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Late Miocene to present day structural development of the Polish segment of the Outer Carpathians

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Abstract. This paper presents a few pieces of evidence on neotectonic structural evolution of the Polish segment of the Outer Carpathians. During the Late Neogene, structural development was largely controlled by normal faulting and block uplift. However, there are also indications of compressional stress setting, at least during the Pliocene and particularly within the medial and eastern parts of the belt. In the Quaternary, in turn, structural development has been mainly controlled by compressional stress arrangement, with σ_1 orientated roughly perpendicular to the belt. The Pliocene-Quaternary tectonic mobility of the Polish Outer Carpathians has been relatively weak and mostly of thin-skinned character. Normal faults were formed on the margins of intramontane basins and in the western part of the belt. Rates of uplift of individual structures were variable and the amount of uplift was the greatest in the Late Pliocene and Early Quaternary times. Geomorphologically-detected zones of uplift are relatively narrow and arranged subparallel or under small angle in respect to the strike of principal thrusts and frontal parts of large slices. Such an arrangement is interpreted as resulting from the steepening of frontal thrusts due to horizontal compression within the overthrust flysch nappes. This hypothesis is confirmed by the results of recent break-out and GPS studies, as well as by focal solutions of some Outer Carpathian earthquakes.

1 Introduction

This paper presents an insight into structural development in the Polish segment of the Outer Carpathians since the completion of Tertiary subduction until Present. The timing of this completion is poorly constrained and the existing pieces of evidence on structural development are very scarce.

The time-span considered is frequently referred to as “neotectonic period”. From among different definitions of neotectonics, we are inclined to accept that by Şengör et al. (1985): ... “the time that elapsed since the last major whole-scale tectonic reorganization”.

2 Geological setting

The Polish segment of the Outer Carpathians is a north-verging thrust-and-fold belt comprising several nappes (Fig. 1) which are largely composed of Lower Cretaceous to Lower Miocene flysch strata. In intramontane basins, unfolded Neogene to Recent strata unconformably overlie the Outer Carpathian nappes.

To the north, the Polish segment of the Outer Carpathians (Figs. 1, 2) is thrust over the Carpathian Foredeep which is filled by Miocene strata mostly of Badenian, Sarmatian, and also Pannonian age (cf. Oszczypko, 1998; Wójcik et al., 1999). Close to the Carpathian frontal thrust, this Miocene complex is tightly folded and cut by north-verging thrusts. This folded zone, called the Zgłobice Unit (Kotlarczyk, 1985), is up to 10 km wide. To the south, the Outer Carpathians are in contact along subvertical faults with the Pieniny Klippen Belt (Birkenmajer, 1985).

The Miocene strata of the Carpathian Foredeep unconformably overlie the Precambrian to Mesozoic complexes of the European Platform (Oszczypko et al., 1989). In the study area, the European Platform is subdivided into the Upper Silesian block to the west and the Małopolska block to the east (Figs. 1, 2, 15). These two blocks are separated by the Kraków-Lubliniec fault zone, the locus of repeated strike-slip movements that have been active since the Palaeozoic up to Quaternary times (Żaba, 1999, and references therein).

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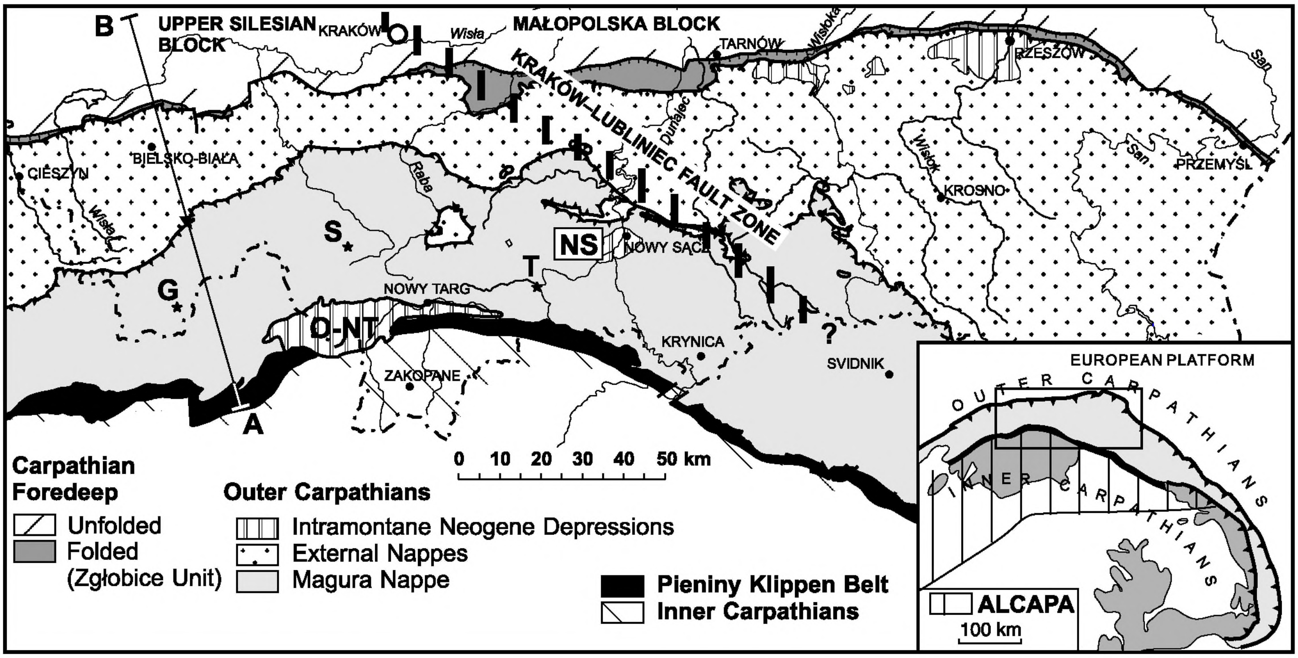

Fig. 1. Polish segment of the Carpathian arc (geology after Żytko et al., 1989; supplemented). Intramontane basins: O-NT = Orava – Nowy Targ, NS = Nowy Sącz; localities mentioned in the text: G = Glinka, S = Sidzina, T = Tylmanowa. Note that the Kraków-Lubliniec fault zone is located in the Carpathians' basement.

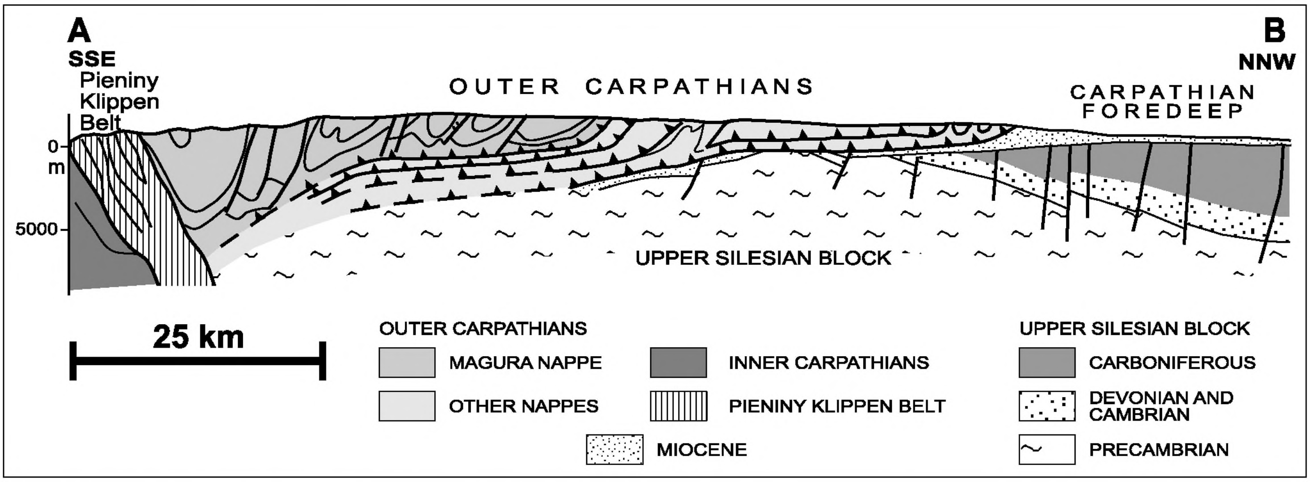

Fig. 2. Schematic cross-section (after Żytko et al., 1989). For location see Fig. 1.

3 Pre-neotectonic history

The main structural elements of the Polish segment of the Outer Carpathians (Fig. 1) were formed during Tertiary times when the belt was locus of the southward-directed subduction of the southern margin of the European Platform below the ALCAPA unit (sensu Csontos et al., 1992; Csontos 1995; Oszczypko, 1998; Fodor et al., 1999). The subduction-related synsedimentary shortening (Tokarski and Świerczewska, 1998, and references therein; Żytko, 1999; cf. also Żytko, 1977) resulted in successive incorporations of the Outer Carpathian nappes and the Zgłobice unit into the subduction-related accretionary prism (cf. Fodor et al., 1999). These incorporations started during Eocene times in the Magura nappe (Świerczewska and Tokarski, 1998) and terminated after the Badenian in the Zgłobice unit (Oszczypko, 1996, 1998, and references therein).

Results of recent structural analysis (Decker et al., 1997, 1999) performed at over 120 exposures suggest that the accretion-related shortening might have been at first, since at least the Paleocene (Kopciowski et al., 1999), directed towards the NW (in the present-day coordinates) (Fig. 3) and afterwards apparently rotated towards the NE (cf. Aleksandrowski, 1985; Decker et al., 1997). Results of recent

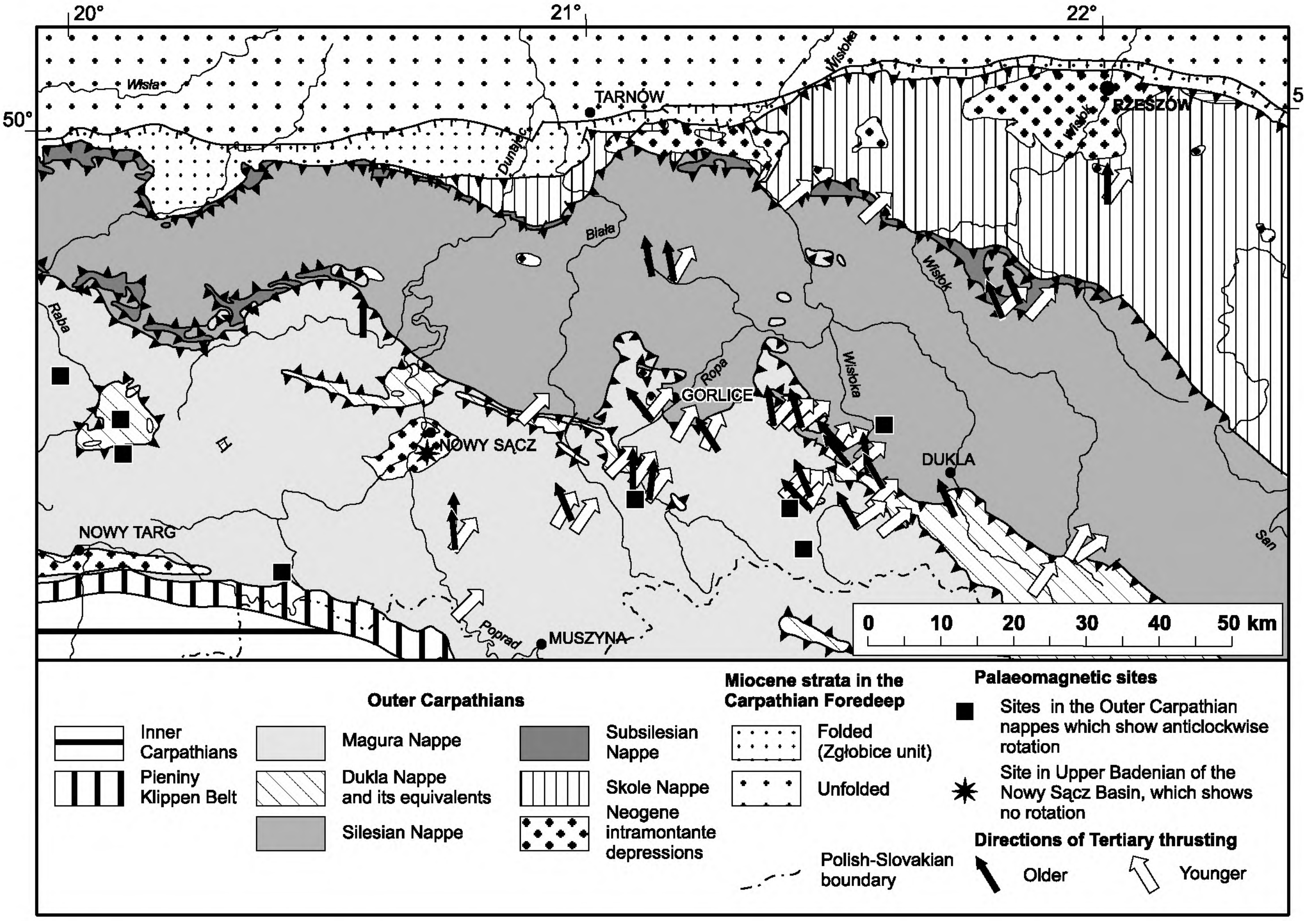

Fig. 3. Medial-eastern part of the Polish segment of the Carpathian arc (geology after Żytko et al., 1989; supplemented) showing results of structural analysis (after Decker et al., 1999) and locations of palaeomagnetic sites within the Outer Carpathians (after unpublished data by Márton and Tokarski).

palaeomagnetic research performed at 58 localities appear to indicate that the apparent clockwise rotation of the regional stress field was probably due to the large-scale post-early Badenian anticlockwise rigid body rotations observed in the Polish segment of the Inner (Márton et al., 1999a) and Outer Carpathians (Márton et al., 1999b) (Fig. 3), as well as within the Zgłobice unit (Márton et al., 1999c). The results from the upper Badenian strata (Oszczypko et al., 1992) of the intramontane Nowy Sącz Basin show that the anticlockwise rotation could have been completed before the late Badenian, at least in that part of the Outer Carpathians. The data from the Slovak and Hungarian parts of the Inner Carpathians show that the Neogene anticlockwise rotation took place there in two or three successive steps (Kovač and Márton, 1998, and references therein). We believe that the process of the rotation could have been similar within the Polish segment of the Carpathians. However, so far we have not enough data to check this hypothesis.

The age of termination of the accretion-related shortening has been considered to be younging eastwards along the strike of the Carpathians (cf. Uhlig, 1903; Sawicki, 1909; Alexandrowicz, 1964): from 15 Ma at the westernmost part of the Polish segment, until 12 Ma at the easternmost part of the segment (Nemčok et al., 1998, and references therein). This interpretation stems from the age of the youngest Miocene strata in the Carpathian Foredeep that are thrust over by the Carpathians. However, recent discovery of the Pannonian strata overthrust by the Outer Carpathian nappes in the western part of the Polish segment of the belt (Wójcik and Jugowiec, 1998; Wójcik et al., 1999) appears to contradict this conjecture and implies that the final episode of thrusting must have occurred after the Pannonian.

4 Late Miocene – Quaternary structural history

The bulk of evidence for the structural development during this period comes from the Outer Carpathian nappes. This is supplemented by the results of observations within intramontane basins.

Within the Outer Carpathian nappes, the structures resulting from the accretion-related shortening are commonly overprinted by normal faults (Decker et al., 1997, 1999; Rubinkiewicz, 2000). These faults (Fig. 4), which appear

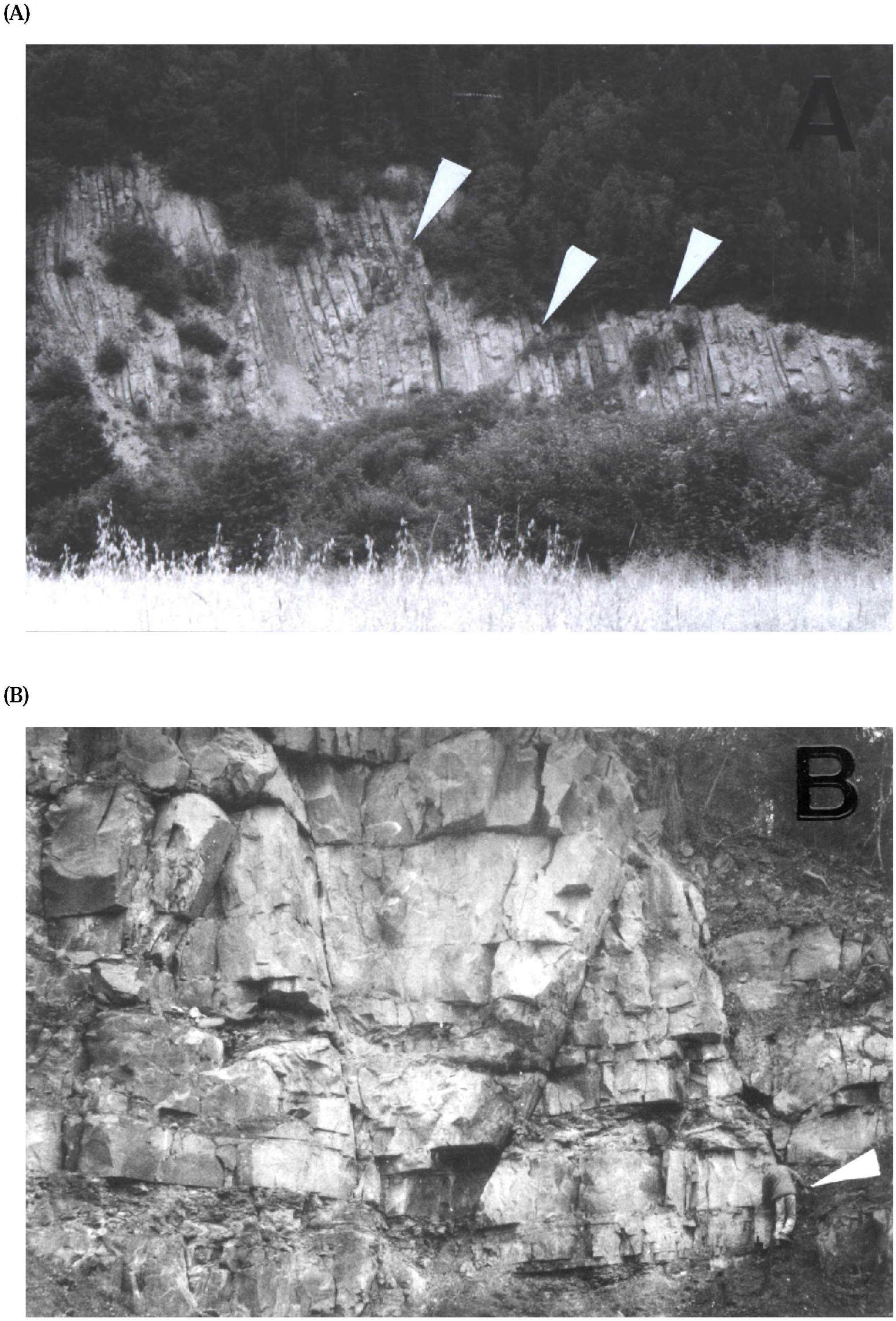

Fig. 4. Normal faults at Sidzina **(A)** and Glinka **(B)**: A – normal faults (arrowed) cutting subvertically dipping strata, the exposure is 20 m tall; B – tectonic graben, man (arrowed) for scale. For location see Fig. 1.

to be the youngest tectonic features affecting the nappes, are widespread throughout the whole Polish segment of the Outer Carpathians. At particular exposures, populations of the discussed normal faults were formed due to either N-S or E-W extension (Fig. 5). It is still uncertain whether the faulting took place during successive phases of differently-orientated extension or during one or more phases of multidirectional extension. The age of faulting is also difficult to estimate; its formation most probably postdated the last episode of thrusting that occurred after the Pannonian in the

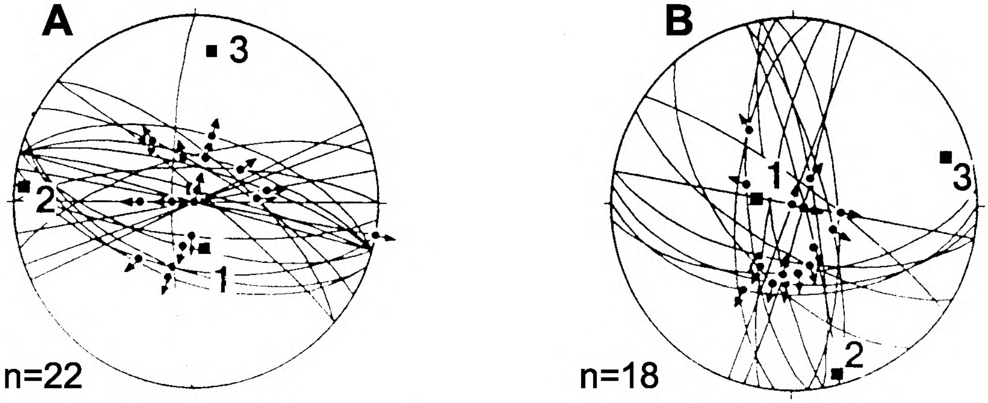

Fig. 5. Plots of normal faults at Glinka **(A)** and Tylmanowa **(B)**, showing orientation of extension. For location see Fig. 1. 1, 2, 3 – $\sigma_1, \sigma_2, \sigma_3$

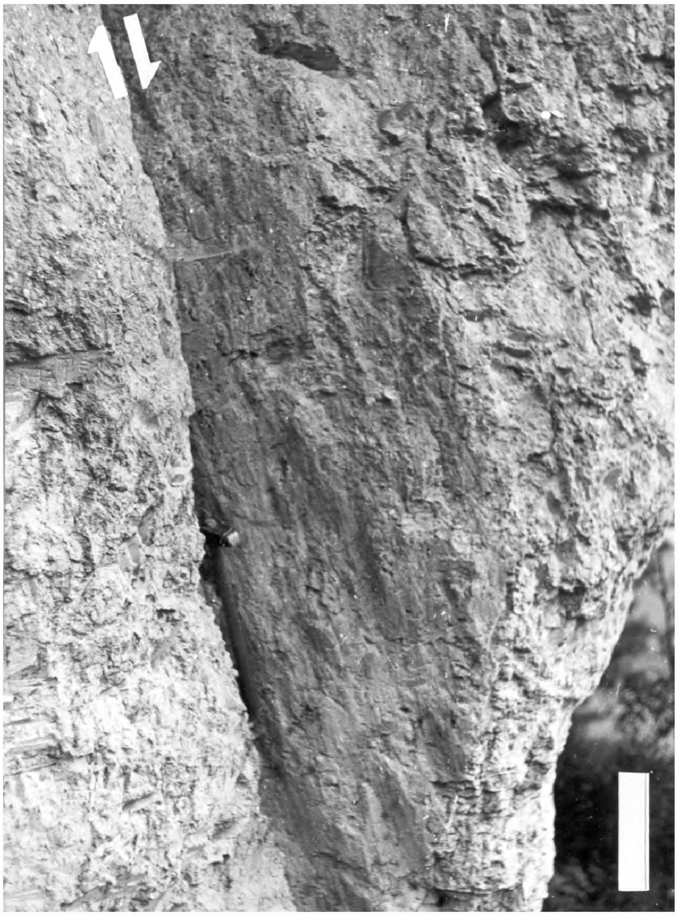

Fig. 6. Normal fault cutting Quaternary loessial loams in the Nowy Sącz intramontane basin. Scale bar is 20 cm long. For location see Fig. 1.

marginal part of the Outer Carpathians (cf. Oszczypko and Tomaś, 1985). Alternatively, the onset of the normal faulting could have been diachronous, younging outwards across the Outer Carpathians.

The Orava-Nowy Targ intramontane basin (Fig. 1) is a W-E trending tectonic graben bordered to the south and north by sets of normal faults, with throws up to few hundred metres for each set (Pomianowski, 1995, and references therein). The faulting started during the Late Miocene (Pomianowski, 1995) and at least some of the faults were still active during Quaternary times (cf. Niedzielski, 1971; Baumgart-Kotarba, 1996). The Quaternary normal faulting took place also in the Nowy Sącz intramontane basin (Tokarski, 1978), where loessial loams of the penultimate

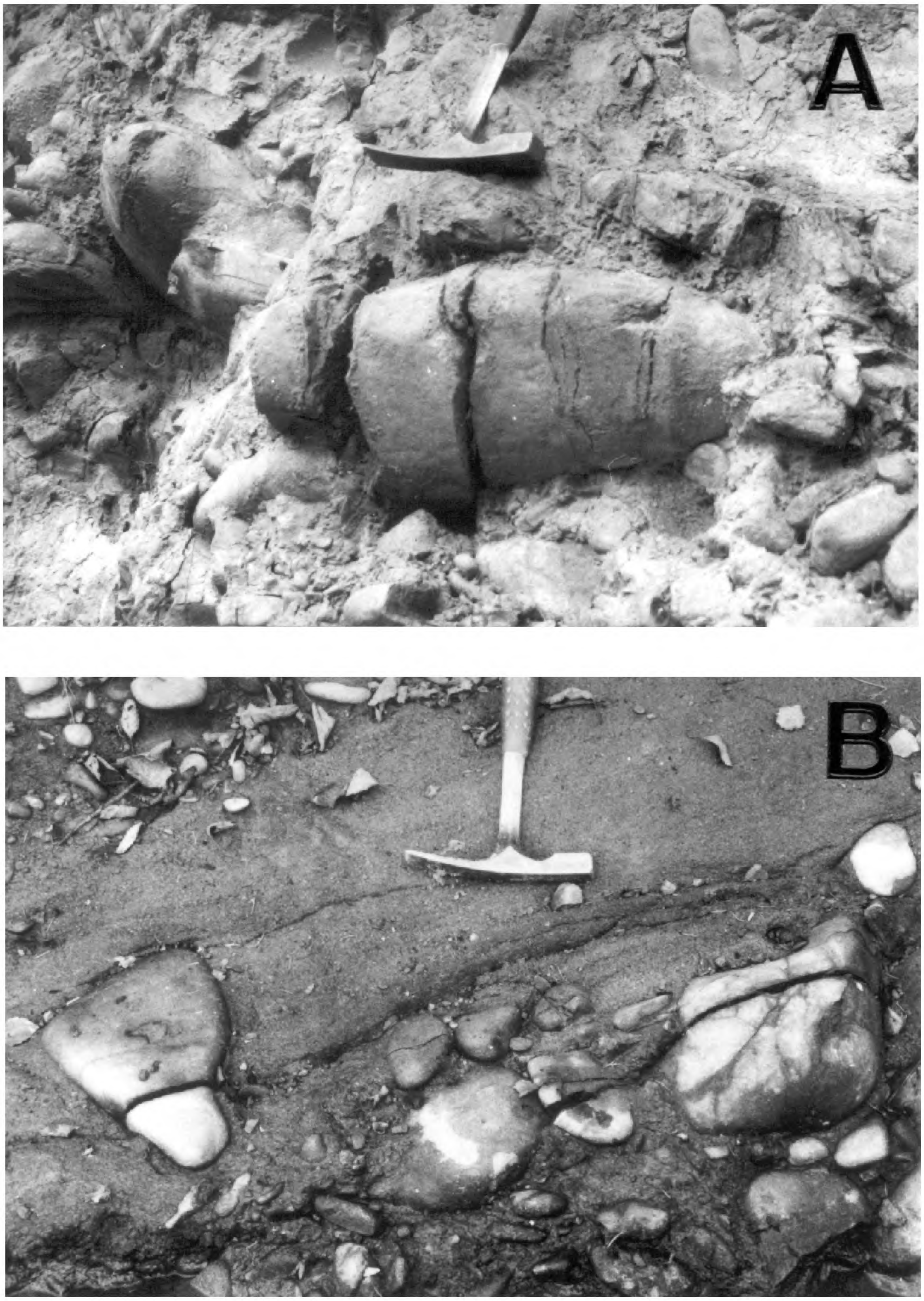

Fig. 7. Fractured clasts (**(A)**, **(B)**) in the Domański Wierch conglomerates (Orava – Nowy Targ intramontane basin). Note that fractures at B are oriented independently of the clast shape. For location see Fig. 1.

glacial stage are cut by a normal fault (Fig. 6).

The other examples of Middle through Late Quaternary normal faulting, though documented less convincingly, come from the Beskid Żywiecki Mts. (Wójcik, 1989, and references therein) and southern part of the Jasło-Sanok Depression (Zuchiewicz, 1987; cf. also Fig. 11).

The Domański Wierch conglomerates form an intercalation within the infill of the Orava-Nowy Targ Basin (Fig. 1). These poorly-cemented conglomerates are Sarmatian to Pliocene in age (Zastawniak, 1972; Sikora and Wieser, 1974; Oszast and Stuchlik, 1977; Birkenmajer, 1979). Sandstone and limestone clasts within the conglomerates are commonly fractured (Tokarski and Zuchiewicz, 1998; Kukulak, 1999; cf. also Fig. 7). Most of the fractures are subvertical and strike irrespectively of the clast shape and of the present-day topography. The fractures show a well- con-

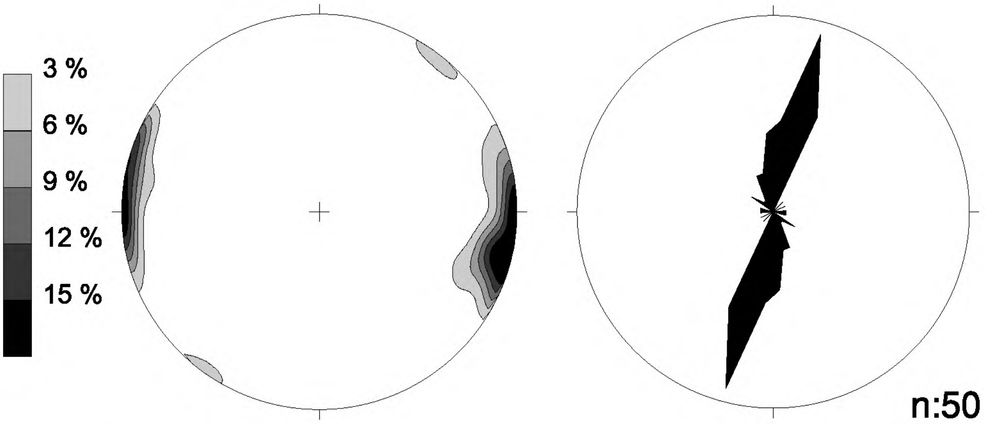

Fig. 8. Lower hemisphere plot and rose-diagram of fractures cutting clasts of the Domański Wierch conglomerates. For location see Fig. 1.

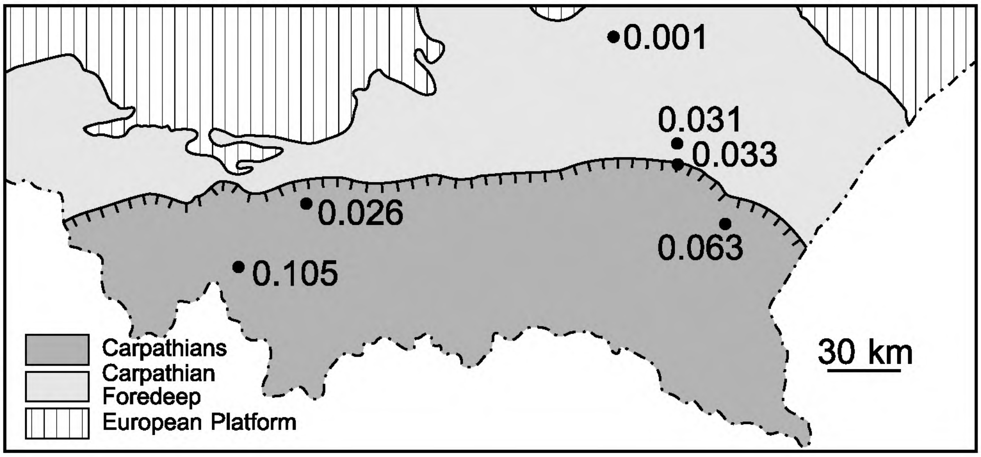

Fig. 9. Long-term isostatic uplift rates (mm/yr) during the past 10 million years, calculated for some wells in the Outer Carpathians and Carpathian Foredeep (based on data provided by Oszczypko, 1996).

strained maximum orientated NNE (Fig. 8). In our interpretation (Tokarski and Zuchiewicz, 1998), the fractures were formed due to regional strike-slip stress field in which σ_1 was orientated NNE.

The presented pieces of evidence show that after completion of the Tertiary subduction, structural development of the Polish segment of the Outer Carpathians took place in extensional stress regime. Data from the Orava-Nowy Targ and Nowy Sącz intramontane basins (normal faults) imply that the extension lasted there until Quaternary times. Fractured pebbles in the Orava Basin could indicate that the extension was at least locally replaced by a single compressional episode.

5 Pliocene-Quaternary geomorphological history

Conventional geomorphic studies aiming at the reconstruction of long-term landform development in the Polish Outer Carpathians have dealt with gross features of the topography, including ridge and valley patterns, the number, origin and age of planation surfaces, as well as the history of fluvial changes, aided by palaeogeographic reconstructions (cf. Starkel, 1972; Henkiel, 1977–78; Zuchiewicz, 1995, and references therein).

5.1 Planation surfaces and post-orogenic uplift

The concept of three Pliocene and one early Quaternary planation surfaces, preserved upon bedrock of variable resistance and deformed during a few orogenic pulses, has been dealt with by numerous authors until the late 1980s (cf. Starkel, 1972; Zuchiewicz, 1984; Klimaszewski, 1988; and discussion therein). However, the lack of correlative deposits makes the precise dating of planation episodes impossible; therefore, the rates of uplift approximated by those of downcutting of planation surfaces or inferred from different estimates of Neogene denudation, appear to be poorly constrained.

The amount of uplift of the medial segment of the Polish Outer Carpathians during Late Neogene and Quaternary times, approximated by the size of erosional dissection of

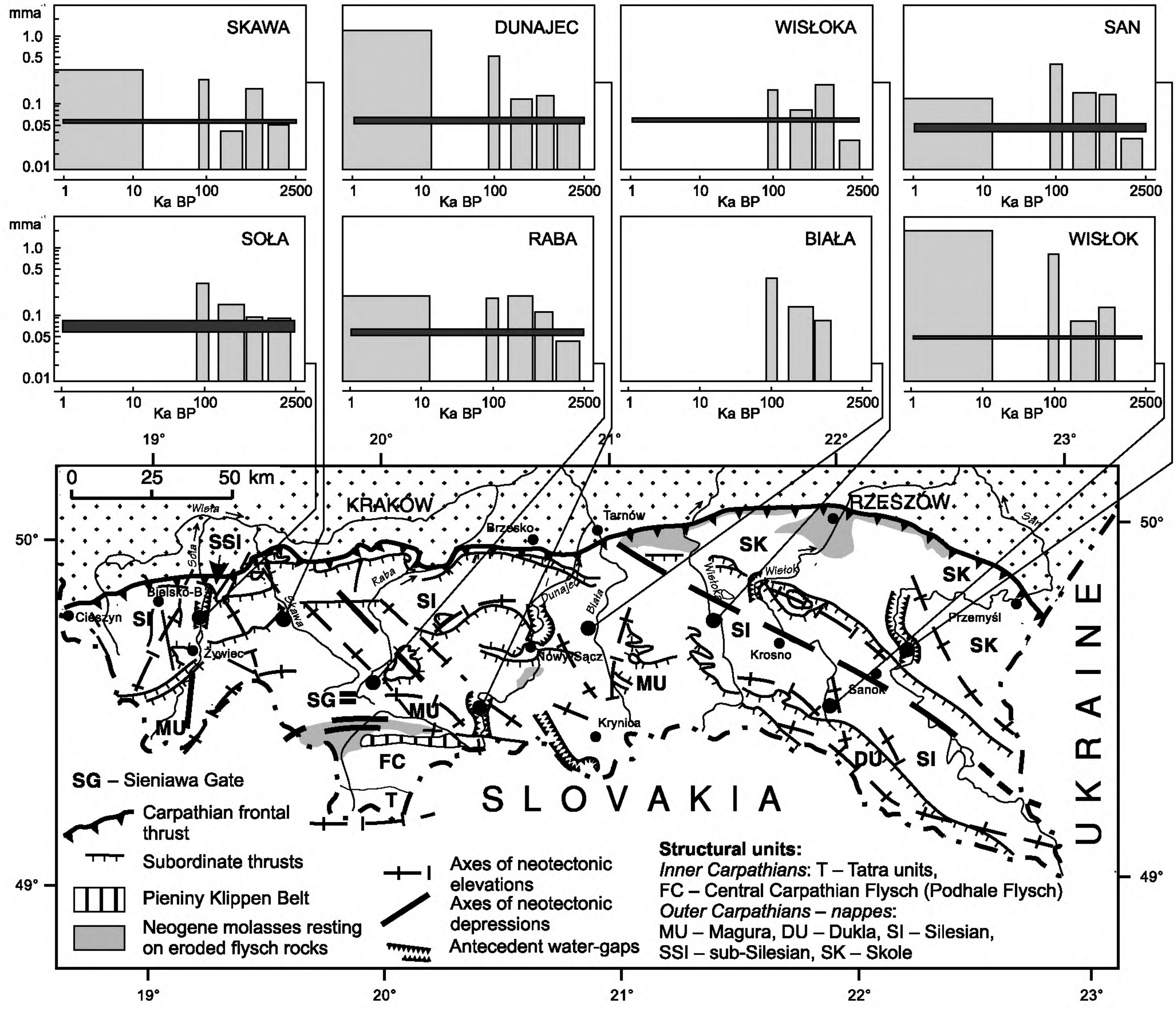

Fig. 10. Neotectonic sketch of the Polish Carpathians (based on Zuchiewicz, 1998). Diagrams portray rates of Quaternary downcutting of straths in those segments of the Polish Carpathian valleys which dissect neotectonically uplifted structures. Solid lines denote average rates of downcutting throughout the Quaternary.

different erosional surfaces, ranged from 150 to 900 m, averaging at ca. 300 m (Zuchiewicz, 1984, 1991). These figures conform well with the results of seismostratigraphic studies that clearly indicate a minimum of >200 m rebound of the lithosphere during the post-late Badenian times (Krzywiec and Zuchiewicz, 1993).

More reliable results are provided by analyses of the minimum size of post-tectonic, isostatic uplift during the past 10 to 11 million years that has been calculated for ca. 1 km in the West Beskidy Mts. to some 260–360 m in the Carpathian Foothills (Oszczypko, 1996), the maximum rate of uplift being 0.1 mm/yr (Figs. 9, 13). Less convincing are different estimations of the amount of denudation, based on reconstructions of the hypothetical position of palaeo-summit surface in the eastern segment of the Polish Outer Carpathians (4–5 km; Kuśmierek, 1990), analyses of the degree of diagenesis (Kotulova et al., 1998), fluid inclusion (Hurai et al., 2000) or compaction studies of overthrust flysch strata and underlying molasses (Oszczypko et al., 1993). Recent studies indicate that the generally modest Bouguer gravity anomalies point to nonisostatic processes causing the postflexural uplift, ranging from 250 m to 550 m (Zoetemeijer et al., 1999). Reliable estimates will only be provided by fission track studies.

5.2 Structural control on landforms and differentiated Quaternary uplift

Structurally-controlled landforms have been either mapped or inferred from the analysis of morphometric maps and statistical modelling of the topography (Fig. 10).

Morphological manifestations of Quaternary tectonic ac-

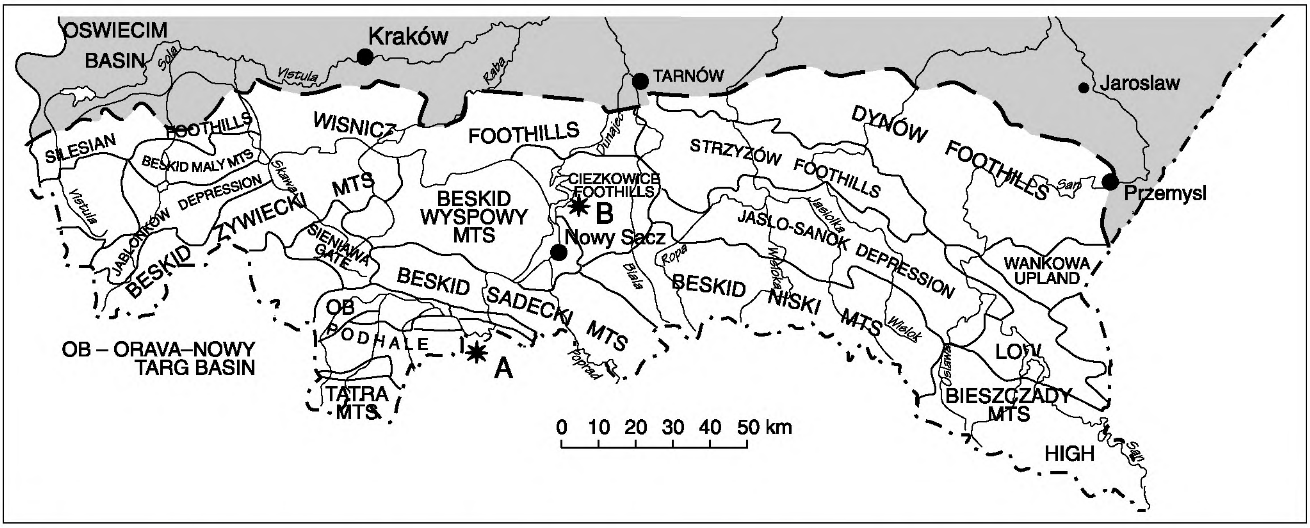

Fig. 11. Geomorphological subdivision of the Polish Carpathians (based on Starkel, 1991; modified). OB = Orava – Nowy Targ Basin; A/B = medial segment of the Dunajec River valley, whose longitudinal profile is shown in Fig. 12.

tivity include: disturbed longitudinal profiles of strath terraces (Starkel, 1972; Zuchiewicz, 1991, 1995) of all main Outer Carpathian rivers, frequently indicating Recent reactivation of the pre-existing fault zones (cf. Figs. 11, 12), incomplete sequences of alluvia in the Jasło-Sanok Depression (Starkel, 1985; Zuchiewicz, 1987), convex-upward slope profiles in strongly elevated regions, mainly in the Beskid Sądecki Mts. (Starkel, 1972), young changes in the drainage pattern in the Jasło-Sanok Depression and the Strzyżów Foothills (Gerlach et al., 1985; Zuchiewicz, 1987), tilting of Upper Pleistocene lacustrine sediments in the southern part of the Jasło-Sanok Depression (Koszarski and Koszarski, 1985), and some examples of young subsidence in the intramontane Orava – Nowy Targ and Nowy Sącz basins (Baumgart-Kotarba, 1991–92, 1996; Zuchiewicz, 1984).

In the western and medial segments of the Polish Outer Carpathians, predominance of strongly dissected areas results mainly from Pliocene-Quaternary uplift (Starkel, 1972; Zuchiewicz, 1995, and references therein). For instance, a large morphological depression located north of the Orawa Basin, the Sieniawa Gate (cf. Figs. 10, 11), is composed of thick-bedded flysch strata of the Magura nappe, which are exactly as resistant as those which build the neighbouring, strongly elevated and dissected physiographic units to the west (Beskid Żywiecki Mts.) and east (Beskid Sądecki Mts.; cf. Fig. 11).

Conventional geomorphological analyses focusing on structural landforms and disturbances recorded in deformed longitudinal profiles of strath terraces lead to a conclusion that the Pliocene-Quaternary differential vertical movements have resulted in the formation of several elevated and subsided structures orientated roughly parallel to the structural grain of the area (Figs. 10, 11), the maximum size of Quaternary uplift attaining some 150 m in the Beskid Sądecki Mts., and in other regions varying from 50 to 100 m (cf. Starkel, 1980; Zuchiewicz, 1984, 1995).

5.3 Rates of river downcutting and the periodicity of uplift

Rates of river downcutting are one of necessary tools for understanding rates of erosion, landform evolution, and tectonic uplift. Variations in downcutting rates along the valley's profile help to reconstruct the spatial pattern of uplift (cf. Schumm, 1986; Burbank et al. 1996).

Valleys of the main Outer Carpathian rivers bear 8 to 9 terrace steps of Quaternary age (Zuchiewicz, 1984, 1991). Most of Pleistocene terraces are strath or complex- response terraces (cf. Bull, 1990); the Weichselian and Holocene steps are usually cut- and-fill terraces, except for those which are located in the neotectonically elevated structures and are characterised by the presence of young straths (Starkel, 1972; Zuchiewicz, 1984, 1998; cf. also Fig. 12).

Longitudinal profiles of individual strath terraces frequently show divergence, convergence or tilting that can be indicative of young tectonic control (Zuchiewicz, 1987, 1991, 1995; Henkiel et al., 1988, Wójcik, 1989). 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 (cf. Figs. 10, 13). This applies particularly to neotectonically uplifted regions dissected by antecedent watergaps of the main Outer Carpathian rivers (Fig. 10). Rates of river downcutting result mainly from climatic changes throughout the glacial-interglacial cycles (cf. discussion in Starkel, 1985, 1996 and Zuchiewicz, 1995), but their spatial differentiation throughout a relatively small area appears to be tectonically, and not climatically- controlled. Figures 10 and 13 portray variable rates of fluvial downcutting of strath terraces within those valley reaches which truncate geomorphic units uplifted in Plio-Quaternary times (cf. also Starkel, 1972; Zuchiewicz, 1998). These figures differ from unit to unit, although three episodes of increased downcutting rates can be distinguished in the Polish Outer

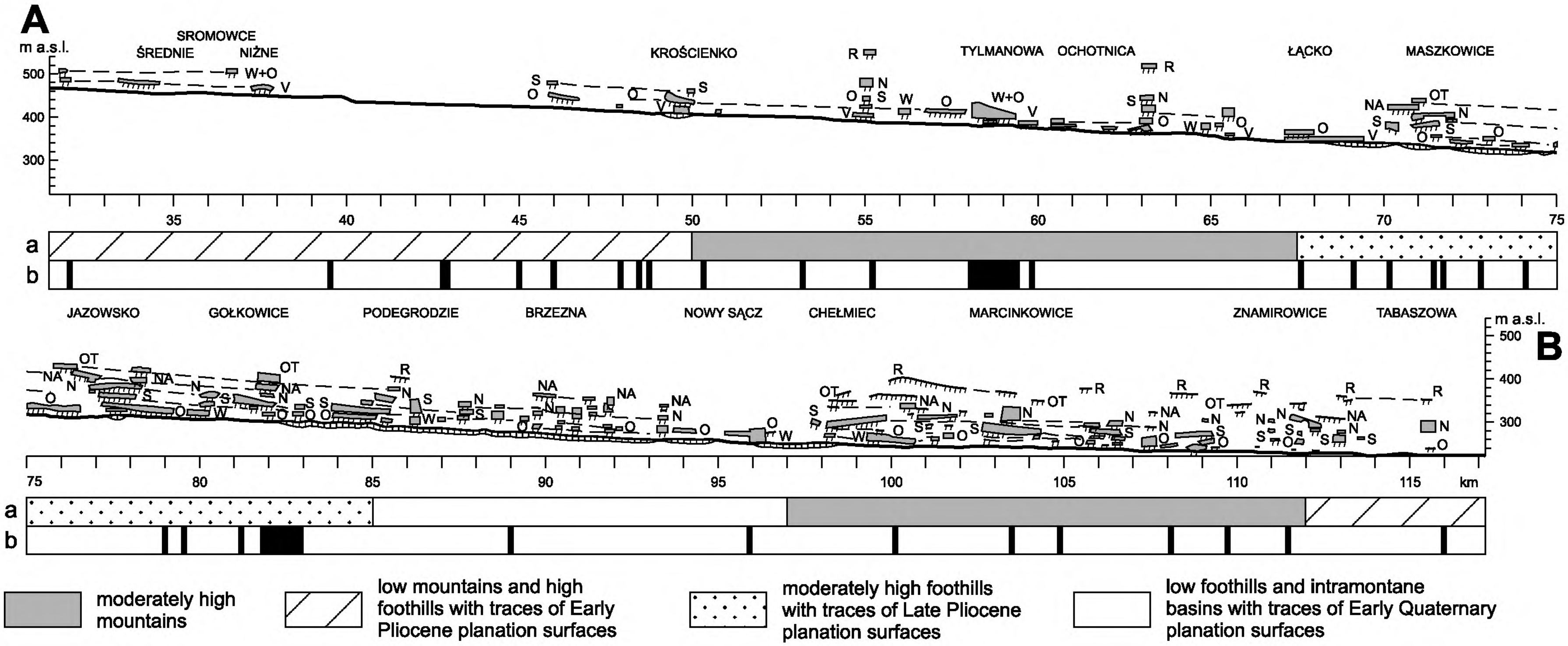

Fig. 12. Longitudinal profile of terraces in the medial segment of the Dunajec river valley (see segment A/B in Fig. 11). Note disturbances seen in strath profiles; fence lines = straths, grey hatchure = thickness of alluvia, Quaternary stages: R = Różce (Praetiglian), OT =Otwock (Eburonian), NA = Narew (Menapian), N = Nida (Elsterian-1), S = San (Elsterian-2), O = Odra (Saalian), W = Warta (Wartanian), V = Vistulian (Weichselian). Lower bar diagrams: a = types of relief, b = main fault zones in flysch strata.

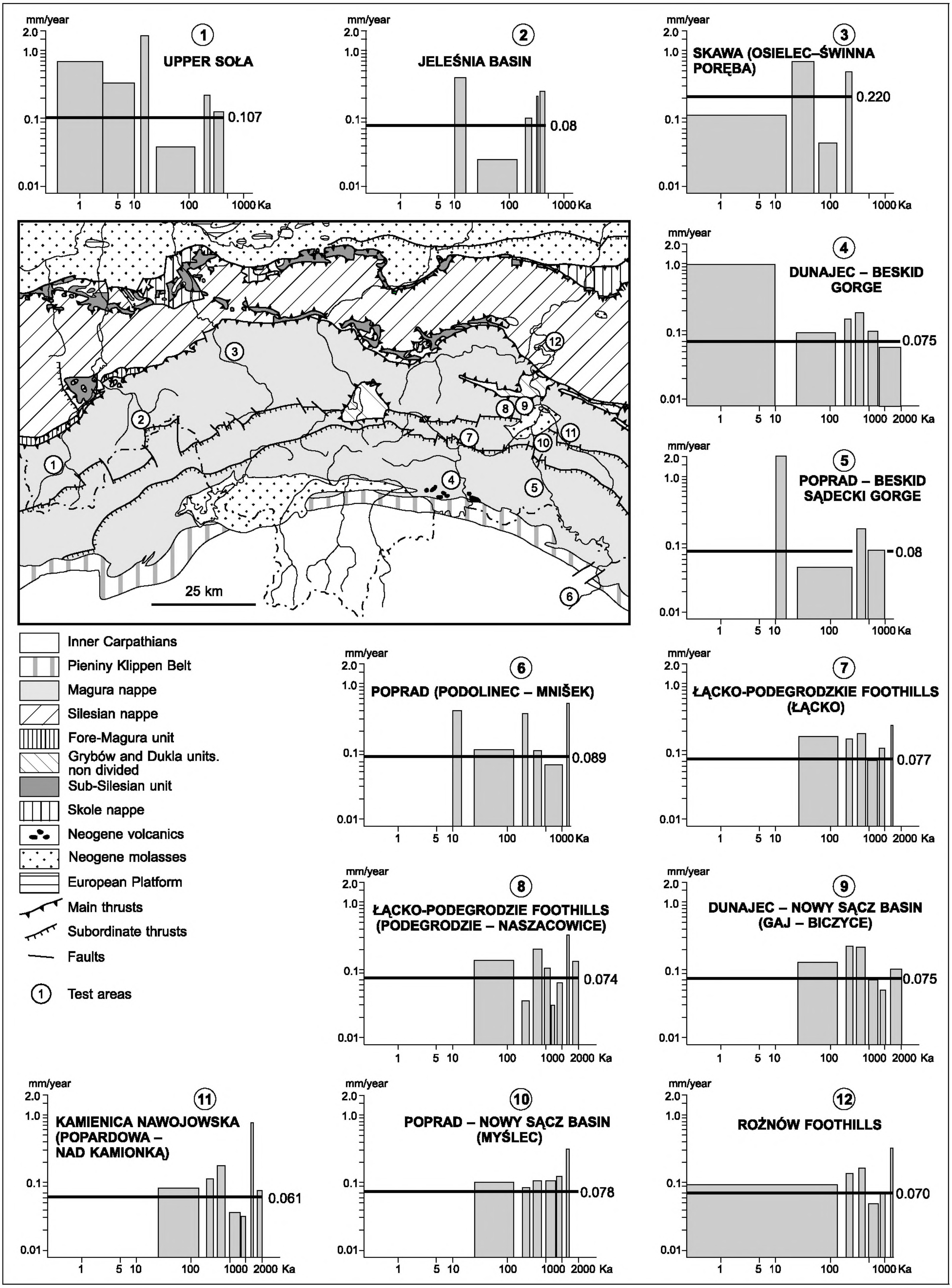

Fig. 13. Rates of fluvial downcutting into Quaternary straths at selected test areas in the Polish Outer Western Carpathians. Solid lines denote average rates of downcutting throughout the Quaternary.

Carpathians as a whole (Zuchiewicz, 1991), including the Cromerian-Elsterian 1/2 (0.15–0.21 mm/yr), Eemian-Early Weichselian (0.18–0.40 mm/yr) and Late Glacial-Holocene (0.2–2.0 mm/yr) time-spans. A word of caution should be added that the quoted rates are estimates of fluvial downcutting, and not uplift rates proper. Nevertheless, increased rates of downcutting into solid rocks (straths) can be used as proxy data for episodes of more vigorous uplift. These rates have been calculated as ratios of fluvial downcutting into solid bedrock, i.e. strath terraces of climatostratigraphically-estimated age (the amount of dissection of fluvial covers proper being excluded as mostly climatically-controlled), to the age of downcutting which, usually, corresponds to the duration of individual interglacial stages.

The above mentioned episodes of increased fluvial downcutting (800–472 ka, 130–90 ka, and 15–0 ka BP) were particularly well marked in localised physiographic units, such as: the Beskid Sądecki Mts., Bieszczady Mts., and the northern margin of the Beskid Niski Mts. (cf. Figs. 10, 11, 14). The earliest episode coincides with one of global episodes of increased Quaternary tectonic mobility, distinguished by Kukla (1982) and Mörner (1994).

5.4 Morphometric indices

Some morphometric parametres (river-bed gradients, relief, valley floor width/valley floor height ratios, bifurcation ratios, the amount of 1st-order valleys, concavity ratios of the normalized river-bed profiles, physiographic parametres of small drainage basins, etc.) are indicative of young tectonic tendencies (cf. Keller and Pinter, 1996). For instance, abnormally high river-bed gradients and increased altitudes of valley divides, as well as unusually low values of valley widths and valley floor width/valley height ratios point to neotectonic uplift (cf. Zuchiewicz, 1987, 1995, and references therein; see also Fig. 14).

Taxonomic analysis of the links between the structure and character of valleys, ridges and landslide niches in the Polish segment of the Outer West Carpathians indicates young age of those ridge and valley patterns which are independent of bedrock structures (Jakubska, 1995). Detailed maps of relief energy and summit surfaces clearly show zones of increased resistance to erosion, as well as those associated with uplifted morphostructures. Relief energy values change from 50–100 m in the foothills areas and the Jasło-Sanok Depression to >500 m in the highest-elevated regions of the Beskid Sądecki Mts. (Zuchiewicz, 1995).

Another approach represents more or less successful attempts at digital processing of some morphometric parameters of small drainage basins (cf. Zuchiewicz, 1987, 1991) and time-series analysis of river-bed gradients or the valley floor width/valley height ratios (Zuchiewicz, 1995). The zones of abnormally high and low values of the first and second parameter, respectively, are aligned subparallel to the structural grain of the Outer Carpathians, their number increasing from the west to the east (Fig. 14). They also coincide to a large extent with the axes of neotectonically uplifted structures detected on geomorphic maps (cf. Fig. 10). In the eastern segment of the Outer Carpathians some of uplifted structures are located at or in front of the present-day Carpathian frontal thrust, cutting it obliquely and passing into the Carpathian Foredeep (Fig. 14).

Relatively small widths of these structures (15–25 km) and their subparallel arrangement with respect to the strike of principal thrusts and imbricated slices led Zuchiewicz (1995, 1998) to hypothesize about Plio-Quaternary relaxation of remnant horizontal stresses, built up during the Neogene thrusting.

5.5 Implications for structural development

The presence of long and narrow zones that show alternately uplifting and subsiding tendencies in the eastern segment of the Outer Carpathians of Poland and are aligned subparallel to or crossing under small angles the structural grain of the region appears to exclude their purely isostatic origin. Uplift of these zones could have resulted from recent relaxation of horizontal stresses accumulated within the overthrust nappes. Such a mechanism explains: (a) manifestations of localised young uplift occurring along frontal thrusts of some imbricated slices, (b) the present-day configuration of S_{hmax} recorded by breakouts in wells that pierce through the flysch nappes and their substratum (cf. Jarosiński, 1998; see also discussion below), and revealed by focal mechanisms of the 1992–1993 Krynica earthquakes (Wiejacz, 1994; Dębski et al., 1997).

En echelon arrangement of theses zones, however, slightly different in the western and eastern parts of the study area (Figs. 14, 15) can also indicate young sinistral motions along the Kraków-Lubliniec fault in the substratum of the overthrust nappes. This hypothesis needs to be verified by future studies.

6 Present-day picture

Contemporary stress field from borehole breakouts

6.1 Breakout data

Directions of present-day stress have been investigated in fifteen deep wells located in the Polish part of the Outer Carpathians (Fig. 15) by means of borehole breakout analysis. Orientation of borehole cross section elongation due to breakouts was detected with 6-arm caliper tool and in some cases with borehole acoustic scanner tool (Jarosiński, 1998, 1999; Jarosiński and Zoback, 1998). Using these tools one can discriminate between stress-induced breakouts and technological "key seats". The analysed dipmeter data come from a depth greater than 1000 m (except for a few short intervals in shallow Carpathian nappes) and usually reach more than 3000 m depth. Fourteen of fifteen wells pierce through the Carpathian flysch nappes and penetrate the autochthonous complexes. Four of the wells reach the Precambrian metamorphic basement of the Upper Silesian Massif.

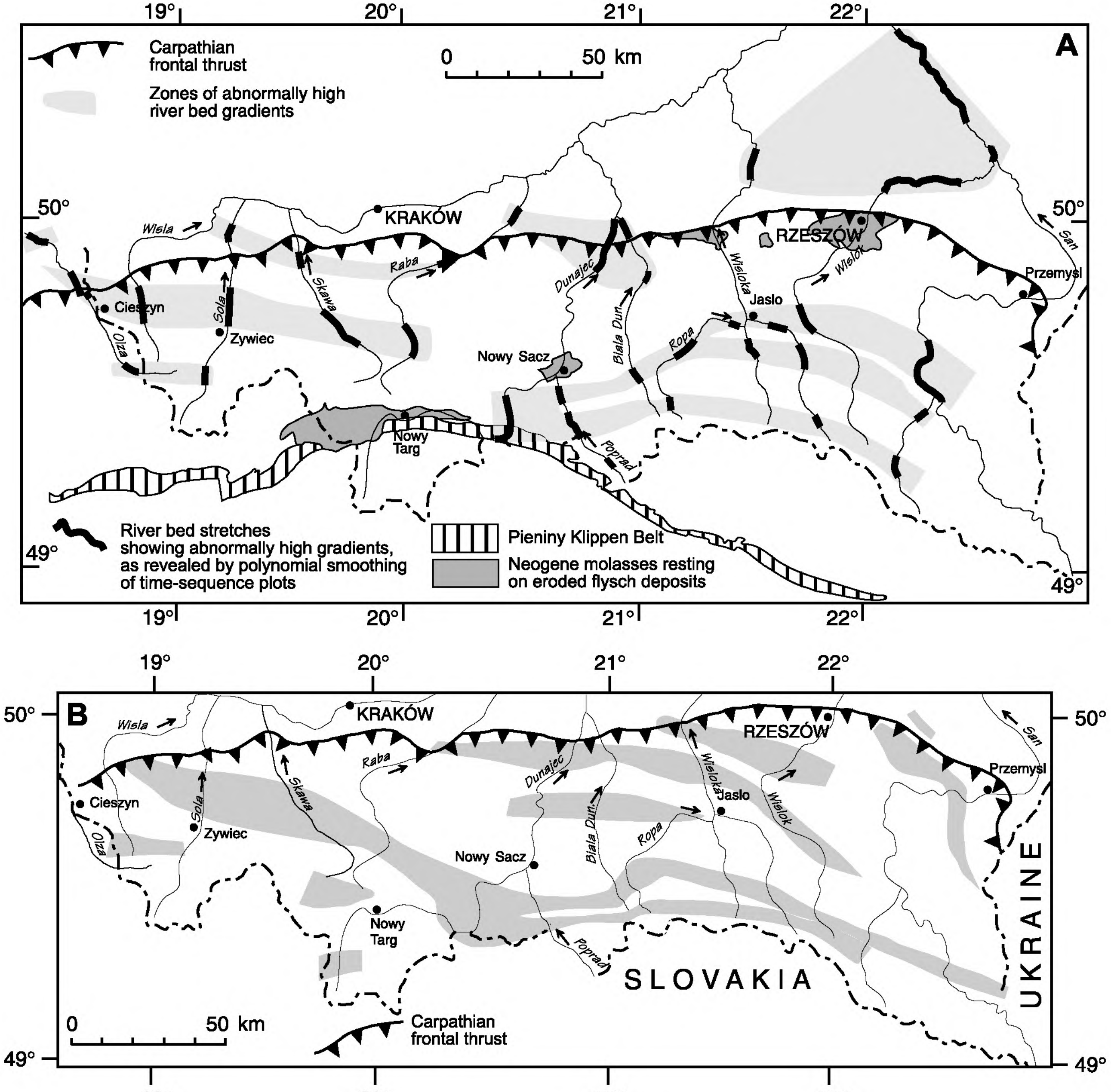

Fig. 14. Neotectonic tendencies in the Polish Outer Carpathians, indicated by selected morphometric indices: **(A)** – river-bed segments showing abnormally high gradients, **(B)** – distribution of minimum values of the valley floor width/valley floor height ratio, pointing to Recent uplift tendencies (redrawn from Zuchiewicz, 1995).

In the Carpathian flysch nappes, due to intensive tectonic deformations breakouts are irregularly shaped. Beneath them, in the autochthonous Miocene molasse complex, breakouts are usually scarce and rather shallow. The best-developed breakouts were found in the autochthonous sedimentary and metamorphic rocks. In general, breakout data from the autochthonous basement are of higher quality than those from flysch nappes.

In the first approach breakout profile from each well was divided into intervals with relatively stable breakout orientation. Next, for each depth section the weighted mean depth of breakouts, the total length of them and the quality of stress determination were computed, according to the standards of the World Stress Map Data Base (Zoback, 1992). Due to considerable differences in stress directions between the two Outer Carpathian domains with the Upper Silesian massif basement and Małopolska massif basement, the results are presented separately for these regions.

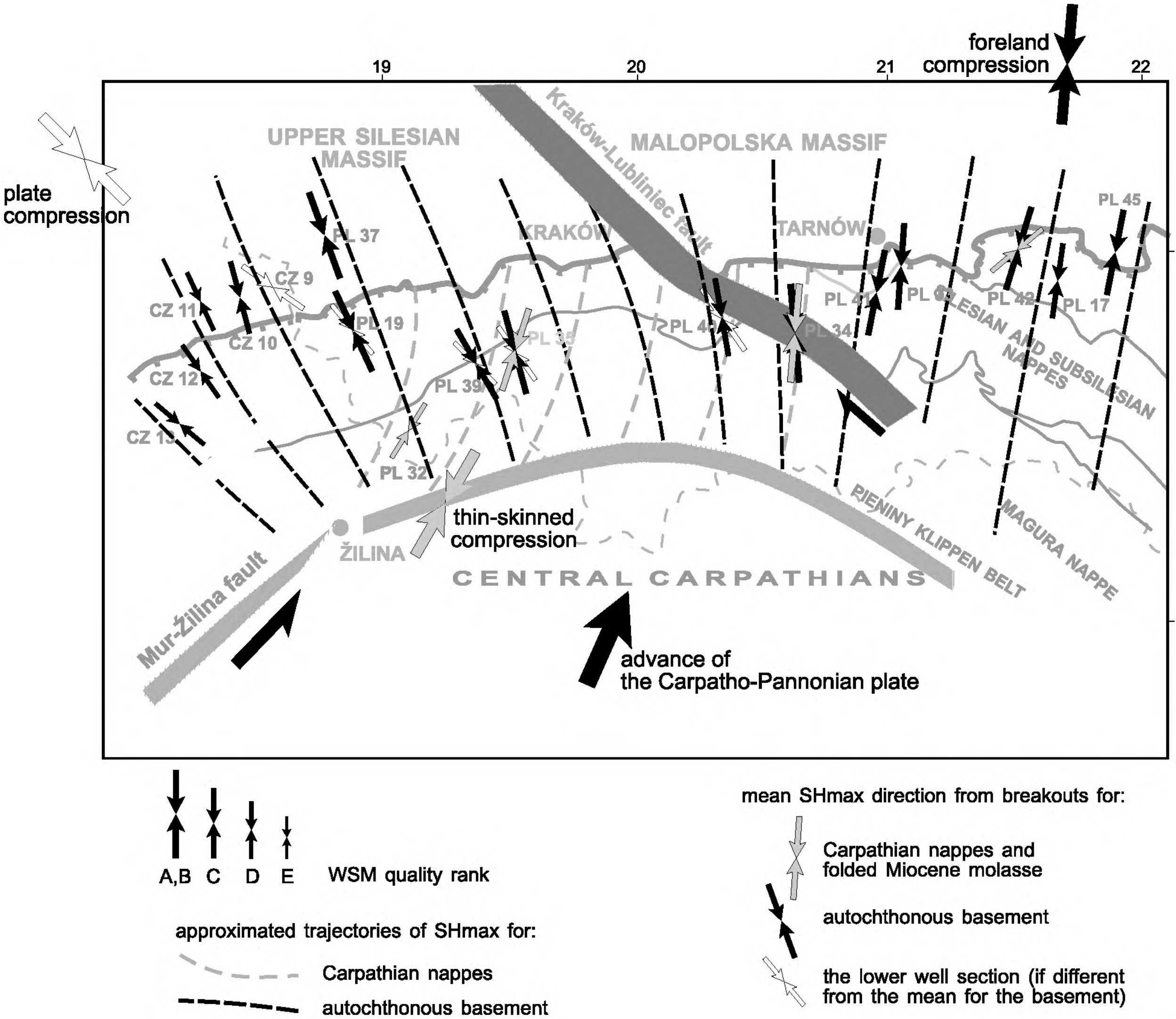

Fig. 15. Directions of S_{hmax} in the Polish Outer Carpathians and their basement. Trajectories of S_{hmax} are constructed separately for the Carpathian nappes and for their autochthonous basement. Where possible, trajectories for the lower geodynamic level are also drawn. Sizes of arrows express the World Stress Map quality rank, with A being the highest quality and E the lowest one.

6.2 Present-day tectonic stress directions

In the Upper Silesian massif domain, the most prominent feature is rotation of S_{Hmax} directions with depth and also its distortion in plane. With increasing depth, S_{Hmax} rotates systematically counterclockwise, showing quite consistent orientation within separate structural tiers (Fig. 15). For the flysch nappes, the mean NNE direction of S_{Hmax} was determined. On the contrary, for the autochthonous basement, breakouts indicate in average NNW-directed S_{Hmax}. In this basement the same sense of minor stress rotation is also detectable, thus in the deepest wellbore sections S_{Hmax} turns to be ca. NW-orientated. Although the shift of stress directions across the Carpathian decollement was directly recorded only in the well PL 35, systematic differences in stress orientations between the nappes and their basement allow us to suspect stress partitioning along the floor thrust. Maximum stress rotation between the nappes and the deepest metamorphic basement reaches 60° (well PL 35). The degree of stress rotation decreases towards the margins of the Upper Silesian massif domain. In the Carpathian foredeep basin (well PL 37), no breakout rotation was observed in the long breakout profile, down to a depth of 4 km.

In the Małopolska massif domain, stress directions were determined only beneath the flysch nappes (Fig. 15). Here, orientation of S_{Hmax} is more stable than in the Upper Silesian massif domain. For the autochthonous complex, the mean S_{Hmax} direction is limited to the narrow range of azimuths of 1–19° NE. Nevertheless, minor clockwise rotation of S_{Hmax} (in the range of error bars) from the north in unfolded Miocene molasses to NNE in the deeper basement can be detected. Considerable deviation of S_{Hmax} orientation towards the NE occurred only within folded Miocene molasse, directly below the floor thrust of the Carpathian nappes (well PL 42).

6.3 Recent geodynamic conditions

In the autochthonous complex of the Outer Carpathians, stress trajectories create radial pattern with S_{Hmax} trajectories approximately perpendicular to the suture zone located at the Pieniny Klippen Belt (Fig. 15). The mean S_{Hmax} directions change from NNE for the Małopolska Massif domain to NNW in the Upper Silesian Massif domain. Farther to the west, within the Bohemian Massif basement, breakout data suggest consequent trend of stress distortion towards the NW (Peška, 1992) (Fig. 15). The other characteristic feature of the stress field is S_{Hmax} rotation with depth and possible stress partitioning between the flysch nappes and their basement.

Both phenomena, S_{Hmax} rotation with depth and its distortion in plane, might be explained assuming interaction between three main factors:

1) plate-scale stress, which per analogies to the West European stress province is assumed to be NW-orientated (Müller at al., 1992);

2) tectonic push of the ALCAPA unit towards the NE, which is suggested by left-lateral strike-slip motion along the Mür-Žilina fault zone (Tomek, 1988) and by the first results of GPS measurements (Hefty, 1998);

3) passive buoyancy forces due to the structure of the orogen that are assumed to act perpendicularly to the trend of the arc. Due to lack of deep crustal roots beneath the Carpathians this factor is not expected to produce significant stresses.

From these assumptions the following geodynamic setting can be proposed. The ALCAPA unit advancing towards the NE pushes the Carpathian nappes, exerting NE- to NNE-orientated thin-skinned compression in the allochthonous cover of the Upper Silesian massif. Similar direction of compression can be expected in the nappes above the Małopolska massif. In contrary, the basement of the Upper Silesian massif shows significantly different, NNW or NW direction of S_{Hmax}, which can be related to the European plate compression. Such stress partitioning in the foreland plate requires weak, low friction contact between plates in the western segment of Carpathian suture. In the autochthonous sedimentary cover of the Małopolska massif basement, the N-S to NNE orientation of S_{Hmax} suggests that the basement is partially affected by the ALCAPA's tectonic push. Similar, N-S-directed S_{Hmax} was determined for the distal part of the foreland plate (Jarosiński, 2000), what excludes the passive buoyancy forces as the main source of stress deviation from plate direction. Thus, for the eastern segment of the suture resistive contact between plates is likely. According to the results of deep seismic sounding (Tomek, 1993), the Carpathian slab is steeper in the eastern segment than in the western one, what can be one of the reasons why the plate in the eastern segment resists stronger against horizontal tectonic forces.

Seismicity and recent crustal movements

Within the Polish segment of the Outer Carpathians, recent seismicity is confined to some strike-slip faults (Prochazková et al., 1978). Magnitudes of historical earthquakes do not exceed 5.0 on the Richer scale (Pagaczewski, 1972; Prochazková et al., 1978). Focal solutions are available only for the sequences of earthquakes that occurred in 1992 and 1993 in the vicinity of Krynica (Fig. 1). The focal depths were probably less than 5 km (Dębski et al., 1997), and the focal solutions point to either compressional stress arrangement with σ_1 trending NNW (Wiejacz, 1994), or to both strike-slip (indicating the N-S orientation of σ_1) and extensional stress pattern (Dębski et al., 1997).

Geodetically measured vertical crustal movements range from 0 to +1 mm/yr (e.g. Wyrzykowski, 1985; Nikonov et al., 1987). Results of recent GPS campaigns indicate a NNE direction of horizontal motions in the Polish Outer Carpathians (Hefty, 1998).

7 Conclusions

The presented pieces of structural evidence imply that during the Late Neogene (post-Pannonian?) times structural development of the Polish segment of the Outer Carpathians was largely controlled by normal faulting. This interpretation is corroborated by geomorphic data indicative of *en block* uplift of some near-surface portions of the flysch cover in the western part of the belt. However, there is no unequivocal evidence to decide whether the faulting was due to successive phases of alternating N-S and E-W extension or owing to one or more phases of multidirectional extension.

Moreover, the geomorphic data from the medial and eastern parts of the belt and fractured pebbles in the Orava Basin suggest the occurrence of compressional stress regime during Late Neogene times. It follows that during the Late Neogene the stress arrangement was differentiated depending on time and the position in the belt. We find it interesting that the stress arrangement could have been so differentiated during such a short period of time. Usually in tectonic reconstructions, tectonic phases are of longer duration and during particular phases stress arrangement is uniform within the studied area.

The Pliocene-Quaternary tectonic mobility of the Polish Outer Carpathians was relatively weak and mostly of thin-skinned character. Normal faults were formed on the margins of intramontane basins and in the western part of the belt. Rates of uplift of individual structures was variable and the amount of uplift was the greatest in the Late Pliocene and Early Quaternary times. Geomorphologically-detected zones of uplift are relatively narrow and arranged subparallel or under small angle in respect to the strike of principal thrusts and frontal parts of large slices. Such an arrangement is interpreted as resulting from the steepening of frontal thrusts due to horizontal compression within the overthrust flysch nappes. This hypothesis is confirmed by the results of recent break-out and GPS studies, as well as focal solutions of some Outer Carpathian earthquakes. En echelon pattern of the uplifted zones, slightly different in the western and eastern portions of the belt can also suggest young sinistral motions along the Kraków-Lubliniec fault zone beneath the overthrust nappes. The last conjecture, however, requires verification by future geological and geodetic studies.

The recent stress pattern indicates that the ALCAPA unit advancing towards the NE pushes the Carpathian nappes, exerting NE-to NNE-orientated thin-skinned compression in the allochthonous cover of the Upper Silesian massif. Similar direction of compression can be expected in the nappes above the Małopolska massif. On the other hand, the basement of the Upper Silesian massif shows significantly different, NNW or NW directions of S_{Hmax}, which can be related to the European plate compression.

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