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QUATERNARY EVOLUTION OF A CARPATHIAN FOOTHILLS AREA: AN EXAMPLE FROM THE EAST CARPATHIANS OF POLAND

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Abstract: The East Carpathian Foothills of Poland witnessed two episodes of relief planation in the Pliocene, followed by formation of Early Pleistocene strath terraces preserved on flat-topped meander spurs in the San River valley at altitudes of 100–120 m above recent floodplains. In the following stages, intense erosion produced of a flight of strath terraces that are provisionally dated to the Narevian or Sanian-1 (Menapian or Elsterian-1; 75–80 m), Sanian-2 (Elsterian-2; 40–60 m), Odranian and Wartanian (Drenthe, Warthe; 20–30 m), and Vistulian (Weichselian; 8–16 m) times. During glacial stages, solifluction deposits mantled the feet of gentle slopes being coeval with fluvial deposition and accumulation of loesses and loess-like sediments on either side of the San River valley, particularly intense in the Weichselian. Interglacial warmings fostered downcutting of the pre-existing fluvial sediments as well as formation of fossil soils within loess sequences and deposition of peat in abandoned channels. In the Late Pleistocene and at the beginning of the Holocene, diversified tectonic movements took place leading to displacement of Weichselian and Holocene straths. During the Holocene, in turn, cut-and-fill terrace steps were shaped, organogenic sediments filled abandoned channels and oxbow lakes, and slopes became re-modelled by landslides and slopewash.

The pattern of different types of relief, together with spatial distribution of topolineaments and some photolineaments in the eastern portion of the Polish Outer Carpathians, has been shaped due to mutual interactions between climatic, lithologic and tectonic factors. Well-pronounced topolineaments either follow fault-related zones of weakness, are associated with dense network of extensional cross-fold joints, or indicate recent reactivation of some faults and/or joint sets.

Key words: Quaternary sediments, tectonic geomorphology, neotectonic evolution, Carpathians, Poland.

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INTRODUCTION

The Outer Carpathians of Poland represent a typical fold-and-thrust belt that was affected by postorogenic collapse coupled with relaxation of some remnant horizontal stresses. Geophysical studies indicate that the generally modest Bouguer gravity anomalies point to non-isostatic processes causing the postflexural uplift, ranging from 250 m to 550 m (Zoetemeijer *et al.*, 1999). Numerous lines of evidence provided, *i.a.* by well-bore breakouts, deformation of oil industry well cores, structural data and geomorphic studies, all indicate Late Cenozoic tectonic activity of the Polish Outer Carpathians. The Pliocene–Quaternary (“neotectonic”) activity resulted in deformation of geomorphic surfaces of the early Pliocene, late Pliocene and early Pleistocene ages, as well as in upwarping, downwarping, tilting and/or faulting of straths of Quaternary fluvial terraces (*cf.* review papers by Zuchiewicz, 1995, 1998, 2009).

The late Palaeogene to Miocene history of the Carpathians is related to the change from collision to strike-slip faulting, surface uplift and sedimentary basin formation (Decker & Peresson, 1996). The Outer Carpathian belt was formed as an accretionary prism during the southward-directed subduction of the European plate under the AL-CAPA (Pescatore & Ślączka, 1984; Oszczypko & Żytko, 1987, Oszczypko *et al.*, 2005, 2008; Golonka *et al.*, 2009), resulting in the NW-directed shortening followed by major rotation of either the regional stress field (Aleksandrowski, 1985; Decker & Peresson, 1996; Zuchiewicz, 1998) or the belt itself (Márton *et al.*, 2009). This rotation gave rise to the NE-directed shortening and was postdated in Late Neogene times by regional collapse associated with normal faulting (Decker *et al.*, 1997; Zuchiewicz *et al.*, 2002). Recent studies appear to indicate that post-thrusting exhumation (< 10 Ma) and related extension and denudation of the Outer Carpathians of Poland, particularly in their eastern part, were associated with reactivation of some thrusts as low-angle extensional faults (Mazzoli *et al.*, 2010).

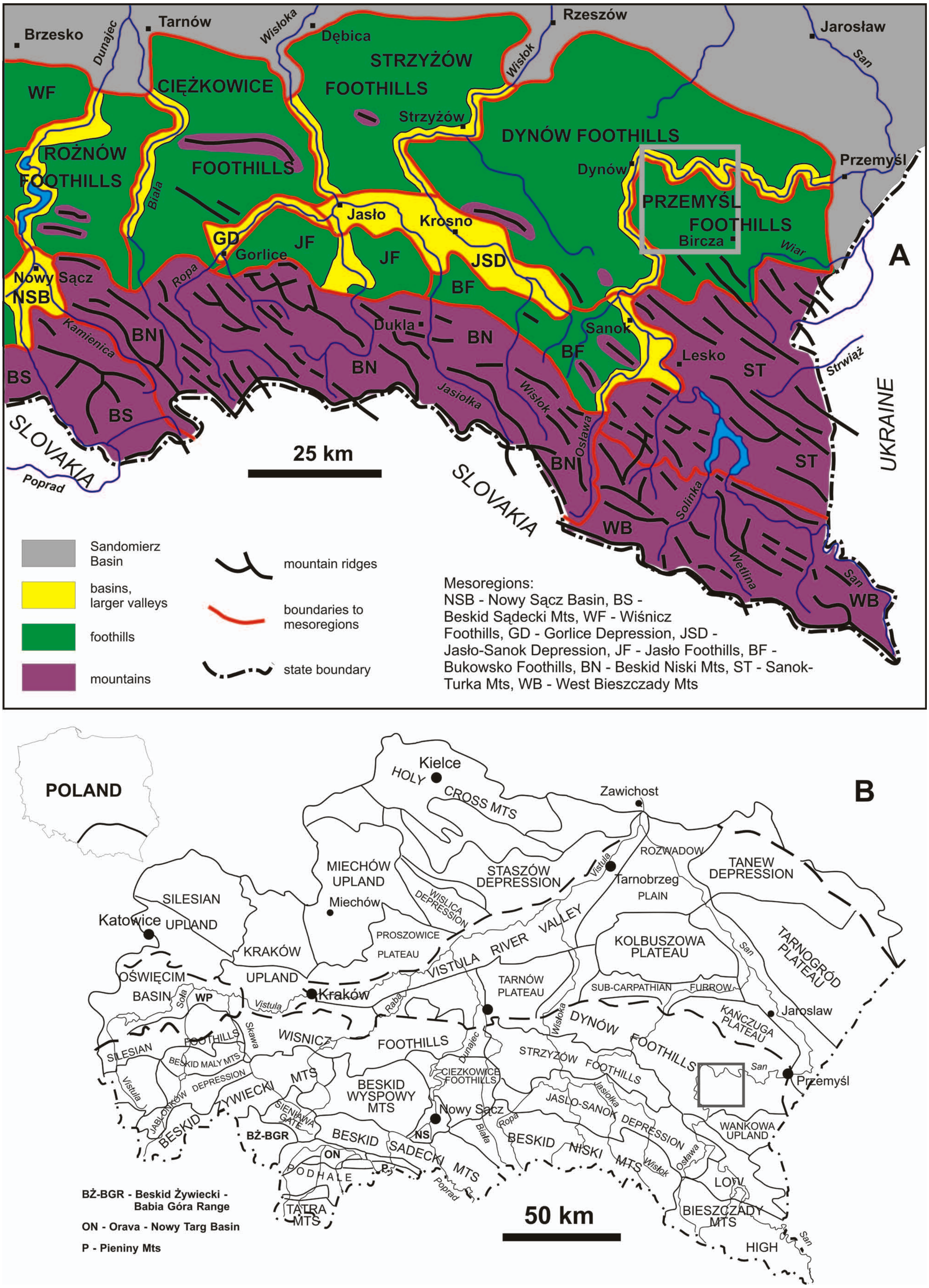

Fig. 1. Location of the study area (grey box) at the background of physico-geographic (A – Kondracki, 2000; modified) and geomorphic (B – Starkel, 1991; Gilewska, 1999) subdivisions of the Polish Carpathians

The aim of this paper is to reconstruct Quaternary evolution of a fragment of the Carpathian Foothills in the Polish Eastern Carpathians and to review several pieces of geomorphic tectonic proxies pertaining to diversified young tectonic activity of the area. This approach complements traditional geomorphic study of mapping and landform description as well as analysis of Quaternary sediments. The study area has a relatively good coverage by detailed geological maps and was the locus of repeated geomorphic and neotectonic investigations by numerous geoscientists.

The study area is located in the eastern portion of the Outer Carpathians of Poland, within the Middle Beskidy Foothills, more precisely in the Przemyśl Foothills south of the San River valley, and Dynów Foothills north of the latter (Kondracki, 2000), or – basing on subdivisions by Klimaszewski (1972), Starkel (1972, 1991) and Gilewska (1999) – in the Dynów Foothills, within the Beskid Niski Foothills region (Fig. 1).

GEOLOGICAL SETTING

The area is situated within the Skole Nappe, a prominent external tectonic element of the Outer Carpathians (Figs 2, 3). The nappe is composed of several imbricated thrust folds (“skybas”) emplaced between the late Oligocene and the end of the Sarmatian (*cf.* Roca *et al.*, 1995), usually trending NW–SE, and built up of Upper Cretaceous through Oligocene flysch strata. The Skole Nappe is thrust over the Stebnik Nappe in the NE and the Zgłobice thrust sheet (composed of folded Miocene molasses) in the north. Both thrust faults and map-scale folds within all these units trend predominantly NW–SE and are cut by strike-slip faults orientated NE–SW to NNE–SSW, subordinately WNW–ESE and N–S (Fig. 4). The north-central part of the study area is occupied by the Piątkowa Elevation, composed of the “Inoceramian” (Cretaceous–Palaeocene beds), probably stituated upon a high in the substratum (Rauch *et al.*, 2010). Some of the fault zones are marked in the topography, controlling orientation of main river valleys, including fragments of the San River valley. Figure 5 shows deep structure of the entire region (Kotański, 1997).

The amount of erosion of the flysch cover in post-Early Miocene time (after the Early Sarmatian) in the Polish Eastern Carpathians, namely during the past 21 Ma in the Magura Nappe and 12.5 Ma in the outer part of the Skole Nappe, ranged between 50 m and >900 m (Fig. 6), attaining increased values in the High Bieszczady Mts. (Kuśmierek, 1995a,b; see also Maćkowski *et al.*, 2009). In the study area, two zones of moderate erosion (200–350 m) trend NE–SW in the western and eastern parts, being separated by a zone of decreased values (100–150 m) of the same orientation.

The pattern of principal and subordinate photolineaments in the eastern segment of the Polish Carpathians (Fig. 7; Bażyński *et al.*, 1984; Doktór *et al.*, 1989) reveals that some of them coincide with known faults or reclinear valley reaches, clustering around NNE to NE orientation, whereas the others appear to follow zones of increased joint density or have no association with any structural features at all. Topolineaments visible on digital elevation models appear to follow some rectilinear river bed stretches (Fig. 8). It is likely that any “neotectonic” significance of such a picture is difficult to assess, since the sole coincidence of the existing zone of weakness (increased fracture density) with a topolineament does not necessarily mean its young tectonic reactivation.

STATE OF RESEARCH

Quaternary sediments of the study area were described for the first time by W. Szajnocha (1895, 1896, 1901; *vide*: Klimaszewski, 1948), Łoziński (1907) and Konior (1932), who noted the presence of Pleistocene alluvium, loess and erratic boulders. Detailed studies of Pleistocene and Holocene terraces in the San River valley were carried out by Klimaszewski (1936, 1948) who also described slope and loess deposits. The proposed stratigraphic scheme of fluvial terraces became modified in the 1960s by the same author (Klimaszewski, 1967). More detailed data concerning fluvial and slope sediments are comprised in papers summarizing the results of geological mapping conducted by the Polish Geological Institute (Wdowiarz, 1939, 1948; Wójcik, 1976; Borysławski *et al.*, 1980; Gucik & Wójcik, 1982). Distribution of erratic boulders in the zone of maximal extent of the Sanian-2 (Elsterian-2) glaciation was studied by Dudziak (1961). Palynological analyses of organogenic sediments exposed at Podbukowina and Babice were done by Mamakowa (1962) and T. Szczypek (in: Pękala, 1973), respectively. Geological and geomorphological studies of selected areas and sites are summarized in a series of papers by: Henkiel and Pękala (1965), Pękala (1973, 1988), Henkiel *et al.* (1988), Butrym *et al.* (1988a), Łanczont (1997a, 2000), and Łanczont and Wojtowicz (2000). Detailed descriptions of sedimentological properties and age of loess covers were provided by Pękala (1973, 1988), Butrym *et al.* (1988a), Łanczont (1993, 1997a, 2000), and Chlebowski *et al.* (2003). Besides older papers, data pertaining to the distribution and characteristics of landslides in the study area are comprised in the works of Pękala (1964) for the Bircza area, Rajchel (1989) for the Dynów – Pawłokoma area, and Wójcik and Zimnal (1996) for the San River valley. Recently, Quaternary sediments and geomorphic features have been mapped at the scales of 1:50,000 and 1:100,000, respectively (Rauch *et al.*, 2010).

The first geomorphic descriptions and attempts at dating stages of geomorphic development of the region were presented by Klimaszewski (1936, 1948), and later by Henkiel and Pękala (1965), Starkel (1965, 1972), Henkiel (1977, 1982), Wójcik (1976), Łanczont (1987-88), Henkiel *et al.* (1988), and in the past two decades by Łanczont (1997 a,b, 2000).

MORPHOMETRIC INDICATORS

One of cartometric approaches to the study of geomorphic traces of neotectonic activity consists in construction of envelope and subenvelope maps (Rączkowski *et al.*, 1984; Zuchiewicz & Oaks, 1993; Keller & Pinter, 1996).

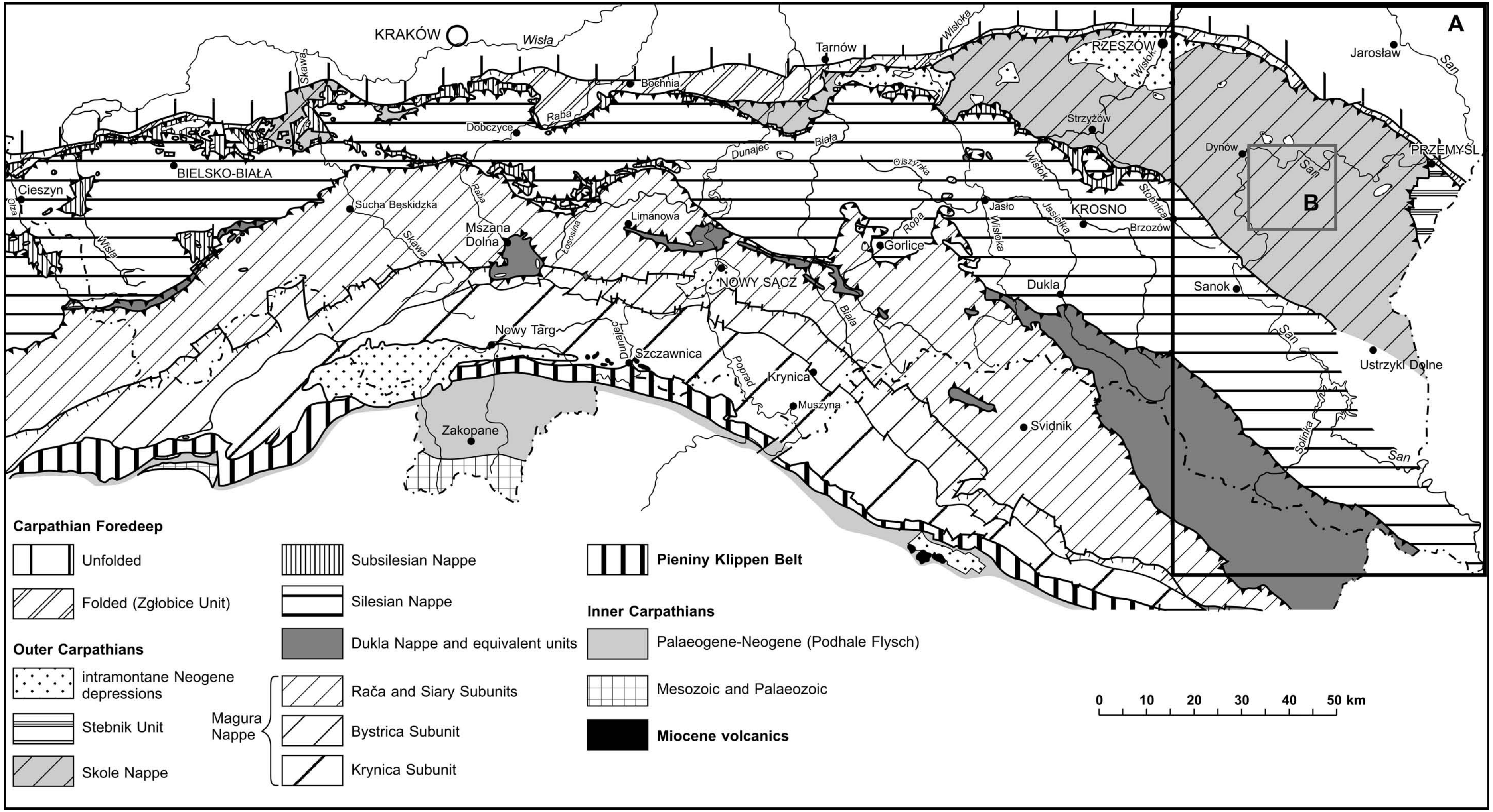

Fig. 2. Tectonic sketch of the Polish Carpathians (based on Żytko *et al.*, 1989). A – region shown in Fig. 3, B – study area

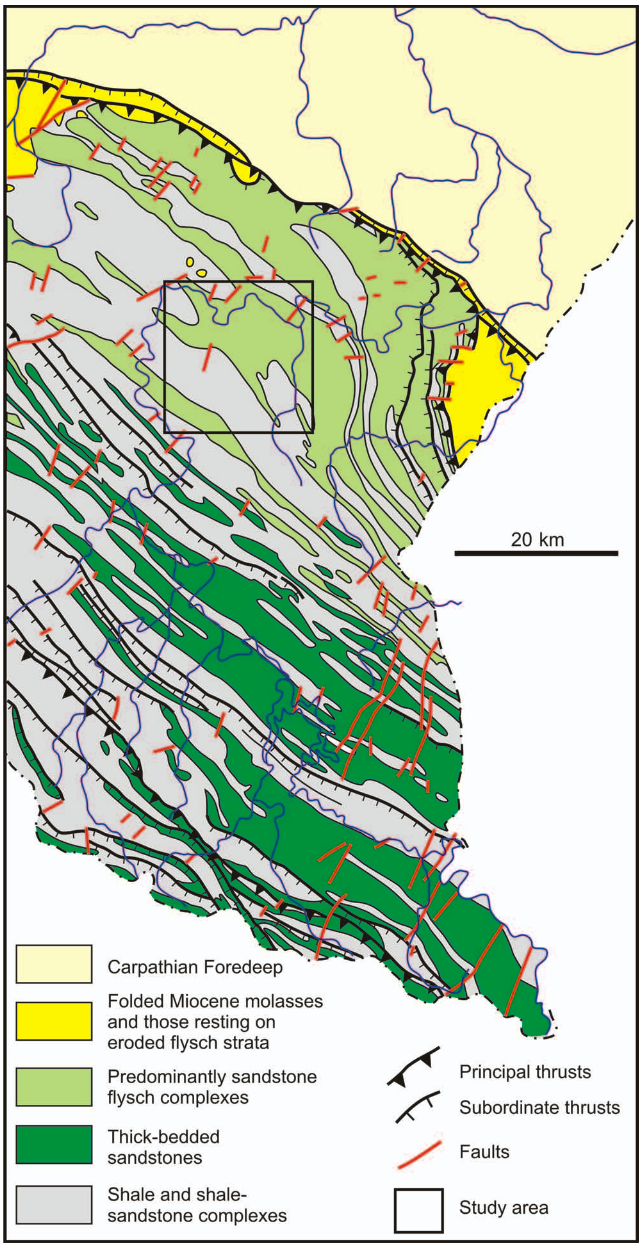

Fig. 3. Map of rock resistance in the eastern portion of the Polish Carpathians (based on Borysławski *et al.*, 1980; Gucik *et al.*, 1980; Żytko *et al.*, 1989; modified). See Fig. 2 for location

The former portray the highest elevations of a terrain, the latter reconstruct the level to which the streams have eroded by connecting points of equal elevation between the streams. A series of such maps produced for drainage networks, classified according to the Horton–Strahler hierarchy and called the base-level surface maps, makes it possible to compute maps of residuals between individual surfaces of different orders and to hypothesize about either uplift or subsidence tendencies, indicated by dense/sparse pattern of isobases and increased/decreased relief portrayed on residual maps. Reliable interpretation of such maps, however, is impossible without knowledge about the number and age of geomorphic cycles that affected the study area. Therefore, both envelope and subenvelope maps should

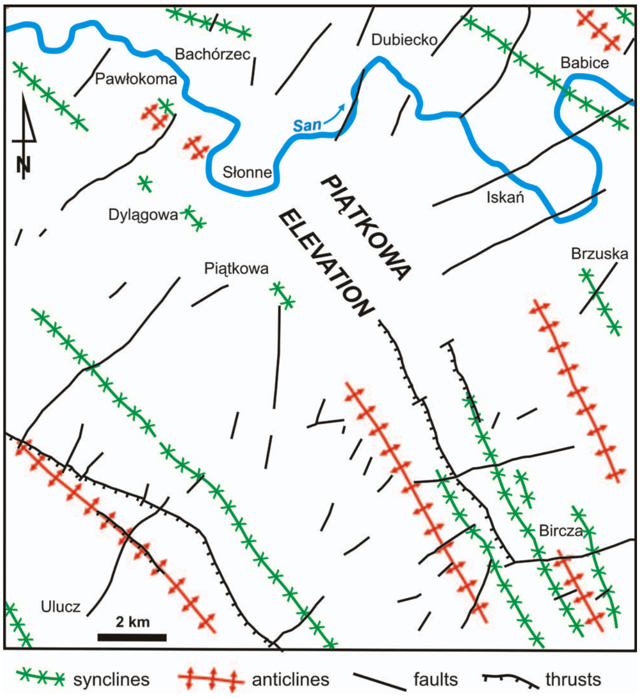

Fig. 4. Sketch-map of dominant tectonic elements in the study area (based on Rauch *et al.*, 2010; modified). See Figs 2 and 3 for location

complement traditional geomorphic mapping (*cf.* Starkel, 1985).

Figure 9 shows a series of three subenvelope maps constructed for valleys of the 4th, 5th and 6th order, classified on 1:100,000 topographic maps (*cf.* Zuchiewicz, 2000). Both the 5th and 6th-order subenvelope maps reveal a few elevated areas that are orientated NW–SE in the medial and northern parts of the Outer East Carpathians of Poland, as well as NNW–SSE in the southern part, their strikes obliquely cutting under small angle the overall trend of imbricated slices and map-scale folds. Elevations of the 5th-order isobases range between 250 and 750 m a. s. l., those of the 6th-order ones change from 200 to 500 m a. s. l. Residuals between these two subenvelope surfaces do not exceed 100 m, a figure taken by Rączkowski *et al.* (1984) as a proxy for Quaternary uplift of this region. Analysis of geomorphological maps, showing the size of erosional dissection of early Pleistocene planation surfaces gives comparable results (*cf.* Starkel, 1972; Henkiel, 1977). In the study area, elevated regions portrayed by the 4th-order base-lavel map (Fig. 9) coincide nearly perfectly with zones of increased erosion of the flysch cover in post-Early Miocene time (Fig. 6).

Residual maps portraying the relief energy (Hmax – Hmin) in the eastern portion of the Polish Carpathians (Fig. 10, *cf.* also Zuchiewicz, 2000) expose several, not very long zones of increased relief energy (200–400 m in the south, 75 to 100 m in the north), the orientation of which in the Silesian Nappe approximates that of principal folds, and in the Dukla Nappe and Fore-Dukla Zone is aligned at low angles to the fold axes. Such a pattern, resulting from both lithological control and uplifting tendencies of some WNW–ESE orientated structures, is fairly similar to that obtained

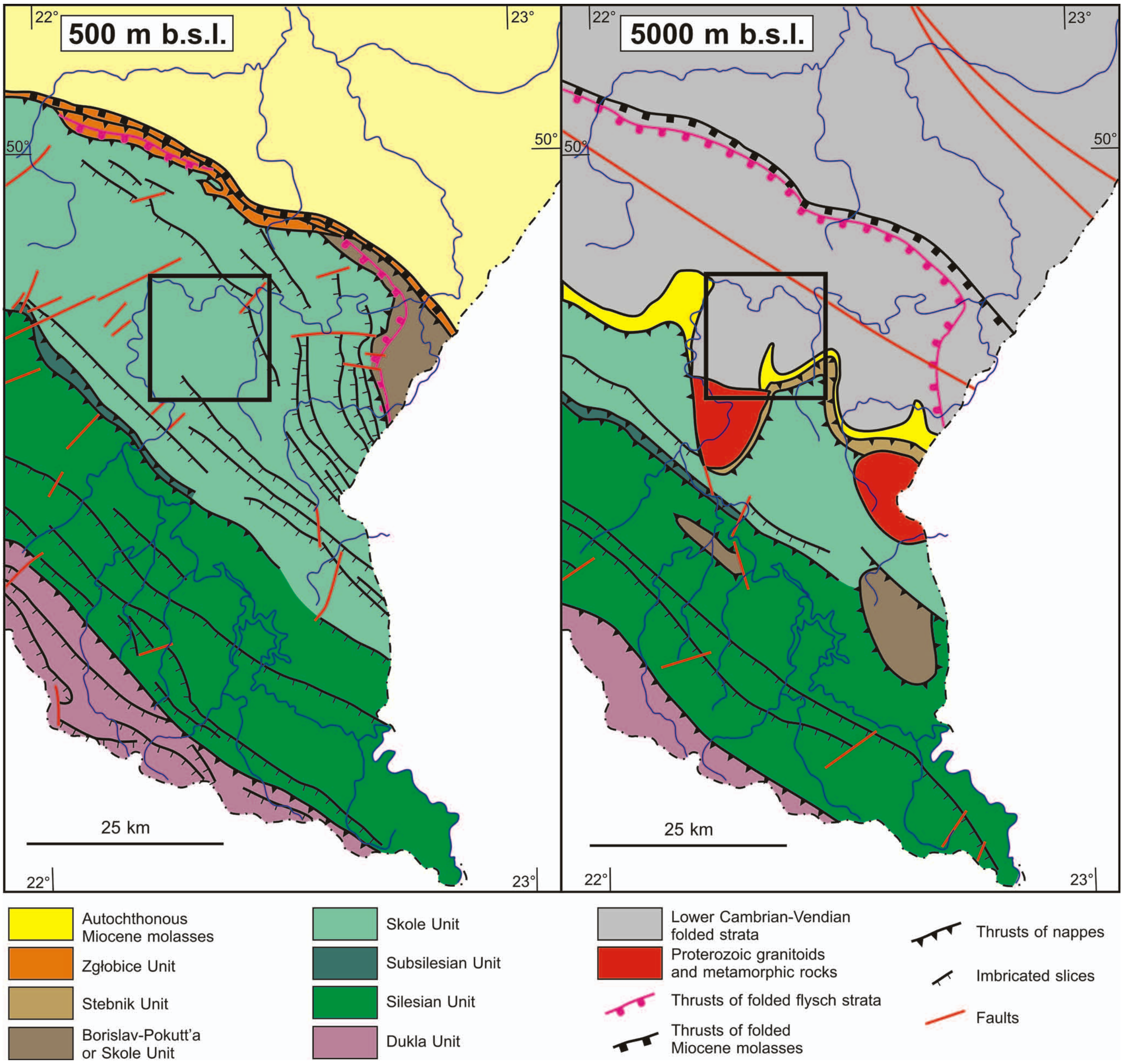

Fig. 5. Maps of horizontal cutting of the eastern portion of the Polish Carpathians (based on Kotański, 1997)

by Henkiel (1977, 1978) due to reconstruction of topography of the early and late Pliocene planation surfaces, deformed by subsequent motions within the flysch cover.

GEOMORPHIC SETTING

The southern part of the Skole Nappe, composed of moderately to poorly resistant flysch strata, is a topographically well expressed low-mountain terrain rising upon the Central Carpathian Depression. These gross features of topography do not appear to be lithologically controlled, probably due to post-orogenic uplift. Smaller-scale landforms, in turn, are largely influenced by lithological properties of the bedrock. That is why a number of earth scientists considered this area particularly suitable for mapping neotectonic structures, which are usually arranged subparallel to the structural grain of the region (Klimaszewski, 1965; Starkel, 1965, 1972, 1980; Henkiel 1977, 1978, Zuchiewicz, 1995, 1998; and references therein).

In the study area, morphology typical for middle foothills bearing fragments of Late Pliocene planation surfaces prevails, whereas in the SW part low mountains and high foothills with preserved fragments of Early Pliocene planation surfaces dominate (Fig. 11; see also Starkel, 1972, 1980). Surrounding the San River valley, patches of low foothills bearing fragments of Early Pleistocene erosional surfaces occur (Starkel, 1980). Terrain altitudes change between 211.5 m a.s.l. in the San River valley to 530.2 m a.s.l. in the SW part of the area. The principal valley is that of the San River, trending mostly E–W and showing relief energy values not exceeding 170 m. Farther west of the study area,

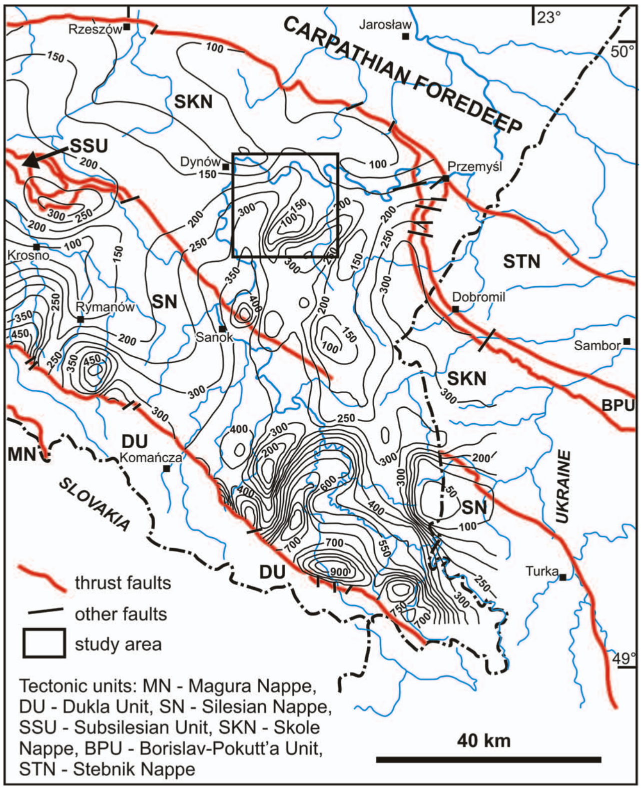

Fig. 6. Amount of erosion (in metres) of the flysch cover in post-Early Miocene time (based on Kuśmierek, 1995a,b and Maćkowski *et al.*, 2009; simplified)

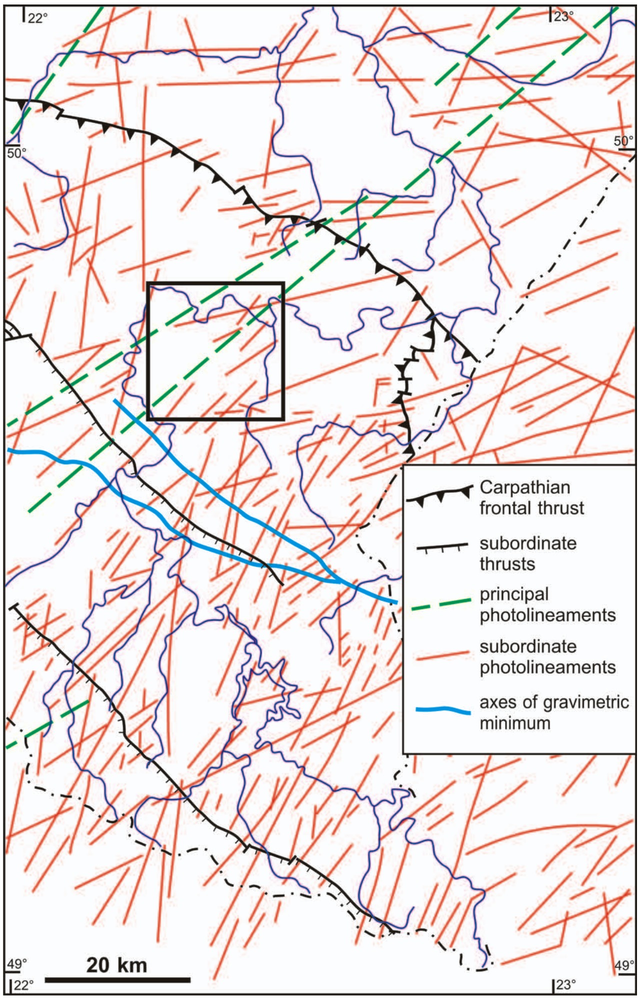

Fig. 7. Map of photolineaments in the eastern portion of the Polish Carpathians (modified from Bażyński *et al.*, 1984 and Doktór *et al.*, 1989). The study area is boxed

south of Dynów, the San River uses a N–S orientated antecedent water gap (Klimaszewski, 1965; Starkel, 1972), whereas the downstream, E–W orientated valley segment is insequent in respect to the strike of map-scale folds and roughly parallel to a neotectonic elevation, distinguished here by Klimaszewski (1965) and Henkiel (1977). In the latter segment, the valley forms a few large meanders. Right-hand valley sides are distinctly more steep compared to the opposite ones.

The landforms are strongly controlled by bedrock resistance and attitude of tectonic structures. Individual ridges trend NW–SE in the west and NNW–SSE to N–S in the south-east, being related to exposures of thick-bedded "Inoceramian" (Cretaceous–Palaeocene), rarely Krosno (Oligocene) beds. Most of the ridges are broad (250–500 m, usually 100–150 m) and rounded. In the northern part, these are mainly anticlinal, rarely synclinal ridges; although those orientated obliquely to map-scale fold axes or showing relief inversion are fairly frequent. Ridges developed on imbricated anticlines occur also east of Bircza, while farther SW of this locality relief inversion becomes dominant (*cf.* also Pękala, 1964). Narrow and rounded ridges are relatively short and usually built up of strata belonging to either Menilite or – rarely – Krosno beds. Hogback ridges are characteristic for the SE part of the area, being confined to exposures of cherts of the Oligocene Menilite beds. A single hogback ridge in the NW part is composed of "Inoceramian" sandstones, and scattered ridges occurring in the NE part are usually developed on either Menilitic cherts or Krosno sandstones. Dome-like and – rarely – cone-like summits range in elevation between 328 and 530 m a.s.l.

The ridges bear fragments of erosional surfaces ("planation surfaces") of different ages, assigned to the so-called intramontane (Early Pliocene) and foothills (Late Pliocene) levels (Klimaszewski, 1936; Starkel, 1965, 1972, 1980; Henkiel, 1977; Henkiel *et al.*, 1988). The former is poorly preserved, and its reconstructed surface slopes below 480 m a.s.l. (Henkiel *et al.*, 1988), while the latter (380–410 m a.s.l., *i.e.* 200 m above valley bottoms) is preserved best upon exposures of "Inoceramian" beds that build cores of anticlines. This level is overtopped by 40–50 m high monadnock summits. Reconstructing topography of this level, Henkiel (1977) marked an E–W orientated depression sloping to the east, presently used by the San River valley (Fig. 12), and suggested that during dissection of the level a trellis drainage pattern was formed, being typified by longer valleys in the southern limb. He also inferred that, perpendicular to the former, valley segments of the structural water-gap type must have been shaped at that time. Traces of a still younger, "riverside level", occur upon meander spurs of the San River valley and represent in fact Early Pleisto-

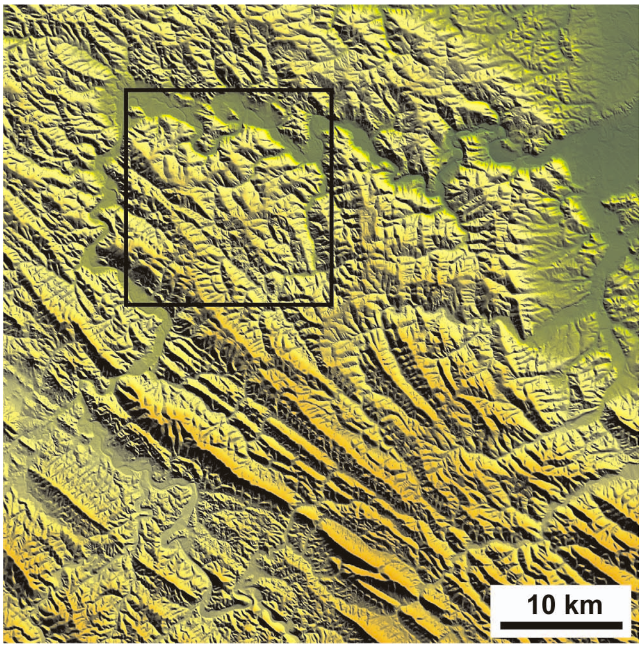

Fig. 8. Digital elevation model (SRTM level 2) of the eastern portion of the Polish Carpathians, showing location of the study area

cene strath terraces that rise 100–120 m above recent floodplain. In isolated places, these straths are overlain by gravel covers, first described by Klimaszewski (1936) as strongly weathered flysch-derived gravels up to 10 cm in diameter, bearing a single cobble of red granite (*cf.* also Henkiel *et al.*, 1988). According to Klimaszewski (1936), the foothills and intramontane levels became deformed by a reactivated anticline crossing the Słonne spur, recently called Słonne Elevation (Fig. 4). One has to bear in mind, however, that age constraints pertaining to the time of formation of these "planation surfaces" are very poor. The Polish Outer Carpathians lack reliable pieces of evidence that would enable dating of planation events. The only attempts at apatite fission track and (U-Th)/He dating of teschenite intrusions in the Outer Western Carpathians in the Czech Republic (Danišík *et al.*, 2008) suggest that "planation surfaces" in this area post-date the Pannonian (7.1 Ma), what does not contradict Pliocene ages inferred for the Polish segment of the Outer Carpathians (see discussion in Zuchiewicz, 1984, 1995).

Valleys of trunk rivers are orientated NW–SE, W–E, WSW–ENE and N–S (Fig. 13), being usually confined to the structural grain of the area and main fault zones. Some of these valleys tend to have water gap segments of steep slopes and narrow bottoms. In the San River valley, the most important water gap occurs close to Słonne, where the

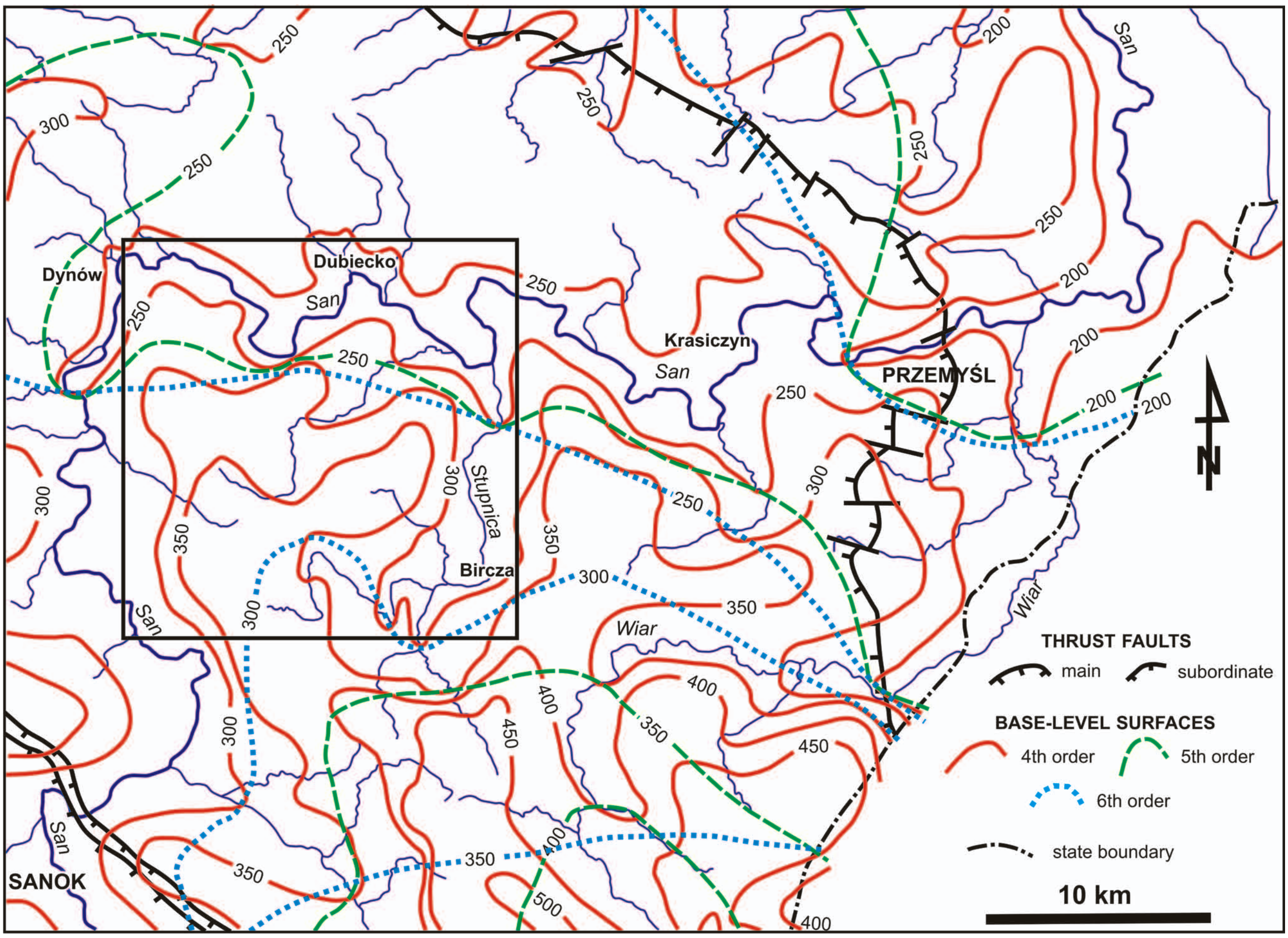

Fig. 9. Map of base-level surfaces of different orders in the study area (based on Rączkowski *et al.*, 1984; modified and supplemented)

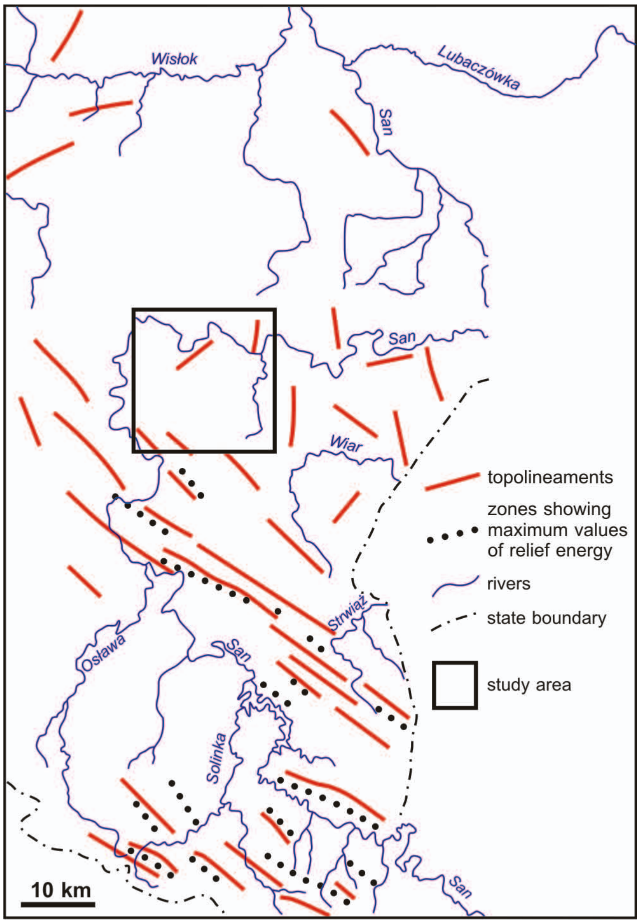

Fig. 10. Principal topolineaments and zones of maximum relief energy in the eastern portion of the Polish Carpathians interpreted from dense-contour relief energy map, showing location of the study area (modified from Zuchiewicz, 2000)

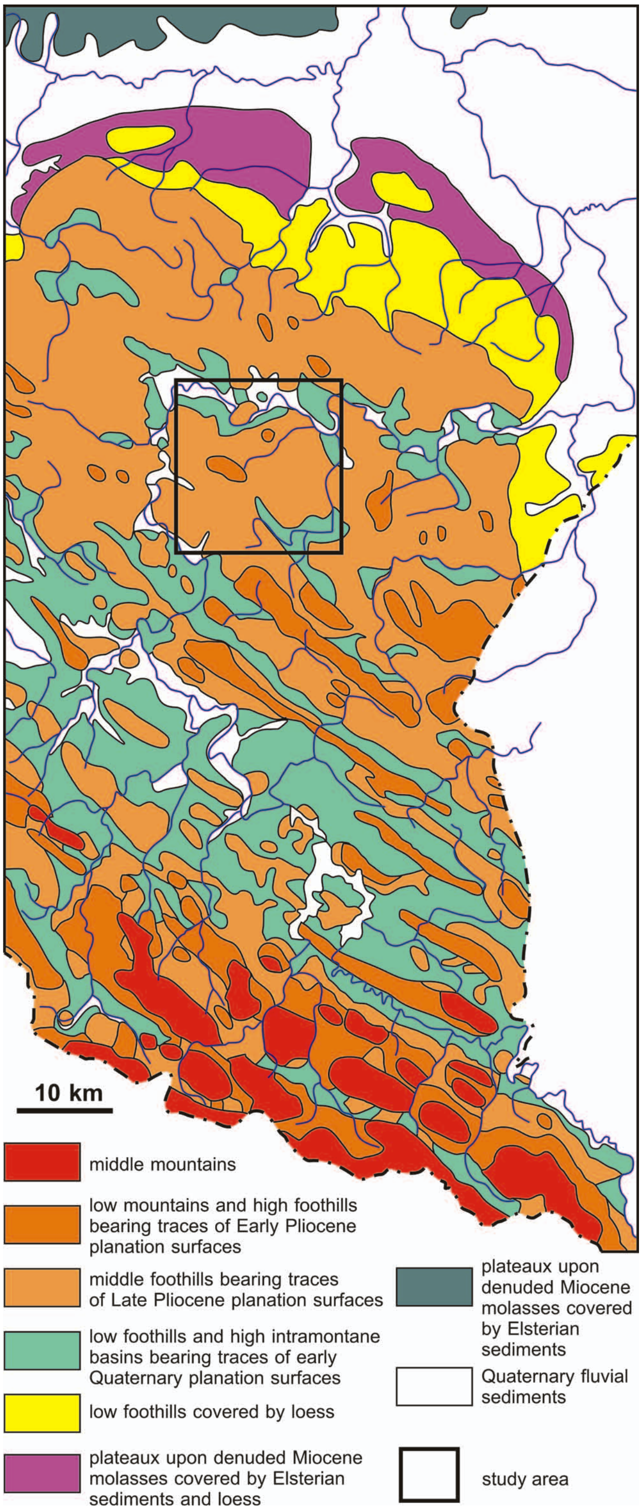

Fig. 11. Types of landscapes in the eastern portion of the Polish Carpathians, showing location of the study area (modified from Starkel, 1980, 1991)

river cuts through a neotectonic elevation. The San River valley is composed of alternating consequent and subsequent segments (*cf*. also Wdowiarz, 1948). The valley density changes from 1.4 to 4.2 km/km^2, averaging 2.2 km/km^2 (Łanczont, 1987-88). The most frequent are V-shaped valleys of steep gradient and ungraded profile, although box-like, flat bottomed valleys are also present, particularly in the SW and NE parts of the area. The latter mark a transitional type between V-shaped upper, and lower terraced valley reaches. Pleistocene dellen formed during the last glacial stage occur upon slopes of larger valleys. Leaving aside the San River valley and its main tributaries, river beds are typically narrow and cut into solid bedrock.

The valley bottoms and sides commonly bear flights of strath and cut-and-fill terraces. The San River valley shows preserved fragments of straths rising: 90–110 m (Early Pleistocene), 75–80 m (Elsterian-1 or Menapian), 40–60 m (Elsterian-2) and 20–30 m (Saalian), as well as cut-and-fill terraces dated to the Weichselian (8–16 m) and Holocene (4–7 m, 1–3 m). The highest terraces are confined solely to large meander spurs of the San River valley, whereas Late Pleistocene and Holocene terrace steps are to be found along the entire length of the San River and its main tributaries. Vast surfaces of Holocene terraces in the San River valley are cut by few generations of abandoned channels of variable sizes. The Late Glacial (Dubiecko) and Holocene (Ulucz, Bachów) oxbows are filled with peat and peat-bearing silts.

Slopes and valley sides are usually convex-concave ones, rarely convex or straight. Their inclination changes,

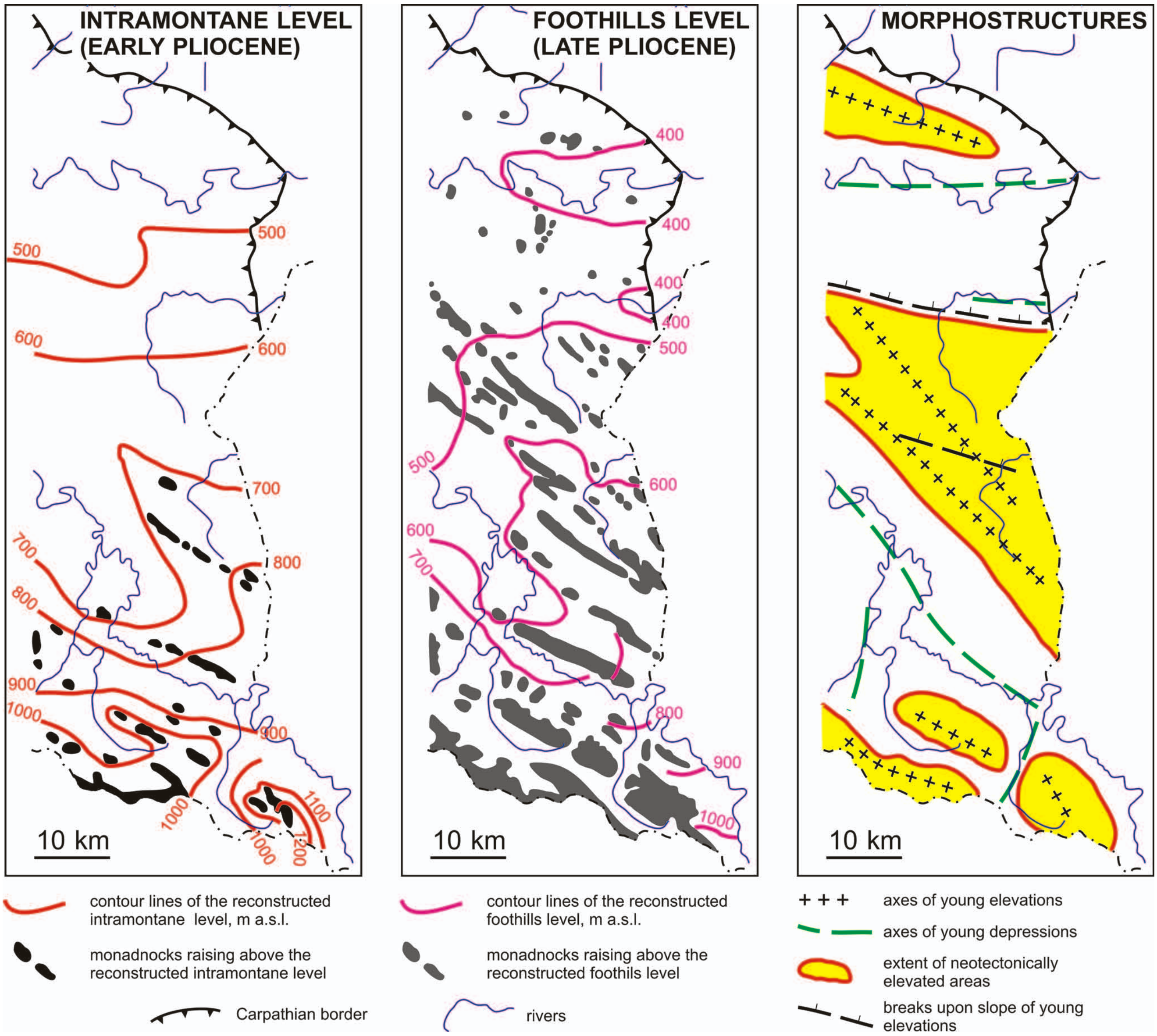

Fig. 12. A reconstruction of topography and neotectonic structures during formation of the Pliocene planation surfaces in the eastern segment of the Polish Carpathians, as proposed by (Henkiel, 1977); see also Zuchiewicz (2000)

depending on bedrock resistance, from 5–6° to 30–35°, most frequently attaining 20–35°. The upper parts of slopes in the northern portion of the study area bear structural-denudational breaks of slope, usually trending NW–SE (Fig. 14). They developed at the contact between shales and thin-bedded sandstones of the Krosno and Menilite beds, as well as upon exposures of the Kliwa Sandstones (Oligocene).

The study area numbers nearly 600 landslides, half of them being located on the San River valley slopes and nearly one third on the slopes of the Stupnica River valley. The highest density of landslides characterizes the north-western, south-western and south-eastern parts of the study area (Fig. 14), showing high relief energy values. Numerous landslides developed upon slopes built up of the "Inoceramian" (Cretaceous–Palaeocene), Hieroglyphic (Eocene) and Menilite (Oligocene) beds, as well as at the contacts between strata of contrasting resistance to erosion and within fault zones. In the Stupnica River valley north of Bircza, landslides occupy the entire slope surfaces. In the SW part of the study area, a large structural landslide is accompanied by a 20-m-deep lateral spreading (*cf.* Margielewski, 2004)

Values of the index of landslide occurrence calculated as the percentage of the area occupied by landslides, quoted by Bober (1984), change from 1.52% near Bircza to 1.66% near Dynów, and 1.74% to the north of the San River valley close to Babice. A more recent paper by Wójcik and Zimnal (1996) concerning the San River valley in the discussed segment enables one to increase these values by one order of magnitude. Rock and rock-debris, structural, usually insequent, more rarely subsequent, elongated landslides of small and medium size dominate here upon slopes inclined at 8–10°, and developed parallel to the main fault zones. Close to Bircza, in turn, consequent valley landslides prevail, attaining 0.25–7 ha in area and having scars up to 30 m high (Pękala, 1964). The lengths of landslide tongues

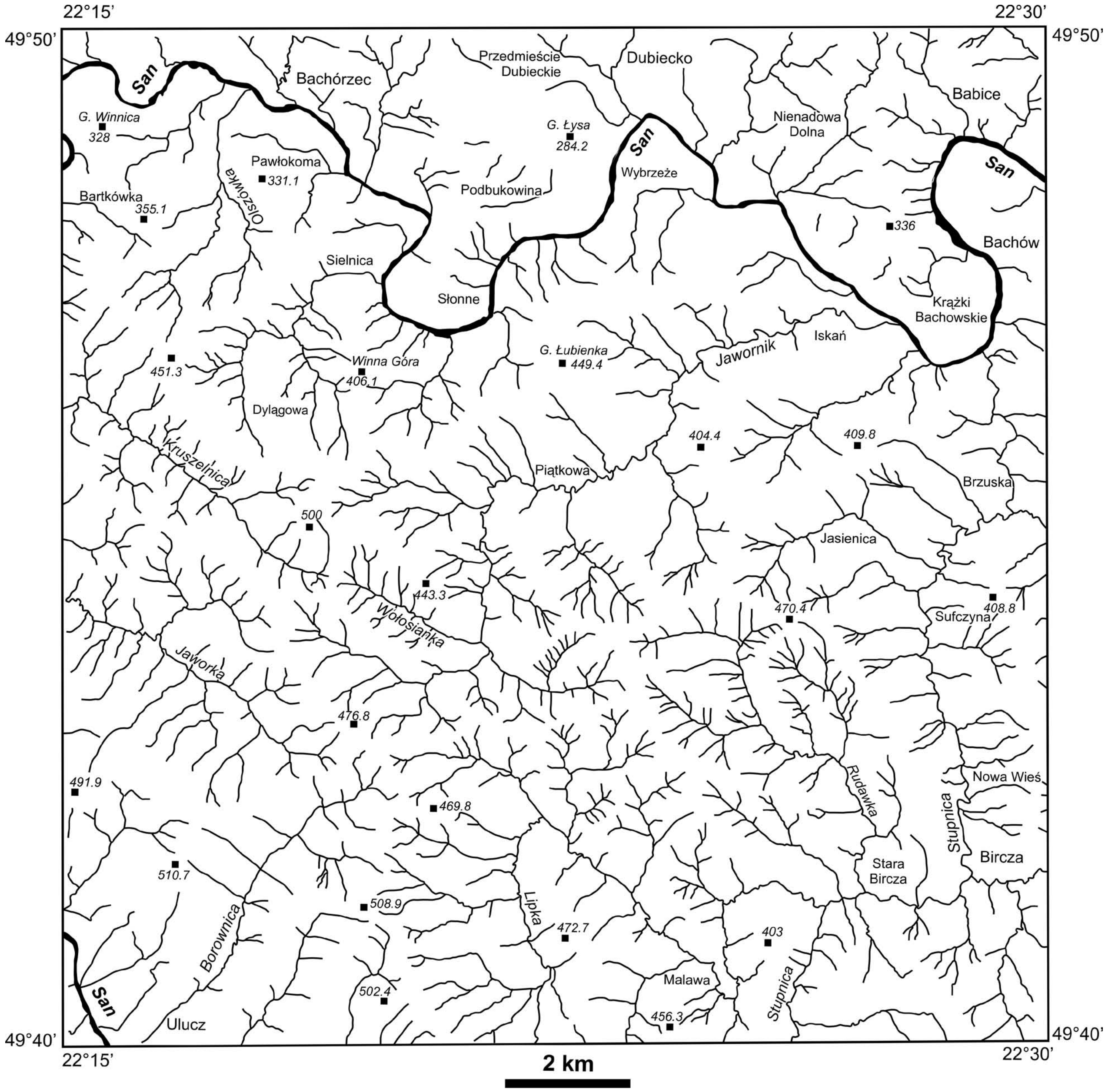

Fig. 13. Drainage pattern in the study area showing also place names mentioned in the text

change from 200–500 m to 1,250 m, usually averaging 500–700 m; whereas their widths range between 125 and 2,250 m, averaging 375–550 m. The longest landforms are to be found in the SW part of the area, the broadest ones occur north of Bircza. Landslide scars are usually semi-circular, from a few to *ca*. 30 m high, and inclined at 35–40° and even 60–70°. Landslide tongues are typified by irregular topography, with frequent swells, steps and closed depressions. The latter are in places filled with small lakes or peat. In the northern and south-eastern parts of the area, landslide tongues frequently encroach upon Holocene terraces. In the lower course of the Stupnica River valley they even block the valley, leading to its strong narrowing. Landslide colluvium is composed of clays, sandy and sand-silty loams usually bearing angular debris of sandstones, mudstones or cherts of variable sizes, as well as huge blocks or even large packets of detached flysch strata. The thickness of colluvial deposits ranges between ten and few tens of metres, attaining maximum values in the south-west (near Ulucz) and south-east (north of Bircza).

The lower, concave-upward slope segments and dellen are covered with solifluction-slopewash sediments, whereas lower parts of slopes of the San and lower Stupnica river valleys are overlain by loesses and loess-like sediments, which will be dealt with in the next chapter. The highest thicknesses of loess covers (>20 m) are observed in the NE part of the study area, near Babice. These sediments are developed in different facies: alluvial, paludal, slopewash, solifluction and aeolian ones, the slopewash type being dominant (Łanczont, 1997a). The onset of subaerial silt deposition upon high terraces started in Saalian time, on the middle terraces – in the older Weichselian pleniglacial, and on the highest and lowest Pleistocene terraces during the Last Glacial Maximum (Łanczont, 1997a).

QUATERNARY SEDIMENTS

Quaternary sediments, ranging in thickness between 0.5–1 m to more than 20 m, cover a large part of the study area, particularly within the San River and its tributary valleys. These are mostly fluvial and slope sediments as well as different varieties of loess and loess-like deposits (Figs 14, 15).

Fluvial sediments

Early Pleistocene

The highest-elevated terrace covers are preserved on the right side of the San River valley east of Pawłokoma, rising 90–110 m above recent floodplain (Figs 13–15). The strath is overlain by a 4 m to 7 m thick cover composed of clays, small gravels (1.5–2 to 4 cm in diameter), sands and brown silty loams. Another fragment is preserved on the left-hand side of the San River valley at Babice, in the NE part of the study area. Isolated gravels, 3–6 cm in diameter, rest here on a strath situated 115 m above recent floodplain. The age of this cover is difficult to constrain; it probably corresponds to one of the Early Pleistocene cold stages, most probably Różce or Otwock ones, which are roughly equivalent to the Praetiglian and Eburonian stages, respectively.

South-Polish glacial stages (Elsterian)

Terraces rising 75–80 m above recent floodplains occur on either side of the San River valley near Sielnica and Babice (Figs 13, 14). Poorly preserved gravels resting within loamy, vari-grained sands average in size between 3 and 6 cm. East of the study area at Krasice, terrace alluvium TL-dated at 555±114 ka is covered by a two-fold till assigned to the Sanian-2 (Elsterian-2) glacial stage (Butrym *et al.*, 1988b; Łanczont, 2000). Łanczont (1997a, 2000) related the age of this terrace cover to the Sanian-1 (Elsterian-1) stage. Farther downstream, the fluvial cover in question is overlain by 8 m thick loesses, dated to the Sanian-2 (Elsterian-2), Liwiec (Fuhne, *i.e.* early Saalian), and Vistulian (Weichselian) stages. One cannot exclude, however, that the age of deposition of terrace alluvium took place during the Narewian (Menapian) stage.

Strath terraces rising at 40–60 m above recent floodplains are preserved on large meander spurs in the San River valley, in the northern part of the study area (Fig. 14). South of Dubiecko, on top of an isolated meander hill, a 6–7 m thick gravel cover bears erratic blocks (Wdowiarz, 1948; Dudziak, 1961). Poorly preserved gravel covers resting on straths rising 50–55 (60) m occur also in the NW part of the study area and near Słonne (*cf.* also Butrym *et al.*, 1988a). Farther downstream, east of the study area, Scandinavian erratics frequently occur within the discussed gravel covers what makes possible to relate the entire fluvial series with the so-called "mixed gravels" described from Optyń Mt. near Przemyśl (Butrym *et al.*, 1988c, Łanczont *et al.*, 1988, Łanczont, 1997b), which mark coeval fluvial and glaciofluvial deposition during the end of the Sanian-2 (Elsterian-2) glacial stage when the Scandinavian ice-sheet reached the Carpathian margin blocking the outlet of the San River valley. East of the study area, the discussed alluvium is overlain by 17–23 m thick loesses deposited during the Odranian (Drenthe), Wartanian (Warthe) and Weichselian stages (Łanczont, 2000).

Middle-Polish glacial stages (Saalian)

Terraces rising 20–30 m above recent floodplains occur in the San River valley near Ulucz in the south-west and in the northern, E–W orientated, segment of the valley (Figs 13, 14). They build one or two steps of the so-called "middle terrace", which are frequently overlain by slopewash and loess sediments (Fig. 15). Close to Słonne, alluvium rests on two straths rising 20 m and 30 m above recent floodplain (*cf.* Henkiel *et al.*, 1988; Butrym *et al.*, 1988a).

On the right-hand side of the San River valley at Bartkówka, alluvium of the 24–32 to 22–26 m high terrace is composed of single gravels, 2–5 cm in diameter, resting within strongly loamy fine-grained sand and sandy loam. Farther south, Łanczont and Wojtowicz (2000) described a 20 m high terrace step, wherein 11–12 m high strath is overlain by 3 m thick gravels covered with alluvial and slope-facies loesses (more than 11 m thick), deposited during the last glacial stage. Close to Dubiecko, alluvium of the 16–20 m terrace is composed of silty loams bearing loosely packed gravels 2–6 cm in diameter and overlain by loess-like silts. South of Łazy Nienadowskie, poorly preserved gravels were found 18–19 m above the recent floodplain. North of Iskań, in turn, small terrace steps rising 29–31 m are built up of light-brown sandy loams with single gravels, 4–5 cm in diameter. Close to Babice, gravels 2–3 to 8–10 cm in size, variably rounded and bearing admixture of angular debris, rest within yellow, medium- and fine-grained sand and build a 5 m thick cover that overlies a 9 m high strath. Alluvium is overlain by sandy loess. Farther downstream, a 27–31 m high terrace step is composed of light-brown sands with gravels overlain by loess.

The "middle terrace" at Babice, rising 17–23 m (up to 35 m in the near-slope part), was mentioned by Klimaszewski (1936, 1948) and Wójcik (1976), described in detail by Pękala (1973, 1988), and dated for the second time by Łanczont (2000). The 2–5 m high strath is overlain by 4 m thick bedload and overbank sediments and overtopped by strongly compacted peat bearing interstadial-type pollen flora including pine, birch, fir, beach and hazel (det. by T. Szczypek, in: Pękala, 1973, 1988). The top of the peat was eroded and covered by another layer of bedload deposits, infilling sometimes erosional cuts within older alluvium, and including redeposited bone remnants of large mammals, probably mammoths. The latter were dated by fluoro-chlorine-apatite method by T. Wysoczański-Minkowicz (*cf.* Pękala, 1973) to 250–270 ka. These sediments are, in turn, overlain by bi-partite loess of deluvial (slopewash) facies. A higher-situated flat surface is covered by two-fold solifluction deposits, slightly eroded at the top and overlain by silty loams with a podzol-type palaeosoil, also partly eroded and

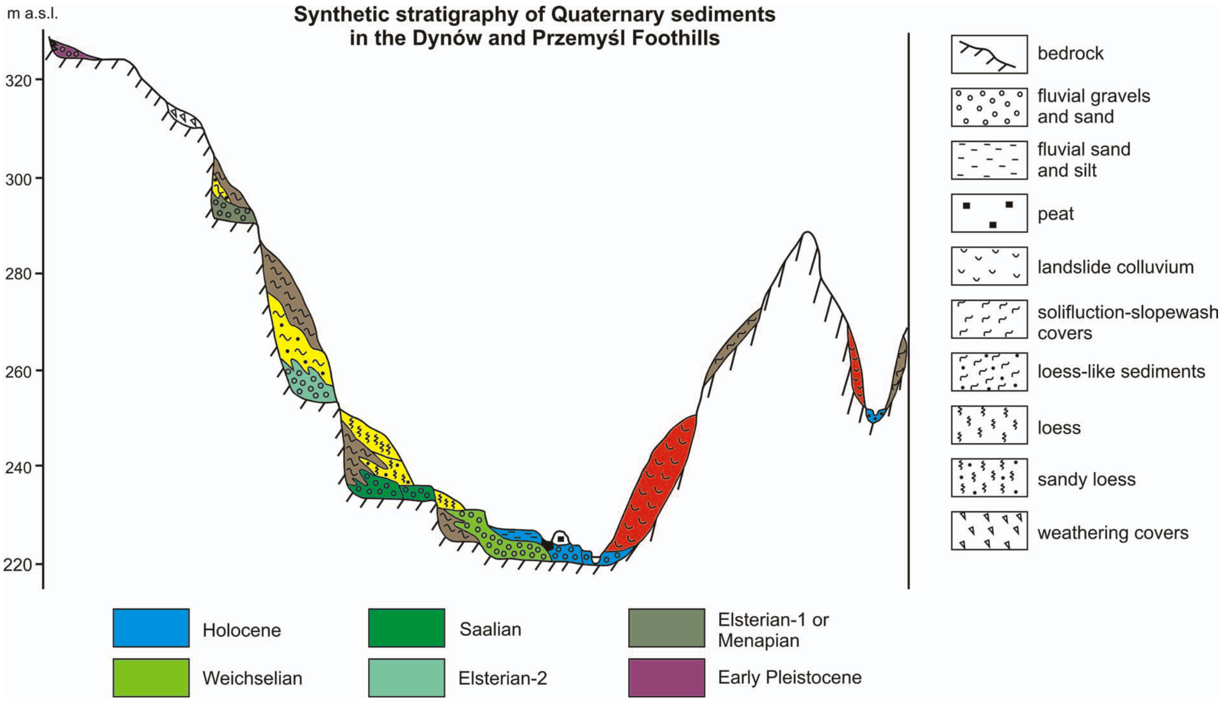

Fig. 15. Stratigraphic scheme of Quaternary sediments exposed in the study area

covered by laminated loams bearing single, angular debris. These loams underlie an interstadial-type soil with thick humus horizon, and are overlain by the upper, top layer of loess (Pękala, 1973, 1988). In other sections, palaeosoils occurring within loess covers were considered age equivalent of the Babice peat. Not far to the east (2 km), a 16 m high strath is overlain by a series of gravel and sand, upon which a palaeosoil underlying solifluction loams occurs. These deposits were partly eroded and then overlain by sand and fine gravel as well as silt-sandy sediments and deluvial loess. Results of TL age determinations by J. Butrym (in Pękala, 1988) suggested a Holsteinian age of gravel-sandy series, an Odranian (Drenthe) and Odranian/Wartanian age of sands with palaeosoil, while the higher situated solifluction loams were linked with the Wartanian (Warthe) stage and the upper palaeosoil horizon – with the Eemian. The two-fold loess sediments were assigned a Weichselian age. On the other hand, Łanczont (2000), basing on TL age determinations made by J. Kusiak (Maria Curie-Skłodowska University, Lublin), related formation of the 4–16 m high strath with the Mazovian (Holsteinian) Interglacial, and suggested that deposition of the overlying bedload gravels took place during the Liwiec (Fuhne) cooling (and not in younger part of the Mazovian Interglacial as inferred by Pękala, 1988). Hence, accumulation of overbank sands should have occurred during early stadials of the Odranian (Drenthe) stage, development of the palaeosoil horizon – in the Odranian/Wartanian warming (“Lublin Interglacial”), and slope sediments – during the Wartanian (Warthe) stage. According to Łanczont (2000), erosion active during the Eemian Interglacial must have cut the strath of the younger step of the “middle terrace”, upon which, during the earliest phases of the Weichselian, accumulation of gravels and sands (109 ka) pre-dated deposition of loess: first of paludal and then subaerial facies. The true age of the above succession of depositional events is still unknown and requires further study.

Vistulian (Weichselian) glacial stage

Strath and cut-and fill terraces rising 8–16 m above recent floodplains occupy vast areas close to Przedmieście Dubieckie and – to a smaller extent – in the other segments of the San River valley and its main tributaries (Figs 13, 14). Terrace surfaces gently pass into lower parts of slopes being overlain by solifluction covers. Altitudes of straths are strongly variable, both in cross sections and in longitudinal San valley profile (Wójcik, 1976; Henkiel *et al.*, 1988).

Between Ulucz and Bartkówka, two terrace steps rising 10–14 m (11–12 m) and 15 m occur on the right-hand valley side. South of Bachórzec, on the left-hand San River valley side, 13–16 m high terrace step is composed of a 7–8 m high strath overlain by gravel series bearing clasts 0.5–6 cm in diameter, resting within loamy vari-grained sand. Close to Słonne and Zasanie, two terrace steps appear: 10–12 m and 16 m high. At Nienadowa Dolna, a 15–16.5 m high terrace step, built up of loosely packed gravels 2–5 cm in diameter, has a strath rising 3–4 m (Wójcik, 1976). South of Przedmieście Dubieckie, a vast 9–10 (12) m terrace is composed of fine- and very fine-grained sands bearing gravels 0.5–4 cm in diameter and sandy loams with densely packed gravels, 2–8 cm in size. This terrace steps becomes lowered south of Dubiecko to 9 m, and close to Nienadowa Dolna rises again to 7–11 m above recent floodplain.

The San River meander loop at Dubiecko-Podbukowina (Figs 13, 14) was shaped at the turn of the Eemian and Weichselian, and alluvial deposition terminated during the last glacial pleniglacial (Butrym *et al.*, 1988a). Such an interpretation stems from the fact that sandy sediments occur-

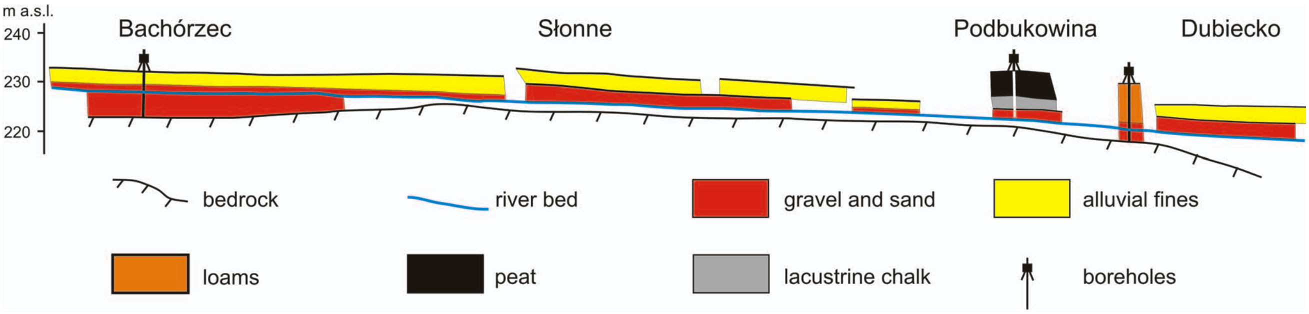

Fig. 16. Long profiles of Holocene terraces of the San River valley between Bachórzec and Dubiecko (based on Butrym *et al.*, 1988a)

ring east of the meander spur were TL-dated at 40–22 ka, and deluvial loesses at Podbukowina revealed ages between 50 and 28 ka (Butrym *et al.*, 1988a). The abandoned channel itself is filled with organogenic sediments, the deposition of which was initiated in the Allerød (Mamakowa, 1962).

In a well drilled SW of Przedmieście Dubieckie (Rauch *et al.*, 2010), the following sequence was identified (from the top): 6 m of brown, poorly decomposed peat, underlain by 1.6 m thick, white-beige, reddish and again greenish-beige lacustrine chalk, bearing fragments of snail shells in the upper part and wood fragments in the lower part. These sediments rest on grey clays rich in brown organic matter (40 cm thick), underlain by 2.8 m thick sandy gravels, 1–5 cm in diameter, overlying weathered bedrock. In another well drilled in an abandoned channel south of Łysa Góra, 1.4 m thick brown and rusty silty loam and 3.5 m thick silty sands are underlain by 1.5 m thick silts and sandy silts overlying 0.8 m thick strongly decomposed black peat and 1.5 m thick brown peat. The peat rests on 0.6 m thick layer of cobbles, which are underlain by grey clays.

The peat, already noted by Wdowiarz (1948) and Starkel (1960), was pollen-dated by Mamakowa (1962) in two sections (see also Gucik & Wójcik, 1982; Henkiel *et al.*, 1988; Butrym *et al.*, 1988a). The onset of organogenic deposition, initiated after cutting off the channel by accumulation of light-grey clays and sandy clays with lacustrine chalk, took place in the Allerød. The Younger Dryas sediments include alternating layers of peat with pollen flora *Pinus* t. *sylvestris*, *Betula*, *Salix*, *Typha latifolia* and others, as well as lacustrine chalk with numerous snail shells (Mamakowa, 1962). A layer of 7.6 m thick peat was deposited between the Preboreal and Atlantic phases of the Holocene. In the Podbukowina II section, the Preboreal phase was marked by deposition of lacustrine chalk with an admixture of peat, then sedge-moss peat and again lacustrine chalk. At the turn of the Preboreal and Boreal phases, small-scale charcoals appeared, and then light-grey lacustrine chalk with peat interlayers, passing upward into poorly decomposed Sphagnum peat. The Podbukowina II well documented the course of organogenic sedimentation in the entire Holocene. The Preboreal phase was marked by clays with organic matter and transitional peat; in the Boreal deposition of both transitional and Sphagnum peat took place, whereas in the Atlantic, Subboreal and Subatlantic phases poorly decomposed Sphagnum peat dominated (Mamakowa 1962).

On the left-hand side of the San River valley at Iskań, a gravel series rising up to 5–5.5 m above recent floodplain is overlain by grey to light-brown sandy loams, *ca*. 5 m thick. On the right-hand side, in turn, a 14–16 m high terrace step gently passes into slope mantled by solifluction cover. There occur light-brown sandy loams bearing single gravels, 3–5 to 8–10 cm in diameter. Close to Bachów, the right-hand San River valley side is occupied by 11–12 m high terrace step, composed of dark-brown sandy loams with single, moderately rounded gravels up to 5 cm in diameter. North of Bachów, this terrace step rises 8.5–11 m to 10–15 m, and the height of its strath does not exceed 3–4 m.

In the Stupnica River valley, the Weichselian terrace steps rise 7–12 m above recent floodplain. A vast terrace step, up to 200 m in width, occurs at Bircza and Stara Bircza (Figs 13, 14). Close to Bircza, terrace strath is up to 5–6 m high and alluvial cover is composed of sandstone, marl and diatomite gravels, up to 20 cm in diameter. Gravels are intercalated by sands, and at the top overlain by slope sediments: silty loams with angular debris and loess-like sediments, 2–5 m thick.

According to Wójcik (1976), gravel series were laid down during the early part of this stage and covered by sand-silty loams in the main stadial of the Weichselian.

Holocene

Cut-and-fill terraces 4–7 m high tend to build two terrace steps (4–5 m and 5–7 m), attaining greatest widths (250–1,000 m) in the San River valley and at the mouths of its larger tributaries (Fig. 14). The strath slopes below recent river bed even to 9 m depth (*cf.* Wójcik, 1976; Henkiel *et al.*, 1988). Terrace surfaces are dissected by numerous abandoned channels of variable sizes. On the right-hand side of the San River valley at Ulucz (Figs 13, 14), a vast 4–6 m high terrace step is composed of alluvial fines overlying recently exploited gravel series. Below the 3.4 m thick layer of brown, beige and dark-brown silts and clayey silts there occur 0.6 m thick silty clays and 0.5 m thick grey silts with single granules and infrequent pieces of wood, which overlie 3 m of gravels, up to 3 cm in diameter, resting on 1.5 m thick layer of grey, fine-grained sand. Near Bartkówka, this step rises to 6.5–7 m above present-day river bed, and farther downstream, at Bachórz, a vast terrace surface rising 5–7 m is dissected by numerous abandoned channels and inactive oxbows, 2 to 4.5 m deep. A well drilled in one of such channels revealed 1 m of brown and grey-brown and rusty loams resting on: 0.5 m thick layer of dark-grey clay with small pieces of wood, 20 cm of clays with poorly decomposed peat, 30 cm of clays with wood fragments and 30 cm clays with peat, which overlie a 1.5 m thick layer of dark-grey silts bearing numerous chunks of wood, up to 2 cm in thickness. These sediments rest on 1.2 m thick sands with gravel and wood fragments, being underlain by 0.7 m of grey sandy silts and 30 cm of grey silty sand.

Close to Pawłokoma (Figs 13, 14), vast surfaces of the 5–6 m and 6–7 m high terraces are overlain by sediments of alluvial fans, rising up to 9–10 m above present-day river bed. The 6–7 m terrace step east of Pawłokoma is composed of densely packed gravels 2–15 cm in diameter, av. 5–7 cm, overlain by 0.5–0.75 m thick alluvial fines. On the right-hand side, at Sielnica, only one terrace step, 3.5–4.5 m high occurs, being composed of fine sands with loosely packed gravels, 3–6 cm in diameter. On the left San River bank south of Bachórzec, in turn, two steps appear: 4–5 m and 6–6.5 m high, which are built up of gravels 0.5–8 cm in diameter and silt-sandy sediments. Close to Słonne, a terrace step 5.5–6 m high dominates. It is composed of loamy sands, rarely sands bearing fine gravel, and at Zasanie, on the left river bank, a step 7.5 m high with 4 m strath overlain by 2–8 cm gravels in yellow, vari-grained sand is to be seen.

Upstream of the Słonne water gap, the base of 4–5 m high terrace alluvium is placed at a depth of 4.5–5 m below the present-day river bed, in the water gap itself rock exposures occur in the river bed, while at Dubiecko and Nienadowa the base of alluvium slopes again 5 to 9 m below the river bed (Fig. 16; *cf.* Wójcik, 1976, 1977; Butrym *et al.*, 1988a). The quoted authors relate such differences to Holocene uplift affecting the water gap section of the San River valley.

Close to Nienadowa Dolna (Figs 13, 14), a vast 5.5–8.5 m terrace step is built up of 2–8 cm gravels and fine sands. South of Dubiecko and near Krążki Bachowskie and Bachów, terraces rising 4.5–5 m appear, which are sometimes overlain by sediments of alluvial fans, and composed of yellow, fine- to very fine-grained sands or sandy loams bearing loosely packed gravels 4–6 (10) cm in diameter. NW of Iskań, rocky exposures are to be seen in the river bed; they also build a 0.1–0.2 m high strath of the 4 m high terrace. Farther downstream, the 4–5 m terrace is composed of very fine-grained sands with loosely packed gravels, 3–5 to 7–8 cm in diameter, moderately rounded and poorly sorted.

Cut-and-fill terraces 1–3 m high are relatively narrow and occur both in the San River valley and its tributaries (Fig. 14). Close to Ulucz, a narrow bench of 2-m-high terrace occurs, built up of 1-m-thick gravels overlain by alluvial fines, while near Pawłokoma (Figs 13, 14) two steps (2 and 3 m high) are composed exclusively of densely packed gravels 2–4 to 10–15 cm in diameter. It is in this area where bedrock exposures are to be found in the river bed; farther downstream the San River dissects its own alluvium, except Sielnica-Słonne and Nienadowa Dolna regions. On the left river bank at Bachórzec, the 2.5–3 m high terrace step is built up entirely of alluvial fines. South of Dubiecko these are represented by fine-grained sands, and farther to the east (Krążki Bachowskie) by light-brown silts overlying a thin layer of gravels, *ca*. 20 cm thick. The widths of terrace benches rarely exceed 70 m.

Solifluction and slopewash sediments

Clays, loams, sands and debris-bearing loams, originated due to solifluction and slopewash processes, commonly mantle the lower segments of gentle, concave-upward slopes, particularly north of Dubiecko, as well as within saucer-shaped periglacial dellen (Figs 14, 15).

On the left-hand side of the San River valley south of Wybrzeże hamlet (Figs 13, 14), a solifluction cover with angular debris of Menilite shales underlies a 7-m-thick bed of sandy, faintly laminated loess. At Babice, in turn, a bed of sandy loess is overlain by laminated loess sediments that bear two horizons of angular sandstone debris, 2–5 cm to 10–20 cm in diameter, individual clasts being aligned parallel to the slope, and of total thickness up to 3–3.5 m.

In the SW part of the study area, near Huta Poręby, slopewash and solifluction deposits are exposed in a 7-m-high scarp on a left bank of the Jaworka stream. In the lower part (up to 2.5 m), lenses of angular sandstone and flint debris occur within poorly rounded and sorted fluvial pebbles with grey sands and fine granules. These are overlain by 3–3.5-m-thick sequence of grey and rusty-grey silty and sandy loams, grey silts bearing numerous muscovite flakes, and 3–10 cm thick intercalations of both fine (1–2 cm in diameter) and coarse (10–15 cm) angular sandstone debris resting in silt-sandy matrix. The upper part is dominated by laminated silty loams with sandy intercalations, and the amount of angular debris decreases.

A 3–3.5-m-thick section of solifluction-slopewash sediments is exposed in the Jawornik stream valley, in a wall of a small quarry at Żohatyn (Figs 13, 14). The bedrock is overlain there by a 0.5–1 m thick layer of angular sandstone debris that rests in beige sandy loam bearing 10–20 cm large blocks of long axes aligned parallel to the slope. These sediments pass upwards into light-beige, loess-like sandy loam, 1.2 m thick, on top of which a 20-cm-thick horizon of dark soil developed. The latter underlies another layer of angular debris, 2.5–3 m thick.

In the NW part of the study area close to Bartkówka, 2 m thick slopewash sediments overlie weathered Krosno beds. These sediments include alternating grey-brown and beige, sandy and silty loams, bearing at the base ferrugineous concretions.

Loess and loess-like sediments

Typical loesses, dominated by silty fraction, tend to occur in the northern part of the study area, mainly at Babice and Krążki Bachowskie (Figs 13–15). On the left-hand side of the San River valley south of Dubiecko (Wybrzeże), patches of loess sediments overlie alluvium of the last glacial stage terrace and adjoining foot of gentle, concave downwards slope. At Babice, loesses cap the 21–31 m high terrace. The thickness of loess sediments ranges from 3.5 to 8 m, tapering upslope to 3 m, whereas the width of this loess cover attains 200 m. At the base, these are sandy and loamy loesses, passing upwards into typical silty loess, either massive or laminated one, 5–6 m thick. The sediments are light-yellow, bearing abundant muscovite flakes, and at 38 m above recent floodplain strongly calcareous with numerous gastropod shells. Proceeding upwards, loess sediments become more sandy and then loamy, rusty in colour; at their base angular debris and intercalations of grey sandy silts occur. At an elevation of 47 m above recent floodplain, two weathering horizons occur within 3-m-thick laminated loess sediments. Between Babice and Zawada, 5 m to 7–8 m high walls of both massive and laminated, light-yellow loess deposits, sometimes with intercalations of light-grey silts and single horizons of initial soils, are exposed.

Grain-size studies of the Upper Younger Loess sediments (deposited during the younger Weichselian pleniglacial time), conducted by Łanczont (1993) close to Babice, Krążki Bachowskie and Bachów, pointed to changeable values of the average mean grain diameter (4.75–6 to 5.5–6 phi), sorting index (2–3 to 2.5–3.5 phi), and skewness (0.35–0.45 phi). Proceeding from the valley bottom up the slope, the average mean diameter tends to decrease, the sorting becomes successively poorer, and the skewness measures increase, probably as a result of changeable, orographically-controlled wind directions that transported silt particles at relatively short distances. This material originated from fluvio-periglacial covers present in the valley bottoms.

Loess deposits bearing increased content of sand are exposed on the southern San River valley side near Pawłokoma and Sielnica, on the northern valley side near Słonne, as well as on both San and Stupnica river valley sides in the NE part of the study area. Isolated loess patches are also present in the SW part, close to Huta Poręba. On the left-hand side of the San River valley at Zasanie, 4–6 m thick massive and – in the upper part – faintly laminated loess sediments occur up to 13 m above recent floodplains. Massive and laminated sandy silts are to be observed north of Łysa Góra near Dubiecko, and south of Babice 4–7 m thick sandy loesses cap alluvium of the 20–30 m high terrace step. On the left-hand side of the San River valley between Iskań and Krążki Bachowskie, sandy loess overlies fluvial sediments of the Weichselian terraces, while SW of Babice it caps alluvium of the Saalian terrace steps. SW of Krążki Bachowskie, above Weichselian alluvium (10.5–14 m above recent floodplain), alternating very fine-grained sands and silty sands are overlain by 3-m-thick sandy loess bearing mollusc shells, which in turn underlie 2.5-m-thick laminated sandy loess. According to Łanczont (1997a, 2000), sediments of the "middle" (20–30 m high) terrace step of Saalian age are overlain close to Babice by four loess beds that belong the Lowermost, Lower, Middle and Upper Younger Loesses (*sensu* Maruszczak, 1991), the thickness of which is 15–20 m. Loess and loess-like deposits cap in places the 8–16 m high terrace step, shaped in the early Weichselian glacial stage.

DISCUSSION AND CONCLUSIONS

Following folding, thrusting and post-orogenic collapse, the Pliocene time witnessed relief planation in the study area. The so-called intramontane and foothills levels developed according to differentiated bedrock resistance to denudation and erosion as well as minor neotectonic activity of some structures, like that near Sielnica-Słonne. This stage was also accompanied by formation of recent drainage network. Another period of relief planation took place in the Early Pleistocene when the so-called riverside level originated. This level tends to comprise flat-topped meander spurs in the San River valley, preserved at altitudes of 100–120 m above recent floodplains. These are sometimes capped by a thin veneer of fluvial gravels (Pawłokoma), probably deposited during the Praetiglian or Eburonian times. In the following stages, intense erosion led to formation of a sequence of strath terraces that are provisionally dated to the Narevian or Sanian-1 (Menapian or Elsterian-1; 75–80 m), Sanian-2 (Elsterian-2; 40–60 m), Odranian and Wartanian (Drenthe, Warthe; 20–30 m), and Vistulian (Weichselian; 8–16 m) times. In the northern part of the study area, during the Elsterian-2 stage, glaciofluvial waters shed erratic material presently found within fluvial covers of the 40–60 m high terrace steps. During glacial stages, solifluction deposits mantled the feet of gentle slopes being coeval with fluvial deposition and accumulation of loesses and loess-like sediments on either side of the San River valley, which were particularly intense in the Weichselian. Interglacial warmings favoured downcutting of previously deposited fluvial sediments as well as formation of fossil soils within loess sequences and deposition of peat in abandoned channels (Babice). In the Weichselian Late Glacial, some large meanders of the San River became cut off (Dubiecko-Podbukowina) and filled with organogenic sediments. In the Late Pleistocene and at the beginning of the Holocene, in the San River water gap near Słonne and farther east, up to Nienadowa region, diversified tectonic movements took place leading to displacement of Weichselian and Holocene straths. During the Holocene, in turn, cut-and-fill terrace steps were shaped, organogenic sediments filled abandoned channels and oxbow lakes, and slopes became intensively modelled by landslides. Recently, larger valleys witness predominance of fluvial accumulation and the slopes are covered with newly-formed or reactivated landslide colluvium and slopewash sediments.

The pattern of different types of relief, together with spatial distribution of topolineaments and some photolineaments in the eastern portion of the Polish Outer Carpathians, has been shaped due to mutual interactions between climatic, lithologic and tectonic factors. Lithology is important as far as small-scale landforms are concerned and controls the state of preservation of individual planation surfaces, particularly in higher elevated regions (*cf.* Starkel, 1969), but appears to have reduced influence upon the orientation of zones of deformed planation surfaces, distribution of zones of abnormally increased river bed gradients or some morphometric parametres, like those portraying relationship between valley floor width and relief energy. Well-pronounced topolineaments either follow fault-related zones of weakness, providing that one side of the fault is composed of strongly resistant rocks, are associated with dense network of extensional cross-fold joints, or indicate recent reactivation of some faults and/or joint sets.

The scale of neotectonic deformation of straths of Quaternary terraces in the study area has been relatively weak and restricted to the Late Pleistocene time. The most important disturbances are confined to the Słonne Elevation, showing prolonged tendencies to uplift in the Late Cenozoic.

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