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Development of the relief of Roztocze Upland
(with electronic geomorphological map 1:50 000, elaborated by J. Buraczyński and Ł. Chabudziński)

In memory of Professor Mieczysław Klimaszewski
a world-renowned geographer,
author of the methodology and initiator
of geomorphological mapping in south Poland.

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Abstract: The paper presents the development of the relief of Roztocze Upland constituting a ridge in the northern forefield of the Carpathians. It discusses the stages of evolution of the relief determined by the tectonics and lithology of the bedrock, as well as climate changes. The paper is supplemented by a multi-colour geomorphological map 1:50,000 prepared following the instructions by M. Klimaszewski. The colour code indicates the genesis and age of the landform. The map constitutes the summary of research on the evolution of relief and changes of the entire environment. The description of the evolution of the relief and its cartographic image are complementary.

Key words: geomorphological map, structural relief, fluvial, eolian, and glacial.

Introduction

Roztocze is located in the belt of Central Polish Uplands, where a range of elevations develops connecting the Lublin Upland with Podole, and separating the Sandomierz Basin from the Basin of the upper Bug River. The Roztocze Upland with a length of 185 km and width of 15–28 km extends from Polichna to Lwów. To the south, it is confined by straight-line scarps with a height of 50–100 m. Culminations reach a height of 290 m a.s.l. at the NW boundary, and gradually increase to 380–396 m a.s.l. southwards.

The orography of Roztocze shows a clear division into subregions. They are determined by longitudinal valleys of the Gorajec and Wieprz Rivers and the Tanew River graben with the Narol-Bełżec valley. In the territory of Poland, they divide Roztocze into four regions: Roztocze Gorajskie (Goraj), Roztocze Szczebrzeszyńskie (Szczebrzeszyn), Roztocze Tomaszowskie (Tomaszów), and Roztocze Rawskie (Rawa) (Fig. 1).

Review of the study

The establishment of a university with a department of geography in Lublin after the war caused increased interest in Roztocze. Study results concerning its structure and relief were presented at the Meeting of the Polish Geographical Society in 1954. The period was summarised in works by Jahn (1956) and Maruszczak and Wilgat (1956).

In further years, geological research was undertaken concerning the Cretaceous (Cieśliński, Wyrwicka 1970), Miocene (Areń 1962, Ney 1969ab, Musiał 1987), and tectonics (Jaroszewski 1977). Geographers studied the structural relief (Maruszczak 1972, Buraczyński 1980/81, Harasimiuk 1980), loess relief (Buraczyński 1961, 1989/90, Maruszczak 1961), and aeolian relief (Buraczyński 1998). The synthesis of the geological and geomorphological studies was included in monographs (Buraczyński 1997, 2002, 2013) and publications from Meetings (Główne… 1998, Budowa… 1998). At the end of the 20th century,

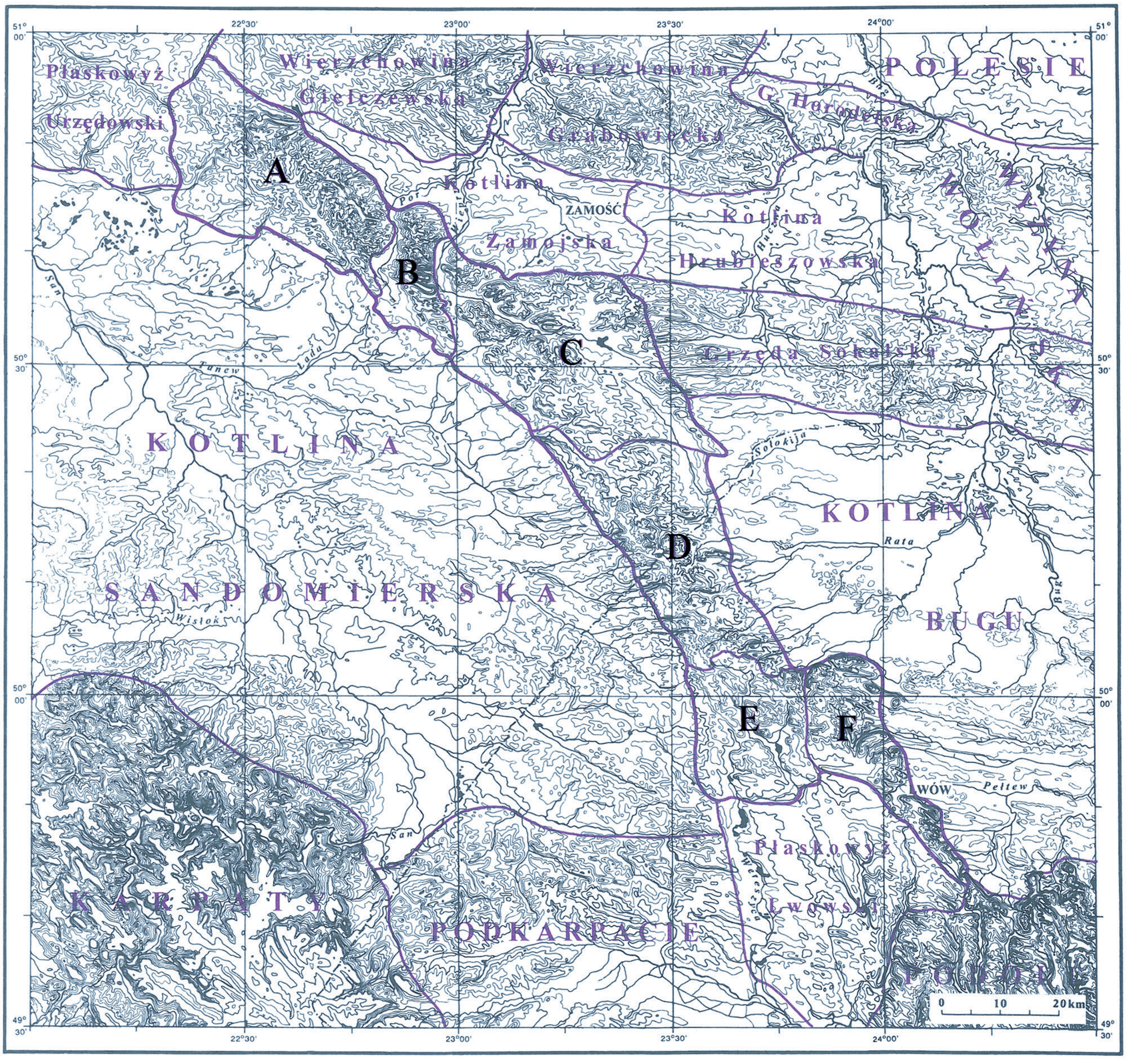

Fig. 1. Geomorphological regions of Roztocze (Buraczyński 1997)
A – Gorajaskie, B – Szczebrzeszyńskie, C – Tomaszowskie, D – Rawskie, E – Janowskie, F – Lwowskie

a geological map 1:50 000 with explanations was prepared (SMGP 1988–2007) [1].

Geomorphological map

The geomorphological map of Roztocze was prepared in accordance with the concept by Klimaszewski (1956, 1968). The manuscript of the map at a scale of 1:10 000 was prepared by J. Buraczyński based on field research (1968, 2002). The author also performed geomorphological interpretation of markings on the *Detailed geological map of Poland* (SMGP 1988–2007). A uniform legend was applied, where the age and genesis of the relief were marked with colours on the hypsometry background.

Ł. Chabudziński prepared a digital geomorphological map at a scale of 1:50,000. The first stage involved obtaining analogue topographic maps at a scale of 1:10,000 to which landforms were "manually" introduced, and marked with different colours, signatures, and description. Then, the maps were georeferenced in the "1965" layout, and reprojected to the PUWG 92 layout, recognised as standard for digital maps in Poland (Kaczmarek, Medyńska-Gulij 2007, Dmowska et al. 2010). Vectorisation of the introduced content was performed. Depending on its actual representation, it was processed as polygon, linear, or point objects in the vector data model. Next, the geomorphological elements and landforms were described by adding attributes. In the further process of development of maps, this allowed for the generalisation of the content and its visualisation. The final visualisation used the content of the topographic map 1:50,000 in the

[1] (SMGP 1988–2007), sheets: Zakrzówek, Wysokie, Janów Lub., Turobin, Szczebrzeszyn, Biłgoraj, Zwierzyniec, Krasnobród, Józefów, Tomaszów Lub., Lubycza Kr., Horyniec, Hrebenne.

1942 layout, in a vector data model. The map was entirely developed in ArcGIS 10.1 software.

The monograph on the relief of Roztocze shows how important function would be fulfilled by geomorphological maps not only in recording of landforms, but also in the investigation of the evolution of relief and assessment of the economic importance of relief as well as the entire natural environment (Buraczyński 2013).

Geological structure and tectonics

The Roztocze Upland is located in the zone of a concave element of the Variscan structure within the Radom-Kraśnik elevation, horst of Tomaszów and Rawa Ruska. Older elements underlie a Laramian syncline covering the Lublin-Lvov structural complex (Żelichowski 1972, Chiżniakow, Żelichowski 1974).

In the Mesozoic, the Alpine phase was manifested in gradual collapse and development of the marginal synclinorium. Sedimentation of platform formations of the carbonate and carbonate-silica formations continued throughout the Upper Cretaceous. Roztocze is composed of Cretaceous formations of the Campanian and Maestrichtian level. In the southern part, these are opokas and marl opokas, transitioning northwards into marls and gaizes (Cieśliński, Wyrwicka 1970). In the Late Maestrichtian, the lifting movements of the Laramian phase caused the retreat of the sea from the Lublin-Lviv basin. Roztocze is located in the south-western part of the Laramian syncline. The syncline, confined to the marginal Young Alpine faults (Zaklików-Płazów to the south, and Zakrzew-Sułów and Zamość-Rawa Ruska to the north), developed an elevated block of Roztocze (Ney 1969b, Pożaryski 1974).

In the Palaeocene, the elevated land developed an upland – the Meta-Carpathian arch (Nowak 1927). Determined by variable relief-forming processes, it was corrugated land with a relative height of up to 50 m (Table 1).

In the Middle Eocene, the sea from the northern basin reached the northern slope of the Meta-Carpathian arch. A dissection developed on the line of the Zamość-Rawa Ruska fault, along the northern boundary of Roztocze, where the sea entered from the east (Kasiński et al. 1993, Buraczyński and Krzowski 1994). In the Sołokija River basin, mudstone-clay series developed in the sea in the neritic zone. In the upper section, it transitions to sediments of the delta developed in the littoral zone (Fig. 2).

In the Upper Eocene and Oligocene, the Meta-Carpathian arch, free from floods, was subject to denudation and further development of the Paleogenic levelling surface (Buraczyński, Rzechowski 2007a).

In the Miocene, the most important stage of the morphogenetic development of Roztocze occurred, related to the Young Alpine orogenesis in the Carpathians. At the beginning of the Miocene, the southern slope of Roztocze dissected with valleys began separating from the Meta-Carpathian arch (Krzywiec, 1997).

The Carpathians in Roztocze Rawskie are represented by the land boggy lignite fraction. In limnic conditions, a land fraction occurred with abundant contribution of bald cypress (Krąpiec et al. 2011). Wood of the cypress family fossilised or was subject to silification in the marine environment. Fragments of petrified wood were preserved redeposited in the younger Miocene sediments in the narrow belt of the marginal zone (Buraczyński 2002, Kłusek 2006).

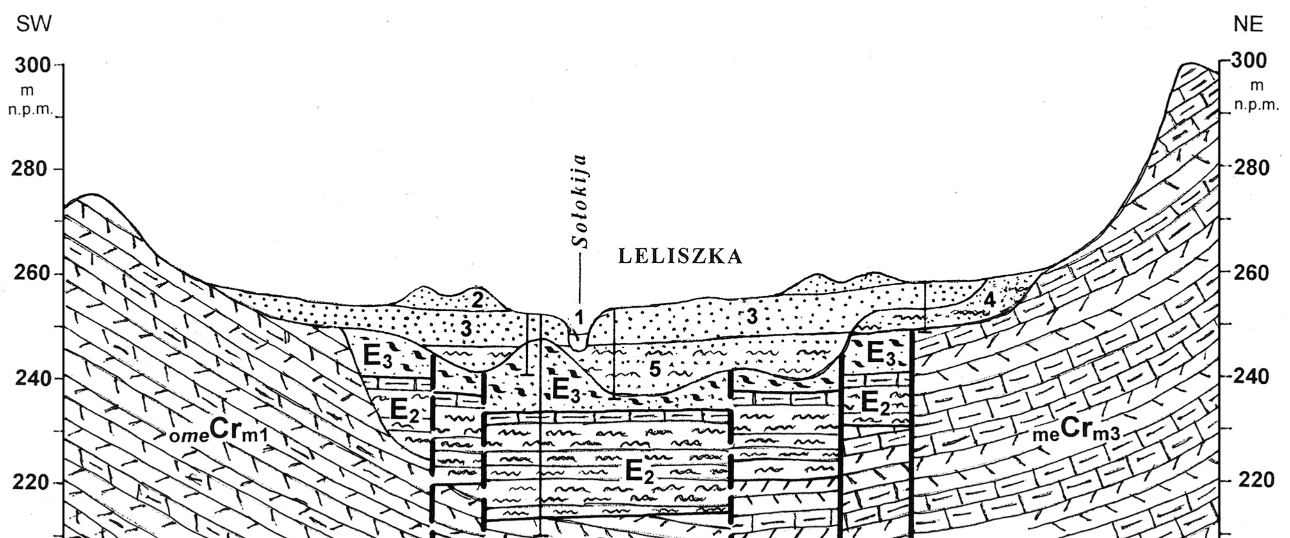

Fig. 2. Geological section of Sołokija graben (Buraczyński, Rzechowski 2007)
Quaternary: 1 – fluvial silts, Holocene, 2 – aeolian sands, 3 – terrace sands, Pleniglacial, 4 – silty sands, Grudziądz Interstadial, Vistulian, 5 – fluvial sands and silts, Mazovian. Palaeogene: E_3 – glauconitic sands, Upper Eocene, E_2 – silts and mudstones, Middle Eocene. Cretaceous: $_{me}Cr_{m3}$ – marls, Upper Maestrichtian, $_{ome}Cr_{m1}$ – marl opokas, Lower Maestrichtian

Table 1. Occurrence of some processes and their effects in Roztocze during the Neogene (Buraczyński 1997, orogenic phases by Zuchiewicz 1984, climate by Stuchlik 1980)

CHRONOSTRATIGRAPHY			OROGENIC PHASES absolute age (min. Years)		TECTONICS	CLIMATE	PROCESSES
QUATERN.		Eopleistocene				Moderate, periodically dry, with violent downpours	Denudation Terraces in valleys Intensified deep erosion - development of main valleys
PLIOCENE		Roman	2.5	Wallachian	Uplift of Roztocze	Moderately warm, semi-dry; mean annual temperature+12°C	Development of planations: - lower level,
PLIOCENE		Dak	3.7	Rodanian		Moderate to moderately cool, rather humid	- upper level, - residual hills of the oldest relief
PLIOCENE		Pont	5.2	Attycka		Moderate, dry, mean annual temperature +7°C	
MIOPLIOCENE		Pannonian	8.1			Moderately warm, humid, periodically dry, in subtropical optimum; mean annual temp. +16°C	Surface dissection, lateral development of slopes
MIOCENE	Sarmatian	Upper	10.5	Moldavian	Tectonic transformation: elevating movements	Moderately warm, very dry	Intensified erosion in Roztocze, development of fans in the foredeep
MIOCENE	Sarmatian	Lower			Fault-block tectonics: lowering of the external basin uplift of Roztocze		
MIOCENE	Badenian	Cosovian	13.2	Leitha		Moderately warm, relatively dry	Reef-detrital facies
MIOCENE	Badenian	Wielician	14.0	Styrian			Chemical sediment facies
MIOCENE	Badenian	Moravian	15.1			Moderately warm, humid	Loamy-sandy facies Baranov formation
MIOCENE	Carpathian		16.5	Early Styrian	Badenian transgression Development of the Carpathian Foredeep: external basin	Moderately warm to subtropical with high precipitation	Strong denudation,
MIOCENE	Ottnangian		17.8				Undulating land, relative height up to 50 m
MIOCENE	Eggenburgian		19.0		internal basin		
OLIGO-MIOCENE		Eger	23.0	Savian		Subtropical, humid	
OLIGOCENE		Upper	29.0				Denudation
OLIGOCENE		Middle					
OLIGOCENE		Lower				Hot, dry	Silification of sands – Batiatycze sandstones
EOCENE		Upper	36.6	Upper Eocenian	Block tectonics	Subtropical, humid	Delta accumulation
EOCENE		Middle	43.6		Eocene transgression		Accumulation of sands and quartz-glauconitic muds
EOCENE		Lower	52.0	Late Lutecian	Lowering movements on the fault Zamość-Rawa R.		Palaeogenic planation surface
PALAEOCENE		Upper	57.8	Late Laramian		Moderately warm to subtropical	
PALAEOCENE		Middle					
PALAEOCENE		Lower	63.4 65.4	Early Laramian	Elevating movements: development of the Meta-Carpathian ridge		Deep decalcification opokas and gaizes

In the Lower Badenian, marine transgression entered a morphologically varied area. The transgression covered the near-marginal zone and plateaus of Roztocze Rawskie, depositing sands and sandstones with a thickness of up to 80–100 m. In the Middle Badenian, no tectonic activity was recorded. The sea shrunk and dried out. A fraction of evaporites with gypsum developed on Roztocze Rawskie. In the Upper Badenian, the overthrust of the Carpathians caused the subsidence of the trough and expansion of the sea northwards. In the near-marginal zone, the transgressive sandy series is the best developed. Between the external and internal edge a calcareous series occurs, and on scarps of active blocks – a reef series (Areń 1962, Ney 1969a, Musiał 1987).

The formations of the Sarmatian developed on the southern slope of Roztocze Gorajskie and Roztocze Tomaszowskie (Musiał 1987).

Tectonics

An increase in horizontal stresses caused by the pressure of the Carpathians resulted in the activation of the Laramian faults and elevation of Roztocze as a horst structure (Fig. 3).

In the Early Sarmatian, the pressure of the sliding sheets of the External Carpathians caused rapid lowering of the Fore-Carpathian trough and elevation of continental crust in its northern foreland. Marginal dislocation on the line Zaklików–Hedwiżyn–Płazów determines the boundary of two facial areas: deep-water mudstone-sandy facies and shallow-water coastal facies, and in Roztocze lagoon, detrital, and reef facies (Krzywiec 1997).

At the end of the Sarmatian, after the retreat of the sea from the trough, the pressure of folding Carpathians resulted in the activation of the main faults and elevation of Roztocze as a horst structure, as well as the development of the fault-block tectonics. Antitheric scarps, normal faults, and lateral compensating faults and grabens devel-

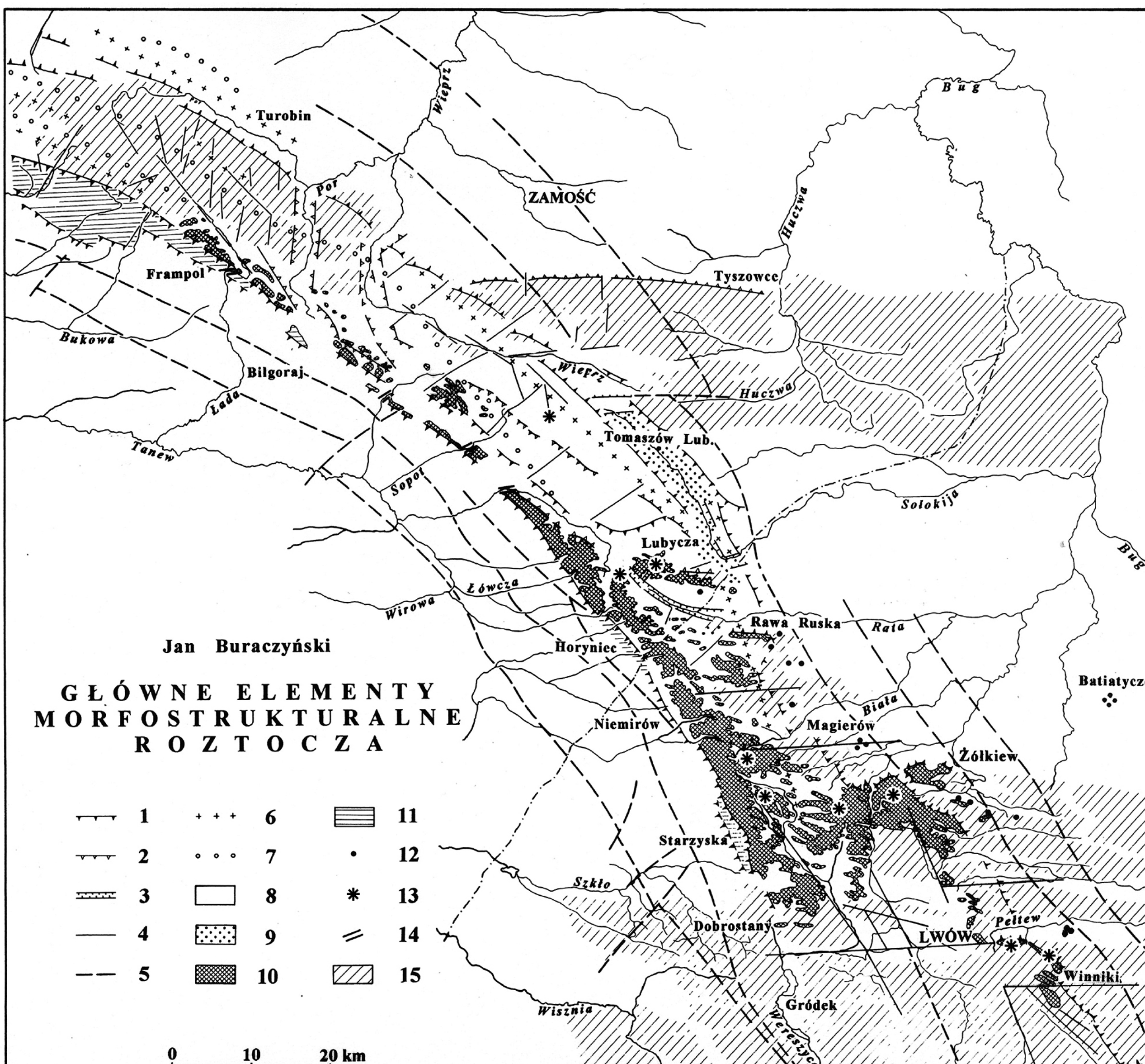

Fig. 3. Main morphostructural elements (Buraczyński 1997)

1 – fault-line scarps, 2 – escarpments on tectonic lines, 3 – trough faults, 4 – valleys in dislocations, 5 – main dislocations of the basement, 6 – axis of anticline, 7 – axis of syncline, 8 – Cretaceous plateau, 9 – rift valley filled with Eocene sands, 10 – Miocene table hills, 11 – structural step of Miocene limestone, 12 – residual blocks of Tertiary sandstone, 13 – residual hills, 14 – antecedent gap valleys, 15 – loess covers

oped in Roztocze (Ney 1969). In the Pliocene (Walachian phase), the pressure of the Carpathians again caused the activation of faults and elevation of Roztocze as a horst structure, as well as the development of numerous blocks and grabens (Jaroszewski 1977).

Morphological development of Roztocze

Relief development in the pliocene

The morphostructural analysis showed a considerable role of tectonics in the relief development. The Roztocze Upland constitutes a mosaic of blocks and depressions with a character of narrow valleys, grabens, or basins (Fig. 4). The area between the Gorajec River valley and the Tanew-Rata Rivers valley was the strongest dissected in the zone of intersection of the NW–SE and NNW–SSE dislocations. Various types of morphostructural relief developed: denudational, structural-denudational, and accumulation surfaces (Buraczyński 1980/81, 1997, Brzezińska-Wójcik 1997).

Research on vegetation in the Carpathians suggests climate cooling and drying proceeding in the Pliocene (Stuchlik 1980). The climate of the Pannonian was moderately warm and humid, periodically dry, with a mean annual temperature of 16°C. In the early Pliocene (Pont), moderate dry climate occurred, with a mean annual temperature of 7°C. In the Middle Pliocene (Dak), the climate was moderate, cool, and rather humid, and in the Late Pliocene (Roman), moderately warm and rather dry. Climatic transformations in the Pliocene were manifested in fluctuations in precipitation amount, resulting in the thinning of the forest cover in favour of steppe.

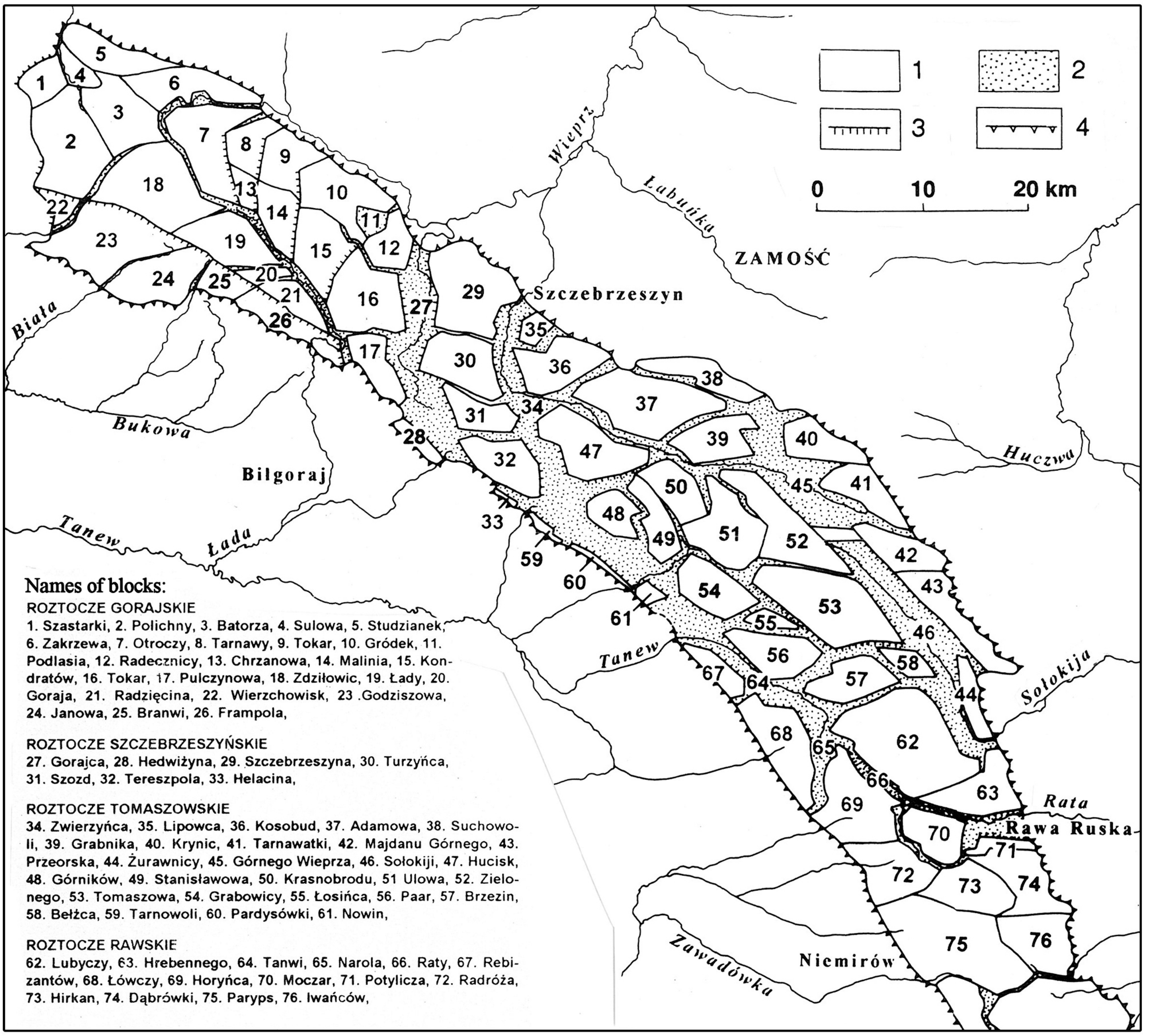

Fig. 4. Map of tectonic blocks and grabens in Roztocze relief (Buraczyński 1997)
1 – tectonic block, 2 – graben and valley, 3 – secondary tectonic edge, 4 – main tectonic edge

Planation surfaces/plateau levels

In the Pliocene, degradation processes in Roztocze led to the development of planation surfaces: the upper level (340–360 m a.s.l.) and lower level (300–320 m a.s.l.). The Oldest landforms are elevated above them as residual hills (Jahn 1956, Maruszczak, Wilgat 1956, Maruszczak 1972).

Detailed field research suggests that the issue of planation is complex. Plateaus built of opokas and marls are distinguished by high variability of resistance. Opoka outcrops develop several flat surfaces at various heights, sometimes emphasised by a structural scarp. The issue is additionally complicated by the development of block tectonics (Jaroszewski 1977) and uneven elevating movements (Brzezińska-Wójcik 1997). The role of tectonics in the development of the structural relief of Roztocze has been emphasised earlier (Buraczyński 1980/81), and confirmed by the latest geological research (SMGP 1992–2007). Therefore, the term plateau level is more applicable than planations.

The height of plateaus increases from north-west to south-east. In Roztocze Gorajskie, the upper plateau level (310–320 m a.s.l.) develops a narrow ridge in the axis of the hump, and the lower level (280–290 m) occurs in patches. The levels are covered with loess (Fig. 5). In the southern marginal zone, the plateau is developed by a structural as like-table (300–310 m a.s.l.) built of Miocene detrital limestones with elevated residual hills from Sarmatian reef limestones. (*map Turobin*).

In Roztocze Szczebrzeszyńskie, the upper plateau (330–340 m a.s.l.) is developed by a structural-denudational level in Cretaceous formations. Residual hill Góra Dąbrowa (343.8 m) and Tokarzowa Góra (343 m) rise above it. To the north, it is surrounded by the lower plateau level (300–310 m) in the form of narrow humps with a loess cover, and to the south, a structural flattening occurs in Cretaceous and Miocene formations (*map Szczebrzeszyn*).

In Roztocze Tomaszowskie, north of the Wieprz River valley, a well developed lower plateau level occurs (300–320 m) with a loess cover. The upper level (340–350 m) develops hills (Kamienna Góra) (Kurkowski 1993, 1994). In the axis of the hump, the plateau level develops a narrow ridge (Obrocz–Pasieki) built of opokas and gaizes. Wapielnia (386 m a.s.l.) rises above it, a residual hill of the oldest relief with a cover of Badenian reef limestone (map *Krasnobród*). To the south, a compact patch (5–10 × 20 km) of the lower plateau level occurs (300–320 m a.s.l.), confined to the south with an internal scarp (30-40 m) from Majdan Nepryski to Narol (Buraczyński et al. 1992, 2002, Buraczyński, Rzechowski 2007a, b).

In Roztocze Rawskie, the upper plateau level (350–360 m a.s.l.) is developed exclusively by Badenian detrital limestones (Popielski 1996, 2000, Rzechowski 1997, Rzechowski et al. 2008). It develops a structural surface with features of a like-table, extending in a belt (2–5 km) along the southern edge. Table hills or hillocks rise above it, representing the oldest relief of Roztocze: Wielki Dział 390.1 and Długi i Krągły Goraj 391.5 m a.s.l. (Fig. 6, *map Horyniec*). Residual hills are built of Miocene sands and sandstones with reef limestone in the uppermost layers. The lower plateau level occurs in patches, and in the zone of the southern edge it is developed by the structural level (320–330 m a.s.l.) built of lithotamnium-detrital limestones (Buraczyński et al. 1992, 2002, Popielski 1996, 2000).

Relief of escarpment zone

The development of the relief of the southern escarpment zone of Roztocze was largely determined by tectonic processes breaking it into a number of blocks (Jaroszewski, Piątkowska 1988, SMGP 1988–2007). Steps separated by faults developed along the southern edge. The varies re-

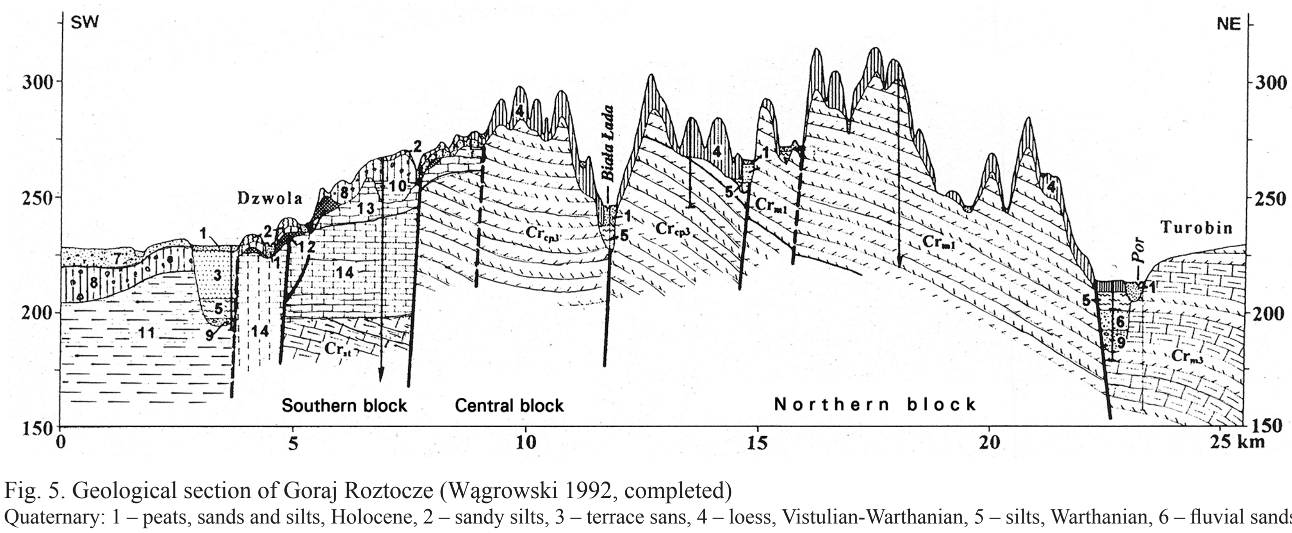

Fig. 5. Geological section of Goraj Roztocze (Wągrowski 1992, completed)
Quaternary: 1 – peats, sands and silts, Holocene, 2 – sandy silts, 3 – terrace sans, 4 – loess, Vistulian-Warthanian, 5 – silts, Warthanian, 6 – fluvial sands with gravels, 7 – fluvioglacial sands, 8 – till, Odranian, 9 – fluvial sands with gravels, Mazovian, 10 – till, Sanian 2. Neogene: 11 – claystones, 12 – reef limestone, Sarmatian, 13 – detrital limestone, Grabovian, 14 – lithotamnion limestone, Opolian-Wielician. Cretaceous: Crm3 – marls and opokas, Upper Maestrichtian, Crm1 – opokas, Lower Maestrichtian, Crcp3 – opokas, Upper Campanian, Crst – marls, Santonian

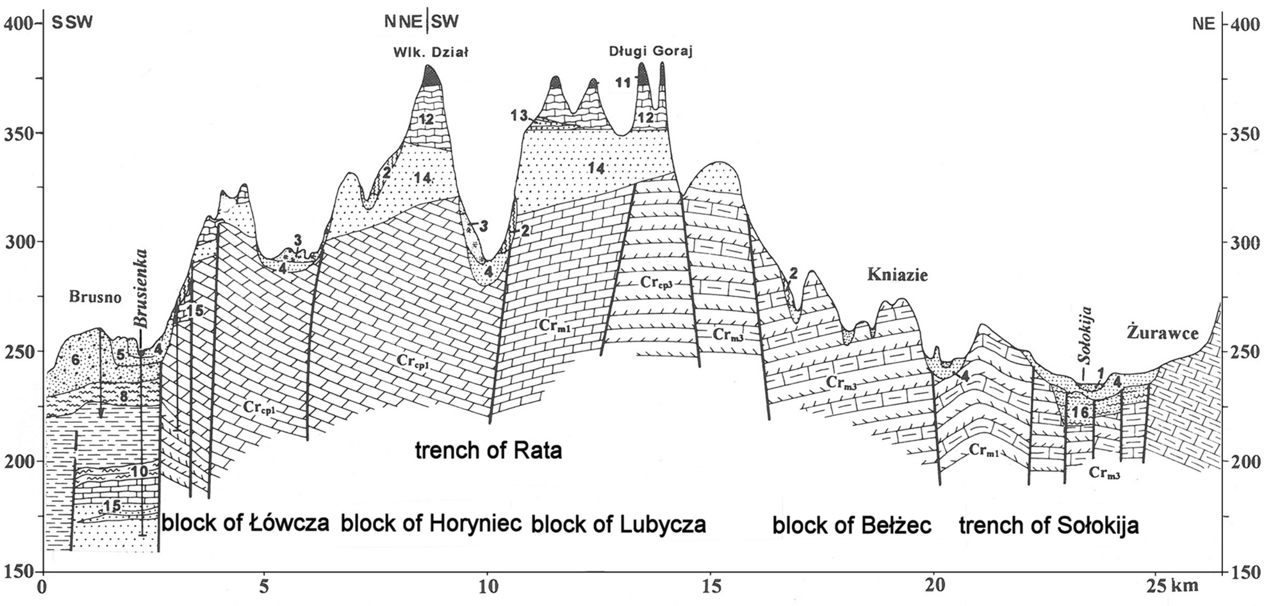

Fig. 6. Geological section of Rawa Roztocze (Popielski 1996 and Buraczyński, Rzechowski 2007)
Holocene: 1 – fluvial sands, 2 – slope sands. Quaternary: 3 – aeolian sands, 4 – terrace sands, Vistulian, 5 -fluvioperiglacial sands, Warthanian, 6 – glacial sands with gravels, 7 – till, Sanian 2, 8 – lake silts, Ferdynandovian. Neogene: 9 – mudstones, Sarmatian, 10 – clays, Grabovian, 11 – reef limestone, 12 – detrital limestone, 13 – lithotamnium limestone, 14 – sands and sandstones, 15 – limestone, sands and sandstones, Wielician+Opolian. Eocene: 16 – glauconitic sands. Cretaceous: Crm3 – marls and opokas, Upper Maestrichtian, Crm1 – gaize, Lower Maestrichtian, Crcp3 – gaize, Upper Campanian, Crcp1 – gaize, Lower Campanian

lief of the marginal zone is related to the occurrence of Miocene formations (lithotamnium-detrital limestones, reef limestone, and sands and sandstones).

In Roztocze Gorajskie, the southern marginal zone covers the internal scarp, step, and external scarp (*map Turobin*). The structural level 240–260 m a.s.l. is built of Miocene detrital and lithotamnium limestones. To the south, it is confined to the edge on the dislocation line (NW–SE) from Modliborzyce to Frampol. Lateral faults (SW–NE) divide the step into four blocks shifted in relation to each other (Buraczyński 2002, Wągrowski 1992, 1995). To the south-east, the structural level develops the block of Kajetanówka and Hedwiżyn (240 m a.s.l.). An residual hill of Sarmatian reef limestones rises above the step of Kajetanówka (Popielski 1994b).

In Roztocze Szczebrzeszyńskie, the zone of the southern edge comprises a belt of hills, internal scarp, marginal step, external scarp, and external hills (Maruszczak, Wilgat 1956, Buraczyński 1997).

The Tereszpol Hills (320–326 m a.s.l.) develop two lines of table hills and round hills built of reef limestones, lithotamnium limestones, and sandstones. To the south, they are confined to the external scarp with tectonic basis (*map Zwierzyniec*). The marginal step (270–280 m a.s.l.) is built of lithotamnium and detrital limestones confined by the external scarp with a height of up to 20 m. (Maruszczak, Wilgat 1956, Buraczyński 1980/81, 1997). The complicated image of development of the relief of the southern marginal zone suggests the lithological predisposition and a role of tectonic phenomena (Popielski 1994a).

In Roztocze Tomaszowskie, the marginal zone is distinguished by diversified relief. The main elements is the Górniki block with complicated geological and tectonic structure (Figs 7, 8, *map Józefów*). It is developed by Maestrichtian gaizes covered by Baden formations (10–30 m). The plateau (340–345 m a.s.l.) built of lithotamnium limestones develops a like-table hill confined with a structural scarp. To the south, it is accompanied by lower like-table hills (320–335 m a.s.l.). The Górników block is divided into smaller units with longitudinal NW–SE faults and lateral SSW–NNE faults (Musiał 1987).

The in Late Baden, intensified tectonic activity caused the development of normal faults in a steps system and antitetic rotation. Biogenic limestones developed on the steps, and sandy sediments and detrital limestones in other places. At the beginning of the Sarmatian, tectonic movements in the basin of the external trough intensified. An increase in horizontal stresses was accompanied by the development of oblique-slip faults. The renewal of fault steps and the accompanying longitudinal grabens caused an increase in denivelation. A bank developed along the internal scarp, and a belt of barrier accumulation along the external scarp. The Pardysówki Hills constitute a primary form of barrier accumulation, and the Padół Józefowski covers the badenian fault step and the scarp of antitetic blocks (Jaroszewski 1977).

In Roztocze Rawskie, the zone of the southern scarp covers the Huta Różaniecka bank neighbouring with the Tanew River valley to the north (*map Tomaszów, Horyniec)*. The upper structural level (300–320 m a.s.l.) is built of detrital limestones. A lower level occurs locally (280–290 m a.s.l.), hearing Campanian gaizes. To the south, Roztocze Rawskie determined the internal scarp with tectonic basis with a height of 10–15 m. To the east, it neighbours with the Bug River basin. Residual Kiczera hill 318 m a.s.l. rises above the scarp with a denudational level 250 and 270 m a.s.l., shearing marls (*map Hrebenne*), (Rzechowski et al. 2008)

Relief development in the Pleistocene

At the turn of the Pliocene and Eopleistocene, in the Walachian phase, the Carpathians with the forefield were elevated. Favourable climate conditions were an impulse for the development of valleys (Table 2). This is evidenced by erosional terraces (30 and 60 m) on the slopes of the Gorajec and Wieprz River valleys (Maruszczak, Wilgat 1956). In the Eopleistocene (Rożce and Ponurzyce horizons), intensive deep erosion occurred of Gorajec and Wieprz River flowing from the Sandomierz Basin. In the Older Quaternary, the valleys were deeper than currently by 50–70 m (Fig. 9).

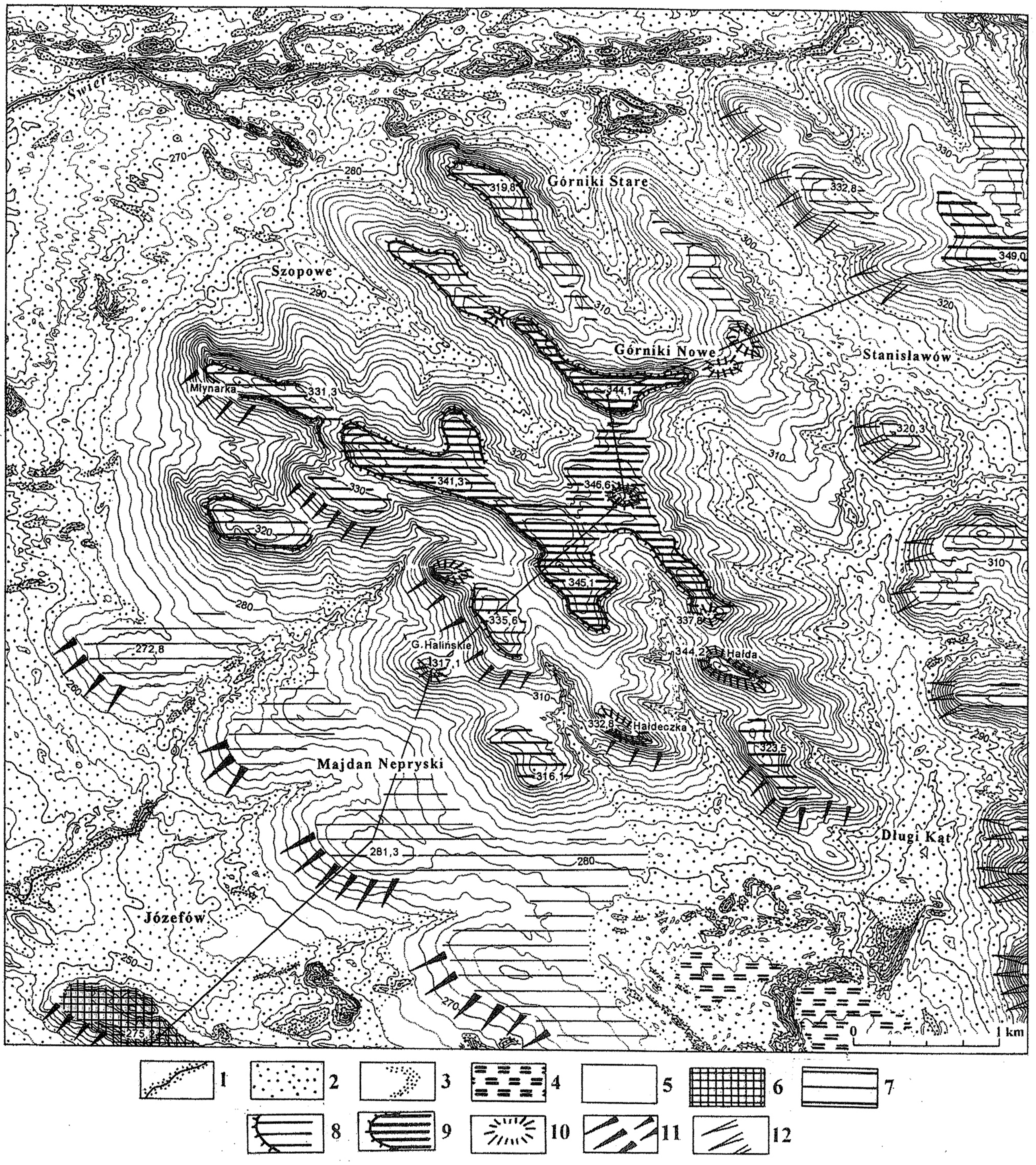

Fig. 7. Geomorphological map of Górniki block (Buraczyński 2002)
1 – valley floor, 2 – accumulation terrace and dry valley floor, 3 – dunes, 4 – blow-out depressions with peat, 5 – slopes, 6 – escarpment hills (280 m) in limestone, 7 – denudation surface of escarpment zone (270–280 m), 8 – lower surface, table-like hills (320–330 m), 9 – high structural surface, (340–350 m), 10 – residua hills, 11 – fault-line scarps, 12 – fault slopes; contour interval every 2,5 m

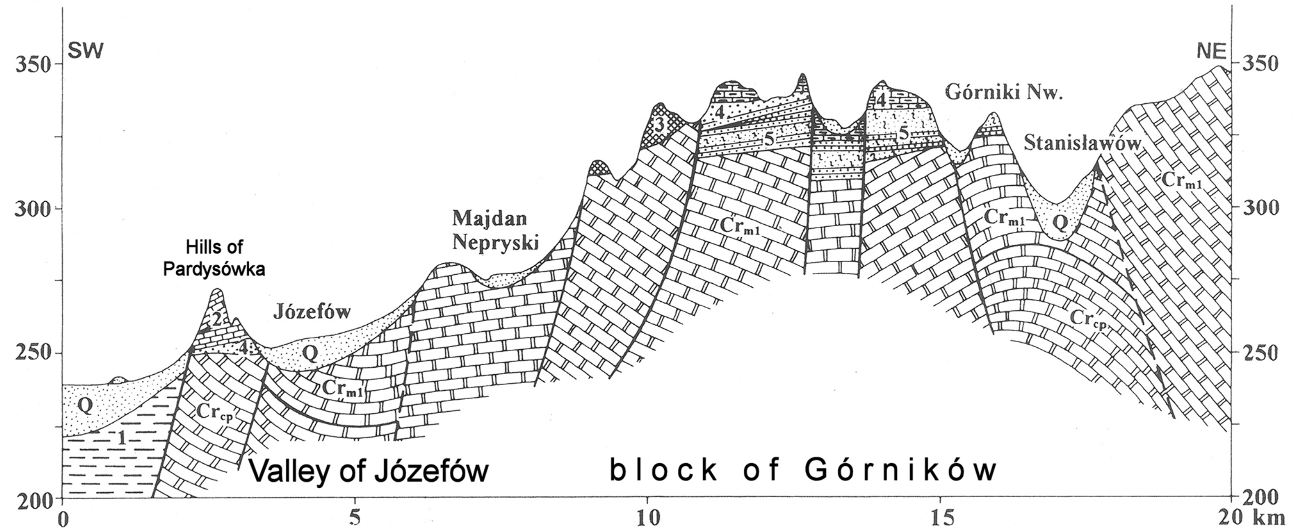

Fig. 8. Geological section of block Górniki (elaborated after Musiał 1987)
Q – Quaternary. Neogene: 1 – claystones and mudstones, Sarmatian, 2 – detrital limestone, 3 – reef limestone, 4 – sands and sandstones, 5 – glauconitic sands, Badenian. Cretaceous: Crm1 – gaize, Lower Maestrichtian, Crcp – gaize, Campanian

In the cold Otwock horizon, the aggradation phase occurred and filling the valleys with fluvial series composed of sands and Cretaceous gravels (Fig. 10) corresponding with the Krasnystaw series (Mojski 1964). They were recorded in the fossil valleys of Pre-Gorajec in the Sandomierz Basin (Laskowska-Wysoczańska 1981) and in Roztocze in Tarnowola, Gorajec, and Sąsiadka (Kwapisz 1998, Marszałek et al. 2000), as well as in the Pre-Wieprz River valley in Zwierzyniec (Buraczyński 2002).

In the warm Celestynanian horizon, limnic muds were deposited, suggesting obstructing flow in the Pra-Gorajec River valley (Kurkowski 1994). Intensifying neotectonic movements caused the elevation of the Hedwiżyn block and scarp near Józefów, and separated the upper basin of Pra-Gorajec and Pra-Wieprz. The discontinued connection with the upper basin caused draining Roztocze southwards.

Relief development in the Mesopleistocene

Roztocze and the Sandomierz Basin from the times of the first glaciations (Narew and San 1) and interglacial periods (Augustovian and Ferdynandovian) have scarce data permitting the presentation of the overview of the palaeogeography of the area.

During the Narevian Glaciation (850–720 ka BP), Roztocze was located in the periglacial zone, and was subject to weathering and denudation. In the valleys, fluvial accumulation of sands occurred. The sands at the boundary of Roztocze and in the Gorajec River valley were dated TL for 732 and 755 ka BP (Popielski 1994).

In the Augustovian Interglacial (720–680 ka BP), the activity of erosional processes was manifested in grooving and deepening of river valleys. In Roztocze in the Gorajec and Wieprz River valleys, sands and fluvial-overbank muds were deposited (Kurkowski 1993, Marszałek et al. 1995).

During the Sanian 1 Glaciation (680-580 ka BP), the ice sheet entered the Sandomierz Basin through the Polish Uplands and the Vistula River gorge. In the Sandomierz Basin, till has been preserved in deep valleys (Laskowska-Wysoczańska 1992, Popielski 1994). Roztocze was then located in the periglacial zone.

The Ferdynandovian Interglacial (580–520 ka) is determined by fluvial-overbank muds in the Pre-Wieprz River valley (Kurkowski 1994), and those deposited in depressions along the boundary of Roztocze (Popielski 1994).

Relief development during the Sanian 2 Glaciation

During the Sanian 2 Glaciation (520–420 ka BP), the ice sheet with a thickness of several hundred metres covered Roztocze and the Sandomierz Basin, reaching the Carpathians. During the overthrust, the ice sheet had high exaration strength. This was manifested in continuous collection of material from the substrate. The contribution of local material from Cretaceous and Miocene substrate in moraine till increased.

The presence of the ice sheet in Roztocze and the Sandomierz Basin is evidenced by post-glacial sediments preserved in valleys. In Roztocze Gorajskie, glacial formations occur on the surface in the marginal zone between Janów Lubelski and Frampol (Buraczyński 2002). The surface till in the vicinity of Hedwiżyn and Tereszpol are periglacially impoverished in the silty-loamy fraction (Popielski 1994). In the Tanew and Sołokija River valleys, fluvioglacial sands occur (Buraczyński et al. 2002).

In the Sandomierz Basin, large patches of the till occur on the surface on the Tarnogród and Lubaczów Plateau (*map Biłgoraj, Horyniec*). Between Huta Różaniecka and Brusno, the southern boundary of Roztocze Rawskie is ad-

Table 2. Occurrence of some processes and their effects in Roztocze during the Quaternary (Buraczyński 2013, stratigraphy by Mojski 2005, intensity of neotectonic movements by Baraniecka 1983)

AGE x 1000	STRATIGRAPHY Glaciation Interglacial		NEO-TECTONICS	PROCESSES	SEDIMENTS
	Holocene	NEOPLEISTOCENE		Erosion and fluvial accumulation	Fluvial sands, peats
115	VISTULIAN			Aeolian processes Loess accumulation Periglacial weathering and denudation Fluvial accumulation in valleys	Eolian cover sands and dunes Younger loess – Goraj and Szczebrzeszyn Roztocze; Fluvial terrace sands Slope and valley sands
130	Eemian			Soil processes; deep erosion	Fossil soil
180	WARTHANIAN			Periglacial conditions: Loess accumulation Weathering and slope denudation Fluvial accumulation	Older loess on N slope of Roztocze Muds in valleys and basins (Podlesie) Terrace sands in S zone of the edge
240	interstadial Lublinian			Soil processes	Fossil soil
305	ODRANIAN			Transgression of ice sheet reaching the West edge of Goraj Roztocze Aeolian accumulation	Till and fluvioglacial sands (Brzozówka, Godziszów, Frampol) Marginal lake muds (Szastarka, Podlesie) Oldest loess (Błażek, Zamość Basin)
	interstadial Zbójno			Flood and limnic accumulation	Fluvial muds (Wieprz valley) Limnic muds (Podlesie Basin)
360	LIWIEC stadial			Weathering and denudation	Moraine pavement on plateaus
420	Mazovian	MESOPLEISTOCENE	■	Fluvial accumulation Intensive deep erosion	Fluvial sands (Gorajec, Tanew, Wieprz) Development of latitudinal Wieprz valley
520	SANIAN 2			Ice sheet transgression covers Roztocze and Sandomierz Basin	Till (in Wieprz and Tanew valley and Sandomierz Basin). Fluvioglacial in Gorajec valley. Kames and eskers (Komarów)
580	Ferdynandovian		■	Denudation and accumulation	Fluvial-flood muds (Pre-Wieprz)
680	SANIAN 1			Ice sheet transgression	Fluvioglacial Till in Sandomierz Basin
720	Augustovian			Fluvial erosion and accumulation	Limnic muds Fluvial sands and gravels, waterflood clayey sands (Pre-Wieprz valley)
850	NAREWIAN (MENAPIAN)		■	Weathering and slope denudation in periglacial conditions	Stagnant muds
	Warm period Celestynonian (waalian)	EOPLEISTOCENE	■	Fluvial-flood accumulation	Limnic muds (Pre-Wieprz)
1400	Cold period OTWOCK (EBURONIAN)			Development of Gorajec and Wieprz valley: Fluvial accumulation	Fluvial sands and gravels – Krasnystaw series in Pre-Gorajec and Pre-Wieprz val. Sandomierz Basin - Korytków
	Warm period Ponurzycanian (tiglian)			Intensive erosion and denudation	Denudation-erosional terrace 30 m in Gorajec and Wieprz valley
1750	Cold period ROŻCE (PRETIGLIAN)			Intensive erosion and denudation	Denudation-erosional terrace 60 m in Gorajec and Wieprz valley
	PLIOCENE		■		

jacent to the undulating moraine plateau and sandy-gravel hills with a height of 5–7 m (Popielski 2000).

In the Sandomierz Basin, deglaciation was of areal character. Meltwaters from the stagnant glacier flew westwards. Ice blocks remaining in valleys and on plateaus developed lakes, creating lakeland landscape (Laskowska-Wysoczańska 1992). A trace of post-glacial sediments is till with a current thickness of up to 25 m (Kurkowski 1995a). The undulating moraine plateau adjacent to Roztocze Rawskie was dissected into a number of patches.

Relief development in the Mazovian Interglacial

In the Mazovian Interglacial (420–360 ka BP), after the retreat of the ice sheet, the depressurisation of the rock mass caused long-lasting erosion and exposure of original valleys. High denivelations favoured intensive denudation and removal of glacial sediments. On plateaus, traces of the Sanian 2 Glaciation are residuals of till (Buraczyński et al. 2002). In the Wieprz and Gorajec River valleys, fluvial sediments developed. A new river system developed connected with the basin of the San, Wieprz, and Bug Rivers.

In the Mazovian Interglacial, basins developed with a diameter of approximately 1 km with tectonic basis in Majdan Sopocki (Kurkowski 1998), and in Podlesie on the intersection of faults, as a neotectonic landform (*map Józefów and Turobin*). The discussed basins are filled with limnic muds (Buraczyński 2002, Marszałek et al. 2000).

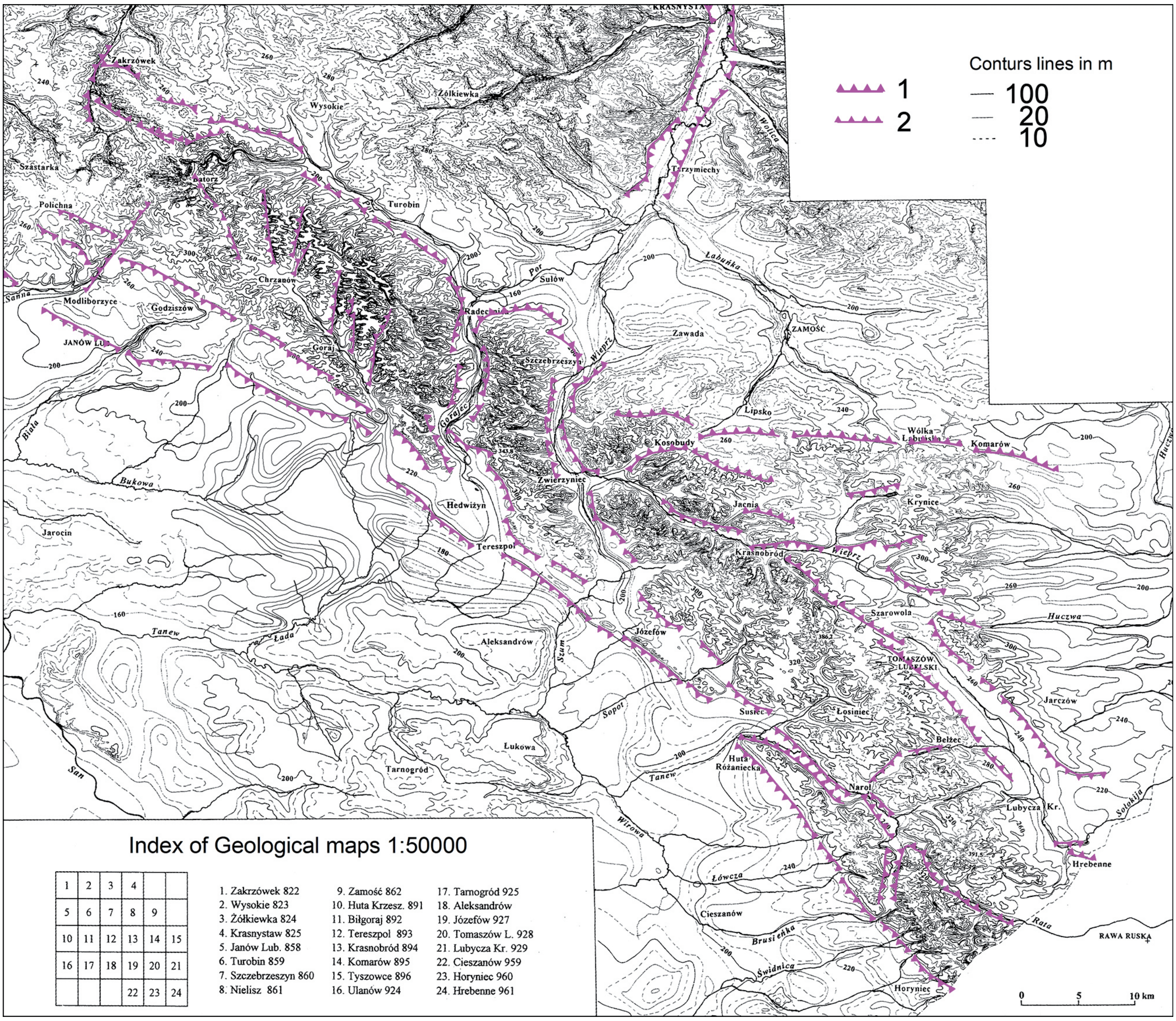

Fig. 9. Relief of Subquaternary surface of Roztocze and environs (united Buraczyński 2013)
1 – escarpment on tectonic lines, 2 – escarpment in fault slopes

Relief development during the Odranian Glaciation

Odranian Glaciation (305–240 ka BP)

In the periods of its maximum range, the ice sheet reached the Lublin Upland, and then entered the depression of the Vistula River valley. The elevated ice sheet between the Małopolska Upland and Roztocze entered the Sandomierz Basin with the tongue. The range of the ice sheet is determined by the western boundary of Roztocze Gorajskie. Roztocze was now located in the direct contact with the terminus of the ice sheet on line Studzianki–Godziszów–Frampol (Buraczyński, Superson 1998).

The marginal zone of the ice sheet is determined by subglacial kame hills and eskers developed in the dead ice environment. Blocking the outflow of meltwaters caused the development of a postglacial stagnant lake near Polichny (Fig. 11, *map Janów*). In the period 255–240 ka BP, muds were deposited there (Buraczyński, Butrym 1989). In the marginal zone of Roztocze Gorajskie, during the areal deglaciation, a dead ice moraine developed. Waters from melting ice in the Sandomierz Basin deposited fluvioglacial sands, and in the Gorajec River valley, along the internal scarp of Roztocze (*map Zwierzyniec*), they developed an erosional-accumulation terrace with a height of 10–20 m (Popielski 1994, 2000). On the northern slope of Roztocze Gorajskie and Szczebrzeszyńskie, older loess was deposited directly on the Cretaceous substrate or on till of the Sanian 2 Glaciation (Marszałek et al. 2000).

Lublin Interstadial (240–220 ka BP)

In the climate optimum, moderately cool climate occurred (Janczyk-Kopikowa 1991). Podzolised brown soil developed on older loess. It was recorded in a number of loess profiles (Łanczont, Wojtanowicz 1999, Marszałek et al. 2000). In the Gorajec and Wieprz River valleys, muds were deposited dated for 212 ka BP (Marszałek et al. 2000). A peatland developed in place of the lake in Polichna (Buraczyński et al. 1986).

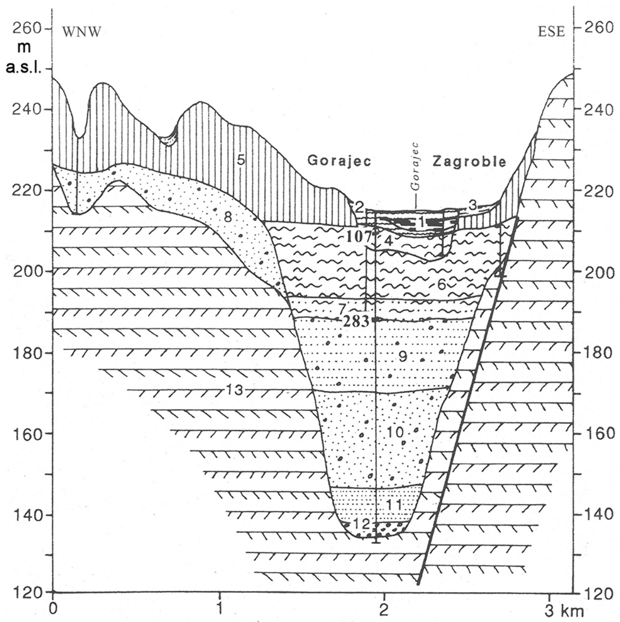

Fig. 10. Geological section of the Gorajec valley (Marszałek et al. 2000, changed)
Quaternary: 1 – peats, 2 – silts, 3 – slope silts, Holocene, 4 – fluvial silts, Eemian, 5 – loess, Vistulian, 6 – lake silts, Warthanian, 7 – fluvial sands, Lublinian, 8 – fluvioglacial sands, Odranian, 9 – fluvial sands, Mazovian, 10 – fluvioglacial sands, Sanian 2, 11 – fluvial sands, Augustovian, 12 – gravels, Preglacial, Cretaceous: geCrm1 – gaizes, Lower Maestrichtian

Warthanian Glaciation (220–135 ka BP)

During the Warthanian Glaciation, Roztocze was located in the periglacial zone, and was subject to intensive weathering. Denudation caused the degradation of older loess covers. Products from slopes were transported to valleys, where fluvial-overbank muds were deposited. In the river valleys of the escarpment zone of Roztocze, accumulation of sands prevailed (Buraczyński et al. 2002). Lakes near Polichna (*map Janów*) and Podlesie (*map Turobin*) were activated again, and loamy-silty muds were deposited in them (Buraczyński et al. 1986, Marszałek et al. 2000).

On the northern slopes of Roztocze Gorajskie and Szczebrzeszyńskie, older loesses developed with a thickness of 4–10 m (Marszałek et al. 2000). Three evident periods of blowing dust are distinguished: lower loamy loess (225–200 ka BP), middle non-weathered loess (195–175 ka), and upper carbonate loess (180–135 ka BP), (Maruszczak 1987).

Eemian Interglacial (130–115 ka BP)

The climate of the interglacial was increasingly warm, transitioning to moderate. At the beginning of the optimum, deciduous forests were predominant. It was followed a cooling with spruce and fir, and then pine and birch forests (Mamakowa 1989). On loess, leached forest brown soil or luvic soil developed (Maruszczak 1987). Interglacial soil was recorded in a number of loess profiles on the northern slope of Roztocze (Fig. 12).

In the interglacial, strong denudation and deep erosion occurred. The sediments of the Odranian and Warthanian glaciations were locally entirely removed from valleys. Deepening of channels stopped as a result of intensified denudation of slopes and accumulation if mineral sediments in valleys, as well as gradual elevation of valley floors (Jahn 1956). In the Wieprz River valley near Rozłopy, an Eemian valley was recorded grooved 15 m into the sediments of the Warthanian glaciation. The fos-

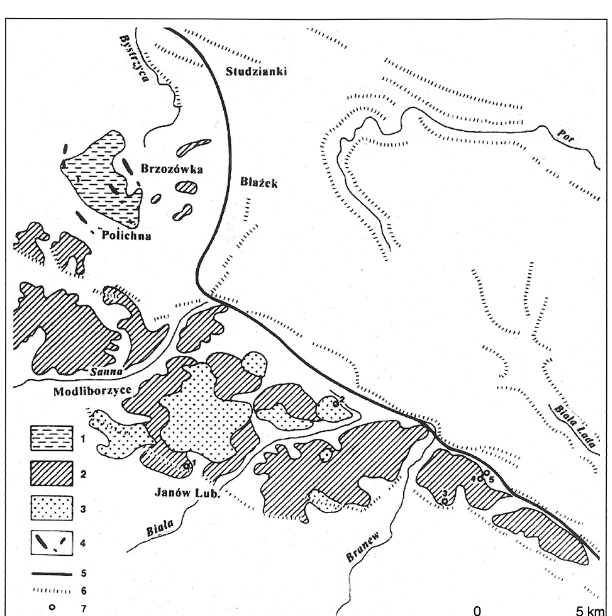

Fig. 11. Extent of the Odra Glaciation in Goraj Roztocze (Buraczyński, Superson 1998)
1 – lake clays, 2 – till, 3 – fluvioglacial sands, 4 – kames and eskers, 5 – maximal extent of the glacier, 6 – morphological edges, 7 – drill holes

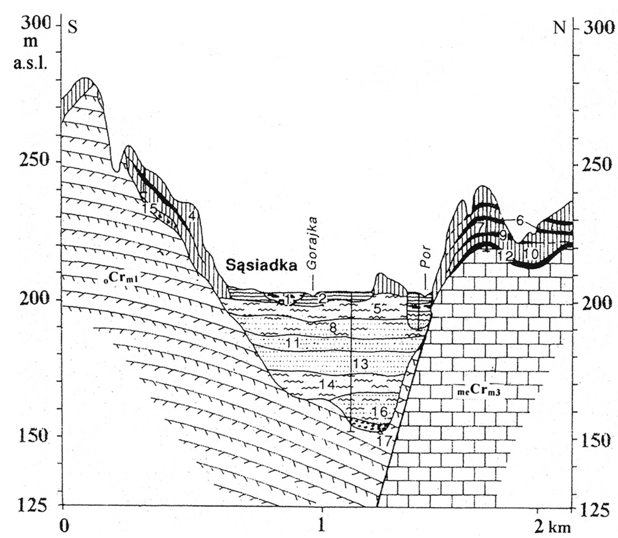

Fig. 12. Section of the Por valley (Marszałek et al. 2000, changed)
Quaternary: 1 – peats, 2 – silts, 3 – fluvial sands, Holocene, 4 – younger loess, 5 – fluvial silts and sands, Vistulian, 6 – forest soil, Eemian, 7 – older loess, 8 – fluvial sands and silts, Warthanian, 9 – soil, Lublinian, 10 – oldest loess, 11 – fluvial sands, Odranian, 12 – rendzina soil, 13 – fluvial sands, 14 – lake silts, Mazovian, 15 – till, Sanian 2, 16 – fluvial sands, Augustovian, 17 – gravels, Preglacial. Cretaceous: meCrm3 – marls, Upper Maestrichtian, oCrm1 – opokas, Lower Maestrichtian

sil valley is filled with fluvial sands with gravels transitioning into muds dated by the TL method for 98 ka BP (Marszałek et al. 2000).

Relief development during the Vistulian Glaciation

In the last glacial cycle, Roztocze was located in the periglacial zone. The cyclical character of climate changes, cooling-warming, caused short-term environmental changes. Periglacial morphogenesis favoured the production of clastic material which was removed from slopes to valleys by means of gravitational, water, and eolian transport. The Vistulian Glaciation covers the Radunka Interstadial, Świecie Stadial, Grudziądz Interstadial, Main Stadial, and Late Glacial (Mojski 2005).

The Radunka Interstadial (115–75 ka BP) determines the beginning of the last cold horizon with variable climate conditions. Vistulian 1 and 2 was distinguished by tundra with longer periods of cooling (mean temperature in July ~10°C and January ~0°C). They were interrupted by the brörup and odderade warming with boreal climate (mean temperature in July 15°C) and development of birch and pine to pine and spruce forests (Mamakowa 1989).

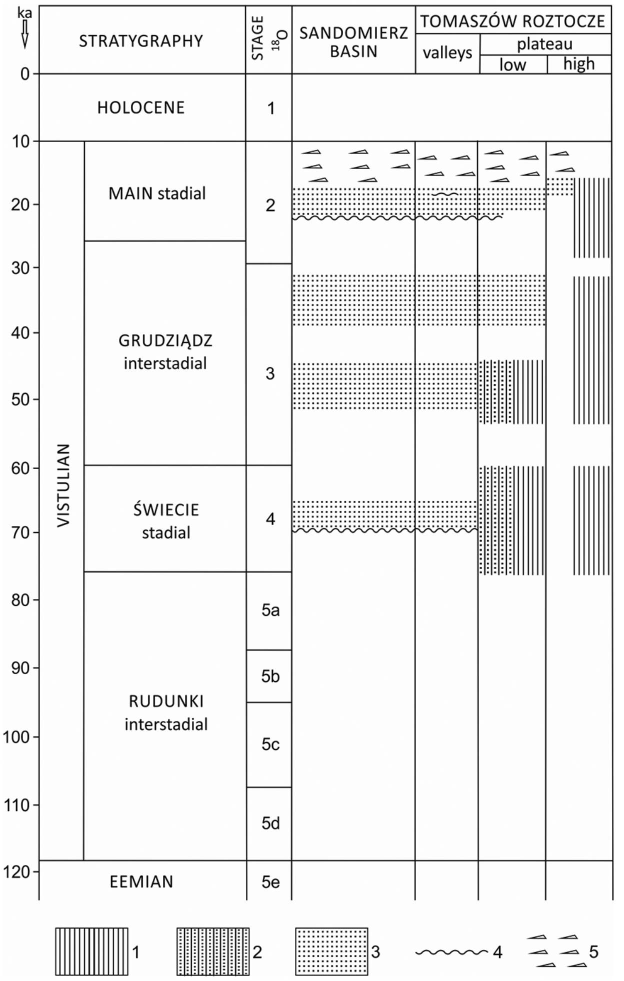

Fig. 13. Eolian accumulation in periglacial zone of the Vistulian in SE Poland (Buraczyński 1994)
1 – loess, 2 – sandy loess, 3 – eolian coversands, 4 – deflation surface, 5 – dunes

In the cool period (Vistulian 2) on Roztocze Gorajskie and Szczebrzeszyńskie, loess accumulation developed. In periods of climate warming, humic soil developed on loess (Jersak 1973).

In the Świecie Stadial (75–58 ka BP) in Central Poland, Subpolar and dry climate occurred with a mean annual temperature from –2°C to −4°C (Maruszczak 1987) and steppe-tundra (Mamakowa 1989). In the periglacial zone, the main processes included weathering and blowing dusts to uplands. The area of deflation was located to the north from where dust was blown by winds from various directions (Mojski 2005). On Roztocze Gorajskie and Szczebrzeszyńskie, lower younger loess was deposited (Maruszczak 1987). Simultaneously with the accumulation of loess on plateaus and slopes, slope covers and periodical rivers developed in valley floors (Fig. 13).

A transitional zone between loess and sand accumulation occurs near Tomaszów Lubelski. The hump of Majdan Górny (320–350 m a.s.l.) is covered by typical loess, and low humps by sandy loess neighbouring with eolian cover sands. This suggests high dynamics of eolian processes on the boundary of accumulation of dusts and sands (Buraczyński 1994). In the southern part of Roztocze, slopes were subject to weathering and denudation. Valleys were buried with slope sands, subsequently deposited on valley floors by periodical rivers. Slope and river formations accumulated this way developed the main terrace on Roztocze (Buraczyński 1998).

In the Grudziądz Interstadial (58–25 ka BP), rapidly changing climate conditions occurred, from boreal to subarctic. Short periodical climate warmings (oerel, moershoofd ~43 ka, hengelo ~35 ka, and denekamp ~29 ka BP) were distinguished by an increase in the mean temperature of July of up to 10°C, and mean annual temperature from 0°C to –2°C (Jersak et al. 1992).

On Roztocze Gorajskie and Szczebrzeszyńskie in the Hengelo-Denekamp period, a weathering horizon developed on loess in the form of initial Subarctic gleyed brown soil (Maruszczak 1987). In the Pleniglacial at the beginning of summer, the northern slopes were subject to denudation. Precipitation and melt waters flowing freely on a frozen slope supplied high amounts of material of the flood fraction to the valley floor. On the northern forefield of Roztocze in the Wieprz and Por Rivers, intensive accumulation of loess of aquatic origin occurred, developing the middle terrace (Harasimiuk, Szwajgier 1985, Jersak et al. 1992, Starkel et al. 2007).

The middle terrace of the Wieprz River reaches the greatest height in the subslope part and at side mouths of dry valleys. In the Por River valley, it was a width of 2 km, and at the mouth of the Wieprz River, it widens to 5 km (*map Szczebrzeszyn*). The surface of the terrace includes depressions with a depth of up to 3 m, width of several tens of meters, and length of up to 1 km. They constitute remains of former river channels developed in the end stage of development of the terrace (Jersak 1991).

In the southern part of Roztocze Szczebrzeszyńskie and in Roztocze Tomaszowskie, small river valleys were buried with sand originating from slope denudation. Periods of climate warming were manifested in the accumulation of muds with laminae of organic formations in the Wieprz River valley (Fig. 14), (Starkel et al. 2007). In the fossil Łada River valley with a mouth to the Bukowa River valley, in dead channels, peats were recorded from the period of moershoofd-denekamp warming, as suggested by the TL dating from 48 to 31 ka BP (Buraczyński, Butrym 1989).

The Main Stadial (25–14.3 ka BP) on the Polish Lowland was distinguished by stops of the ice sheet terminus in the Leszczyńska, Poznańska, and Pomeranian phase. The last overthrust of the ice sheet in the north of Poland occurred in the period of approximately 22–20 ka BP. The evolution of the relief of Roztocze was related to the periglacial zone, distinguished by the deepest climatic crisis. In the period of the maximum cold, the mean temperature in July amounted to 2–3°C, and mean annual temperature to −6°C, and subpolar climate occurred (Goździk 1994). Roztocze was located in the zone of permafrost which after the Pomeranian phase (approximately 14 ka BP) occurred in patches, with a very thick active layer (Mojski 2005).

The deep climatic crisis played a particular role in the development of young eolian covers. The periglacial zone is distinguished by the belt character of eolian processes (Dylik 1967, Starkel 1988), differentiated into the silty and sandy fractions. The accumulation of eolian fractions varied in terms of space occurred simultaneously. Winter sedimentation was caused by strong north-eastern gravitational winds, and in summer by variable winds (Goździk 1991).

The loess zone occurs as a compact cover in Roztocze Gorajskie and Szczebrzeszyńskie, and in patched in Roztocze Tomaszowskie (Fig. 15). Upper younger loess with the highest thickness and content of carbonates was deposited in the severe Arctic climate, in the period 22–15 ka BP (Maruszczak 1987).

Periglacial denudation was proceeding more rapidly in loess areas, prone to washing and solifluction. Characteristic groups of landforms developed: valley sides, dry valleys, and denudational-accumulation humps. Narrow loess humps determine plateaus elevated from 290 to 340 m a.s.l. Dry valleys reflecting the relief of the bedrock develop strongly branched systems with a length of several km, depth of 20–60 m, and floor width of 10–50 m.

In the Wieprz River valley at the beginning of the Main Stadial, the valley floor was buried with slope material. A terrace was developed by braided rivers with a high contribution of loess silt (Buraczyński, Superson 1996). In the neighbouring dry valleys, a 5 m filling with silts was recorded, dated for 25–21 ka BP (Gawrysiak, Zagórski 1998). Accumulation developed with varied intensity until the end of the stadial. It resulted in the development in the valleys of the most common accumulation terrace in the entire belt of Polish uplands (Mojski 2005).

The sandy zone covers the Sandomierz Basin and the Bug River Basin, as well as the part of Roztocze located within the belt (Fig. 15). On the southern slope of Roz-

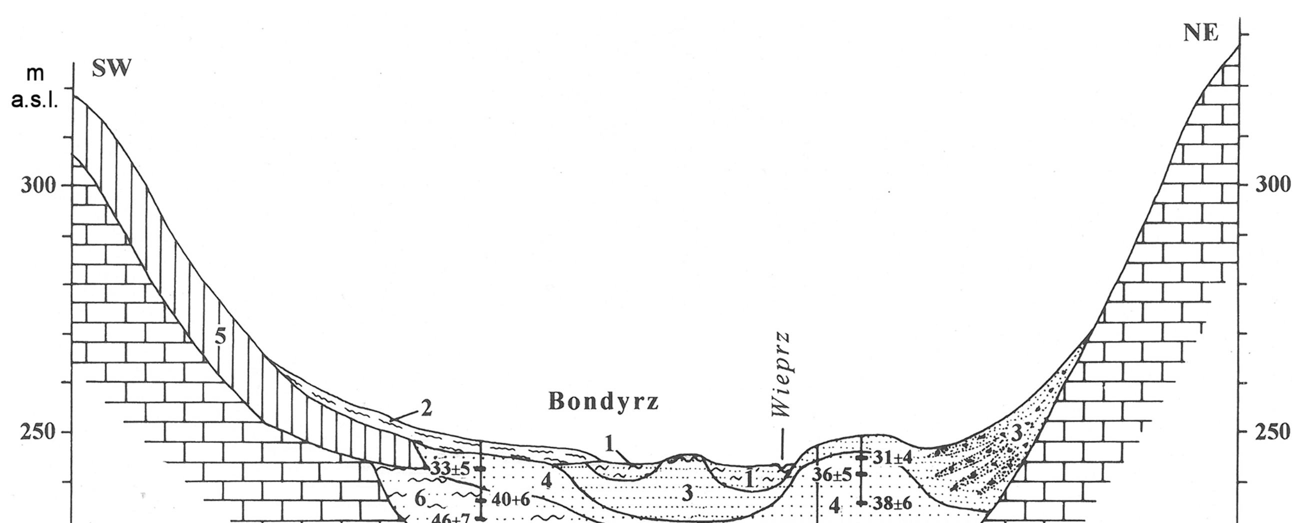

Fig. 14. Section of the Wieprz river valley (Buraczyński 2002)
Quaternary: 1 – sands and silts, 2 – silts of alluvial fan, Holocene, 3 – terrace sands, Pleniglacial, 4 – fluvial sands, 6 – sandy silts, Grudziądz Interstadial, 5 – loess, Vistulian, 7 – fluvial sands, Świecie Stadial, 8 – silts, Warthanian, 9 – fine sands with limestone gravels, Mazovian, 10 – gravels, Sanian 2. Cretaceous: 11 – gaizes, Maestrichtian. Age TL in ka

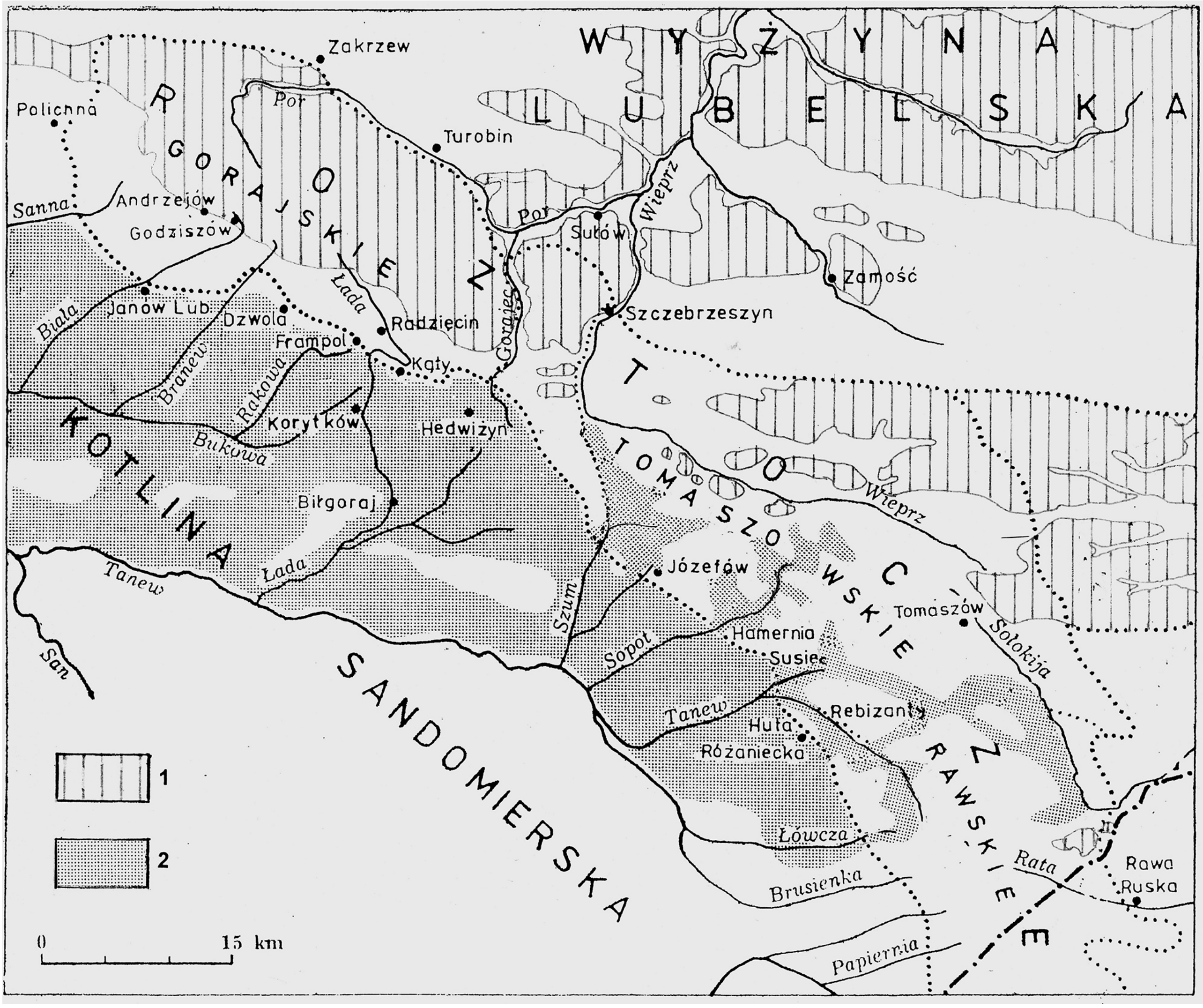

Fig. 15. Distribution of loess cover in Lublin Upland and Roztocze Upland (Maruszczak 1961), and sand cover in Sandomierz Basin and in Roztocze (Buraczyński and Butrym 1989)

tocze, weathering processes supplied high amounts of materiel accumulated in depressions by fluvial-slope and niveo-eolian processes (Superson 1983). Aerodynamic conditions occurred in the basin, favouring high activity of western wind. Dry sand was subject to multiple transport from valleys to the plateaus of Roztocze. This is suggested by a high content of quartz grains with advanced eolian processing in the sandy covers (Buraczyński 1998).

In the mouths of river valleys from Roztocze, alluvial fans developed. Together with slope formations, they developed a sandy plain extending along Roztocze with a belt with a width of approximately 15 km. A large alluvial fan of the fossil Łada River valley was recorded in the mouth from Roztocze (*map Biłgoraj)*. Its development began in the Main Stadial, and was completed in the Late Glacial (Fig. 16). In the younger part of the Main Stadial (18–16 ka BP), increased deep erosion was recorded, caused by slow degradation of permafrost releasing small amounts of water (Mojski 2005).

Late Glacial (14.3–10 ka BP)

In the Late Glacial, permafrost degradation was manifested on the surface of upper younger loess in the development of thermokarst. Thermokarst and thermoerosion played an important role in the development of slopes. This was accompanied by intensified solifluction smoothing slopes. This was the beginning of the transformation of the relief of loess areas (Jersak et al. 1992). Slope denudation favoured the accumulation of high amounts of material in valley floors.

Eolian processes initiated in the Main Stadial developed intensively in cold periods of the Late Glacial: in the Oldest Dryas (14.3–12.4 ka BP) and Older Dryas (12.1–11.8 ka BP), interrupted by short-term Bølling warming.

In the Allerød (11.8–10.7 ka BP), climate warming and an increase in humidity favoured the formation of weakly developed soil with eluvial-accummulation horizon A_1 and thin podzolisation A_2 (Manikowska 2002). The climate conditions contributed to an increase in the level of groundwaters. In deflation depressions, lakes developed

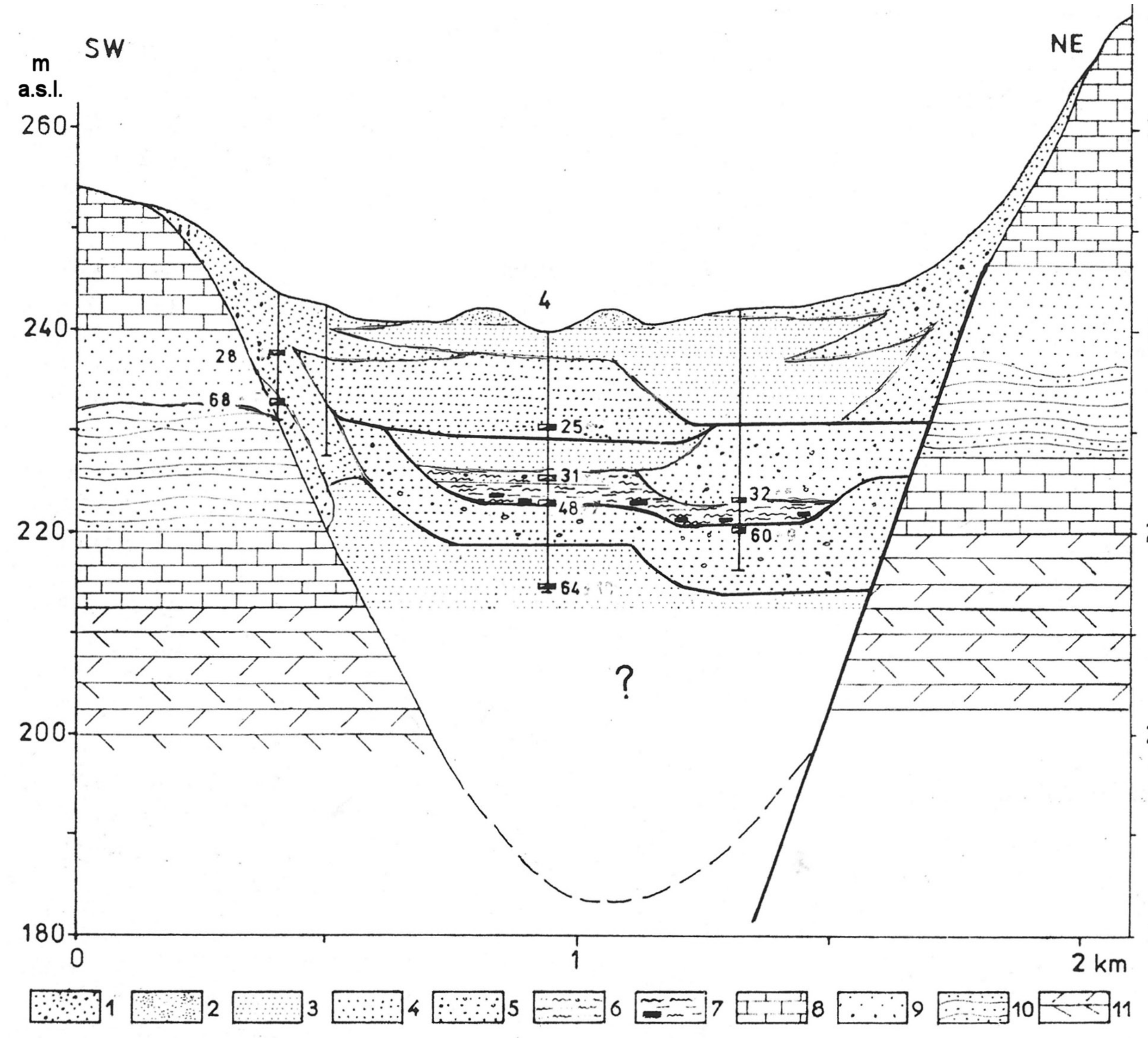

Fig. 16. Section of the fossil Biała Łada valley, near Kąty (Buraczyńskiego, Butryma 1989)
Quaternary: 1 – slope sand, 2 – aeolian sand, 3 – fine sand, 4 – medium sand, 5 – sand with limestone gravels, 6 – silt, 7 – silts with peat. Miocene: 8 – detrital limestones, 9 – sands, 10 – sandstone. Cretaceous: 11 – gaize, Campanian; TL age in ka

in Hamernia, Tarnawatka, and Krasnobród, where gyttja sedimentation began 11780 years BP (Bałaga 1998).

In the younger Dryas (10.7–10.0 ka BP), a rapid change of climate conditions occurred. The diminishment of permafrost, lack of dense vegetation cover, and considerable lowering of the level of groundwater caused drying of the uppermost part of sediments. Winds with high transporting power from western directions intensified.

At the foothills of Roztocze, an extensive sandy plain provided favourable conditions for eolian processes. Large groups of parabolic dunes developed on the sandy plain. Sand-air streams blew sand to Roztocze. In valleys along windward slopes, dune banks developed (Fig. 17). A belt system of dunes developed, extending for tens of kilometres (Goździk 1991, Buraczyński 1998).

The southern part of Roztocze Szczebrzeszyńskie and Tomaszowskie was located in the belt of activity of dune-forming western winds. Dunes developed in the scarp zone, in dry valleys and on plateaus. Transport of sand in depressions occurred freely. Only before hills the strength of wind weakened and bank dunes developed. On the plateau (350 m a.s.l.) near Łuszczacz, on the intersection of courses of sand blowing from the Sopot and Zwierzyniec Basin, a dune developed with a height of 10 m (*map Józefów and Tomaszów*) (Buraczyński 1998).

Relief development in the Holocene

In Roztocze, at the turn of the Late Glacial and the Holocene, a radical channel reorganisation occurred in the development of river valleys, similarly as in south Poland. The process was related to climate warming and humidification (Starkel 1988a). The degradation of permafrost and release of considerable amounts of water caused a change in the fluvial regime, and a change in the type and amount of material supplied to the river. This resulted in a change

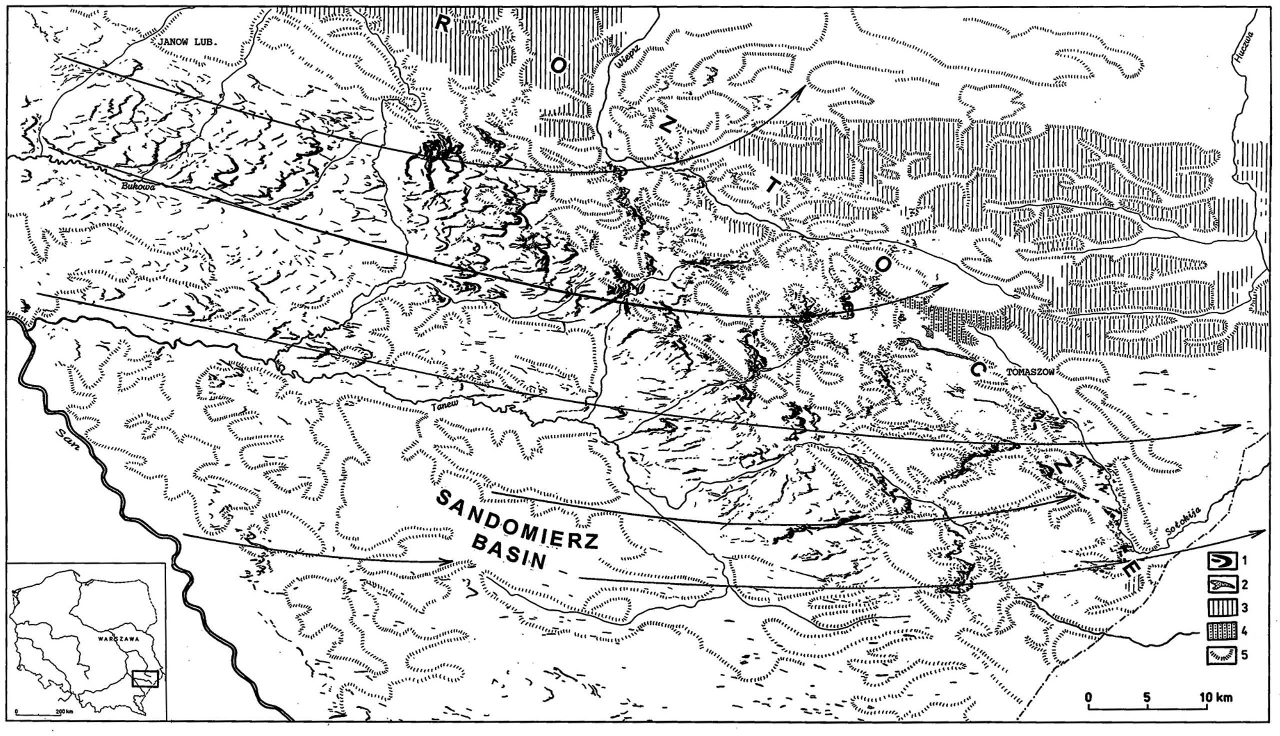

Fig. 17. Directions of major sandflows in Sandomierz Basin and in Roztocze Upland (Buraczyński 1998)
1 – dunes, 2 – eolian coversands, 3 – loess cover, 4 – sandy loess, 5 – edges and valley slopes

of development of the braided river into a meandering river. River valleys transitioned from the aggradation phase to the phase of linear erosion (Starkel et al. 2007).

In the Preboreal period (10.25-9.3 ka BP), climate warming was accompanied by the development of birch and pine forests. The evolution of the vegetation cover from the Late Glacial until the modern times is documented by pollen diagrams of peatlands (Bałaga 1998).

In the Wieprz River valley rapid changes in the regime of the river occurred towards even discharges and transition into a meandering river. The processes of dissection of the terrace occurred in stages, as suggested by fragments of the lower terrace cut in the sediments of the main terrace. The meanders cut deep into the slope of the terrace, confined by the edge of the terrace. A terrace developed with a height of 2–3 m, and below Bondyrze 5-6 m. Dead channels are filled with organic sediments and aggradate muds. Inside certain meanders, meander bars are visible. The alluvia of the valley floor are represented by the channel and alluvial mud facies. At the mouths of branch valleys, the valley floor is aggradated by alluvial fans (*map Szczebrzeszyn*). The Wieprz River was a wide-channel meandering river developing an extensive valley floor, similarly as other Polish rivers (Szumański 1982).

In the Borreal period (9.3–8.4 ka BP), pine and birch forests with hornbeam occurred. On valley floor, riverine communities developed. Permanent climate warming favoured dissecting of the valley floor, with a maximum in the Borreal period. Temperatures in summer were similar to those in the modern times, and winters were mild. Low amounts of precipitation resulted in a decrease in outflow and frequency and size of floods, similarly as determined in other areas (Starkel 1988a). Due to the humidification of the climate, accumulation developed, and the valley floor was aggradated. This resulted in the transformation of channels with bed load into transitional or suspension load (Starkel, Gębica 1995).

In the Atlantic period (8.4–5.0 ka BP), in the climate optimum, Roztocze was occupied by deciduous forests, and floodplain forests appeared in the valley (Bałaga 1998). In the Wieprz River valley, the narrow channel with small-radius meanders stabilised (10–30 m). In the meandering belt (200–300 m), sands of the channel facies were deposited on the levee, and in the remaining part of the valley – muds of the flood facies. The formations with a thickness of 2 m develop older alluvial soil. In dead channels, organic sedimentation started, suggesting the diminishment of water flow (Buraczyński 1996). In the basin of the upper Wieprz River, from approximately 7.3 ka BP, shallowing of the lake occurred, and a fen began developing throughout the Atlantic, Subboreal, and Subatlantic period (Bałaga 1992).

In loess areas, products of degradation of slopes were deposited in floors of dry valleys as muds with a thickness of up to 10 m. The Jędrzejówka valley is filled with non-carbonate silty muds. The eroded uppermost layer contains humus, with a layer of peat. The organic sediments were ^{14}C dated for 7860 years BP (Śnieszko 1995).

The effect of human activity on the vegetation of Roztocze is observed from the end of the Atlantic phase with the migration of Mesolithic and Neolithic tribes. In the period 6700–6500 ka BP, changes in the curves of tree pollen can be associated with the hunting-gathering economy of Mesolithic tribes. The maximum of indicators of human activity (5600–5000 ka BP) was related to rearing cattle and land cultivation. The most considerable changes in the environment were caused by the penetration of Roztocze by the Neolithic tribes of the Linear Pottery Culture, and the Funnel Beaker culture (Gurba, Libera 2011).

In the Subboreal period (5.0–2.8 ka BP), a deterioration of climate was manifested in an increase in humidity and a decrease in temperature. Climate humidification initiated another stage of flooding of blow-out depressios, and development of new peat bogs (Wielkie Bagno from 3500 ka BP), as well as peat bogs in the wellhead zone of the Gorajec, Szum, Tanew, and Wieprz Rivers (Bałaga 1998, Krąpiec et al. 2012).

From Zwierzyniec to Szczebrzeszyn, the valley transitions into a latitudinal valley with a width of up to 1.5–2 km. In the Holocene, a meandering river dissected the sandy terrace. The former course of the channel is determined by large palaeomeanders with a radius of 100 m, and dead channels with a small radius (10–30 m), visible on the right side of the valley. On the left side of the valley, palaeomeanders were covered with alluvial fans and slope formations. In Topólcza, at a depth of 4 m, a fossil meander was recorded with peat dated for 3190 years BP (Krąpiec et al. 2012). The Wieprz River valley outside Roztocze near Szczebrzeszyn dissects a medium-sized terrace confined by a scarp with a height of 7–9 m (*map Szczebrzeszyn*).

In the Subatlantic period (from 2.8 ka BP), forests were primarily composed of hornbeam and beech with a substantial contribution of fir. Human activity in the Roman-La Tene period resulted in considerable development of herbaceous vegetation, suggesting the development of cultivated fields and pastures. In the Hamernia peatland, pollen of rye, wheat, and buckwheat was recorded from 1.7 ka BP (Krąpiec et al. 2012). The influence of agricultural communities from the beginning of the Neolithic on the natural environment was limited to small settlement areas dispersed in forests. At the end of the Neolithic, intensive settlement in Roztocze was related to the shepherd communities of the *Corded Ware Culture* (2900–2200 years BC). The communities dealt with rearing cattle, goats, and sheep on the extensive hills of Roztocze (Gurba, Libera 2011).

The Wieprz River valley floor is distinguished by the occurrence of flood channels, suggesting their shovelling, and not free meandering. This is a typical phenomenon in aggradation valleys (Starkel, Gębica 1995). The youngest phase of development of the Wieprz River valley was manifested by the accumulation of younger alluvial soil, suggesting an increasing role of the anthropogenic factor, and deforestation of the area (Śnieszko 1995, Buraczyński 1989/90).

Gap valleys

The escarpment zone of Roztocze is dissected by rivers consequently flowing in the SW direction. They are the following rivers: Biała, Szum, Niepryszka, Sopot, Jeleń, Tanew, and Łówcza. Only the Biała Łada River valley varied from the pattern. In the Late Glacial, a considerable transformation of river channels occurred. This resulted from the diminishment of permafrost, leading to the release of vast amounts of water in summer (Mojski 2005). The so far braided rivers transitioned into meandering rivers (Starkel et al. 2007). The terrace was dissected in Roztocze, and the sandy plain in its forefield. In the marginal zone, the development of gap valleys began in the Older Dryas. They reached the highest depth in the Atlantic phase. The detailed development of gap valleys is presented based on the example of the Tanew River valley (*map Józefów*).

The Tanew River valley dissects the south-western slope of Roztocze. Its right slope simultaneously constitutes an extension of the external scarp. The valley floor with a width of up to 1.5 km is occupied by a terrace with a height of 3 m, dissected by a Holocene valley with a width of 200 m with a meandering channel (Buraczyński et al. 1992).

Near Rebizanty, the river develops a gap in the zone of the marginal bank. The valley has a depth of 10 m with a floor inclination of 10‰. At the external scarp, the depth increases to 20 m, and the floor inclination amounts to 5‰. In the gap section on the valley slope, an upper erosional terrace occurs (10 m), cutting into a sandy slope. Reaching resistant bedrock, the meandering river began broadening the valley to the sides. A lower erosional terrace developed in Cretaceous rocks (4 m). Large-radius meanders in deep undercuts of the slopes develops dead channel with peat. In the lower part of the valley, the lower erosional terrace (2 m) cuts into sands (Fig. 18).

Four series of rapids occur in the river channel. In the third series of rapids below the mouth of the Olszanka River, along a channel of 200 m, 24 steep rapids occur with azimuth of 140–160°. Depending on the thickness of rock banks, their height amounts to 0.5–1.0 m.

In the morphological analysis of the valley, the distribution of large meanders and slope undercuts permits the reconstruction of the course of the channel of the meandering river. In the Borreal phase, an erosional terrace developed with meandering slope undercuts. In the Atlantic-Subboreal phase, the channel cut into the bedrock, reducing the length of the river (*map Józefów*). In the gap valley, the modern channel is straight, and below, it develops small meanders (Buraczyński 1980/81, 1996).

Anthropogenic changes in the environment

Several climate changes were recorded in the historical times (Lamb 1977). In the years 600–1000 AD, the climate was cool. The following period 1000–1200 years was very cool with high precipitation. The climate pessimum in the 11^{th}–12^{th} century was distinguished by a decrease in temperature by 2°C. In the years 1200–1550, climate warming occurred along with a small climate optimum with a mean annual temperature of up to 9°C. An increase in precipita-

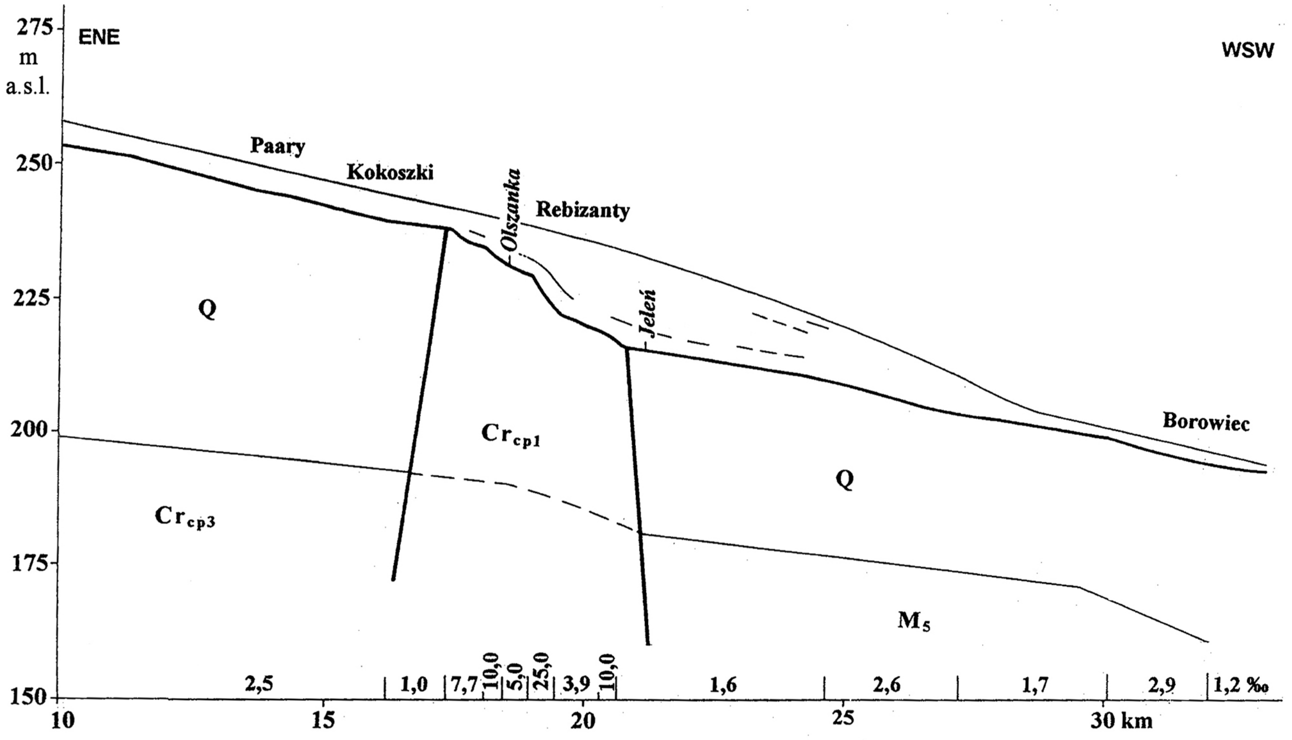

Fig. 18. Longitudinal profile of the bottom valley and terrace Tanew valley (Buraczyński 1997)
Q – Quaternary, M5 – clays, Sarmatian, Crm1 – opokas, Lower Maestrichtian, Crcp3 – gaizes, Upper Campanian, Crcp1 – gaizes, Lover Campanian; slope of the floor in ‰

tion in the years 1550–1850 was accompanied by a wave of climate cooling covering the Little Ice Age. At the end of the 17th century, the cooling reached its minimum with a mean annual temperature of approximately 5°C. Subsequently, the climate was moderately warm (1850–1960). A phase of proceeding cooling is currently observed.

Almost throughout the prehistoric times, Roztocze constituted a scarcely populated boundaries of inhabitancy by the contemporary cultural units. Settlement was gradually introduced to Roztocze through valleys. In the Wieprz River valley, numerous villages were established: Szczebrzeszyn (after 1250), Topólcza (1379), Wywłoczka (1497), Turzyniec (1564), and Kawęczyn (1565). From the 14th to the 16th century, agriculture developed, associated with the deforestation of slopes. The period was distinguished by the intensification of cultivation as a result of transition from the two-field to the three-field rotation farming (Skowronek 1999).

The intensifying economic activity in the loess areas of Roztocze was accompanied by intensive erosional processes (*map Turobin, Szczebrzeszyn*). In the dry valleys of the Gorajec River basin in the bottom layer of deluvia, tree trunks were encountered (Jahn 1956, Buraczyński 1968). The dating of the wood by means of the ^{14}C method for 870 years BP (Śnieszko 1991) suggests that they date back to approximately 1100. Rapid covering with a thick layer of sediments suggests intensive erosion resulting from catastrophic downpours. Burying the valleys occurred over several tens of years at the turn of the 11th and 12th century (Śnieszko 1995). The stabilisation of the floor of dry valleys and completion of the denudation of slopes corresponds with the 14th–15th century. It is determined by the upper fossil soil commonly occurring in dry valleys in Roztocze Gorajskie (Jahn 1956). The soil profile is distinguished by thicker horizon A_1 with 3.4% of humus. It is covered with a several meters thick layer of sediments of intensified agricultural denudation, with the modern soil containing only 1.5% of humus.

The detailed analysis of the *Jedliczny Dół* gully near Turzyniec suggests the cyclical occurrence of gully erosion. The dissection of the dry valley with a gully occurred after clearing the forest in the 14th century. This is suggested by the ^{14}C age of sediments found at the bottom of the gully of 714±25 years BP (1260 AD). In the 15th and 16th century, the main gully was filled with a layer of dusts with interlayers of Cretaceous gravels, material originating from the denudation of slopes and gully erosion in the upper part of the catchment. At a depth of 1 m, charcoal was dated by ^{14}C method for 388±23 years BP (1620 AD). The period of stabilisation of the dry valley lasted from the beginning of the 19th century. In the middle 19th century, the gully developed again, reaching a depth of 5 m (Schmitt et al. 2006).

Human economy contributed to an increase in the rate of soil and gully erosion. The process was particularly intensive in loess areas. This was particularly favoured by wet summers in the first half of the 14th century (Lamb 1977). Clearing of forests and development of land cultivation in the 14th–18th century resulted in the intensification of gully erosion and increased accumulation in dry valleys (Buraczyński 1968, Śnieszko 1991). Along the left (W) slope of the Wieprz River valley, at the mouths of dry valleys, large alluvial fans developed (*map Szczebrzeszyn*). Intensive accumulation of dusts in the valley floor developed alluvial soil (3–4 m). The process led to the diminishment of meandering, and the development of a braided river (Szumański 1986).

At the beginning of the 19th century, economic activity considerably intensified. Potato and sugar and fodder beet plantations rapidly became very common. Fragmentation of farms and appearance of narrow fields with a length of several kilometres was an unfavourable factor. Lack of dense vegetation cover and reduction in the compactness of soil multiply runoff. The processes of surface runoff play the greatest role in the modelling of loess slopes under agricultural use with high differences and inclination (Rodzik et al. 2008).

In loess areas with high differences, gullies are the most characteristic landform (*map Turobin and Szczebrzeszyn*). They dissect floors of valley-sides and dry valleys. The most important gully-forming processes include: linear erosion, evorsion, and mechanical suffosion. Intensive development of gullies results from rapid snowmelt or downpours lasting for several days, causing linear runoff. Their development is largely affected by summer downpours occurring every several tens of years (Rodzik et al. 1998). Eroded material is accumulated in floors of dry valleys, and is transported over considerable distances. In Roztocze Gorajskie and Szczebrzeszyńskie, gullies with a depth of up to 15 m, develop branches systems with a length of up to a dozen km. The mean density of the gully system amounts to 2.1 km km^{-2}, with a maximum of 10.5 km km^{-2} (Buraczyński 1989/90).

Summary

The modern relief of Roztocze is a result of tectonic and climatic changes. The last pressure of folding Carpathian Mountains caused the activation of faults and development of the Meta-Carpathian arch, as well as the elevation of Roztocze as a horst structure.

In the Pliocene, as a result of denudational processes, two planation surfaces developed. Tectonic activity in the Upper Pliocene caused the division of the upland into a number of blocks. The Roztocze Upland was determined by denudational escarpments with tectonic basis, then worn down and partly buries with cover formations in the Pleistocene. In the Sandomierz Basin, the Pliocene-Quaternary relief was preserved by fluvial and periglacial accumulation. The San 2 Glaciation covered Roztocze and the Sandomierz Basin. Glacial sediments were removed from Roztocze by denudational-erosional processes in the Masovian Interglacial, and in the Sandomierz Basin, moraine plateaus remained. The extent of the Odranian ice sheet is determined by till, eskers, and kames at the boundary of Roztocze Gorajskie, and fluvioglacial sands in the Sandomierz Basin.

The last glacial cycle had a considerable effect on the relief. Periglacial covers developed (loess and sands). On loess covering the plateaus of Roztocze Gorajskie and Szczebrzeszyńskie, loess relief developed. In the remaining part of Roztocze, river valleys and dry valleys buried with a dozen metre thick sand layer developed a accumulation terrace. At the forefield of Roztocze, a sandy plain developed. In the Late Glacial, on the surface of the sandy plain and the accumulation terrace, eolian relief developed. The Younger Dryas evidences that considerable relief transformations can occur within a period of several hundred years.

In the Holocene, fluvial erosional-accumulation processes developed. As a result of human activity, particularly in loess areas, intensive soil erosion occurred, as well as gully development and increased accumulation in valleys.

The relief of Roztocze is a result of covering old landforms by new ones, tectonic by erosional ones (Pliocene), and erosional by accumulation ones and the other way round (Quaternary). The modern polygenic relief results from the adaptation of the existing relief to the changing geographical environment.

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