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Geology of the Pieniny Klippen Belt and the Tatra Mts, Carpathians
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Part XX

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Quaternary glacigenic deposits between the Biała Woda and the Filipka valleys, Polish Tatra Mts, in the regional context[2]

(Fig. 1; Pl. I)

Abstract. A succession of residual moraine covers and glaciomorphological forms, correlatable with the Pleistocene Mindel, ?Riss and Würm glaciations, and superimposed glacial/nival moraines and morphological forms (Late-Pleistocene/Early Holocene), have been distinguished between the Biała Woda and the Filipka valleys, Polish Tatra Mts. Their stratigraphic ages are discussed in the regional context.

Key words: Pleistocene, Holocene, glacial deposits and morphological forms, Tatra Mts, West Carpathians.

INTRODUCTION

Quaternary deposits in eastern part of the Polish Tatra Mountains (Fig. 1), between the Biała Woda Valley and the Filipka Valley, have been re-mapped to a 1:10,000 scale by the present author in the years 1998–2004 (Birkenmajer, 2008a). This area is regarded an important one for studying the development and succession of Pleistocene glacial covers in the Eastern Tatra Mountains (e.g., Romer, 1930; Klimaszewski, 1988).

There are several modern cartographic presentations of Quaternary glacigenic, glacifluvial, fluvial and related deposits and forms of the Eastern Tatra Mountains:

(1) Lukniš (1968), in his geomorphological map, 1:50,000 scale, of the Slovak Eastern Tatra Mountains and their forefield, has distinguished glacigenic and related deposits correlated by him with the Würm and pre-Würm (Riss, Mindel,

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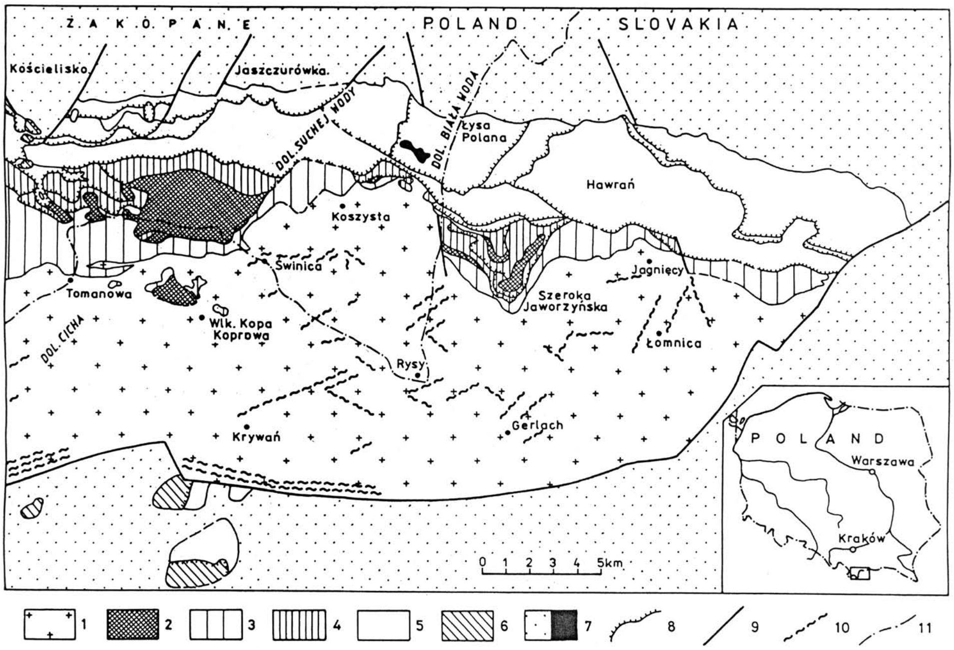

Fig. 1. Position of the Biała Woda Valley in the Eastern Tatra Mountains. Geological features after Bac-Moszaszwili *et al.* (1979), simplified and slightlty modified. *1* – Hightatric crystalline core (pre-Mesozoic); *2* – Hightatric overthrust crystalline rocks; *3* – Hightatric Mesozoic sedimentary cover of the crystalline core; *4* – Hightatric tectonic units (Mesozoic sedimentary rocks); *5* – Lower Subtatric Nappe (= Križna Nappe: Mesozoic sedimentary rocks); *6* – Middle Subtatric Nappe (Choč Nappe: Mesozoic sedimentary rocks); *7* – Podhale Palaeogene (stippled) and the Rusinowa Conglomerate Formation (?Upper Cretaceous – in black); *8* – important overthrusts; *9* – important faults; *10* – younger mylonites: *11* – Polish-Slovak state boundary

Günz, Donau – mainly with question marks) glaciations. In the Würm Glaciation deposits, several 'oscillations' corresponding to glacier advances (stadials) and retreat (interstadial) have been mapped by him mainly along the south-eastern margin of the Tatra Mountains;

(2) Sokołowski and Jaczynowska (1979a, b, 1980), at three sheets of geological maps, 1:10,000 scale (A5 Kopy Sołtysie, A4 Kopieniec, and B5 Wołoszyn), have mapped, i.a., Pleistocene moraines and glacifluvial (terrace) deposits. They did not attempt, however, at a closer stratigraphic age determination of the Pleistocene deposits; their extension was mainly traced on aerial photographs;

(3) Bac-Moszaszwili *et al.* (1979), in their geological map, 1:30,000 scale, have distinguished gravelly-sandy glacifluvial deposits, and blocky-clayey morainic deposits. They did not attribute them to particular Pleistocene glacial/interglacial epochs;

(4) Nemčok *et al.* (1994), in the geological map of the Tatra Mts (Slovak and Polish parts), 1:50,000 scale, have distinguished six age groups of Pleistocene deposits, i.a.:

(i) the Early Pleistocene (prae-Mindel: ?Biber-Donau and Günz) glacifluvial and fluvial deposits;

(ii) the Middle Pleistocene, older part (Mindel) glacial moraines and glacifluvial deposits;

(iii) the Middle Pleistocene, younger part (Riss) glacifluvial deposits and glacial moraines, further subdivided into Early Riss and Late Riss stages;

(iv) the Late Pleistocene (Würm) glacifluvial deposits and glacial moraines;

(v) the Pleistocene/Holocene transition proluvial and deluvial deposits;

(vi) the Holocene (early Postglacial) bouldery-blocky glacial moraines, mainly in glacier-formed corries.

(5) Results of more detailed studies of Pleistocene glaciation in the Polish part of the Biała Woda Valley (PL: Dolina Białej Wody; SK: Belovodská dolina) and its tributaries, supplemented with sketchy geological maps, were presented by Baumgart-Kotarba (1978, 1998a, b), Baumgart-Kotarba and Kotarba (2001), and Lindner *et al.* (1990, 1993, 2003, 2008). In lower part of the Sucha Woda Valley, Late Quaternary glacigenic deposits were studied in particular by Baumgart-Kotarba and Kotarba (2001b), Derkacz *et al.* (2008), Iwanow *et al.* (2008) and Birkenmajer (2008a, b).

MAIN STAGES OF THE NEOGENE–EARLY QUATERNARY HISTORY IN THE TATRA MTS AND THEIR NORTHERN FOREFIELD

The period between the youngest Podhale Flysch deposits, represented by the Upper Oligocene = Chattian (Gedl, 1999) Ostrysz beds, and the Middle Pleistocene Mindel Glaciation (0.78 Ma – base Brunhes polarity chron – date from Gradstein *et al.*, 2004), covers about 22 Ma. This period includes several successive stages of dynamic terrestrial history of the Carpathian Foldbelt – folding, strike-slip- and gravity faulting, upwarping and downwarping (formation of grabens), denudation and development of planation surfaces, fluvial and lacustrine deposition.

The Tatra Block during Early-Middle Miocene

Major rock complexes. Lithospheric block of the Tatra Mountains (further abbreviated as the Tatra Block), consisted during the Miocene of three major rock-complexes:

(1) The Palaeogene cover consisting of: (i) the Podhale Flysch (Oligocene), some 3000 m thick, underlain by (ii) the nummulitic limestones (Upper Eocene) and (iii) the Sulov'-type basal conglomerates (Middle Eocene), the latter two units together are up to several hundred metres thick;

(2) The mid-Cretaceous Fatric nappes (Križna and Choč nappes), consisting of Lower Triassic through Lower Cretaceous deposits;

(3) The Tatric structural units: (i) large-scale recumbent folds (resp. nappes), consisting of crystalline basement slices and their Lower Triassic through Lower

Cretaceous deposits; (ii) autochthonous unit consisting of crystalline core with its Lower Triassic through Lower Cretaceous sedimentary cover.

Southern and eastern margins. The Tatra Block is delimited from the south, east and west by important faults (see, e.g., Nemčok *et al.*, 1994) that developed during the Miocene.

Along the southern margin, crystalline core of the Tatra Block comes into direct contact with marine Palaeogene strata of the Liptov Depression. At south-eastern edge of the Block, the southern fault turns north-eastward and continues in this direction as far as the Pieniny Klippen Belt.

Nemčok *et al.* (1994, cross-sections) interpret the southern fault as a dip-slip one, downthrowing to the south. An alternative interpretation, that the fault surface steeply dips northward, causing the Liptov Palaeogene and its Fatric nappe substratum to plunge under the Tatra crystalline core, has also been proposed (see, e.g., Birkenmajer, 1985b, fig. 12, 1986, fig. 3).

Western margin. The Tatra Block is delimited from the west by a SW–NE-directed fault downthrowing to NW. There, the Fatric and Tatric structural units of the Block contact directly with the Podhale Palaeogene cover (see Nemčok *et al.*, 1994).

Age of faulting. Based on comparison with the Pieniny Klippen Belt, the southern longitudinal fault of the Tatra Block might have developed during the Early Miocene Savian phase. In the Pieniny Klippen Belt, during this orogenic phase, strong compression caused refolding of the Upper Cretaceous (Laramian) nappes and their Maastrichtian and Palaeogene cover. At that time, strike-slip faults had developed along southern and northern margins of the Klippen Orogen. They delimit the Klippen Belt from the surrounding flysch units: the Magura Nappe in the north, and the autochthonous Podhale Flysch in the south. Horizontal translation along these faults, related to rotation of the Central Carpathian Block, probably continued until Middle Miocene (Birkenmajer, 1983, 1985a, b, 1986).

The eastern and western, SW–NE-directed, faults which delimit the Tatra Block, might have developed during the Middle Miocene Styrian phase. This phase of faulting is very well pronounded in the Pieniny Klippen Belt (*op. cit.)*.

Northern margin. No fault line comparable to those recognized along the southern, eastern and western margins of the Tatra Mountains, delimits the Tatra Block in the north. The Palaeogene cover, which unconformably overlies the meso-Cretaceous Fatric (Subtatric = Križna and Choč) nappes, dips there at 30–35° north towards the centre of the Podhale Depression (e.g., Sokołowski, 1973, fig. 4; Bac-Moszaszwili *et al.*, 1979: geological cross-sections; Lefeld & Gaździcki, eds, *et al.*, 1997; Kępińska, 1997: figs 19, 22, 23). The Fatric nappes continue northward under their Palaeogene cover as far as the southern boundary fault of the Pieniny Klippen Belt; this is well proved by boreholes (see, e.g., Kępińska, 1997, figs 19, 22).

The Tatra Block and its Northern Forefield during Middle-Late Miocene

The Middle-Late Miocene epochs (c. 11 Ma–c. 8 Ma) represent an important stage in structural development of the Carpathian Foldbelt. It was dominated by flysch nappe thrusting in the Outer Carpathians, and by transversal faulting in the Inner Carpathians, the latter attributable to the Styrian phase.

Transversal faulting. During the Styrian phase, the Tatra Block, together with its Palaeogene cover, was dissected by dense vertical- to strike-slip faults, directed mainly SSW–NNE (e.g., Bac-Moszaszwili *et al.*, 1979; Nemčok *et al.*, 1994; Birkenmajer, 2000a, b), best recognizable along the northern margin of the mountains (Birkenmajer, 1999).

The Styrian tectonic phase was best expressed in the Pieniny Klippen Belt. There, the transversal faults (Styrian) displaced the older (Savian) large-scale strike-slip boundary faults, and the first-phase andesite intrusions, the latter K-Ar-dated at 12.8–11 Ma (Birkenmajer & Pécskay, 1999, 2000).

Horizontal outward arching achieved by the Pieniny Klippen Belt during the Middle Miocene, as a result of continued meridional push to the north of the Central Carpathian Block (Slovak Block), eventually caused opening of some transversal faults at Wżar Mount in the Pieniny Mountains. This facilitated penetration of magma of the second-phase andesites, K-Ar-dated at 11–10 Ma (*op. cit.)*. Both andesite magmas derived from a chamber situated probably at a depth of 10–12 km below the present level (Birkenmajer, 2003).

Miocene transversal faults recognized in the Tatra Mountains have not been dated with such detail thus far. Apatite fission-track dates, between 36 and 10 Ma (mainly 20–10 Ma), obtained from granitoids, gneisses and amphibolites by Burchart (1972), might be an effect of several faulting phases and/or of differences in the depth of burial.

Neogene fresh-water accumulation in the Orawa–Podhale area

Miocene–Pliocene deposition in the Orawa Depression. In the Orawa Depression, up to 1000 m thick lacustrine clays and sands with brown-coal interlayers, palaeobotanically dated at Upper Miocene (Tran Dinh Nghia, 1974), or at Upper Miocene and Pliocene (Oszast, 1973, pp. 15–18), are devoid of crystalline and sedimentary rock fragments of the Tatra Mts origin. Their clastic material derived mainly from already well weathered flysch rocks of the Magura Nappe (northern source).

In the Czarny Dunajec 994-m deep borehole, above the basal sandstone conglomerate 30-m thick, there appears a 102-m thick (848 m down to 950 m) complex of clay, silty clay and sand with plant detritus, with subordinate intercalations of gravel, correlated by Oszast and Stuchlik (1997) with the Badenian.

From 885 m down the column, the Miocene sediments show dense fracturing and the presence of faults. This brittle deformation was correlated with the Styrian phase located then at the Badenian/Sarmatian boundary, about 14 Ma (Birkenmajer, 1978, tab. 1), i.e. at the Langhian/Serravallian boundary (13.65 Ma) in the new Neogene Time Scale (Gradstein *et al.*, 2004, fig. 5a). Taking into account the K-Ar dates of andesite intrusions, and the age of associated Styrian faulting (11–10 Ma) in the Pieniny Volcanic Arc (Birkenmajer & Pécskay, 1999, 2000; Birkenmajer, 2003), the age of the Styrian faulting of the lower deposits in the Czarny Dunajec borehole should now be shifted to the Serravallian/Tortonian boundary (11.61 Ma – see Gradstein *et al.*, *loc. cit.*).

The upper part of the Neogene column in the Czarny Dunajec borehole, 818 m thick (from 30 m down to 848 m), consists of clay, silty clay and sand with plant detritus, with thin brown-coal seams. Subordinate gravel intercalations never reach there the thickness of the basal conglomerate. A well pronounced cyclicity is expressed in a part of the column by repetition of gravel-sand-clay (the latter often with brown-coal seams) complexes. According to palynologic dating by Oszast & Stuchlik (1977), these sediments correspond to the Sarmatian (848–565 m), the Pannonian (565–478 m), and the Pontian (478–30 m) stages, i.e. the Late Miocene (14–5 Ma) in the regional Peritethyan time scale (see Birkenmajer, 1978, tab. 1). Contrary to the pre-Styrian Middle Miocene (Badenian) deposits, there are no stronger brittle deformations observable in the upper part of the borehole column.

Lack of clastic rock material of the Tatra origin in the Czarny Dunajec borehole, supports the view that during the Miocene–Pliocene times, the Tatra Mountains were low, and that fluvial erosion did not yet reach the base of their Palaeogene cover.

Miocene and Pliocene at Domański Wierch. At the south-eastern margin of the Orawa Depression exposed between Stare Bystre and Miętustwo, there occur faulted coal-bearing Miocene clays covered by a huge alluvial deposition of the Domański Wierch cone well known from good field exposures, and from a 228-m deep borehole (Birkenmajer, 1954, 1958, 1979; Urbaniak, 1960; Plewa, 1969; Kukulak, 1998a, b).

In the southernmost part of the cone, the coal-bearing Miocene clays unconformably overlain by very coarse conglomerates (together 170 m thick), rest directly upon the Podhale Palaeogene flysch (Zakopane beds). They are faulted and dip north at 20–45 degrees (Birkenmajer, 1979, fig. 15). A 1–2 m thick rhyolite tuff-tuffite layer (Sikora & Wieser, 1974) found at the base of the conglomerates (Birkenmajer, *loc. cit.*), probably correlates with the 3rd phase rhyolites of Slovakia. These beds were provisionally attributed to the Sarmatian, while their faulting – to the Moldavian phase (Sarmatian/Pannonian – Birkenmajer, 1978, tab. 1).

The northern part of the Domański Wierch cone between Stare Bystre and Miętustwo exposes about 100 m of fresh-water deposits predominantly consisting of coarse gravel-conglomerate, with lignite-clay and sand intercalations. Numerous breaks in deposition and slight angular unconformities, are recognizable at bases of thicker conglomerate horizons in the Jaszczurów Gorge section (Birkenmajer, 1954, 1958; Birkenmajer & Stuchlik, 1975, tab. 3). As a whole, the beds deep there at 15–20 degrees north (Birkenmajer, 1979, figs 13–15), towards the centre of the Orawa Depression. At Stare Bystre, basal conglomerates of the Domański Wierch cone rest directly upon strongly eroded Mesozoic rocks of the Pieniny Klippen Belt (e.g., Birkenmajer, 1954, 1958, 1979, fig. 15).

In the 228-m deep borehole located at top of the Domański Wierch, the base of the Neogene deposits was not reached. Palynological dating of the whole section suggested to Oszast (1970, 1973) a younger Pliocene age, or the Pliocene/Pleistocene transition. Pliocene leaf flora has been determined from the northern exposures of the cone by Zastawniak (1972).

The clastic material of the Domański Wierch cone derived almost exclusively from the Podhale Flysch, either from the Gubałówka Range (situated immediately north of the Tatras) or from the now non-existing original Palaeogene cover of the Tatra Mountains. Sandstone fragments, gravels and boulders known from the conglomerates, were derived from the Chochołów beds (Oligocene). There is also a small admixture of Mesozoic rock material from the Pieniny Klippen Belt (Birkenmajer, 1954, 1958, 1979).

Cyclic deposition, and appearance of numerous intraformational unconformities (see Birkenmajer, 1979, fig. 14; Birkenmajer & Stuchlik, 1975, tab. 3), suggest a rather complex history of the cone, in which changes of meandering or braided river courses, lacustrine sedimentation at margins of the cone, continued upwarping of the Tatra Block, and downwarping in the Orawa Depression, certainly played parts.

Middle-Late Pliocene and Pliocene/Pleistocene deposits at Mizerna. At Mizerna near Czorsztyn, well preserved plant remains recovered from fresh-water clays, 13–28 m thick (Birkenmajer, 1954), were elaborated in detail by Szafer (1952, 1954). According to him, the lower part of the borehole sections (9–13 m thick – see Szafer, 1954, fig. 2) represents the Middle and Upper Pliocene, while the top part (c. 13 m thick – *op.cit.*) – the Late Pliocene/Early Pleistocene transition.

In the southern boreholes, both units are divided by a fluvial gravel layer 1.7 m thick, consisting of granite and Werfenian quartzite pebbles derived from the Tatra Mountains (Szafer, 1954, fig. 2; Birkenmajer, 1954, 1958, 1961, 1979). This is the *first evidence* from the northern foreland of the Tatra Mountains, that river erosion in the Tatra Block had cut through its Palaeogene cover down to Lower Triassic strata and their granitic basement.

Late Neogene–Early Pleistocene planation levels, river courses and downfaulting

Upwarping in the Tatra Block during the Miocene and Pliocene times was slow. Erosional removal of its Palaeogene cover and, successively, the Fatric and Tatric rock complexes, down to the crystalline core, had not been achieved before the end of the Pliocene (see the preceding chapter). During the Miocene and most of the Pliocene times, morphology of the Tatra Block certainly did not resemble the present Alpine-type Tatra Mountains.

Late Neogene is considered to be the main epoch of development of the major planation levels in the Tatras and in their forefield (Klimaszewski, 1948, 1950-51, 1988; Klimaszewski & Starkel, 1972). However, tracing and dating of these levels is still difficult or inadequate, as the whole area was subject to differentiated vertical movements during the Pliocene through Early Pleistocene times – upwarping in the Tatra Mountains and downwarping in the Orawa–Nowy Targ Depression (e.g., Birkenmajer, 1979, p. 59). During that epoch, the planation levels could have been displaced by faulting, their altitudes and degrees of inclination considerably changed.

Intramontane planation level. In the West Tatra, fragmentarily preserved intramontane planation level is sloping north from 1700 m to 1500 m a.s.l. (500–450 m above the present valley bottoms). In the High Tatra, this level is recognizable at 1860 down to 1600 m a.s.l. (600–550 m above the present valley bottoms). At the time of its formation, the peaks in the Tatras towered by 400–500 m above the valley bottoms (Klimaszewski, 1988, pp. 493–494).

Submontane planation level (A-level). In the West Tatra, this level is sloping north from c. 1500 m to 1200 m a.s.l. (300–250 m above the present valley bottoms). In the High Tatra, this planation level is recognizable at 1800 down to 1500 m a.s.l. (430–380 m above the present valley bottoms) – Klimaszewski (1988, p. 494).

Further north, in the Podhale–Orawa area, the submontane planation level is traceable from the Gubałówka Range (1100–1000 m a.s.l.) northwards, as far as the top of the Domański Wierch cone (735–730 m a.s.l.).

The A-level was considered by Klimaszewski (in Klimaszewski & Starkel, 1972, fig. 17) to be of an early Pliocene age. However, it cuts the cone deposits, for which a late Pliocene age has been suggested on palynologic dating by Oszast (1973). Thus, a late Pliocene age of the A-level should rather be preferred (Starkel, in Klimaszewski & Starkel, 1972; Starkel, 1975). The Pliocene beds of the cone are overlain by residual glacifluvial granite-quartzite gravels of the Mindel Glaciation (e.g., Birkenmajer, 1979, p. 78; Kukulak, 1998a, b); thus, an Early Pleistocene age of the submontane planation level cannot be ruled out.

Valley planation level (B-level). In the West Tatras, this planation level is recognizable at 1400 down to 1100 m (180–150 m above the present valley bottoms). In the High Tatra, this level is recognizable at 1600 down to 1200 m a.s.l. (260–230 m above the present valley bottoms) – Klimaszewski (1988, p. 494). To this level, Klimaszewski (1988, p. 495) included the planation level recognizable in the Polana pod Wołoszynem alp (1250 m a.s.l.), and from the Rusinowa Polana alp (1200 m a.s.l.) to Hurkotne (1100 m a.s.l.).

The name 'Hurkotne' presently refers to the Polana Hurkotne alp (its upper part lies at 950 to 1019 m a.s.l.), which is located on eastern slope of the Wierch Poroniec hill (see Pl. I), on left slope of the Białka River valley. Klimaszewski's (1988) 'Hurkotne' refers to top of the Wierch Poroniec hill (1101 m), lying 80–150 m higher than the Polana Hurkotne alp (see *Topographic Map of the Tatra Mountains, 1:10,000 scale*, 1984).

The valley planation level (B) of the Podhale area was considered by Klimaszewski (in Klimaszewski & Starkel, 1972) a result of Pliocene rejuvenation and early Pleistocene deepening of the valleys; this level would, rather, be of Early Pleistocene age (see Starkel, 1975).

River courses. During the Pliocene, three major rivers of the Podhale region, i.e. the Czarny Dunajec, the Biały Dunajec and the Białka rivers, had their head valleys already established in the Tatra Block. At its northern forefield, during deposition of the Domański Wierch alluvial cone, the Czarny Dunajec River flowed westward to join the Orawa (Orava) River belonging to the Black Sea catchment area, while the Biały Dunajec and the Białka rivers together flowed east to reach the Poprad River belonging to the Baltic Sea catchment (Birkenmajer, 1958, 1979, 2006). Transfluence of the Czarny Dunajec River from the Black Sea to the Baltic Sea catchments must have happened during Pliocene–Early Pleistocene times. Since then, all three major rivers of the Podhale region flowed jointly (as the Dunajec River) through the Dunajec River Gap in the Pieniny Range towards the north, to join the Wisła River.

The Frydman Graben. The Frydman Graben, situated at eastern end of the Orawa–Nowy Targ Depression, terminates east just before the entrance to the northern gate of the Czorsztyn–Niedzica Dunajec River Gap. The graben is filled with Quaternary deposits (85 m thick), mainly fluvial granite-quartzite gravels, alternating with fluvial to lacustrine sand and clay, resting on clays (>25 m thick) resembling a higher part of the deposits from Mizerna (Niedzielski, 1971; Birkenmajer, 1978, 1979). The gravelly material is predominantly of the Tatra Mountains provenance. The fluvial series has been provisionally interpreted as formed during the Donau to Günz stages of the Early Pleistocene (Birkenmajer, 1976, 1978, 1979, fig. 12), for which the age limits are: 1.81 Ma (Pliocene/Pleistocene boundary – Gradstein *et al.*, 2004), and ca. 0.75 Ma (base of Cromerian – Van Eysinga, 1975) or 0.78 Ma (base of the Brunhes chron, Middle Pleistocene – Gradstein *et al.*, 2004). The faulting which initiated the graben formation, was thus of an Early Pleistocene age.

ONSET OF PLEISTOCENE GLACIATION IN THE TATRA MOUNTAINS

Fluvial and glacifluvial deposits correlatable with the Early Pleistocene Alpine glacial epochs, the ?Biber-Donau-, and the Günz glaciations, have been recognized in the southern forefield of the Tatra Mountains (Lukniš, 1968; Nemčok *et al.*, 1994). In the northern forefield of the Tatra Mountains, Early Pleistocene deposits (Günz and Günz/Mindel) have been recognized in the Szaflary quarry below the Mindel fluvioglacial cover (Birkenmajer & Stuchlik, 1975). Early Pleistocene deposits have, so far, not been found inside the Tatra Mountains.

Early Pleistocene Deposits at Szaflary

Stratigraphic succession

South of Nowy Targ, in the Szaflary quarry, a strongly karstified Jurassic limestone surface (Małkowski, 1924, 1928; Wójcik, 1960; Birkenmajer, 1968, 1976; Birkenmajer & Stuchlik, 1975) is overlain by a complex of Early to Middle Pleistocene deposits (Birkenmajer & Stuchlik, 1975; Birkenmajer, 1976):

(1) **Red regolith** (0.1–3 m) filling karst holes;

(2) **Reworked regolith** (0.05–0.5 m). Besides the local rock fragments, this bed contains also granite pebbles derived from the Tatra Mts, and sandstone pebbles from the Podhale Flysch. Locally, this bed passes upward into the lower gravel;

(3) **Lower gravel** (up to 1.4 m). This is a channel-type fluvial deposit consisting of well-rounded to subrounded pebbles and cobbles (5–40 cm in diameter) of granite (strongly weathered, 5–40 cm in diameter) and quartzite (5–50 cm in diameter) pebbles and cobbles, with an admixture (up to 25%) of flat sandstone pebbles from the Podhale Flysch, in greenish sandy-clayey matrix;

(4) **Banded clay** (0.3–1 m). This is a very characteristic bed resembling varved clay. It consists of alternating, thin (usually below 1 cm) laminae of clay and clayey silt; microlamination (0.1–1 mm) can be recognized within the laminae. Their colouration varies between brown and black, depending on amount of carbonaceous organic matter. Fine sand admixture and small angular fragments of sandstone and limestone occur. Sharp contacts delimit the banded clay from the underlying and overlying gravels;

(5) **Upper gravel** (1–8 m). This unit unconformably covers both the deposits (1)–(4) and their Jurassic bedrock. It consists of granite (up to 60% vol.) and Werfenian quartzite (35% vol.) pebbles, cobbles and boulders (1–60 cm, sometimes up to 1 m in diameter). Admixture of flat sandstone pebbles (from the Oligocene Podhale Flysch), Oxfordian radiolarite and Cretaceous marl (from the Pieniny Klippen Belt) usually does not exceed 1% vol. but, locally (especially in lower part of the unit), may increase to 25% vol. or more. The matrix of the gravel consists of yellow-rusty to brownish sandy clay (4% vol.).

The granite pebbles-boulders are, as a rule, strongly weathered, soft, easily disintegrating into granitic sand; radiolarite and marl fragments, and sandstone pebbles, are less weathered, and only quartzite pebbles-boulders are fresh. Near the upper surface of the unit, the amount of sand and clay derived from completely weathered granite pebbles/boulders, may increase up to 60% vol.

Age

Planation surface. The planation surface which at Szaflary quarry cuts the Jurassic limestone (Czorsztyn Succession of the Pieniny Klippen Belt) at 656–664 m a.s.l. (c. 30 m above the Biały Dunajec River bed), quickly rises south (at Szaflary-Bańska Niżna) to 690 m a.s.l. (40 m above the Biały Dunajec River bed – see Birkenmajer & Stuchlik, 1975, fig. 9). According to the present author, this planation surface is correlatable with the 'Valley planation level' (B-level) of Klimaszewski (1988), which in the High Tatras occurs much higher – at 260–230 m above the Biała Woda Valley bottom. Drop of the B-planation level from 1200–1100 m a.s.l. (between Rusinowa Polana and Wierch Poroniec) to 690–656 m a.s.l. (between Bańska Niżna and Szaflary quarry), at a distance of c. 15 km, is thus of the order of 400–500 m.

Exhumation by river erosion of the Szaflary Jurassic klippe, and formation of the B-planation surface, preceeded the warm-climate epoch during which the Jurassic limestone was deeply karstified. It was proposed (Birkenmajer, in Birkenmajer & Stuchlik, 1975, tab. 3) that this erosion acted during the Early Pleistocene Donau Glaciation epoch.

The regolith (1). The regolith, which underlies the reworked regolith (2) and the lower gravel (3), has also been formed during the Early Pleistocene time. Taking into account the deep karstic (lapiez-type) sculpturing of the limestone surface (cf. Małkowski, 1924, 1928; Romer, 1930; Z. Wójcik, 1960), the formation of terra-rossa-type regolith (1) was dated at an interglacial-type epoch – the Donau/Günz Interglacial.

The reworked regolith (2) and lower gravel (3) beds were correlated with the Günz Glaciation. The Tatra gravel bed was deposited by an ancient Biały Dunajec River which flew, in the area of Szaflary quarry, at about 30 m above the present bed of this river. It was not possible to determine, whether the lower gravel has a fluvioglacial or only a fluvial origin. Thus, this gravel gives no clues as to glaciation of the Tatra Mountains at that time.

The banded clay (4) was correlated with the Günz/Mindel Interglacial. It resembles very much varved clays formed in ice-dammed lakes during cold glacial epochs. However, the pollen-spectra elaborated by Stuchlik (in Birkenmajer & Stuchlik, 1975) show interglacial and not interstadial characteristics.

The upper gravel (5), at 656–665 m a.s.l., belongs to the fluvioglacial terrace gravel system attributed in the Podhale area to the 'South-Polish Glaciation' = **Mindel Glaciation** (cf. Halicki, 1930; Birkenmajer, 1962, 1964, 1970; Birkenmajer & Stuchlik, 1975). From this terrace, Lindner *et al.* (1993, site 15: figs 1, 3) obtained a TL date of c. 328 Ka.

In the vicinity of the Szaflary quarry (Birkenmajer, 1970), the Mindel residual fluvioglacial cover is up to 20–25 m thick: its base is at c. 656 m and top at c. 680 m a.s.l. South of the quarry (at Szaflary-Bańska Niżna), towards the Tatra Mts, this cover quickly thickens to 30–35 m: its base is at 690 m and top at 725 m a.s.l. (see Birkenmajer & Stuchlik, 1975, fig. 9).

Another remnant of the fluvioglacial terrace cover correlatable with the Mindel Glaciation, occurs at top of Domański Wierch (735 m) unconformably upon Late Pliocene deposits (Birkenmajer, 1979, p. 78, fig. 14). The Mindel cover, 3–5 m thick, deposited by the Czarny Dunajec River, consists of yellow sandy clay with quartzite and nearly completely weathered granite pebbles.

QUATERNARY GLACIAL DEPOSITS AND FORMS IN THE BIAŁA WODA AND FILIPKA VALLEYS

Between the Biała Woda Valley and the Filipka Valley, there are five complexes of glacigenic deposits, attributable – according to the present paper – successively to the Mindel, ?Riss, Early Würm, Late Würm, and the Pleistocene/Holocene boundary glacial epochs (Pl. I). Their characteristics, areal distribution, mutual relationships, and possible ages, will be described below.

It should be pointed out, that stratigraphic attribution of particular glacial epochs/stages was based mainly on the degree of weathering/destruction of the moraines and on mutual relationships between particular glacigenic deposits deciphered during detailed geological mapping of the area. The age/event correlations across the northern Tatra Mountains are now possible only with respect to the Würm Glaciation, for which new stratigraphic standards have recently been proposed by Lindner and his co-workers (Lindner *et al.*, 1990, 1993, 2003, 2008). However, in the present author's opinion, dating of the Würm glacial stages distinguished by them in the middle-lower parts of the Biała Woda Valley, based only on scarce TL-dates, is still inadequate, while the ^{14}C and ^{36}Cl datings are missing.

The detailed Quaternary geology map presented here (Pl. I) might serve the purpose of future detailed dating of glacier advance and retreat stages during the Würm Glaciation. Without such dating, it is difficult, or even impossible, to correlate particular Würm glacigenic deposits and forms even between the neighbouring Biała Woda and Sucha Woda valleys.

The Wierch Poroniec moraine (Mindel)

Areal distribution. The oldest Pleistocene glacial deposits of the area between the Biała Woda and Filipka valleys, are represented by a residual moraine which caps the top of a prominent morphological ridge 3.8 km long, between the Wierch Poroniec mount (1100 m) and the Rusinowa Polana alp (1200 m) – Pl. I. This is the Wierch Poroniec moraine – the Poroniec moraine for short.

Bedrock. Between Wierch Poroniec and Rusinowa Polana, the bedrock of the Poroniec moraine consists of the Podhale Flysch (Zakopane beds, Oligocene) in its northern and middle parts. In the southern part, this bedrock is formed by Triassic through Lower Cretaceous strata of the Lower Subtatric Nappe (see Sokołowski & Jaczynowska, 1979a), locally also by the ?Upper Cretaceous Rusinowa Conglomerate Formation (Birkenmajer, 2000a) – Pl. I.

Sub-morainic planation level. A well recognizable, gently northward sloping sub-morainic planation level, truncates the bedrock between Rusinowa Polana (1200 m) in the south and Wierch Poroniec (1100 m) in the north. It correlates with the 'Valley planation level' (B-level) of Klimaszewski (1988). Similarly as in the Szaflary quarry section, it may have formed during Early Pleistocene.

Moraine description and origin. Glacigenic deposits which cover morphological ridge betwen Rusinowa Polana and Wierch Poroniec, are represented by a strongly weathered bottom moraine of the boulder-clay type, probably maximum up to 5 m thick. Oversized boulders/blocks of granite, usually 1–3 m in diameter, are strewn over its whole surface. The largest blocks, up to 5 m in diameter, occur in the area between Międzydrogi and Las Wapienny Piec, south of Las Brzanówka (Pl. I). Other boulders include quartzite (Werfenian) and, seldom (at Siedlarska Droga north of Las Wapienny Piec), limestone and dolostone (Middle Triassic).

In the southern part of Rusinowa Polana, up to 1250 m a.s.l., erratic granite blocks 1–3 m in diameter are weathered at the surface, their edges often rounded by weathering. Still higher, up to 1350 m a.s.l., there occur also loose Triassic limestone blocks 1–1.5 m in diameter; they show no connection with the Poroniec moraine.

The Poroniec moraine was deposited by the Biała Woda Glacier which carried granitic rock material derived mainly from its tributaries – the Roztoka Glacier, the Rybi Potok Glacier, and the Belovodská Valley Glacier (see geological maps by Bac-Moszaszwili *et al.*, 1979; and Nemčok *et al.*, 1994). Werfenian quartzite and, much less frequent, Middle Triassic carbonate blocks, might derive mainly from the Široká Javorinská tectonic depression (right side of the Biała Woda Glacier valley) where such rocks are well represented (Nemčok *et al.*, 1994; Birkenmajer, 2000b) and, partly, from the Dolina Waksmundzka valley (see Sokołowski & Jaczynowska, 1980; Bac-Moszaszwili *et al.*, 1999; and Pl. I).

Due to strongly advanced weathering of granite boulders, the majority of which (with the exception of the largest blocks, over 1 m in diameter) had already disintegrated to quartz sand and clay, the Poroniec moraine appears to be apparently enriched in quartzite boulders. They are chaotically set in yellow residual sandy clay.

There are no natural outcrops available in the moraine which would enable its closer geological examination. The moraine surface is smooth, largely overgrown with forest. The forest road-cuttings are small and shallow; thus far, no drilling or shaft digging was performed in this part of the Tatra National Park.

Morphological features. During the successive interglacial epoch, deep dissection of the moraine, its bedrock and sub-morainic planation level by the Białka River in the east, and the Filipczański Stream in the west, caused isolation of the Rusinowa Polana–Wierch Poroniec ridge, and helped preserve its residual moraine. During the successive glaciations, this ridge was traversed by glaciers in its southern part only (Pl. I).

Oversized granite erratics. There are numerous, 2–5-m-large granite boulders/blocks (erratics), which occur within solifluction clays or lie directly upon flysch on western and eastern slopes of the ridge, at Las Brzanówka (northern and southern parts), and at forest road south of Polana Hurkotne, respectively (Pl. I). Evidently, they slid down several hundred metres off their original location on top of the ridge, under periglacial conditions that favoured gelifluction during the next glacial epoch(s).

There are also numerous oversized granite boulders (erratics) sticking out of solifluction clay, or within active landslide, to the north of the Łysa Skałka threshold (1119–1175 m). They, evidently, also slid down from the Poroniec moraine cover.

A. Wójcik *et al.* (in Iwanow, A. *et al.*, 2008: point 3.10) are inclined to consider large granite erratic blocks which occur at right slope of the Złota Dolina valley (called: Antek), as an evidence for transfluence of the Biała Woda Glacier from the Biała Woda to the Filipka valley systems. However, during the Würm Glaciation, these valleys were effectively divided from each other by the Goły Wierch–Wierch Poroniec ridge (see Pl. I). Solifluction clay which covers the Antek slope is still creeping, carrying down displaced granite boulders derived from the Poroniec moraine.

Goły Wierch roche moutonnée. Goły Wierch (1200 m) is a gentle hill 200 x 200 m in a horizontal section, located about 500 m NE from Rusinowa Polana (Pl. I). The hill stands up from the Poroniec moraine in its southern part, exposing Upper Triassic rocks: dark Rhaetian limestone and variegated Keuper shales. No glacial striations have been preserved on the easily weathering Triassic rocks. The moraine cover is here about 5 m thick.

Stratigraphic age. The Poroniec boulder clay is the oldest moraine cover of the East Tatra Mountains. It directly covers the Early Pleistocene 'Valley planation level' (B-level) of Klimaszewski (1988) at 1200–1100 m a.s.l., and is isolated from the east and west by deeply incised river valleys – the Biała Woda-Białka Valley (970–920 m a.s.l.), and the Dolina Filipka-Złota Dolina valleys (1200–900 m a.s.l.), respectively.

In its southern part, the Poroniec moraine contacts with lower lying marginal/retreat moraines of the Late Würm Glaciation. In southwestern part, just below Rusinowa Polana, the Poroniec moraine contacts with a narrow residual Early Würm bottom moraine which fills the Złota Dolina valley.

By its strongly advanced state of weathering, the Poroniec moraine resembles very much residual fluvioglacial covers at the Szaflary quarry and at Domański Wierch, both laid down during the Mindel Glaciation (see the preceding chapters). Therefore, a Mindel Glaciation age is suggested for the Poroniec moraine.

Equivalents and correlation

(1) The Poroniec boulder clay corresponds to glacigenic deposits termed 'The Hurkotne "Deckenschotter" (H)' by Romer (1930, p. 25). The name 'Hurkotne' was applied by him (*op. cit.*, map) to the prominent morphological ridge ["high plateau of Hurkotne (1171) and Poroniec"] covered by boulder clay, between the Oswald Balzer Highway (at Wierch Poroniec hill) and Goły Wierch hill (near Rusinowa Polana). Romer (*op. cit.*, p. 26) classified these glacigenic deposits as formed during the "Hurkotne (H) period".

The 'Hurkotne "Deckenschotter" (H)' of Romer strictly correlates with the Wierch Poroniec moraine (resp. Poroniec moraine), as used in the present paper.

(2) The geographical name 'Hurkotne' is no longer used for the morphological ridge ("plateau") between Wierch Poroniec and Goły Wierch. It is used, instead, for the 'Polana Hurkotne' alp located on eastern slope of Wierch Poroniec, in upper part of the Białka River Valley (see, e.g., *Topographic Map of the Tatra Mountains, 1:10,000 scale*, 1984).

(3) The name 'Hurkotne' has recently attained a geological meaning completely different from that of Romer's (1930). Unfortunately, it was applied, as the "Hurkotne phase", about 32–25 Ka, to the oldest phase of the "Białka Stadial" of the Late Würm Glaciation (Lindner *et al.*, 1990, pp. 344–345, figs 2, 3; 1993, fig. 1). This homonymous name, incorrect from stratigraphic viewpoint, still exists in geological literature of the Tatra Mts Pleistocene glaciations (e.g., Nowacki, 2006; Lindner *et al.* 2008, fig. 1; Dzierżek & Rączkowski, 2008, fig. 4).

The "Hurkotne moraine" (Lindner *et al.*, 1990, p. 345), and the "Hurkotne site" (Lindner *et al.*, 2003, p. 274), are other mismatched names introduced without due consideration to the Würm Glaciation deposits of the Polish Tatra Mountains. Together with the "Hurkotne phase", they should disappear from the geological literature as soon as possible.

(4) According to Halicki (1930, pp. 467–468), the "Hurkotne platform" was once covered by the glacier. In the attached map (*op. cit.*, pl. XII), he marked there moraines of the IInd glaciation (= Riss).

(5) Sokołowski and Jaczynowska (1979a) classified moraine deposits at top of the Wierch Poroniec–Goły Wierch ridge as "older than the last glaciation".

(6) Klimaszewski (1988, p. 560) attributed the Hurkotne moraine cover to the Riss Glaciation.

(7) Nemčok *et al.* (1994, signature 14a) attributed these morainic deposits to the Early Riss Glaciation.

(8) Residual moraine granite blocks (0.8–1 m in diameter) and clay (2–3 m thick) at Rusinowa Polana (1200–1240 m a.s.l.), and the "Hurkotne cover", were attributed by A. Wójcik *et al.* (in: Iwanow *et al.*, 2008, pp. 124–125) to the Riss Glaciation.

(9) A. Wójcik (2008, fig. 1), in a section from Rusinowa Polana (WNW) to Palenica Białczańska (ESE), has distinguished the following moraine deposits (metres a.s.l.): 1210–1200 (Rusinowa Polana: ?Donau); 1200–1170 (Hurkotne: Günz); 1170–1120 (Mindel); 1120–1040 (Riss); 1040–990 (Würm). According to the present author (see Pl. I), Wójcik's "?Donau", "Günz" and "Mindel" moraines do not essentially differ from one another representing the same residual morainic cover here described as the Wierch Poroniec moraine and attributed to the Mindel Glaciation.

The Palenica Białczańska moraine (?Riss)

Along lower slope of the Biała Woda Valley at Palenica Białczańska, at 1000–1050 m a.s.l., below the fresh-preserved Würm Glaciation moraines crops out a degraded moraine, here called the Palenica Białczańska moraine, or the Palenica moraine for short (Pl. I).

Description. This is a granite-quartzite boulder deposit enriched in yellow-weathering clay, slightly enriched in quartzite boulder due to partially weathered out granite boulders.

Thickness. The thickness of the Palenica moraine is calculated at c. 50 m.

Bedrock. The bedrock of the Palenica moraine is nowhere exposed. It should be represented by Mesozoic rocks of the Lower Subtatric Nappe (see Sokołowski & Jaczynowska, 1980; Birkenmajer, 2000a, fig. 3).

Relationships. The Palenica moraine does not contact with the Poroniec moraine. It occurs at the Biała Woda Valley bottom, some 200 m below the Poroniec moraine. Its topographic position suggests a deep dissection of the valley, nearly to its present level, during an interglacial epoch (Mindel/Riss) which succeeded the Mindel Glaciation. The Palenica moraine is directly covered by left lateral/marginal moraines of the Late Würm Glaciation.

Stratigraphic age. By its position below the Late Würm moraine cover (Białka moraines – Pl. I), the Palenica moraine could qualify at the ?Riss Glaciation. However, in the lack of more detailed dating, its Early Würm age cannot be ruled out. If the younger age be accepted, no Riss Glaciation deposits would be present in the area under study.

The Złoty Potok moraine (?Early Würm)

Areal distribution. The glacial eposits form a narrow, 1.5 km long strip in the Złota Dolina (Złoty Potok)-Filipczański Potok valleys, from northern margin of the Rusinowa Polana alp as far north as the entrance to the Dolina Filipka valley (just east of the Filipczański Wierch mount) – Pl. I. These deposits are here named the Złoty Potok moraine.

Bedrock. The bedrock of the moraine is mainly formed by deeply eroded rocks of the Lower Subtatric Nappe; the Podhale Flysch bedrock occurs at the northern termination of the moraine.

Moraine description. This is a rather degraded bottom moraine, consisting of a thin boulder-clay which paves the valley bottom, and of numerous blocks of rather fresh granite (0.5–3 m in diameter) which were washed out of the moraine by the Złoty Potok stream. The boulders are angular or slightly subrounded. The moraine material was brought here from the Dolina Waksmundzka valley by a glacier tongue probably not connected with the Biała Woda Glacier.

Stratigraphic age. The Złoty Potok moraine fills a deep erosional valley which post-dates the Poroniec moraine (Mindel), and could have formed during the Mindel/Riss and/or Riss/Würm interglacials. The moraine occupies a S–N-directed strip along the valley bottom. It has no connection with the recession/lateral/bottom moraines which were a joint product of the Waksmundzki Glacier and the Biała Woda Glacier during the Late Würm Glaciation (see Pl. I).

An abrupt southern termination of the moraine suggests an erosive epoch which succeeded it, during which the highest part of the moraine (at Rusinowa Polana) was washed away exposing the Mesozoic bedrock. An Early Würm age is thus suggested for the Złoty Potok moraine.

The Białka moraines (Late Würm)

The morainic deposits of this group, called the Białka moraines, are very well preserved, consisting predominantly of fresh granite boulders and blocks. They are widely distributed along left side of the Biała Woda Valley between Roztoka (in the south) and Łysa Polana (in the north), moreover to the north of the Łysa Skała cliff. They were mainly formed by the Biała Woda Glacier, subordinately by the Waksmundzki Glacier.

The area of the Białka moraines shown in Pl. I offers a very good opportunity for a detailed study of the last stages of the Biała Woda Glacier – the largest Late Pleistocene glacier of the Tatra Mountains.

Moraine categories. The following moraine categories have been distinguished (see Pl. I):

(1) The left **lateral moraines** of the Biała Woda Glacier are well distributed between Roztoka and Łysa Polana;

(2) The **terminal moraines** of the Waksmundzki Glacier are preserved at Rówienki;

(3) The **terminal hummocky moraines** of the Biała Woda Glacier are preserved to the north of the Łysa Skała cliff, between 1080 and 1028 m a.s.l. (up to 92–93 m above the Białka River bed). Their irregular morphology suggests that they were once ice-cored;

(4) The **bottom moraines** of the Biała Woda Glacier and its tributary Waksmundzki Glacier occur: between Roztoka and outlet of the Waksmundzki Potok stream; at outlet of the Dolina Waksmundzka valley; between Czerwone Brzeżki and Łysa Skała cliff;

(5) The **retreat morainic ridges** of the Biała Woda Glacier are well preserved between Czerwone Brzeżki and the Łysa Skała cliff: the highest and outermost arcuate ridge (below Las Wapienny Piec: at Zielonka), occurs at 1155–1160 m a.s.l.; a lower arcuate ridge (west of Łysa Skała), occurs at 1150–1100 m a.s.l.; the remaining successive ridges (between Łysa Skała and Czerwone Brzeżki) run at 1100–1000 m a.s.l.

The lateral and bottom moraines between Roztoka and Waksmundzka Dolina valleys consist almost exclusively of fresh or only slightly weathered granite boulders/blocks, usually 0.2–1 m in diameter; sand and clay fraction matrix between the boulders is subordinate. Werfenian quartzite blocks may be found mainly along the Waksmundzki Potok stream valley, while Middle Triassic dolostone and Keuper variegated shale – south and north of the Polana pod Wołoszynem alp and, in particular, near Dziadowa Jama.

The boulders are predominantly angular, while subangular to subrounded boulders (evidence for glacial river action), are rare. The lateral moraines are largely amorphous; this indicates that they were once ice-cored and had lost their original shape due to dead-ice melting during glacier retreat. Erosional escarpments and morphological steps preserved within the moraines might be evidences of some successive stages in ice-thickness decrease during the glacier's retreat.

The morainic recession ridges between Czerwone Brzeżki and Łysa Polana consist of granite blocks 1–4 m in diameter. Their well preserved morphological form indicates that they were never ice-cored.

Oversized granite blocks, up to 4–5 m in diameter, occur within the left-lateral moraines, particularly in their morphologically lower parts, just above the road to Morskie Oko, east of Las pod Wołoszynem and Polana pod Wołoszynem, moreover above Palenica Białczańska (Pl. I). They form a kind of ridge, not necessarily a trace of median moraine but, rather, an accumulation of largest blocks which slid down the valley during melting of glacier ice. The largest granite block, about 10 m in diameter, sticking out 5–6 m above the moraine, occurs at lower slope of the valley (at 1040 m a.s.l.) above Palenica Białczańska.

North of the Łysa Skałka ridge, oversized granite blocks up to 3–4 m in diameter occur within hummocky terminal moraine of the Biała Woda Glacier.

Marginal river outflow. A well preserved erosional scarp running along contact of the left lateral Białka moraine with the Poroniec moraine, from Rusinowa Polana in the south-west to Łysa Skałka in the north-east, is a remnant of a marginal outflow channel which once carried meltwater from the Biała Woda-Waksmundzka Dolina glacier couple to the Łysa Polana gate. Granite boulders washed by glacial river out of the Poroniec moraine, locally form there a small kame-type ridge.

Bedrock. The bedrock of the Białka moraines is represented by the Hightatric crystalline (granitoid) core and its Triassic cover deposits in the south (between Roztoka and Dolina Waksmundzka), by the Triassic–Lower Cretaceous rocks of the Lower Subtatric Nappe (Križna Nappe) in the middle (between Dolina Waksmundzka and Łysa Polana), and by the Podhale Flysch (Oligocene) to the north of the Łysa Skała cliff (Pl. I). This bedrock was deeply dissected, nearly as deep as the present bottom of the Biała Woda Valley, already prior to the onset of the Late Würm Glaciation.

Along the left side of the Biała Woda Valley, the bedrock of the Białka moraines is exposed to the SE, E, and N of the Polana pod Wołoszynem alp, to the east of the Rusinowa Polana alp, at Łysa Polana-Łysa Skałka, and to the north of Łysa Skałka.

The Łysa Skałka threshold. During the Late Würm time, the Middle Triassic limestones overlain by the Keuper shales of the Łysa Skałka cliff (1119 m), formed a rocky ridge elevated up to about 200 m above the glacier bottom. The only glacial cover preserved at the top of this threshold is that belonging to the Poroniec moraine.

As indicated by the position of arcuate marginal/terminal Białka moraines south of the Las Wapienny Piec (at about 1130 m a.s.l), the Łysa Skałka threshold, rising 45–50 m above the glacier-ice front (from 1119 m to about 1175 m a.s.l.), could effectively block the ice passage to the north. The Biała Woda Glacier ice was then forced to flow east to north-eastwards, through the **Łysa Polana Gate.** Its fan-wise hummocky terminal moraine was laid down at 1030–950 m a.s.l. north of the gate (see Pl. I).

Glacier-ice thickness. The above analysis of the Biała Woda Glacier motion directions, and the shape and morphological position of its moraines, suggest that near Łysa Polana, the ice-thickness during the latest stage of the Biała Woda Glacier did not exceed 60 m.

A. Wójcik (2008, p. 216) thinks that during the Würm Glaciation top surface of the Biała Woda Glacier at Łysa Polana did not exceed 1000 m a.s.l.; this gives a similar value of c. 50 m of ice thickness. Wójcik believes that, during the Würm Glaciation, the glacier ice reached up to a maximum of 1050–1060 m a.s.l. between the Łysa Skałka cliff and Palenica Białczańska alp. However, as it is shown by the geological map (Pl. I), the valley slope was then completely buried under glacier ice, nearly as high up as the Rusinowa Polana alp.

Stratigraphic age

(1) There seems to be a general agreement that the Białka moraines represent the Late Würm Glaciation events (e.g., Baumgart-Kotarba, 1998; Baumgart-Kotarba

& Kotarba, 1998; Lindner *et al.*, 2008; A. Wójcik, 2008). However, any more detailed attribution of the Białka moraines in lower part of the Biała Woda Valley (between Roztoka and Łysa Polana) to particular "stages" or "phases" of this glaciation should await proper dating of the moraines, which is presently missing. Therefore, the present author refrains from applying detailed standards introduced by Lindner *et al.* (2008 and earlier papers).

(2) A. Wójcik (2008, fig. 1) attributed the moraines in a section from Rusinowa Polana (WNW) to Palenica Białczańska (ESE), to the Riss (at 1120–1040 m a.s.l) and the Würm (at 1040–990 m a.s.l.) glaciations. However, as shown in Plate I, the extensive uniform cover of the Würm moraines (lateral, bottom and recessional) creeps uninterrupted from the bottom of the Biała Woda Valley (near Łysa Polana) through the Las Palenica forest up to Rusinowa Polana, where it joins with the lateral/bottom Late Würm moraines left over by the Waksmundzka Dolina Glacier. In the present author's opinion, there is no reason to attribute a part of these moraines to the Riss Glaciation, based solely on their higher morphological position.

Youngest glacigenic deposits and forms

The youngest glacigenic deposits and morphological forms which post-date the Late Würm Białka moraines, are represented by two groups: the Waksmundzki Potok glacigenic deposits; and the Wołoszyn talus/nival moraines. They could have formed at the Pleistocene/Holocene transition.

The Waksmundzki Potok glacigenic deposits

Along the Waksmundzki Potok stream, from the Dolina Waksmundzka valley gate at c. 1250 m a.s.l. to the stream's outlet to the Biała Woda river at c. 980 m a.s.l., there occur the youngest glacigenic deposits of the area. They show arrangement of boulders in form of lateral moraine ridges aligned parallel with the present stream valley; bottom moraines and arcuate terminal moraines (at eastern termination of the valley) are also well distinguishable. These glacigenic deposits are superimposed upon the Late Würm Białka moraines.

In an abandoned gravel pit, c. 700 m WNW from the Potok Waksmundzki/Biała Woda junction, we see a glacifluvial-type deposit. It consists mainly of granite boulders 0.1–2 m in diameter, with a subordinate admixture of quartzite bolders. A granite-gravel fraction, 5–20 cm in diameter, makes up to 25%, while slightly clayey sand – 20–10%.

Origin and age. Morphological arrangement and lithological character of the deposits in question indicate their glacigenic origin. These deposits were most probably laid down by a wet **surging-type glacier** which, for a short time, filled a narrow stream valley that had developed at the Pleistocene/Holocene transition after withdrawal of the Waksmundzka Dolina/Biała Woda glaciers.

The Wołoszyn talus/nival moraines

Along red tourist trail (Roztoka–Toporowa Cyrhla) below Mount Wołoszyn, at 1100–1200 m a.s.l., as far north as the mouths of the Waksmundzka Dolina valley, there occur numerous very characteristic, well preserved festoon-like narrow ridges up to 5–10 m high, consisting of fresh unworked granite fragments up to 5 m in diameter. In upper part of the Biała Woda valley, these ridges rest directly upon granitic bedrock, in lower part – on slightly weathered Late Würm left lateral Białka moraine, or directly upon Triassic bedrock.

Age and origin. Towards the Waksmundzka Dolina valley, these ridges rest directly upon the Białka bottom moraine or upon the Waksmundzki Potok bottom moraine. In the latter case, their arrangement (Pl. I) shows that they belong to the same post-Late Würm system of glacigenic deposits.

These glacigenic deposits and forms correspond to talus moraines, as known, e.g., from Spitsbergen and East Greenland (Birkenmajer, 1982). In the Biała Woda valley, already set free from the glacier ice, they originated by the way of granite-debris avalanches and accumulation of single blocks which slid down over wet surface of small, steep ice tongues or snowfields (nival moraines) that occupied ravines at eastern slope of Mt Wołoszyn. They fall within the category of 'fossil rock glaciers' which, in the High Tatra Mountains, had formed mainly at the Pleistocene/Holocene boundary (Dzierżek & Nitychoruk, 1986).

DISCUSSION AND REMARKS

(1) Lindner *et al.* (1990–2008) have distinguished three glacial stages of the Würm Glaciation in the Polish Tatra Mountains: the Sucha Woda stage (c. 115–80 Ka), the Bystra stage (c. 70–40 Ka), and the Białka stage (c. 32–9 Ka), separated by two interstadials. However, in the northern forefield of the Tatra Mountains (the Podhale area), the Würm fluvioglacial terraces ('Baltic Glaciation' – e.g., Birkenmajer, 1962, 1965a, b, 1970), show neither the presence of distinct morphological steps in the bedrock surface, nor important changes in lithology of the Würm fluvioglacial covers, which could be correlated with the two interstadials distinguished by Lindner *et al.* in the Tatra Mts. Instead, in well studied sections of the Würm terrace, at Białka village, and at Brzeziny near Czorsztyn, have been recognized only **two fluvioglacial gravel covers** divided by finer-grained, plant-bearing deposits (Szumański, in Stupnicka & Szumański, 1957; Birkenmajer & Środoń, 1960; Sobolewska & Środoń, 1961), the latter correlatable with the Aurignacian Interstadial.

(2) Bipartite subdivision of the Riss Glaciation, as proposed by Nemčok *et al.* (1994) for Pleistocene glacigenic deposits of the Biała Woda Valley, finds no confirmation in the present author's study. Even the existence of the Riss Glaciation deposits is questionable there. In the northern forefield of the Tatra Mountains (Podhale area) where fluvioglacial covers attributable to the Riss Glaciation (Halicki, 1930; Middle-Polish Glaciation = Riss, Birkenmajer, 1962, 1965a, b,

1970) are well developed, so far it was not possible to recognize its two stages (R-1 and R-2) separated by a morphological step and sediments correlatable with the Riss-1/Riss-2 interstadial.

(3) The Wierch Poroniec moraine seems to be the oldest Pleistocene moraine recognized thus far in the Polish Tatra Mountains. Accordingly, weathering of its granite boulders (with the exception of the largest ones), has been advanced so far that the moraine had long became transformed into boulder clay apparently enriched in Werfenian quartzites. In this respect, it resembles very much the Szaflary quarry fluvioglacial gravels which are well dated at the Mindel Glaciation (Birkenmajer & Stuchlik, 1975). Thus, a Mindel age of the Poroniec moraine seems most probable.

(4) The Poroniec residual moraine uniformly covers the bedrock, its top truncated by the 'Valley planation level' (B-level of Klimaszewski, 1988). There are neither significant erosional steps recognizable in the bedrock and/or in the planation level, nor significant changes in lithology of the moraine, to allow for dividing it into three glaciations: the ?Donau, the Günz, and the Mindel ones, as proposed by A. Wójcik (2008).

(5) It would be of great scientific interest to perform some shallow boreholes in the Wierch Poroniec moraine in order to obtain its geological section and, eventually, to discover some datable plant-bearing deposits.

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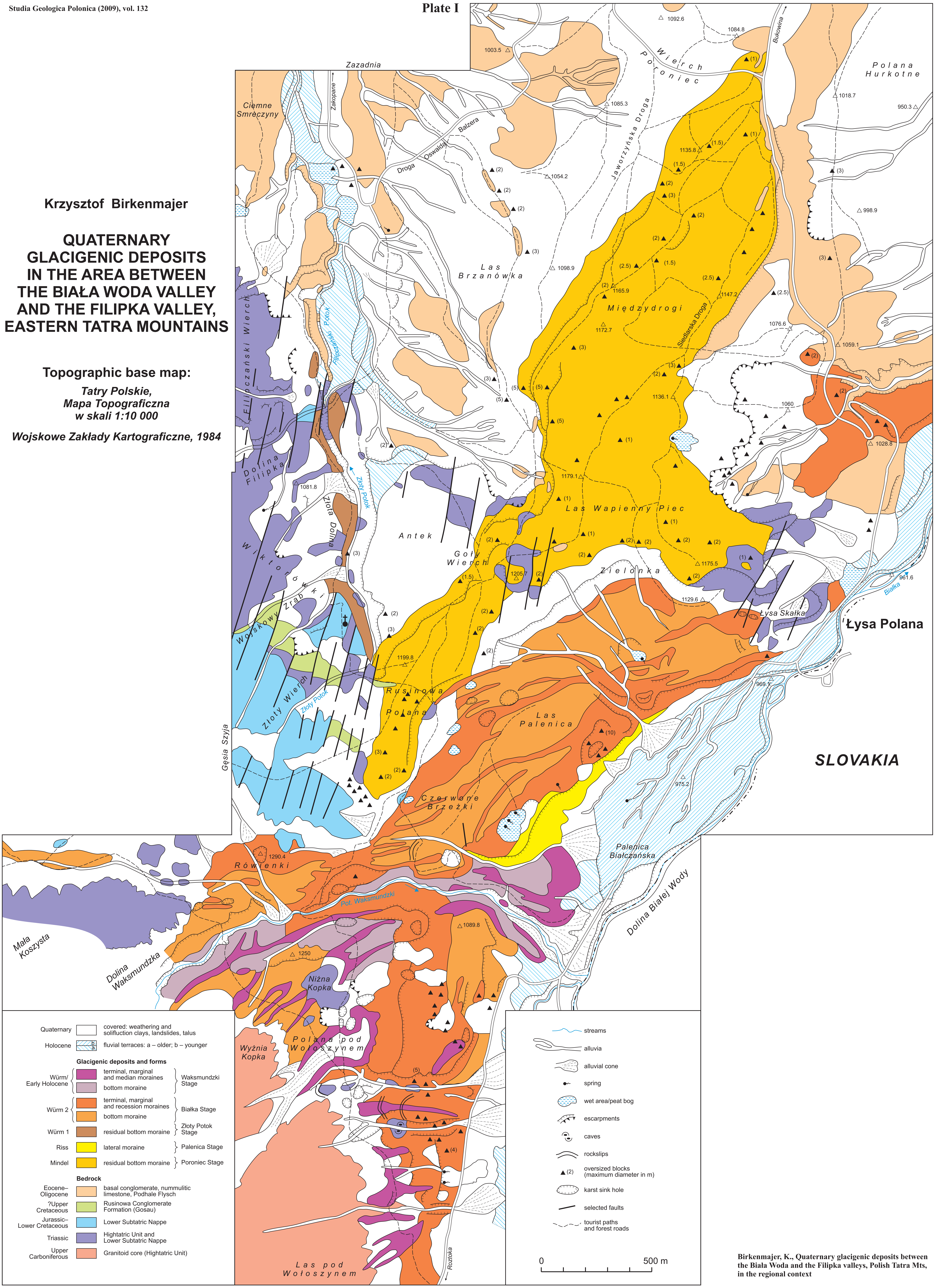
Plate I



Birkenmajer, K., Quaternary glacigenic deposits between the Biała Woda and the Filipka valleys, Polish Tatra Mts, in the regional context