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PLEISTOCENE TECTONIC ACTIVITY OF THE POLISH WESTERN CARPATHIANS: INSIGHTS FROM FLUVIAL TERRACES

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ABSTRACT

Fluvial archives of the Polish Carpathians bear a record of both climatic and tectonic signatures. The former consist in cyclic development of terrace covers interfingering with and/or overlain by soliluction and slopewash sediments; the latter include disturbances within strath long profiles and differentiated size of erosional downcutting. Valleys of the Outer Carpathians bear five to nine terrace steps of Pleistocene age. Most of these terraces are strath or complex-response ones; the Weichselian and Holocene steps are usually cut-and-fill landforms, except those located in the neotectonically elevated structures characterized by the presence of young straths. Long profiles of individual strath terraces frequently show divergence, convergence, upwarping, downwarping, or faulting that can be indicative of young tectonic control. Moreover, 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. Rates of river downcutting result mainly from climatic changes throughout the glacial-interglacial cycles, but their spatial differentiation appears to be influenced by tectonic factors as well. Examples based on detailed examination of deformed straths and fluvial covers in selected segments of the Polish Carpathian rivers appear to indicate Quaternary reactivation of both normal and thrust bedrock faults. The latter are mostly confined to the eastern portion of the Outer Carpathians. The Early Pleistocene, Holsteinian and Eemian stages of reactivated faulting dominated throughout the study area.

KEYWORDS: fluvial terraces, neotectonics, faulting, Pleistocene, Carpathians, Poland

INTRODUCTION

Long profiles of strath terraces in young tectonic settings frequently display upstream or downstream convergence, dome-or basin-like warping and/or faulting (Fig. 1). This also holds true in the Polish segment of the Carpathians (cf. Zuchiewicz, 1995, 2009). The size and rates of erosional downcutting of individual straths differ from one structural unit to another irrespective of climatic or lithologic controls, implying neotectonic influences (Starkel, 1994; Schumm, 1986; Blum and Törnqvist, 2000; Brocard and van der Beek, 2006). The rate of fluvial incision is largely dependent on climate changes in successive glacial-interglacial cycles (Bridgland and Westaway, 2008a,b; see also discussion in: Starkel, 1985, 1994, 2003), but its spatial differentiation within one climate zone could have easily been controlled by tectonic tendencies.

The aim of this paper to provide an overview of young tectonic deformations of fluvial terraces in selected reaches of the Carpathian rivers with a view to constrain neotectonic stress field of the region.

NEOTECTONIC BACKGROUND

The Polish segment of the Carpathian fold-and-thrust belt (Figs. 2, 3) features several zones showing tendencies to neotectonic uplift. The highest rates of the latter were identified in the Tatra Mts. in the Inner Carpathians as well as in the Beskid Żywiecki, Beskid Sądecki and Bieszczady mountains in the Outer Carpathians. Uplift rates during successive Pleistocene stages ranged between 0.1 and 0.4 mm/yr, while those of subsidence within intramontane depressions (Orava-Nowy Targ Basin, Nowy Sącz Basin, Jasło-Sanok Depression) were 0.05-0.12 mm/yr (Zuchiewicz, 1984, 1998, 2009).

The rates of erosional downcutting of strath terraces changed between 0.02 to 2 mm /yr, increasing in the Late Pleistocene and Holocene in the western portion of the Outer Western Carpathians (OWC), when intensive erosion was restricted to neotectonically active elevations truncated by the Raba and Dunajec river valleys (Zuchiewicz, 1984, 1995, 1998; Wójcik, 1989; Olszak, 2008). In the medial segment of the OWC (Gorce Mts.), rates of

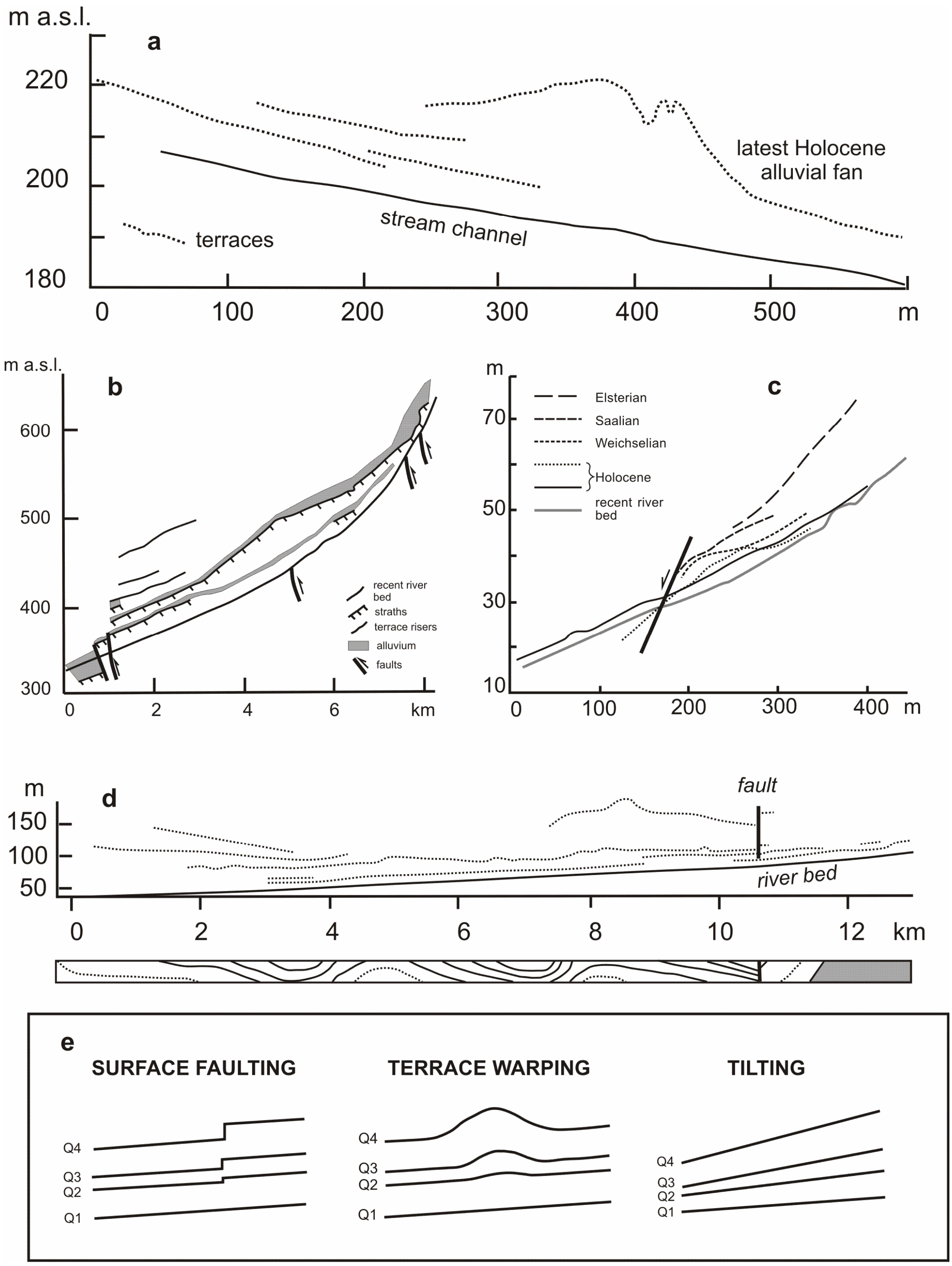

Fig. 1 Examples of tectonic deformations recorded in long profiles of fluvial terraces:
a – deformation of Holocene terraces of the Waimangarara River (New Zealand) induced by surface ruptures of the Hope thrust fault (after Bull, 2007; simplified), b – deformed late Quaternary strath terraces of the Little Tujunga Canyon (California), upwarped and displaced by reverse faulting (based on Bull, 2007; simplified); c – long profiles of terraces in a gorge dissecting the northern marginal normal fault of the Yanqing Basin, Yenshan Mts., China (based on Fang Zhongjing et al., 1996; modified); d - upwarped Quaternary terraces over anticlines in the Neogene strata, Oguni River, Japan. Note that older terraces are displaced by a fault (based on Sugimura, 1967 in: Bloom, 1978; simplified); e – typical patterns of tectonic deformation of fluvial terraces showing progressive deformation through time (after Keller and Pinter, 1996; modified).

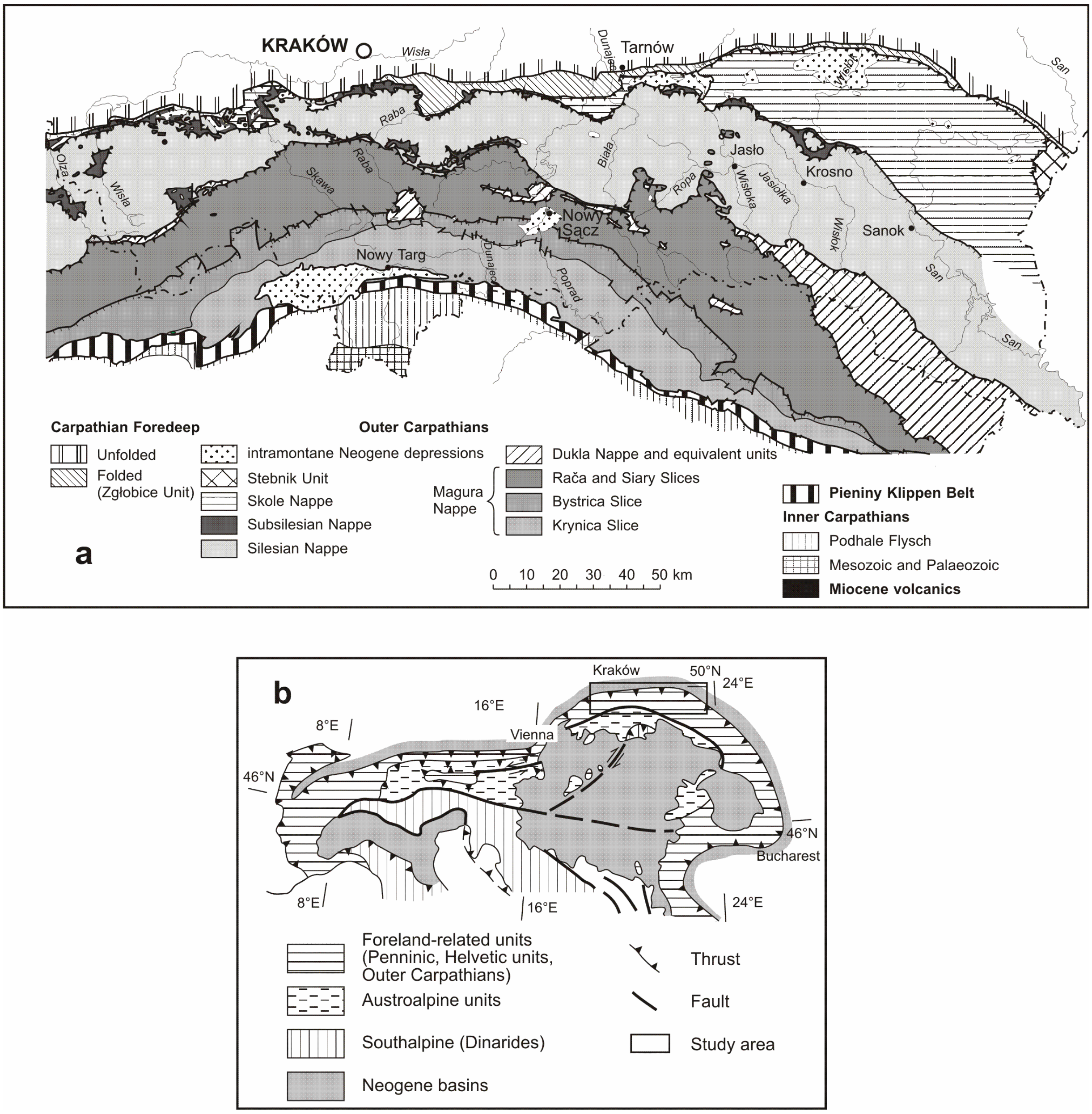

Fig. 2 Geological sketch-map of the Polish Carpathians (a) and structural sketch of the Carpatho-Pannonian region (b; based on Neubauer et al., 1997; modified).

dissection during successive interglacial stages (Cromerian Complex through Eemian) increased from 0.12-0.14 mm/yr to 0.30-0.36 mm/yr (Olszak, 2009). In the Inner Carpathians, diversified rates of incision of the Białka Tatrzańska River point to increasing intensity of surface uplift of the eastern Podhale region, from 0.1 to 0.7 mm/yr, throughout the Quaternary (Baumgart-Kotarba, 1978). In the eastern portion of the OWC (Jasło-Sanok Depression), in turn, a reverse trend dominated (Wójcik, 2003). The amount of deepening of the Tatra Mts. valleys during the last 100-200 thousand years did not exceed 0.2-0.3 mm/yr, and good state of preservation of old speleothems (170 ka) within caves situated close to the present-day valley bottoms indicates minor transformation of the Tatras' landscape in the middle and late Pleistocene (cf. Gradziński et al., 2009).

The maximum amount of Quaternary uplift (up to 150 m) was documented for the Beskid Sądecki Mts. in the OWC, dissected by antecedent water-gaps of the Dunajec and Poprad rivers (Starkel, 1972; Zuchiewicz, 1984, 1998, 2009). Holocene terraces are typified by straths in axial parts of neotectonic elevations only, and their rates of dissection have been

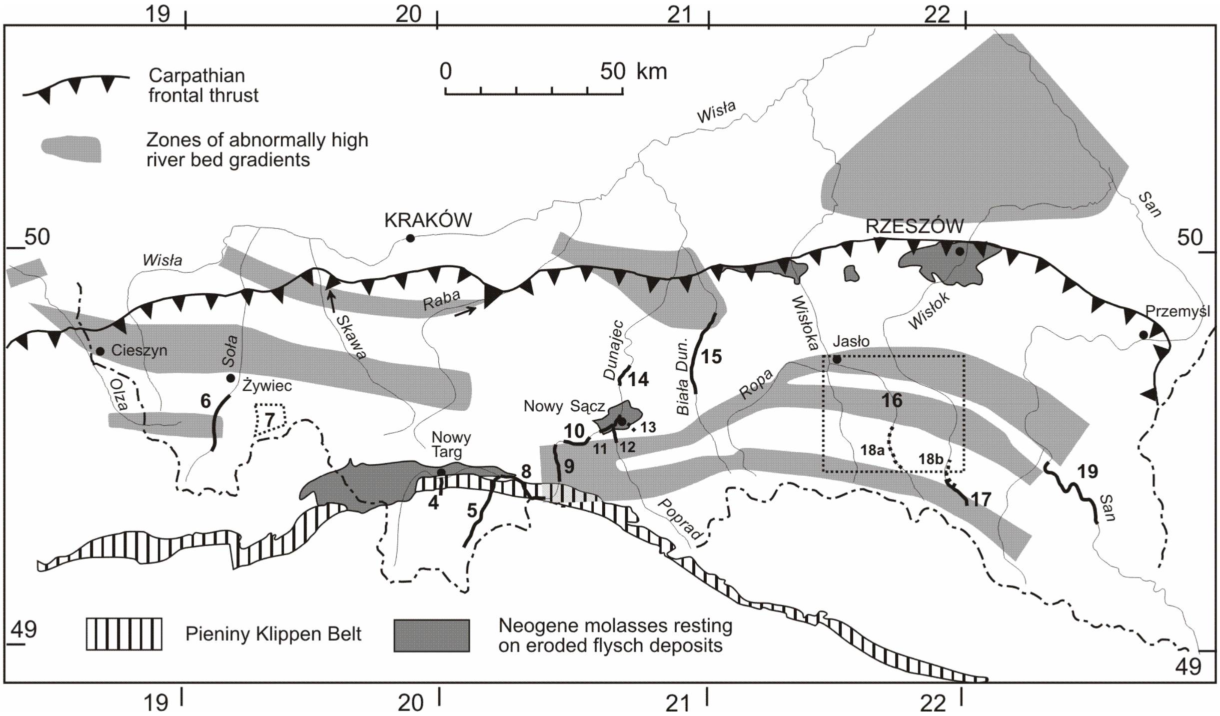

Fig. 3 Neotectonic sketch of the Polish Carpathians showing location of the discussed river valley profiles. Numbers refer to respective text figures (6-19).

highest in the Beskid Sądecki Mts. and along the northern margin of the Beskid Niski Mts. Average rates of fluvial incision in Quaternary times (0.06-0.22 mm/yr) are compatible with long-term rates of isostatic uplift of the OWC during the past 10 million years, which were 0.03-0.11 mm/yr (cf. Oszczypko, 1998; Poprawa et al., 1999). The latter estimates result from comparative analyses of compaction curves of Neogene strata filling the Carpathian Foredeep Basin as well as from extrapolation of erosionally truncated seismic reflectors (Krzywiec and Zuchiewicz, 1993).

STATE OF RESEARCH

Analysis of long profiles of terraces of the main Carpathian rivers has been a mater of debate since the beginning of the 20th century (cf. Łoziński, 1922; Klimaszewski, 1966; Starkel, 1969, 1971, 1972, 1983, 1985, 2003). The first systematic review for the entire Polish Carpathians was presented by Klimaszewski (1948), who noted deformation of some terraces in water-gap reaches. Long-term detailed studies concerned the Dunajec River valley, the best studied valley in the Polish Carpathians (Klimaszewski, 1937, 1948; Gerlach, 1967; Froehlich et al., 1972, Oszczypko, 1973; Wójcik, 1975; Starkel, 1976; Oszczypko and Wójcik, 1984; Zuchiewicz, 1978, 1980, 1983, 1984, 1985, 1992, 1995; Łój et al., 2009). Among the other research areas, the following river valley segments should be listed: Soła (Szaflarski, 1931a, 1932; Ziętara, 1972; Alexandrowicz, 1991), Koszarawa (Wójcik, 1989), streams dissecting the Żywiec Basin margins (Żółkiewski, 1971; Wójcik, 1996), Skawa (Szaflarski, 1931b; Mądry, 1971; Grzybowski, 1998a,b, 1999; Bińka and Grzybowski, 2001; Zuchiewicz et al., 2009), Raba (Szaflarski, 1931b; Grabowski, 2004), Kamienica and Ochotnica in the Gorce Mts. (Olszak, 2009, 2011), Poprad (Golonka and Rączkowski, 1984; Zuchiewicz, 1984), Kamienica Nawojowska (Zuchiewicz, 1984), Ropa (Breitmajer, 1938; Wójcik, 1997), Wisłoka (Fleszar, 1914; Pawłowski, 1925), Wisłoka, Jasiołka and Wisłok at the margin of the Beskid Niski Mts. and within the Jasło-Sanok Depression (Świdziński, 1933, 1971; Krajewski, 1933; Świdziński and Wdowiarz, 1953; Drzewicka-Kozłowska, 1961; Wdowiarz and Zubrzycki, 1985, 1987; Zuchiewicz, 1988, 1989, 1990; Magiera, 1990, 1991a,b; Kuśmierek and Magiera, 1991, 1993; Wójcik et al., 1992, 1993; Wójcik, 2003, 2005), San (Klimaszewski, 1936; Dziewański and Starkel, 1962; Starkel, 1965, 1966; Wójcik, 1976; Henkiel et al., 1988), and Strwiąż (Henkiel, 1969); and within the Inner Carpathians – Biała Woda in the Tatra Mts. (Baumgart-Kotarba and Kotarba, 1979), Białka Tatrzańska (Mastella, 1976; Baumgart-Kotarba, 1978, 1980, 1981, 1983, 1985; Klimkiewicz et al., 2009), Czarny Dunajec (Baumgart-Kotarba, 1989, 1991, 1992, 1996, 2000), and other streams of the Western Podhale area (Kukulak, 1993). Moreover, fluvial terraces used to be described when preparing successive sheets of the detailed geological map of Poland 1:50,000, although with different accuracy.

As far as the Outer Carpathians are concerned, intensive uplift post-dating the San-2 (Elsterian-2) glacial stage was documented east of the Dunajec River valley (Teisseyre, 1933; Klimaszewski, 1948; Starkel, 1965, 1966, 1971, 1972). Another episode of uplift was thought to have occurred in the Eemian, when amplitude of neotectonic motions attained 35 m near Sanok, in the San River valley (Klimaszewski, 1936, 1948). Zuchiewicz (1983, 1984, 1985, 1988, 1992, 1995), based on climato- and allostratigraphic subdivisions of Quaternary fluvial series in the Outer Carpathians, attempted to calculate the rates of erosional dissection of strath terraces in successive Pleistocene stages and to analyse different types of deformation of individual straths, distinguishing four "neotectonic phases": at the beginning of the Pleistocene, in the Early Pleistocene, at the Brunhes/Matuyama boundary (Interglacial II, Cromerian Complex), and in the Holsteinian ("Nowy Sącz Phase" of greatest intensity and extent). Smaller-scale tectonic mobility was also noted in the Eemian Interglacial, Weichselian Late Glacial and at the beginning of the Holocene. This concept of tectonic "phases" resulted from an assumption that the rates of strath downcutting represent proxy data for tectonic surface uplift. In later publications, the idea of separate "phases" was abandoned, since river valley segments in different regions used to be dissected with variable rates in different time spans, pointing to continuous although differentiated neotectonic mobility. A notable example is the Jasło-Sanok Depression, where the highest rate of neotectonic uplift was documented in the Lublin (Schöningen, mid-Saalian) warming in the south, in the Zbójno Interglacial (Reinsdorf, early Saalian) in the north, and in the Eemian Interglacial in the east (cf. Wójcik, 2003).

MATERIAL AND METHODS

The main OWC river valleys bear a flight of five to nine Pleistocene terrace steps and two to four Holocene terraces. These are strath, cut-and-fill and complex response-type (Bull, 1990) terraces. The last glacial (Weichselian) and Holocene terraces are mainly cut-and-fill landforms except axial parts of neotectonically uplifted structures.

Dating fluvial sediments that are older than the last glacial stage meets serious difficulties, necessitating application of morpho-, climato- or allostratigraphic procedures. Climatostratigraphic subdivision is based on "interfingering" of fluvial and solifluction covers at the base of hillslopes; a feature indicative of coeval deposition in a periglacial climate zone (Klimaszewski, 1971). Another constraint is provided by correlation along valley long profiles between glaciofluvial fans shed in front of mountain (Tatra) glaciers, fluvial terraces in glacial-free area, and glaciofluvial covers accompanying marginal zones of continental ice sheets (Carpathian Foothills).

Based on the above criteria, an attempt was made to present a climatostratigraphic succession of alluvial covers in main Carpathians valleys in relation to analogous stratigraphic subdivisions used in lowland areas. The scheme presented below is largely adopted from my work (Zuchiewicz, 1983, 1984, 1985, 1992) in the Dunajec River valley, which transects different geomorphic units of the Inner and Outer Carpathians: from the zone of mountain glaciation in the Tatras, through the Beskidy Mts. which were not glaciated in Pleistocene time, to the Carpathian Foothills reached by the San-2 (Elsterian-2) continental ice sheet. This climato- and morphostratigraphic classification of fluvial terraces is as follows: T_1, Różce stage (Praetiglian); T_2, Otwock stage (Eburonian); T_3, Narew stage (Menapian); T_4, Nida stage (Elsterian-1); T_5, San stage (Elsterian-2); T_6, Odra stage (Drenthe, Saalian-1); T_7, Warta stage (Warthe, Saalian-2); T_8, Wisła stage (Vistulian, Weichselian); T_9, Late Glacial erosional step (15-10 ka), and $T_{10\text{-}13}$ – Holocene steps.

Figure 3 shows a neotectonic sketch of the Polish Carpathians with marked river valley segments dealt with in the subsequent chapter.

CASE STUDIES

INNER CARPATHIAN VALLEYS

The Early Pleistocene uplift of Podhale area in respect to the Pieniny Klippen Belt has been variably estimated at 40 m (Pepol, 1972; Mastella, 1976), 80 m (Halicki, 1930, 1963) or even 100 m (Baumgart-Kotarba, 1978, 1981). According to Baumgart-Kotarba (1978), the post-Elsterian uplift of southern Podhale exceeded by some 30 m that of the northern part of this region, and deformations in the Eemian time were thought to document reactivation of the Białka fault. Recent activity of meridional fault zones in the eastern Podhale was also suggested by Mastella (1976; cf. also Klimkiewicz et al., 2009). Quaternary uplift of the Pieniny Klippen Belt by some 100 m was inferred by Halicki (1930), Jaranoff (1934-35) and Klimaszewski (1952), and 50-85 m of post-Elsterian uplift was deduced from deformations of the Dunajec River terraces by Zuchiewicz (1980). Minor Holocene uplift probably affected the eastern part of the Pieniny Mts.

Birkenmajer (1976) described Holsteinian reactivation of the northern marginal fault bordering the Pieniny Klippen Belt at Szaflary (Fig. 4). The southern side of this fault became tilted by ca. 10º to the south. Baumgart-Kotarba (1978), in turn, assigned the last episode of faulting in this region to the Eemian Interglacial. Long profiles of Pleistocene terraces display deformation by two faults located at the boundaries between the Pieniny Klippen Belt, Magura Nappe and young infill of the Nowy Targ Basin, affecting Elsterian and, to a lesser extent, Saalian glaciofluvial covers (Fig. 4).

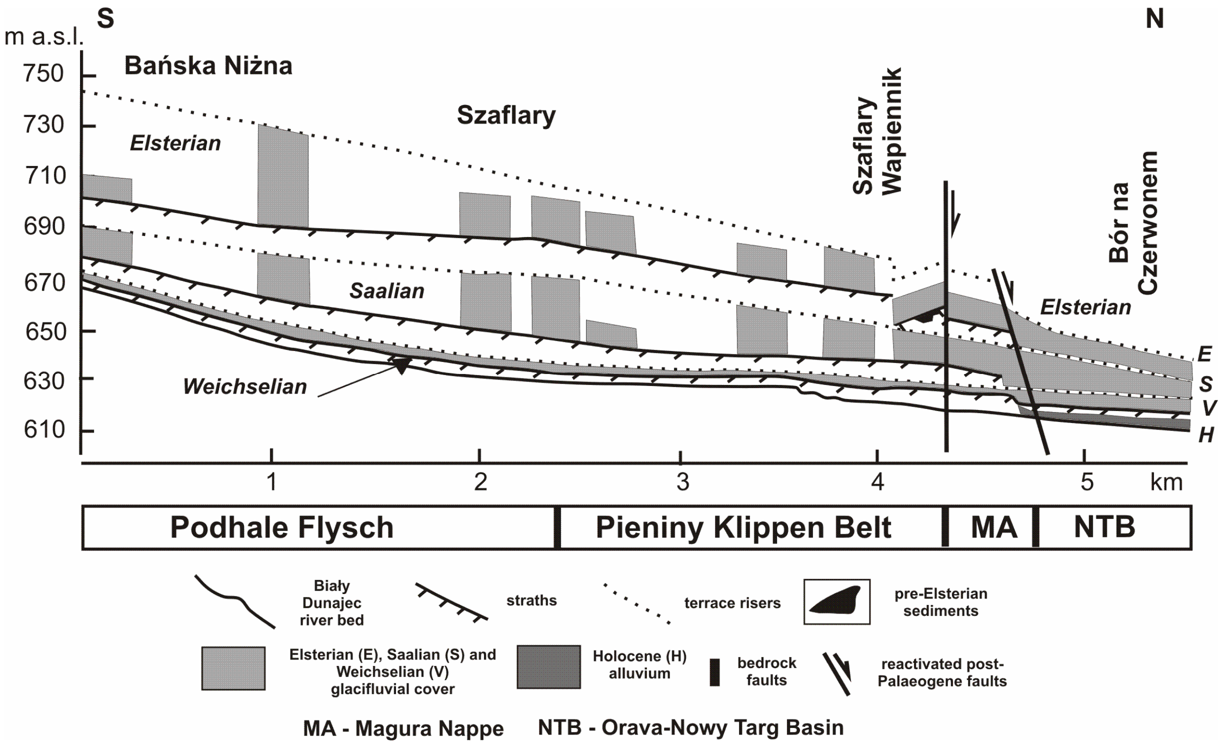

Fig. 4 Long profile of a fragment of the Biały Dunajec River valley (based on Birkenmajer, 1976; modified).

According to Halicki (1930), Badak (1965) and Książkiewicz (1972), Quaternary subsidence of the Nowy Targ Basin took place in the Holsteinian and Eemian times. The Dębno-Frydman graben in the eastern portion of the Nowy Targ Basin, 1.5-2 km wide and ca. 7 km long, is filled with 85 m thick Quaternary strata overlying >25 m thick Pliocene terrestrial series (Niedzielski, 1971; Birkenmajer, 1979; Pomianowski, 1995, 2003). Baumgart-Kotarba (1978) assigned the youngest episode of subsidence in this area to the Eemian, although traces of younger deformations occur as well (Baumgart-Kotarba, 1983). These disturbances are clearly visible in long profiles of Pleistocene terraces of the Białka Tatrzańska River (Fig. 5). In the southern Podhale region, minor disturbances in long terrace profiles are noticeable between Rzepisko and Oprzędków Wierch, featuring dome-like warping of Elsterian straths and faulting of both Elsterian and Saalian sediments close to Ubocz Jurgowska and Rzepisko. All Pleistocene terraces converge downstream, towards the axis of young subsidence associated with the Dębno-Frydman graben (Fig. 5).

OUTER CARPATHIAN VALLEYS

The number of Pleistocene terrace steps in the OWC is variable, increasing in some areas (Zuchiewicz, 1984, 1995, 2009; Łój et al., 2009).

The upper and middle reaches of the **Soła** River valley (Fig. 6) display minor deformations of long profiles of the Elsterian-2, Saalian-1 and Saalian-2 straths between Cisiec and Wieprz as well as south of Żywiec, coinciding with bedrock faults (Alexandrowicz, 1991). Well marked are deformations associated with faults bordering the Żywiec tectonic window. Straths of the Weichselian Late Glacial slope downstream from 3 m height at Milówka to 1-1.5 m below present-day river bed at Żywiec and to 8 m below river bed north of this town. Older terraces appear north of Żywiec; the highest ones (Eburonian and Menapian? in age) rise 120 m and 70-90 m, respectively, above present-day river bed (Szaflarski, 1932; age interpretation by Zuchiewicz, 1995). Deformed straths appear to indicate Quaternary uplift of the Beskid Żywiecki Mts., relative stability or minor subsidence of the Żywiec Basin, and stronger uplift of the Beskid Mały Mts. near Tresna-Porąbka.

The **Jeleśnia Basin**, situated in the Beskid Żywiecki Mts. and Jabłonków Depression (Fig. 7), bears 5 Pleistocene and 2-3 Holocene terrace steps. The Weichselian and Holocene terraces are cut-and-fill landforms, the remaining ones represent strath terraces (Wójcik, 1989). In the southern part of the basin, the Saalian fluvial cover attains 25 m in thickness and its base slopes to 22 m below recent river bed. The area is bounded on the west and east by fault zones, and on the south by the thrust of the Rača slice of the Magura Nappe. Pleistocene subsidence in this region commenced in the Holsteinian and

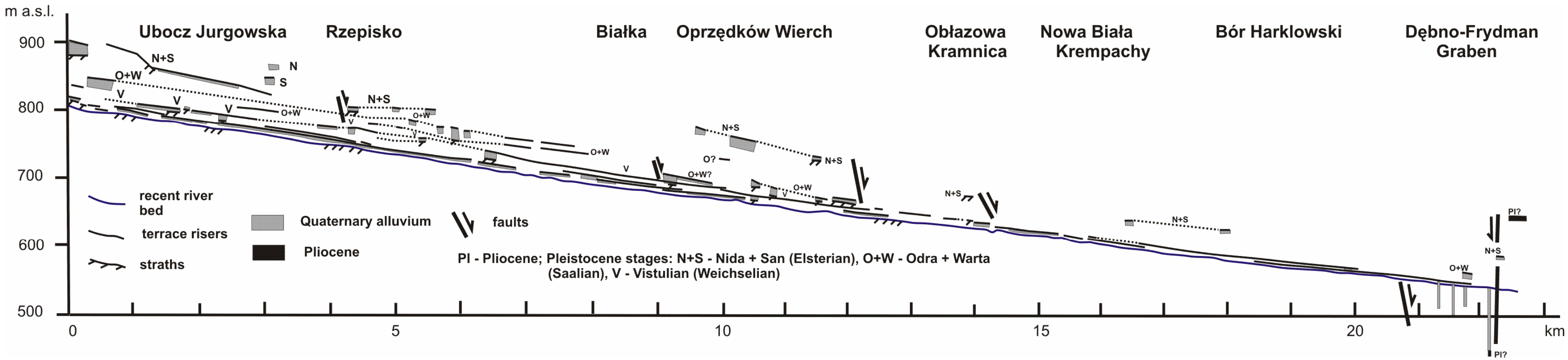

Fig. 5 Long profile of the Białka Tatrzańska River valley (based on Baumgart-Kotarba, 1978, 1981; modified).

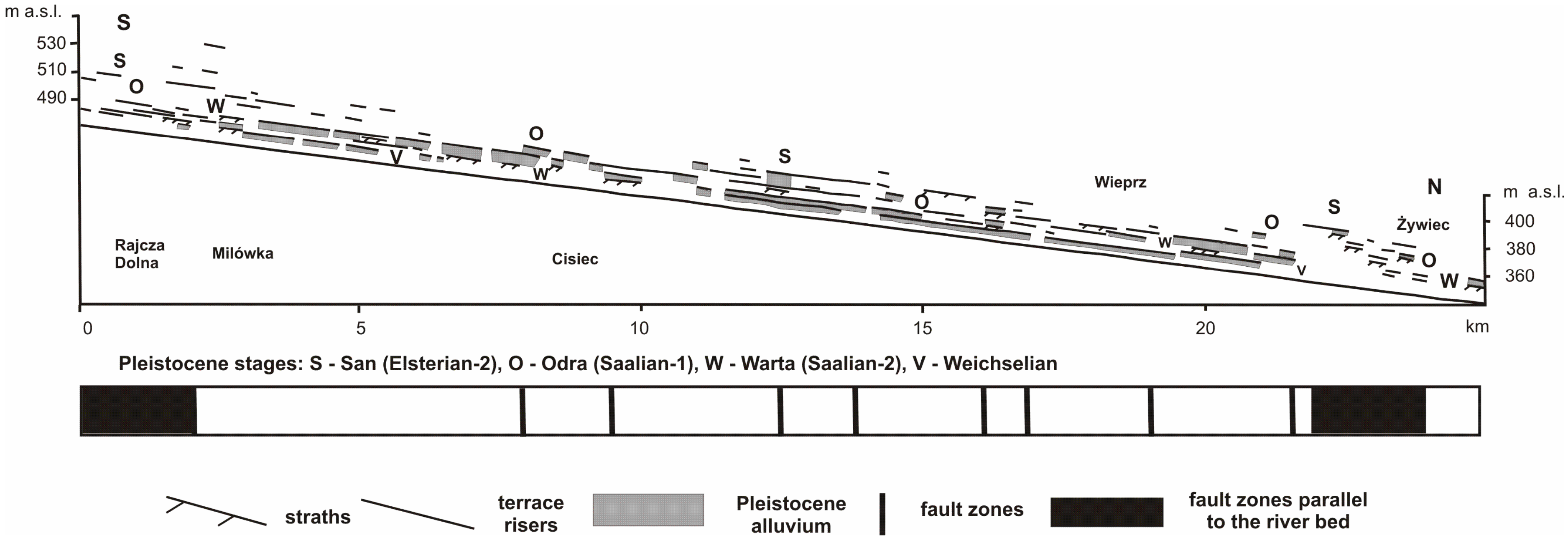

Fig. 6 Long profile of the middle segment of the Soła River valley (based on Alexandrowicz, 1991; modified).

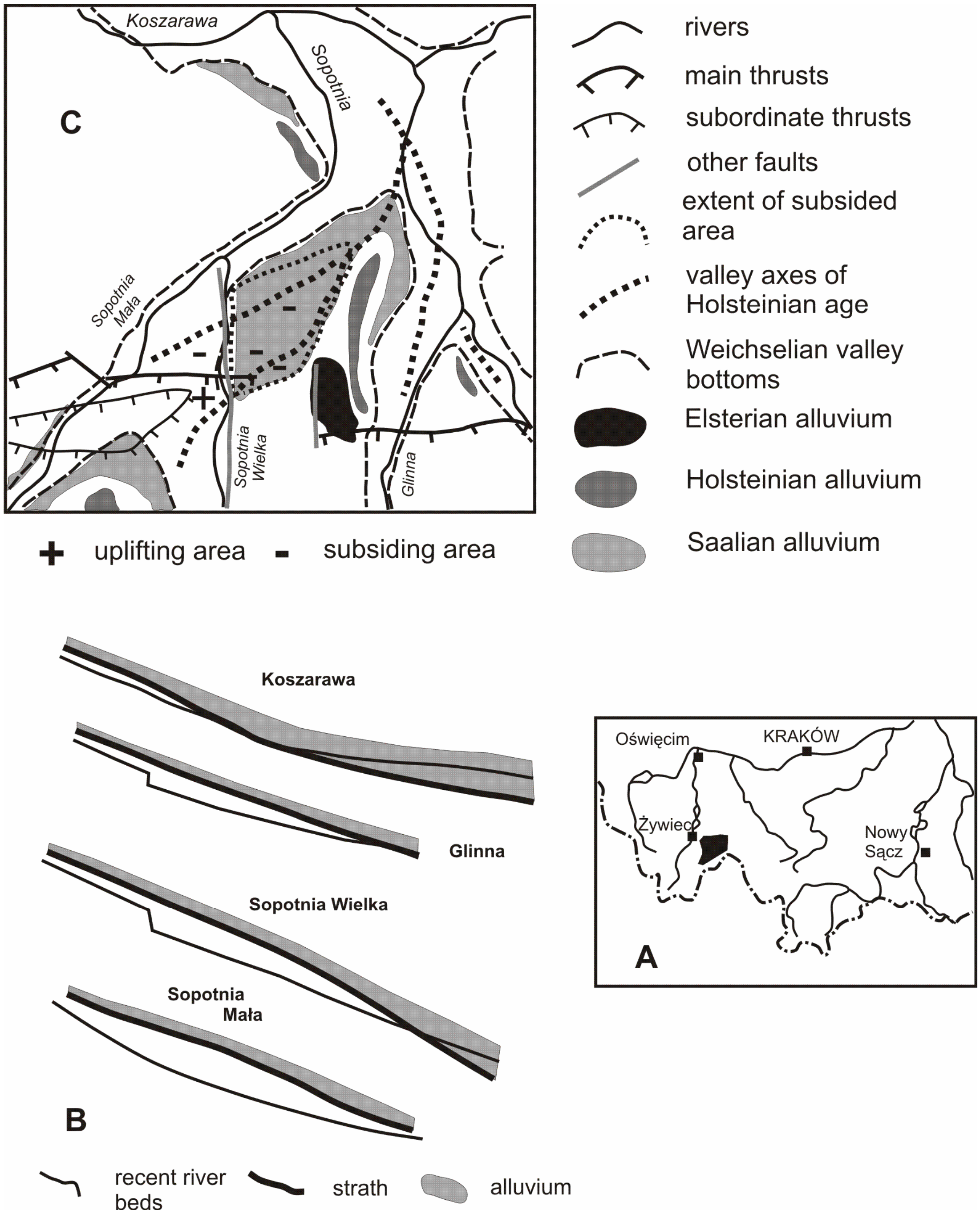

Fig. 7 Neotectonics of the Jeleśnia Basin (after Wójcik, 1988; modified): a – location sketch, b – long profiles of valleys bearing Weichselian alluvium, c – neotectonic sketch.

continued with deposition of the Saalian alluvium. The rate of subsidence changed from 0.1 to 0.2-0.58 mm/yr (Wójcik, 1989). Deformations of strath terraces during the Holsteinian, Saalian-1, Weichselian and Holocene were related to reactivation of the frontal Rača slice thrust, coeval with mobility of some faults cutting the thrust zone. Differential neotectonic movements on either side of this thrust (uplift in the south and subsidence in the north) made their appearance also in the last glacial and Holocene times. The zones of greatest strath deformation in all river valleys in the basin coincide with map-scale fold axes of the Rača slice. The quoted author pointed out block-type mobility of this area, although his data appear to be indicative of steepening of thrust zones and minor remnant folding.

In the Skawa River valley, deformations of Pleistocene straths document Late Pleistocene

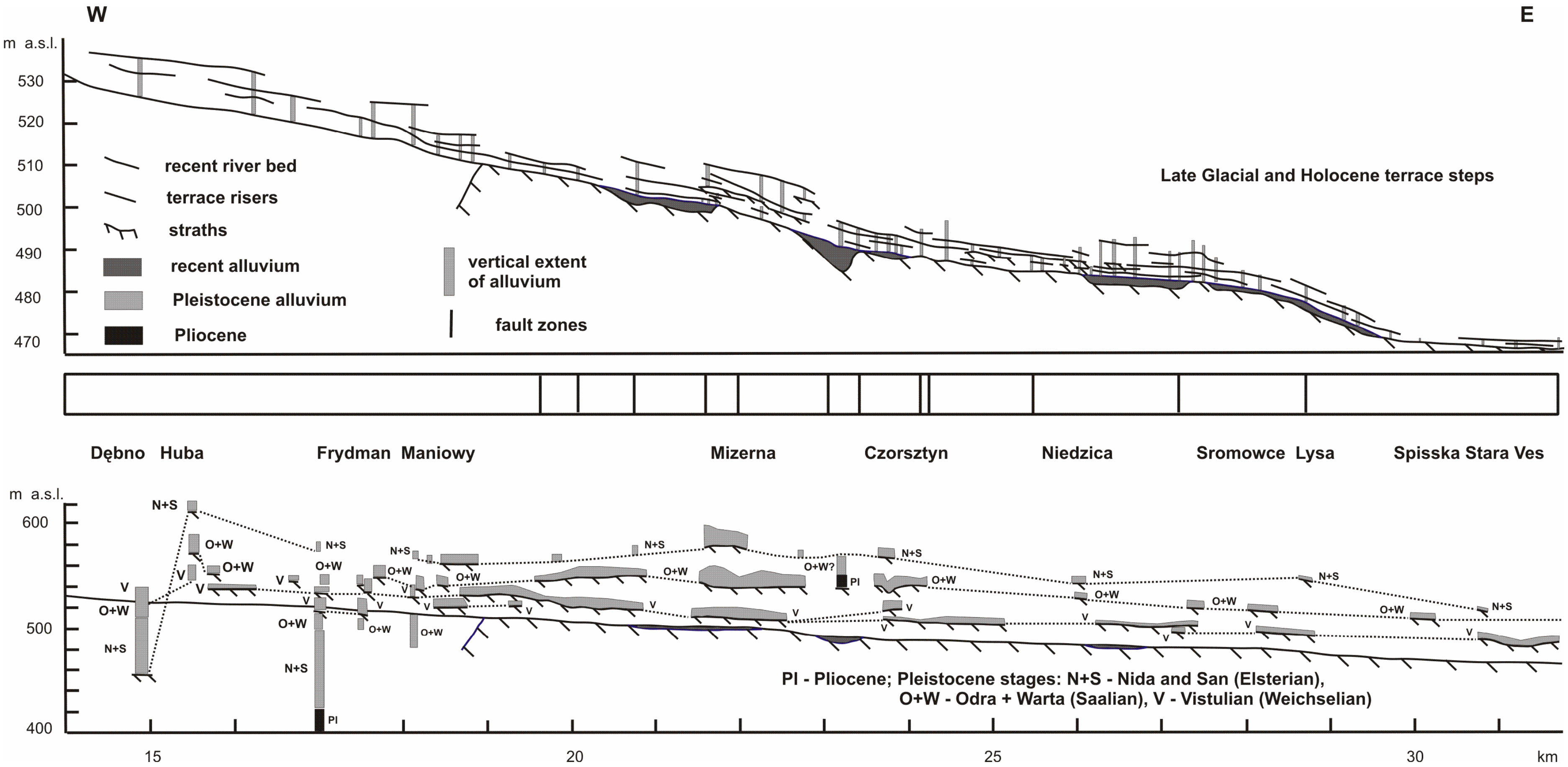

Fig. 8 Long profile of the Dunajec River valley in the Nowy Targ Basin and Pieniny Mts. (based on Zuchiewicz, 1980; modified and supplemented).

reactivation of the Silesian and, to a lesser extent, Magura frontal thrusts, as well as NNW-trending normal faults (cf. text-Figs. 13 and 14 in: Zuchiewicz et al., 2009). This is indicated, for instance, by abnormally high position of the Weichselian Early Glacial strath on the western valley side, the highest in the OWC of Poland (Grzybowski, 1998a, b, 1999; Zuchiewicz et al., 2009).

Long profiles of terraces of the Ochotnica and Kamienica Łącka rivers, left-hand tributaries of the Dunajec River in the Gorce Mts., indicated that up to the Lublin (Lubawa, Schöningen) warming faster erosional dissection affected the Kamienica River valley, while during the Eemian and Holocene twice as much faster dissection typified the Ochotnica River valley (Olszak, 2009). The author tried to explain this feature by Quaternary reactivation of some thrusts within the Magura Nappe, namely that of the Krynica slice which is thrust over the Bystrica slice.

Long profiles of terraces of the **Dunajec** River valley between Pieniny Mts. and Rożnów Foothills (Figs. 8-11, 14) are strongly deformed at the contact between the Pieniny Klippen Belt and the eastern part of the Nowy Targ Basin (Fig. 8), in a water-gap in the Beskid Sądecki Mts. (Fig. 9), along some transverse faults cutting the contact between the Krynica and Bystrica slices of the Magura Nappe in the Łącko-Podegrodzie Foothills (Fig. 10) and Nowy Sącz Basin (Fig. 11), as well as in the southern part of the Beskid Wyspowy Mts. and in Rożnów Foothills (Fig. 14). Relative heights of straths tend to diminish in the Nowy Sącz Basin, and deformations visible between Gostwica and Brzezna appear to coincide with reactivated Miocene faults that cut the basin fill (Fig. 11). Rates of Quaternary uplift, estimated from erosional downcutting of individual straths, changed from 0.05 to 0.72 mm/yr, attaining in the Holocene ca. 1 mm/yr in the axial part of the Beskid Sądecki Mts. The youngest episode of uplift affected the northern fringe of the Nowy Targ Basin, Pieniny Mts. and Beskid Sądecki Mts. At the eastern boundary of the Nowy Targ Basin, faults bordering the Dębno-Frydman graben displace Elsterian through Weichselian fluvial series. Farther east, close to Mizerna, Czorsztyn and Sromowce, dome-like warping of Elsterian and Saalian straths becomes evident (Fig. 8). The Dunajec River water-gap in the Beskid Sądecki Mts. reveals two deeply incised meanders separated by a rectilinear valley segment following the trace of the Dunajec fault. This is an antecedent water-gap (cf. Zuchiewicz, 1978, 1984, 2009), whose meanders originated due to Quaternary uplift and eastward tilting of the Beskid Sądecki longitudinal elevation (Fig. 9). Proceeding downstream, in the Łącko-Podegrodzie Foothills (Fig. 10), the base of Last Glacial and Holocene alluvium is strongly uneven, plunging at places to 8 m below present-day river bed. Older straths are either displaced or terminate at reactivated Miocene bedrock fault zones. In the Nowy Sącz Basin (Fig. 11) strath displacement and tilting is mainly confined to the northern side of the basin, near Brzezna and Nowy Sącz.

The downstream segment of the **Poprad** River valley (Fig. 12) reveals faulted straths older than the Saalian-2 stage. These faults coincide with reactivated Miocene faults that cut the Magura Nappe and Neogene infill of the Nowy Sącz Basin near Myślec and Stary Sącz. In the **Kamienica Nawojowska** River valley (Fig. 13), tilted straths clearly correlate with bedrock faults, particularly between Zawada and Falkowa. These deformations concern mainly the Praetiglian and Eburonian, less markedly Menapian and Drenthe straths.

North of Nowy Sącz (Fig. 14), two zones of strath warping occur between Wielopole and Marcinkowice and near Znamirowice. Moreover, reactivated bedrock faults displace Elsterian and older straths at a few places.

A segment of the **Biała Dunajcowa** River valley between Grybów and Tuchów (Fig. 15) bears terrace covers dated to the Saalian, Weichselian and Holocene. Small-scale disturbances in strath long profiles are noticeable close to Bobowa and Zborowice, not always coinciding with bedrock faults.

A pattern of deformation of long profiles of the **Wisłoka**, **Jasiołka** and **Wisłok** river terraces in the western portion of the Jasło-Sanok Depression is shown in Fig. 16. According to Wójcik (2003), these disturbances are related to reactivation of bedrock faults, including reverse ones, that cut map-scale folds of the Silesian Nappe. The area is typified by relatively small relief and dominated by a number of basins separated by resequent ridges that developed upon imbricated anticlines (Świdziński, 1953; Wójcik, 2003 and papers cited therein). Main valleys dissecting the Jasło-Sanok Depression bear eight Pleistocene terrace steps, which were dated by Wójcik (2003) to the Elsterian, Saalian and Weichselian stages. Differences in relative height among individual terrace steps are greater on the southern margin of the depression compared to those of the northern one, pointing to nearly twice as much higher rate of surface uplift: 0.11 mm/yr in the south and 0.06 mm/yr in the north. The size of dissection after the Elsterian amounted to 30 m in the north and 70 m in the south. Active subsidence was marked following Saalian-2 time (Wójcik, 2003). Unlike the western portion of the OWC, rates of uplift successively decreased throughout the Pleistocene. The quoted author points also to reactivation of strike-slip faults that controlled changes in the drainage pattern, particularly in the Jasiołka and Wisłok rivers interfluve. Deformation pattern shown in Fig. 16 appears to indicate remnant Quaternary folding in this area, and not necessarily block-type motions as suggested by Wójcik (2003).

The upper, poorly dissected reach of the **upper Jasiołka** River valley reveals strath terraces from the Saalian-2, Weichselian and Holocene times (Zuchiewicz, 1988). Traces of older fluvial activity

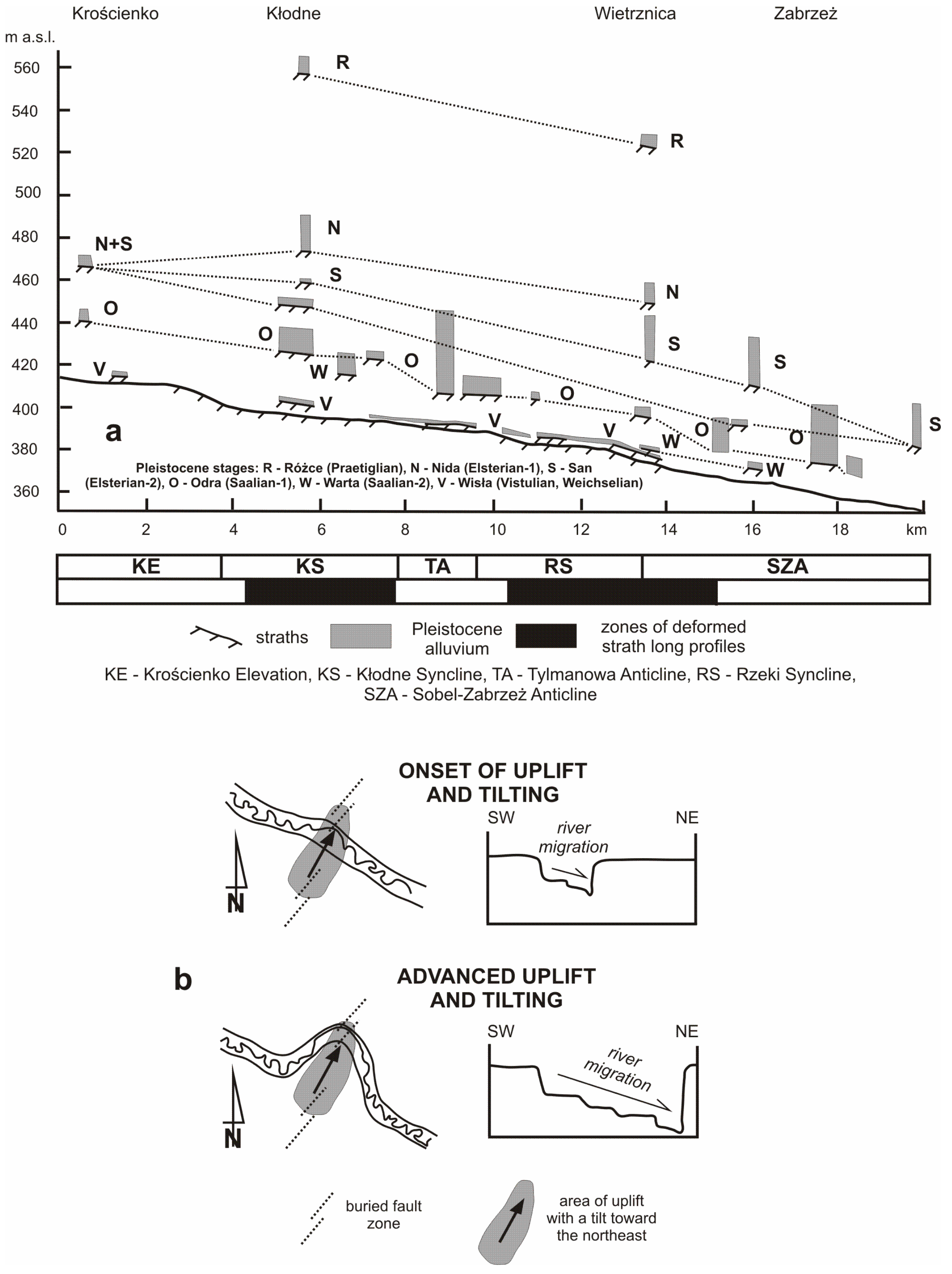

Fig. 9 Long profile of the Dunajec River valley in the Beskid Sądecki water-gap segment (based on Zuchiewicz, 1978, 1984; modified and supplemented). Flights of terraces within Kłodne and Wietrznica meander loops (a) could have originated like in an hypohetical model (b) of incised meander formation in an area affected by uplift and tilting (after Schumm et al., 2000; simplified).

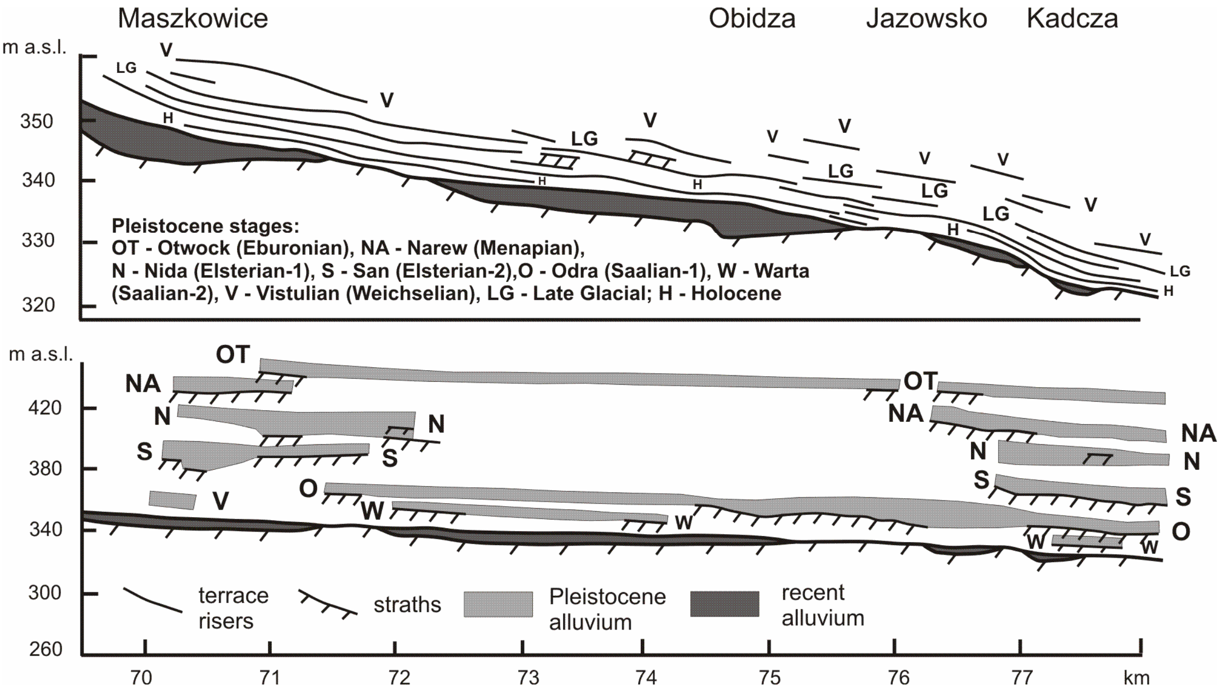

Fig. 10 Long profile of the Dunajec River valley in the Łącko-Podegrodzie Foothills (based on Zuchiewicz, 1984 and Rutkowski and Zuchiewicz, 1992; modified and supplemented).

are preserved as minor rock benches. Deformations of terrace long profiles coincide in part with bedrock faults, mainly downstream of Jaśliska and near Tylawa. In the middle reach of this river (Fig. 18a), a dome-like warping of the Saalian-2 and Weichselian terraces was identified near Dukla, Równe and Wrocanka (Kuśmierek and Magiera, 1993). The upper reach of the **Wisłok** River valley (Fig. 17) shows at least four zones of dome-like warping of the Saalian-2 and Weichselian straths, the most remarkable one being confined to the downstream segment, associated with the marginal part of the Beskid Niski Mts. (Zuchiewicz, 1988). In the same area and farther downstream (Fig. 18b), in a segment analysed by Kuśmierek and Magiera (1993), warping of late Pleistocene terraces is marked between Surowica and Wernejówka, close to Rudawka Rymanowska and downstream of Besko (Kuśmierek and Magiera, 1993).

Long profiles of terraces mapped by Starkel (1965) in the middle segment (within the Carpathian reach) of the San River valley display both basin- (Rajskie-Solina) and dome-like (Myczkowce, Lesko) warping of Elsterian and Saalian straths (Fig. 19). Such a picture may, however, result as well from mid-Pleistocene faulting.

DISCUSSION

The above review points to differentiated neotectonic behaviour of faults displacing or warping strath terraces of Pleistocene age. In the western portion of the OWC, rates of erosional downcutting and, probably, surface uplift of individual structures tended to increase throughout the Pleistocene, while those in the eastern portion showed a reverse trend. The pattern of deformation was also variable: terrace warping in some areas appears to have been related to either remnant folding or – more likely - thrust fault reactivation (segments of the Skawa, Dunajec, Wisłoka, Jasiołka, and Wisłok river valleys), while tilting and abrupt terminations of individual terraces in other valley reaches can easily be associated with normal reactivation of fault zones striking perpendicular to the overall trend of folds and thrust sheets (e.g., Skawa River at Świnna Poręba, segments of the Soła, Dunajec or San river valleys). It would be difficult to conclude about periodicity of neotectonic movements, however, most of individual case studies appear to indicate increased mobility during the Early Pleistocene, Holsteinian, and Eemian stages. Traces of Weichselian Late Glacial and Holocene activity are restricted to axial parts of neotectonic elevations like that of the Beskid Sądecki Mts. dissected by the Dunajec and Poprad river valleys. Variable patterns of deformation observed in the western and eastern portions of the study area may have been related to differentiated behaviour of the bedrock blocks underlying overthrust flysch nappes: the Upper Silesian block in the west and Małopolska block in the east showing different rheological properties (Jarosiński et al., 2006). The former is cut by fault zones that continue from the middle/upper crustal

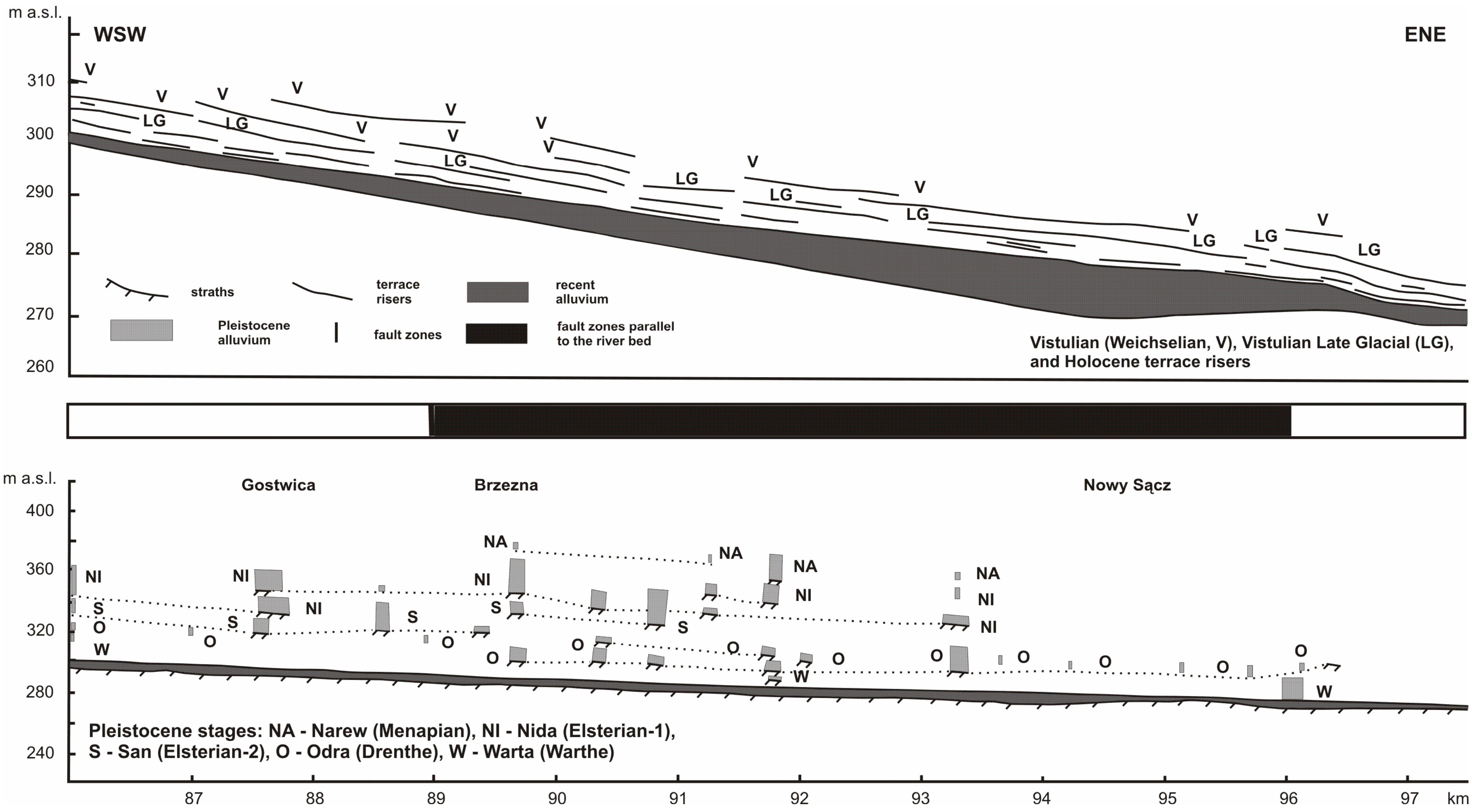

Fig. 11 Long profile of the Dunajec River valley in the Nowy Sącz Basin (based on Zuchiewicz, 1983, 1984; modified and supplemented).

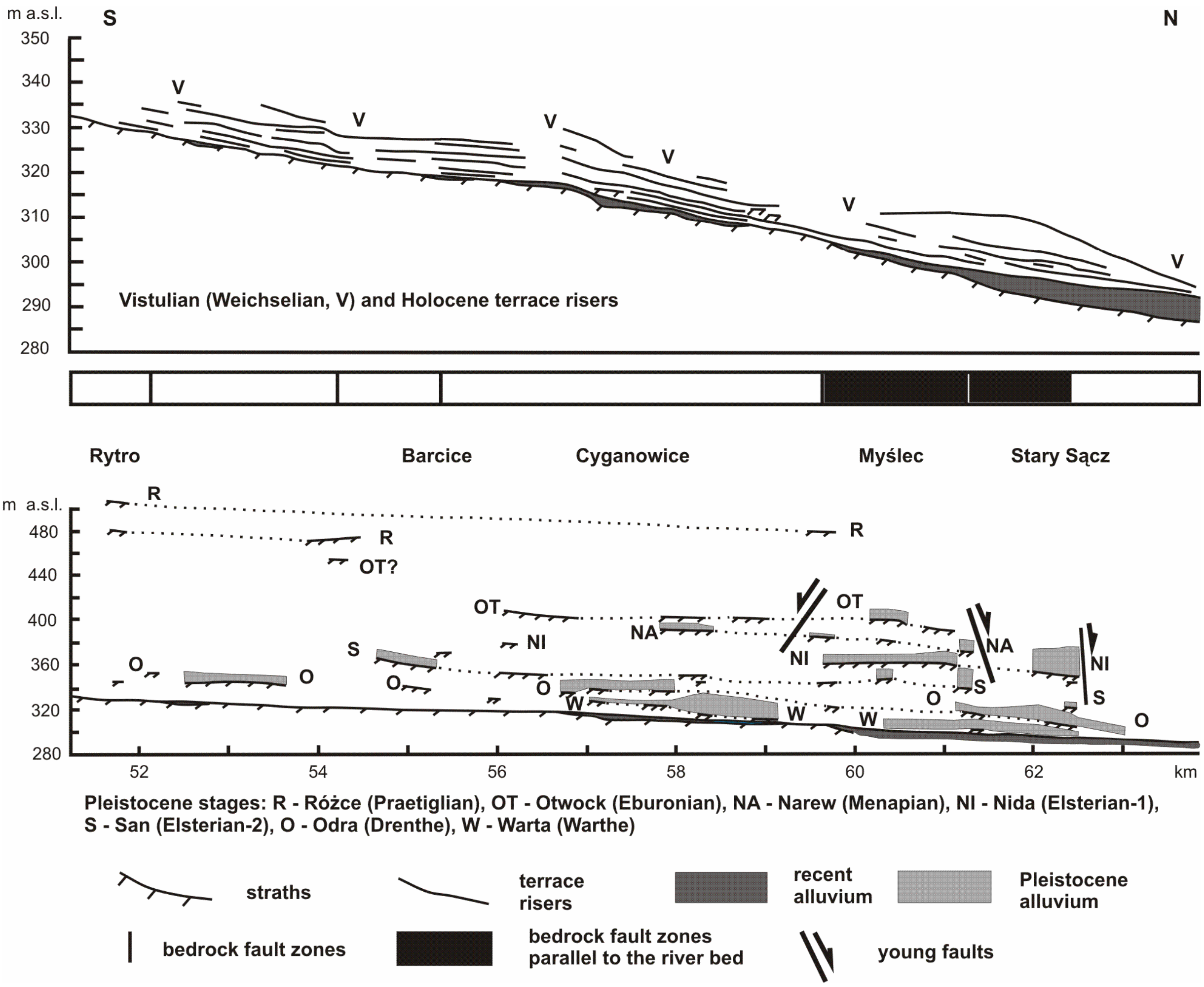

Fig. 12 Long profile of the lower segment of the Poprad River valley (based on Zuchiewicz, 1984; modified and supplemented).

layers nearly up to the ground surface (Golonka et al., 2009; Pietsch et al., 2010).

PALAEOCLIMATE VERSUS TECTONIC FACTORS

It is commonly accepted nowadays that long-timescale terrace staircases record regional surface uplift (Bridgland, 2000; Bridgland and Westaway, 2008a,b and references therein), although the role of alternating periglacial and warm climate fluctuations is equally acknowledged (Veldkamp and Van den Berg, 1993; Maddy et al., 2001; Vandenberghe, 2002; Starkel, 2003 and others). Bridgland and Westaway (2008a,b) have recently concluded about cyclic formation of river terraces as resulting from climatic fluctuations as well as about global acceleration of uplift during and due to the Mid-Pleistocene onset of 100 kyr Milankovitch eccentricity-driven cycles that replaced previously dominating 41 kyr obliquity-driven ones. Time-averaged fluvial incision rates in the period following this transition in the temperate zone of the Northern Hemisphere range between 0.03 and 0.2 mm/yr (Bridgland and Westaway, 2008a). These authors also hypothesize that increased rates of surface uplift in the Late Pliocene and early Middle Pleistocene are largely induced by flow in the lower continental crust triggered by surface processes (mostly icesheet loading and deloading cycles as well as fluvial incision and accumulation) and represent, therefore, “atectonic” deformation typical for intraplate settings. Well-developed flights of terraces typify young, Phanerozic crust and stable low-relief valleys dominate cratonic areas underlain by old crust of Precambrian consolidation (Westaway, 2002; Bridgland and Westaway, 2008b and references therein). The relatively small number of terrace steps in the Polish Carpathian valleys (compared, for instance, with 31 terraces of the Maas River near Maastricht) probably results from high rates of uplift exceeding the value of 0.07 mm/yr, which is considered typical for the Middle-Late Pleistocene of north-western and central Europe (see discussion in: Westaway, 2002). According to this author, at rates

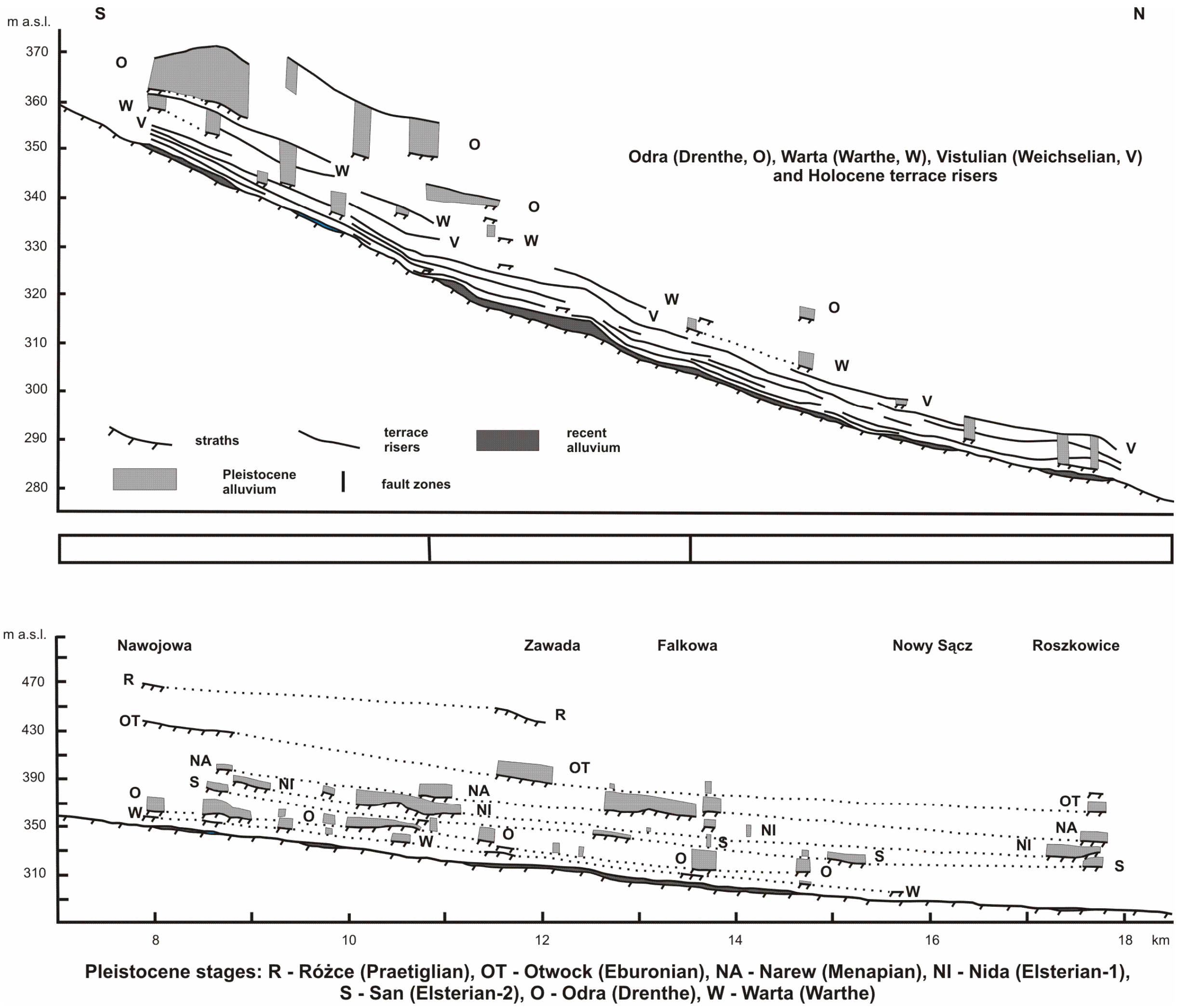

Fig. 13 Long profile of the lower segment of the Kamienica Nawojowska River valley (based on Zuchiewicz, 1984; modified and supplemented).

either lower or higher than 0.07 mm/yr terrace sequences become either indistinct or less clear.

Flights of fluvial terraces tend to form due to downcutting either at warming, both warming and cooling, or at cooling transitions (Bridgland and Westaway, 2008a). As far as the Polish Carpathians are concerned, different pieces of evidence recently summarized by Olszak (2011) indicate that valley incision and deepening typified both glacial-interglacial and glacial-interglacial transitions as well as interglacials themselves; the rates of uplift throughout the entire Pleistocene remaining constant. Aggradation in valley bottoms during glacial stages led to smoothing out of river bed long profiles, whereas climate amelioration in late glacial phases fostered dissection of periglacial, glacifluvial and niveofluvial covers (Starkel, 1983, 1985, 1986, 2003). Short-term episodes of deep incision of strath terraces were associated with early interglacial phases. Lack of erosion in the OWC valleys during glacial stages led Dziewański and Starkel (1962) and Starkel (1965, 1978) to hypothesize about continuous tectonic uplift that was reflected in the landscape with some delay, the duration of which is difficult to estimate precisely. Such a delayed response of the fluvial system is also applicable to climate changes. It is hypothesized that rivers are not able to respond to climate oscillations that have a duration comparable to that of the delay time (Vandenberghe, 2002). The amount of slope degradation in one glacial-interglacial cycle was estimated at 10 m, and for the entire Pleistocene at 30-50 m (cf. Starkel, 1965, 1983). Poor state of preservation of solifluction-slopewash covers in the OWC makes reconstructions of climatically-driven degradation and its separation from neotectonic control difficult. Nevertheless, one can compare the number of terrace steps in individual valleys and the size of erosional strath incision (Fig. 20). Poor state of preservation or lack of bedload facies suggests predominance of slope processes over fluvial ones in

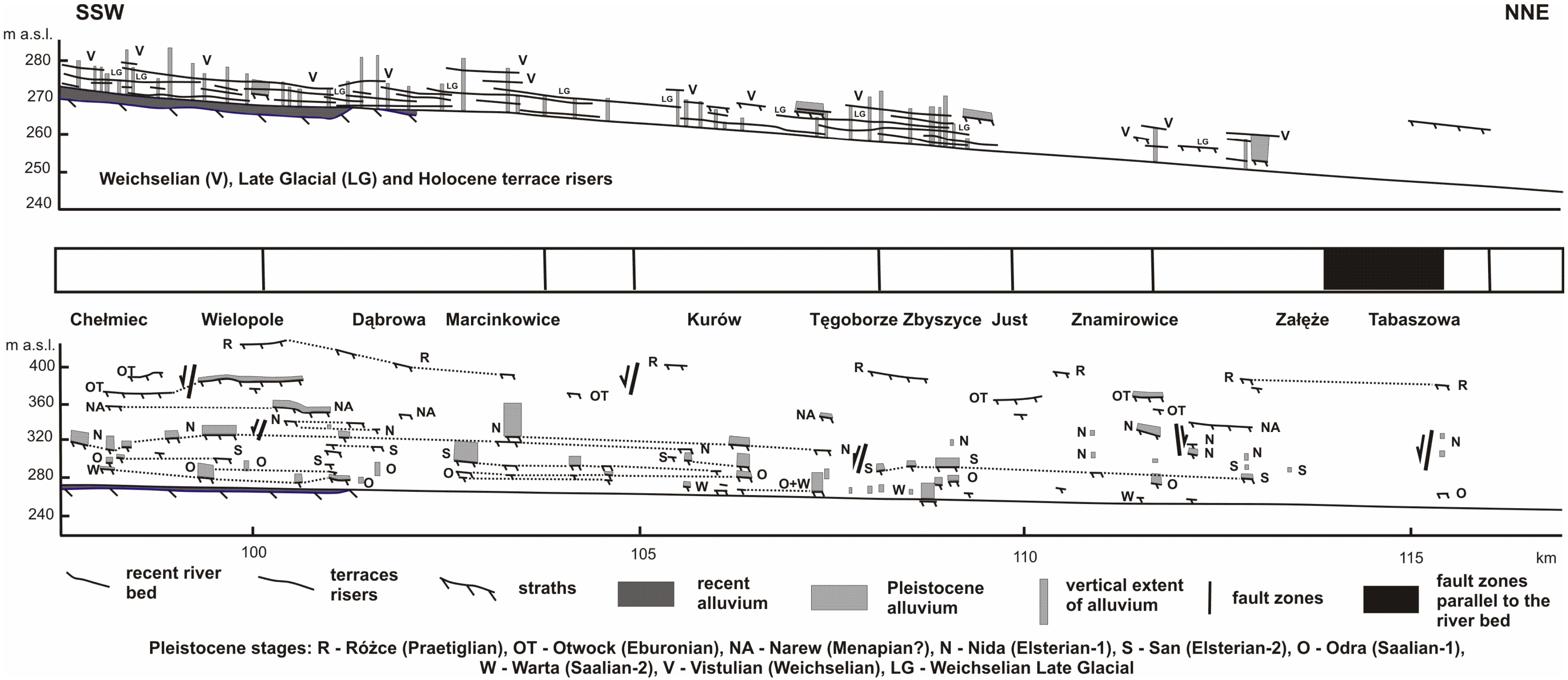

Fig. 14 Long profile of the Dunajec River valley in the Rożnów Foothills (based on Zuchiewicz, 1984; modified and supplemented).

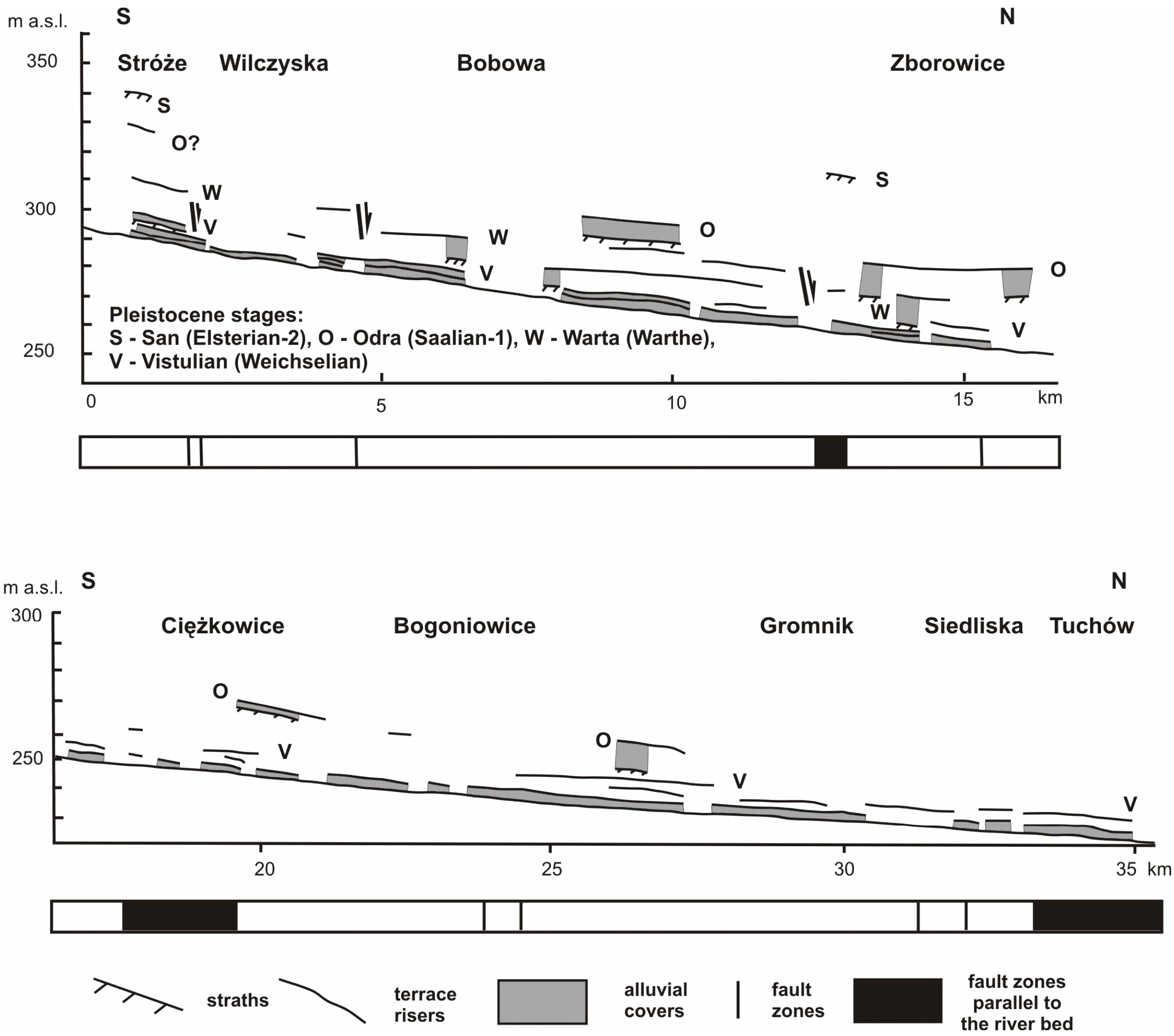

Fig. 15 Long profile of the middle segment of the Biała Dunajcowa River valley (based on Dudek, 2009; modified and supplemented).

the upper valley reaches, while the increasing number and relative height of terraces appears to imply tectonic control. Valleys dissecting more strongly uplifted structures tend to have more numerous terrace steps (cf. Zuchiewicz, 1984). This implies better preservation of terraces with stronger uplift, unless rapid uplift leading to downcutting of steep gorges with channels fixed on highly resistant bedrock makes terrace preservation minimal or impossible (Bridgland and Westaway, 2008a). A smaller number of terraces compared to that of glacial-interglacial cycles may result from different succession of cold and warm phases during climatic cycles of different age (Starkel, 1983), or indicate that only the major climatic events (supercycles) are represented (Kukla, 2005; Bridgland and Westaway, 2008a) . The youngest, Weichselian-Holocene cycle terminated with a warm phase that was preceded by a very strong cooling; a feature suitable for development of separate terrace steps (Pleniglacial, Late Glacial and Holocene ones). Terrace formation during earlier cycles and their preservation potential were, in turn, largely controlled by the intensity of neotectonic movements. This is indicated by a comparison of the number of terrace steps in areas showing different tectonic tendencies, like the Alps and their foreland (Kukla, 1978, 1981; Brunnacker et al., 1982; Häuselmann et al., 2007).

According to Starkel (1985, 2003), in areas showing minor tectonic uplift, small-scale climate fluctuations are reflected in a series of small erosional cuts and alluvial infills. In more strongly uplifted areas, in turn, the number of strath terraces increases, and climate cycles of short duration (up to 20 thousand years) may lead to shaping of several erosional steps. Climatically-driven delay in erosional downcutting, related to increased accumulation during the last cold stage, does not favour tectonic interpretation of increased erosional dissection in the

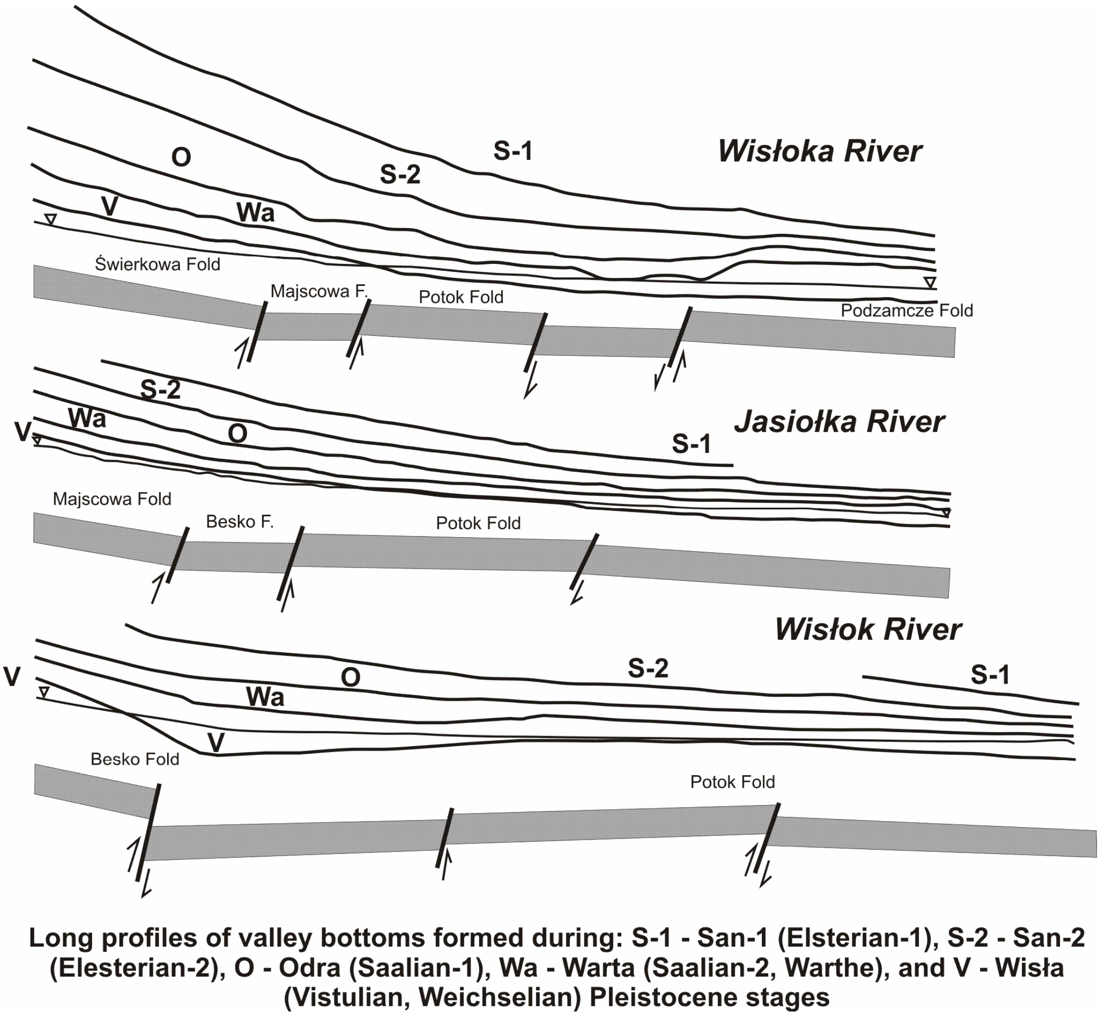

Fig. 16 Summary diagram of long profiles of terraces of rivers truncating the Jasło-Sanok Depression (based on Wójcik, 2003; modified).

Holocene. Moreover, eroded bedrock (strath) underlying one terrace cover of a given age may show in a cross section through the valley differences in relative height up to 10 m. When such a strath becomes undermined by river channel migrating laterally to a variable extent in different valley reaches, this may lead to apparent presence of 2-3 erosional benches, which, in fact belong to the same strath although being exposed either closer to of farther away from the hillslope. Such benches may, hence, be erroneously interpreted as separate terrace steps (Starkel, 1985, 2003). Changing elevations in long valley profiles may also result from downcutting of high-gradient segments underlain by resistant bedrock, smoothing river bed profiles by aggradation in cold climate and renewed epigenetic dissection, incorrectly suggesting differentiated rates of neotectonic uplift (Starkel, 2003). Such a climate-oriented type of reasoning precludes any tectonic interpretation of terrace deformation in moderately to weakly uplifted mountain areas, unless proved otherwise.

Recent estimates point to three episodes of increased fluvial dissection of strath terraces (Zuchiewicz, 1995, 1998, 2009): Cromerian – Elsterian 1-2 (ca. 800-472 ka; 0.15-0.21 mm/yr), Eemian – Weichselian Early Glacial (130-90 ka; 0.18-0.40 mm/yr), and Late Glacial – Holocene (15-0 ka; 0.2-2.0 mm/yr). These were mainly confined to marginal zones of overthrust nappes, 100-250 km long and 15-25 km wide. Maximal rates are noted in river valley segments dissecting the Beskid Sądecki Mts., Bieszczady Mts. and the northern part of the Beskid Niski Mts. Actual rates must have been a little bit higher, if – according to Starkel (1985) – we restrict the duration of individual episodes of fluvial incision to 10-20 thousands of years. Of importance are notably higher rates of erosion, particularly in Late Pleistocene time, along the margins of some thrusts, like those of the Rača slice in the Magura Nappe,

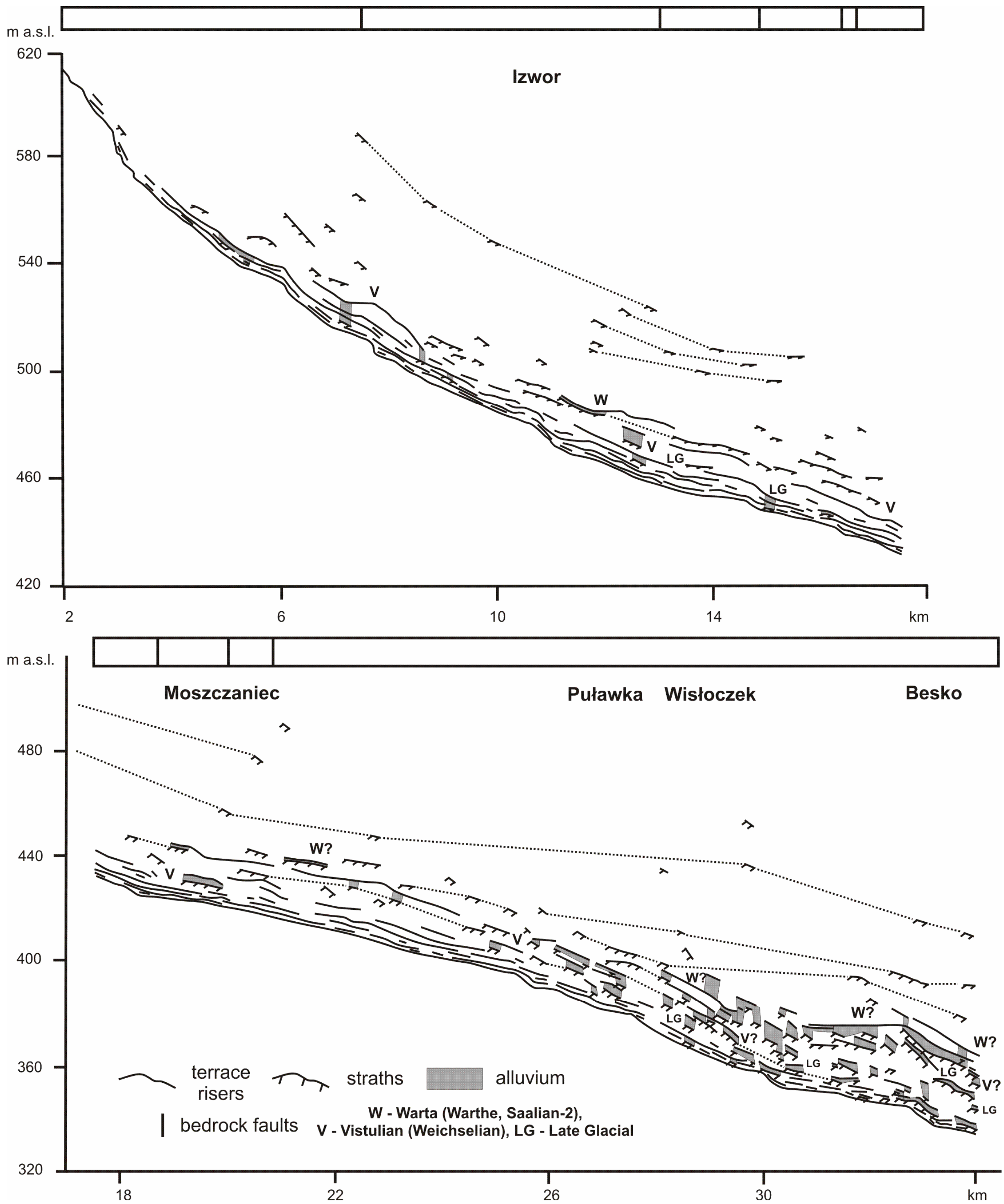

Fig. 17 Long profile of the upper reach of the Wisłok River valley (based on Zuchiewicz, 1988; modified and supplemented).

Silesian Nappe in the western portion of the OWC, or Dukla Nappe in the eastern portion of this unit. Recently measured rates of erosion are considerably higher; for instance, in the Gorce Mts. they exceed 3 mm/yr (Niemirowski, 1974). This results from an extremely short period of observations as well as from human impact.

The above review indicates that young tectonic mobility of the Carpathians is largely inferred from deformations of long river bed profiles and variable rates of strath dissection. As far as the OWC are concerned, some authors concluded of decreasing rates of uplift throughout the Quaternary and the lack of tectonic activity in Holocene times (Sawicki, 1909;

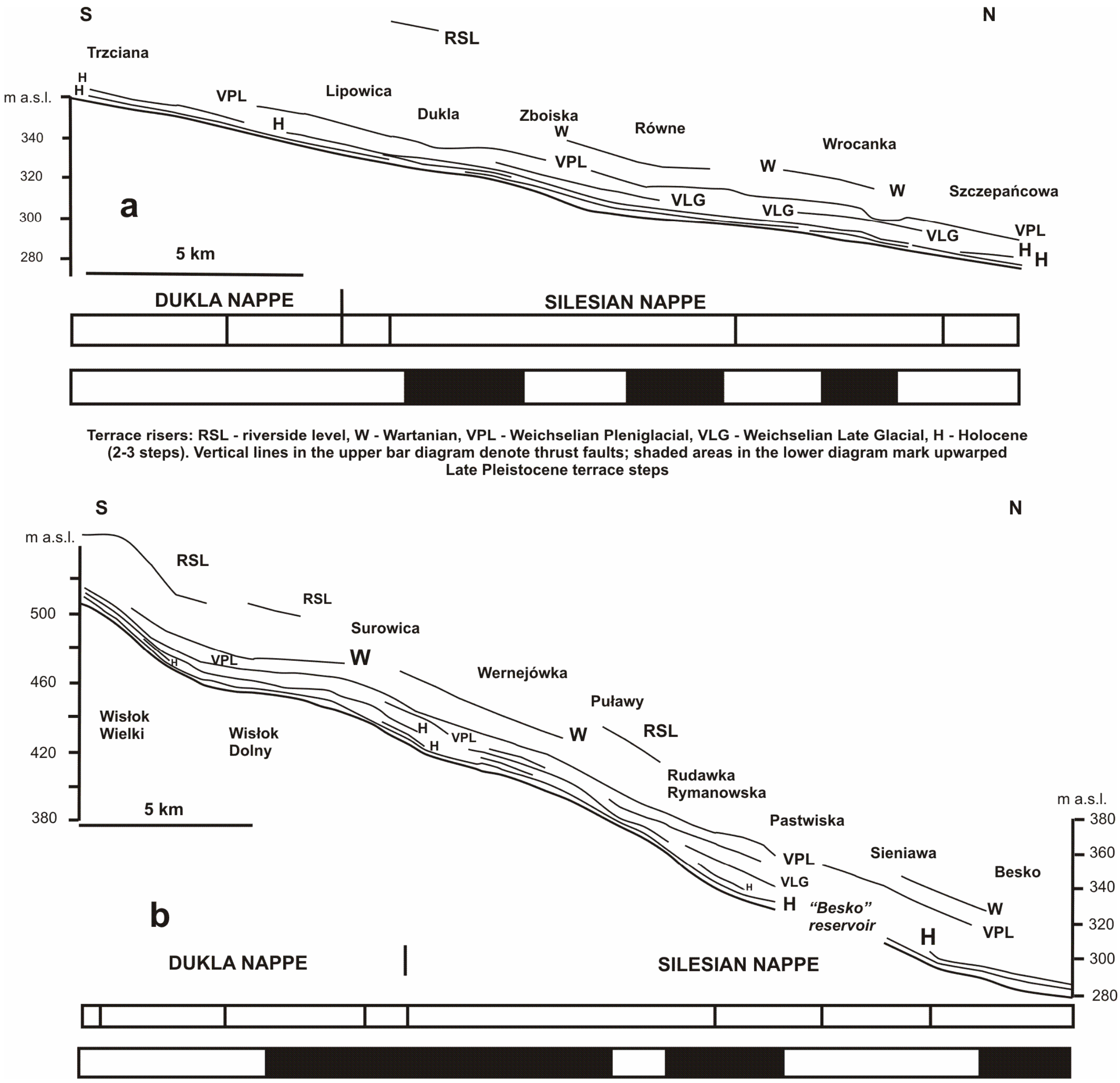

Fig. 18 Long profiles of middle reaches of the Jasiołka (a) and Wisłok (b) river valleys (based on Kuśmierek & Magiera, 1993; modified).

Klimaszewski, 1948; Dziewański & Starkel, 1962; Starkel, 1965), while others advocated the reverse tendency (Henkiel, 1972; Wójcik and Zuchiewicz, 1979; Wójcik, 1989). According to Starkel (1971), uplift post-dating Saalian stages persisted in axial parts of the Beskidy Mts. only. Data collected by Wójcik (2003) in the Jasło-Sanok Depression point to a more complicated history: the rates of strath dissection tended to increase during interglacials (0.2-0.65 mm/yr, averaging 0.04-0.12 mm/yr between Elsterian-2 and Recent), although showing decreasing intensity in successively younger Pleistocene stages. Reliability of all these considerations is, however, undermined by very poor age control of Pleistocene fluvial covers; the existing stratigraphic concepts are based on indirect pieces of evidence (climato-, morpho- or allostratigraphic ones), while numerical dating, particularly those based on cosmogenic isotopes (cf. Siame et al., 2006; Häuselmann et al., 2007), are lacking. This gap should be filled in the nearest future.

Another problem arises from the time-scales taken into consideration. Henkiel (1972), Wójcik and Zuchiewicz (1979) and Wójcik (1989) pointed out to increasing rates of neotectonic uplift in the Late Pleistocene and Holocene. One should bear in mind, however, that long-term rates (i.e., for the entire Quaternary) are always one order of magnitude lower from those calculated for individual stages, not to speak about recent rates. Let us imagine, for instance,

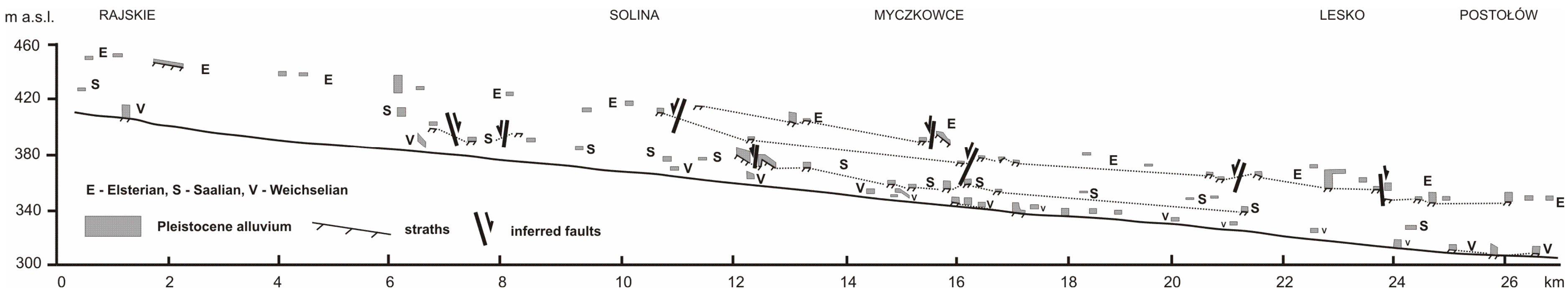

Fig. 19 Long profile of the middle reach of the San River valley (based on Starkel, 1965; modified and supplemented).

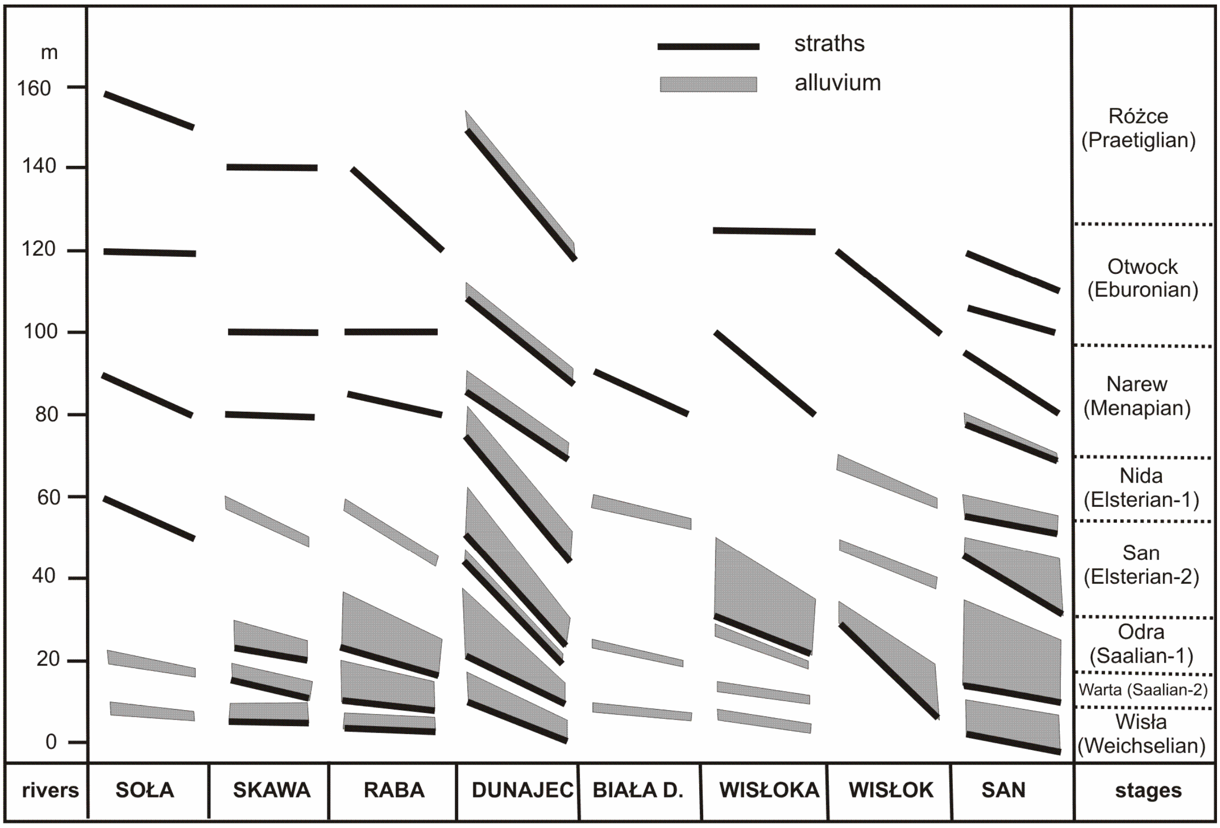

Fig. 20 Stratigraphic position of fluvial terraces in main valleys of the Polish Outer Carpathians based on different authors (age reinterpretation by Zuchiewicz, 1990, 1995; modified).

a well-dated terrace staircase showing a total of 100 m incision during the Quaternary and that this figure results from a sum of five episodes of downcutting, 20 m each. The average rate of Quaternary incision (during 2.59 Myr) in this case would be 0.04 mm/yr, while episodes of incremental downcutting – generally restricted to interglacial-glacial, glacial-interglacial or interglacial transitions lasting some 10-15 kyr - give rates ranging between 1.33 and 2 mm/yr each. Moreover, "increased" rates of Holocene downcutting are largely controlled by anthropogenic factors, related to deforestation, land use, gravel exploitation, and river regulation (cf. Klimek, 1987; Wyżga, 2001).

CONCLUSIONS

Fluvial archives of the Polish Carpathians bear a record of both climatic and tectonic signatures. The former consist in cyclic development of terrace covers interfingering with and/or overlain by soliluction and slopewash sediments; the latter include disturbances within strath long profiles and differentiated size of erosional downcutting. The size and rate of dissection of straths of comparable age are different in different structural units; a feature pointing to variable pattern of Quaternary uplift. Rates of river downcutting result mainly from climatic changes throughout the glacial-interglacial cycles, but their spatial differentiation appears to be influenced by tectonic factors as well. Quaternary reactivation of both normal and thrust bedrock faults was particularly noticeable during the Early Pleistocene, Holsteinian and Eemian stages, while differentiated patterns of neotectonic mobility in the western and eastern portions of the area could have resulted from different properties of the crust of the underlying Upper Silesian and Małopolska blocks.

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