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EVIDENCE FOR DIFFERENTIAL CRUSTAL UPLIFT BETWEEN THE NEIGHBOURING KAMIENICA AND OCHOTNICA RIVER VALLEYS IN THE POLISH OUTER WESTERN CARPATHIANS

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Abstract: Young tectonic movements in the Carpathians, both vertical and horizontal ones, display local variations. The Dunajec River valley is one of the areas where this differentiation has been documented best. New data on differentiated tectonic uplift, based on the study of changing elevations of five levels of fluvial strath terraces, were obtained in the lowermost reaches of two Dunajec's tributaries: Kamienica and Ochotnica. The results indicate a change in the rate of valley bottom incision during the Pleistocene. Initially, the rate of incision was higher in the Kamienica River valley during *ca*. 600–350 ka BP. Later, since *ca*. 130 ka BP until now, the proportion became reversed and the rate of incision was nearly twice as fast in the Ochotnica River valley than in the Kamienica River valley. This is probably related to the mobility of the overthrust of the Krynica slice onto the Bystrica slice, both building the inner portion of the Magura Nappe. Reactivation of this thrust may be a result of neotectonic activity of large-scale faults situated at the depths of 5–20 km and possibly rooted in the Palaeozoic–Mesozoic basement.

Key words: strath terraces, neotectonics, Outer Western Carpathians, Poland.

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INTRODUCTION

River valleys in the Outer Western Carpathians have well developed systems of Quaternary fluvial terraces that include strath surfaces overlain by alluvial covers of variable thicknesses. Quaternary climate oscillations and vertical tectonic movements have been accepted as the two major factors responsible for stepwise evolution of the valley bottoms (*e.g.*, Klimaszewski, 1967; Zuchiewicz, 1998, 2001; Starkel, 2003). During interglacial stages, the valley bottoms widened and strath terraces were formed, providing the base for subsequent alluvial deposition. The main phases of aggradation were taking place during the glacial stages and partly also in the interglacials. Incision and deepening of the valleys were mainly confined to the phases of glacial-interglacial and interglacial-glacial transitions, additionally also during interglacials; while the area was being uplifted constantly throughout the Pleistocene (Starkel, 1969; Olszak, 2006). The age of the terraces used to be constrained owing to correlation with continental glaciations in the Polish Lowlands (Zuchiewicz, 1992). The aim of this paper is to characterize strath terraces in the lower reaches of the Kamienica and Ochotnica river valleys, and to discuss the reasons for diversified river incision, mostly induced by crustal uplift.

GEOLOGICAL SETTING

The Polish segment of the Outer Western Carpathians represents a fold-and-thrust system of several nappes that were thrust over each other during the Middle to Late Miocene (Książkiewicz, 1977; Oszczypko & Żytko, 1987), as a result of convergence between the North European and ALCAPA plates. The nappes are thrust to the north onto the Miocene strata filling the Carpathian Foredeep Basin. The age of nappe thrusting becomes younger towards the north. The Magura Nappe, where the study area is located, is the biggest one and forms the internal part of the Outer Carpathians. The nappe is composed of four slices (from the south: Krynica, Bystrica, Rača and Siary slices) thrust upon each other. These slices are built of flysch series: alternating sandstones, shales and marls of the Cretaceous through Oligocene age, and of different thicknesses.

NEOTECTONIC SETTING

The Kamienica and Ochotnica rivers are left tributaries of the Dunajec River in that part of its course, where it forms an antecedent water-gap across one of the most prominent neotectonic elevations in the Western Carpathians

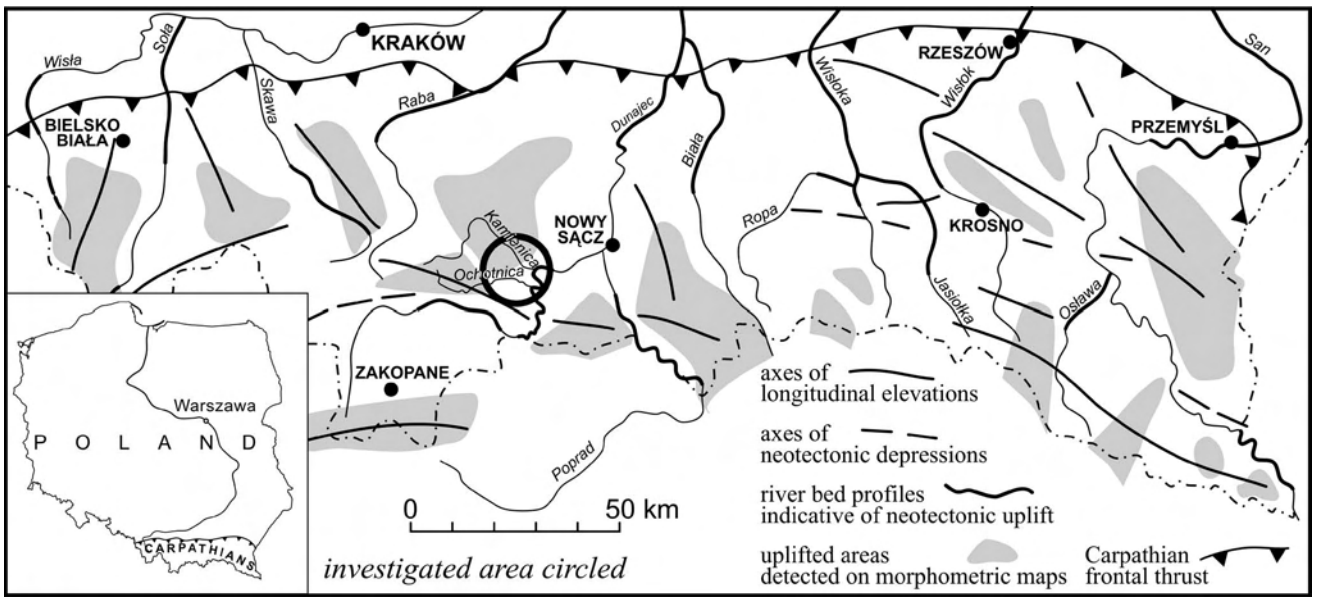

Fig. 1. Neotectonic elements of the Polish Carpathians (after Zuchiewicz, 1998)

(Zuchiewicz, 1998; Fig. 1). The Dunajec River valley and the surrounding area are still subject to uplift (*e.g.*, Starkel, 1968, 1969, 1972; Zuchiewicz, 1984; Forma & Zuchiewicz, 2002), though tectonic activity in the Polish Outer Carpathians has been relatively weak. The average rate of Quaternary uplift in the Polish Outer Carpathians ranged from 0.02 to 2.0 mm/yr (Zuchiewicz, 1998). The distribution and intensity of young vertical and horizontal movements features a distinct zonation across the Carpathian arc, which is controlled by variable crustal thickness and isostatic anomalies (Zuchiewicz, 1998). Dziewański and Starkel (1962) accepted an idea that the uplift of the Carpathians proceeded at a roughly constant rate throughout the Quaternary. However, three stages of increased uplift of the Polish Carpathians, 800–472 ka, 130–90 ka and 15–0 ka BP, have been distinguished by Zuchiewicz (1998). The uplift led to deepening of the Carpathian river valleys by 100–160 m during the last *ca*. 2.5 Ma (Zuchiewicz, 1984). Most of the valleys tend to have now several strath terraces dating from the Pleistocene to the Holocene. Some sections of the present-day river bed profiles are indicate of active uplift as well (*cf.* Starkel, 1972; Zuchiewicz *et al.*, 2009).

METHODS

Interpretation of the relative rates of river incision is based on detailed mapping of fluvial strath terraces in the Kamienica and Ochotnica river valleys, and especially terrace elevations above the present-day river beds. The elevations of strath terraces were determined with 1 m resolution using a pressure altimeter. The results, including the spatial extent of terrace surfaces, were plotted on a 1: 10,000 topographic map. The fluvial terraces are preserved in patches, so morphostratigraphic principles were used and terrace patches of comparable elevations above the river bed were treated as belonging to the same terrace level. The identified seven terrace levels were labelled T1 to T7. Ages if individual terraces were assigned basing on correlations with the terraces in the Dunajec River valley, surveyed and dated by Zuchiewicz (1984, 1992). Five samples of sediments from alluvial cover of T3 strath terrace (Fig. 2) have been dated using optically stimulated luminescence, single aliquot regenerative dose technique (OSL-SAR; see Aitken, 1998) at the Luminescence Dating Laboratory, Silesian University of Technology in Gliwice, Poland.

The rate of valley incision was calculated taking into account the vertical amount of dissection of the strath terraces, excluding the overlying alluvial covers. Assuming that the incision occurred mainly during the interglacial and transitional periods (Olszak, 2006), only the durations of these time intervals were used for calculating the incision rate. The average rate of incision during the last 0.6 Ma was calculated for the entire time interval, including the glacial stages.

STRATH TERRACES

Strath terraces in the Kamienica and Ochotnica river valleys are complex-response terraces *sensu* Bull (1990), being related to tectonic uplift and climate oscillations (Olszak, 2006). They are elevated up to 68 m above the present channels (Fig. 2; Table 1). Seven fluvial terrace levels were mapped; this paper deals with the five (T1 – T5) oldest ones only. The youngest terraces throughout most of river courses are mainly cut-and-fill terraces; their strath surfaces are visible in a few places only. No terrace corresponding to the Elsterian-2 stage has been recognized. All the terrace levels form a staircase-like relief, where each lower terrace step is younger. The surfaces of strath terraces are uneven, often inclined toward the valley axes and are buried under alluvial mantles, 1 to 8 m thick, and/or slope sediments.

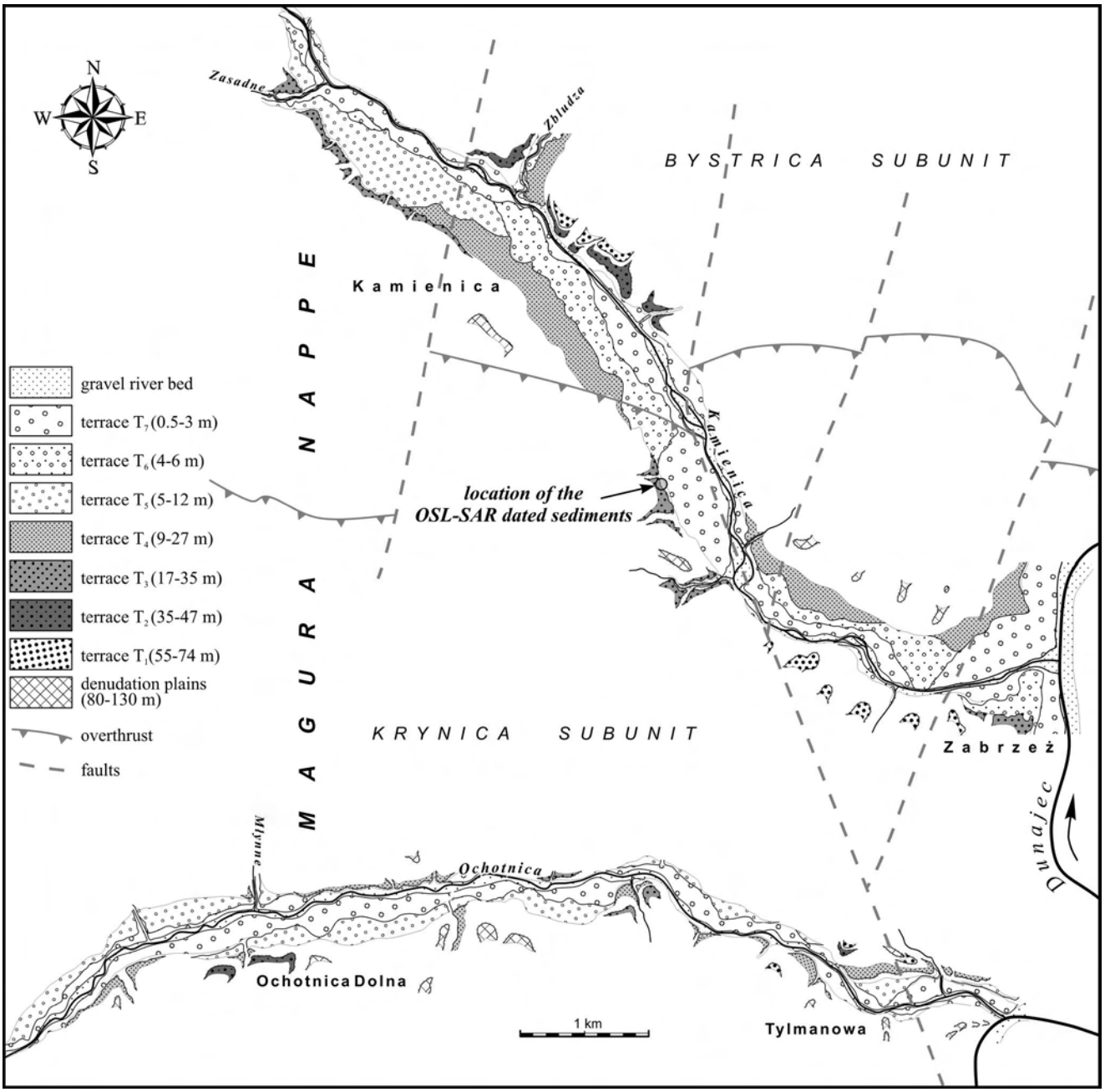

Fig. 2. Fluvial terraces in the study area. Tectonic sketch after Oszczypko *et al.* (1999)

The altitude of each strath terrace level above the present-day river bed decreases upstream. The differences in elevation between the lowest and highest points of a single strath surface may reach 11 m along one longitudinal profile (Fig. 3). No clear dislocations of strata in the strath longitudinal profiles have been recognized that would point to the presence of faults crossing the river valleys (*cf.* Oszczypko *et al.*, 1999).

Sediments for OSL-SAR dating were sampled on the right bank of the Kamienica River valley (Fig. 2), where a big outcrop of the terrace T3 is located. No strath is visible at the outcrop, but a nearly 8-m-thick series of sediments consisting of gravel at the bottom, clay or sandy clay in the middle, and another gravel layer at the top (Fig. 4), all the sediments being beige in colour, was identified. No tributary of the Kamienica River exists close to the outcrop, so the dated sediments could not represent a part of an alluvial fan covering older strata. The results of OSL-SAR dating, spanning an interval of 72.8±2.5 to 96.3±3.9 ka BP, indicate that sediments overlying the T3 strath terrace (Figs 2, 4) are younger than inferred by Olszak (2006). These sediments, earlier attributed to the Wartanian glaciation, were most likely deposited during the early stage of the Weichselian. The obtained dates show, however, a peculiar inversion up the section, which requires further studies. A word of caution should be added, therefore, when concluding about younger ages of the discussed terrace cover, until other test age constraints using the OSL SAR technique are provided.

Table 1

Strath terraces in the Kamienica and Ochotnica river valleys (lower reaches)

Terrace	Altitude*of terraces/**strath surfaces**		**Estimated age** based on chronological evidence and correlation between terraces in the Dunajec River Valley, after Zuchiewicz (1984, 1992)
	Kamienica	Ochotnica	
T1	55-74/52-62	60-70/57-68	Elsterian-1
T2	35-36/31-32	40-47/39-41	Saalian
T3	17-25/12-18	23-35/19-27	Wartanian**
T4	9-18/5-10	10-27/7-21	Weichselian
T5	5-8/2-3	5-12/2-7	LG

* in metres above river bed

** OSL-SAR dating suggests younger age of the terrace, but this is one of the first attempts at using the OSL-SAR technique for dating alluvial sediments in the Polish Carpathians. Therefore, until other datings are made, one should refrain from assigning definitive age to terrace covers in this area.

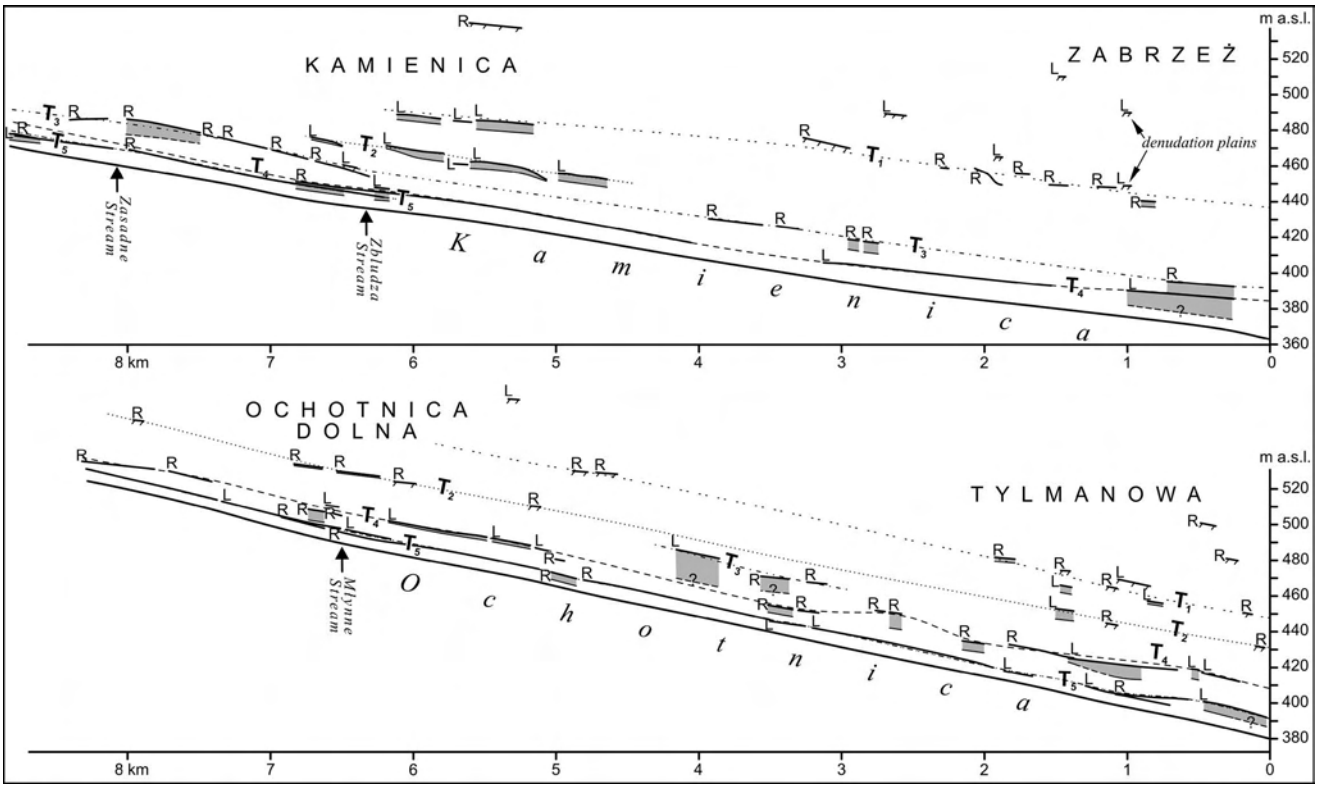

Fig. 3. Schematic longitudinal profile of Quaternary terraces in the Kamienica and Ochotnica River valleys (lower reaches): R – right slope, L – left slope. Shaded areas represent alluvial covers, fence lines denote straths

VARIATION IN THE RATE OF INCISION

The rate of deepening of the Kamienica and Ochotnica river valleys varied during the last 0.6 Ma, as did the proportion between the incision rates in both rivers. The average rate of valley incision during that time equals 0.1 mm/year. Initially (*ca*. 0.6–0.35 Ma BP), the Kamienica River valley was being incised slightly faster – 0.14 mm/year (Figs 5, 6). During the period of *ca*. 230–180 ka BP the rate of incision in both valleys was nearly equal. Beginning with the Eemian interglacial, the difference in the incision rate between both valleys began to rise in favour of the Ochotnica River valley, so that during the Holocene the latter valley was deepening nearly twice as fast – 1.22 mm/year (Fig. 6). Permanent rise in the incision rate is characteristic of both valleys in the studied interval.

The data presented above were evaluated using the terrace ages estimated by correlation with the Dunajec River valley (Table 1). The OSL-SAR dates indicate another age than hitherto accepted; hence, the estimates of the incision rates should be taken with caution until all terraces are numerically dated. Anyway, the rates of incision varied between the valleys (Fig. 5), only the rates themselves and their timing require further study.

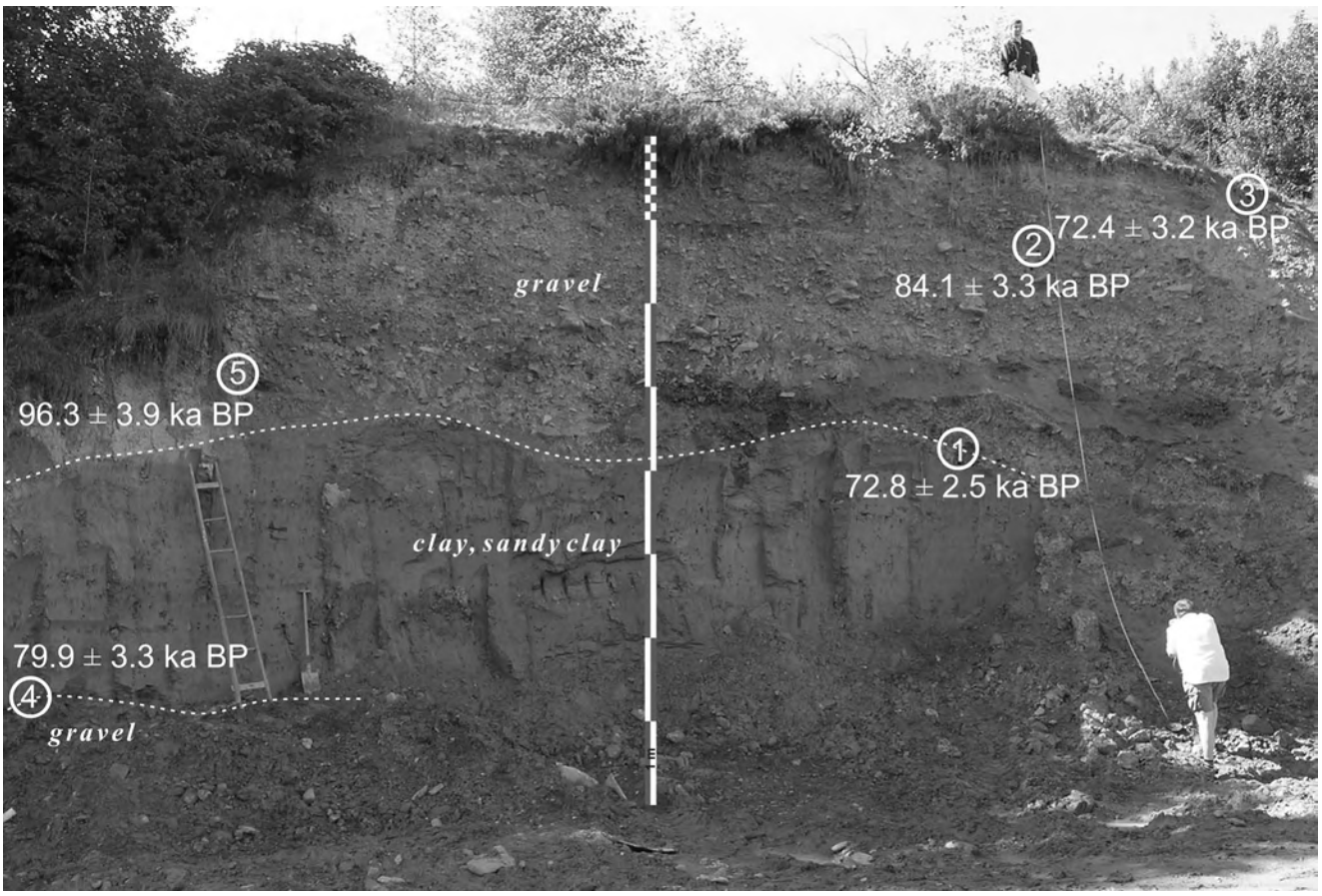

Fig. 4. Section of the T3 terrace sediments, showing the location of OSL-SAR sampling sites

DEVELOPMENT OF STRATH TERRACES

The differences in the rate of river incision between the lower reaches of both valleys are most likely related to the zone of overthrust of the Krynica slice on the Bystrica slice of the Magura Nappe. According to the maps by Oszczypko *et al.* (1999) and Paul (1980), this thrust zone runs roughly between both valleys, only near the mouth of the Kamienica River valley it crosses the valley and passes into its left slope (Fig. 2). Traces of increased uplift in the frontal zones of the Carpathian overthrusts have recently been noted by Tokarski *et al.* (2007) and Zuchiewicz *et al.* (2009). This activity seems to be corroborated by the results of studies on fractured clasts in the zones adjacent to the overthrusts, where dominant orientations of fractures within clasts are parallel to the strike of thrust fronts of minor tectonic subunits within the Magura Nappe (Tokarski *et al.*, 2007).

The differential uplift between both studied valleys may be related to the presence of a steeply-dipping fault, inferred for the depth of 5–20 km on the base of magnetotelluric soundings (Czerwiński *et al.*, 2003), which probably cuts the base of the Magura overthrust. The mouth of the Kamienica River lies at the continuation of this fault to the surface. The fault is probably active now as a reversed fault with downthrown northern side. The presence of this structure in the basement may induce increased activity of the thrust front and uplift of the Krynica slice relative to the

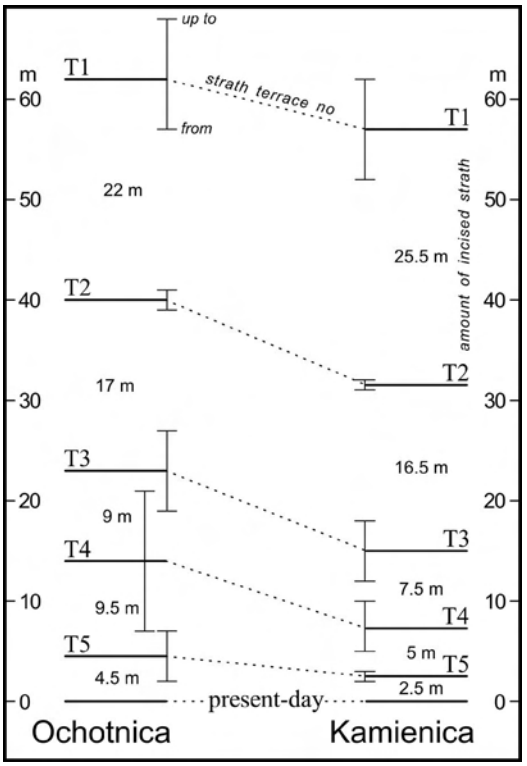

Fig. 5. Average, maximal and minimal altitudes of strath terraces above the present-day river beds

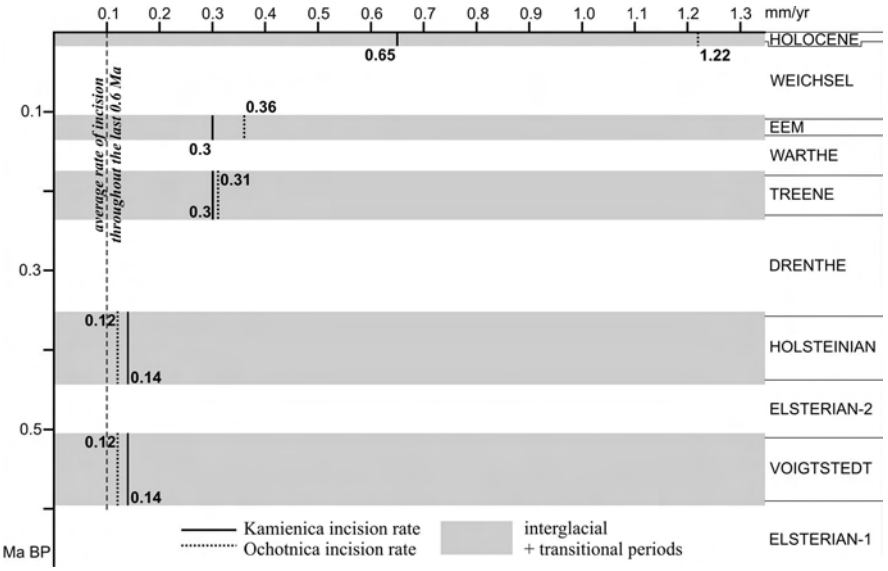

Fig. 6. Approximate rates of incision of the straths (mm/yr) in their lower and middle reaches (geological time scale after Mojski, 2005 and Ber *et al.*, 2007)

Bystrica slice. The lower rate of incision in the Ochotnica River valley (Fig. 4) may imply that until *ca*. 350 ka BP the sense of movement on this fault was a reverse one. This resulted in relatively higher uplift of the area of the Kamienica River valley. Another fault of similar orientation lies several kilometres to the north (Czerwiński *et al.*, 2003). The block delimited by these two faults is now relatively lowered, with a marked downbending of the overlying flysch units. This subsidence is marked in relief as the "depression" of Łącko, where the base of alluvium of lower terraces of the Dunajec River descends below the river bed (Zuchiewicz, 1984). The tectonic structures inferred at the base of the overthrust Carpathian flysch seem to be rooted in the Palaeozoic–Mesozoic basement of the Carpathians. The basement in this area is shaped as a trough *ca*. 20 km deep, bounded by extensional faults (Ryłko & Tomaś, 2001).

CONCLUSIONS

The development of strath terraces in the Kamienica and Ochotnica river valleys has been controlled by neotectonic uplift of the Magura Nappe. The results of geomorphic mapping show that the uplift of this area is still alive and the rate of uplift has been increasing since the Meso-Pleistocene until present-day. The Holocene is the most noticeable epoch of diversified incision rates of the straths. It may be explained by neotectonic activity increasing between the two subunits of the Magura Nappe. Some geophysical data indicate connections between neotectonic movements of flysch units and the solid basement of the Carpathians. This hypothesis, however, requires confirmation by reflection seismic profiling.

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