had occurred during the LGM (21–19 ka; Baumgart-Kotarba, Kotarba 2001) (Fig. 4). This view was supported by OSL and SAR dating of minerogenic material (Baumgart-Kotarba, Kotarba 2001) (Fig. 4), as well as by cosmogenic ^{36}Cl dating of moraine boulders (Dzierżek et al. 1999) in the Sucha Woda Valley. Thus, there is no evidence of outstanding LGM glacial chronology of the Tatra Mts. in comparison with the Alps and Scandinavian Ice Sheet (Baumgart-Kotarba, Kotarba 2001). Only in case of the Białka Valley the more extensive middle Würmian (70–60 ka) advance was distinguished in front of the LGM moraines (RA, advance) (Fig. 4a). This age was estimated on the basis of terrace stratigraphy and correlation with archaeologically dated sediments from the Obłazowa Cave located at the northern Tatra foreland (Baumgart-Kotarba, Kotarba 2001).

These authors distinguished a twofold division of maximal moraines from the last glaciation (WB1, WB2) and from seven to ten deglaciation stages recorded in moraine sequences of the Sucha Woda and Białka valleys, respectively (Fig. 4). The age of Lateglacial advances was partially supported by the stratigraphy of sediments from Żabie Oko depression (Baumgart-Kotarba, Kotarba 1997) as well as the oldest ^{14}C date in the Tatra Mts. (12,550 ± 420 ^{14}C ka BP; 15.96 – 13.65 cal. ka BP; Baumgart-Kotarba, Kotarba 1993) obtained from Czarny Staw Gąsienicowy Lake (Fig. 4). The chronological position for most recessional moraines was adopted from Alpine glacial morphostratigraphy according to G. Patzelt (1975). Early Holocene glaciation (the equivalent of Alpine Venediger and Schlaten advances) and rock glacier activity in the High Tatra Mountains were assumed on the basis of the interpretation of Żabie Oko lake sediment stratigraphy and ^{14}C dating (Baumgart-Kotarba, Kotarba 1997) (Fig. 4). According to this view, small cirque glaciers could have persisted in the highest parts of the High Tatras until 8.3 ^{14}C ka BP (9.5–9 cal. ka BP).

THE WARSAW SCHOOL

The Warsaw School of glacial chronology was mainly based on the results of TL dating of moraines (Butrym et al. 1990; Lindner et al. 1990, 2003) and fluvioglacial sediments from the Tatra foreland (Lindner et al. 1993), further supported with TL, ESR, and ^{14}C dating of cave speleothems (Hercman et al. 1987) as well as lacustrine sediments (Krupiński 1983; Marciniak, Cieśla 1983; Szeroczyńska 1984). On the basis of geomorphologic analyses and to some extent TL dating of fluvioglacial deposits from the foreland, L. Lindner et al. (2003) distinguished eight episodes during which the Tatra Mts. were glaciated during the Quaternary. They were correlated with the Scandinavian and Alpine glacial chronology. The last glaciation was divided into three stadials: Sucha

Woda (89±13 – 81±12 ka), Bystra (69±10 – 57±8 ka) and Białka (32±5 – 25±4 ka), with the most extensive glaciation occurring during the Bystra stadial (Fig. 5). The areal extent of the pre-Würmian glaciations, as well as that of the two older Würmian stadials, is unknown due to a lack of moraines. Only the spatial extent of the Białka stadial has been established in the Polish Tatra Mountains. This stadial is subdivided on the following phases: Hurkotne (32–25 ka), Łysa Polana (23–17 ka), Włosienica (16 ka), and four-partite Pięć Stawów Polskich phases (14–9 ka) (Fig. 5). L. Lindner et al. (2003) argued that the maximum extent

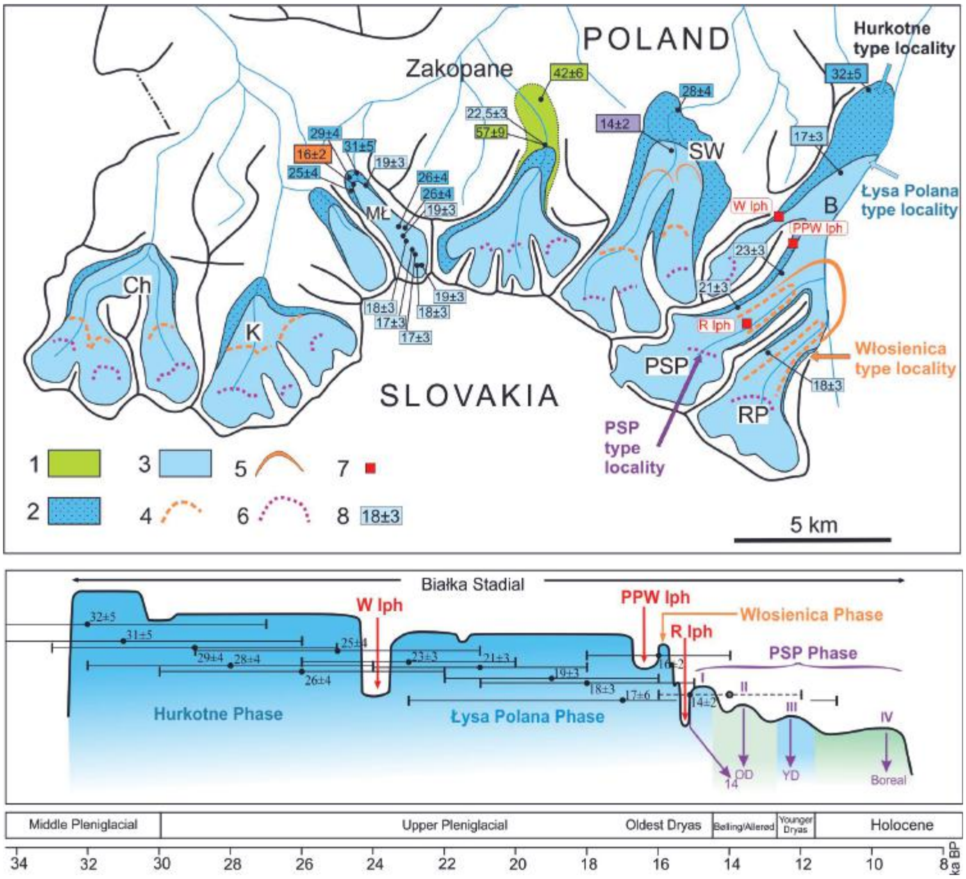

Fig. 5. Glacial chronology of the Polish Tatra Mountains according to "Warsaw school" (Butrym et al.1990; Lindner et al. 1990, 2003, 2008). Ages in ka BP obtained from TL datings of tills (Butrym et al.1990; Lindner et al.1990). Glacier extent: 1 – Bystra Stadial, 2 – Hurkotne Phase (H), 3 – Łysa Polana Phase (ŁP), 4 – Włosienica Phase (W) (Lindner et al. 1990), 5 – Włosienica Phase (Lindner et al. 2008), 6 – Pięć Stawów Polskich) Phase (PSP), 7 – type localities of the Białka Stadial interphases (Lindner et al. 1990): W Iph – Waksmund Interphase, PPW Iph – Polana pod Wołoszynem Interphase, R Iph – Roztoka Interphase, 8 – TL sampled sites. Colour refers to given glacial phase. Localities: Ch – Chochołowska Valley, K – Kościeliska Valley, MŁ – Mała Łąka Valley, SW – Sucha Woda Valley, B – Białka Valley, PSP – Pięć Stawów Polskich Valley, RP – Rybi Potok Valley.

of the Białka stadial during the Hurkotne phase had occurred significantly earlier than the maximum extent of the Alpine and Scandinavian ice sheets. In the Warsaw School's scheme, the last stage of deglaciation (Pięć Stawów Polskich phase IV) occurred during the Early Holocene (Boreal) and was represented by rock glaciers activity (Dzierżek, Nitychoruk 1986) (Fig. 5).

META-ANALYSIS PHASE (1998–)

The last two decades have witnessed a major advance in our understanding of Late Pleistocene evolution in the Tatra Mts. because of the advent of new, absolute dating methods based on cosmogenic isotopes ^{36}Cl and ^{10}Be, and the use of glacier reconstruction and glacier-climatic modelling. The common use of TCN datings (Balco et al. 2011) and glacier-climate models (Kerschner et al. 1999) have substantially revolutionized our knowledge on the past mountain glaciation worldwide. Additionally, a large availability of high-resolution digital elevation models (LiDAR), has substantially improved our knowledge on spatial pattern of glacial landforms. We begin this most recent phase with a publication by B. Gądek (1998) who produced the first glacier reconstruction and glacier-climate model, and also J. Dzierżek (1999) who published the first results of TCN datings (Fig. 6). The methods presented in these seminal papers however, were widely implemented a one decade afterwards.

TCN EXPOSURE AGE DATING

J. Dzierżek et al. (1999) were the first to use cosmogenic Chlorine-36 (^{36}Cl) to date moraine boulders and glacial-scoured bedrock in the Tatra Mountains (Fig. 6). It was the first application of cosmogenic exposure age dating in the entire Carpathians. On the other hand, the first use of Beryllium (^{10}Be) dating in the Carpathians was described by A. Reuther et al. (2007) for the Retezat Mountains (Romania), whereas Z. Engel et al. (2015) and M. Makos et al. (2016) used ^{10}Be dating for the first time in the Slovak and Polish parts of the Tatra Mountains, respectively.

Most exposure ages obtained by J. Dzierżek et al. (1999) were later recalculated by J. Dzierżek (2009) using a new ^{36}Cl production rate and calibration procedure (details not published), which produced a new ^{36}Cl dataset with a tendency to spread toward older ages relative to the original dataset (1–21 ka older). The result of pioneer studies based on the cosmogenic isotope ^{36}Cl made the picture of Tatra glaciation somewhat more confusing, as the age distribution of the samples exhibited large variability and did not coincide with the established stratigraphic order and expected chronology. The maximum extent of Tatra glaciers during the last glacial stage was given by J. Dzierżek (2009) as 43–32 ka, thus it was found to occur during the relatively warm interstadial pe-

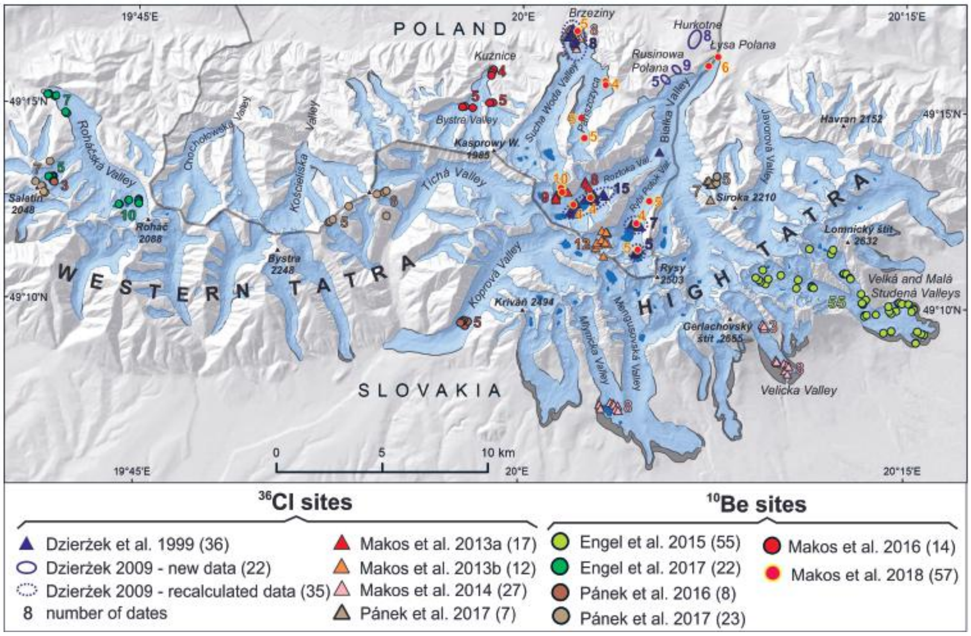

Fig. 6. Terrestrial cosmogenic nuclide dating sites in the Tatra Mountains. Numbers refer to the number of TCN samples in each site, numbers in brackets refer to a total number of published datings in each paper. LGM glacier extent after (Z a s a d n i and K ł a p y t a 2014).

riod, which is in conflict with local paleoenvironmental proxy data (H e r c m a n et al. 1987, 1998; H e r c m a n 2000; B a u m g a r t-K o t a r b a, K o t a r b a 1997).

M. M a k o s et al. (2013a, b; 2014) and M. M a k o s (2015) used ^{36}Cl dated glacial trimlines as well as ice-moulded bedrock and moraine boulders to establish a new exposure age deglaciation chronology of the High Tatra Mountains (Fig. 6). Two maximal stages: LGM I (25–20 ka) and LGM II (ca 18 ka), and three recessional stages: LG 1 (17–16 ka), LG 2 (15 ka) and LG 3 (12.5 ka), were distinguished. The first stage of deglaciation occurred simultaneously in both the ablation and accumulation areas of glaciers at about 21.5 ka (M a k o s et al. 2013a, 2014) and caused ice withdrawal from maximum positions and exposition of the uppermost trimlines.

Recently M. M a k o s et al. (2018) presented a revised deglaciation chronology of the Polish High Tatra Mountains during the LGM and Lateglacial based on ^{10}Be exposure age dating (Fig. 6). The time range of LGM glacial activity shifted to between 28 and 25 ka (LGM I) and at around 20.5 (LGM II), which is 1.5–2 ka earlier than previously presented (M a k o s et al. 2014). Additionally, four recessional stages: LG1 (16.6 ka), LG2 (16.5–15.5 ka), LG3 (15.5 ka) and LG4 (12.5 ka) were distinguished. These data show synchronization between glacial events occurring in the Tatra Mountains and the European Alps as well as climate records in the North Atlantic region.

Z. Engel et al. (2015) presented an extensive ^{10}Be dataset for the Last Glacial Maximum and post-LGM deglaciation of the Velká and Malá Studená valleys in the Slovak High Tatra Mountains (Fig. 6). Similarly, Z. Engel et al. (2017) generated new data on the timing of glacier maximal extent and deglaciation stages in the Roháčská Valley in the Western Tatra Mountains (Fig. 6). The timing of dated glacier advances was broadly synchronous with those determined for the High Tatra Mts. by cosmogenic ^{36}Cl dating (Makos 2015) and for ^{10}Be dating in the Bystra Valley in the Western Tatras (Makos et al. 2016) (Fig. 6). Z. Engel et al. (2017) provide also the first chronological evidence for Lateglacial activity of rock glaciers in the Salatínska Valley, which occurred before 13 ka BP (Fig. 6).

T. Pánek et al. (2016, 2017) were able to produce ^{10}Be exposure ages of prominent rock avalanches and sackungen in the Tatra Mountains (Fig. 6), which indicated that large rock slope failures seldom react immediately to glacier withdrawal, but could display a temporal delay after deglaciation lasting up to several millennia (>5 ka) (Panék et al. 2017).

At this point, 300 cosmogenic nuclide dates had been published for the Tatra Mountains, among them 121 were ^{36}Cl and 179 were ^{10}Be (Fig. 6). A larger number of data obtained recently via TCN datings enabled for the first time a construction of independent local Tatra glacial chronologies. Along with absolute dating, the use of relative age dating techniques based on Schmidt Hammer rebound values with respect to moraines and rock glaciers helped to test the applicability of this method and more accurately assess regional stratigraphic relationships in the Western and High Tatra Mts. (Kotarba et al. 2000; Kłapyta 2011, 2013; Zasadni, Kłapyta 2016).

GLACIER RECONSTRUCTION AND GLACIER-CLIMATE MODELLING

Two novel issues, which have emerged during the last two decades, are glacier reconstruction and paleoclimate modelling based on geomorphologic records and glacier-climate relations. Together with cosmogenic exposure dating, these provide a better understanding of regional patterns of glacial advance and retreat and their broader paleoenvironmental significance.

B. Gądek (1993–1994, 1998) was the first to use glacier-climate modelling of LGM and Lateglacial paleoglaciers in the Tatra Mts. He pointed to very severe continental climatic conditions during the LGM and low glacier activity. He indicated that some moraines from the last glaciation were related to glaciers surging instead of steady-state mass balance conditions.

M. Makos and Ł. Nowacki (2009) presented a model of the ice-surface geometry of the part of the Białka glacier during the LGM which for the first time was processed using GIS software. M. Makos and J. Nitychoruk (2011) presented glacier-climate modelling outcomes for the Sucha Woda and Białka glaciers during the LGM. They obtained paleoclimate conditions from glacier geometry using two different methods. The first was based on ablation gradient model (K e r s c h n e r et al. 1999; I v y-O c h s et al. 2006), which estimates paleoclimate conditions from glacier mass turnover between selected glacier cross sections (M a k o s, N i t y c h o r u k 2011). The second one fit the modelled glacier length to existing LGM terminal moraines. The glacier model utilized one-dimensional ice-flow and took into account changes in climatic conditions in comparison to present-day values using a degree-day model (S a r i k a y a et al. 2008). The latter approach was widely applied in subsequent works of M. Makos' team (M a k o s et al. 2013a, b, 2014, 2016).

J. Z a s a d n i and P. K ł a p y t a (2014) created a detailed reconstruction of glacier geometry as well as a three dimensional model of all 55 glaciers in existence during the LGM in the Tatra Mountains (Fig. 1). They highlighted the role of Tatra massif asymmetry on the pattern of glaciation, which is manifested via a relatively large glacier extent on the southern Tatra slope resulting from higher elevations of alimentation areas. The reconstructed average thickness of the LGM glaciers was estimated to be 90 m. In addition, J. Z a s a d n i and A. Ś w i ą d e r (2015) presented a photorealistic virtual landscape of the reconstructed Białka Glacier during the LGM by applying Terragen software.

During the meta-analysis phase, a glacier equilibrium line altitude (ELA) was estimated for the first time using AAR (accumulation area ratio) (G ą d e k 1998; M a k o s et al. 2013a, b; E n g e l et al. 2015; Z a s a d n i, K ł a p y t a 2016). Recently, the more advanced AABR (area attitude balance ratio) method was also applied to Lateglacial advances in the Pięć Stawów Polskich Valley (Z a s a d n i, K ł a p y t a 2016). The result of glacier-climate modelling (Z a s a d n i, K ł a p y t a 2009) showed that both the modern (2,450–2,650 m) and Little Ice Age (2,300––2,450 m) climatic snow line (temperature-precipitation ELA) was located above the Tatra summits. This shows that the Tatra Mts. are too low for present-day (Holocene) glaciation. This radically revised the earlier estimation of the snow line position at an elevation of 2,200 m (H e s s 1968; K l i m a s z e w s k i 1988) and changed the paradigm that links the lack of modern glaciation with an excessively steep topography for glacier inception to occur.

DISCUSSION

Quaternary glaciations in the Tatra Mountains have been studied for over 160 years. During this relatively long history of research, the field of glacial geomorphology has changed many times as a result of the development of new research methods. Nevertheless, some fundamental research problems remain unchanged including the number, age, and extent of older Pleistocene glaciations. Other key points include the timing of the maximum extent of glaciation during the last glacial cycle and the chronology of glacier recession during the Lateglacial as well as the timing of final glacier withdrawal.

OLDER GLACIATIONS

NUMBER OF GLACIATIONS

During the pioneer and mapping phases, three to four Tatra glaciations were widely distinguished on the basis of the morphologic division of glacial deposits (moraines, till cover), alluvial terraces, and gravel cover across the Tatra foreland (Partsch 1923; Romer 1929; Halicki 1930; Lukniš 1973; Klimaszewski 1988). The number of glacial cycles significantly increased during the geochronological phase. Up to the eight glaciations were proposed by L. Lindner et al. (2003) on the basis of alluvial terrace morphostratigraphy and TL dating of the Tatra foreland. The oldest radiometric date (TL 443 ± 36 ka) was obtained for gravel cover that corresponds to the Mindel glaciation (Lindner et al. 1993). In contrast, recent results of OSL dating of alluvial deposits across the Podhale foreland (Olszak et al. 2016) revealed that the oldest gravel cover attributed previously to the Mindel glaciation is no older than 83–89 ka. This finding opens up a new discussion on the absolute age of alluvial terraces and gravel cover found across the Tatra foreland and also brings into question the ages and number of Tatra glaciations proposed based on TL dating.

The achievement of the pioneer phase of research was distinguishing two morphologic units within the studied glacial deposits. Freshly shaped moraines and hummocky till cover were defined as "younger moraines" (Partsch 1923). Outside "younger moraine" limits "older moraines" were distinguished (Partsch 1923), which exhibit only subdued relief without any distinct moraine walls, often featuring fields of large boulders (Fig. 1). Since the latter part of the pioneer phase, there has been a broad consensus that "younger moraines" represent the Last Glaciation, whereas the "older moraines" (MEG) represent primarily Riss glaciation (Lukniš 1973; Klimaszewski 1988; Baumgart-Kotarba, Kotarba 1997; Birkenmajer 2009). Additionally, M. Lukniš (1973) distinguished on the southern Tatra foreland two morphological zones inside the "older moraine" unit. The zones were attributed to Mindel and Riss glaciations. Recently performed cosmogenic exposure age dating and glacier reconstructions show agreeably that the previous attribution of "younger moraines" to the Last Glaciation was correct, which is discussed below. In contrast, the chronology of the "older moraine" geomorphologic unit in the Tatra Mountains is poorly defined.

AGE OF GLACIATIONS

Most of the chronological discussion and dating related to MEG till cover in the Tatra Mountains were focused on the area between Wierch Poroniec and Rusinowa Polana glade – called the Hurkotne site, after E. Romer (1929) (Fig. 1). At this location, strongly weathered till cover of the boulder-clay type ("older moraine") is preserved beyond morphologically fresh moraines of the last glacial cycle ("younger moraine") on the relatively flat-topped watershed ridge between the Białka and Filipka valleys (Fig. 1). This location thus illustrates the clearest stratigraphic relationship between these two units of glacial sediments. The Hurkotne site may be attributed to the non-formal type locality of the MEG (pre-LGM glaciation) in the High Tatra Mountains (Romer 1929). In most cases, the age of the Hurkotne cover has been tentatively correlated with Mindel and/or Riss glaciations (Partsch 1923; Romer 1929; Lukniš 1973; Klimaszewski 1988; Baumgart-Kotarba, Kotarba 1997; Birkenmajer 2009) (Fig. 4).

L. Lindner et al. (1990, 2003) and L. Lindner (1994) use TL dating to argue for a significantly younger age of the Hurkotne deposits (32–25 ka) and propose a new chronostratigraphic unit – the Hurkotne Phase – as the oldest phase of the Białka Stadial during the Late Würm glaciation (Lindner et al. 1990) (Fig. 5). For the first time, the typical location of "older moraines" in the Tatra Mountains was attributed to the LGM. Although the type locality of the Hurkotne Phase was defined in the Białka Valley, most of the TL datings that support the age of this phase were obtained for fresh and steep terminal moraines ("younger moraine" unit) in the Mała Łąka and Sucha Woda valleys (Lindner et al. 1990) (Fig. 5). This dating strategy ignores stratigraphy and the boundary of mappable geomorphologic units – and fully relies on TL ages. The TL-based Hurkotne Phase concept was also contested in the past via geomorphologic analysis (Baumgart-Kotarba, Kotarba 1997, 2001; Birkenmajer 2009) and also with the use of paleoenvironmental evidence (Hercman et al. 1987, 1998, 2000).

J. Dzierżek (2009) attempted to date Hurkotne till cover using cosmogenic ^{36}Cl exposure ages (Fig. 6). Dated moraine boulders yielded exposure ages in the range 20–90 ka. J. Dzierżek (2009) suggested that the distribution of boulder ages may be explained by a complex, repeated deposition during at least two Würmian glacier advances between 85–90 ka and 43–32 ka. Such interpretation can only be taken into the consideration if the dated boulders in two age intervals would also be spatially separated at their location. Unfortunately, a map showing the distribution of dated boulders has never been published. Nevertheless, these data evidence the older age of the Hurkotne moraine cover in relation to that published by L. Lindner et al. (1990, 2003; 32 ka TL) (Fig. 5) and strongly support its pre-LGM age. However, the obtained age is much younger than that produced by previous estimations (Partsch 1923; Romer 1929; Halicki 1930; Klimaszewski 1988; Baumgart-Kotarba, Kotarba 1997). The large age inconsistency of these data suggests post-depositional exhumation and erosional processes occurring on boulders (compare Heyman et al. 2011), thus the true age of this deposit may be much older than that proposed by J. Dzierżek (2009).

Interestingly, the unsolved problem of MEG chronology in the Tatra Mountains is best exemplified by its type locality for the Hurkotne site, where the age of glacial deposition suggested in the literature spans for more than 2 million years from the Pliocene (Martonne 1911) to the Late Pleistocene (Lindner et al. 1990, 2003).

EXTENT OF GLACIATIONS

The extent of MEG was vigorously discussed during the pioneer phase of research. This discussion led to the conclusion that the spatial extent of MEG was only a little greater than the extent of LGM. Interestingly, this discussion recently returned due to new conceptions of much larger extent of pre-LGM glaciation in the northern Tatra foreland. L. Lindner et al. (2008) and K. Pliszczyńska (2012) reconsidered the previously mapped highly weathered fluvioglacial terraces and gravel covers of the Białka Valley (Baumgart-Kotarba 1983), located a few kilometres north of the edge of the Tatra Mountains, as "remnants of glacial till." In these studies, MEG in the Białka Valley is supposed to be of the Mindel and Riss age and reach down to the village of Jurgów (Fig. 7). It is five kilometres further downvalley than the LGM glacier extent (Lindner et al. 2008; Pliszczyńska 2012) (Fig. 7).

In our view, the substantial "shift" of MEG glacier extent far into the Tatra foreland has not been proven substantially enough by sedimentological evidence. Similarly, as in the pioneer phase, this new conception is based on an interpretation of sediments with a sandy-loamy matrix and a concentration of granite boulders as "true" glacial diamicton (till). According to L. Lindner et al. (2008) and K. Pliszczyńska (2012) the fundamental criterion for attributing glacial genesis to sediments is an abundance of granitic boulders in the loamy matrix. K. Pliszczyńska (2012) supports her detailed stratigraphic framework of Białka valley glacial and fluvioglacial deposits with petrographic analysis and observations of gravel weathering. This method of stratigraphic studies of the Tatra mountain foreland, however, was questioned by M. Baumgart-Kotarba (1983), as the weathering rate of granitic gravels is mostly dependent on local hydrogeological conditions rather than the age of sediments. Surprisingly, the smallest size of clasts described as glacial-derived sediments was only 30 cm (Lindner et al. 2008; Pliszczyńska 2012), but the maximum clast diameter of these deposits have not been provided in these studies. In contrast, Tatra mountain fluvioglacial outwash deposits commonly contain well-rounded quarzitic and granitic gravels with a clast size more than 1 m in diameter, as shown by B. Halicki (1930) and M. Baumgart-Kotarba and A. Kotarba (1997). Similarly, the maximum fraction of granite gravel found in the present-day channel of the Bialka River at Jurgów is commonly 70–100 cm (Baumgart-Kotarba 1983). However, in both "young" and "old" moraine geomorphologic units in the Tatra Mountains, the maximum diameter of granitic boulders in glacial sediments commonly reaches 2–5 m. If we apply this criterion to distinguish till and alluvial sediments, MEG till cover occurs only outside the Sucha Woda

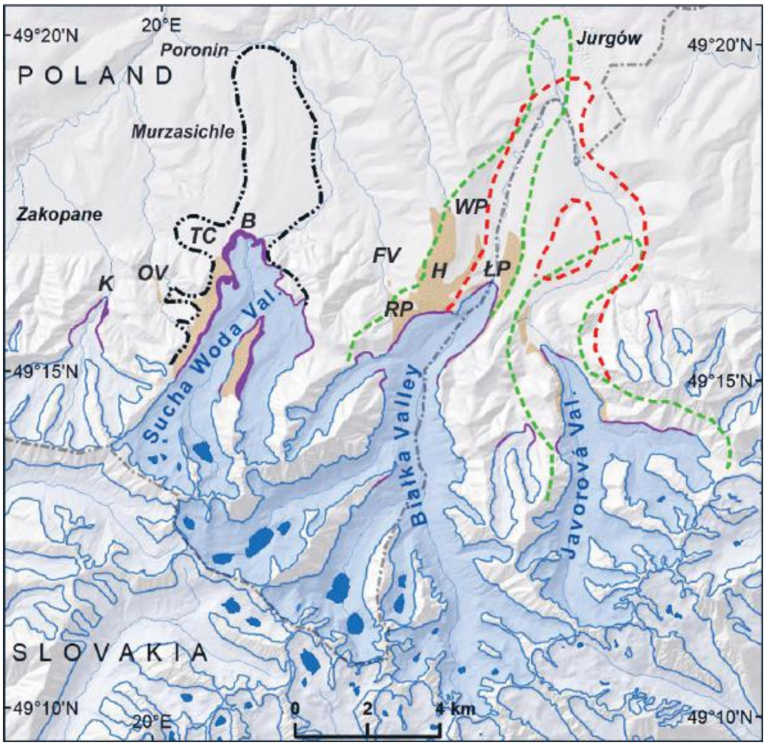

Fig. 7. The recent proposition of larger extent of pre-LGM glaciation on the northern forelands of the High Tatra Mountains. Black line – MEG according to W. Rączkowski (2015). Red line – the extent of Mindel glaciation, green line extent of Riss glaciation according to K. Pliszczyńska (2012). For the map legend and references see Figure 1.

glacier LGM moraines in Olczyska Valley and outside Białka glacier LGM moraines at the Hurkotne site. Therefore, the spatial extent of MEG for the Tatra Mountains was only ca. 1–1.5 km greater than the extent of LGM (Fig. 1, 7).

Furthermore, the return to the pioneering concept of much larger pre-LGM glaciations was substantially supported by the Detailed Geological Map of the Tatra Mountains (DGMT) (Derkacz et al. 2009; Piotrowska et al. 2015; Wójcik, Rączkowski 2015; Fig. 8). In comparison with the previous edition of the DGMT (Guzik, Sokołowski 1958–1980), the new edition of the map provides a significantly simplified cartographic image of both Quaternary landforms and sediments, whereas it stratigraphy has been largely extended (Fig. 2d).

Similar to L. Lindner et al. (2008), the authors of the new DGMT designated loamy supported gravelly sediments, previously classified as fluvioglacial outwash deposits, as glacial tills. The presence of distant till covers is proposed in area north of the Sucha Woda Valley, in the Tatra Mountains foreland (Toporowa Cyrhla fan) (Fig. 8). With the exception of the direct vicinity of distinct LGM moraines of the Sucha Woda glacier, where the presence of remnants of glacial till with large boulders (> 2 m in diameter) cannot be ruled out (Derkacz et al. 2009), the mapping campaign (400 measurements of boulder size) on the forefield of Sucha Woda LGM terminal moraines (Toporowa Cyrhla fan) evidences that the maximum length of boulders decreases there gradually from 1.4 to 1.2 m at a distance 0.25–4.0 km from LGM moraines (Kałuża 2016). Additionally, clast sorting and segregation supports a water-laid genesis of the Toporowa Cyrhla fan as commonly accepted in previous studies (Baumgart-Kotarba, Kotarba 2001).

The concept of a several kilometer longer glacial extent described in a paper by A. Wójcik and W. Rączkowski (2015) requires detailed documentation and strong sedimentological evidence, which were not provided in the study. Additionally, glaciological and paleoclimate implications for such extensive glaciation were not discussed. For example, the MEG the European Alps was only 10 to a few tens of percent larger than that of the last glaciation (Anderson et al. 2012; Barr, Lower 2014). Conversely, the extent of the largest glaciation in the Tatra Mountains proposed by A. Wójcik and W. Rączkowski (2015) is 60–80% larger than the LGM (Fig. 8), which seems to be rather an extraordinary situation in the context of European mountains. Additionally, these authors do not exclude the possibility that the Tatra glaciers could have reached even the area of Nowy Targ, which is 20 km beyond the LGM ice limit (Wójcik, Rączkowski 2015). This is returning to the concept of the early pioneer phase of research (e.g. Romer 1927, 1929). Such extremely large glacier extent requires not only detailed geologic evidence, but also paleoclimatical and glaciological explanations.

On the other hand, the stratigraphic framework proposed by A. Wójcik and W. Rączkowski (2015) ignores well-documented achievements of previous research phases, which coherently underscored a well-defined difference in relief freshness and morphologic contrast of the glacial deposits of the last and older glaciations, which typically was attributed as a boundary between classical Alpine Riss and Würm glaciations (Partsch 1923; Klimaszewski 1988; Baumgart-Kotarba, Kotarba 1997). The new map presents the chronology and distribution of glacial deposits in a way which has never been discussed in the literature before. Within a sequence of maximum and recessional moraines, which were previously attributed to the last glacial cycle ("younger moraine" unit), A. Wójcik and W. Rączkowski (2015) distinguished moraines associated with the Mindel, Riss, and Würm (LGM) glaciations (Fig. 8). The glacier extent during the LGM was reduced to the youngest recessional moraines in this sequence. In consequence, the glaciers of the last glaciation were supposed to be long and narrow with a limited thickness (50 m; Fig. 8), which seems to be in conflict with glaciological principles. On the other hand, within the "older moraine" cover at the Hurktone site, sediments of the Alpine Donau and Günz glaciation was proposed on the map, (Fig. 8). The proposed correlation with Alpine glaciation scheme is highly speculative. The assignment of each mapped unit

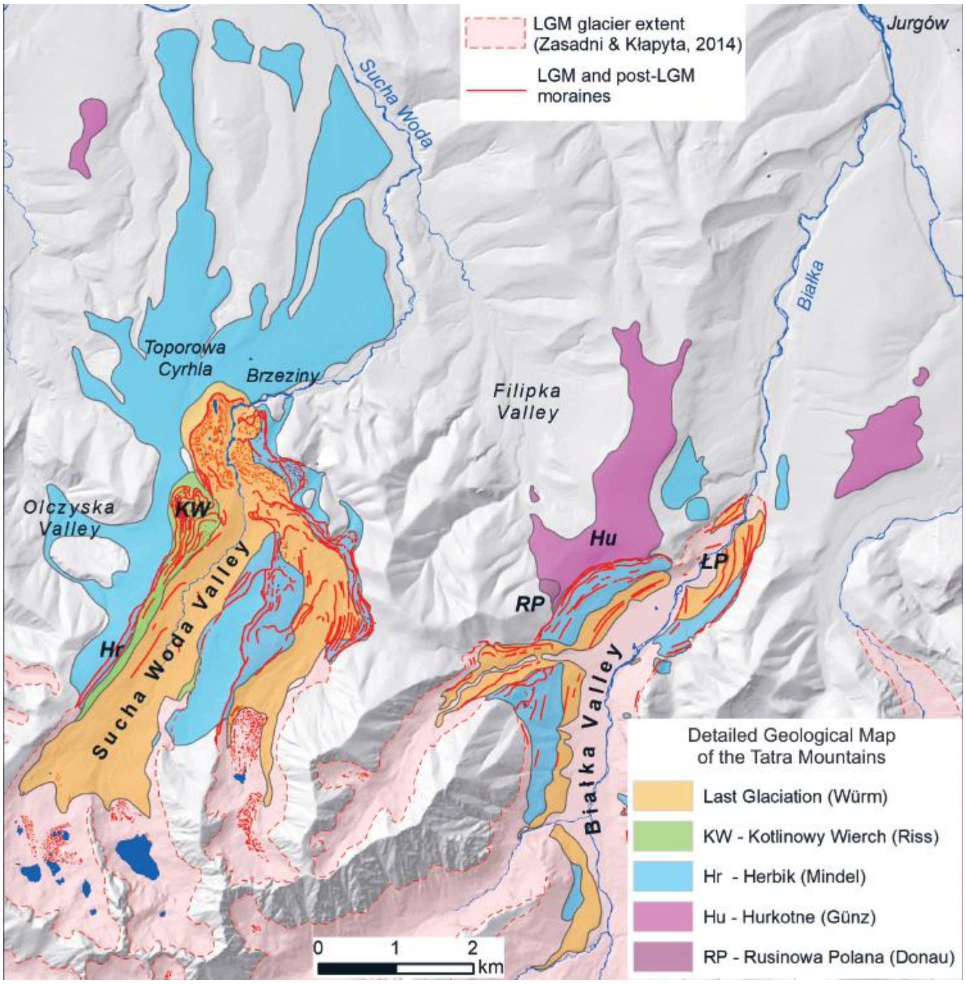

Fig. 8. Extent and stratigraphy of glacial sediments in the Polish part of the High Tatra Mountains according to Detailed Geological Map of the Tatra Mountains 1: 10,000 (Piotrowska et al. 2015; Wójcik, Rączkowski 2015).

to a particular glaciation is not explained by the authors (Piotrowska et al. 2015), as is the case with the criteria used for distinguishing mappable units. In addition to these problems, we would like to note that the consequence of the proposed stratigraphy of glacial sediments consists of a shift back in time of the distinct morphologic boundary between “older moraine” and “younger moraine” units. In the Białka Valley, this boundary lies between the Günz and Mindel glaciations, while in the Sucha Woda Valley between Günz and Mindel as well as Mindel and Riss glaciations (Fig. 8). In contrary to the literature, the authors of the DGMT ignore this boundary as the major stratigraphic line. The map shows also that this boundary is diachronic, which also needs explanation.

The stratigraphic conception proposed by A. Wójcik and W. Rączkowski (2015) was criticized by M. Baumgart-Kotarba et al. (2008) and K. Birkenmajer (2009). M. Baumgart-Kotarba et al. (2008) argue that there is no reason to distinguish deposits of several glaciations within the uniform "younger moraine" geomorphologic unit using individual moraine walls as evidence for separate glaciations; moraines may not be correlated like levels of river terraces. Similarly, K. Birkenmajer (2009) notes that the "older moraine" unit does not exhibit a difference in both sediments and relief in order to be subdividing it into several mappable units.

Our current knowledge on the number, age, and extent of older Tatra glaciations remains unresolved. If we abandoned a speculative correlations with the classical Alpine glaciation scheme (Günz, Mindel, Riss, Würm) then the above issues would be even more problematic today than they were in the past. A major problem is reliable dating of the oldest glacial sediments. Cosmogenic exposure age dating can yield young ages due to the significant post-depositional exhumation and erosion of moraine boulders, as this geomorphologic unit was most likely exposed to intensive degradation for more than 100 ka longer in the cold climate in comparison with "fresh" LGM moraines.

Future progress in understanding the Pleistocene glacial history of the Tatra Mountains will also hinge on luminescence dating of fluvioglacial outwash sediments preserved notably in the southern foreland of the High Tatra Mountains. Two particularly interesting locations are the Veľká Žltá stena and Mala Žltá stena (Lukniš 1973), where the stratigraphic framework is quite visible in large, natural outcrops and the chronology of sediments remains unknown. The studies of the chronology of pre-LGM glaciations are a serious challenge for future studies. They should also take into account the role of neotectonic uplift as well as the rate of glacial erosion, whose impact on the geologic record of glaciation was important over a long time period (10^5–10^6 years).

MAXIMUM EXTENT OF GLACIERS DURING THE LAST GLACIAL CYCLE

Currently, the best-recognized issues in Tatra glacial geochronology are the nature and timing of maximum ice extent during the last glacial stage. The detailed extent and ice-surface geometry of all 55 LGM Tatra glaciers indicate that they occupied a total area of 279.6 km^2, with the most area on the southern slopes (Zasadni, Kłapyta 2014) (Fig. 1). This glaciation asymmetry was linked to the high-altitude ice-surfaces of southern-facing glaciers, which were found 200 to 250 m higher than northern-facing glaciers.

The widespread chronologic evidence obtained by multiple ^{36}Cl and ^{10}Be exposure age dating efforts (Dzierżek 2009; Makos et al. 2013a, 2014, 2016, 2018; Engel et al. 2015, 2017) shows that the maximum glacial extent was widely coincident with the global Last Glacial Maximum (LGM; 26.5–19 ka; Clark et al. 2009). However, a recent dataset obtained by M. Makos et al. (2018) (Fig. 6) indicates that the glaciers reached their maximum position as early as 28–25 ka (LGM I) and the time of the final stabilization of the moraines was biased by the melting of buried dead ice. A twofold glacial advance occurring during the LGM (LGM I and LGM II) was distinguished on the northern Tatra slopes (Makos et al. 2018). A large exposure age dataset obtained for the LGM terminal moraines of several independent glacial systems in the Tatra Mountains shows us that both pre-exposure (inheritance) and post-depositional processes should be taken into account when dating Tatra LGM moraines. Thus, a large number of sample boulders are needed for a good sampling strategy (Engel et al. 2015). In particular, the LGM moraine in the Bystra Valley exhibits young ages (ca 15.5 ka) due to various post-depositional processes (Makos et al. 2016). In contrast, recently obtained cosmogenic exposure ages from Białka LGM moraines from the Łysa Polana glade range between 25 and 57 ka (Makos et al. 2018), which clearly indicates that LGM moraines may have been partially built of supraglacial transported boulders coming from rock avalanches on the glacier surface, which had had non-zero exposure. Furthermore, a similar conclusion may be drawn for the Lateglacial moraine sequence of "too old" ages in the Sucha Woda/Pańszczyca moraines (Makos et al. 2018), where a dominance of debris-covered glaciers has been suggested on the basis of geomorphologic records (Zasadni 2015). This shows that the ice surfaces of Tatra Pleistocene glaciers were more "dirty" than "clean."

The results of LGM glacier-climate modelling point to a decrease in the mean annual temperature by 11–12°C and a reduction in annual precipitation by 60% on the northern and 40–50% on the southern Tatra slopes (Makos et al. 2018). Overall, the obtained paleoglaciological and chronological data yield the most comprehensive picture of LGM glaciation in the Carpathians.

New chronological data produced in the meta-analysis phase of research support early views on the timing and stratigraphy of the Last Glaciation presented in the works of M. Baumgart-Kotarba and A. Kotarba (1997, 2001), but are in conflict with schemes of Late Pleistocene glacial advances in the Tatra Mountains presented by M. Lukniš (1959, 1964, 1973) and L. Lindner et al. (1990, 2003). According to M. Lukniš (1959, 1964, 1973), the morphologically pronounced and fresh moraine complex found at the mouth of the Veľká Studená Valley was formed during multiple phases of the last glaciation (MIS 5d – MIS 2) (Fig. 3a). Application of the Schmidt-hammer test (Mida, Křižek 2013) and detailed reconstructions of the geometry of Tatra glaciers (Zasadni, Kłapyta 2014) suggest that these moraine deposits belong to one morphologic system (LGM) and represent a multi-lobed geometry typical of debris-covered glaciers. More recently, these assumptions became fully supported by the use of cosmogenic exposure age dating (Engel et al. 2015) (Fig 3). No age differences were found between the secondary moraine lobes (Fig. 3), which according to M. Lukniš (1973), represent individual Würmian readvances. An arithmetic mean age of 22.5 ± 2.9 ka calculated for the moraine boulders indicates that the prominent morainic amphitheatre of the Veľká Studená Valley formed close to the global LGM. As the stratigraphic framework proposed by M. Lukniš (1973) for the southern slopes of the Tatra Mountains was deconstructed for the type locality; therefore, the division of the Würm into stadial oscillations (i.e. WA, WB, WC, WD) and the estimated chronology of the Last Glaciation should then be abandoned.

Recent results of cosmogenic exposure age dating indicate that there is no chronological evidence for extensive glacial advances during the early and middle parts of the last glaciation, as it was stated so far (Lindner et al. 2003; Baumgart-Kotarba, Kotarba 2001).

DEGLACIATION CHRONOLOGY AND FINAL ICE MELTING

APPROACHES TO THE CONSTRUCTION OF THE DEGLACIATION SCHEME

Post-LGM chronology is the issue which was extensively studied during all phases of Tatra geomorphologic research and has produced a large number of published papers. Due to a lack of geochronological control during the pioneer phase, a deglacial moraine sequence was tentatively correlated with the earliest Alpine morphostratigraphic scheme available (Penck, Brückner 1901–1909). As a consequence, three recessional stages of the last glaciation were formally identified in the Tatras' glacial record – Bühl, Gschnitz, and Daun (Lucerna 1908; Partsch 1923; Halicki 1930; Szaflarski 1937).

During the mapping phase, the advent of paleobotanical studies and the biostratigraphic subdivision of the Lateglacial and Holocene into warmer and colder periods (Iversen 1954) created an opportunity to associate glacier advances with climatic cooling. The construction of glacial chronologies thus relied on the assumption that each known paleoclimatic phase such as the Oldest Dryas, Older Dryas, Younger Dryas, Preboreal, and Boreal should correspond to a moraine in the glacial record (Klimaszewski 1967; Lukniš 1973). The employment of such an assumption was encouraged by the fact that located close to the Tatra Mountains was one of the earliest paleobotanically studied sites in Central Europe (i.e. Na Grelu peat bog, Koperowa 1958). However, W. Koperowa's bog biostratigraphy lacked a quantitative, paleoenvironmental dataset, which was then partially adopted from other works. Timberline fluctuations were adopted from the work of W. Szafer (1952), while summer paleotemperatures from the Alpine research results of G. Lang (1952). Due to the use of Hiller's sampling technique, the pollen diagram was "heavily contaminated" by younger pollen, which limited the paleoenvironmental significance of this paleobotanical profile (Obidowicz, personal communication in 2008). The quality of the major paleoclimatic inferences from W. Koperowa's (1958) paleobotanical study as well as the tentative way of linking these results with the moraine record in the Tatra Mountains (Klimaszewski 1967; Lukniš 1968, 1973) make these glacial chronologies a historical concept only. During the geochronological phase of research, new pollen-derived data concerning air temperatures and timberline fluctuations during the Lateglacial and Holocene were presented by A. Obidowicz (1993, 1996) for several sites in the Tatra Mountains. These new data substantially changed older concepts on the Tatra Lateglacial paleoclimate. For example, the elevation of the upper timberline during the Younger Dryas was estimated by W. Koperowa (1958) to be 800 m, while according to A. Obidowicz (1996) the correct value is 1,100 m. Paleobotanical results generated by A. Obidowicz (1993, 1996) were then adopted during the geochronological phase by M. Baumgart-Kotarba and A. Kotarba (1997, 2001) in studies on glaciation and the Lateglacial paleoclimate in the Tatra Mountains. Nevertheless, the historical paleoenvironmental dataset of Koperowa, is still taken into account during the meta-analysis phase (e.g. Dobiński 2004; Makos et al. 2016, 2018).

Interestingly, during the mapping phase of the research, the authors avoided assigning a multi-moraine sequence to one climatic phase whenever possible, e.g. the Younger Dryas was normally represented by only one moraine. This organizational paradigm persisted also during the geochronological phase of research but in this case Lateglacial-Holocene moraine sequence of the Tatras was correlated to the Alpine and Polish Lowland glacial chronologies which offer more stages than known paleoclimatic phases (Baumgart-Kotarba, Kotarba 1997, 2001; Lindner et al. 2003) (Fig. 4b).

ECHO FROM THE ALPS

In each phase of glacial research history, there were attempts to find an analogy between Tatra and Alpine deglaciation schemes. Researchers studying the Tatra Mountains, however, did not pay attention to the fact that the Alpine scheme had substantially evolved over time. The pioneering, seminal publication of A. Penck and E. Brückner (1901–1909) proposed a total of three post-Würmian recessional glacial advances in the Alps (Bühl, Gchnitz and Daun). This scheme was then systematically updated with new glacial stages and vigorously discussed. Between the 1960s and 1980s the scheme was the most extensive with 6–12 glacial stages (e.g. Bühl, Pinzgau, Schlern, Steinach, Gschnitz, Calavdel, Daun, Egesen I-III, Kromer, Kartel, Schlatten, Venediger (Penck, Brückner 1901–1909; Kinzl 1932; Heuberger 1966; Senarclens-Grancy 1956; Mayr, Heuberger 1968; Patzelt, Bortenschlager 1973; Gross et al. 1977; Maisch 1981). It should be noted, that this scheme has never been accepted with all the above-mentioned stages at any particular time.

Recent reinvestigation of Late Pleistocene Alpine stratigraphy based on geological mapping and sedimentological studies accompanied by absolute dating (Reitner 2007; Reitner et al. 2016) led to a significant reduction in the number of stratigraphic divisions of the Alpine deglaciation scheme. Stages previously placed before the Gschnitz stadial (Bühl, Steinach) were abandoned as the true climate-driven glacial advances and a new stratigraphic term was coined: Early Lateglacial Ice Decay (ELgID); (Reitner 2007). The ELgID corresponds to the time and process of massive deglaciation and prominent ice-reorganization of large transection glacier systems into small mountain glaciers (Reitner et al. 2016; Wirsig et al. 2016). In this context, the Gschnitz is the first true climate-driven mountain glacier advance during post-LGM deglaciation (Ivy-Ochs 2015). New data also call into question the stratigraphic significance of the post-Gschnitz and pre-Bølling stadials – Clavadel and Daun (Reitner et al. 2016). The discussion of the Alps is ongoing. Interestingly, it is now being suggested that the Lateglacial scheme may be shown in the form of three major groups of moraines and ice-marginal landforms (ELgID, Gschnitz and Egesen), which signals, in fact, a return to the three-stage division of A. Penck and E. Brückner (1901–1909). The ELgID stratigraphic unit has replaced and redefined the stratigraphic position of the Bühl. The Gschnitz remains unchanged in the scheme and the Egesen moraine sequence represents the same moraine system as the "pioneer Daun".

From this short review, we may conclude that an analogy between the Alps and Tatras cannot be expected for stadials older than the Gschnitz. This is because during the post-LGM deglaciation of the Tatra Mountains there was no rapid reorganization of the large transection glacier system into small mountain glaciers, as it had happened in the Alps. In other words, due to a different mode of early deglaciation, in contrast to the Alps, we may expect in the Tatras the presence of true climate-driven glacial advances older than the Gschnitz--equivalent stadial.

Nevertheless, M. Lukniš (1964, 1973) used in the Tatra Mountains the Alpine scheme in its 1960s stage of evolution, which showed, for example, that the Gschnitz is the Younger Dryas and the Egesen stadial is the Early Holocene (currently the Oldest Dryas and Younger Dryas, respectively). In contrast, M. Baumgart-Kotarba and A. Kotarba (1997, 2001) adopted the Alpine scheme at its 1970s stage of evolution, which was at a time after an important turning point, which showed that the Gschnitz is the Oldest Dryas and the Egesen stadial is the Younger Dryas (Patzelt 1972, 1975), which is accepted till now (Ivy-Ochs 2015).

However, during both the mapping and geochronological phases of research, the Alpine scheme was used in its older stage of evolution before important turning point which showed that the redefined Daun stadial (Kinzl 1932) is not the Older Dryas but the pre-Bølling (Oldest Dryas) (Maisch 1981, 1982). After the papers of M. Maisch (1981, 1982), the Alpine deglaciation scheme, in fact, rejected the Older Dryas as a climate event which could leave moraines in a deglaciation sequence. This event lasted only 100 years in a relatively warm Bølling/Allerød phase, lasting 1,800 years (Litt et al. 2001). With regards to duration and climatic severity, it is not comparable to the next Younger Dryas phase (lasting 1,200 years), which had to "override" and destroy Older Dryas moraines, had they ever formed (Ivy Ochs et al. 2008). In fact, Older Dryas moraines may be considered Bølling/Allerød interphase moraines. In this interphase, there were another two or three comparable short-duration cold events known from high-resolution paleobotanical studies and Greenland ice cores (Litt et al. 2001; Rasmussen et al. 2014), but none had been used previously in glacial chronologies. The Older Dryas is exceptional in this case only because it was known for a long time from the advent of biochronological studies in northern Europe (Iversen 1954; Mangerud et al. 1974). The consequence of adopting the now outdated Alpine scheme in all Tatra deglaciation schemes (Klimaszewski 1967, 1988; Lukniš 1973; Baumgart-Kotarba, Kotarba 1997, 2001; Lindner et al. 2003) is the assumption that there should be some moraines formed during the Older Dryas climatic phase. In this case, the lesson from the Alps has not been learned. The suggested Older Dryas moraines in the Tatras have never been proven quantitatively during the geochronological phase.

Interestingly, recent TCN datings suggest the presence of Older Dryas moraines exclusively in the northern slope valleys of the Western Tatra Mountains (Makos et al. 2016; Engel at al. 2017). For the first time, Older Dryas moraines are evidenced independently from the Alpine scheme. However, there are several important reasons why we are skeptical about these results. First, the uncertainty associated with the TCN dating method is too large (500–700 years) to detect a climatic event lasting 100 years. M. Makos et al. (2016) yield an average age for two moraines of 14.0 ka (n 5) and 13.7 (n 5), but individual moraine ages range between 16 and 12 ka. Z. Engel at al. (2017) confirmed the conclusions of M. Makos et al. (2016) using the age 13.4 (n 3) obtained for a moraine (rock glacier?) in the Roháčská Valley (Fig. 6). Individual ages are between 12.4 and 14 ka. Moreover, M. Makos et al. (2016) and Z. Engel at al. (2017) use different snow corrections (20 cm/3 months/year and 42cm/6 months/year, respectively) at similar locations and elevations (NW part of the Tatras, 1,300 and 1,500 m). These two approaches to exposure age calculation, however, can produce differences of several hundred years. If applying Z. Engel at al. (2017) larger snow cover shielding to the age calculation for M. Makos et al. (2016) data sets, this will yield a 500–700 years older age. This will give much older moraines in the Bystra Valley, which would fall before the Bølling, thus we would exclude the Older Dryas, as proposed by Makos et al. (2016). In consequence, the age correlation suggested by Z. Engel at al. (2017) does not exist between these two dated moraines because taking the same strategy of age calculation, the age difference between these sites would be ca 1 ka. In addition to the problems of age calculation and interpretation, the proposed concept of Older Dryas moraines in the Tatra Mountains suggests indirectly that the Older Dryas in the Tatras represents a stronger climatic downturn than the Younger Dryas, as Older Dryas moraines were not destroyed by the Younger Dryas glacier advance. This should be discussed in the context of local paleoclimate records from High Tatra lakes (Kłapyta et al. 2016 and references therein), as well as the wider context of Central European paleoclimatic records (Renssen, Isarin 2001; Feurdean et al. 2008) which indicate unfavourable condition for glacier re-advance during Bølling/Allerød interphase. Even if the Older Dryas event is recognizable in these paleoarchives, it is not stronger anywhere than the Younger Dryas climatic phase. This fact brings in question the possibility that glaciers being in equilibrium with climate condition, as glacier-climate model of M. Makos et al. (2016) assumes, could reach similar size as during the Younger Dryas. In fact, the Younger Dryas moraines in the Bystra Valley has not been proved. The problem of Older Dryas moraines in the Tatras needs to be re-examined in greater detail.

Similarly, as in the problem of Older Dryas moraines, the concept of early Holocene moraines in the upper parts of High Tatra valleys has emerged as a result of tentative correlation of the youngest Tatra moraines with the Egesen stadial in the Alps in the first Tatra stratigraphic scheme by M. Lukniš (1964, 1973) (see discussion in J. Zasadni and P. Kłapyta 2016). The alpine deglaciation scheme at that stage of evolution (before a paper by Patzelt, 1972) considered the Egesen stadial to be the Early Holocene (Kinzl 1932; Heuberger 1966; Mayr, Heuberger 1968), while today it has been shown that it is the Younger Dryas (Ivy-Ochs et al. 2008, and references therein). As a result, a deglaciation of High Tatra cirque basins was assumed during the Holocene, and the final ice melting was presumed to have occurred during the Atlantic thermal optimum (Lukniš 1973; Halouzka 1977; Lindner et al. 2003; Baumgart-Kotarba, Kotarba 1997, 2001). M. Baumgart-Kotarba and A. Kotarba (1997) argued that a distinct mineral layer in the Żabie Oko lake sediments could be linked with an intense deposition during the youngest glacial-prone cold stage and was related to glacier activity in the upper part of the catchment. This event was correlated with the Alpine Venediger glacial stage, and the youngest moraines in the deglacial sequence were assigned to this stage. The Early Holocene age of moraines in the Tatra Mountains has not been proven directly by numerical datings. Recent results by M. Makos et al. (2018) in the Pusta Valley (Polish High Tatra Mountains) and new, preliminary results of ^{10}Be TCN campaign datings (Opyrchał et al. 2017; Zasadni et al. 2018) in the Slovak High Tatra Mountains suggest that the youngest moraines and relict rock glaciers developed during the Younger Dryas, thus there are no landforms in the highest part of the High Tatra Mountains left which may be attributed to the Early Holocene. Interestingly, in this context, the earliest morphostratigraphic conception of M. Lukniš (1964, 1973) which correlates the youngest moraines to the Egesen stadial is still valid, although his chronological considerations should be treated as a historical concept.

MORAINES ARE GETTING OLDER

Over the last four decades, since the beginning of the geochronological phase, the chronological position of Tatra post-LGM moraines has shifted systematically back in time with an increasing number of radiometric ages and dating sites. This trend is the effect of a systematic displacement of morphostratigraphical-based correlations with the Alpine deglaciation scheme, which was commonly adopted during the mapping phase. For example, M. Lukniš (1964, 1973) described moraines of several kilometre-long glaciers in the High Tatra Mountains which he assigned to the Younger Dryas (Gschnitz at the time). The same moraines were assigned to the Oldest Dryas (also Gschnitz-equivalent but in a modern chronological position) after the turning point related to the advent of the geochronological phase of research (Baumgart-Kotarba, Kotarba 1997, 2001). Similarly, the Early Holocene age of the youngest moraines suggested by J. Dzierżek et al. (1987) along with L. Lindner et al. (2003) and M. Baumgart-Kotarba and A. Kotarba (1997) is recently dated to the Younger Dryas (Makos et al. 2018; Zasadni et al. 2018). This shows that current progress in geochronological knowledge yields an older age of the youngest recessional moraines found high in glacial cirques in comparison with their suspected age from the mapping phase of research. The consequence of this evolution is the fact that glacier extent of given stage has become systematically smaller. This process is also observable during the meta-analysis phase. A good example of this is the glacial chronology of the Pięć Stawów Polskich Valley where J. Zasadni and P. Kłapyta (2016) presented proofs of a much smaller Younger Dryas glacier extent than previously published in the valley (Gądek 1998; Dzierżek 2009; Makos et al. 2013a). This limited Younger Dryas glaciation was confirmed recently by M. Makos et al. (2018) with TCN dating (10.9±0.6 ka; n 5) on Pusta valley cirque moraines.

The Alpine deglaciation scheme underwent a similar evolution from younger to older ages for the array of glacial stages studied. The best example of this process is the evolution of the chronological position of the Gschnitz stadial moraines. First, they were assigned to the post-Younger Dryas (Preboreal – Klebersberg 1950; Senarclens-Grancy 1956), then Younger Dryas (Mayr and Heuberger 1968), Older Dryas (Patzelt 1972), and finally to the Oldest Dryas phase (Patzelt 1975; van Husen 1977). The Oldest Dryas age of this stage was dated using the TCN method by S. Ivy-Ochs et al. (2006). Therefore, the described evolution of the Tatra Mountains scheme is partially an "echo" of Alpine scheme evolution.

BIO- AND MORPHO-STRATIGRAPHY VS. TL-BASED CHRONOLOGY – THE GEOCHRONOLOGICAL PHASE

The deglaciation scheme produced by M. Baumgart-Kotarba and A. Kotarba (1997, 2001) on the basis of geomorphologic mapping provides valuable information on both the Tatra moraine stratigraphy and its deglaciation pattern. This scheme filled in the gap in the Polish High Tatras left by M. Klimaszewski (1988), who was not focused on the details of glacial morphostratigraphy and chronology. The detailed pattern of deglaciation documented using the landform distribution (moraines, relict rock glaciers; Fig. 4) is currently used as the geomorphologic framework for TCN datings (Makos et al. 2018). The achievement of the Cracow School is the introduction of the intra-Tatra biostratigraphy as well as radiocarbon ages obtained for lake sediments as a means of interpreting the minimal age of moraines (Fig. 4).

Among the series of available radiocarbon ages, particularly important is the oldest ^{14}C date inside the Tatra mountain glacial land system (12.550 ± 420 ^{14}C ka BP; 15.96 – 13.65 cal. ka BP; Baumgart-Kotarba, Kotarba 1993) obtained from Czarny Staw Gąsienicowy Lake sediments (Fig. 4). Radiocarbon and biostratigraphic data indicate that glacial retreat and lake formation in cirques found at high elevations (1,600 to 1,700 m) began at the end of the Oldest Dryas or at least in the Bølling-Allerød warming. From this data, the post-LGM moraine sequence was divided into moraines older and younger than the Bølling interphase. Yet, the chronological position of a particular moraine system inside these two groups of moraines has no age control. They age were adopted from the Alpine scheme formulated in the 1970s, thus, as discussed above, this part of the chronological framework should be abandoned. The Alpine scheme is now being systematically tested via new TCN datings during the meta-analysis phase of research (Makos et al. 2018).

The TL-based glacial chronology (Lindner et al. 1990, 2003) was an independent approach used to obtain post-LGM moraine ages and the deglaciation pattern (Fig. 5). The TL method is no longer used in modern glacial geochronologies (Fuchs, Owen 2008), as it is unreliable for dating glacial sediments. This is mostly because glacial sediments may never become exposed to daylight before being deposited, thus often their luminescence signature is not reset (Fuchs, Owen 2008). Hence, the TL-based chronology was questioned in previous works (Hercman 2000; Baumgart-Kotarba, Kotarba 2001; Mojski 2005; Makos 2015). The Warsaw School Lateglacial chronology is solely based on TL ages with limited documentation of the morphostratigraphic relationships at the sampled sites (Fig. 5).

The type localities of the deglacial phases of the Last Glaciation (Białka stadial) were defined for the Białka Valley (Dzierżek et al. 1986); however, most of the TL datings were obtained at different localities (Fig. 5). The Łysa Polana phase defined in the terminal moraines of Białka glacier (Dzierżek et al. 1986) was dated both at terminal moraines in the Mała Łąka and Bystra Valleys and upper parts of the Mała Łąka and Białka Valley (Fig. 5). The Włosienica Phase, defined in the Rybi Potok Valley (Dzierżek et al. 1986), was dated at terminal moraines (LGM) located in the Mała Łąka Valley (Lindner et al. 1990) (Fig. 5). Similarly, the Pięć Stawów Polskich I phase originally established at the mouth of the Pięć Stawów Polskich cirque (Dzierżek et al. 1986) was dated in the lower part of the Sucha Woda Valley (Lindner et al. 1990) (Fig. 5). The significance of the Włosienica Phase type locality is not clear because of extremely variable glacier extent during this phase proposed by J. Dzierżek et al. (1986) and

L. Lindner et al. (2008) (Fig. 5). The Pięć Stawów Polskich Phase encompasses the time span between the Oldest Dryas and the Boreal (Fig. 5). It does not take into consideration the Bølling/Allerød interphase, which is well-documented in Tatra lacustrine sediment data (Krupiński 1983; Baumgart-Kotarba, Kotarba 1993). In contrast, the interphases proposed in the scheme (Waksmund, Polana pod Wołoszynem and Roztoka) are not supported by biostratigraphic and/or radiometric data. Currently, both the scheme and the associated stratigraphic terminology of Warsaw school are no longer used (Zasadni, Kłapyta 2016; Makos et al. 2016, 2018).

CONCLUSIONS

The history of research on the Tatra Mountains glaciations began in 1856 when Ludwi Zejszner discovered the legacy of the Pleistocene glaciation in the Bystra Valley near the town of Zakopane. It was one of the earliest discoveries in European mountains following the advent of glacial theory coined in the Alps in the first half of the 19th century. The history of glacial research in the Tatra Mountains began with pioneering observations in the 19th century and the detailed geomorphologic mapping phase through a geochronological phase when the first forms of radiometric control of glacial chronology emerged and continue with the current meta-analysis phase that began two decades ago.

Recent improvements in the chronological control of moraine age by TCN exposure age dating has occurred in parallel with the modeling of the paleoclimate-based on glacier reconstructions. The achievements of the meta-analysis phase help us to better understand the climatic significance of reconstructed glacier advances and more sophisticated inter-regional correlations. This is particularly true of the Last Glacial Maximum (LGM) – the Lateglacial chronology for which abundant datings are currently available and their number is still growing. The freshly shaped “younger moraines” in a maximum position were dated for seven individual glacial systems on both northern and southern slopes of the Tatra Mountains. The obtained ages of moraine formation/stabilization are between 28 and 18 ka providing the strongest evidence of LGM chronology in the entire Carpathians mountain arc. These new TCN data substantially reject certain previous morphostratigraphic-based chronologies from the mapping phase of research, which should be taken into account when reconsidering old chronologies in the new research. The chronology of the last deglaciation is currently vigorously discussed in the literature in light of the increasing number of available TCN datings.

Over the last four decades, the general pattern is that the age of post-LGM moraines has shifted systematically back in time due to an increasing number of radiometric ages and dating sites. This means that the current state of knowledge yields an older age for the youngest recessional moraines located high in glacial cirques in comparison with their previously suspected age. We suggest that this pattern is an effect of the systematic displacement of morphostratigraphic-based correlation in the Alpine deglaciation scheme – commonly used during the mapping and geochronological phases. In fact, the Alpine scheme underwent a similar transformation from younger to older ages for particular glacial stages. This evolution has never been taken into account in studies in the Tatra Mountains.

The most popular schemes by M. Lukniš (1968, 1973) and studies of M. Baumgart-Kotarba and A. Kotarba (1997, 2001) were based on two different stages of evolution of the Alpine scheme and produced some degree of confusion concerning the adopted chronologic position of the given moraines. The Tatra deglaciation scheme has not been updated with regard to the Alps since the 1980s. From a review of the literature, we suggest that the concepts of Older Dryas and Early Holocene moraines in the Tatra Mountains are directly related to the adoption of outdated Alpine schemes. The timing of the final meltout of the Tatra glaciers has not been subjected to reliable radiometric control until now. However, preliminary new results suggest that glaciation in the Tatras ended with the beginning of the Holocene, and the Younger Dryas stadial was the last climatic downturn when glaciers were active in this mountain range.

There remains a major challenge in the Tatra Mountains to evidence the chronology and extent of the most extensive glaciation(s) (MEG), which is recorded as "older moraines" or till cover outside the LGM limit. Current standards of scientific research and argumentation cannot simply use morphostratigraphic inferences and tentative correlations with either the Alpine or Scandinavian glaciation schemes, as was the standard approach in previous phases of research history. In old, highly degraded glacial sediments, TCN dating is prone to yield ages that are too young. Nevertheless, a good starting point for solving this problem is encouraging a scientific focus on this subject with the statement that the pre-LGM glacial chronology in the Tatra Mountains may be treated as a blank slate.

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