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NEOTECTONIC ACTIVITY OF THE SKAWA RIVER FAULT ZONE (OUTER CARPATHIANS, POLAND)

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Abstract: The Skawa River catchment basin in the Outer Western Carpathians of Poland is situated upon morphostructures showing differentiated mobility in the Quaternary. Long profile of river channel reveals the lowest values of concavity index among the Polish Outer Carpathian rivers, pointing to low degree of river profile maturity, particularly in its middle reach coinciding with a zone of abnormally high river bed gradients.

The Skawa River valley utilizes in its middle and northern reaches the Skawa River Fault Zone (SRFZ) composed of differently oriented oblique-slip faults, visible on DEM images as well-marked, rectilinear topolineaments. The NNW–SSE to N–S faults in the Silesian Nappe were probably reactivated in Late Pleistocene times as normal faults downthrowing their eastern sides, as shown by abnormally high position of the Weichselian Early Glacial straths on the western valley side. Such an episode of neotectonic activity (late Early Glacial times of the Last Glacial stage) has not been recognized so far in the other river valleys of the Polish segments of the Western Outer Carpathians. We conclude that some of the NNW–SSE to N–S trending faults were reactivated as strike-slip faults. This would conform to the present day stress arrangement within the Polish segment of Carpathians. Moreover, deformations of the Pleistocene straths between Osielec in the south and Wadowice–Zator areas in the north appear to indicate both pre-Weichselian and Weichselian reactivation of the Silesian and – to a lesser extent – Magura frontal thrusts. These movements continued also in the Holocene, although to a smaller extent, most probably due to moderately strong and/or strong earthquakes of magnitudes exceeding 5.5–5.7, resulting in clast fracturing within Holocene alluvium, particularly strong on the Silesian frontal thrust, and less intensive on the Carpathian marginal and Magura frontal thrusts, as well as on some faults that belong to the SRFZ.

We are convinced that the record of seismically-induced clast fracturing on one of major fault zones in the Outer Carpathians should lead to revision of the hitherto-existing seismic risk assessment of this region, and particularly of the city of Kraków and other urbanized areas, as well as the planned artificial water reservoir at Świnna Poręba.

Key words: neotectonics, morphotectonics, fractured clasts, seismic hazard, Skawa River valley, Outer Carpathians, Poland.

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INTRODUCTION

The Polish segment of the Outer Western Carpathians composes a fragment of a fold-and-thrust belt built of a series of nappes, which were finally thrust one over another during the Middle-Late Miocene (Książkiewicz, 1972; Oszczypko, 2006; and references therein). The nappes are composed predominantly of Cretaceous through Lower Miocene flysch strata. The thrusting proceeded as a result of convergence between the North European and ALCAPA plates. This convergence was nearly finished by latest Miocene time (Decker & Peresson, 1996; Oszczypko *et al.*, 2005; and references therein). Studies of balanced cross sections appear to suggest that the only possibility of the Pliocene–Quaternary (neotectonic) deformations in the Outer Carpathians is due to reactivation of the inner parts of the orogenic belt via out-of-sequence thrusting, backthrusting in the Silesian nappe, and reactivation of some fault zones (Roure *et al.*, 1993). In the Pliocene and Quaternary, the area witnessed differential vertical and some remnant horizontal movements, resulting in the formation of elevated and subsided areas (*cf.* extensive discussion in Zuchiewicz, 1995a and Zuchiewicz *et al.*, 2002).

In this paper we are dealing with the Skawa River Fault Zone (SRFZ; *cf.* Figs 1–3), one of major fault zones in the Polish segment of the Outer Western Carpathians that reveals neotectonic activity. To assess this activity and its seismic potential, we attempt to combine the results of field geomorphic studies, analysis of some morphometric parameters derived from topographic maps and digital elevation models, as well as examination of fractured clasts found within the Holocene alluvium.

The Carpathians belong to one of the most seismically active regions of Poland, which was particularly active in the last centuries. The strongest historical earthquakes in Poland (1443 and 1786 AD) caused considerable destruction to some Kraków buildings, including the Mediaeval St. Catherine's church (Pagaczewski, 1972). The 1786 event led also to a rockfall at Tyniec, shortly west of Kraków, where blocks of a total weight of 1, 000 tons were displaced (Alexandrowicz, 1956). The 1443 earthquake epicentre was situated in Žilina (Pagaczewski, 1972), Western Carpathians of Slovakia, whereas that of the 1786 earthquake was placed in the Polish segment of the Outer Carpathians (Pagaczewski, 1972; Mortimer, 2002; Guterch & Lewandowska-Marciniak, 2002). The seismicity of the Carpathian region, therefore, poses a threat to the city of Kraków and other localities that significantly expanded in population and area since the end of the 18th century, as well as to the planned artificial water reservoir in Świnna Poręba region. Proper seismic risk assessment of this area requires a detailed reconstruction of neotectonic deformations, including mapping of neotectonically active fault zones, their kinematic analysis, as well as examination of fractured clasts in the Neogene and Quaternary sediments. Historical records and instrumental data are not sufficient enough to estimate the seismic risk, mainly due to imprecise character of historical descriptions and restriction of earthquake catalogues to the past few hundred years. In the study area, as in many intra-plate settings, rates of faulting are relatively small resulting in very long recurrence intervals (10^3 to 10^6 years), like in the case of the disastrous Basle earthquake (1356 AD) of surface magnitude up to 6.5 (Cloetingh *et al.*, 2003), similar to that of the 2003 AD Mw 6.6 Bam earthquake in Iran (Fu *et al.*, 2007). To estimate the recurrence interval of strong earthquakes it is necessary to observe a few seismic cycles, covering a sufficiently long period of time. One of possible tools that would enable long-term seismic prediction is analysis of fractured clasts in Quaternary sediments. The geological record of numerous strong (>5.5) earthquakes in the Outer Carpathians should compel us to reconsider seismic risk in this area.

METHODS

Field studies consisted in detailed geomorphic mapping at the scales of 1: 10, 000 and 1: 25, 000 of a portion of the Skawa River valley comprised between Osielec in the south and Świnna Poręba in the north (Fig. 3), as well as in measuring fractured clasts within the Holocene terrace covers at a number of localities distributed between Zator and Bystra. We also re-interpreted already published data pertaining to morphometric indices indicative of neotectonic activity, which were measured from 1:100,000, 1:50,000 and 1:25,000 topographic maps of the entire Polish Outer Carpathians, using standard morphotectonic procedures described by Bull and McFadden (1980), Zuchiewicz (1995a, b), Keller and Pinter (1996), Burbank and Anderson (2001), and Bull (2007). Detailed description of individual parameters will be given in a separate chapter. Digital elevation model (*Shuttle Radar Topography Mission*, SRTM level 2) was helpful in identification of topolineaments of different rank and their comparison with the location of major faults marked on 1:200,000 (Golonka *et al.*, 1981) and 1: 50,000 (Książkiewicz, 1951b, 1974a, b; Cieszkowski *et al.*, 2006a) geological maps, and photolineaments published by other authors (Doktór *et al.*, 1985, 1989, 2002; Ozimkowski, 2008).

The number of fractured clasts per square metre was calculated for all gravel exposures bearing fractured clasts, whereas the architecture of clast-cutting fractures and clast packing indices were analyzed at selected exposures only. For particular exposures, the number of fractured clasts per sq. metre is the number of fractured clasts divided by the area of the exposure. When examining clast packing we followed quantitative indicators commonly employed in sandstone fabric analysis, *i.e.* the packing proximity and packing density (*e.g.* Pettijohn *et al.*, 1972). The analyses were carried out along traverses marked on photos of exposures. For showing spatial relationships among clasts, the packing proximity percentage was calculated as the number of clast-to-clast contacts divided by the sum of all clast contacts along the studied traverses. The packing density percentage expresses the sum of the widths of grains divided by the length of studied traverses. The packing density percentage shows the share of matrix. Proportions among clasts showing the point and long contacts were also calculated.

GEOMORPHIC SETTING

The Skawa River, 96.4 km long, is situated in the Outer Western Carpathians, crossing a number of geomorphic units. These are, from the south to the north, the Beskidy Mts. including: Sieniawa Gate, a fragment of Beskid Wyspowy Mts., Beskid Żywiecki Mts. Jabłonków Depression, Beskid Mały Mts., as well as the Silesian and Wiśnicz Foothills, and Oświęcim Basin, which belongs to the Subcarpathian Depression (Fig. 1A, *cf.* Starkel, 1991). The latter unit embraces the Wilamowice Plateau in the south and the Upper Vistula River valley in the north (Gilewska, 1999). In a slightly different subdivision by Kondracki

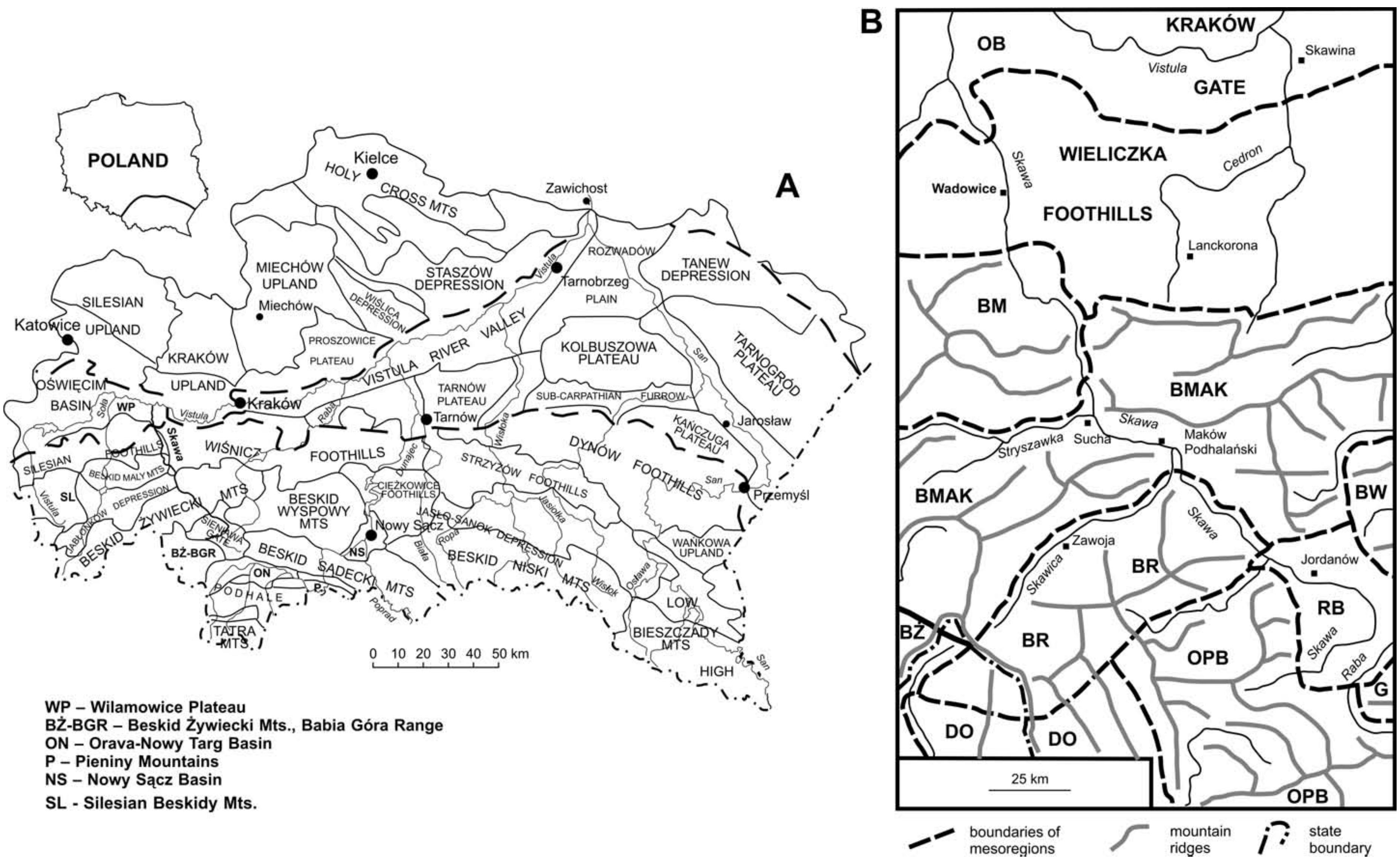

Fig. 1. Physiographic subdivisions of southern Poland (**A**; based on Starkel, 1991 and Gilewska, 1999; modified), and the Skawa River catchment basin (**B**; based on Kondracki, 2000; modified). Thick dashed lines in (**A**) denote boundaries between the South-Polish Uplands in the north, sub-Carpathian Depression in the middle, and Carpathians in the south. Mesoregions in (**B**): OB – Oświęcim Basin, BM – Beskid Mały Mts., BMAK – Beskid Makowski Mts., BŻ – Beskid Żywiecki Mts., BR – Babia Góra Range, OPB – Orava-Podhale Beskid Mts., BW – Beskid Wyspowy Mts., G – Gorce Mts., RB – Rabka Basin, DO – Działy Orawskie Foothills

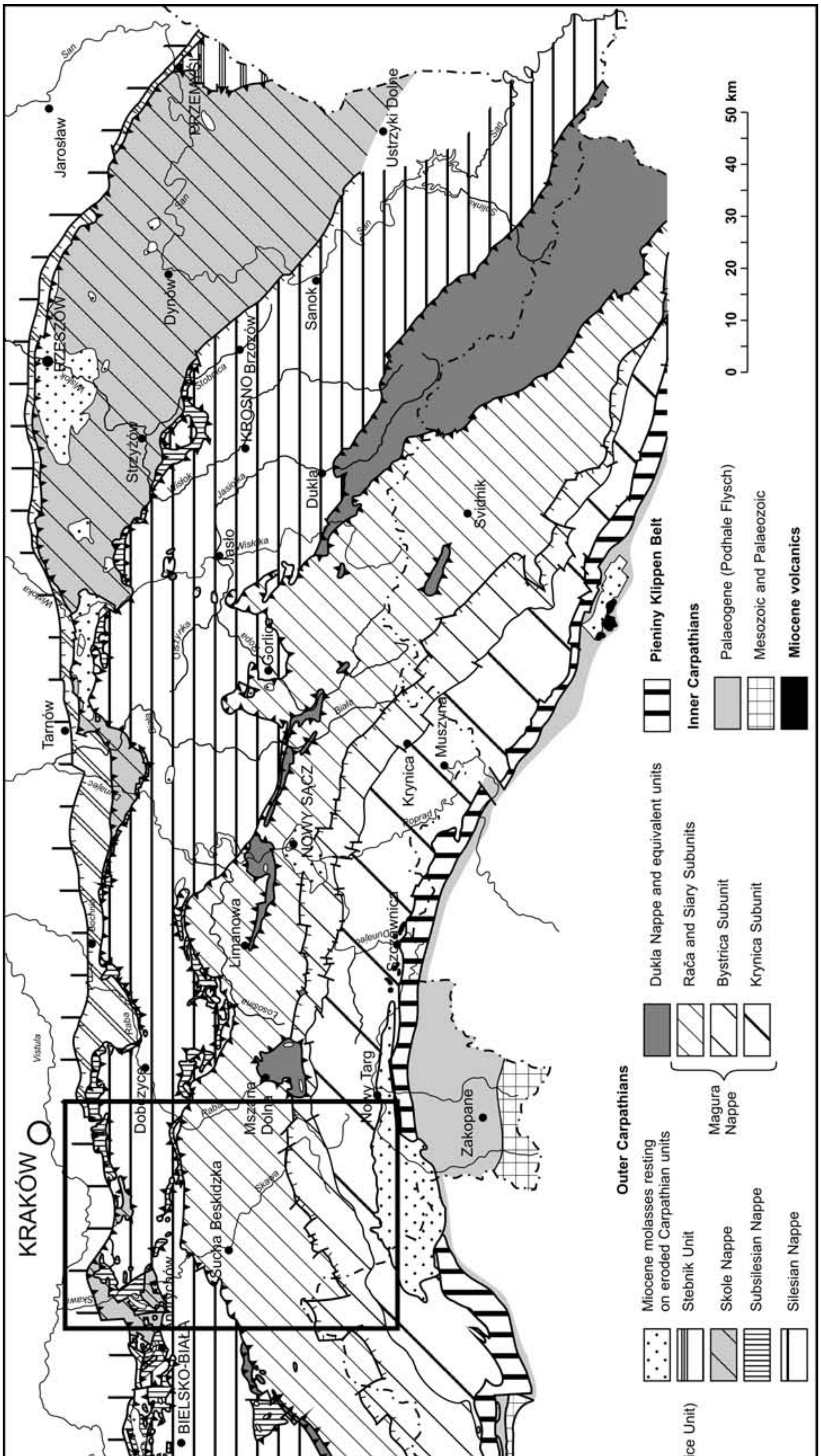

Fig. 2. Geological sketch-map of the Polish Carpathians (based on Żytko *et al.*, 1989; modified), showing location of Fig. 3

(2000), individual mesoregions truncated by the Skawa River include the Western Beskidy Mts. (Orava–Podhale Beskid Mts., Rabka Basin, Babia Góra Range, Beskid Makowski Mts., Beskid Mały Mts.) and the West Beskidy Foothills (Wieliczka Foothills), as well as the Oświęcim Basin (Fig. 1B). The Beskidy Mts. are typified by moderately high mountain ranges composed of either monoclinal or synclinal ridges, whereas the foothills are usually low to moderately-high (Starkel, 1972).

The Beskid Żywiecki Mts. are dominated by SW–NE and N–S oriented, broad mountain ridges built of thick-bedded middle Eocene sandstones, and separated by tectonically-controlled deeply-cut valleys. Relief energy values range between 350 and 760 m; slopes are inclined at 15° to even 35°. The Jabłonków Depression forms a belt of irregular depressions, dissected up to 440 m and oriented WSW–ENE, shaped along the contact between the Magura and Silesian nappes (Fig. 2). Its southern margin is delimited by the thrust of the Rača slice onto the Siary slice of the Magura Nappe; the NE margin coincides with the lower Skawa River fault (Rączkowski *et al.*, 1985). The Beskid Mały Mts., in turn, are largely composed of W–E oriented ridges built of resistant Upper Cretaceous sandstones of the Silesian Nappe, separated by deeply-cut, steep-sided valleys. East of the Skawa River, this unit contacts with the Beskid Makowski Mts. The foothills are represented by flat-topped ranges elevated 350–410 m a.s.l., separated by broad valleys. The southern (Babia Góra Range) and medial portions (Beskid Mały Mts.) of the Skawa River catchment, developed on synclinorial and anticlinorial units of the Magura Nappe, respectively, are dominated by mountain ridges which clearly show relief inversion and poor concordance with structural grain of this nappe; a feature indicative of young uplift. Prevailing orientations of more than half of transversal valleys, in turn, tend to follow fault zones (Jakubska, 1978, 1987, 1995). Drainage density values in the southern part of the catchment change between 1.9 km/sq. km on thick-bedded sandstones to 2.3 km/sq.km on thin-bedded shale-sandstone complexes (Jakubska, 1995).

The upper part of the Skawa River catchment is typified by mature landscape of low relief energy (Szaflarski, 1931; Klimaszewski, 1932; Kukulak, 1995). In the northern part, particularly between Skawce and Mucharz, three structural (Mądry, 1971) and – possibly – antecedent (Klimaszewski, 1955) water gaps occur, in which the river cut deep meanders. Some authors concluded about the Pliocene/Early Quaternary drainage pattern changes in this zone, consisting in eastward directed relocation of the Skawa River (Mądry, 1971). Farther upstream the Skawa River flows in a braided channel. Remnants of erosion surfaces are preserved on valley sides and surrounding ridges, rising 300–350 m, 200–225 m, 150–175 m, and 75–100 m above the present river bed. Traditionally, these used to be related to the Beskidy, intramontane, foothills and river-side levels (“planation surfaces”; Starkel, 1969, 1972; Malarz, 1974; Malarz & Ziętara, 1975; Zuchiewicz, 1984), respectively, the lowermost of which is represented by highly elevated Early Pleistocene strath terraces or soft-rock pediments. The hitherto-suggested Late Miocene and Pliocene ages of higher situated older surfaces are poorly constrained.

The Skawa River catchment area amounts to 1160 sq. km. Its maximum basin length is 58.4 km, elongation ratio 0.66, median altitude calculated from hypsographic curve 496 m a.s.l., and average slope (Strahler index) 0.026. The last parameter changes considerably in the upper (0.039) and central (0.055–0.051) parts of the catchment (Dobija *et al.*, 1979; Chełmicki, 1991). Difference in altitude between the headwaters and the mouth is 506 m, and the average gradient of river bed amounts to 5.501 m/km (Zuchiewicz, 1995b). The long profile is highly uneven, showing increased gradients in water-gap segments (*cf.* Mądry, 1971; Zuchiewicz, 1980, 1995b) that are cut into strongly resistant Oligocene, Eocene, and Upper Cretaceous flysch sandstones.

GEOLOGICAL SETTING

The main tectonic features of the Outer Carpathians were formed during the Eocene through Miocene subduction, subsequent Miocene collision, and Miocene to Recent collapse. In the southern part of the area, within the Magura Nappe, the Oligocene–Miocene evolution consisted in NW-verging (in the present-day geographic coordinates) synsedimentary folding and thrusting, followed by NE-verging thrusting accompanied by strike-slip faulting, and subsequent regional collapse associated with normal faulting (Decker *et al.*, 1997; Hurai *et al.*, 2000; Zuchiewicz *et al.*, 2002). The kinematics of ongoing faulting has not been reconstructed yet, hence, the reason for the faulting is poorly understood. The most plausible explanations are: ongoing post-collisional shortening, ongoing collapse, or both.

The Skawa River Fault Zone (Fig. 3) cuts through the Bystrica, Rača and Siary slices of the Magura Nappe, the Silesian, sub-Silesian, and Skole nappes composed of Upper Cretaceous through Oligocene flysch strata, and a fragment of the Carpathian foredeep basin filled with Miocene molasses (Fig. 2). The zone is oriented: NW–SE in the northern, NNW–SSE in the middle, and WSW–ENE in the southern (Sucha Beskidzka – Jordanów) segments, respectively (Książkiewicz, 1951a, b, 1958, 1966, 1972, 1974a, b; Unrug, 1980; Cieszkowski *et al.*, 2006a, b; *cf.* Figs 2, 3). The fault displaces sinistrally the Carpathian frontal thrust and frontal thrusts of the Silesian and Magura nappes (Golonka *et al.*, 1981; Żytko *et al.*, 1989). A deep-seated fault beneath Carpathian nappes was believed to accompany the Skawa River course (Borysławski *et al.*, 1981; Żytko, 1985; Paul *et al.*, 1996). This view was later questioned by Ryłko and Tomaś (2001). Recent seismic and magnetotelluric studies appear to indicate that some faults originated in the basement during thrusting of the Carpathian nappes protrude into the latter (*cf.* Pietsch *et al.*, 2007) .

Unrug (1980) distinguished 7 major sinistral strike-slip fault zones in the Polish Outer Carpathians. These zones were considered responsible for clockwise rotation of blocks separated by individual fault zones. One of such zones comprises the SRFZ. A similar view was upheld by Oszczypko and Tomaś (1985) and later by Golonka *et al.* (2004), who considered this fault zone as formed after the Early Badenian (Serravallian) and coeval with shortening of the sub-Silesian Nappe.

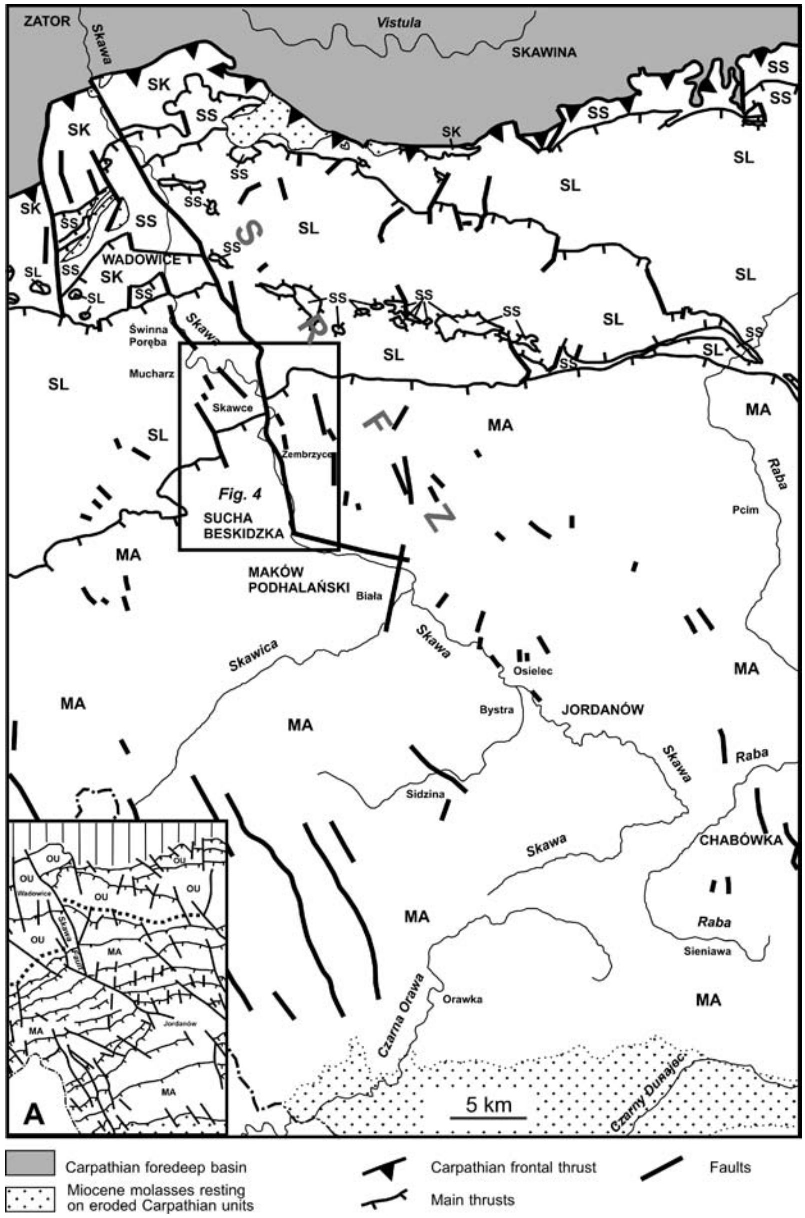

Fig. 3. Geological sketch-map of the Skawa River catchment basin (modified after Golonka *et al.*, 1981). Letter symbols: SRFZ – Skawa River Fault Zone, MA – Magura Nappe, SL – Silesian Nappe, SS – sub-Silesian Nappe, SK – Skole Nappe; **A** – the same fragment of the Polish Outer Western Carpathians redrawn from a map by Jankowski (2007) (modified): barbed lines – major thrusts, fence lines – subordinate thrusts, dotted lines – out-of-sequence thrusts, thick solid lines – faults, dotted area – Neogene infill of the Orava Basin, vertical lines – Carpathian foreland; MA – Magura Nappe, OU – outer units. See Fig. 2 for location

In the middle segment, the SRFZ separates two portions of the Silesian Nappe that show different orientation of map-scale folds and subordinate thrusts: WSW–ENE to the west and E–W to the east. To the west, the Silesian Nappe series build an uplifted block of Beskid Mały Mts. The Siary slice of Magura Nappe is composed of a number of map-scale folds, some of them being imbricated (Książkiewicz, 1972; Golonka *et al.*, 1981; Cieszkowski *et al.*, 2006a, b).

The frontal thrust of Magura Nappe east of the Skawa River and a belt of tectonic windows exposing the sub-Silesian series ESE of Wadowice (Fig. 3A) have recently been described as coinciding with out-of-sequence thrusts (Jankowski, 2007), which were probably formed during the younger of two Miocene episodes of thrusting in the Outer Carpathians of Poland (Zuchiewicz *et al.*, 2002; Tokarski *et al.*, 2006).

Książkiewicz (1966, 1972, 1974a, b) concluded about 5 km post-folding right-lateral displacement of the front of the Magura Nappe along the Skawa River fault system. This hypothesis was questioned by Aleksandrowski (1985, 1989), who, basing on detailed structural studies of fractures, claimed dip-slip character of this fault zone and even challenged the presence of a major fault along the Skawa River valley between Biała and Osielec (Fig. 3). He did not, however, exclude a possibility of formation in pre- or early folding time of a tear fault in this zone, particularly between Skawce and Sucha Beskidzka (Zembrzyce fault). In Aleksandrowski's (1985, 1989) opinion, this fault was active as a dip-slip fault after folding, whereas the Skawa River valley segments Sucha Beskidzka–Maków and Biała–Osielec developed along the strike of map-scale diagonal folds of the Andrychów–Jordanów tectonic zone, formed during the younger episode of folding in the Western Carpathians, being coeval with folding in the eastern portion of this fold-and-thrust belt. No major fault was marked in this area on a 1: 500, 000 general tectonic map by Żytko *et al.* (1989). New tectonic studies led to "re-appearance" of the SRFZ, with a proposal of partly new terminology for individual faults and formal lithostratigraphic units (Fig. 4; *cf.* Golonka *et al.*, 2004; Cieszkowski *et al.*, 2006a, b). Authors of the second quoted paper maintain that sinistral motions along individual faults of this zone resulted in the formation of isolated pull-apart basins both in the Silesian and Magura nappes. They also conclude about the presence of a largely independent fault system within the Magura Nappe; few faults only protruding from the Silesian Nappe. In Cieszkowski *et al.*'s (2006a, b) opinion, during thrusting of the Magura Nappe, the Silesian Nappe was already faulted. These faults became reactivated in part, protruding into the marginal, anticlinorial part of the Magura Nappe; whereas the inner Magura slices are only cut by the Skawa fault. The remaining faults are characteristic for the Magura Nappe itself. The oldest fault set in the Magura Nappe is thought to be oriented NNE–SSW (Cieszkowski *et al.*, 2006a). The Silesian and Magura frontal thrusts are displaced to the north by 10 km and 5 km, respectively, east of the SRFZ. The NNW–SSE and N–S trending faults between Zembrzyce and Skawce are considered as downthrowing their eastern sides: thick-bedded Upper Cretaceous sandstones on the west are in contact with Eocene–Oligocene strata on the east. These map-scale faults were interpreted from cartographic intersection criteria; no further detailed structural studies following Aleksandrowski's (1985, 1989) work were performed.

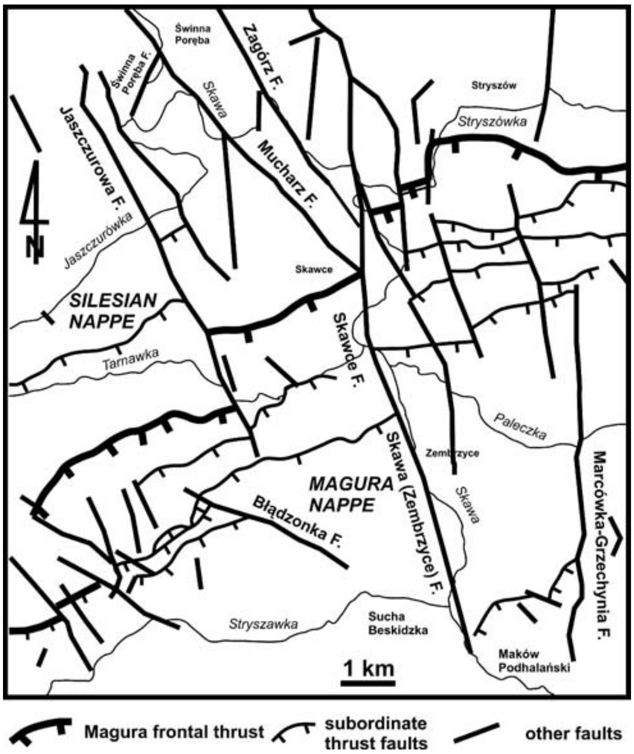

Fig. 4. Geological sketch map of the middle portion of the Skawa River catchment basin, showing location of major faults (modified after Cieszkowski *et al.*, 2006a). See Fig. 3 for location

FAULT PATTERN

We analyzed spatial distribution of map-scale faults within different tectonic units underlying the Skawa River catchment basin (Figs 3, 4), basing on geological maps by Golonka *et al.* (1981) and Cieszkowski *et al.* (2006a, b). Dip-slip, oblique-slip and strike-slip faults, of total length amounting to 237 km in the entire studied area shown in Fig. 3, tend to cluster around two dominant orientations: N20–30°W (26%) and N10°W to N–S (15%; *cf.* Fig. 5A), pointing to a dextral sense of motion along the N20–30°W set, which is roughly parallel to the faults accompanying the lower reach of the Skawa River valley within the Silesian, sub-Silesian and Skole nappes, as well as a number of similarly oriented long faults in the south-western part of the Magura Nappe. In the medial segment of the Skawa River valley shown in Fig. 4, crossing the Siary slice of the Magura Nappe and southern portion of the Silesian Nappe, such faults of total length 101 km tend to strike N10°W to N–S (16%) and N30–40°W (16%), indicating a dextral sense of motion along the N30–40°W set (Fig. 5B), coinciding with the fault zone aligned parallel to the Skawa River valley between Sucha Beskidzka and Skawce. On the other hand, thrust faults marked in Fig. 3 (342 km in length) are mainly oriented W–E to N80°W (22%), less frequently N40–50°W (7%; Fig. 5A), whereas those shown in Fig. 4 (57 km in length) cluster around N70–80°E (21%) and N30–40°E (5%; Fig. 5B) orientations.

PHOTO- AND TOPOLINEAMENT PATTERN

The studied portion of the Outer Western Carpathians is cut by two trans-continental photolineaments: one oriented W–E, and another one running NW–SE, roughly along the Skawa River course (Motyl-Rakowska & Ślączka, 1984).

The Skawa River fault zone is accompanied on the east by a regional photolineament identified on satellite scenes (*cf.* Doktór *et al.*, 1985, 1989), and a number of minor topolineaments well-marked on both LANDSAT MSS and SRTM images (Ozimkowski, 2008). As far as photolineament pattern is concerned (Fig. 6), the Skawa River valley parallels two to three medium-sized, subordinate photolineaments, particularly north of Sucha Beskidzka (NNW– SSE to NW–SE) and, to a lesser extent, between Sucha and Osielec (WNW–ESE) (Doktór *et al.*, 1989). The entire Skawa River catchment area is bounded to the west and east by major photolineaments crossing all units of the Outer Carpathians, and oriented N–S to NNW–SSE and NW–SE, respectively (Fig. 6). Dominant orientations of photolineaments in the western portion of the Polish Outer Carpa-

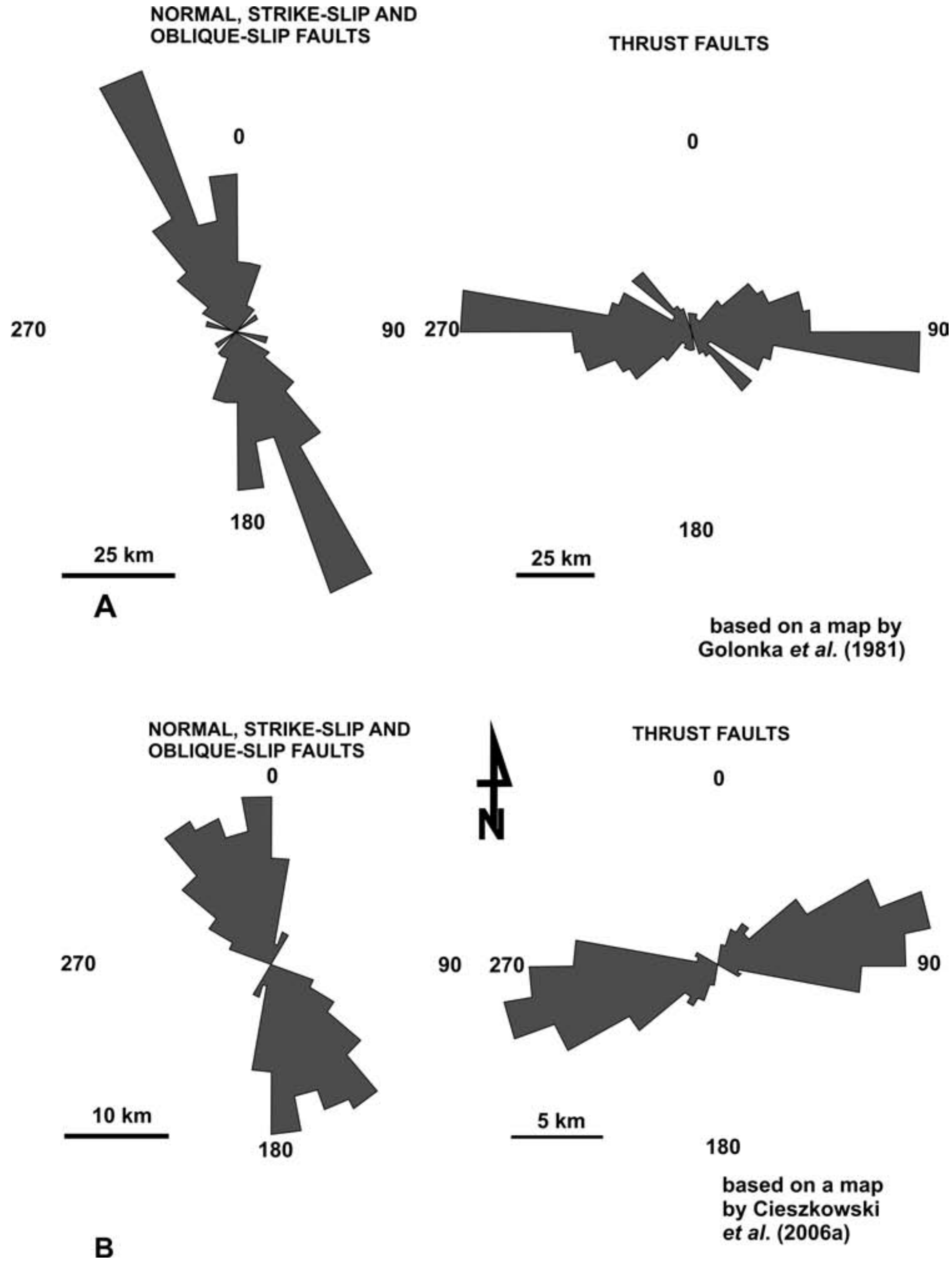

Fig. 5. Polar histograms showing orientation and length distribution of faults measured from figures 3 (upper pair of diagrams) and 4 (lower pair of diagrams)

thians are N30–25°W and N25–40°E (Doktór *et al.*, 2002). Lineaments visible on radar images near Wadowice, east of the Skawa River valley, cluster into two groups oriented N35°W and N25°E, whereas close to the valley itself a NNW–SSE trend prevails (Mastella & Szynkaruk, 1998). The first two groups of lineaments were interpreted by the quoted authors as conjugate strike-slip faults formed in the Early Sarmatian, and later reactivated as normal faults; the third one was described as belonging to the SRFZ.

Principal topolineaments interpreted by us from DEM (SRTM-level 2) image (Fig. 7) coincide to a large extent with mapped faults (*cf*. Fig. 3), although some of them appear to be lithologically-controlled, like those at the Carpathian margin in the NW corner of Fig. 7. The medial and northern portions of the Skawa River valley are composed of a number of rectilinear segments, particularly well visible between Jordanów and Osielec, Maków Podhalański and Sucha Beskidzka, close to Świnna Poręba, as well as SE of Zator. Subordinate, less clearly marked, topolineaments are mostly confined to WSW–ENE oriented depressions and tributary valleys of main rivers, except the NW part of the foothills area.

Dominant orientations of principal topolineaments (Figs 7, 8), of a summary length of 352 km, are grouped into two sets: N20–30°W (16%) and N–S to N10°E (13%), showing a fairly good correlation with orientations of strike-slip, oblique-slip and normal faults portrayed in Figures 3 and 5. Subordinate topolineaments (in total 632 km

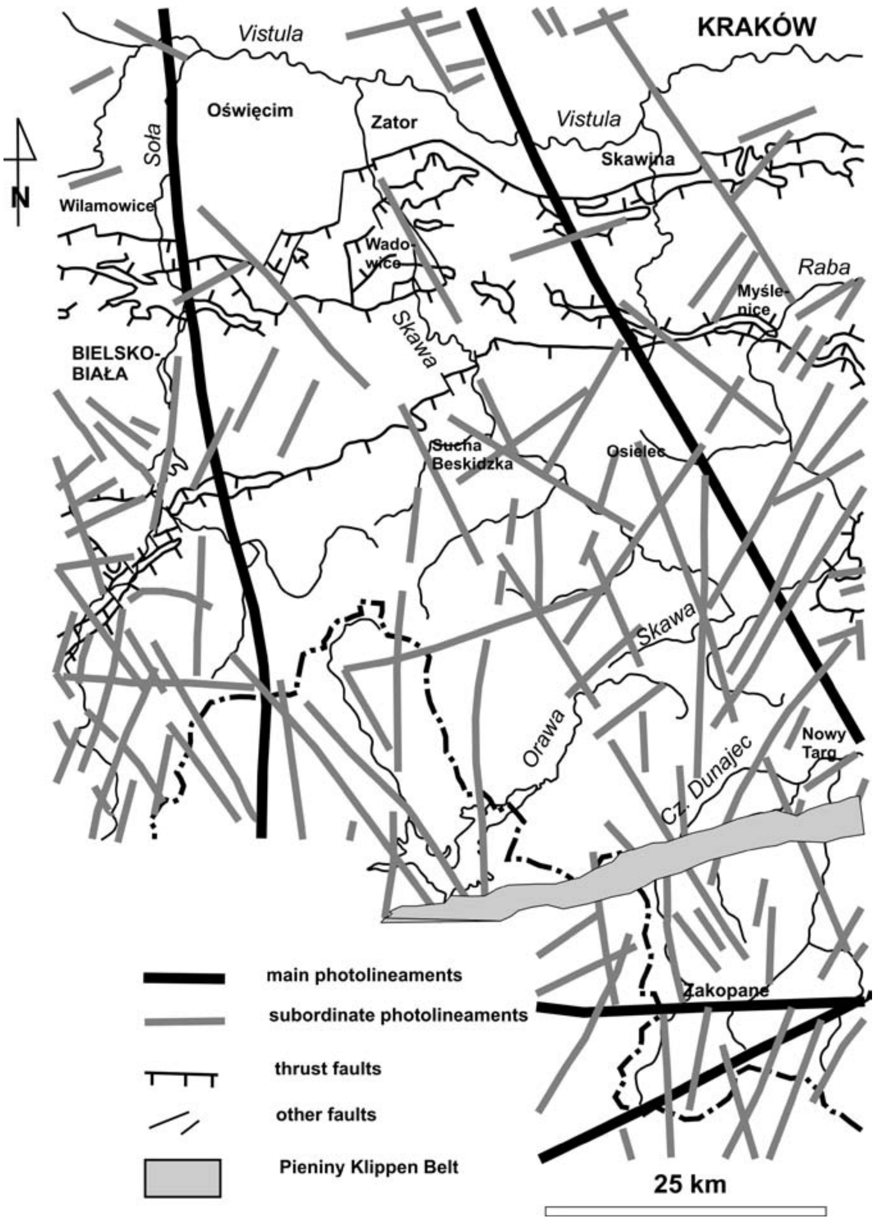

Fig. 6. Photolineament pattern in the Outer Western Carpathians of Poland (modified after Doktór *et al.*, 1985, 1989)

long), in turn, form two sets oriented N60–70°E (8%) and N50–60°W (8%), poorly coinciding with the strikes of mapped faults, although being subparallel to the out-of-sequence thrusts identified in this area by Jankowski (2007) (*cf*. Fig. 3A).

RESULTS OF MORPHOTECTONIC STUDIES

Analysis of rectified drainage network of the Skawa River drainage basin (Zuchiewicz, 1986), classified according to the Horton-Strahler's hierarchy on 1:100, 000 topographic maps, points to a close relationship between the orientation of tributary valleys and map-scale thrust faults, whereas the trunk valley orientation is largely controlled by the strike of individual segments of the SRFZ. Dominant orientation of the ≥4th-order valleys approaches N60°E; subordinate orientations are N–S and N20°W.

Empirical observations of fluvial erosion in different fluvial systems all over the world suggest a positive correlation between channel gradient and rock uplift rate. The latter exerts first-order control on power-law scaling between channel slope and contributing drainage area (Hack, 1973; Moglen & Bras, 1995; Snyder *et al.*, 2000; Kirby & Whipple, 2001; Whipple & Tucker, 2002; Brocard & van der Beek, 2006; Wobus *et al.*, 2006).

The northern and southern segments of the SRFZ coincide with valley reaches that show abnormally high riverbed gradients, marking two well-pronounced, E–W oriented, zones of neotectonic uplift in the western part of the Outer Carpathians (Zuchiewicz, 1995a, 2001) (Fig. 9).

The bifurcation ratio of the Skawa River catchment amounts to 4.92, and the proportion of 1st-order valleys to

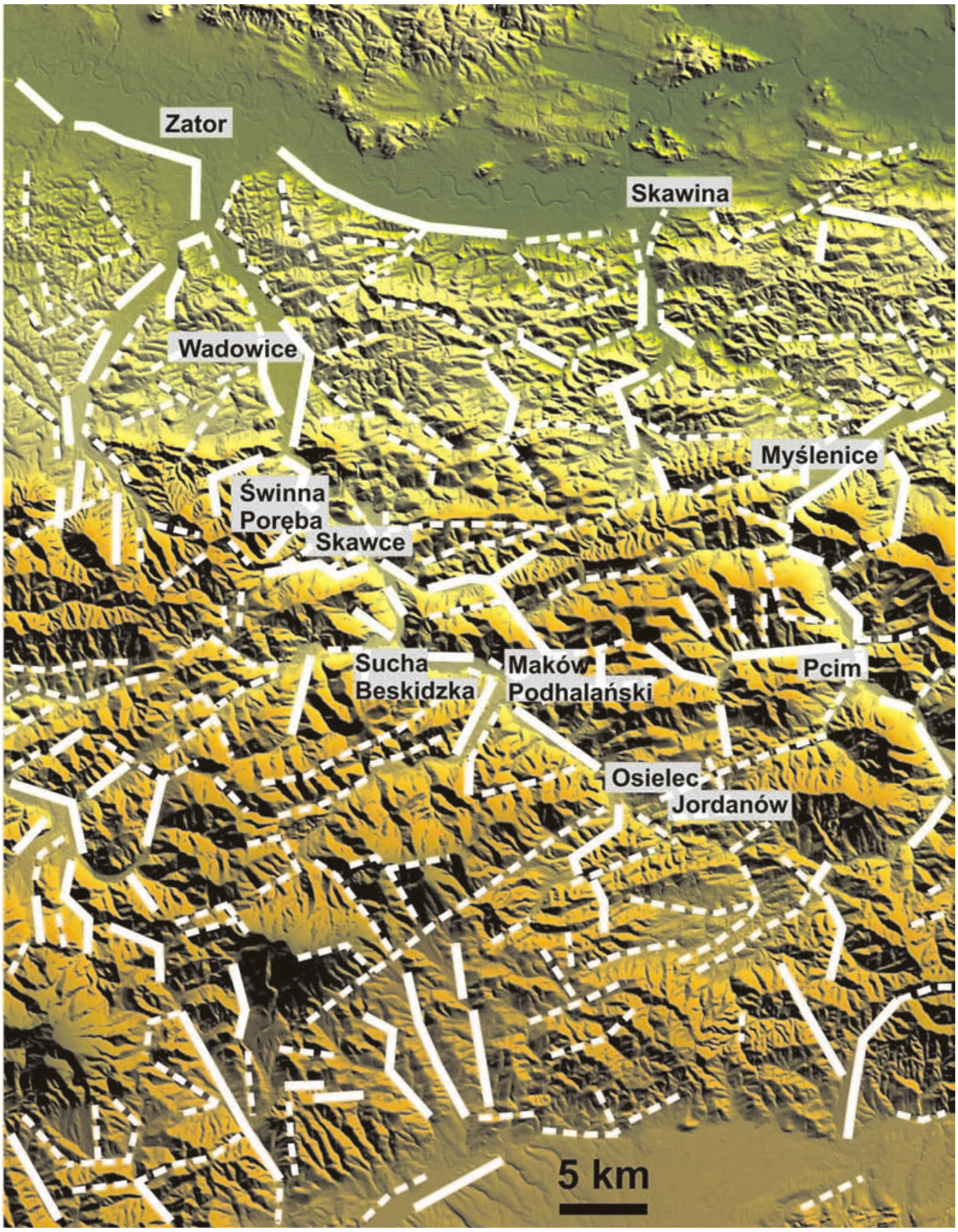

Fig. 7. Topolineaments interpreted from digital elevation model (SRTM level 2). Thick solid lines denote principal, and thin dashed lines subordinate topolineaments

the total number of valley segments (N_1/N) is nearly 77%, ranking high among drainage basins of the Outer Carpathians. The bifurcation ratio (Rb) is the arithmetic mean calculated from fractions N_u/N_{u+1}, where u denotes the valley order, and N is the total number of valleys of a given order. High bifurcation ratios in the Outer Carpathians are confined to areas showing intense Quaternary surface uplift (Zuchiewicz, 1995a). High values of N_1/N ratios are considered to reflect intensive relief rejuvenation, controlled by neotectonic uplift (Zuchiewicz, 1991). Both parameters appear to indicate a relatively high rate of drainage network growth, most probably due to increased neotectonic activity of this region.

Other principal parameters characterizing the Skawa River catchment basin do not differ much from those calculated for other Outer Western Carpathian river basins (Fig. 10). Important is, however, the concavity ratio. This parameter is commonly comprised between 0.3 and 0.6, exceptionally attaining 1.1 for some rivers (cf. Moglen & Bras, 1995; Snyder *et al.*, 2000; Wobus *et al.*, 2006). Low values are characteristic for immature river profile segments. The Skawa River profile attains one of the lowest values of concavity ratio (0.33) among main catchment basins of the Polish Carpathians what points to a relatively low degree of river profile maturity.

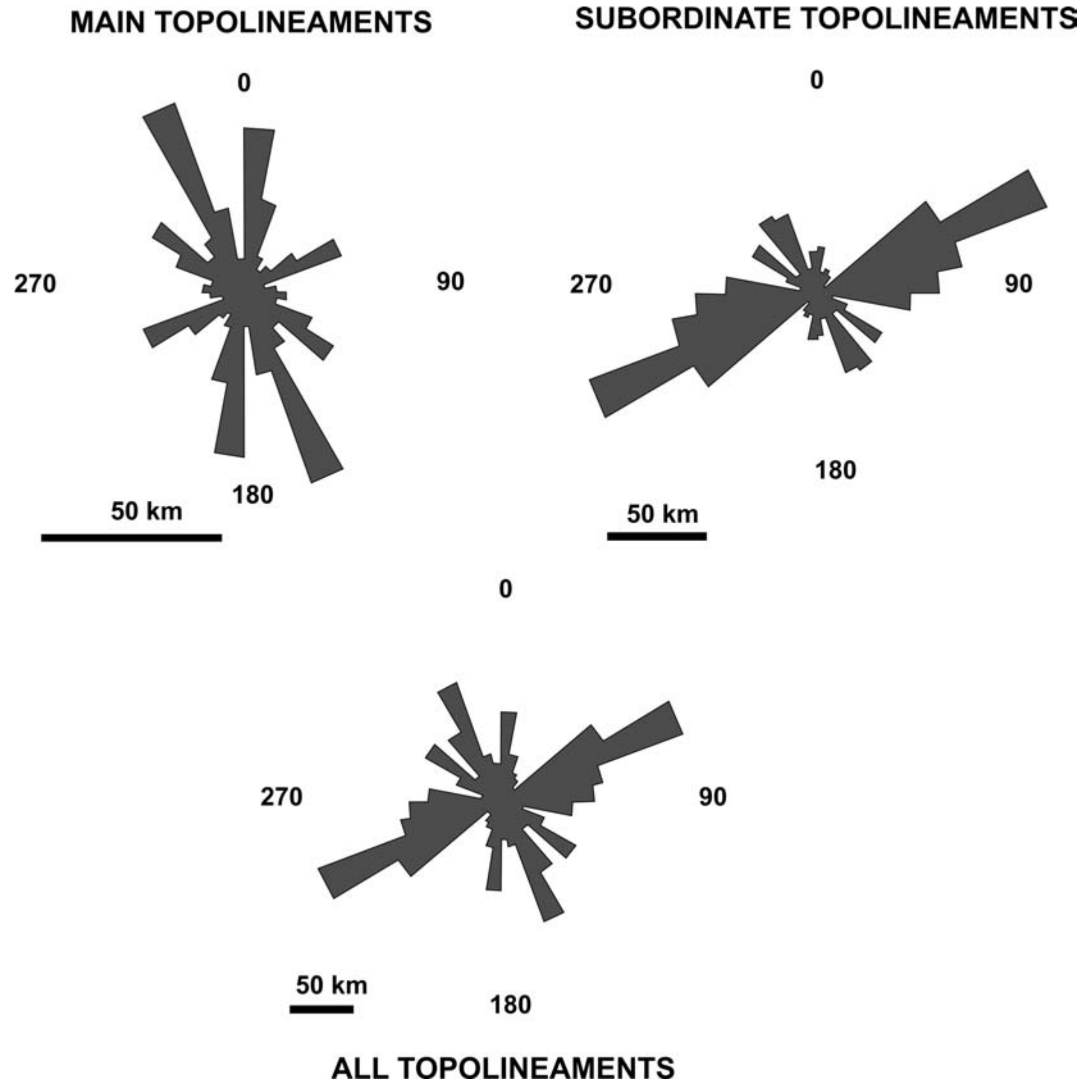

Fig. 8. Polar histograms showing orientation and length distribution of topolineaments measured from Fig. 7

Another important parameter, the valley floor width – valley height ratio (Bull, 1978; Bull & McFadden, 1980), is calculated as:

$$Vf = 2Vfw/[(Eld - Esc) + (Erd - Esc)];$$

where Vfw is the width of the valley floor, Eld and Erd are elevations of the left and right valley divides, respectively, and Esc is the elevation of the valley floor. This ratio differentiates between broad-floored valleys, with relatively high values of Vf, and V-shaped canyons with relatively low values. Low values of Vf reflect deep valleys of actively incising streams, commonly associated with uplift (Keller & Pinter, 1996). This ratio is especially sensitive to Late Quaternary tectonic base-level falls. Figures quoted by Bull and McFadden (1980) for the Garlock Fault zone, California, range between 0.05–47, averaging 1.3–11.0. Tectonic activity classes of mountain fronts in west-central Nevada (Bull, 2007) reveal the following mean values of Vf: classes 1 and 2 (tectonically active) 0.06–0.51, class 3 (moderately active) 1.2–1.7, class 4 (slightly active) 1.0–7.0, and class 5 (inactive) 2.0–7.8. For the Western Transverse Ranges (California), in turn, these values fall into intervals of 0.43–0.80 (class 1), 1.8–1.9 (class 2), and >1.9 (class 3) (Keller & Pinter, 1996). In areas situated in more humid climatic zones, however, the respective figures will certainly attain higher values.

All these parameters have been calculated for 1-km-long river valley segments at the scales of 1: 25, 000 (river bed gradients, Fig. 11) and 1: 50, 000 (other indices, Fig. 12), and then plotted in both discrete and smoothed form. Each time the highest possible polynomial that – controlled by the least-square method – fits the data best, has been applied. The zones of abnormally high gradients are portrayed in map view showing individual peaks indicated by polynomially-smoothed curves. In case of Vf, Eld, Erd, and Vfw indices, this procedure is different compared to original approach of their creators (*cf*. Bull & McFadden, 1980), who attempted to characterize outlets of canyons/valleys dissecting mountain fronts belonging to different classes of tectonic activity. Here, we adapted a method proposed by one of us (Zuchiewicz, 1995a), in which consecutive downstream, 1-km-long, valley segments were taken into account to show differentiation among valley reaches in different

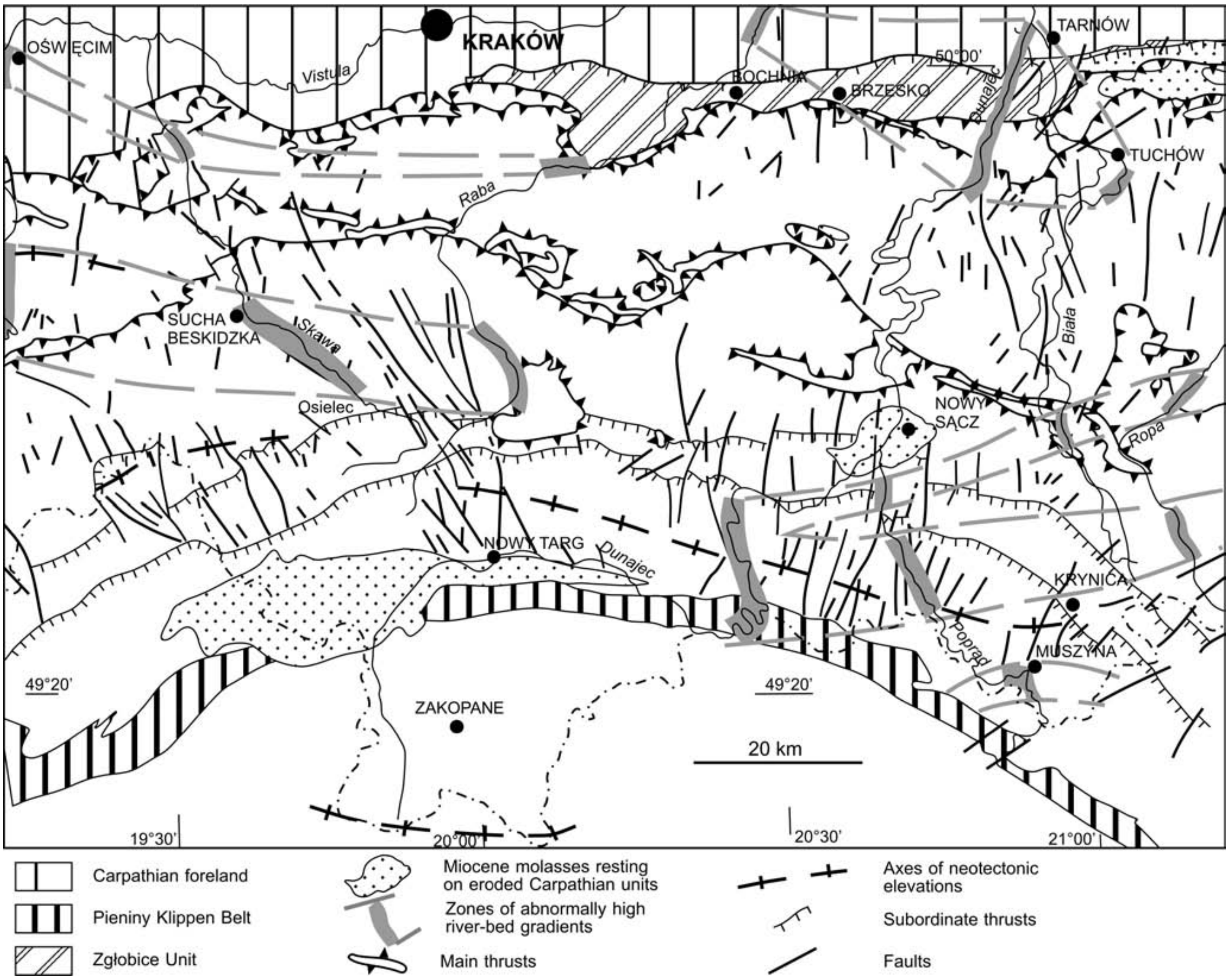

Fig. 9. Neotectonic sketch map of the Western Carpathians of Poland showing location of zones of abnormally high river bed gradients (modified after Zuchiewicz, 1995b; geology based on Żytko *et al.*, 1989 and 1: 50, 000 geological maps of Poland published by the Polish Geological Institute). Note two belts of increased river bed gradients along the Skawa River course

geological and geomorphic units crossed by the river (Fig. 12B, C).

The Skawa River channel is characterized by strongly uneven and, except the upper reach, immature long profile (Fig. 11). Comparison among normalized river bed profiles of main Outer Carpathian rivers (Fig. 11A) shows a peculiar convex-upward segment of the Skawa River in its reach comprised between 30 and 50% of distance from headwaters; a feature comparable only to the Osława River in the East Carpathians, which, however, is much shorter. Farther downstream, two other minor breaks in long profile occur (Fig. 11A, B). This points to distinct segmentation of the profile into reaches of variable, but low concavity ratios, that may reflect young tectonic control (*cf.* Snyder *et al.*, 2000; Kirby & Whipple, 2001; Wobus *et al.*, 2006). Time-series diagram of channel gradients measured for 1-km-long segments, smoothed by the 8^{th}-degree polynomial (Fig. 11C), also shows river bed reaches of abnormally high gradients, bounded by fault zones. The two most prominent high-gradient zones are portrayed in map view in Fig. 9. One of them is situated between Osielec and Sucha Beskidzka in the Magura Nappe, the second one coincides with the lower Skawa River fault cutting the Silesian, sub-Silesian and Skole nappes.

Altitudes of the left divide (Ald = Eld-Esc; Fig. 12B) of the Skawa River valley are highest among all major valleys of the Polish Outer Carpathians (Fig. 12A), amounting to 990 m. High elevation of the western divide compared to relatively low elevation of the eastern one, makes the studied valley one of the most asymmetric valleys in the region. This asymmetry is particularly well marked close to Osielec, *i.e.* at the place where the southern boundary of the zone of abnormally high river bed gradients occurs (*cf.* Fig. 9). Another peak of high Ald values is noticeable near Świnna Poręba, on the western side of the normal Świnna Poręba fault (Książkiewicz, 1974a, b; Cieszkowski *et al.*, 2006a). This peak may reflect both the presence of highly resistant Upper Cretaceous sandstone complexes and reactivation of the fault, downthrowing the eastern side. The second option appears to be confirmed by abnormally high po-

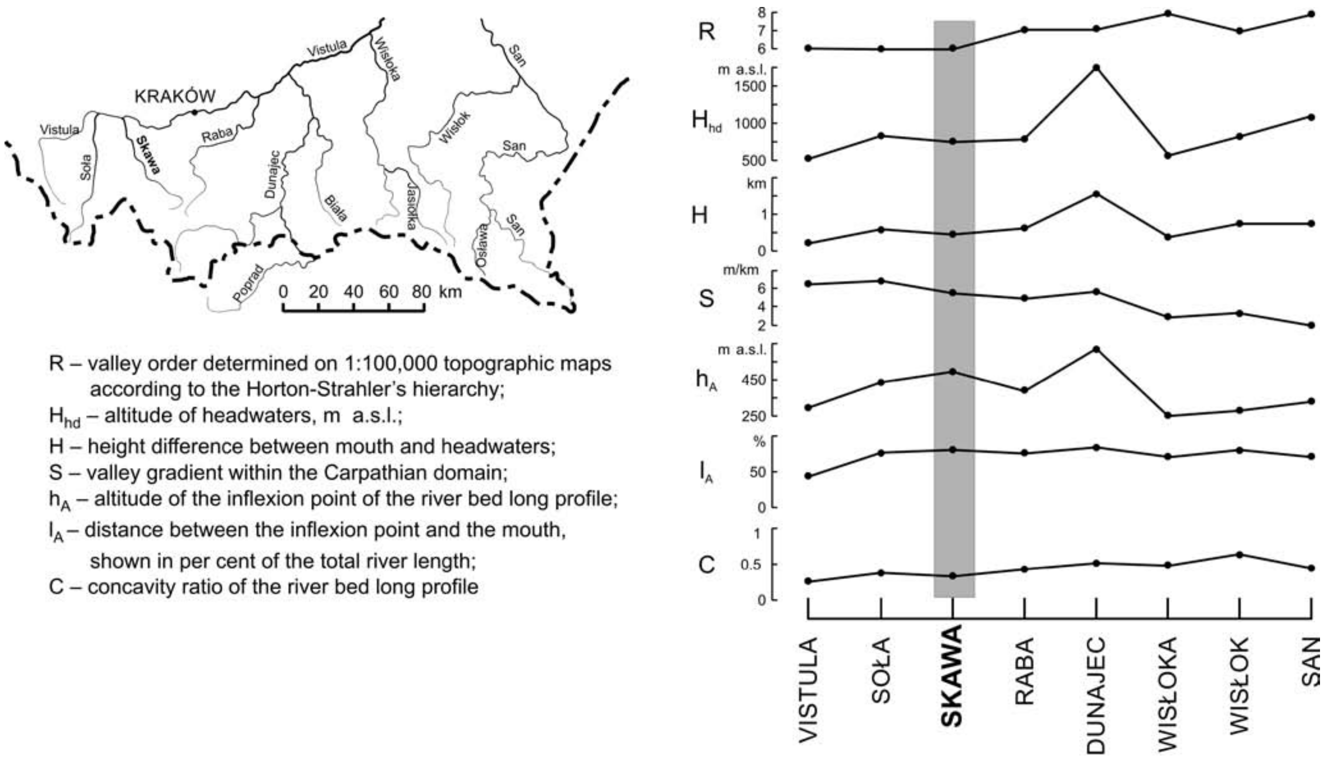

Fig. 10. Selected parameters of the Polish Outer Carpathian drainage basins, showing the position of the Skawa catchment (adapted from and modified after Zuchiewicz, 1995a)

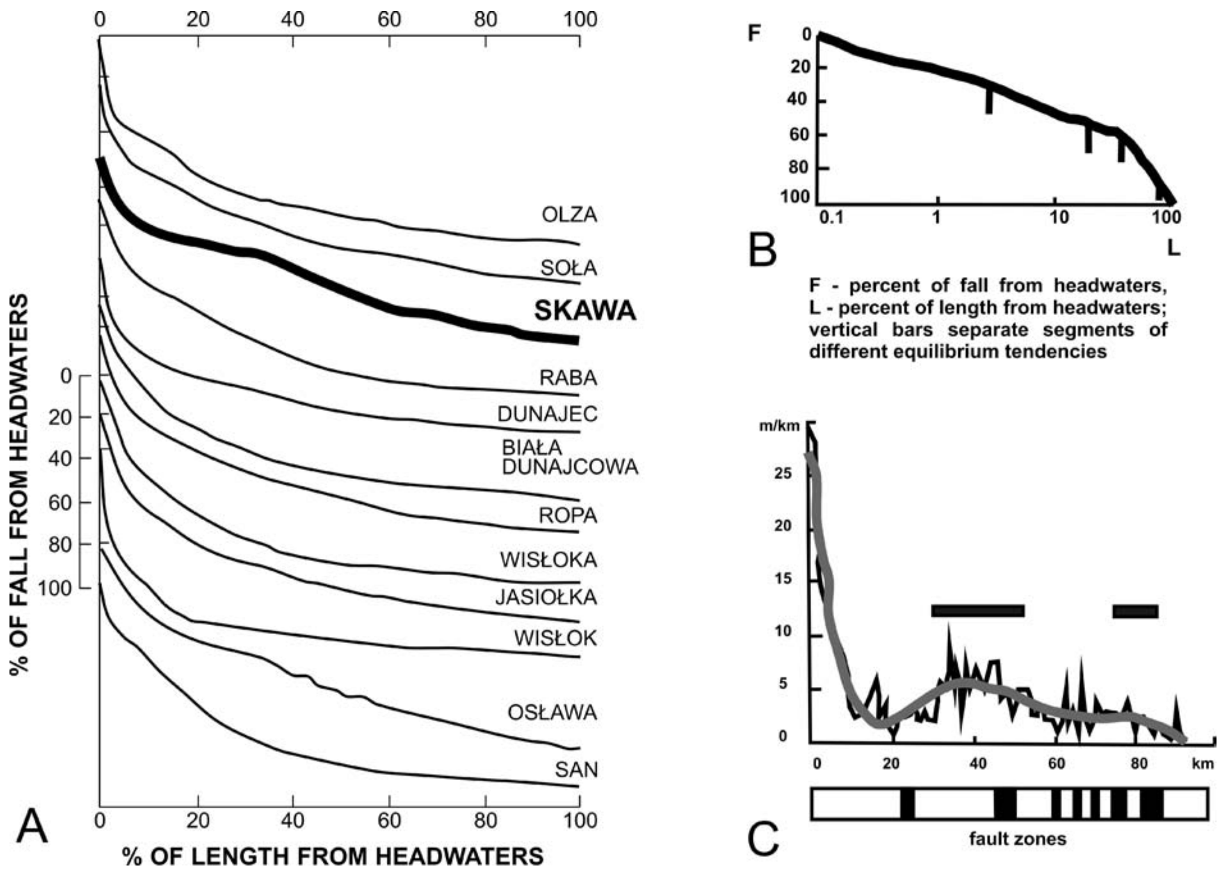

Fig. 11. Normalized river bed profiles (**A**) of the main Polish Outer Carpathian rivers and semi-logarithmic plot of such a profile constructed for the Skawa River (**B**), showing segments of different equilibrium tendencies. Cartoon (**C**) portrays river bed gradients along the Skawa River course, smoothed by the 8th-order polynomial and the location of principal fault zones crossed by the river. Thick bars above diagram denote segments of abnormally high gradients (adapted in part from Zuchiewicz, 1995a, b; modified and supplemented)

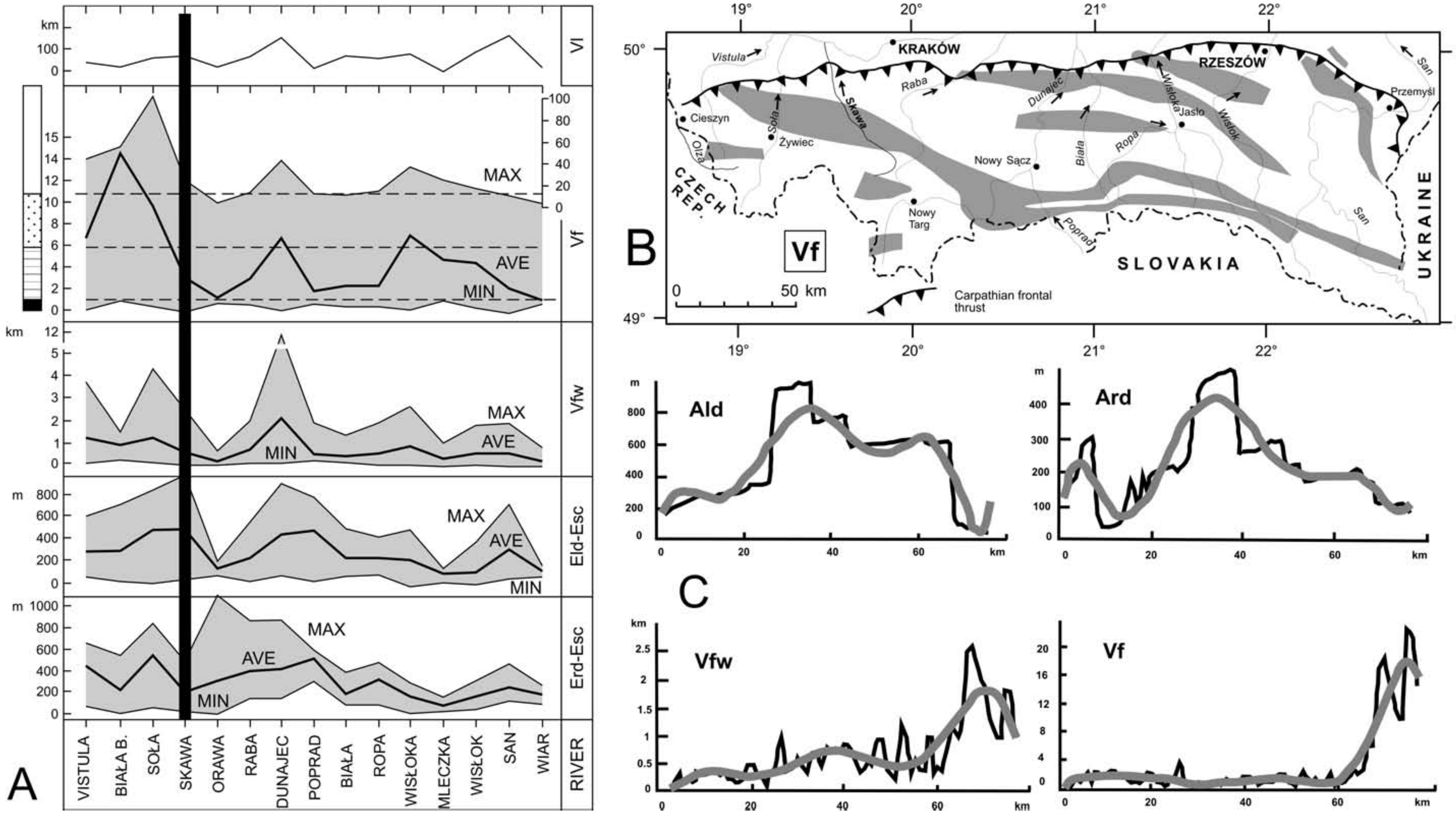

Fig. 12. Selected river valley parameters in the Polish Outer Carpathians (**A**, **B**) and the Skawa River valley (**C**). Vl – valley length, Vf – valley floor width – valley height ratio, Vfw – valley floor width, Eld – elevation of the left divide, Erd – elevation of the right divide, Esc – elevation of river bed; Ald – altitude of the left divide, Ard – altitude of the right divide. Tectonic activity classes in (**A**): black – strong, ruled – moderate, dotted – weak, white – inactive. (**B**) shows spatial distribution of minimal values of Vf parameter in the Polish Carpathians, interpreted from polynomially smoothed time-series analyses of discrete data calculated for 1-km-long valley segments (adapted from Zuchiewicz, 1995a; modified and supplemented)

sition of the Weichselian Early Glacial strath terrace on the western side, described in detail and dated by Grzybowski and Śniadek (1997), and Grzybowski (1998a, b, 1999, 2004).

Vf values throughout the entire Carpathian reach of the Skawa River valley are relatively low (averaging 2.0), increasing by one order of magnitude within the Carpathian Foredeep, in front of the Carpathian frontal thrust (Fig. 12B, C).

DEFORMATION OF QUATERNARY FLUVIAL TERRACES

The studies of Quaternary fluvial sediments in the Skawa River valley along its entire reach were initiated by Szaflarski (1931) and continued by Klimaszewski (1932, 1948). The latter's scheme of terrace ages was later adapted by Książkiewicz (1951a, b, 1974a, b). Late Pleistocene organic sediments overlying alluvium of the last glacial age between Wadowice and Zator were examined by Sobolewska *et al.* (1964), Koperowa and Środoń (1965), and Tokarski (1966), and later revised by Grzybowski and Bińka (1997). Full spectrum of terraces in this area was studied in detail by Bober *et al.* (1980). Farther upstream, within the Skawa River water-gap sector between Skawce and Świnna Poręba, Quaternary terraces were investigated by Mądry (1971), whereas Grzybowski and Śniadek (1997) and Grzybowski (1998b) recognized unusually high situated fluvial sediments of the Weichselian Early Glacial, overlain by palynologically dated Brørup peat at Świnna Poręba. Wójcik and Rączkowski (1994) described terraces of the Skawa River close to Osielec. Grabowski and Miroslaw (1995) analyzed terrace sequence in the Paleczka River valley, a right-hand tributary of Skawa near Zembrzyce. Kopyść (1997) and senior author of this paper (Zuchiewicz, unpublished data 1993–1994) mapped fluvial terraces and related slope sediments in a segment comprised between Osielec and Świnna Poręba, whereas Grzybowski (1998a, 1999, 2004) interpreted changeable gradients of straths, cut-and-fill terraces, and present-day river bed of the Skawa River between Maków Podhalański and Wadowice. Different views on the number and age estimation of individual terraces are listed in Table 1.

Between Osielec and Świnna Poręba (Figs 3, 13A), the highest situated rock benches (T_1) that can be related to Early Pleistocene fluvial activity rise 75–100 m above the present river bed. Their lengths rarely exceed 500 m (av. 200 m), and widths are between 50 and 100 m. These landforms are mainly preserved on eroded flysch strata of high and moderate resistance to denudation and erosion, in the middle segment of the Skawa River catchment.

In the lower valley reach near Wadowice (Fig. 3), a 22 m high strath is overlain by two layers of loams separated by gravels and covered by younger Pleistocene strata (T_2; Bober *et al.*, 1980).

The Middle-Late Pleistocene straths in this segment comprise four steps preserved on valley sides (Fig. 13a, b). The oldest one, devoid of alluvium between Maków and Sucha (Figs 3, 13A, B), and bearing up to 5 m of gravel and sand covered with solifluction-slopewash sediments farther downstream, rise 30–35 (40) m above recent floodplain (T_3). Downstream from Świnna Poręba, in the water-gap segment, they are missing (Fig. 13B) and re-appear close to Wadowice as 15–35 m (Klimaszewski, 1948; Książkiewicz, 1951a, b) or 20–21 m (Bober *et al.*, 1980) high terrace steps, in which 10–14 m straths are overlain by sands, silts and slope loams.

A younger step is represented by terrace risers of 15–20 m (Osielec–Sucha) to 22–30 m (Zembrzyce–Mucharz) height (T_4), with straths rising downstream from 11–12 m to 18–20 m (Zuchiewicz, unpublished data 1993–1994; Kopyść, 1997). Near Wadowice, their equivalent is represented by a buried terrace, where 2–5 m high rock benches are overlain by 7–9 m thick alluvium capped by 16-m-thick loess-like silts (Bober *et al.*, 1980).

Two lower steps display important changes in relative height along the Skawa River course. The higher one rises from 10–15 m close to Osielec to 22 m near Świnna Poręba (T_5), its straths also rising downstream from 6–10 m to 20 m (Zuchiewicz, unpublished data 1993–1994; Kopyść, 1997). At Świnna Poręba, 3 km south of the Silesian frontal thrust, a 18.3–20.7 m high strath is overlain by up to 5 m thick gravel, sand and silt, bearing at the top organic silts and peat of a fossil oxbow lake, palynologically dated to the Brørup interstadial. These strata are unconformably overlain by colluvial and solifluction sediments (Grzybowski & Śniadek, 1997; Grzybowski, 1999). Close to Wadowice, in turn, the top of organic oxbow lake sediments overlying alluvium rises 9.7 m, its substratum being placed 0 m to 4 m below the present river bed (Sobolewska *et al.*, 1964; Bober *et al.*, 1980). These organic sediments are correlated with the Brørup interstadial peat, described from Zator farther downstream (Koperowa & Środoń, 1965).

The lower terrace step (T_6) maintains comparable height along the Skawa River course between Osielec and Świnna Poręba, rising 5–8 m to 9–10 m within alluvial fans at the mouths of tributary rivers. In the upper and middle river course, this is a terrace wherein up to 7 m thick alluvium overlies 1 to 4.5 m high straths. Downstream from Mucharz, this level represents an accumulation, cut-and-fill terrace, in which alluvium rests on bedrock placed 4 m to 3.5–4.5 m below the present river bed near Świnna Poręba (Grzybowski & Śniadek, 1997) and Wadowice (Bober *et al.*, 1980), respectively. In this segment, the described terrace cover is composed of both late Weichselian and Holocene alluvium (Grzybowski & Śniadek, 1997; Bober *et al.*, 1980), the top of which rises 3–5 m at Wadowice.

Lower situated terrace steps are confined to the valley bottom, the width of which changes between 400 and 650 m downstream from Osielec, narrowing near Świnna Poręba to 350 m. These steps do not show any relation to slope sediments. Two higher terraces (4–5 m, 3–3.5 m; $T_{7–8}$) are cut-and fill landforms, except the 4–5 m terrace at Osielec, where alluvium rests on a strath rising 0.5–1 m. Farther downstream, the base of alluvium slopes below present river bed. Lower terraces (2–2.5 m, 1–1.5 m, 0.5–1 m; T_{9-11}) compose recent floodplain and gravel bars (Fig. 13A, B).

Table 1

Views on the number and age of Quaternary fluvial terraces in the Skawa River valley.
Heights of terrace risers in metres (in brackets – heights of straths)

stage (Polish and West European climato-stratigraphy)	Szaflarski (1931)[1]	Klimaszewski (1948)	Książkiewicz (1951a,b, 1974a,b)	Mądry (1971)	Bober *et al.* (1980)[2]	Wójcik & Rączkowski (1994)[3]	Grabowski & Mirosław (1995)[4]	Kopyść (1997)	Grzybowski & Śniadek (1997), Grzybowski (1998a,b, 1999)[5]	terraces (this paper)
Holocene	2-3, 2-4	0.5-1 1-1.5 1-2	1-3 2-3	1-2	3-5[6]	0.5-2 3-8	0.5-1.5 1.8-3 3.5-5.5	0.5-1 1-1.5 2-2.5 3-3.5 4-5 (0.5-1)[7]	2-4 (-4)[6]	T_{11} T_{10} T_9 T_8 T_7
Vistulian (Weichselian) Pleniglacial Early Glacial		3-6	3-6	3-6	3-5[6] 8.5-11.5 (0 to -4)	6-15	17-19	5-8 to 9-10 (1-4.5, av. 2-3) 10-15 (8) to 22 (20)	22.5-23 (18.3) to 9.7 (-2.5)	T_6 T_5
Wartanian (Saalian-2) Odranian (Saalian-1)	16-22 18-30	7-9	7-10 8-14	7-10	11-12.5 (2-5)[8]	15-25	30-35 (25)	15-20 (11-12) to 22-30 (18-20) 30-35-40?		T_4
Sanian (Elsterian-2) Nidanian (Elsterian-1)	35-40	15-30 (10-15)	16-30 15-35	17-23 (12-18)	15-35 (10-15)[9] to 20-21 (12.5-14)			30-35-40?		T_3
older Pleistocene stages	50-60[10] 80-100[10]				26-27 (22)	80-130[10]		75-100[10]		T_2 T_1
Pliocene	110-120[10] 150-170[10]			75				150-175[10]		

[1] no age provided; interpretation by authors of this paper; [2] Wadowice – Zator; [3] Osielec region; [4] Paleczka River valley, right-hand tributary of the Skawa River near Zembrzyce; [5] Świnna Poręba – Wadowice; [6] Weichselian Pleniglacial and Holocene cut-and-fill terrace, base 3.5-4.5 m below the present river bed; [7] strath exposed at Osielec, farther downstream slopes below the river bed; [8] buried terrace, alluvium covered by 16-m-thick loess-like silts; [9] – near Wadowice and Woźniki; [10] rock benches

Discussion

The age of these fluvial landforms is difficult to constrain. The highest situated rock benches (T_1), belonging to the so-called "riverside level" (Starkel, 1969, 1972; Zuchiewicz, 1984), were shaped when intensive down- cutting of older mature landscape of the Carpathians began, *i.e.* in the Early Pleistocene. A younger terrace (T_2), nearly absent upstream from Wadowice except isolated breaks on valley sides, was interpreted by Bober *et al.* (1980) in the lower Skawa River reach as "preglacial" (pre-Elsterian-2) buried terrace cover overlain by younger Pleistocene fluvial and slope sediments. Lower situated straths can be tentatively "dated", basing on the relationship between fluvial and solifluction sediments, which interlayer one with another in near-slope parts of individual terraces pointing to coeval deposition in cold glacial stages, as well as by relating these straths to the reference locality at Świnna Poręba, where Weichselian Early Glacial sediments were identified palynologically (Grzybowski & Śniadek, 1997; Grzybowski, 1998a, b, 1999). Applying these criteria, terrace covers T_3 and T_4 are considered here as formed in Elsterian-2 and Saalian (either 1 or 2) times (Table 1). Close to Wadowice, T_4 –equivalent fluvial sediments do not produce any separate terrace step, being buried under 16-m-thick loess-like silts, the top of alluvium rising 11–13 m above present-day river bed (Bober *et al.*, 1980). Terrace T_5 represents Weichselian (Vistulian) Early Glacial (*cf.* Grzybowski & Śniadek, 1997), its height increasing abnormally high between Osielec and Świnna Poręba to decrease even more dramatically farther downstream, between Świnna Poręba and Wadowice (Bober *et al.*, 1980; Grzybowski, 1998a, b, 1999). A younger, Weichselian Pleniglacial step (T_6) is already cut-and-fill and even buried terrace, its top part between Wadowice and Zator being covered by Holocene alluvium (Bober *et al.*, 1980; Grzybowski, 1998a, b, 1999). In the Paleczka River valley, a right-hand tributary of the Skawa River, fluvial sediments of this terrace bear in

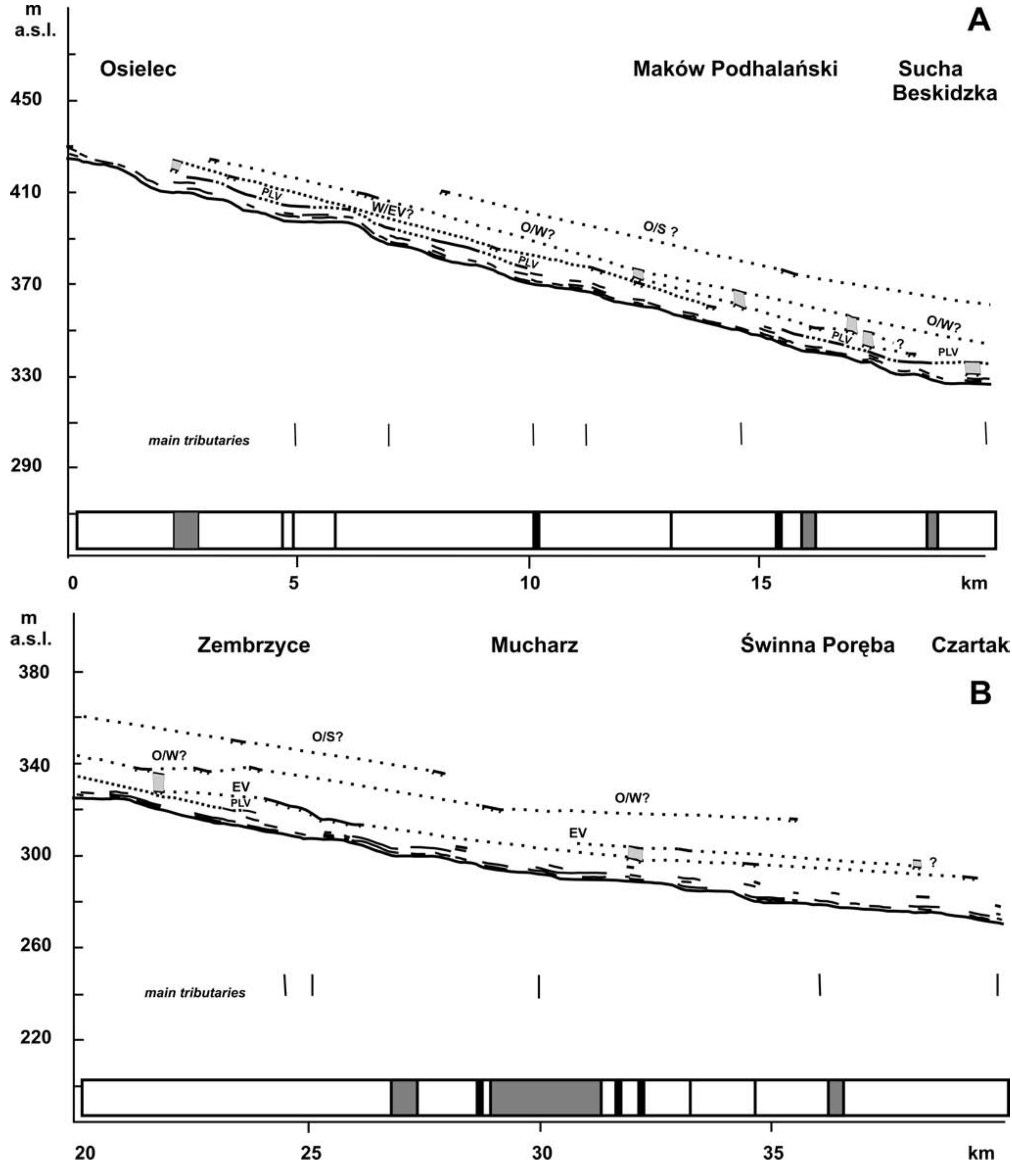

Fig. 13. Long profile of Mid- through Late Pleistocene and Holocene terraces of the Skawa River valley between Osielec and Sucha Beskidzka (**A**) and Zembrzyce – Świnna Poręba (**B**). Grey fields denote vertical extent of Pleistocene alluvium of individual terraces, fence lines mark straths, and dotted lines portray tentative correlation between preserved fragments of terraces. Lower bar diagram shows location of fault zones crossed by the river; grey rectangles indicate faults subparallel to the river course, thick vertical bars mark major thrust faults. Stratigraphy of Pleistocene glacial stages: S – Sanian (Elsterian-2), O – Odranian (Saalian-1), W – Wartanian (Saalian-2), EV – Weichselian Early Glacial, PLV – Weichselian Pleniglacial

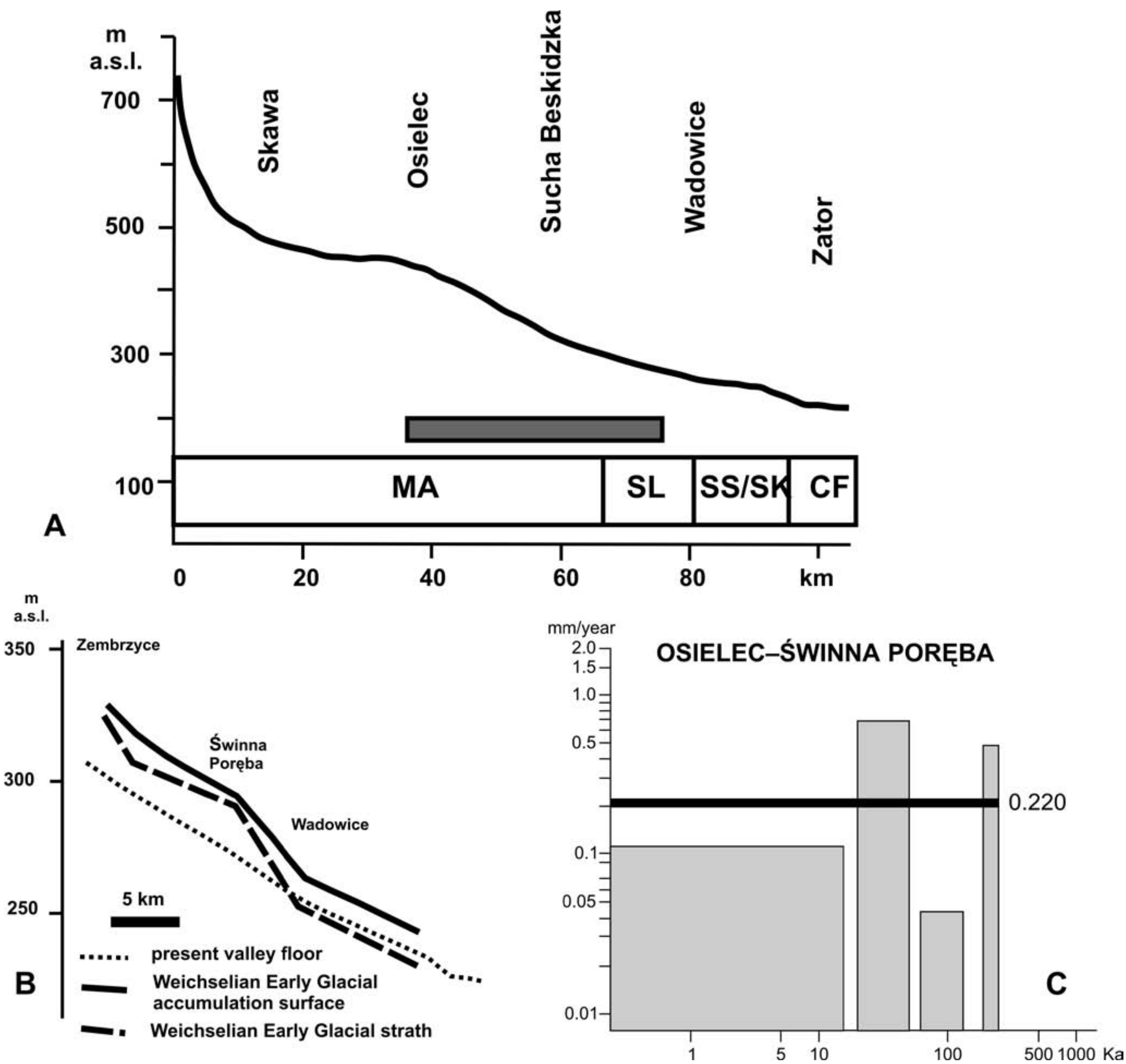

Fig. 14. Long profiles of the Skawa River bed versus location of tectonic units of the Polish Outer Carpathians (**A**), and of Weichselian Early Glacial terrace in the Świnna Poręba – Wadowice region (**B**) (adapted from Grzybowski, 1999; modified). (**C**) Logarithmic plot of the rates of downcutting of Quaternary straths of the Skawa River valley between Osielec and Świnna Poręba (thick bar in **A**), shown in Fig. 13. Thick solid line denotes average rate of downcutting in the last 300 ka. Letter symbols of tectonic units: MA – Magura Nappe, SL – Silesian Nappe, SS – sub-Silesian Nappe, SK – Skole Nappe, CF – Carpathian foredeep basin

the top part organic silts dated to the Bølling interstadial (Grabowski & Mirosław, 1995; Grzybowski, 1998b, 1999). Three to five terrace steps building the Skawa River valley bottom (T_{7-11}) are Holocene landforms, usually cut-and-fill ones, except T_7 terrace, which close to Osielec bears a strath (0.5–1 m) sloping below the present-day river bed farther downstream.

Rates of river downcutting are one of necessary tools for understanding rates of erosion, landform evolution, and tectonic uplift. Variations in downcutting rates along the valley's profile help to reconstruct the spatial pattern of tectonic mobility (Young & McDougall, 1993; Burbank *et al.*, 1996; Granger *et al.*, 1997; Burbank & Anderson, 2001). In the Outer Carpathians, rates of fluvial downcutting result mainly from climatic changes throughout the glacial-interglacial cycles (*cf.* discussion in Starkel, 1985, 1994, 2003 and Zuchiewicz, 1995a), but their spatial differentiation appears to be influenced by tectonic factors as well. Deepening of narrow valley bottoms was limited to early phases of interglacial stages, postdating dissection of periglacial covers during late glacial period of the preceding glaciation (Starkel, 1985). Previous studies in the Polish Outer Carpathians (Zuchiewicz, 1995a, 2001) indicate that the size and rate of dissection of straths of comparable age are different in different morphotectonic units; a feature pointing to variable pattern of Quaternary uplift throughout a relatively small area.

Long profiles of Pleistocene straths in the Skawa River valley are not uniform, as is the amount of terrace dissection in particular valley reaches. In particular, the straths tend to rise in water-gap valley segments and on frontal thrusts of the Magura (Zembrzyce–Skawce) and Silesian (Świnna Poręba) nappes (Figs 13A, B, 14). Holocene terrace risers do not show such differentiation, except that the base of young alluvium slopes downstream from 1–2 m near Osielec to nearly 6 m below the present river bed at Świnna Poręba. In the lower valley reach, downstream from Wadowice, dissection of T_2 sediments before the Elsterian-2, amounted to 8–10 m (in "Cromerian" time, according to Bober *et al.*, 1980), whereas subsequent Holsteinian and Eemian downcutting of the base of alluvium of terraces T_3 and T_4 was estimated in this zone for 7–12 m and 2–9 m, respectively (Bober *et al.*, 1980). Deep erosional downcutting of Weichselian Early Glacial at Świnna Poręba (26 m; cf. Fig. 14B, C), unique in the Polish Outer Carpathian valleys, probably took place at the turn of the Early Glacial and Pleniglacial time (Grzybowski & Śniadek, 1997). Gradients of the Early Glacial strath and top of fluvial cover between Świnna Poręba and Wadowice are 7.4 m/km and 5.7 m/km, while downstream from Wadowice both surfaces reveal comparable gradients of 2.4 m/km. Respective gradients of the Weichselian Pleniglacial terrace riser (3.2 km/km and 2.7 m/km) and recent valley bottom (2.7 m/km and 2.3 m/km) are lower, although showing differences between water-gap valley segment and the downstream reach, situated in front of the Carpathian marginal thrust (Grzybowski, 1998a, b). Such an unusually high position of the Weichselian Early Glacial straths on the western valley side at Świnna Poręba and its subsequent strong dissection was explained by Grzybowski (1998a, b, 1999) by Weichselian late Early Glacial reactivation of the Silesian frontal thrust. An alternative explanation is activation of the Świnna Poręba normal fault, throwing down its eastern wall. Another episode of tectonic mobility, although of smaller magnitude, was thought to occur in the Late Glacial and early Holocene time (Grzybowski, 1998b).

Gradients of the present river bed between Osielec and Świnna Poręba change between 2–3 m/km to 4–4.5 m/km, increasing locally to 6 and even 9 m/km at the outlets of some tributary streams and within fault zones oriented NE–SW in the upper valley reach. No breaks of slope occur on the Magura and Silesian frontal thrusts (Fig. 14A), contrary to the Carpathian marginal thrust, where river bed gradients increase from 2.6–2.8 m/km to 4 m/km (Grzybowski, 1999). This increase was interpreted as a result of the youngest episode of tectonic mobility (Grzybowski, 1999).

In sum, increased rates of fluvial downcutting (0.7 mm/yr compared to average of 0.22 mm/yr for the last 300 ka; *cf.* Fig. 14C) and deformations of Mid-Late Pleistocene straths of the Skawa River point to the role of Weichselian late Early Glacial episode of tectonic activity in the Beskid Mały Mts., probably due to activation of the Silesian frontal thrust, remobilization of the Świnna Poręba fault, or both.

FRACTURED CLASTS

Fractured clasts have commonly been used as a tool in palaeostress analysis and dating of faulting events for a few decades all over the world (see for review: Tokarski & Świerczewska, 2005), and during past few years in the Polish segment of the Carpathians, within the Miocene through Holocene gravels. The share of such clasts at individual exposures exceeds sometimes 60%, and fracture architecture is usually well-organized and independent of clast texture. Gravels and pebbles bearing fractured clasts are exposed mainly close to the map-scale thrusts, strike-slip faults and normal faults, pointing to the ongoing tectonic activity of such structures (Tokarski & Świerczewska, 2005; Tokarski *et al.*, 2007).

In years 2005–2008, we analyzed 56 sites of Holocene fluvial gravels bearing fractured pebbles. These sites spread along the Skawa River course, from Bystra to the mouth (Appendix). The sites represent recent gravel bars, as well as 1.5–2 m, 2–3 m and 4–5 m-high terrace risers. The most numerous sites cluster between Osielec in the south and Zator in the north (Fig. 15). The fractures are represented by joints, as well as normal, reverse and thrust faults, some of them filled by clastic dikes. Individual clasts are cut by either single or – rarely – multiple fractures (Fig. 16). Five valley segments showing variable density of sites are distinguished: (a) Zator – Wadowice (1.04 sites per 1 km length), located on a fault running NW–SE; (b) Świnna Poręba region (1.43), wherein 1 site is located on the Silesian Nappe frontal thrust oriented WSW–ENE, and 4 sites being placed right on N–S to NNW–SSE striking faults; (c) Mucharz – Zembrzyce (1.50), situated on N–S to NNE–SSW trending faults; (d) Sucha Beskidzka – Maków Podhalański (3.75), showing most densely spaced arrangement of fracture clasts-bearing sites (15 sites per 4 km valley length), which are placed on a fault striking WNW–ESE; and (e) Maków Podhalański – Osielec (2.50), a segment showing relatively poor correlation with major faults; individual sites appear to be associated with minor, NNE–SSW and NE–SW striking, not very long faults (Fig. 15).

The highest frequency of fractured clasts (>1/square metre) was found at 17 sites (Fig. 15), which are placed: right in front of the Carpathian thrust over the foredeep (no. 6), on major faults comprising the Skawa River fault zone in segments: a (nos. 61, 12, 13), c (no. 22), and d (nos. 91, 26, 27, 33, 34), close to the Silesian (no. 17) and Magura (nos. 20, 92) frontal thrusts, as well as on minor faults oriented NW–SE (no. 78, south of Świnna Poręba) within the Silesian, and NNE–SSW (nos. 31, 36) and NE–SW (no. 39) in the Magura nappes.

The most numerous fractures (45) characterize site no. 17 situated on the Silesian frontal thrust, 3 km north of Świnna Poręba (Fig. 15). At that site, all fractured clasts occur in the interval of 10 – 30 cm below the top of a 2-m-high terrace. The fractures, exclusively joints, tend to align WSW–ESE, *i.e.* exactly parallel to the strike of the Silesian

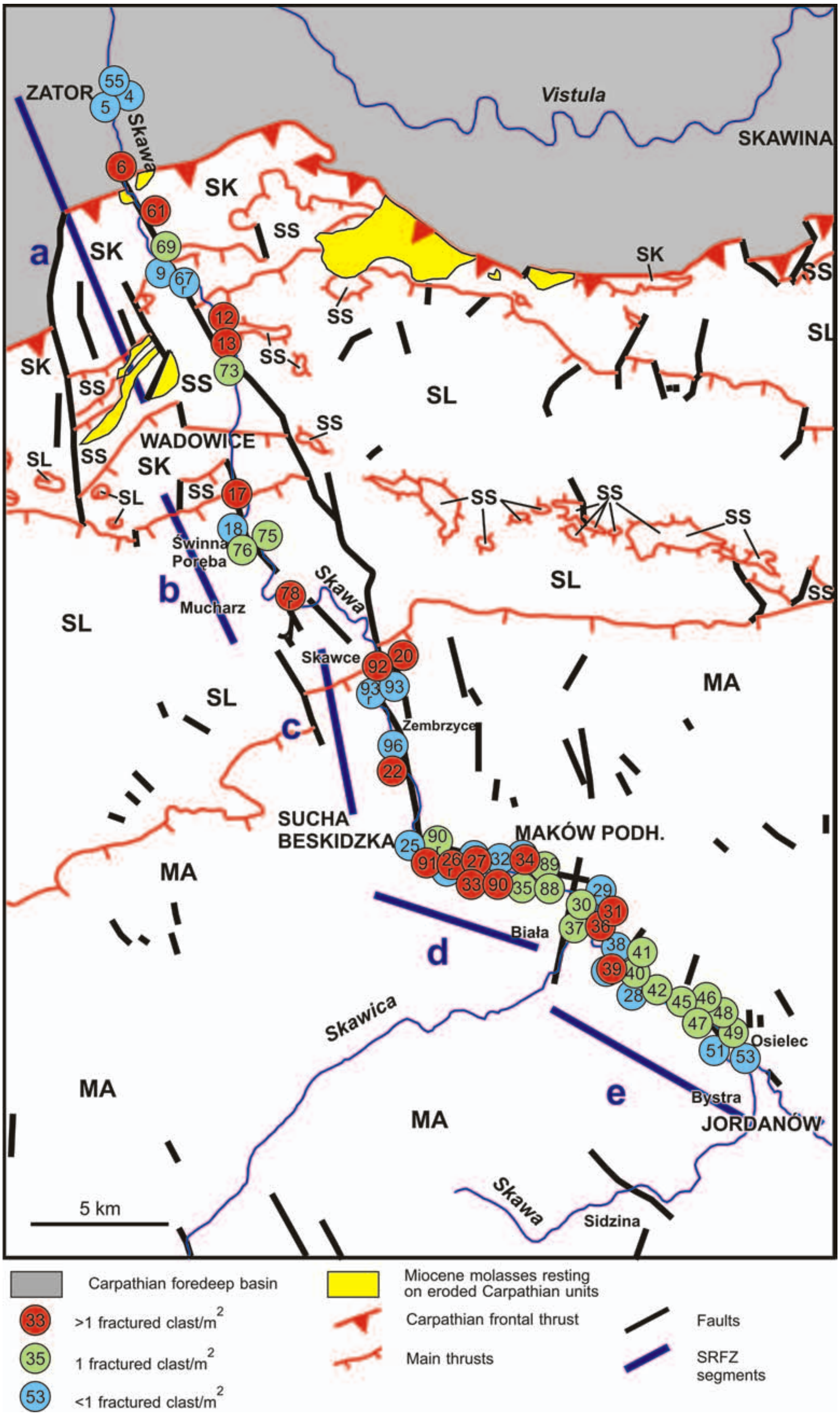

Fig. 15. Tectonic sketch-map of the central and northern portions of the Skawa River catchment (based on Golonka *et al.*, 1981), showing location of sites bearing fractured clasts and the frequency of the latter. For other explanations – see Fig. 3

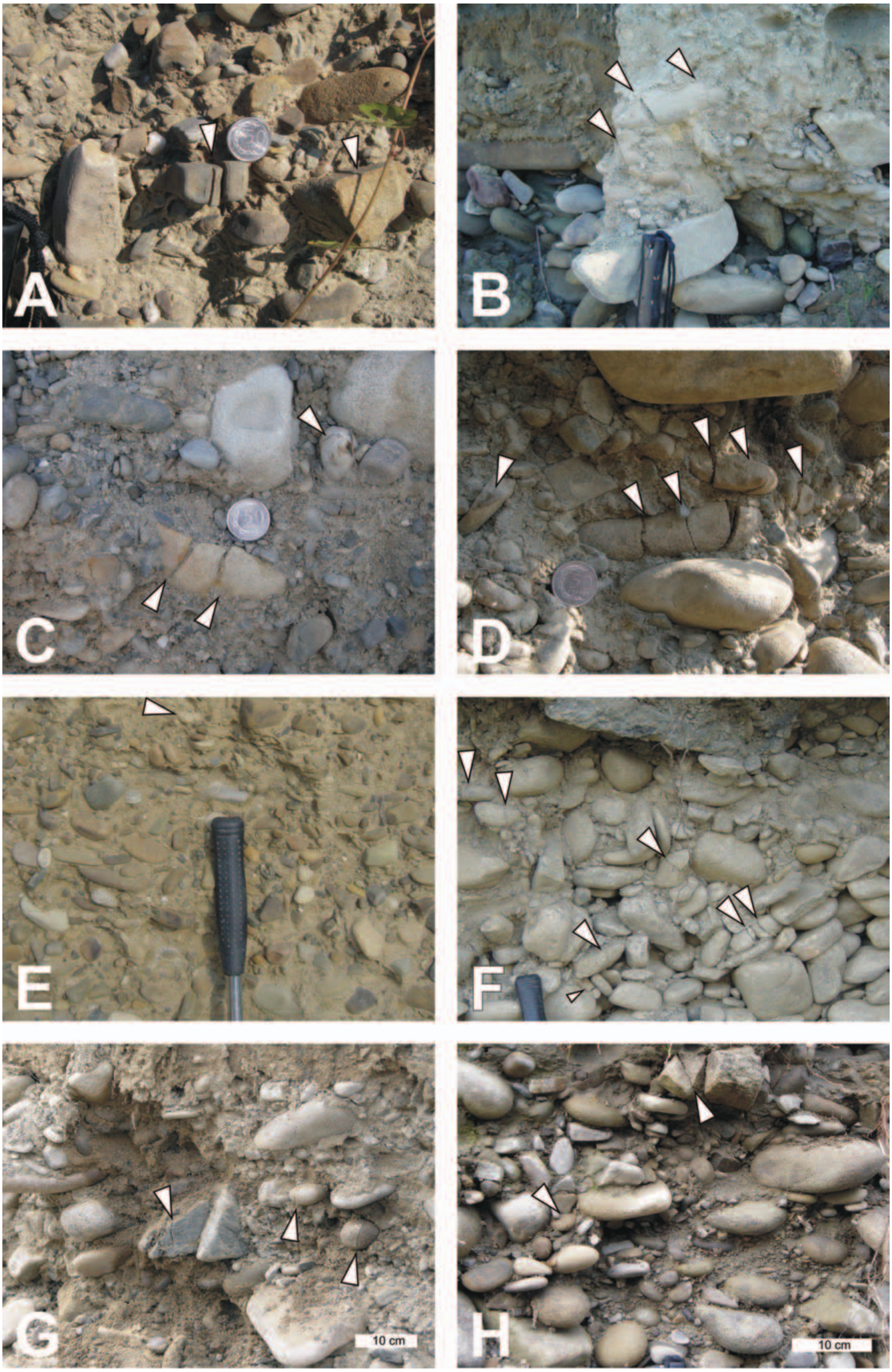

Fig. 16. Examples of clasts within Holocene alluvium of the Skawa River valley cut by single (**A**, **B, E–H**) and multiple fractures (**C**, **D**); **E–H** exposures of gravels with frequency of fractured clasts higher than $1/m^2$; **E** – site 12, **F** – site 13, **G** – site 17, **H** – site 91. Diameter of coin is 19 mm

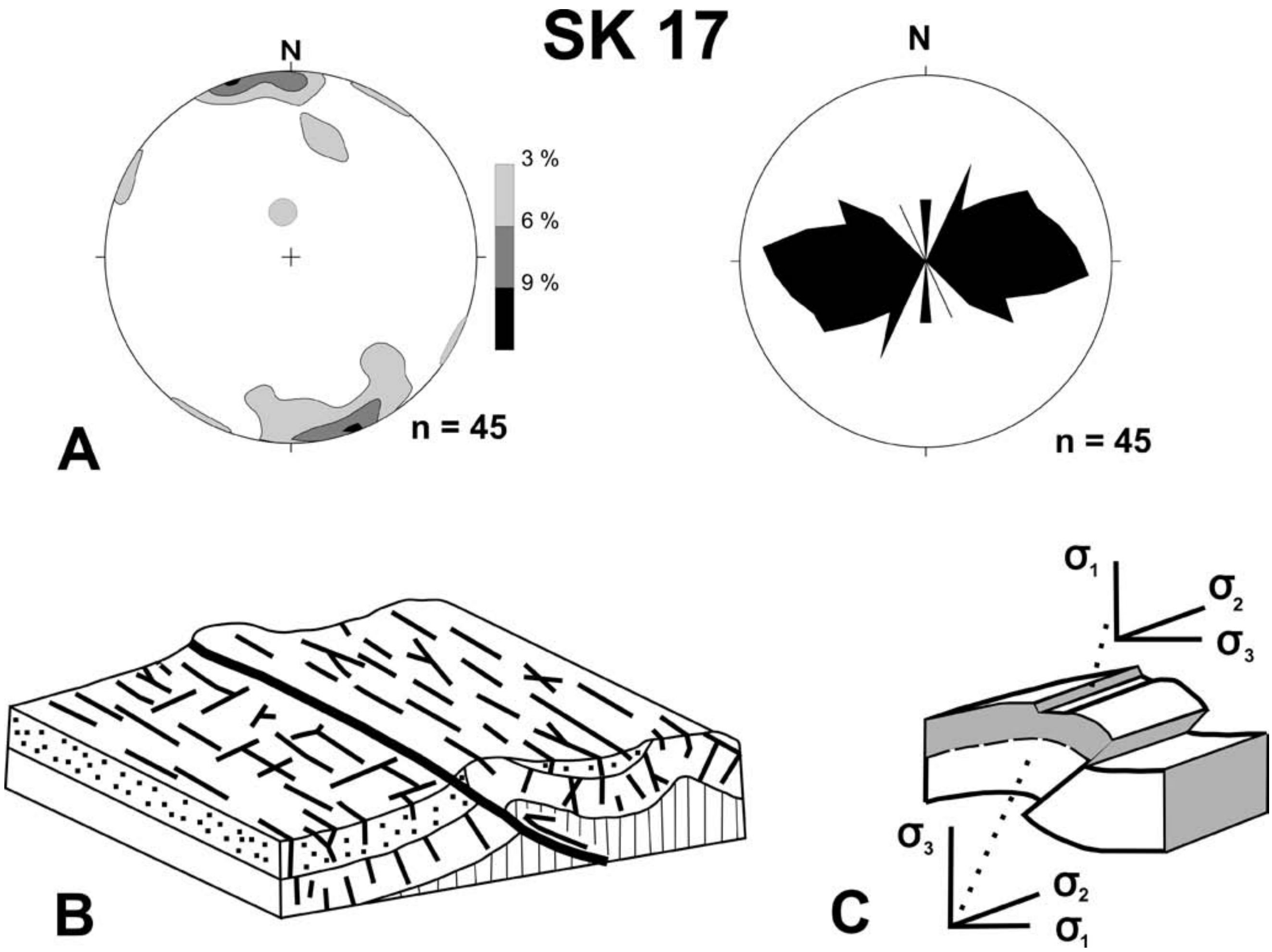

Fig. 17. A – Lower hemisphere stereoplot and rose diagram of fractures within clasts of Holocene alluvium at site 17, located at the Silesian Nappe frontal thrust. See Fig. 15 for location; **B** – common pattern of joints symmetrically arranged about thrust faults; joints parallel to the thrust occur both in the footwall and hanging wall; those at right angles to the thrust being restricted to strata immediately beneath the thrust (modified after Hancock, 2000); **C** – an example of typical deformation and related stress patterns associated with the 1980 El Asnam (Algeria) thrust earthquake. Local stress variations resulting from flexing of the hangingwall anticline produced bending-moment crestal grabens (modified after Philip & Meghraoui, 1983)

Nappe frontal thrust (Fig. 17A). Their spatial arrangement is fairly similar to that observed in Alpine (Fig. 17B) and recent, earthquake-produced thrusts (Fig. 17C). This fracture architecture results from local rotation of principal stress axes due to thrusting-related uplift.

In numerous exposures, irregular patches bearing numerous fractured clasts within strata devoid of such clasts or bearing very few fractured clasts are rather common. Four exposures of gravels with the number of fractured pebbles higher than 1/m^2 were selected for fabric studies (Fig. 16E–H). These gravels comprise exclusively clasts derived from the Outer Carpathian sedimentary rocks. The calculated fabric indicators show considerable variations in the examined exposures (Table 2). The packing proximity percentage varies from 29 to 68%, the packing density percentage changes from 43 to 64%, whereas the proportions between point and long contacts are between 0.53 and 2.22. At site no. 17, where the number of fractured clasts is the highest and where gravel is rich in matrix, the number of clasts showing point contact is over two times larger than that of clasts displaying long contact.

Table 2

Fabric indicators in the studied gravels

Exposure	Fabric indicators		
	packing density	packing proximity	point contact/ long contact
SK12	62%	57%	0.80
SK13	52%	68%	0.53
SK17	43%	29%	2.22
SK91	64%	68%	0.84

Discussion

Fractured clasts have been described from areas of Quaternary (Tanner, 1976; Owen, 1989; Tokarski & Zuchiewicz, 1998) and historical seismicity (Arlhac *et al.*, 1987; Carbon *et al.*, 1995). This was most probably the case of clast fracturing within young Holocene alluvium composing cut-and-fill terraces 0.5 m to 1.5–2 m high (3–4 m high at site no. 12 only) in the Skawa River valley. According to the new twelve-degree earthquake intensity scale (Guerrieri & Vittori, eds, 2007), fractures within loose alluvial deposits originate starting from slightly damaging earthquakes (degree VI), and those in competent rocks tend to be formed starting from heavily damaging earthquakes (degree VIII). In terms of local magnitudes, one can expect clast fracturing at M ≥ 5.5–5.7. The presence of fractured clasts in the Skawa River valley, both on thrust and other faults, leads us to conclude about relatively strong seismicity in this region, probably of long recurrence intervals, and posing potential threat in the future. Fractured clasts were observed in gravels showing large differentiation of fabric indicators. It appears that gravels rich in matrix are possibly more prone to fracturing.

FINAL REMARKS AND CONCLUSIONS

The Skawa River catchment basin in the Outer Western Carpathians of Poland is situated upon morphostructures showing differentiated mobility in the Quaternary. Of particular importance are two zones showing uplifting tendencies, which are indicated by abnormally high channel gradients and low values of the valley floor width – valley height ratios. The southern zone is confined to the Rača and Siary slices of the Magura Nappe, the northern one is placed within the Silesian and sub-Silesian nappes. Long profile of river channel reveals the lowest values of concavity index among the Polish Outer Carpathian rivers, pointing to low degree of river profile maturity, particularly in its middle reach coinciding with the southern zone of abnormally high river bed gradients.

The Skawa River valley utilizes in its middle and northern reaches the Skawa River Fault Zone composed of differently oriented oblique-slip faults, visible on DEM images as well-marked, rectilinear topolineaments.

The NNW–SSE to N–S faults in the Silesian Nappe were probably reactivated in Late Pleistocene time as normal faults downthrowing their eastern sides, as shown by abnormally high position of the Weichselian Early Glacial straths on the western valley side. Such an episode of neotectonic activity (late Early Glacial time of the last glacial stage) has not been recognized so far in other river valleys of the Polish segment of the Outer Western Carpathians. Furthermore, we believe that some of the NNW–SSE to N–S trending faults were reactivated as strike-slip faults. This would confirm the present day stress arrangement within the Polish segment of the Carpathians (Jarosiński, 2005).

Moreover, deformations of Pleistocene straths between Osielec in the south and Wadowice–Zator areas in the north appear to indicate both pre-Weichselian and Weichselian reactivation of the Silesian and – to a lesser extent – Magura frontal thrusts. These movements continued also in the Holocene, although to a smaller extent, most probably due to moderately strong and/or strong earthquakes of magnitudes exceeding 5.5–5.7, resulting in clast fracturing within Holocene alluvium, particularly strong on the Silesian frontal thrust, and less intensive on the Carpathian marginal and Magura frontal thrusts, as well as on some faults that belong to the SRFZ.

We are convinced that the record of seismically-induced clast fracturing on one of major fault zones in the Outer Carpathians should lead to revision of the hitherto-existing seismic risk assessment of this region (*cf.* Schenk *et al.*, 2001; Guterch & Lewandowska-Marciniak, 2002), and particularly of the city of Kraków and other urbanized areas, as well as the planned artificial water reservoir at Świnna Poręba.

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Appendix

Location of exposures of Holocene gravels bearing fractured clasts

Exposure	Latitude N	Longitude E
SK-4	49°59.435'	19°26.987'
SK-5	49°59.365'	19°27.019'
SK-6	49°58.180'	19°27.137'
SK-9	49°56.111'	19°28.278'
SK-12	49°54.965'	19°30.130'
SK-13	49°54.849'	19°30.173'
SK-17	49°51.318'	19°31.113'
SK-18	49°50.597'	19°30.833'
SK-20	49°47.934'	19°35.628'
SK-22	49°45.788'	19°35.867'
SK-25	49°44.321'	19°36.532'
SK-26r	49°43.848'	19°37.398
SK-27	49°43.795'	19°38.149'
SK-27r	49°43.751'	19°38.818'
SK-28	49°41.390'	19°43.457'
SK-29	49°43.083'	19°42.046'
SK-30	49°42.935'	19°42.063'
SK-31	49°42.719'	19°42.113'

Exposure	Latitude N	Longitude E
SK-32	49°43.807'	19°38.576'
SK-33	49°43.761'	19°38.452'
SK-33r	49°43.770'	19°38.889'
SK-34	49°43.766'	19°39.368'
SK-34r	49°43.723'	19°39.680'
SK-35	49°43.717'	19°39.500'
SK-36	49°42.579'	19°41.735'
SK-37	49°42.561'	19°41.516'
SK-38	49°42.607'	19°41.981'
SK-39	49°41.929'	19°42.843'
SK-40	49°41.884'	19°42.873'
SK-41	49°41.840'	19°42.909'
SK-42	49°41.256'	19°43.571'
SK-45	49°41.029'	19°45.098'
SK-46	49°41.021'	19°45.096'
SK-47	49°40.678'	19°45.576'
SK-48	49°40.523'	19°45.886'
SK-49	49°40.438'	19°46.041'
SK-51	49°40.065'	19°45.972'
SK-53	49°39.711'	19°46.572'
SK-55	49°59.592'	19°26.614'
SK-61	49°57.227'	19°27.602'
SK-67r	49°55.859'	19°28.733'
SK-69	49°56.557'	19°28.155'
SK-73	49°54.033'	19°30.652'
SK-75	49°50.321'	19°31.550'
SK-76	49°50.461'	19°31.352'
SK-78r	49°49.485'	19°32.418'
SK-88	49°43.599'	19°40.028'
SK-89	49°43.613'	19°39.975'
SK-90	49°43.771'	19°38.418'
SK-90r	49°43.751'	19°38.818'
SK-91	49°44.083'	19°36.853'
SK-92	49°48.156'	19°36.017'
SK-92a	49°47.865'	19°35.503'
SK-93	49°47.474'	19°34.944'
SK-93r	49°47.145'	19°35.054'
SK-96	49°46.041'	19°35.830'

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