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Outline of Quaternary glaciations in the Tatra Mts.: their development, age and limits

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Geomorphological and geological data collected over many years suggest at least eight episodes during which the Tatra Mts. were glaciated during the Quaternary. Evidence of glaciers can be found both in the Slovakian and Polish parts of the mountains as glaciofluvial deposits located at different altitudes, and in some cases also as terminal and lateral moraines. There are no moraines for the three oldest glaciations, Biber, Donau and Günz, maybe as a result of less intense development of glaciers. During the Mindel (Sanian 2) Glaciation the glaciers occuped a larger area in the High Tatra Mts. in comparison to the Western Tatra Mts., whereas during the succeeding younger pre-Riss (Liviecian) Glaciation their development was more restricted. A greater extent of the Tatra Mts. glaciers occurred again during the Riss I (Odranian) Glaciation, while they were less extensive during the Riss II (Wartanian) Glaciation. During the Würm (Vistulian) Glaciation the glaciers were surprisingly large. This might have resulted from many factors, including changes in atmospheric circulation responsible for the distribution of precipitation, as well as changes in the position of the permanent snow limit due to climatic changes and/or neotectonic movements. Glaciers finally retreated from the Tatra Mts. by the end of the pre-optimal part of the Holocene.

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INTRODUCTION

The history of the Tatra Mts. glaciations outlined here comprises a substantial part of the Quaternary history in the Slovakian and Polish parts of the Tatra Mts. It has been reconstructed on the basis of geomorphological-geological analysis of glacial and glaciofluvial deposits (e.g. Partsch, 1923; Romer, 1929; Halicki, 1930, 1951; Klimaszewski, 1961, 1967, 1988; Lukniš, 1968; Halouzka, 1977; Dzierżek *et al*., 1982*a*, *b*, 1987; Lindner *et al*., 1990; Nemčok, 1993*a*, *b*; Kotarba and Krzemień, 1996; Baumgart-Kotarba and Kotarba, 1997, 2001). The reconstruction began with the morphogenetic, morphometric and morphochronologic analysis of the main glaciofluvial levels and terminal and lateral moraines, determining the glacier limits (Figs. 1 and 2). This analysis was integrated with TL-ages of the glacial and glaciofluvial deposits (e.g. Prószyńska-Bordas *et al*., 1988; Butrym *et al*., 1990; Lindner *et al*., 1993), cosmogenic ^{36}Cl isotope ages (Dzierżek *et al*., 1996, 1999) and lithogenetic analyses of tills (Kenig and Lindner, 2001). The retreat of the glaciers from the Tatra Mts. during the last glaciation was constrained by biostratigraphic and radiocarbon dating of lake deposits (e.g. Wicik, 1979, 1984; Marciniak, 1982; Marciniak and Cieśla, 1983; Krupiński, 1984; Szeroczyńska, 1984; Baumgart-Kotarba and Kotarba, 1993; Lindner, 1994; Obidowicz, 1996).

MORAINES AND GLACIOFLUVIAL LEVELS AND GLACIER LIMITS

The studies noted above allow us to distinguish traces of eight Quaternary glaciations (Table 1) in the Tatra Mts. and in their foreland, for which the Alpine nomenclature (see Lindner, 1992; Mojski, 1993) is proposed. The three older glaciations (Biber, Donau and Günz) are represented only by glaciofluvial deposits. The five younger glaciations (Mindel, pre-Riss, Riss I, Riss II and Würm), with the exception the pre-Riss Glaciation, are documented by both glaciofluvial deposits and terminal and lateral moraines, and in the case of the Würm Glaciation also by three basal tills and glacially polished rock surfaces.

Table 1

Main stratigraphic units of the Quaternary in the Alps, Tatra Mts. and the Polish Lowland

	ALPS	TATRA MTS.	POLISH LOWLAND		
				Interglacials	Glaciations
QUATERNARY	Holocene	Holocene	Holocene		
	Würm	Würm	PLEISTOCENE		Vistulian
	R/W	RII/W		Eemian	
	Riss	Riss II			Wartanian
		RI/RII		Lubavian	
		Riss I			Odranian
		pre-R/RI		Zbójnian	
		pre-Riss			Liviecian
	M/R	M/R		Mazovian	
	Mindel	Mindel			Sanian 2
	G/M	G/M		Ferdynandovian	
	Günz	Günz			Sanian 1
				Małopolanian	
					Nidanian
	D/G	D/G		Podlasian	
	Donau	Donau			Narevian
			PRE-PLEISTOCENE	Celestynovian	
					Otwockian
	B/D	B/D		Ponurzycian	
	Biber	Biber			Różcian

BIBER (PRE-TEGELEN) GLACIATION

The glaciofluvial level (terrace) of this glaciation, considered as the oldest Quaternary glaciation in the Tatra Mts., was identified only in their Slovakian part, in the area of the Sub-Tatra Basin, where it is described as the Nowá Lesná deposits (Halouzka, 1979). It is represented by poorly sorted sands with eroded and strongly kaolinized granite grains. These sands forms the highest terrace surfaces (Figs. 1 and 2) in the southern part of the Western Tatra Mts. foreland, on the southeastern slope of the Bela Creek Valley, as well as in the southern and southeastern foreland of the High Tatra Mts. They are represented by watersheds separating the valleys of most creeks running southwards from Štrbské Pleso, Stary Smokovec and eastwards from Tatranska Lomnica. Slovakian scientists correlate the glaciofluvial deposits of this level, and the development of the corresponding glaciers, with the pre-Tegelen climatic cooling (Nemčok, 1993*a*, *b*). It is represented in the Polish Lowlands (Table 1) by the pre-glacial deposits of the Różce series (see Lindner *et al*., 1995). The lack of terminal moraines associated with this glaciation in the Tatra Mts. may indicate their smaller extent in comparison with younger glaciations.

DONAU GLACIATION (EBURONIAN + NAREVIAN?)

Slovakian scientists (Nemčok, 1993*a*, *b*) refer the accumulation of the lower glaciofluvial level (terrace) with the Donau Glaciation (Figs. 1 and 2). The level is also preserved in the southern part of the Tatra Mts. only. It is represented by the Hyba Beds, best preserved in the region of Štrbské Pleso and Stary Smokovec, where they are developed as coarse sands with gravel and boulders up to 40 cm in diameter. The boulders include strongly weathered granites, in many cases undergoing degradation into more or less isolated quartz grains. Occasionally, boulders of quartzite are also present.

Deposits of this level occur up to 55 m above the bottoms of the present-day valleys and reach *ca*. 6 m in thickness. Taking into consideration the fact that boulders of glacial origin prevail in deposits of this level (particularly in the region of Štrbské Pleso), it is most possible that during the Donau Glaciation the glaciers may have had a larger extent than during the earlier glaciation. The glaciofluvial deposits linked with the Donau Glaciation in the northern foreland of the Tatra Mts. are preserved only as a small patch on a watershed between the valleys of the Białka and Javorový creeks (Fig. 1).

The rhythm of climatic changes during the earlier Quaternary indicates that the development of the older glaciers may be correlated with coolings such as the Eburonian (corresponding to the preglacial accumulation of the Otwock series of sediments in the Polish Lowlands), and most probably also with the younger, more distinct cooling, influencing the development of the Scandinavian ice sheet during the Narevian Glaciation (Table 1).

GÜNZ GLACIATION (NIDANIAN? + SANIAN 1)

Slovakian scientists (Nemčok, 1993*a*, *b*) have linked the Günz Glaciation with the formation of the lower glaciofluvial level (terrace) preserved in the southern foreland of the Western Tatra Mts. (westwards from the junction between the Bela and Račková Creeks), as well as in the southern foreland of the High Tatra Mts. (southwards of Stary Smokovec) (Figs. 1 and 2). The level forms here distinct terrace surfaces on the slopes of the creek valleys. It comprises up to 14 m of gravels and sands. Numerous weathered granite boulders occur within them. In the southern foreland of the Tatra Mts., in the Szaflary–Wapiennik section (16 km north of Zakopane) in Podhale, accumulation of the "lower gravels" with material from the Tatra Mts., underlying the palynologically documented deposits of the Günz/Mindel Interglacial (Birkenmajer and Stuchlik, 1975), most probably took place.

The lower position of deposits representing this glaciofluvial level in relation to the terminal moraines of the Mindel Glaciation in the southern foreland of the Tatra Mts. (Nemčok, 1993*a*, *b*) suggest that they are equivalents of the Günz Glaciation, which had a smaller extent than the Mindel Glaciation. Furthermore, analysing the position of the "lower gravels" from the Szaflary–Wapiennik section in relation to the succeeding younger glaciofluvial levels in the Biały Dunajec River valley (see Birkenmajer and Stuchlik, 1975), and their position in relation to the high terraces of the Dunajec River (see Zuchiewicz, 1985), a correlation of this glaciofluvial level with the climatic cooling influencing the development of the

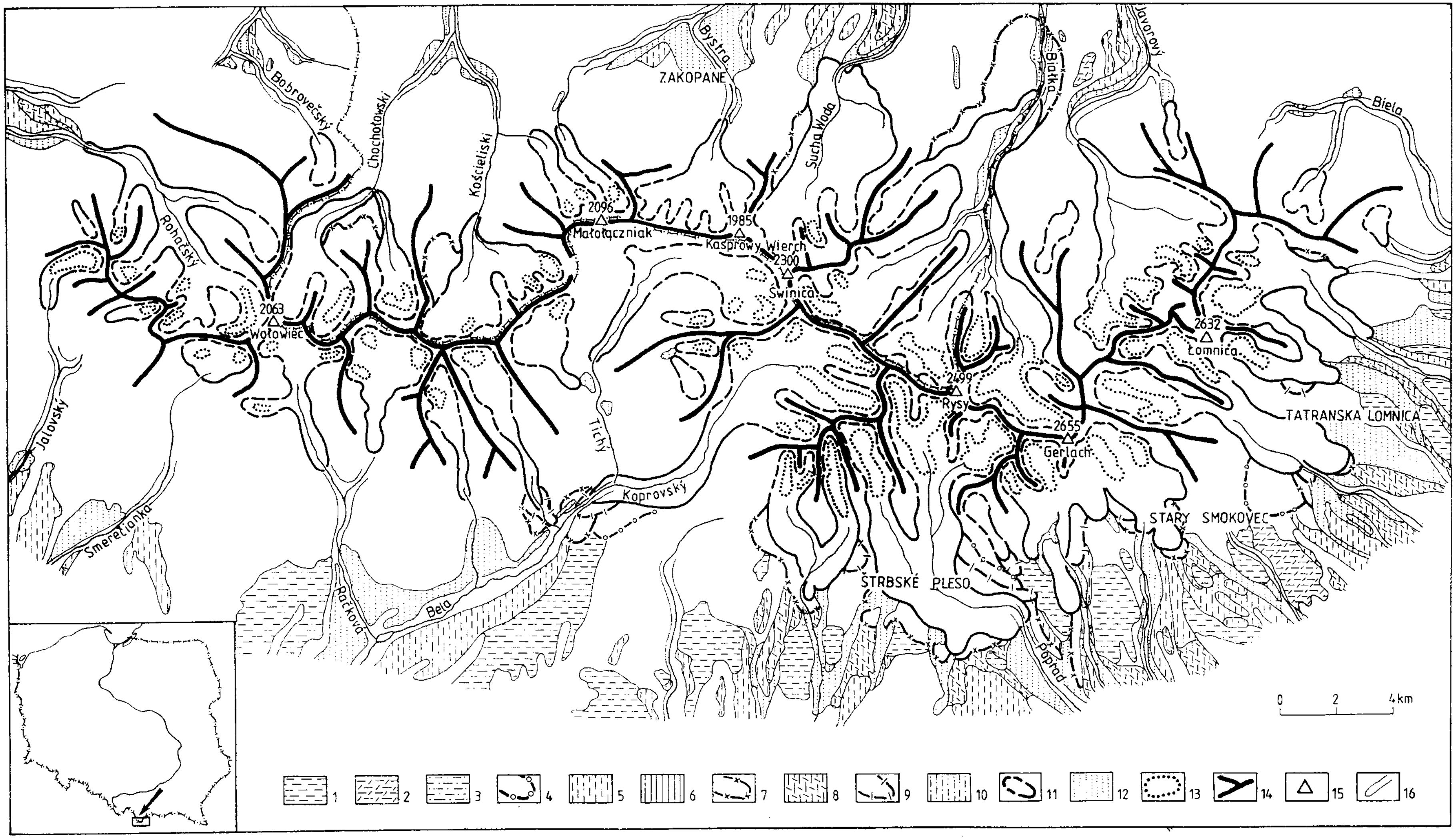

Fig. 1. Limits of glaciers and glaciofluvial levels in the Tatra Mts., after Nemčok (1993*b*), simplified with later supplements

Biber Glaciation: 1 — glaciofluvial level; Donau Glaciation: 2 — glaciofluvial level; Günz Glaciation: 3 — glaciofluvial level; Mindel Glaciation: 4 — glacier limit, 5 — glaciofluvial level; pre-Riss Glaciation: 6 — glaciofluvial level; Riss I Glaciation: 7 — glacier limit, 8 — glaciofluvial level; Riss II Glaciation: 9 — glacier limit, 10 — glaciofluvial level; Würm Glaciation: 11 — glacier limit (solid line) and firn fields limit (dashed line); 12 — glaciofluvial level; Late Glacial and Early Holocene: 13 — extent of glaciers, dead ice and rock glaciers; 14 — main mountain ridges; 15 — main peaks; 16 — river valleys

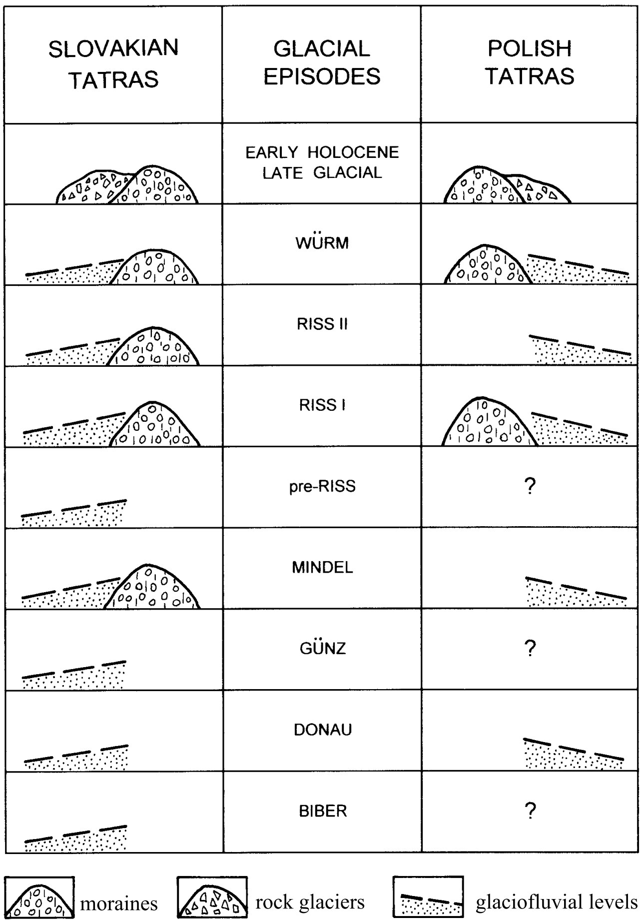

Fig. 2. Scheme of main glacial features in the Tatra Mts.

Scandinavian ice sheet during the Sanian 1 Glaciation in the Polish Lowlands (see Lindner *et al.*, 1993), or even the Nidanian Glaciation (Table 1), is plausible.

MINDEL GLACIATION (SANIAN 2)

This glaciation is represented by the oldest terminal and lateral moraines in the Tatra Mts. They occur only in the Slovakian part of the Tatra Mts., in three main localities (Fig. 1) between Tatranska Lomnica and Stary Smokovec — south of Lomnica, east of Štrbské Pleso — on the left bank of the Poprad River valley, and on the left bank of the Koprovský Creek — near the confluence with the Tichý Creek. The moraines comprise strongly weathered and disintegrating granite boulders, occurring within a silty-sandy deposit with clasts 5–15 cm in diameter. The total thickness of these deposits locally reaches 4 m (Nemčok, 1993*a*). Sandy-gravel deposits with boulders, forming a glaciofluvial terrace, are also linked with this glaciation (Figs. 1 and 2). They are preserved both in the southern and northern part of the Tatra Mts. In the southern foreland of the Western Tatra Mts., they form well-developed flat surfaces on the eastern slopes of the Bela, Smrečianka and Jalovský Creeks. They also occur in the southern and eastern foreland of the High Tatra Mts., in most cases on both sides of the valleys opening southwards from Štrbské Pleso, Stary Smokovec and Tatranska Lomnica, where they reach 10–15 m in thickness and lie up to 16–18 m above the valley bottoms (Nemčok, 1993*a*, *b*).

The distribution of the terminal moraines marking the glacier limits during the Mindel Glaciation in the southern part of the Tatra Mts. indicates that the glaciers had much greater extents in comparison to the earlier glaciations, and in some cases they mark the maximal limit of glaciers in the Tatra Mts. The Mindel Glaciation correlates with the global climatic cooling associated with the development of the Scandinavian ice sheet of the Elsterian 2 = Sanian 2 Glaciation in the Polish Lowlands (Table 1).

In the northern and western foreland of the Tatra Mts. the deposits representing the Mindel Glaciation form the highest surface of the glaciofluvial deposits in the valley (Fig. 1). They are preserved in the lower parts of the Rohačský and Chochołowski Creek valleys, lying over a dozen metres above their present-day bottoms. In the vicinity of Zakopane they also form the highest glaciofluvial level on both sides of the Bystra valley and in the western part of the Sucha Woda Valley, as well as occurring on the watershed between these creeks. They were considered by Halicki (1930) as fragments of a glaciofluvial level from the first (I) glacial period and were TL-dated at 443 ± 36 ka (Lindner *et al.*, 1993). They have also been recognised on the western slopes of the Javorový Creek valley in the northeastern foreland of the High Tatra Mts.

In Podhale, within the Szaflary–Wapiennik section, deposits of the Mindel glaciofluvial terrace cover the organic deposits of the Günz/Mindel Interglacial and are referred to as the "upper gravels" (see Birkenmajer and Stuchlik, 1975). They contain strongly weathered boulders of granites and of cherry-coloured Werfenian quartzites, randomly distributed in clays which formed by chemical weathering of the feldspars from the granite material. The TL-age of these deposits, determined at 328 ± 49 ka (Lindner *et al.*, 1993), indicates that they may also have accumulated during the younger glaciation of the Tatra Mts., determined by Nemčok (1993*a*) as the pre-Riss.

PRE-RISS GLACIATION (LIVIECIAN)

This glaciation is documented in the Slovakian Tatra Mts. as the oldest glaciofluvial level (step) of the Riss Glaciations (Nemčok, 1993*a*, *b*). Its presence has been determined only in the valley system of the Bobrovečský Creek (Fig. 1), in the northern foreland of the Western Tatra Mts. It is composed of sandy-gravel deposits with partly weathered boulders comprising granites and Mesozoic sedimentary rocks from the Western Tatra Mts. Most probably, part of the glaciofluvial deposits hitherto identified north of the Tatra Mts. (e.g. in the Szaflary–Wapiennik section) as representatives of the older glaciation could equally be attributed to this glaciation. The lack of terminal moraines of the pre-Riss Glaciation in the Tatra Mts. suggests a lesser extent of the glaciers during this glaciation. In the European Lowland its equivalent is probably the Fuhne = Liviecian Glaciation (Table 1), during which the Scandinavian ice sheet had a smaller extent than during older and younger glaciations (see Lindner, 1988, 1992).

RISS I (ODRANIAN) GLACIATION

This glaciation is indicated by terminal moraines, as well as by a separate glaciofluvial terrace in the southern and northern part of the Tatra Mts. (Figs. 1 and 2). In the southern foreland the moraines are particularly well developed in the upper part of the Bela valley, beneath the junction of the Tichy and the Koprovský Creeks, as well as in the vicinity of Štrbské Pleso, where they mark the maximum extent of the glaciers in the Tatra Mts. (Fig. 1), and where most moraines are in contact with the glaciofluvial deposits. The glaciofluvial level is developed here as a distinct step preserved over a dozen metres above the present-day valley bottoms.

North of the Tatra Mts. the moraines of this glaciation are largely considered (e.g. Halicki, 1930; Klimaszewski, 1967) as the oldest preserved terminal moraines. Their presence was noted (see Nemčok, 1993*b*) in the upper parts of the Chochołowska and Kościeliska Valleys, in the middle part of the Sucha Woda Valley and in the middle part of the Białka Valley (Fig. 1). The relatively low location of these deposits in the western part of Kościeliska Valley may suggest, though, a younger age. As in the Slovakian part of the Tatra Mts. they comprise boulder-clay-sandy beds, within which the coarse material is represented by the Tatra granites and Mesozoic rocks. In the case of the Hurkotny moraine, earlier correlated to the Riss I Glaciation, TL-datings suggest a younger age and thus link it with the youngest glaciation (Lindner *et al*., 1990, 1993).

The glaciofluvial level of the Riss I Glaciation is preserved in fragments in the northern foreland of the Tatra Mts. (Fig. 1). It forms narrow shelves of sandy-gravel-clayey material in the upper parts of the Rohačský Creek, Bobrovečský Creek, Sucha Woda and Javorový Creek valleys, where their surfaces occur over a dozen metres above the valley bottoms. In the Podhale area in the Biały Dunajec valley, deposits of this level were TL-dated at 228 ± 44 ka, 287 ± 43 ka and 263 ± 36 ka (Lindner *et al*., 1993). According to Halicki (1930) this level is evidence of the development of glaciers during the second (II) glaciation period (Riss I), which currently is correlated with the Drenthian = Odranian Glaciation (Table 1) of the European Lowland.

RISS II (WARTANIAN) GLACIATION

Moraines of this glaciation have not yet been recognised in the northern part of the Tatra Mts. In their southern foreland they occur in the upper part of the Bela Creek valley, directly below the junction of the Koprovský and the Tichý Creeks, as well as in the vicinity of Štrbské Pleso, Stary Smokovec and Tatranska Lomnica (Fig. 1). In all cases they are preserved as distinct banks built of boulder-gravel material with boulders of poorly weathered granite rocks, 0.5–1.5 m in diameter (Nemčok, 1993*a*). In older papers the moraines were treated as traces of the glacier limits from the older stadial of the Würm Glaciation (Lukniš, 1973; Halouzka, 1977).

In the southern foreland of the Tatra Mts. the moraines are accompanied by a contemporaneous glaciofluvial level. Its fragments are distinguishable in the vicinity of Stary Smokovec and in the Jalovsky Creek valley (Fig. 1). They also form shelves on the northern slopes of the Rohačsky Creek valley and in the northern foreland of the Tatra Mts., mainly on the left slope of the Javorový Creek valley and in the Sucha Woda drainage basin east of Zakopane. In this region and in Podhale, Halicki (1930) treated them as the evidence of the IIa glacial period (Riss II). They were also TL-dated at 185 ± 27 ka, 172 ± 25 ka, 160 ± 24 ka and 143 ± 21 ka and correlated with the Wartanian Glaciation in the Polish Lowland (Table 1).

WÜRM (VISTULIAN) GLACIATION

Both in the Slovakian and Polish Tatra Mts. the deposits and glacial surface features (moraines), as well as glaciofluvial features of the Würm = Vistulian Glaciation (Table 1) are well-preserved and easily recognised. Glaciers developed here during three stadials, the youngest subdivided into 3–4 phases (e.g. Lukniš, 1973; Włodek, 1978; Dzierżek *et al*., 1986; Halouzka, 1989; Lindner, 1994; Lindner *et al*., 1990, 1993; Lindner and Marks, 1995; Baumgart-Kotarba and Kotarba, 1997; Gądek, 1998; Kenig and Lindner, 2001).

Terminal and lateral moraines of this glaciation recognised by the character of the deposits (see Nemčok, 1993*a*, *b*) are the basis for the reconstruction of the maximum limits of Würm glaciers and firn fields in the Tatra Mts. (Fig. 1). The map shows that in many cases, both in the Western Tatra Mts. and in the High Tatra Mts., the extents of the glaciers overlapped those of older glaciations. This fact can be explained in several ways. For instance, during the last glaciation this area was subjected to more intense precipitation due to changes in the atmospheric circulation, which resulted in a faster and more extensive formation of the snow-firn cover, leading thus to a greater development of glaciers. In the period directly preceding and during glaciation, this area may have been subjected to a more intense uplift, causing an increase in the area above the permanent snow boundary. It can also be assumed that, during the last glaciation, intense cooling may have caused a more rapid and long-term lowering of the snow-line in mountains of Central Europe in comparison to the situation during the older glaciations. The most probable scenario includes a combination of all these factors.

Geological analysis and the geomorphological position of the moraines marking the ranges of glaciers from the last glaciation in the Tatra Mts. indicate that the features are often 10–20 m high, and the boulder material (mainly granite) reaches 2–3 m in diameter. The moraines form parallel ridges, particularly easily recognisable in the High Tatra Mts. They are best developed in the vicinity of Štrbské Pleso, Stary Smokovec, Tatranska Lomnica and south-east of Zakopane within the lower parts of large postglacial valleys, from which they flowed outwards, emphasising their shapes and determining the limits of the particular tongues.

The moraines constrained the gravel-sandy deposits of the Würm glaciofluvial outwash. In this paper these deposits are presented as a single glaciofluvial level preserved at the outlets of almost all valleys once filled with glaciers. They are particularly well recognisable as wide terrace shelves, 6–10 m high on the right slopes of the Smreczanka and Bela valleys and on both sides of the valleys formed by creeks flowing on the southeastern foreland of the High Tatra Mts.

In the northern and northwestern foreland of the Tatra Mts. fragments of this glaciofluvial level are typically not very wide

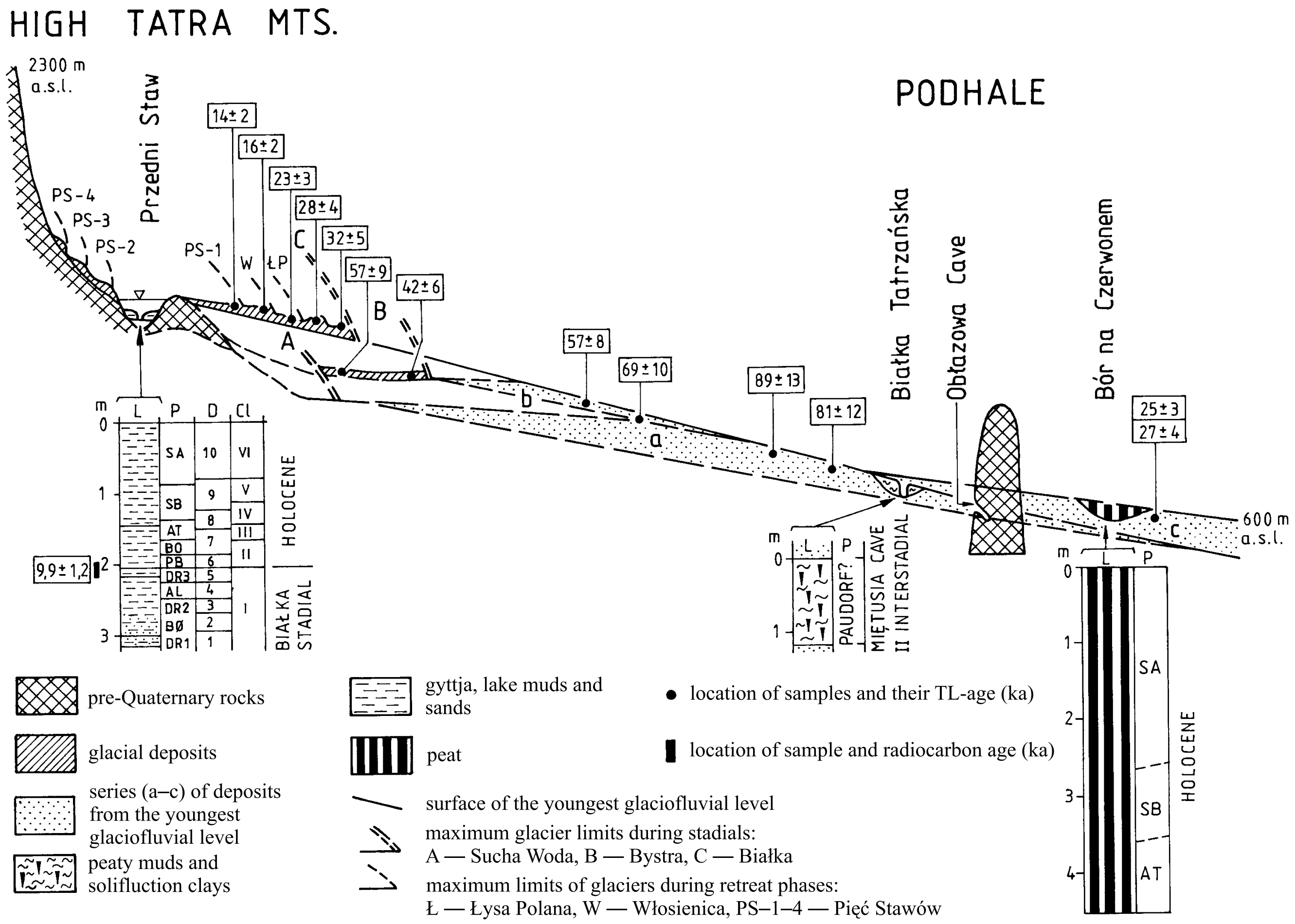

Fig. 3. Chronostratigraphic scheme of deposits of the last glaciation in the northern slopes of the High Tatra Mts. and Podhale, based on various authors, compiled by Lindner (1994)

L — lithology; P — palynological scheme (DR1 — oldest Dryas, BØ — Bølling, DR2 — older Dryas, AL — Allerød, DR3 — younger Dryas, PB — Preboreal, BO — Boreal, AT — Atlantic, SB — Subboreal, SA — Subatlantic); D — diatom phases; Cl — Cladocera phases

due to their confinement in existing valleys. According to Halicki (1930) deposits of this level are evidence of the III glacial period (Würm) in this part of the Tatra Mts. TL-dates of the glaciofluvial deposits vary from 89 ± 13 ka to 25 ± 3 ka, whereas those of the terminal moraines bounding them to the south vary between 42 ± 6 ka and 14.2 ka (Fig. 3). These relationships and the results of TL-datings of the basal till preserved in the upper part of the Bystra valley at 57 ± 9 ka (Fig. 3) and ^{36}Cl datings of boulders on the main terminal moraines of this glaciation in the Sucha Woda Valley at 21–11.6 ka, as well as terminal moraines and glacially polished surfaces of rock and boulders in the upper part of the Białka drainage basin between 17.3 and 6.5 ka (Dzierżek *et al*., 1999), indicate that the last glaciation in the Tatra Mts. area corresponds to the Vistulian Glaciation of the European Lowland (Figs. 3 and 4, Table 1).

In the northern foreland of the Tatra Mts. the glaciation was subdivided into three stadials: Sucha Woda, Bystra and Białka. The oldest deposits of the Würm glaciofluvial level ("a" of Figs. 3 and 4) document the Sucha Woda stadial. They are older than the organic deposits preserved higher at the Poronin site (7 km northwards of Zakopane), which according to Halicki (1930) represent the terminal part of the last interglacial, and according to Birkenmajer and Środoń (1960) the older interglacial within the last glaciation, referred to as Interstadial I of the Miętusia Cave (Lindner, 1994). The Bystra stadial is documented in this part of the Tatra Mts. by deposits of the younger ("b" on Figs. 3 and 4) part of the Würm glaciofluvial level. These deposits are TL-dated here at 57 ± 8 ka, whereas the till of this stadial gives results between 57 ± 9 ka and 42 ± 6 ka (Fig. 3). A site of organic deposits, the age of which is related to the younger (Paudorf?) interstadial (Sobolewska and Środoń, 1961; Stupnicka and Szumański, 1957), referred to as Interstadial II of the Miętusia Cave (Figs. 3 and 4) was documented at Białka Tatrzańska (20 km north-eastwards of Zakopane).

Within these sites the deposits are covered by gravels and sands ("c" on Figs. 3 and 4) of the youngest part of the Würm glaciofluvial level, TL-dated at Podhale at 27 ± 4 ka and 25 ± 3 ka (Fig. 3). Most probably they are in most cases contemporary to deposits building two northwards jutting terminal moraines of the Würm Glaciation in the Białka Valley (32 ± 5 ka at the Hurkotne site and 23 ± 3 ka at the Roztoka site), as well as to the external terminal moraines in the Sucha Woda Valley (28 ± 4 ka) and in the Mała Łąka Valley (between 31 ± 5 ka and 25 ± 3 ka). They document the ages of the two older phases

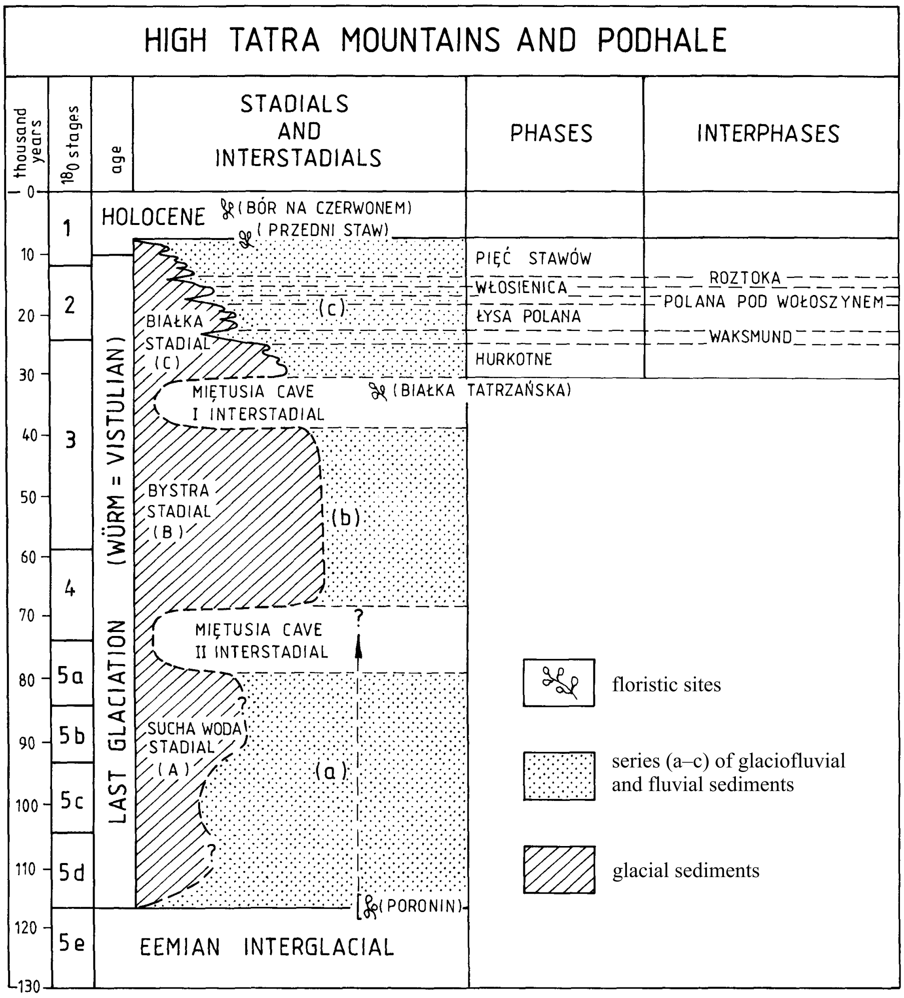

Fig. 4. Stratigraphic scheme of the last glaciation in the High Tatra Mts. and Podhale, after Lindner (1994), simplified

(Hurkotne and Łysa Polana) within the Białka stadial of the Würm Glaciation (Fig. 4). The two younger phases (Włosienica and Pięciu Stawów) within this stadial occur in the form of terminal moraines TL-dated at 16 ± 2 ka and 14 ± 2 ka, respectively (Fig. 3). All four phases are separated by three interphases (Lindner, 1994), considered as glacier retreats in the area, and determined in the Polish Tatra Mts. and in Podhale as the Waksmund, Polana pod Wołoszynem and Roztoka interphases (Fig. 4).

Recent drilling carried out in the upper part of the Kościeliski Creek drainage basin, directly south of the Ornak mountain hut (Kenig and Lindner, 2001), show three tills preserved in one section (Fig. 5). These represent the three older glacier phases of the Białka stadial determined as the Ornak I, II and III phases, separated by the Dolina Kościeliska 1 and 2 interphases, documented by intercalations of weathered debris (Fig. 5). These phases and interphases, as well as the still younger glacier episode of the Białka stadial, documented by terminal moraines above Ornak, may be correlated with the stagnation of glacier tongues distinguished by Baumgart-Kotarba and Kotarba (1997) in the Biała Woda Valley and Baumgart-Kotarba and Kotarba (2001) in Sucha Woda Valley and Pańszczyca Valley, as well as with these phases and interphases in the wider part of the Polish High Tatra Mts. (Kenig and Lindner, 2001).

POSTGLACIAL AND THE HOLOCENE

In the Slovakian and Polish Tatra Mts. the final retreat of the Würm glaciers took place by the end of the Early Holocene. The glaciers possibly persisted in the higher cirques up to the beginning of the Atlantic phase (*ca*. 8500 years ago), characterising the Holocene optimum. Some of the patches, as well as part of the older glacial deposits, may have been transported down the slopes by early and late Holocene periglacial processes as "stony glaciers" (Nemčok and Mahr, 1974), referred to also as rock glaciers (Dzierżek and Nitychoruk, 1986; Kotarba, 1991–1992). Some of them may still have been active when sedimentation in the nearby lakes had already begun. Therefore, line no. 13 on Figure 1 indicates the total extent of glacial features (lobes, moraines, rock glaciers, dead ice) that existed during Late Glacial and Early Holocene times. However, this can not be identified as the limit of the Holocene continuous glacial cover, as suggested by Nemčok (1993*a*).

The Holocene history of the Tatra Mts. has been most completely documented by studies of the postglacial lakes of the

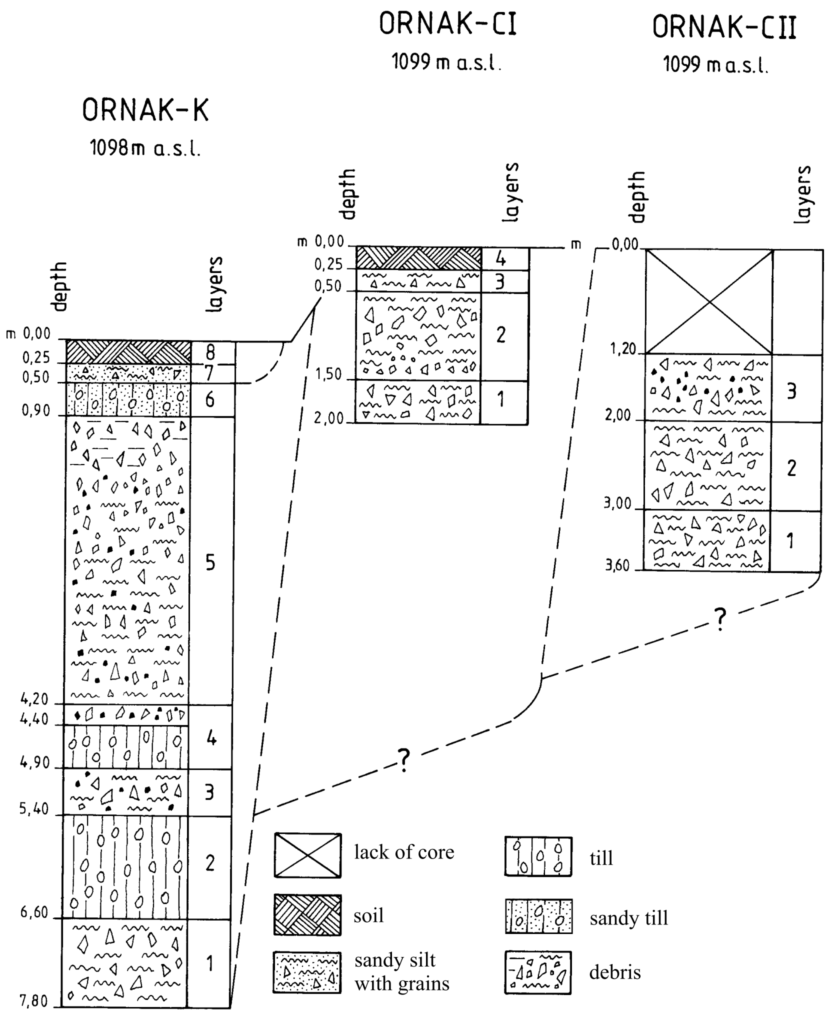

Fig. 5. Borehole sections from the upper part of the Kościeliski Creek drainage basin in the Western Tatra Mts., after Kenig and Lindner (2001)

area. The investigations began in the late 1970's and continue to today. The investigation of the bottom deposits from the Przedni Staw Lake (Fig. 3) in the Pięć Stawów Polskich Valley showed that their accumulation lasted from the terminal part of the Oldest Dryas to the Subatlantic Phase, and in its oldest part (up to the Boreal Period) was probably contemporary with the younger phases of the glacier retreat during the Pięć Stawów Phase.

The analyses indicate that the beginning of the accumulation of these deposits took place during the Bølling warming. The tree flora was dominated by mountain-pine (*Pinus montanus*) with a small admixture of *Betula carpatica* and *Salix* and a large admixture of herbaceous plants (Krupiński, 1984). Among the diatom flora of the late-glacial lake, the *Fragilaria* flora developed and than was replaced by one dominated by *Cyclotella* (Marciniak and Cieśla, 1983). The later cooling of the Older Dryas was reflected by an increase of herbaceous plants, mainly Gramineae and *Artemisia*, by a small decrease of *Pinus* and an increase of *Betula*. The appearance of *Selaginella selaginoides* (Krupiński, 1984) is an important feature. Within diatoms the cooling is registered by a third diatom, characterised by the decline of the *Cyclotella* flora and concomitant increase of diatoms which dwell on rocks and moss, at present encountered in north Alpine and Arctic environments (Marciniak and Cieśla, 1983).

The following warming during the Allerød interphase is registered in the deposits of the Przedni Staw Lake (Fig. 3) by an increase of *Pinus montana* and *Betula carpatica*, and a decrease of Gramineae and *Artemisia* (Krupiński, 1984). In diatoms this warming is registered by diatom phase 4, initially reflected by an increase of *Fragilaria*, followed by an increase in *Cyclotella* (Marciniak and Cieśla, 1983). The youngest late glacial cooling, taking place in the Younger Dryas (Fig. 3), is registered in the deposits of the Przedni Staw Lake as a return of severe climatic conditions, reflected by palynological data (Krupiński, 1984) as well as in the diatom flora of diatom phase 5 (Marciniak and Cieśla, 1983). The further development of the Przedni Staw Lake took place in the Preboreal Period (Fig. 3), as seen by an increase in *Pinus* to 65% and *Betula* to 30%, a culmination of moss and the appearance of *Picea* and thermophilous deciduous trees (*Alnus, Ulmus, Quercus*). This floral assemblage indicates the presence of the upper boundary of forests at altitudes of *ca*. 1100 m a.s.l. (Krupiński, 1984). In the diatom flora this period is documented by diatom phase 6, reflected as the rapid increase of *Fragilaria pseudoconstruens*, followed by *Fragilaria pinnata* and *F. elliptica* (Marciniak and Cieśla, 1983). The considerable quantity of phytoplankton favoured the development of a *Cladocera* fauna (Szeroczyńska, 1984). The Boreal Period in the lake deposits analysed (Fig. 3) is documented by the older and middle part of diatom phase 7, registering the development of *Fragilaria* as well as by the increase of the upper forest boundary to about 1650 m a.s.l. (Marciniak and Cieśla, 1983; Krupiński, 1984). The Atlantic warming (climatic optimum of the Holocene) caused the further increase of the upper forest boundary to 1850–1950 m a.s.l. (Krupiński, 1984), much higher that of the present day, as well as by an increase of planktonic diatoms in diatom phase 8, with *Asterionella formosa*, characterising the optimal climatic and ecological conditions (Marciniak and Cieśla, 1983), indicating the complete retreat of glaciers from the Tatra Mts.

During the Subboreal Period the lowering of the upper forest boundary to *ca*. 1750 m a.s.l. (Krupiński, 1984) took place in the Tatra Mts., at a maximum of *Picea* up to 30% and *Fraximus* up to 8%. In the Przedni Staw Lake deposits this period is documented by the transition between diatom phases 8 and 9 (Fig. 3). It is characterised, for example, by the appearance of large amounts of *Melosira distans*, a species dwelling in cool conditions, widely distributed in mountains and north Alpine water basins. Additionally, *Asterionella formosa* and *Cyclotella quadriiuncta* (Marciniak and Cieśla, 1983) were also present. In the Sub-Atlantic Period in the vicinity of the Przedni Staw Lake the upper forest boundary dropped to *ca*. 1550 m a.s.l. (Krupiński, 1984). In the diatom flora this period is documented by the terminal part of phase 9 and by phase 10 (Fig. 3). In the younger phase the maximum development of *Melosira distans* and *Navicula seminulum* took place, accompanied by an increase of *Asterionella formosa* and a decrease of *Fragilaria brevistrata* and *Cyclotella quadriiuncta*. According to Marciniak and Cieśla (1983) the terminal part of diatom phase 10 is characterised by the reappearance of diatoms typical of the terminal part of the Late Glacial, which evidently documents the deterioration of climatic conditions during the Little Ice Age. From this period come the fragmentary cirque glaciers preserved in the High Tatra Mts., e.g. in the Wielki Mięguszowiecki Kocioł and below Rysy (Wdowiak, 1959, 1961; Dzierżek *et al*., 1982*a*, *b*).

In Podhale, the Holocene climatic conditions are best documented by sections of organogenic deposits filling depressions within deposits of the youngest glaciofluvial level ("c" series in Figs. 3 and 4), investigated by Obidowicz (1990) in the Bór na Czerwonem site and in the "na Grelu" site near Nowy Targ (Koperowa, 1962).

Analyses of the bottom deposits of the Czarny Staw Gąsienicowy and Zielony Staw Gąsienicowy lakes, located in the uppermost part of the Sucha Woda drainage basin and the Żabie Oko Lake (just below the Morskie Oko Lake in the upper part of the Białka drainage basin), particularly their radiocarbon datings and palaeobotanical data (Baumgart-Kotarba and Kotarba, 1993; Obidowicz, 1993) allow the precise dating of the phases of glacier retreat and their correlation with the retreat of the Alpine glaciers.

Recently, much attention has been drawn to the Little Ice Age (from *ca*. 1400 to *ca*. 1850 AD), particularly to its reflection in the deposits of the lakes in the Tatra Mts. The analysis of the bottom deposits from the Morskie Oko Lake (Kotarba, 1993–1994) indicates that the most crucial phase of climatic extremes took place in 1550–1700 AD, and after 1860 AD a distinct decrease of alluvial processes on slopes surrounding the lakes took place. A reshaping of slopes took place up till 1905 AD, as evidenced (see Kotarba, 1992) by numerous debris flows, dated by lichens, in the vicinity of the Hala Gąsienicowa, located in the highest part of the Sucha Woda drainage basin.

FINAL REMARKS

During the Quaternary, the Tatra Mts. were subjected to at least 8 phases of glacier development. Past glaciers are inferred by glaciofluvial deposits at different altitudes and of different ages, and by ridges of terminal and lateral moraines marking glacial limits.

The lack of traces of moraines from the three oldest glaciations, Biber, Donau and Günz, may suggest that those glaciers had a rather restricted development, and thus a more limited extent than the younger glaciations. It is also thought that during the Mindel (Sanian 2) Glaciation the glaciers had greater limits in the High Tatra Mts. than in the Western Tatra Mts., and that during the following pre-Riss (Liviecian) Glaciation the extents of glaciers in the entire Tatra Mts. must have been more limited, as was the case during the three oldest glaciations.

The later wider development of the glaciers in the area took place during the Riss I (Odranian) Glaciation. In many ways this was even more extensive than the Mindel Glaciation. During the Riss II (Wartanian) Glaciation glaciers were again limited, particularly in the area of the Western Tatra Mts. The later, exceptionally extensive glaciation in the Tatra Mts. took place during the Würm (Vistulian) Glaciation. In the Western Tatra Mts. the glaciers were generally characterised by a wider distribution than during all older glaciations, whereas in the High Tatra Mts. their limit was comparable to, and in some cases even overlapped, the limit of glaciers of the Mindel and Riss I glaciations.

The causes of such great development of glaciers in the Tatra Mts. during the last glaciation (Würm = Vistulian) probably reflect the contemporaneous long-term western and northwestern atmospheric circulation. This circulation brought increased precipitation favouring an increase of the ice cover in the Western Tatra Mts. and in the northern and northwestern part of the High Tatra Mts., where glaciers reached limits similar to those of older glaciations. Due to a rapid climatic cooling in the Northern Hemisphere the snow-line could be located at much lower altitudes, and the regionally variable uplift of the Tatra Massif may have influenced the more rapid and wider range of glaciers during the Würm Glaciation.

Glaciers, or rather leftover dead ice-blocks, remained in the Tatra Mts. area in the highest cirques during the entire Late Glacial, and even during the pre-optimal part of the Holocene. The synchronous, gradual retreat of glaciers favoured the formation of ablation moraines enriched with slope material on incompletely melted glacier ice patches and transformed into the "rock glaciers" during the Late Pleistocene and Late Holocene phases.

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