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LANDFORM EVOLUTION IN MOUNTAIN AREAS

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EVOLUTION OF THE WATER DIVIDE BETWEEN THE VISTULA AND DANUBE RIVERS IN THE POLISH CARPATHIANS

Abstract. The water divide between the Vistula and the Danube changed locally its course since Pliocene times. The changes were caused by neotectonic movements (Przemyśl Gate, Orava Depression) and by differences in intensity of erosion, resulting from various distance to and elevation above local bases of erosion (Mid-Bieszczady Depression, Tatra Mountains). The present-day marked differences in altitudes of the bases of erosion still lead to capturing of the Orava tributaries by the Soła, Skawa and Raba, the Dunajec tributaries by the Hornád and Torysa, and the San tributaries by the Uh and Laborec.

Key words: water divide, Vistula, Danube, Carpathians

INTRODUCTION

The highest dynamics of relief change in mountain areas is usually attributed to the valley bottoms. Slopes are also evolving at a fast rate. The water-divide crests are usually considered stable elements of relief, with the lowest rate of morphogenesis (Starkel 1969; Klimaszewski 1981). River power at headwaters is too low to cause changes in relief comparable to those in the lower reaches. Moreover, the water divides usually run along the outcrops of the rocks most resistant to denudation (Baumgart-Kotarba 1974).

Stability of relief in the water divide areas in the Western Carpathians, especially the position of the water-divide line itself, is illusory. The water divide changed position in the past and its evolution is controlled by many factors. It has been accepted that the position of the water divide in mountain areas is controlled by two main factors: vertical tectonic movements (Starkel 1972; Zuchiewicz 1987, 1994; Bumgart-Kotarba 1991–1992, 1996) and denudation (Zuchiewicz 1984; Henkiel 1977–1978). The water-divide line may undergo slow shift if denudation is more intense on its one side (Klimaszewski 1948, 1966; Gerber 1969; Lukniš 1973; Passendorfer 1974). This in turn depends on the position of the local bases of erosion, consequently on the relative

elevation of the weater-divide crest (Wrzosek 1968; Baumgart-Kotarba 1977). To a lesser extent it depends also on the amount and concentration of precipitation on both sides of the water divide, on the attitude and resistance of the bedrock strata (Lobeck 1939; Baumgart-Kotarba et al. 1969; Henkiel 1977–1978; Lacika 2000), and also, during the period of human activity, on the type of land use on slopes.

It is generally accepted that the drainage pattern in the Western Carpathians acquired its shape before the Pleistocene (during dissection of the Intramontane planation surfaces under the influence of locally differentiated vertical movements), and in the northern foreland of the Carpathians during the Pleistocene (during the interglacial periods and under the influence of locally mobile basement) — (Starkel 1972, 1995; Zuchiewicz 1987). New regional drainage patterns emerged at those times and the greatest changes in the position of the water divides have taken place, including those in the Sandomierz Depression (Starkel 1972; Wojtanowicz 1977–1978; Laskowska-Wysoczańska 1983) and the Oświęcim Depression (Klimaszewski 1958; Starkel 1972), at the margin of the Tatra Mountains (Szaflarski 1931; Lukniš 1972; Passendorfer 1974; Lacika 2000) and in the Bieszczady (Pękala 1971; Henkiel 1997). The process is still active in the Carpathians and there are several places where a shift of the Vistula–Danube water divide will occur soon.

This paper presents morphometric data on the Vistula–Danube water divide within the length of the Polish Carpathians and places where piracy will occur. This analysis deals with the water-divide zone between these catchments. The detailed course of the water divide is accepted according to surface relief. The morphometric analysis was based on topographic maps 1 : 10,000 to 1 : 50,000. Detailed data on the water divide in the Bieszczady Wysokie and Działy Orawskie have been collected by the author in the field.

CHARACTERISTICS OF THE WATER DIVIDE

The section of the Vistula and Danube water divide between the Koniakowska Pass (Ochodzita 894 m a.s.l.) in the west and the Uzhok Pass (853 m a.s.l.) in the east is ca 420 km long and the boundary between Poland and Slovakia runs along it over the most part and also with Ukraine over a short section (Fig. 1, 2). The only waters flowing from Poland to the Danube are the headwater reaches of the Váh river tributaries (Kysuca in the Koniaków Gate and Orava in Podhale), while the Poprad and Dunajec rivers (Kacwinka in the Spišska Magura) collect some waters to the Vistula. This is a continental water divide.

The water divide line runs along the crests of the highest mountain ranges of the West Carpathians (Beskid Żywiecki, Tatry, Bieszczady), and through intramountainous depressions between these ranges (Podhale, Podtatranská Kotlina). It should be stressed that the water divide does not usually follow the highest

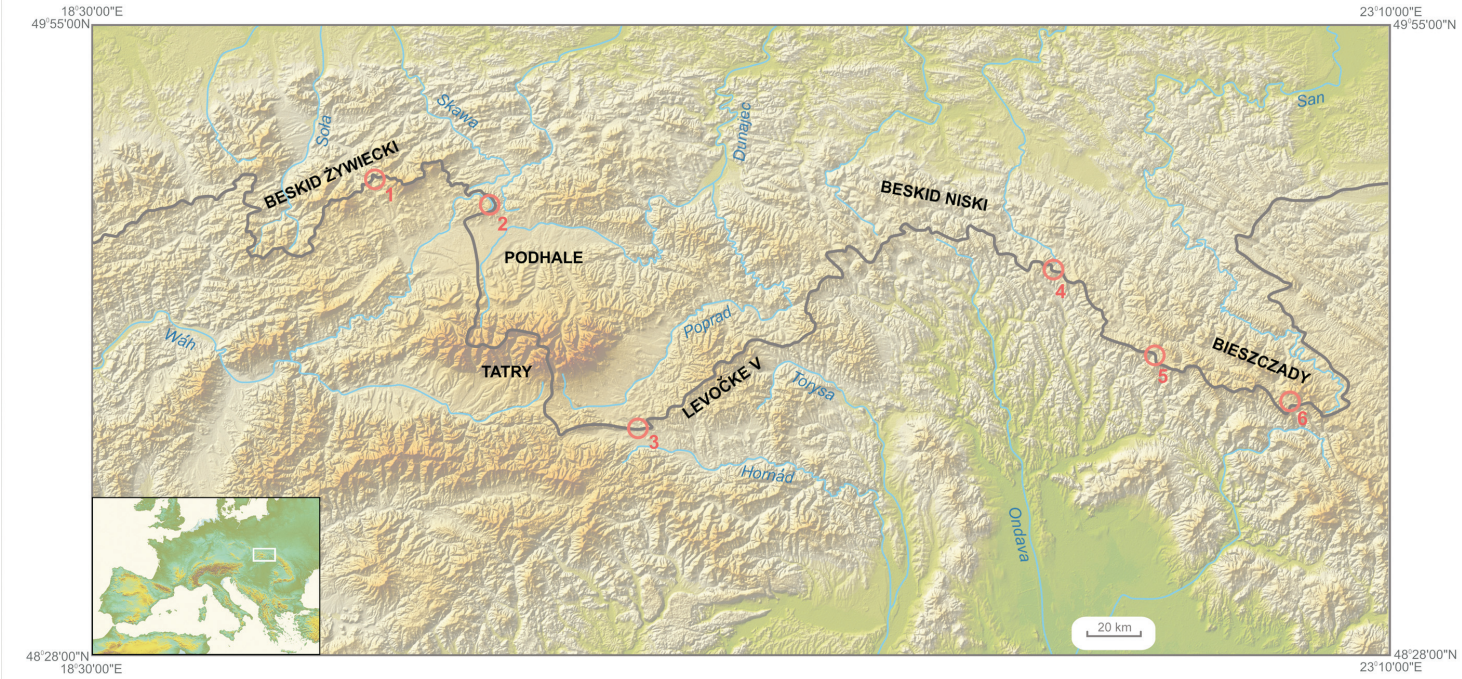

Fig. 1. Position of the Vistula–Danube water divide in the Carpathians. Red dots mark the site of prognosed drainage diversion: 1 — Półgórzanka/Krzyżówka, 2 — Orava/Skawa/Raba, 3 — Hornád/Poprad, 4 — Laborec/Bełcza, 5 — Udava/Solinka, 6 — Uh/Wołosatka

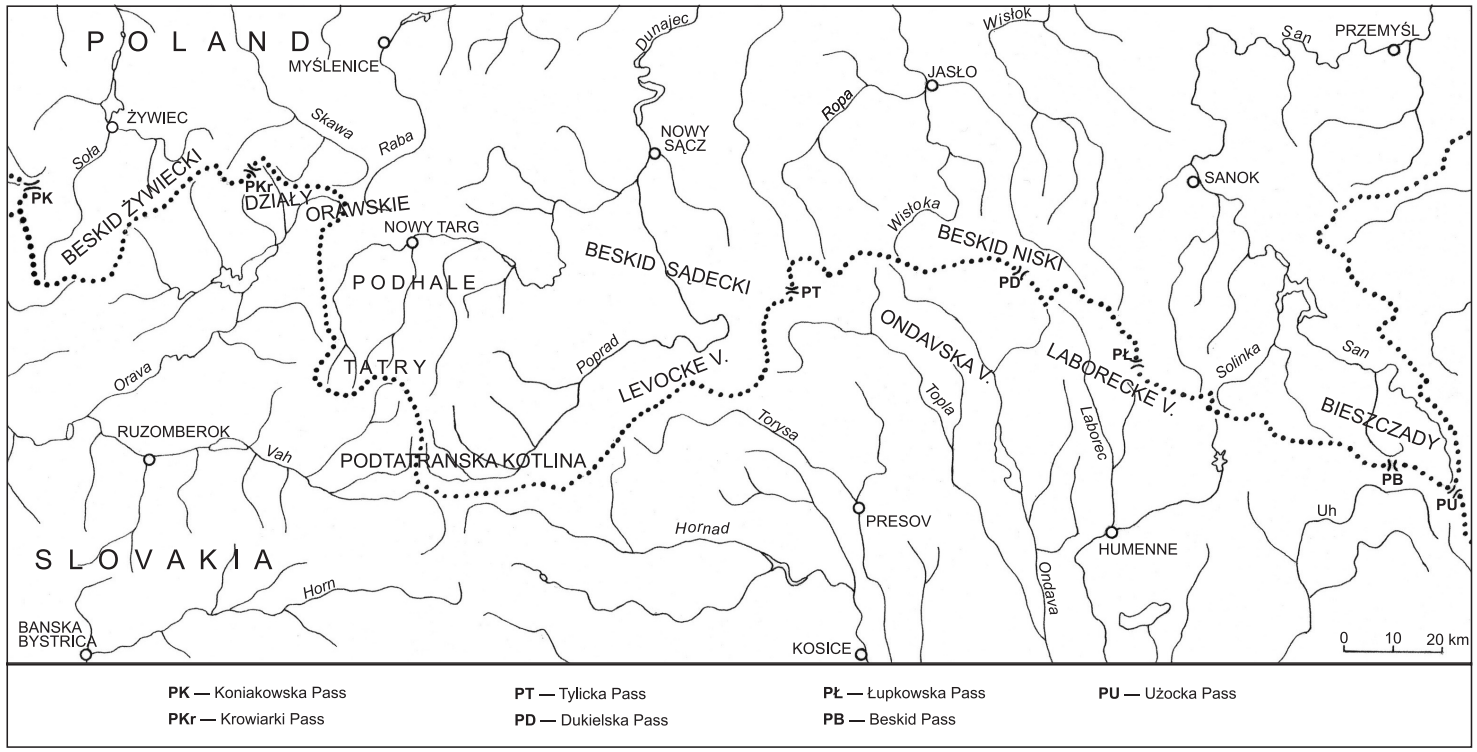

Fig. 2. Position of the Vistula–Danube water divide against the background of the Carpathian river system

crests of these ranges, more frequently it runs besides them. This is the case in the Tatra Mountains, where, the summits of the Bystra, Raczkowa Czuba, Krywań and Hruby lie away from the water divide and are drained by tributaries of the Váh. The water divide lies now on the Kasprowy Wierch — Czerwone Wierchy ridge which is lower than the southern ridge (with Křivan). The latter has been already dissected by headward erosion of a Váh tributary (Tichá Voda). In the Beskid Niski the crests of the Magura Wątkowska and Cergowa lie off the water divide, only between the Dukielska and Łupkowska passes the water divide runs through the highest elevations. The highest elevations of the Bieszczady (Tarnica, Halicz and Krzemień) also lie off the water divide. The divide also avoids completely the massif of Barania Góra in the Beskid Śląski and the Beskid Sądecki.

The longitudinal profile of the water divide is uneven, when drawn with vertical exaggereation — even serrate, with large local amplitudes (Fig. 3). The culminations of the Beskid Żywiecki (especially Pilsko and Babia Góra) stand out in the profile, separated from one another by deep passes. In the Tatra the differences in elevation are much lower, though the Tatra segment as a whole is marked as the highest block. It is aditionally accentuated by the fact that the water divide in its vicinity runs across the bottoms of wide intramountaneous depressions: Podhale and Podtatranska Kotliná. The least elevated section of the water divide is that in the Beskid Niski, the oscillations in elevation are there frequent but their extent is the smallest. It is in this section where the water divide has its lowest point in the Dukielska Pass (503 m a.s.l.). Unusual is the shape of the water divide profile in the Bieszczady, where changes in elevation are especially frequent and high. The two low passes in this segment: Beskid (785 m), Użocka (853 m a.s.l.), do not reach as low elevations as the Dukielska Pass.

It is noteworthy that the shape of the profile (Fig. 3) in individual segments closely reflects the general style of relief in these areas, resulting mostly from their geological structure. In the Bieszczady segment the profile reflects the grill-like pattern of mountain crests, related to the regular pattern of folds and thrusts. The Beskid Niski segment has a profile with low monadnock hills or crests built of resistant rocks, separated by wide depressions. The Tatras with their crystalline rocks form the distinctly highest segment of the water divide profile. The greatest altitude contrasts in the water divide profile are present in the Beskid Żywiecki, but these reflect great differences in resistance between the thick, resistant series of sandstones that build the crests and the soft, thin-bedded sandstone-and-shale series, in which the passes and the deep narrow valleys are carved. Peculiar is the Podhale segment, with a very smooth threshold of Działy Orawskie and a deep and wide basin of the Orava Depression.

The height of the water divide and its stability depend largely on the position of erosional base of the rivers on both sides of the divide. The river dissecting the opposite slopes of the water divide erode downward and headward much stronger on the side where the base of erosion lies lower. The greater the difference in altitude of the bases, the other factors being equal, the stronger is the tendency to

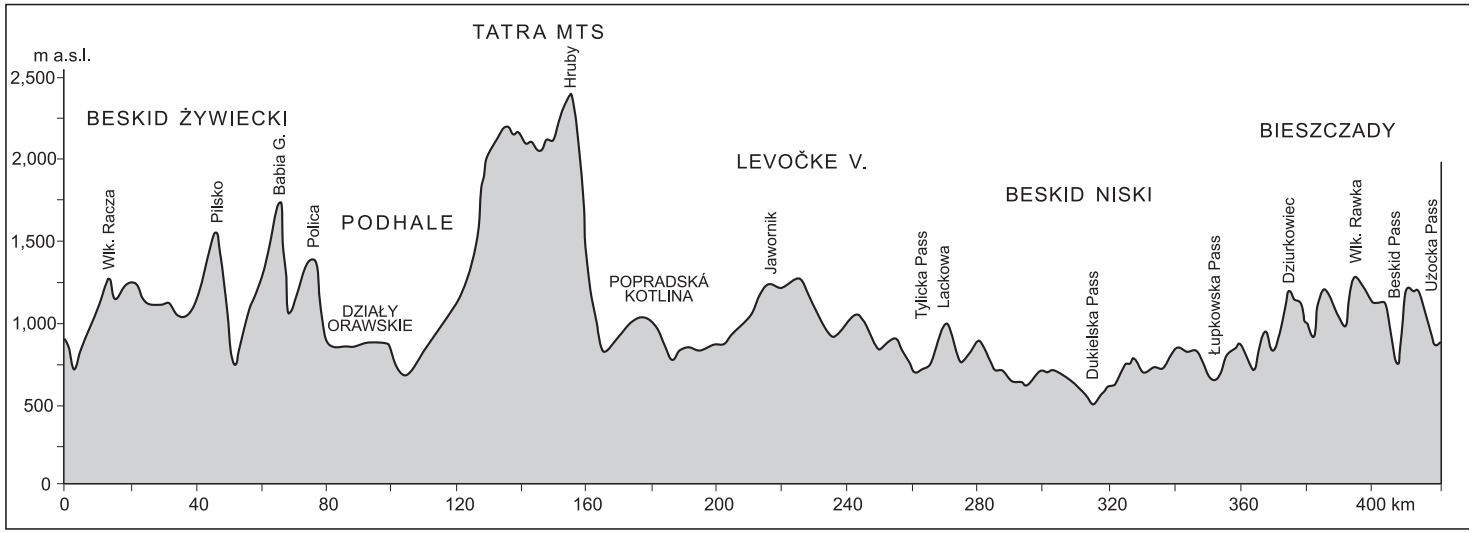

Fig. 3. Altitude of the Vistula–Danube water-divide crest line in the Polish Carpathians

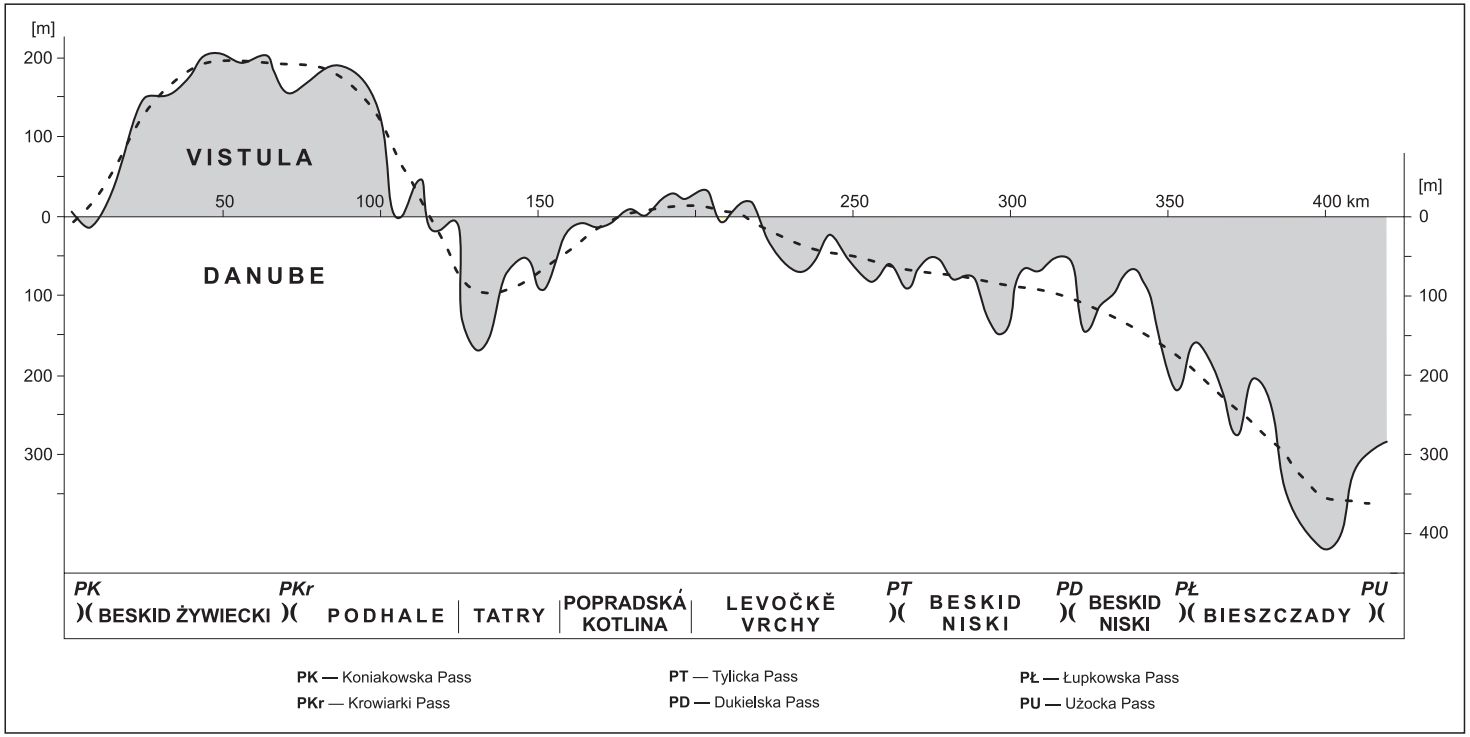

Fig. 4. Differences in altitudes of local bases of erosion on both sides of the water divide (the lower-lying part is coloured)

shifting the water divide toward the less energetic watershed. The streams whose base of erosion lies lower have steeper gradients and incise the water divide more effectively than the rivers on the opposite slopes, whose base of erosion lies higher. The contrasts in altitude of bases of erosion on both sides of the water divide (measured to the place of decrease in gradient) are great (Fig. 4).

Fig. 4 shows that on the side of the Vistula, the upper tributaries of the Soła, Skawa and Raba rivers in the Beskid Żywiecki and on Działy Orawskie have lower lying base of erosion. The difference in altitude relative to the tributaries of the Orava river on the south attains even 200 m. Also in the Popradská Kotlina, the base of erosion of the upper reaches of the Poprad river lies slightly lower than that of the upper reaches of the Hornád river (tributary of the Tisa). The longitudinal profile of the Hornád rapidly lowers downstream and already in the Popradská Kotlina and in the Levočské Vrchy the Hornád flows deeper than the Poprad (L a c i k a 2000). Along the Tatra segment, the erosional base of the Váh river lies about 150 m lower on the southern side. Still greater is the difference eastward of the Šarišské Podolie (from where the Poprad enters Polish territory). The difference increases farther eastward and attains as much as 400 m in the Bieszczady. Such is the situation near the Wielka Rawka in the Pasmo Graniczne (Frontier Range) where the Wołosatka flows to the San at an elevation ca 420 m higher than the Uh to the Tisa. Also close to the water divide in the Beskid Niski extends Ondavská Vrchovina, lying ca 100–200 m lower than the northern area. It may be thus supposed that the water divide will change fastest in those areas where the differences in the position of the base of erosion are the greatest.

Regardless of the differences in altitude of the bases of erosion, the distance from the water divide to the base of erosion is also important. When the distance is short and the difference in altitude between it and the water divide is large, then denudation affects the slopes of the water divide faster and reaches the crest earlier. The line of the water divide then shifts and local embayments form — (B a u m g a r t - K o t a r b a 1977; K l i m a s z e w s k i 1981). This is the situation at the Babia Góra where the water divide is shifted by ca 5 km to the south. The base of erosion of the Skawica river at Zawoja Widły lies much closer to the crest. The headward erosion of the tributaries of the Skawica contributed indirectly to the origin of the giant landslides on the northern slopes of the Babia Góra that accelerated the development of this embayment. The headwater tributaries of the Soła river (Koszarawa, Sopotnia and Krzyżówka) dissect the the Beskid Żywiecki from the north so deeply, that already 10 km from the water divide they attain the same elevation that the tributaries of the Orava attain only 50 km away from the water divide. The shift of the water divide in this area may result in piracy of the streams flowing on the opposite slopes of the crest.

The water divide embayments are most numerous in the Beskid Niski, where the water divide course is diagonal to the crest axes and bedrock structures. The divide runs there along monadnock crests in long, concordant segments, while depressions between the crests it crosses along the shorter sec-

tions, thus creating a zig-zag line. In the Bieszczady such zig-zag line is present on the Połonina Bukowska and on the Kińczyk Bukowski. Successive higher series of thick-bedded resistant sandstones become the segments of the diagonally running water divide between the San and the Uh.

The section of the European water divide near the headwaters of the Orava, Skawa and Raba rivers on Działy Orawskie in Podhale is exceptional (Fig. 5). The Orava for 5–6 km from its source has a gradient of a few per mill and does not incise its bed, whilst the Skawa, the Raba and the tributaries of the Dunajec have steep gradients already at their headwaters (40–120 ‰) and erode downward intensely. Headward erosion at their headwaters led to creation of a sharp thresh-

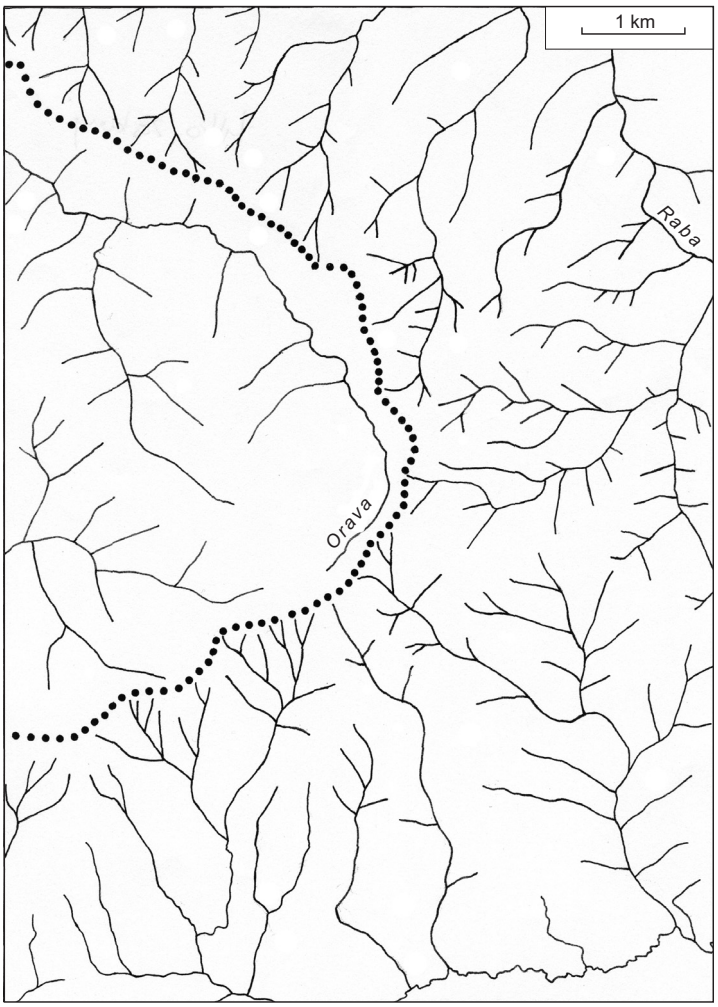

Fig. 5. Drainage pattern near the water divide between the Orava and the tributaries of the Vistula at Podhale

old at the perimeter of the Orava watershed and this threshold get closer and closer to the Orava channel. Over the distance of 8 km the distance between the channel of the Orava and the edge of this threshold does not exceed 500 m, and in many places they are only 20–50 m apart. Only a small remnant elevation is left there from the water divide crest (Fig. 5).

The rapid progress of erosion of this crest by the Skawa, Raba and Dunajec rivers is a consequence of the bases of erosion of these rivers lying low and close to one another. These rivers have bases of erosion at a similar altitude (Raba the lowest, Skawa and Dunajec higher) — (Fig. 6). Similar are also the longitudinal gradients of their tributaries and the hypsometric extent of their headwaters. As the Orava does not display a tendency to downcutting for a long time, this fragment of Działy Orawskie belongs to exceptionally extensive areas on the continental divide where ancient relief is preserved, with the Intramontane planation

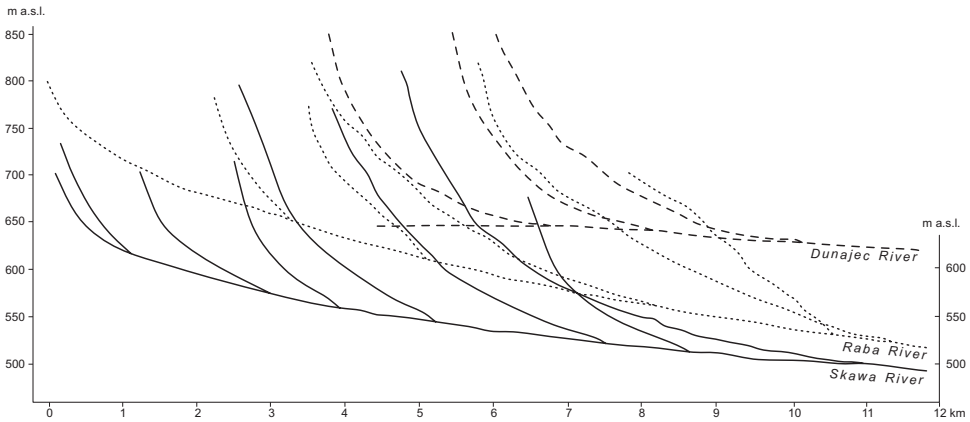

Fig. 6. Longitudinal profiles of the tributaries of the Skawa, Raba and Dunajec rivers in the area around Działy Orawskie

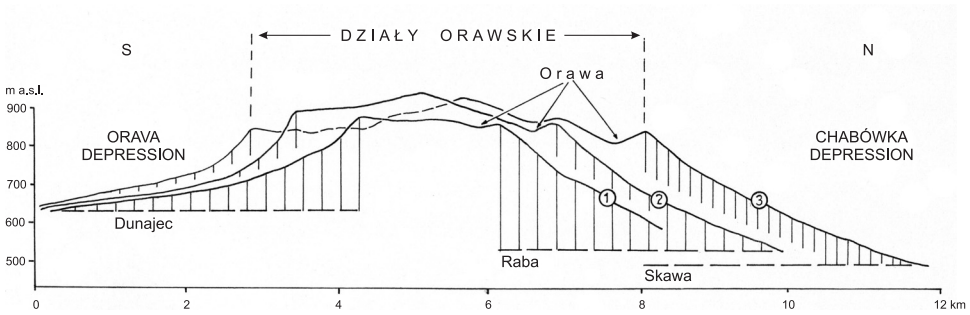

Fig. 7. Differences in altitudes of the local bases of erosion of the Orava (Danube) and tributaries of the Vistula around Działy Orawskie

surface and not rejuvenated valleys (Fig. 7). Equally unusual is the course of this water divide in the Orava Depression itself. Its line is difficult to precise tracing on the glaciofluvial fans of the Czarny Dunajec river because it is not marked in relief.

The water divide between the Danube and the Vistula did not lie ever in the same position as the drainage pattern was periodically subject to significant rearrangement, both in late Tertiary and in Quaternary times. According to H. Teisseyre (1928), I. D. Gofsztejn (1979), W. Laskowska-Wysoczańska (1983), L. Starkel (1995), the waters of the palaeo-Vistula (below the Kraków Gate) and the Danube were flowing to the same sea still at the beginnings of Pleistocene (Fig. 8). The Beskid Śląski and the Beskid Żywiecki were drained then by the Odra. The tributaries of the Vistula after their departure from the Carpathians turned east, to the watershed of the Dnester as is shown not only by the transport direction of the gravels but also by their presence in the Dnester watershed. To this direction of drainage is also related the origin of the Peri-Carpathian palaeochannel with preserved terrace steps and gravels characteristic of the Dunajec river (Starkel 1972; Laskowska-Wysoczańska 1983). The waters of the palaeo-Raba river accumulated the huge series of the Witów Series gravels (Dżułyński et al. 1968). The flow of the Vistula eastward, to the Dnester, was also forced by the front of the continental glacier during the Pleistocene South-Poland Glaciation, known also as the Sanian II (Teisseyre 1928; Starkel 1972). The present-day course of the Vistula with its Carpathian tributaries across the highland belt formed only after this very glaciation, according to the modern views (Pożaryski et al. 1995; Pożaryski, Kalicki 1995; Starkel 1995, 2001). The San was the last to stop draining to the Dnester. Besides the continental glaciers, the changes in the drainage pattern in the Sandomierz Depression were also controlled by the young tectonic movements that uplifted, among others, the water divide between the Vistula and the Dnester (Gofsztejn 1979; Laskowska-Wysoczańska 1983).

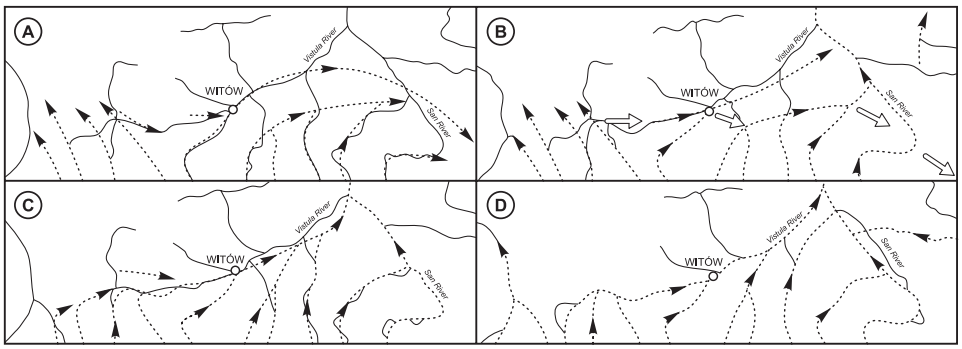

Fig. 8. Pleistocene changes in the drainage pattern in the foreland of the Carpathians (according to: Starkel 1984, 2001; Pożaryski et al. 1994). A — earliest Pleistocene, B — after the Sanian Glaciation, C — duroing the recession of the Odranian ice sheet, D — in the middle of the Vistulian Glaciation

Important changes in the position of the water divide occurred also in the Carpathians, along its present course. The flow of the Dunajec river waters from the Podhale Depression to the north through the Beskid Sądecki formed at the break of the Pliocene and Quaternary (Klimaszewski 1958; Zuchiewicz 1979, 1980). In Pleistocene some part of the Dunajec waters could also flow by the passes on Działy Orawskie — such concept presented by L. Sawicki (1909) had followers (Szaflarski 1934) and contestants (Pawłowski 1928; Klimaszewski 1932; Stolfówna 1932) and the question has not been not resolved yet. It has been proven, however, that waters from the Western Tatra Mountains flew through the Czarny Dunajec to the Orava and Váh rivers nearly to the end of the Tatra glaciation (Baumgart-Kotarba 1991–1992). In the Bieszczady, the San captured the Wołosatka from the Obniżenie Śródbieszczadzkie. It was earlier flowing south to the Uh (Pękala 1971; Henkiel 1997). Very young are the piracy events between the tributaries of the Poprad and Hornád rivers in the Hornádska Kotlina (Lacika 2000).

CONCLUSIONS

The evolution of the drainage pattern along the water divide is still in progress and the sites of successive events of piracy may be indicated (Fig. 1). One is in the western part of the Bieszczady, where the faster deepening its valley Udava river (tributary of the Tisa) reached with its headwaters close to the channel of the Solinka river (tributary of the San). The Udava has its base of erosion at altitude of ca 600 m, Solinka at ca 700 m. At the 6th to 7th kilometre of the Solinka its channel is distant only 200–250 m from the retreating headwaters of the Udava (Fig. 9). In the Bieszczady, the tributary of the Uh (and then the Tisa), with the base of erosion at altitude 525 m, may capture the upper course of the Wołosatka near the Beskid Pass (at altitude 750 m). A similar piracy case is imminent to the Bełcza stream (tributary of the Jasiołka, then the Wisłoka) by a tributary of the Tisa — the Laborec. Earlier may occur piracy of the Półgórzanka strean (a tributary of the Orava river) by the Krzyżówka stream (a tributary of the Soła river) in the Beskid Żywiecki, near Korbielów. The Krzyżówka is dowcutting faster and deeper, the Półgórzanka is more passive and lies higher. For 5 km it flows parallel to the water divide and may be captured by the tributary of the Soła river. In one place the water divide is only 20 m high and is distant by only 130 m from the Półgórzanka. As was mentioned above, on Działy Orawskie in Podhale, the tributaries of the Raba river reach to the upper course of the Czarna Orawa by a distance of only 20–50 m (Fig. 5). The tributaries of the Hornád river in Slovakia deepen their headwater courses faster then the tributaries of the Poprad river and successive cases of piracy may occur there. It is interesting that the struggle for the water divide does not take place only at the mountain passes but also in the bottoms of the intramountainous depressions.

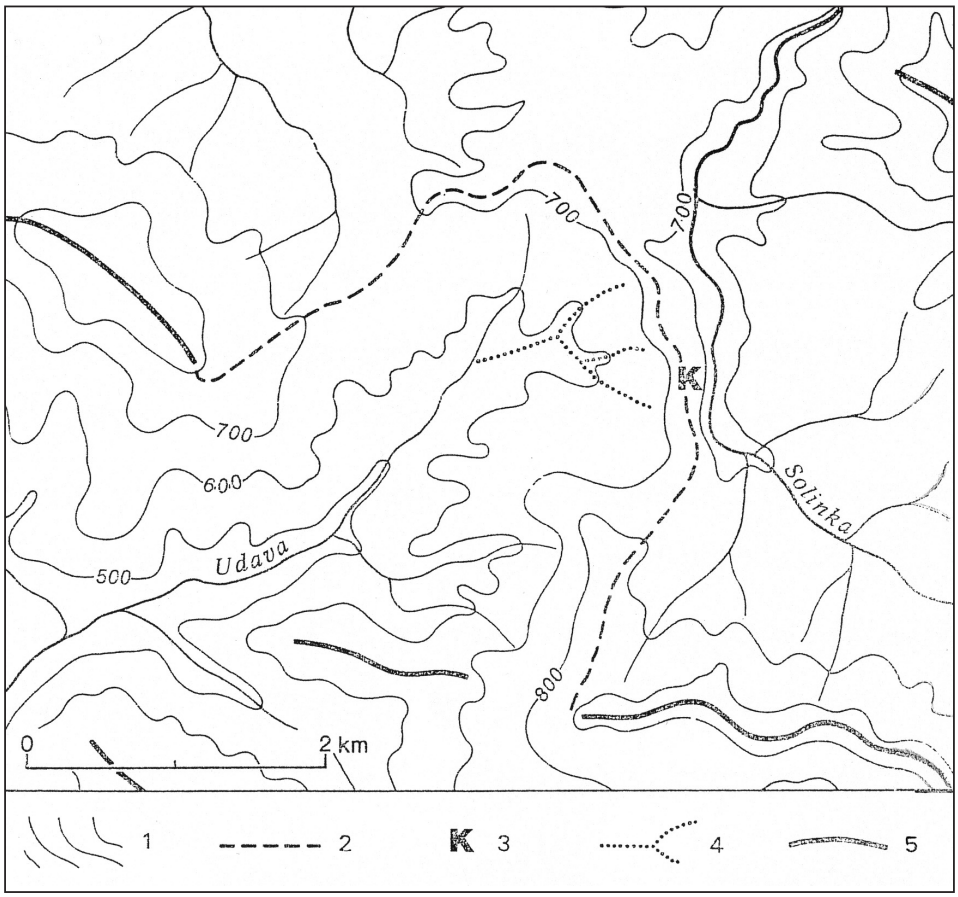

Fig. 9. Prognosed piracy of the Solinka by headward erosion of the Udava (after Klimaszewski 1981). 1 — altitude contours, 2 — water divide, 3 — place of piracy, 4 — streams nearest to the water divide, 5 — crests

Relatively stable is now the course of the water divide in the Koniaków Gate, west of the Ochodzita, where the Olza river does not shows a trend to shifting its water divide relative to the Vistula and Kysuca. This is an exceptional segment of the European water divide in the Carpathians as its line is the main axis of settlement and traffic routes. Also the crest of Levočské Vrchy seems to be a lasting barrier for the waters of the lower Poprad and the Torysa rivers, but the changes in the drainage network may occur at the periphery of the mountains, as is shown by the case of the Tatra. This would cause the mountains to cease to belong to the continental divide.

Summing up we may conclude that:

1. The water divide between the Vistula and the Danube is not a lasting feature in the relief of the Carpathians but it is subject to evolution with respect to its position, altitude and the modes of their change.

2. The essential changes in the position of the water divide in Early Pleistocene are related to the maximum extent of the continental ice sheet in Poland, later mainly stream piracy controlled the process.
3. The present course of the water divide is largely controlled by the geological structure of the bedrock (young tectonics, attitude and resistance of rock series) and by relief characteristics (height and distance to the bases of erosion) and the distance to the bases of erosion, dynamics of processes in headwater reaches along the water divide).
4. The large differences in elevation on both sides of the water divide suggest that piracy will continue by tributaries of the Vistula in the Beskid Żywiecki and on Działy Orawskie, while in the Tatra, Beskid Niski and Bieszczady, the direction of piracy will be opposite to that between the Koniakowska Pass (Beskid Śląski) in the west and the Uzhok Pass (Bieszczady Wysokie) in the east.

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STRESZCZENIE

Józef Kukulak

EWOLUCJA WODODZIAŁU WISŁY I DUNAJU W POLSKICH KARPATACH

Wododział Wisły i Dunaju w Karpatach, ciągnący się od Bramy Koniakowskiej (na zachodzie) po Przełęcz Użocką (na wschodzie), scharakteryzowano morfometrycznie i ewolucyjnie. Zanalizowano jego przebieg w ujęciu regionalnych różnic wysokości bezwzględnych oraz wykazano skalę dysproporcji w położeniu podstaw erozyjnych po obu stronach tego wododziału. Podkreślono ścisły związek obecnego przebiegu wododziału z układem struktur geologicznych i stylem rzeźby terenu. Przedstawiono jego ewolucję od plejstocenu do dziś. Wyodrębniono miejsca zmian tego wododziału w przeszłości i wskazano nowe miejsca, gdzie może dojść do kaptaży dopływów obu rzek w przyszłości. Stwierdzono obecność w strefie wododziału fragmentów dawnej, dojrzałej rzeźby Karpat (Działy Orawskie). Wykazano, że wododziały nie są trwałymi elementami rzeźby.