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The role of neotectonics in the Quaternary evolution of the landscape of the Sowie Mts, Sudetes, southwestern Poland

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Abstract The Sowie Mts range comprises distinct morphological features that may be related to active tectonics. These are large-scale scarps up to100–200 m high, with triangular facets, at the Sudetic Marginal Fault, which separates the mountain range from its foreland; stepped morphology in the mountain interior with 100–300 m high scarps between flat surfaces; and straight, asymmetric valleys. The last two features are related to differently oriented faults. Meso-scale tectonically induced morphological features are represented by localised steepening of longitudinal valley profiles at fault lines (breaks, knickpoints), distinct downstream divergence of terraces, offset terraces, and the formation of fault scarps, basal scarplets beyond the valleys, frequent occurrence of alluvial fans and their onlap, and stream deflections at the Sudetic Marginal Fault. Apart from incipient Neogene offset, two phases of subsequent Quaternary tectonic uplift are possible. Total neotectonic uplift of the Sowie Mts range is about 100–300 m and, most probably, major tectonic activity took place during the Early Pleistocene. Late Pleistocene uplift was much less (10–40 m), although it is much better documented. The late Pleistocene tectonic activity was related to post-early Saalian glacio-isostatic rebound. Generally, the central part of the Sowie Mts was uplifted at least twice as much as the northern and southern area during each tectonic event. As a result, all geomorphic surfaces, including the flat surfaces, are deflected, and the height of the large-scale scarps, valley fault scarps, basal scarplets and knickpoints in the valley longitudinal profiles changes regionally.

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INTRODUCTION

The Sudetic Marginal Fault represents one of the main tectonic lines in the Sudetes Mts. It is about 160 km long, trending from NW to SE, and separating the mountainous region (400–1000 m a.s.l.) from its foreland (200–300 m a.s.l.). The fault plane forms a 100–600 high range front, where the fault scarp is generally degraded, but in some sectors is quite fresh, suggesting Quaternary and/or recent tectonic movements. The Sowie Mts occupies an approximately 30 km long sector near this scarp. The range front in the sector of the Sowie Mts is not only very distinct, but is at its highest (500–600 m) (Fig. 1). The greatest fault throw occurs here, estimated at a maximum of 1200–1500 m (Oberc & Dyjor, 1969). Although the tectonic zone of the Sudetic Marginal Fault developed in the Late Palaeozoic (Closs, 1922; Oberc & Dyjor, 1969), the main development and formation of the morphological scarp took place concomitant with the Late Cainozoic uplift of the Sudetes Mts (Oberc & Dyjor, 1969; Oberc, 1972, 1977). The range front first formed during the Late Oligocene/ Early Miocene (Grocholski, 1977; Dyjor, 1983a), but the main uplift phases have been referred to the Early Miocene (Dumanowski, 1961; Pernarowski, 1963), Middle to Late Miocene (Teisseyre *et al.*, 1960; Dyjor, 1983b, 1986), Late Pliocene (Oberc & Dyjor, 1969; Dyjor, 1983b, 1986) or Early Pleistocene (Krzyszkowski *et al.*, 1998; Krzyszkowski & Biernat, 1998; Przybylski *et al.*, 1998).

The relief of the Sowie Mts is very fresh. All authors describe deep, narrow, V-shaped and often asymmetric valleys that are characterized by strongly irregular longitudinal profiles (Arnold, 1938; Dumanowski, 1961; Pijet, 1991; Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski, 1994; Olejnik, 1996). These valleys cross the stepped morphology, where flat surfaces, numbering from three (Arnold, 1938; Walczak, 1972) to eight (Dumanowski, 1961) have been hitherto interpreted as Tertiary and/or Mesozoic planation surfaces. Both Arnold (1938) and Dumanowski (1961) suggested that fresh morphology and main valley incision originated during the late Tertiary or Early Pleistocene tectonic uplift. On the other hand, Dathe (1887) and Dathe & Finckh (1924) found that glacial

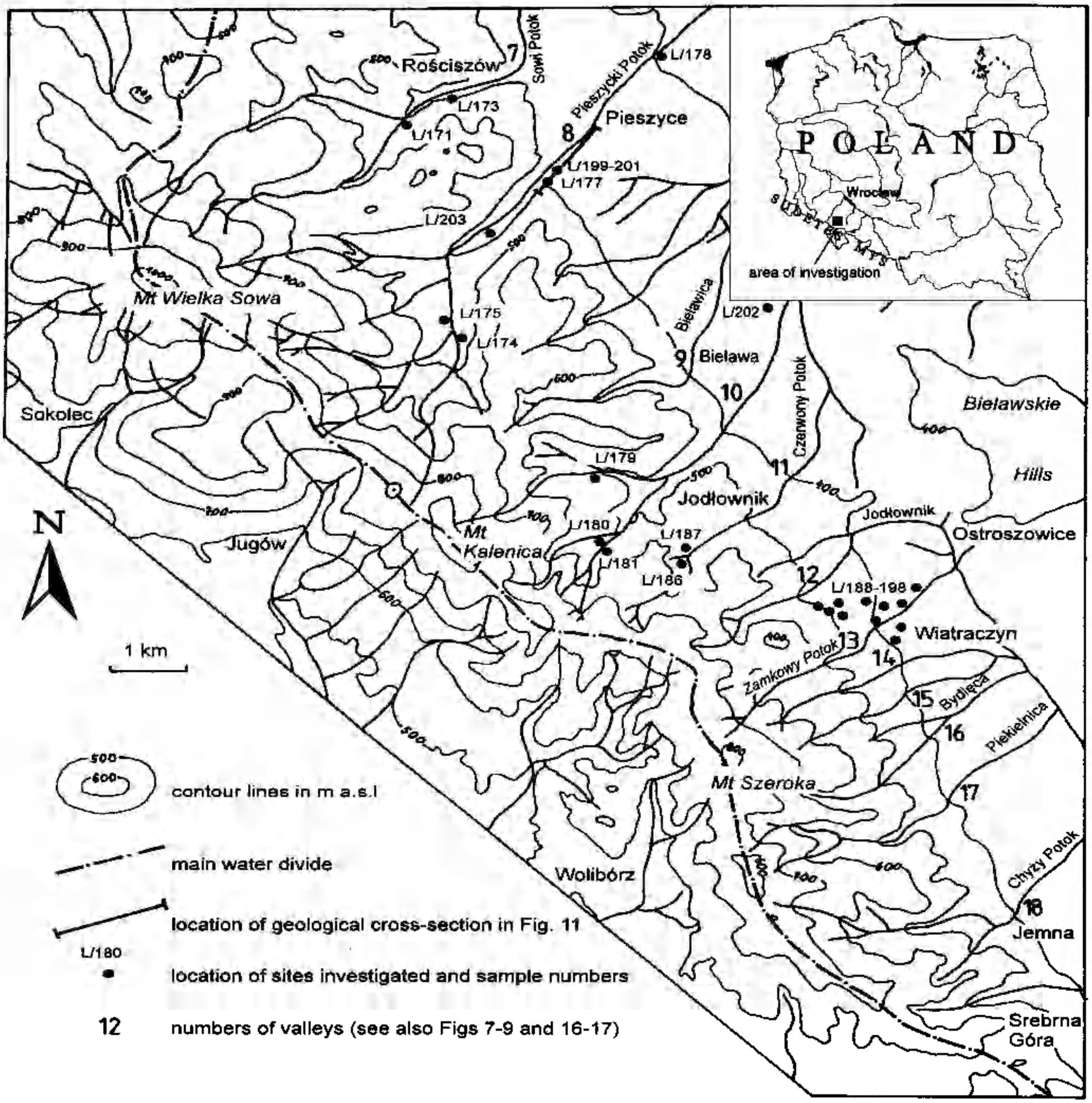

Fig. 1. Central and southern part of the Sowie Mts range. The studied area is located between the Sowi Potok and Chyzy Potok valleys and the main water divide. Valley numbers 7–18 are used consequently throughout the paper; valleys 1–6 are beyond the studied area in the northern part of the Sowie Mts.

deposits, although of limited extent, occur throughout the range front and up to 550 m a.s.l., in places even up to 700 m a.s.l. Some other authors claim much a younger age for the landscape. Zeuner (1928) suggested that the relief could have been refreshed during late Quaternary tectonic movements and he found many young tectonic features in the Nysa Kłodzka valley, about 20 km SE from the Sowie Mts range. Recently, distinct Quaternary tectonic features have been described from river valleys in the northern part of the Sowie Mts range (Pijet, 1991; Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski, 1994; Krzyszkowski & Biernat, 1998). Also, Scharzbach (1942) interpreted different altitudinal positions of glacial deposits in the Sowie Mts as a result of late Quaternary tectonic deflection of the mountain range. Minor late Quaternary tectonic activity may be inferred at least from earthquake activity, where two quakes have been recorded during historical times in the Sowie Mts front range, at Bielawa in 1894 and at Dzierżoniów in 1895 (Pagaczewski, 1972).

This paper aims to describe the morphological features of the central and southern part of the Sowie Mts range and its foreland (Fig. 1), with special attention to the evolution of the river valleys and alluvial fans. These features are attributed to the neotectonic activity of the region, as evidence of the late Quaternary fault activity has been documented in adjacent areas: in the Nysa Kłodzka river valley (Zeuner, 1928; Krzyszkowski *et al.*, 1998) and in the northern part of the Sowie Mts range, including the Bystrzyca river valley (Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski, 1994; Krzyszkowski & Biernat, 1998).

METHODS

The evidence of neotectonic movements in the Sowie Mts was documented during geomorphological and geological mapping of the valleys and alluvial fans. These investigations included measurements of the height above modern channels as well as detailed sedimentological description of deposits and petrological analyses. Superposition of terraces and fans was distinguished and compared within the key sites lying in the northern part of the Sowie Mts (Pijet & Krzyszkowski, 1994; Krzyszkowski & Biernat, 1998). Special attention has been paid to the scarps which lie near fault zones. Trenching, however, has not yet been undertaken. The analysis of longitudinal and cross-valley (fan) profiles was based on 1:25,000 scale topographic map. All marked changes in gradients of longitudinal profiles, and especially these located along the fault zones, are taken to reflect tectonic movements, rather than differential erosion, as the bedrock geology is uniform (Fig. 2A). Besides analysis of the topographic map, three morphometric maps have been constructed: slope inclination, relative relief and relief above headstream incision (Sroka, 1992). The 'relief above headstream incision' shows the height difference between the highest peaks and the highest positions of headwater erosion in drainage basins in the region. This parameter approximates to the 'belt of no erosion' of Horton (1945). High values are taken to indicate increased uplift rates (Sroka, 1992). For the other maps the increased values of the morphometric parameters indicate increased erosion. They may show also increased regional uplift, as differences of lithology and fracturing of bedrock are insignificant (Fig. 2, 3). Additionally, two parameters that describe the interaction of the fluvial system and vertical tectonic movements have been calculated for 18 river valleys, thirteen from the studied area and five from the northern part of the Sowie Mts (Pijet & Krzyszkowski, 1994). These parameters are the valley floor width/valley height ratio (V_f) and basin elongation ratio (R_e) (Bull & McFadden, 1977), where:

$$V_f = \quad V_f = \frac{V\!fw}{0.5(Eld - Esc) + (Erd - Esc)}$$

$V\!fw$ – valley floor width, Eld and Erd – altitude of the left and right divide, Esc – altitude of the valley stream; and

$$R_e = \frac{(2\sqrt{A})/\sqrt{\pi}}{L}$$

A – drainage basin area obtained by planimetric calculations from the 1:25,000 topographic map; L – distance between two most distant points in the drainage basin.

GEOLOGY

The studied area is located entirely within the Sowie Góry gneissic block. This block forms now two parts, separated by the Sudetic Marginal Fault. The southwestern part is elevated and forms the Sowie Mts range, whereas its northeastern part is downthrown and constitutes two tectonic grabens, the Roztoka–Mokrzeszów Graben (north) and a part of the Ząbkowice Graben (south) (Dyjor & Kuszell, 1977; Grocholski, 1977; Ciuk & Piwocki, 1979) with the Bielawskie Hills horst in between them (Fig. 2, 3). The local tectonic pattern comprises two systems of faults, one trending NW–SE, approximately parallel to the Sudetic Marginal Fault, and a younger system, perpendicular or diagonal to the major fault (Żelaźniewicz, 1987) (Fig. 3). Grocholski (1967) and Żelaźniewicz (1987) suggest that the Sowie Góry block plunge as a whole to the southeast, and this is exhibited also in the change of altitude of the top surface of the mountain range from about 1000 m a.s.l. in its central area to 700 m a.s.l. in its southern area (Fig. 1).

The Sowie Mts range is formed mainly of semipelitic or metagreywacke gneiss or migmatic gneiss (Polański, 1955; Żelaźniewicz, 1987), which are dated back to Upper Proterozoic–Lower Devonian (Gunia, 1981, 1985). Upper Carboniferous conglomerates occur in larger patches in the central part the mountain range, lying discordantly on gneiss and are slightly metamorphosed. Carboniferous sediments do not occur in the mountain foreland. Both conglomerates and gneiss comprise veins rocks (Grocholski, 1965; 1967; Łapot, 1986, 1988) (Fig. 2A). The Roztoka Mokrzeszów Graben comprises ca 200 m and the Ząbkowice Graben less than 100 m of Tertiary deposits. They are represented mainly by fluvial and/or lacustrine clay, silt, sand, gravel and diamictons (Dyjor & Kuszell, 1977; Ciuk & Piwocki, 1979).

The Quaternary deposits of the mountain range occur continuously in valleys as fluvial terraces but only in small patches of glacial deposits in interfluve areas. Fluvial deposits are represented by three horizons, the Upper, Middle and Lower Terraces. Their age is conventionally correlated with the late Saalian/Eemian, Middle Weichselian and the Lateglacial/Holocene (Krzyszkowski *et al.*, 1995; Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski,

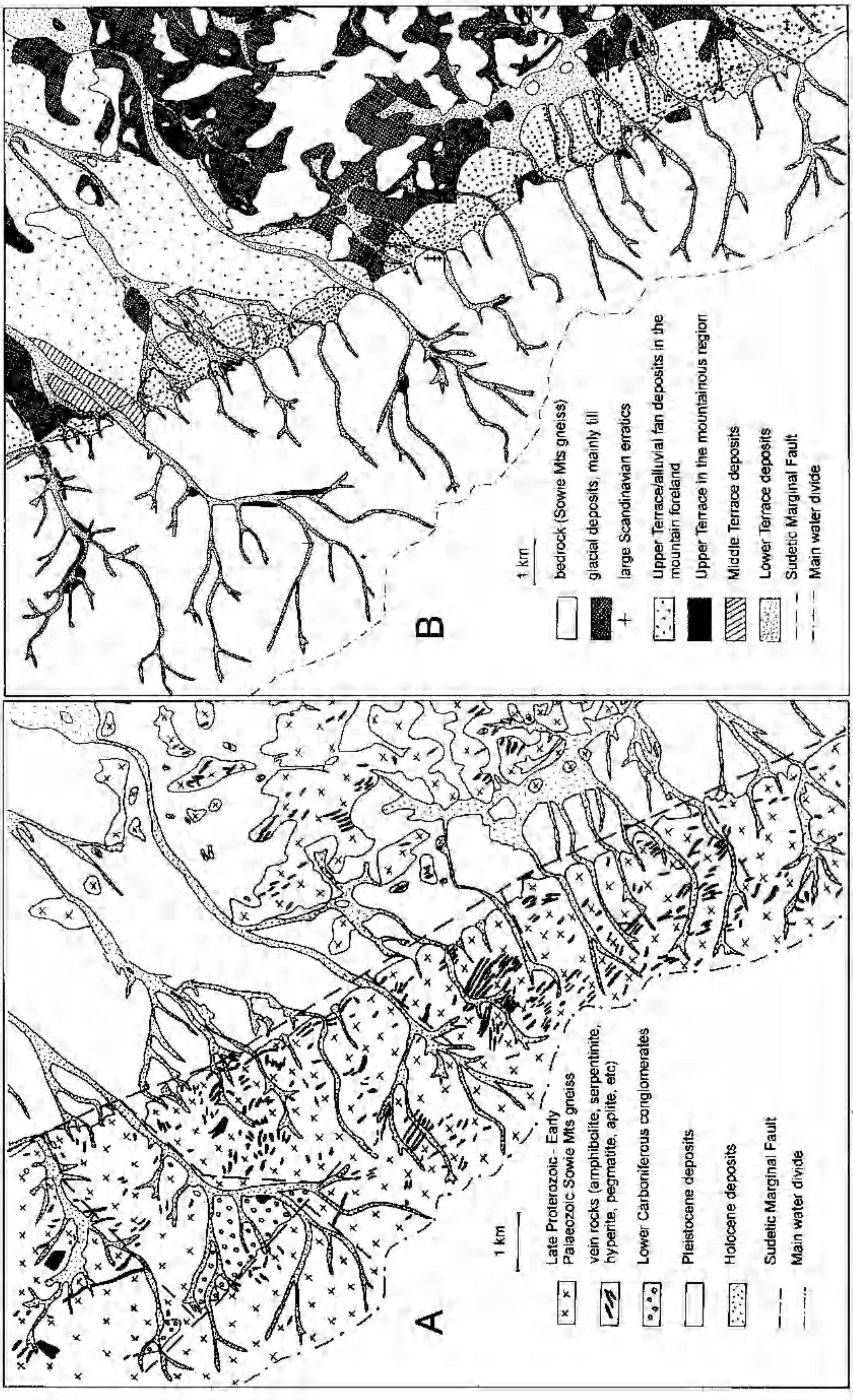

Fig. 2. Bedrock geology (A) and the Quaternary sediments (B) in the Sowie Mts and its foreland.

1994; Krzyszkowski & Biernat, 1998). The glacial deposits occur as till or glaciofluvial deposits or, often, only by erratic (Scandinavian) boulders (Dathe, 1887; Dathe & Finckh, 1924; Arnold, 1938; Schwarzbach, 1942; Trepka & Gawroński, 1957; Gawroński, 1958a, 1958b; Krzyszkowski & Pijet, 1993a, 1993b; Pijet & Krzyszkowski, 1994) (Fig. 2B), most probably deposited. during the early Saalian (Odranian) ice advance (Schwarzbach, 1942; Teisseyre *et al.*, 1960; Jahn & Szczepankiewicz, 1967; Szczepankiewicz, 1969; Walczak, 1972; Krzyszkowski & Pijet, 1993a, 1993b; Krzyszkowski *et al.*, 1995).

The mountain foreland has a more complex Quaternary sequence, with deposits up to 40 m thick in the Roztoka–Mokrzeszów Graben or 20 m in the Ząbkowice Graben (Krzyszkowski, 1993; Krzyszkowski & Ibek, 1996; Badura *et al.*, 1998). The Quaternary sequences of both graben comprise up to three tills. The uppermost till, in a sub-surface position, is early Saalian and the two other are Elsterian.The glacial deposits are interbedded partly with Middle Pleistocene fluvial gravels (Krzyszkowski, 1993, Krzyszkowski & Ibek, 1996) and are underlain in places by Early Pleistocene fluvial sediments (Krzyszkowski & Bowman, 1997; Badura *et al.*, 1998). Young fluvial deposits have an extensive outcrop (Fig. 2B), forming a set of alluvial fans near the Sudetic Marginal Fault scarp and thin alluvial veneers beyond. These young alluvial covers fill partly incised valleys and partly lie on the youngest till. Additionally, a thin cover of loess-like deposits have been observed throughout the region.

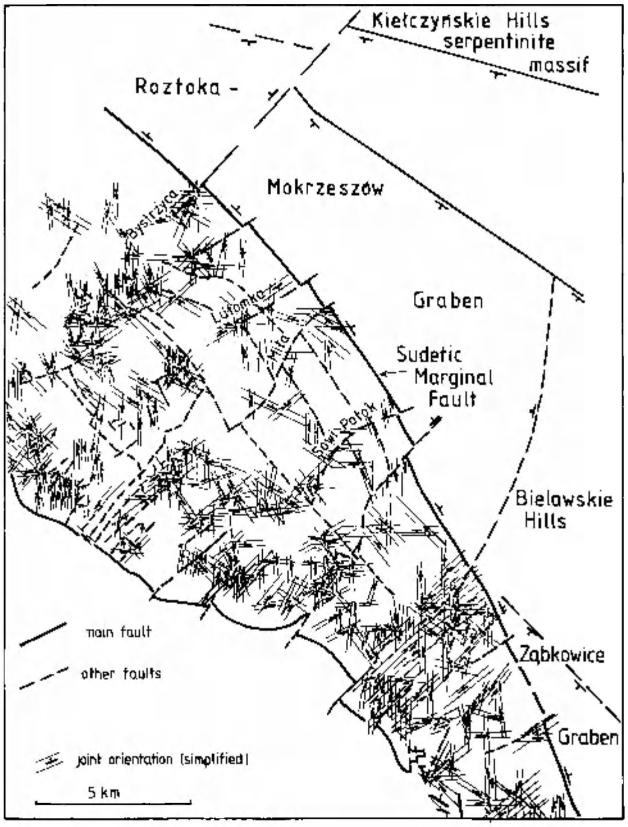

Fig. 3. Fault pattern in the Sowie Mts gneissic block (after Żelaźniewicz, 1987; updated).

GENERAL GEOMORPHOLOGY

The central and southern part of the Sowie Mts range is a 400–600 m high plateau. It reaches about 700 m a.s.l. in the south, rising to the NW and reaching a maximum altitude at 1015 m a.s.l. in its central part, and then lowering again to about 500–700 m a.s.l. in the north (beyond the studied area, *vide*: Pijet & Krzyszkowski, 1994). The foreland plain lies at 320–420 m a.s.l. The summit plateau drops down to NE, to the foreland plain, forming three distinct stepped flats. The upper flat horizon lies at 680–1000 m a.s.l., the middle one at 580–680 m a.s.l. and the lower one at 480–580 m a.s.l., separated from one another by distinct scarps (Fig. 4, 5). The scarp between the upper and middle flat horizons is 200–300 m high, whereas those between the middle and lower horizons and between the lower horizon and the foreland plain are only 100–200 high. The last forms the morphological scarp of the Sudetic Marginal Fault. The upper horizon forms a flat, continuous, 1–2 km wide surface in the summit area of the mountain range (Fig. 4). Another two flat horizons have more restricted occurrences, being preserved in watershed ranges between valleys. However, they occur continuously along the mountain range, except two fragments in the upstream segments of the Pieszycki Potok and Bielawica valleys (middle flat horizon) and the other two zones between the Pieszycki Potok and Bielawica valleys and the Jodlownik and Zamkowy Potok valleys (lower flat horizon) (Fig. 4). The characteristic feature is the consequent rise to the NW of all the flat horizons as well as the rise of the height of scarps between them (Fig. 4). This tendency is reversed north of the Sowi Potok valley (*vide*: Pijet & Krzyszkowski, 1994).

The mountain plateau is incised by several narrow, deep, 1–6 km long valleys. Several of them have straight courses and slope asymmetry in the valley segments close to the Sudetic Marginal Fault. Two valleys, of the Pieszycki Potok and Bielawica, have very wide, triangle-shaped 'basins' in the upstream courses. A tectonic origin of the 'basin' in the Pieszycki Potok valley is confirmed by the occurrence of Lower Carboniferous conglomerates (Fig. 2A). The main river valleys of the Sowie Mts range, such as the Sowi Potok (Rościszów), Pieszycki Potok (Pieszyce), Bielawica (Bielawa), Jodłownik and Piekielnica are located along SW–NE trending faults (Fig. 3); other valleys may follow this pattern also.

The typical inclination of valleys slopes and scarps in the studied area is 15–30°, whereas the flat horizons, especially the summit one, incline between 2–5°. The valley bottoms and the foreland plain have slope inclination below 5°, except the Bielawskie Hills, where the slope inclination may reach locally up to 15° (Olejnik, 1996). Unusu-

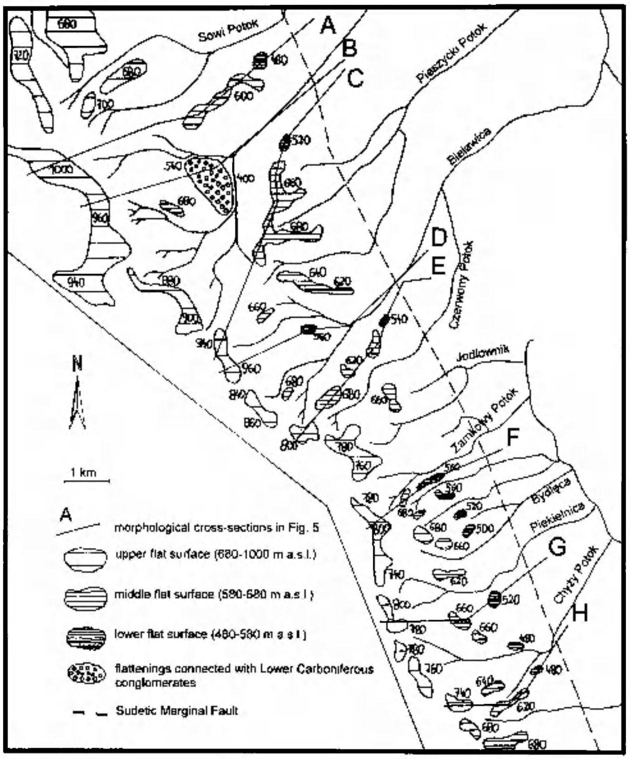

Fig. 4. Sequence of flat surfaces and their altitude in the Sowie Mts; note a systematic altitude change of individual levels. A-F - location of cross profiles in Fig. 5.

ally steep slopes (30–45°) have been observed in the asymmetric valleys that are located along the faults. These steep slopes may represent the fault-related slopes.

The maps of relative relief and of relief above headstream incision highlight the stepped morphology of the mountain range (Fig. 6). Both maps, although very complex in detail (Olejnik, 1996), generally show two alternating belts with low and high parameter values. The zones with low values correlate generally with the middle and upper flat horizons, and zones with high values, most probably, coincide with the scarps between flat horizons. Also, two additional zones with high values of the relative relief occur along the Sowi Potok and between the Jodlownik and Zamkowy Potok valleys. The upper courses of the Pieszycki Potok and Bielawica valleys are characterised by surprisingly low values of relief above the headstream erosion. The lower flat horizon is poorly defined in the morphometric maps, especially that of relief above headstream incision. This is probably because of the small area of the individual flattenings.

VALLEY MORPHOLOGY

More than 20 valleys occur in the central and southern part of the Sowie Mts range, located between the Sowi Potok valley in the north (Rościszów) and the Chyży Potok in the south (Jemna) (Fig. 1). Three of them, the Sowi Potok, Pieszycki Potok and Bielawica, are large valley systems, with drainage basin areas between 8.0–16.3 km^2 and the length of the main valley at least 4–5 km. The other valleys are much much shorter (< 3.5 km), with drainage basin areas between 0.15–4.1 km^2. Thirteen mountain valleys have been examined in detail, including all the large valleys systems.

Sowi Potok Valley

The Sowi Potok valley is 6.1 km long. Its longitudinal profile is highly irregular, with distinct breaks (Fig. 7). The first break occurs 5 km and the next, 3.5 km upstream from the Sudetic Marginal Fault. The last break occurs near this tectonic zone. The average valley gradient is about 8%, which increases in the break zones up to 11.2%; the valley gradient in the mountain foreland is only 3%. The valley changes its shape, from V-shaped in the upstream segment, to the box-shaped in its lower reaches and simultaneously increases its width from a few metres to 170 m near the Sudetic Marginal Fault (Fig. 7).

The valley has a well preserved terrace system, which includes three fluvial horizons. The Upper Terrace occurs throughout the valley and indicates distinct divergence, with a terrace height 5–6 m above the channel in the mountain inerior, increasing throught 10–12 m to 16 m near the Sudetic Marginal Fault (Krzyszkowski & Pijet, 1993; Pijet & Krzyszkowski, 1994). The Middle Terrace occurs only in the wide valley segment near the Sudetic Marginal Fault and is 2–3 m high. The Lower Terrace (floodplain) occurs throughout the valley and it is 1–2 m high. The Upper and Middle Terraces are rock terraces and the Lower Terrace has a cut and fill structure.

Pieszycki Potok valley

The Pieszycki Potok valley is 6.5 km long. Its longitudinal profile is also irregular (Fig. 7). However, only two breaks have been observed. The first occurs 4 km upstream from the Sudetic Marginal Fault and the other within this tectonic zone. The average valley gradient is about 6%, which increases in the break zones up to 8.5%; the valley-gradient in the mountain foreland is 2.5%. The upper break zone is characterized additionally by a rock channel and rapids. The valley changes its shape, from V-shaped in the upstream segment to box-shaped in its lower reaches. The valley width does not exceed 70 m at the begining, and increases rapidly to about 500 m in the zone cut into Carboniferous conglomerates, forming an extensive basin (Fig. 2). The lowermost, straight segment of the valley, although box-shaped, is much narrower than the basin (200 m).

The valley consists of three terraces. The 3 m high Upper Terrace occurs in the upstream segments of the valley, including a wide basin with Carboniferous conglomerates. Downstream, this terrace disappears, and only a 20 m high shelf on the left side of the valley that occurs near the Sudetic Marginal Fault may represent the Upper Terrace. However, this 5–10 m wide shelf is covered by more than 1 m of colluvium, and fluvial gravels have not been found, yet. The Middle Terrace occurs only in the zone near the Sudetic Marginal Fault. It forms a 200–300 m wide and 10 m high shelf on the right side of the valley (Fig. 2B). The Lower Terrace (floodplain) occurs through-

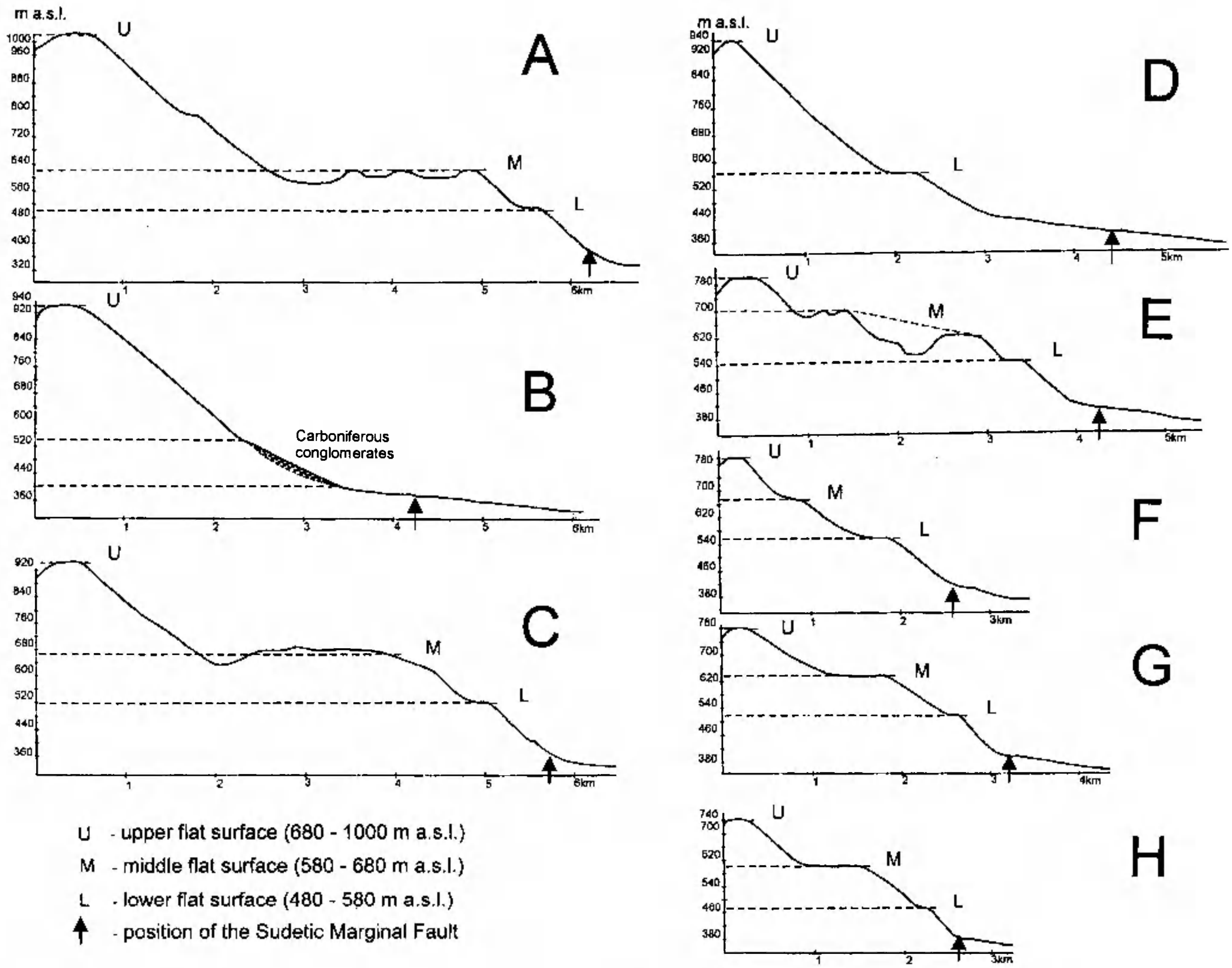

Fig. 5. Cross profiles along the watershed ranges showing the position of flat surfaces. Location of profiles in Fig. 4.

out the valley and is 1–2 m high. The Upper and Middle terraces are rock terraces and the Lower Terrace is a cut and fill structure.

Bielawica valley

The Bielawica valley is 4.5 km long. Its longitudinal profile is highly irregular, with three distinct breaks (Fig. 7). The first break occurs 3.5 km and the next 2 km upstream from the Sudetic Marginal Fault. The last break occurs near this tectonic zone. The average valley-gradient is about 9%, which increases in the break zones up to 14%; the valley gradient in the mountain foreland is only 3.6%. The valley changes its shape in similar manner to the other large valleys. The V-shaped segment of the valley is several metres wide, and it widens below the first break, forming a box-shape, 120 m wide basin. The straight segment in the lower reaches of the valley is much narrower (70 m). The valley again becomes wide (200 m) near the Sudetic Marginal Fault zone (Fig. 7).

Only two terraces occur in the Bielawica valley: the Upper and Lower Terraces. The Upper Terrace occurs in the upstream segment of the valley and its height is about 3 m above the channel. Downstream, this terrace disappears and only a 20 m high shelf appears on the left side of the valley near the Sudetic Marginal Fault. This 10 m wide shelf is covered by more than 1 m of colluvium, and no fluvial gravels have been found. The Lower Terrace occurs throughout the valley and is 1.0–1.5 m high.

Small valleys

Ten small valleys, with lengths between 1.8 and 3.5 km, can be subdivided into two groups: those with two breaks in their longitudinal profiles and those with only one break (Fig. 8, 9). The latter is characteristic for very small valleys (Tartaczny Potok, Szklany Potok; length < 2 km; Fig. 1). The break occurs near the Sudetic Marginal Fault zone (Fig. 8). Other valleys have a similar break in the Sudetic Marginal Fault zone, and an additional one, 1.0–1.5 km upstream (Fig. 9). The valley gradient is usually between 6–12%, but increases to 12–17.5% in the break zones; the valley gradients in the mountain foreland are between 4–8%. The valley shapes follow the same pattern as in the large valleys (Fig. 8, 9).

Usually, the small valleys have only the Lower Ter-

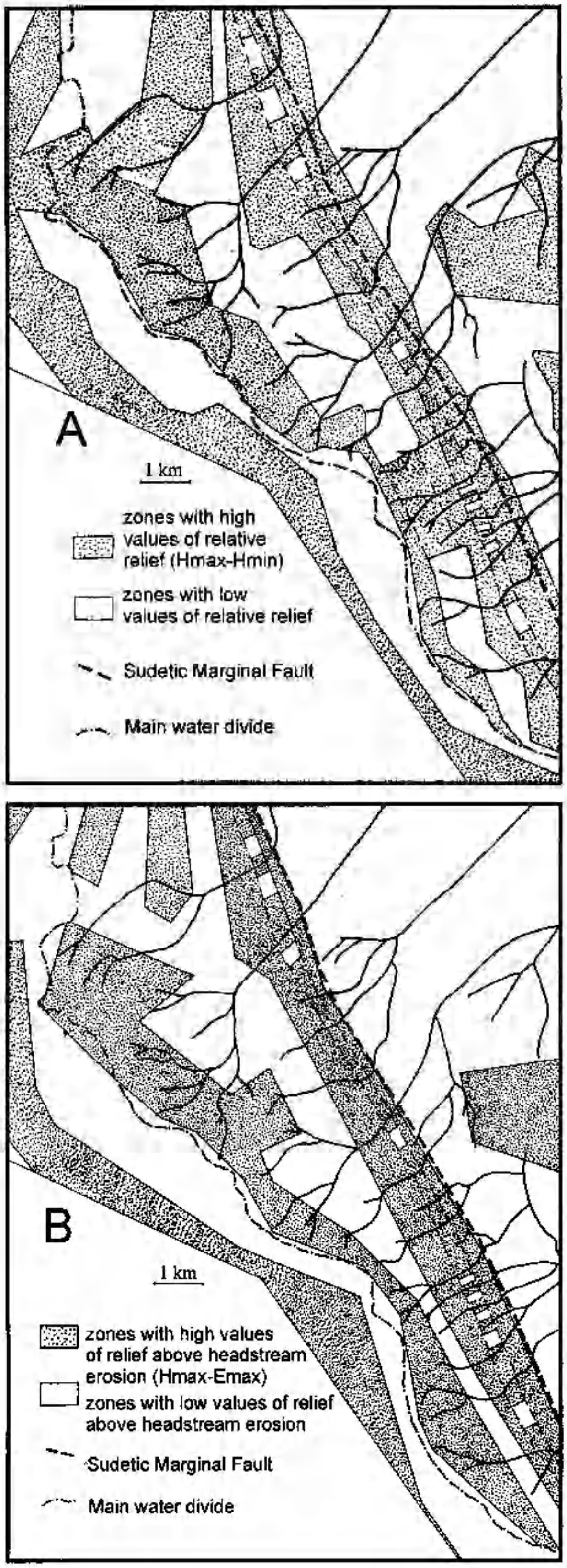

Fig. 6. Generalized maps of relative relief ($H_{max} - H_{min}$) (**A**) and of the relief above headstream incision ($H_{max} - E_{max}$) (**B**). Original measurement points used for calculation are in the middle of $1km^2$ quadrangle (Olejnik, 1996); H_{max} – the highest altitude in the quadrangle, H_{min} – the lowest altitude in the quadrangle, E_{max} – the highest altitude of erosional features (headwater erosion) in the quadrangle.

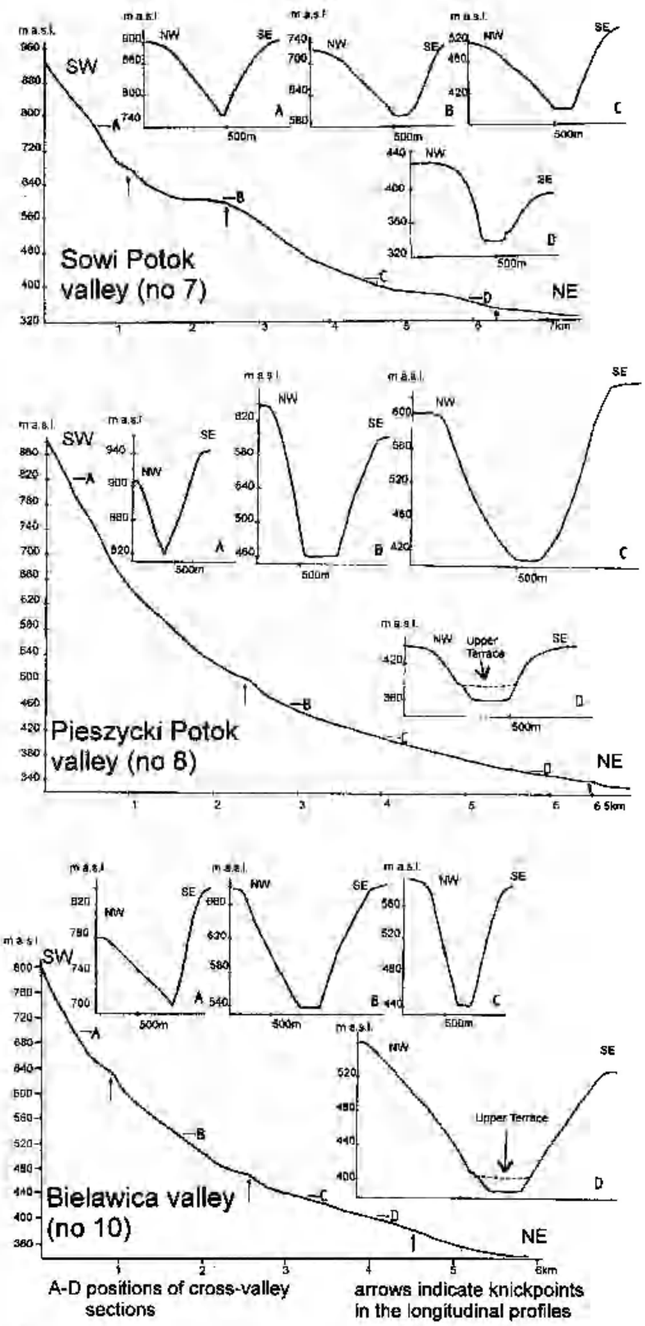

Fig. 7. Longitudinal and cross-valley profiles of the Sowi Potok (7) (upper), Pieszycki Potok (8) (middle) and Bielawica (10) (lower) valleys in central part of the Sowie Mts range.

race (floodplain). Older terraces occur only in two valleys: Czerwony Potok and Bydlęca (Fig. 1, 2B). In the first there is a 3 m high shelf with gravels in the upstream reaches of the valley which may correlate with the Upper Terrace, similarly to Upper Terraces in large valleys. In the Bydlęca valley, there is a 10 m high and 100 m wide shelf near the Sudetic Marginal Fault (Fig. 2B), that may represent the Upper Terrace, but fluvial gravels have not been found. The shelf is covered by at least 1.5 m of fine-grained (loess-like) colluvium.

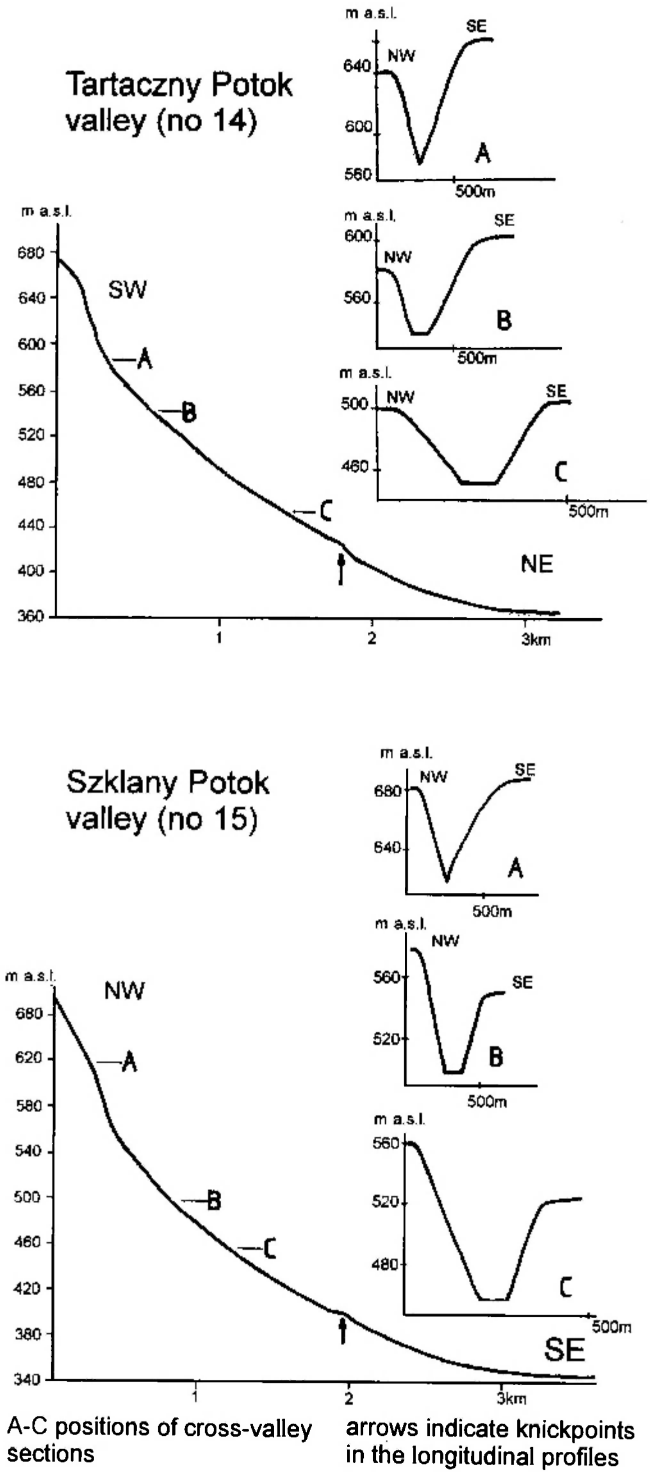

Fig. 8. Longitudinal and cross-valley profiles of the Tartaczny Potok (14) (upper) and Szklany Potok (15) (lower): examples of small valleys with only one knickpoint in the longitudinal profile.

SUDETIC MARGINAL FAULT SCARP

The escarpment of the Sudetic Marginal Fault in the central and southern part of the Sowie Mts range is a typical example of degraded fault scarp (Krzyszkowski *et al.*, 1995; Migoń, 1995). The base of the scarp has receded only 50–200 m from the fault line, and between Pieszyce and Bielawa it is located directly on the fault (Fig. 2). Also, triangular facets are preserved in various fragments of the escarpment. Four other features observed on the scarp can be related to tectonic morphology, these are: 1. systematic changes of altitude of the base and height of the escarpment, 2. the occurrence of basal scarplets, 3. the occurrence of fault scarps truncating the Upper and Middle Terraces, and 4. deflection of streams at the fault line.

The base of the escarpment lies at 320 m a.s.l. near Rościszów and systematically increases to the south until Jodlownik, where it lies at 460 m a.s.l. (Fig. 1). Further southwards, it decreases and near Jemna lies at 360 m a.s.l. Simultaneously, the escarpment fragments change their height from 160 m, through almost 200 m to 120 m. It is clear, that the highest position of the escarpment base and the highest scarp occur between Pieszyce and Jodłownik (Fig. 1). This is most probably due to increased uplift (Oberc & Dyjor, 1969), and is also marked by the shallow bedrock in mountain foreland (Bielawskie Hills horst) (Fig. 2A).

Several fragments of the escarpment are characterised by an increase of slope inclination in their basal parts, which may be interpreted as basal scarplets formed due to fault activity. The best example has been documented near Rościszów. The measurements have shown that the upper slope is inclined at about 18° whereas its lowest segment is up to 29° and the highest inclination values are observed in the most basal part of the slope (Fig. 10). The colluvial fan below the slope is inclined below 15°.

Other fault scarps have been observed in river valleys. The Upper Terrace of the Sowi Potok valley is truncated along the Sudetic Marginal Fault. The height difference between the equivalent fluvial horizons in the mountains (Upper Terrace) and the alluvial fan in the mountain foreland is about 15 m. The scarp inclination is about 14° and the inclination of the alluvial surfaces is less than 6° (Fig. 10). A very similar scarp has been observed in the Pieszycki Potok valley, where the Middle Terrace is truncated. This scarp is only 7 m high, but slope inclination is almost the same: 14° (scarp) and less than 5° (alluvial surfaces) (Fig. 10). It seems likely, that the relatively gentle slope of the fault scarps are due to scarp degradation and deposition of colluvium in a humid climate. The tectonic origin of the fault scarp in the Pieszycki Potok valley is confirmed by geological data. The height difference between the base of Middle Terrace fluvial gravels in sections and boreholes lying on top of the scarp and and at its base is about 10–12 m (Fig. 11).

Deflection of streams at the fault line has been described in detail by Migoń (1993). Several streams are deflected to N and NW (Fig. 1, 2B) and the deflection angle varies from 90° (Sowi Potok) to 65° (Piekielnica). How-

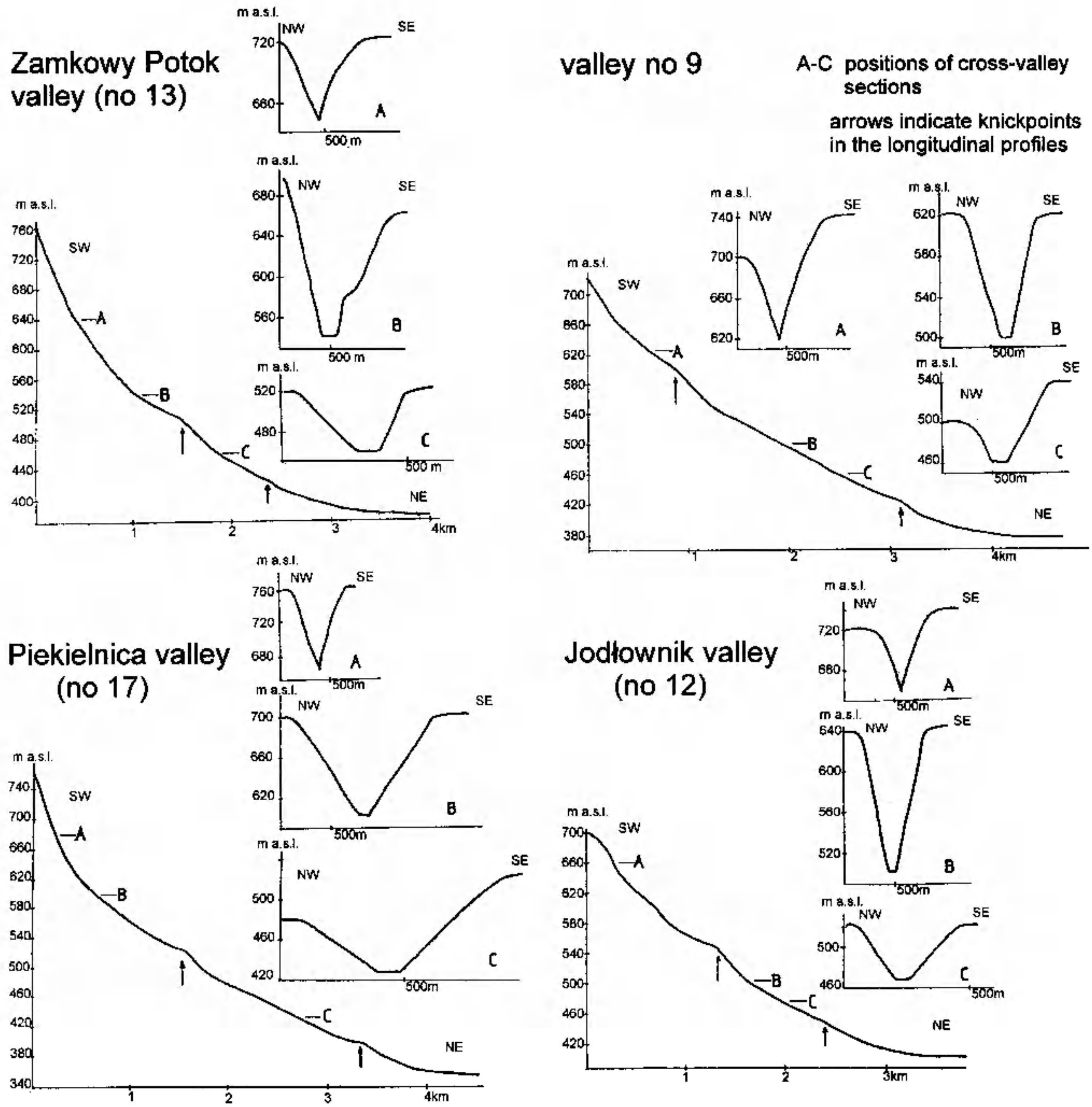

Fig. 9. Longitudinal and cross-valley profiles of the unnamed stream (9) (upper left), Jodłownik (12) (lower left), Zamkowy Potok (13) (upper right) and Piekielnica (17) (lower right): examples of small valleys with two knickpoint in the longitudinal profile.

ever, some streams are not deflected and other are deflected in other directions, even to SE. Migoń (1993) has interpreted this ambiguous pattern as a result of differentiated vertical uplift of separate tectonic blocks in the Sowie Mts range and its foreland.

ALLUVIAL FANS

Well developed alluvial fan morphology is visible along the Sudetic Marginal Fault scarp in the Sowie Mts range. The fans occur continuously along the escarpment, except for a small area near Jodłownik (Fig. 2B). Such common occurrence of fans may suggest strong tectonic activity in the region (Bull, 1977; Blair & McPherson, 1994). Generally, two types of fan, the large and small, can be found.

The large fans (area 15–19 km^2) are connected with the large valleys: Sowi Potok, Pieszycki Potok and Bielawica.

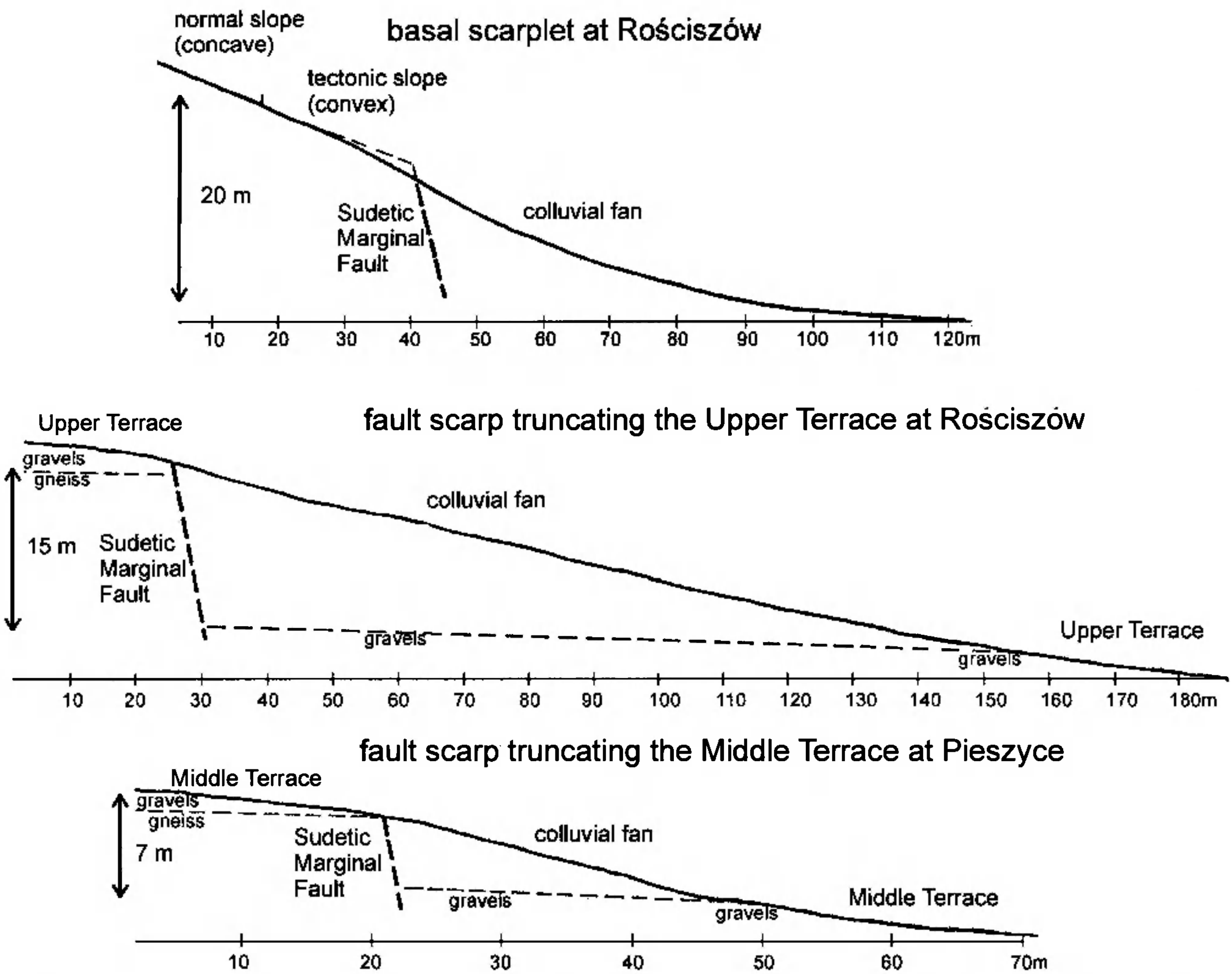

Fig. 10. Longitudinal profiles along the basal scarplet at Rościszów and faults scarps in the Upper (Rościszów) and Middle (Pieszyce) Terrace horizons. Measurements have been taken every 1 m in the field using the clinometer.

Besides having a large area, they are characterized by an elongated shape (width: 1.5–2.5 km, length up to 8 km) and a poorly developed apex. Also, the usual plano-convex shape is not clearly visible. The gradient of the fan surface is regular. Is is inclined about 4° (Fig. 12). The fan deposits are superposed on older deposits, mainly the till, and form a gravel veneer only 1–5 m thick. The original surface of these fans, which may correlate with the Upper Terrace of the montainous area, is locally incised to a depth of 10–15 m, and the Middle and/or Lower Terrace deposits fill these incision (Fig. 12). The small fans (area 0.4–4.0 km^2) have formed at the mouths of small valleys (Fig. 2B). They have a typical fan morphology, with radial shape, plano-convex cross profile, concave longitudinal profile, relatively steep gradients (6–10°) and well developed apices (Fig. 13). The total lenght of these fans is only up to 2.0 km and their width varies from 0.5 to 2.0 km. The thickness of alluvial deposits is not known, but is assumed to be up to 50 m. The alluvial gravels most probably lie on glacial deposits (Fig. 2B). The fan surfaces are commonly incised, forming 50–150 m wide channels of the modern rivers (Fig. 2B, 13).

A more complex development of a small fan has been documented at Wiatraczyn (Zamkowy Potok valley) (Fig. 14). This fan is formed of three distinct segments, presumably representing three episodes of the fan erosion and accumulation. The 'upper' fan is preserved in the SE zone; its surface is the steepest, on average 8–10°, and the cross profile is plano-convex. The 'middle' fan lies a few metres lower and occupies the central zone. It is also plano-convex, but the slope reduces to 4–8°. Additionally, at the boundary of these two fans, there is 20 m wide and 5 m deep erosional channel (Fig. 14). It may represent a remnant of distributary channel from the time of accumulation of the middle fan. The youngest, 'lower' fan fills a 50 m wide and about 10 deep channel that occupies the NW zone of the fan. This channel is partly occupied by modern river and its slope is 2–4°.

From the above it follows that both the large and small fans were formed during three accumulation phases separated by erosion. It seems likely that the main accumulation phase is connected with the formation of the 'upper' fan, correlative with the Upper Terrace. The 'upper' fans were, most probably, formed during continuous and strong uplift (onlap), whereas the younger fans/terraces indicate a subsequent diminishing of tectonic activity (of-

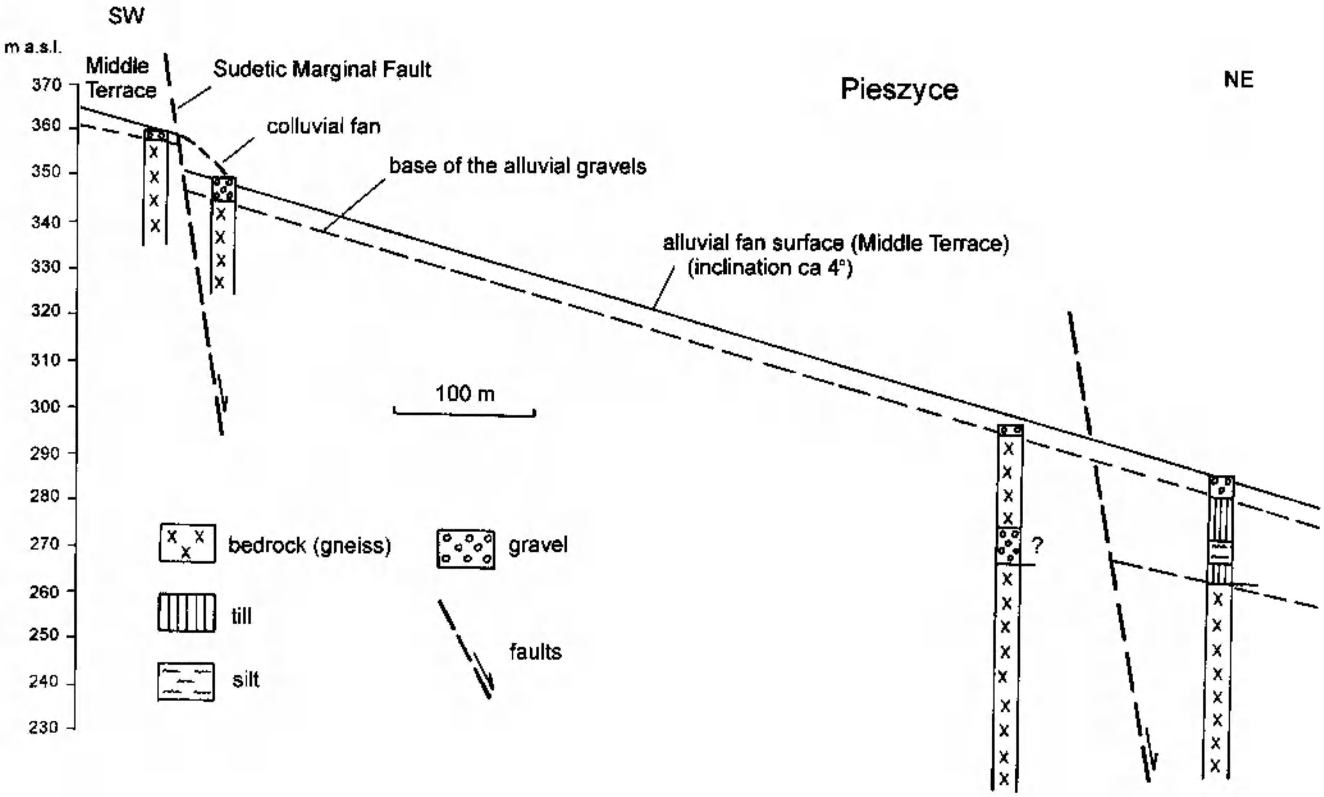

Fig. 11. Geological cross section along the Middle Terrace/fan at Pieszyce; note a displacement of the base of fluvial deposits along the Sudetic Marginal Fault.

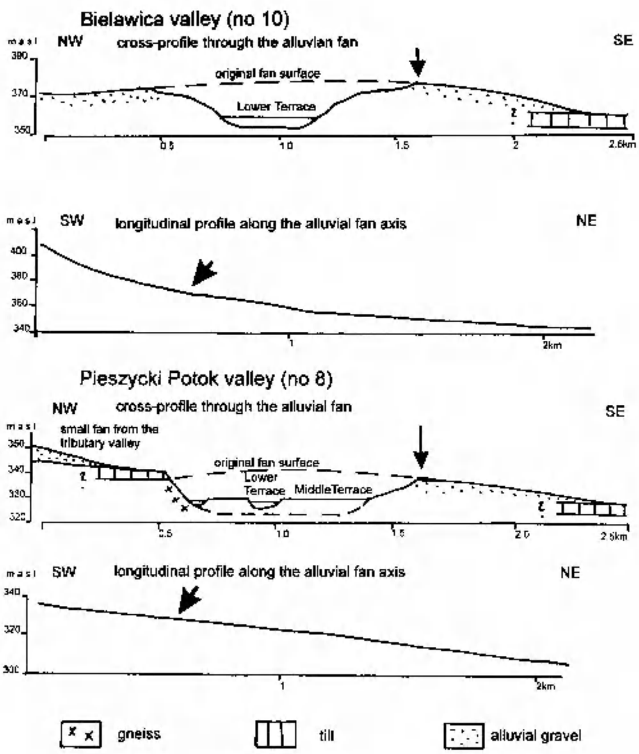

Fig. 12. Longitudinal and cross profiles throughout the large fans at Pieszyce (upper) and Bielawa (lower).

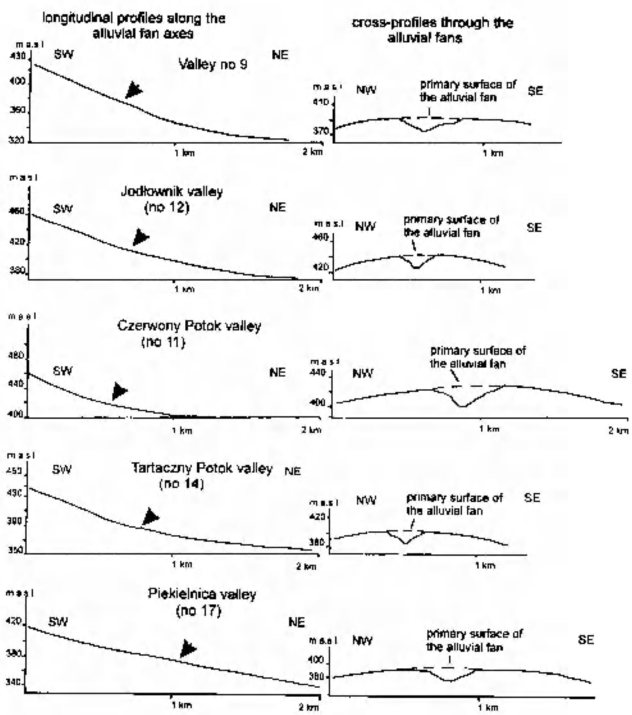

Fig. 13. Longitudinal and cross profiles throughout the small fans: examples include fans with the most dissected recent/Holocene channels.

flap). The large fans developed laterally, forming thin but extensive alluvial veneers and the small fans aggraded vertically, with limited lateral extent. These differences seems to reflect the river palaeohydrology, as small fans occur throughout the escarpment, their size depending on that of the valley/drainage basin in the mountainous region (Fig. 2B).

FLUVIAL DEPOSITS: LITHOLOGY AND PETROGRAPHY

Fluvial deposits in the mountainous region have been described sedimentologically and sampled at several sites (Fig. 1). The surficial deposits of the alluvial fans have been described mainly from Wiatraczyn (all fan levels) and from Bielawa (Lower Terrace) and Pieszyce (Middle Terrace). The fluvial deposits of all stratigraphic horizons are very similar, with subrounded to rounded, massive, matrix-poor, imbricated gravels. The gravel fraction is from 60% to 84%, where cobbles may reach up to 50%. The largest clasts reached 0.5 m in diameter, though are usually 0.2–0.3 m. The matrix is sandy. The mean size of fluvial gravels varies from –1.3 to –2.5 ϕ while sorting ranges from 2.0 to 2.6 ϕ. The fluvial gravels are often covered by coarse-grained slope colluvium (Middle and Upper Terrace) and by alluvial diamictons and/or loess-like deposits (Middle and Lower Terraces).

The petrographic composition of the fluvial gravels is more variable (Tables 1, 2). The Upper Terrace of the mountainous region is characterised by the occurrence of almost only local rocks, mainly gneiss; Scandinavian erratics are rare (Table 1). Also, the Middle and Lower Terraces generally contain less gneiss, more other local rocks, more quartz and more Scandinavian erratics (Table 1), though individual samples from these terraces may not contain Scandinavian rocks. The petrographic composition of the alluvial fan gravels follows the same pattern (Table 2). Similar features have been documented for alluvial deposits in the northern part of the Sowie Mts (Pijet & Krzyszkowski, 1994). The Sudetic porphyry and quartzite, found in the Middle and Lower Terrace/fans, must be interpreted as erratics, in the same way as the Scandinavian

Table 1

Petrographic composition of gravels of the fluvial terraces of the central and southern part of the Sowie Mts range (fraction 10–35 mm)

Sites Sample No.	Local rocks (%)							Snadinavian rocks (red granitoids) (%)
	Sowie Mts gneiss	pegmatite, aplite	amphibolite	quartz	Sudetic porphyry	quartzite	other rocks	
Upper Terrace								
Rosciszów L/171	100	–	–	–	–	–	–	–
Rosciszów L/173	100	–	–	–	–	–	–	–
Kamionki L/174	98	–	0.7	1.3	–	–	–	–
Kamionki L/175	98	–	1.6	–	–	–	–	0.4
Bielawa L/179	89	–	9	2	–	–	–	–
Bielawa L/180	89	5	1	5	–	–	0.3	–
Bielawa L/181	97	3	–	–	–	–	–	–
Jodłownik L/186	83	1	–	9	–	–	–	–
Middle Terrace								
Pieszyce L/177	78	1	1.6	10	2	1.1	0.4	6
Pieszyce L/199	95	1.4	0.6	2.2	–	–	–	0.9
Pieszyce L/200	73	3.1	3.5	15	0.4	3	–	2
Pieszyce L/201	99	0.6	–	–	-	–	0.4	–
Lower Terrace								
Kamionki L/203	74	3.3	2.2	12.1	–	–	5.6	3.2
Jodłownik L/187	87	5	5	3	–	–	–	–
Pieszyce L/178	74	2.2	7	9	–	1.2	0.3	6.3
Bielawa L/202	88	2.5	4	2.5	1	–	–	2

rocks.

Table 2

Petrographic composition of gravels of the alluvial fan at Wiatraczyn, the southern part of the Sowie Mts (fraction 10–35 mm)

Sites Sample No.	Local rocks (%)						Snadinavian rocks (red granitoids) (%)
	Sowie Mts gneiss	pegmatite, aplite	amphibolite	quartz	Sudetic porphyry	quartzite	
'upper' fan							
Wiatraczyn L/189	90	3	3	4	–	–	–
Wiatraczyn L/194	89	1	8	2	–	–	–
Wiatraczyn L/195	86	1	6	7	–	–	–
Wiatraczyn L/196	90	2	7	1	–	–	–
Wiatraczyn L/197	83.5	–	–	–	–	–	–
'middle' fan							
Wiatraczyn L/188	93	–	2	5	–	–	–
'lower' fan							
Wiatraczyn L/190	76.2	1	5.2	10.5	4.1	0.5	2.5
Wiatraczyn L/191	83	–	8.2	4	–	2.4	2.4
Wiatraczyn L/192	95.4	–	2	2	–	–	0.6
Wiatraczyn L/193	86	1	11	1	1	–	–
Wiatraczyn L/198	62.1	3	21	4.2	8.3	–	1.4

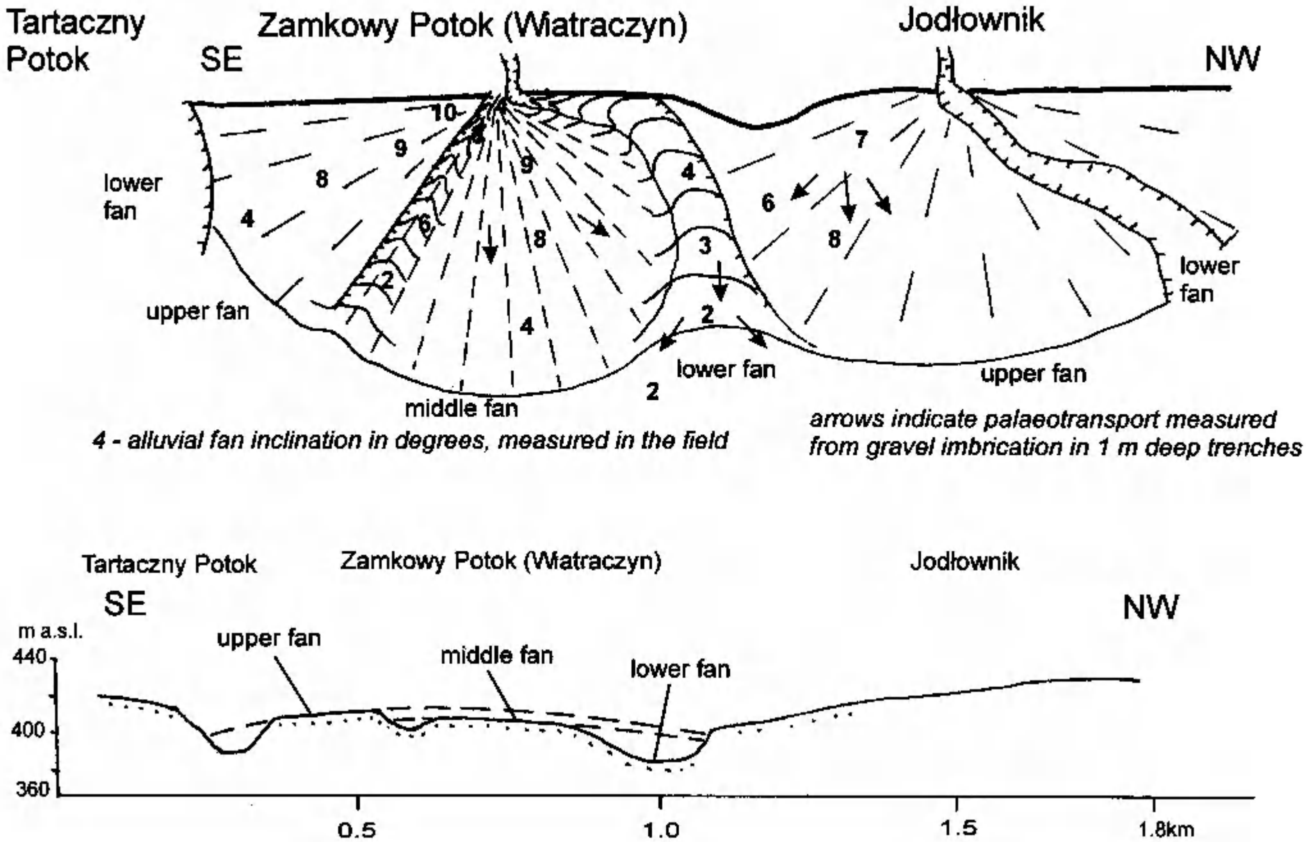

Fig. 14. The small alluvial fan at Wiatraczyn: the map shows three generations of fans, the 'upper', 'middle' and 'lower', and their extents and slope inclinations. Arrows indicate fluvial palaeotransport measured in the imbricated gravels from the uppermost 1 m of the sequence (trenches). Below: longitudinal and cross profiles throughout these fans.

rocks. These rocks occur originally only in the Nysa Kłodzka (20 km to the south) or Bystrzyca river systems (15 km to the north) (Krzyszkowski *et al.*, 1998; Krzyszkowski & Biernat, 1998), and could have been incorporated into fluvial deposits of the Sowie Mts via glacial environment, *i.e.* due to glacial erosion of old alluvial fans and redeposition of tills/glaciofluvial deposits. Indeed, Krzyszkowski & Pijet (1993) have described the till in the northern part of the Sowie Mts range, in the Miła valley (4 km north of the Sowi Potok valley), which comprises, among others, 7.5% of the Scandinavian material and 11% Sudetic porphyries.

TECTONIC RELIEF OF THE SOWIE MTS RANGE: A DISCUSSION

Some landscape features of the Sowie Mts are undoubtedly of tectonic origin (Summerfield, 1987). These are, first of all, the triangular facets at the front of mountain range, the stepped morphology, with benches and intervening scarps parallel to the Sudetic Marginal Fault (Fig. 4, 5), and the straight and asymmetric valleys that are related to transverse faults (Fig. 2, 3). The three flat horizons may represent fragments of a once continuous surface differentially uplifted along a series of NW–SE trending faults (Krzyszkowski & Pijet, 1993a). Furthermore, the varying altitude of benches belonging to any one flat horizon may reflect differential uplift of tectonic blocks separated by transverse faults. All these features were probably initiated during one tectonic episode. This view contradicts former ideas, where stepped features have been interpreted as reflecting episodic uplift and scarp retreat in a humid conditions during the Neogene and valley asymmetry as reflecting Quaternary periglacial conditions (Dumanowski, 1961; Walczak, 1972; Jahn, 1980).

Additional evidence of tectonic activity may be inferred from morphometric maps (Fig. 6) and interpretation of longitudinal valley profiles (Fig. 7, 8, 9). The morphometric maps, when generalized, show a set of belts parallel to each other with contrasting values of parameters. Generally, this pattern may be interpreted as alternating changes of rates of erosion and/or uplift (Fig. 6). The belts of lesser erosion roughly coincide with the flat horizons and the belts with greater erosion with the scarps between them. Severals faults documented by Żelaźniewicz (1987) coincide well with the belts with greater erosion (Fig. 3). Moreover, all breaks in the longitudinal valley profiles are located in the same zones (Fig. 15). The different erosion

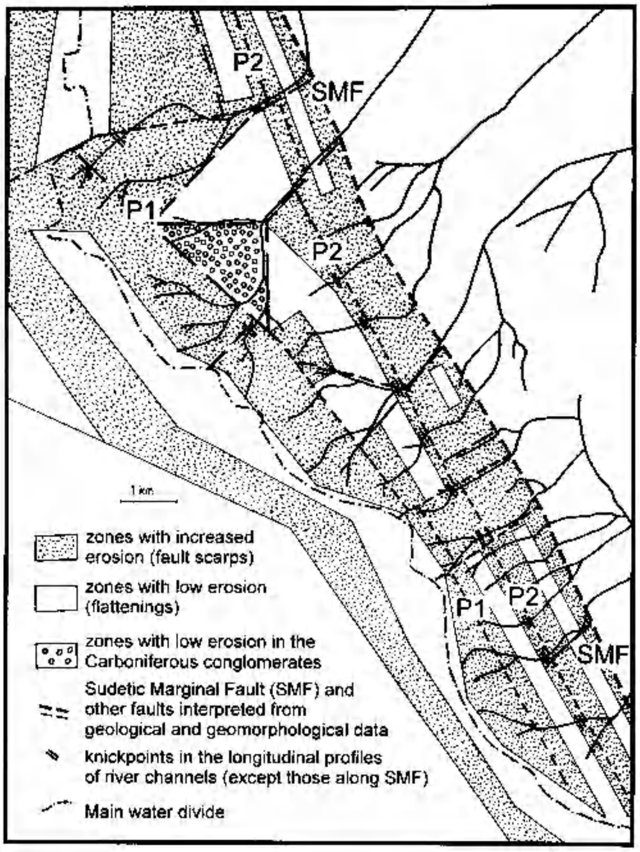

Fig. 15. Summary diagram showing an integrated interpretation of morphologic and morphometric features. The dotted zones show increased values of the relative relief ($H_{max} - H_{min}$) and of the relief above headstream incision ($H_{max} - E_{max}$), that coincide well with the fault scarps between flat surfaces (NW–SE direction) and transverse fault zones (SW–NE direction). The main scarps were formed along the SMF, P1 and P2 are fault zones. Detailed discussion in the text.

Table 3

The morphometric parameters of valley shape (valley width/valley height ratio – V_f) and drainage basin elongation (R_e) from valleys of the Sowie Mts

river	order of the valley	tectonic units in the mountain foreland	mean valley shape parameter (V_f)	mean drainage basin elongation parameter (R_e)
1. Bojanicka Woda	II		0.625	0.595
2. Ceglany Potok	II		0.801	0.620
3. Lutomia	III	Roztoka–Mokrzeszów Graben	0.699	0.610
4. Miła	III		0.654	0.623
5. Graniczny Potok	II		0.649	0.628
6. Potok bez nazwy	II		0.524	0.664
7. Sowi Potok	III		0.411	0.646
8. Pieszycki Potok	III		0.452	0.692
9. Potok bez nazwy	II		0.513	0.682
10. Bielawica	III	Bielawskie Hills' horst	0.439	0.674
11. Czerwony Potok	II		0.400	0.642
12. Jodłownik	II		0.454	0.610
13. Zamkowy Potok	II		0.394	0.568
14. Tartaczny Potok	II		0.332	0.576
15. Szklany Potok	II	Ząbkowice Graben	0.324	0.564
16. Bydlęca	II		0.326	0.574
17. Piekielnica	II		0.309	0.616
18. Chyzy Potok	II		0.274	0.620

rates may be interpreted as a reaction to the tectonic uplift, as the basement is lithologically uniform. Hence, it seems that the integrated data from the divides (scarps intervening flattenings), valleys (knickpoints) and from morphometric maps (changes in erosion/uplift rates) may indicate real fault lines, even if there are no unambiguous geological data to confirm them in the field (compare Fig. 3 and 15). The fault scarps are probably partly degraded and have differentially receded from their original positions on the fault lines, as the belts with increased erosion are usually 0.5–2.0 km wide. Similarly, the knickpoints have receded upstream due to headwater erosion (Fig. 15). If the tectonic interpretation of the scarps is correct, the total uplift along the NW–SE trending faults varies from 200–300 m (fault P1) to 100–200 m (fault P2 and the Sudetic Marginal Fault) (Fig. 15).

Several zones indicate more complex morphotectonic patterns. Two zones, one along the Sowi Potok valley and other between the Zamkowy Potok and Jodłownik valleys, are characterized by continuous high values of relative relief from the main divide down to the Sudetic Marginal Fault (Fig. 6). The first zone also coincides with a rapid change of altitude of the upper (from 1000 to 700 m a.s.l.) and middle (from 680 to 600 m a.s.l.) flat surfaces (Fig. 4). It seems likely that these features may relate to a large transverse fault, that separate the more uplifted central part of the range, from its northern, downthrown area (Fig. 15). Similarly, the zone between the Zamkowy Potok and Jodlownik valleys may represent a tectonic horst, where the lower and middle flats have not been preserved due to continuous uplift and erosion (Fig. 4, 15). The upper courses of the Pieszycki Potok and Bielawica valleys are characterised by especially extensive areas of lower values of relief above the headstream erosion (Fig. 6). They, most probably, represent tectonic grabens, originally filled with Carboniferous conglomerates. The basins are outlined by triangular fault patterns, that is highlighted additionally by the fluvial pattern (Fig. 15). The graben of the Bielawica valley probably subsided less, as Carboniferous sediments are not preserved.

The evidence of tectonic uplift along the Sudetic Marginal Fault includes localised steepening of the longitudinal valley profiles at the fault line (breaks), distinct downstream divergence of the Upper Terraces, offsetting of the Upper and Middle Terraces and formation of fault scarps, the common occurrence of alluvial fans and their onlap, and stream deflections at the fault line. Additional features, that confirm the role of tectonics in the evolution of the Sudetic Marginal Fault escarpment, are the occurrence of basal scarplets beyond the valleys and the variation of

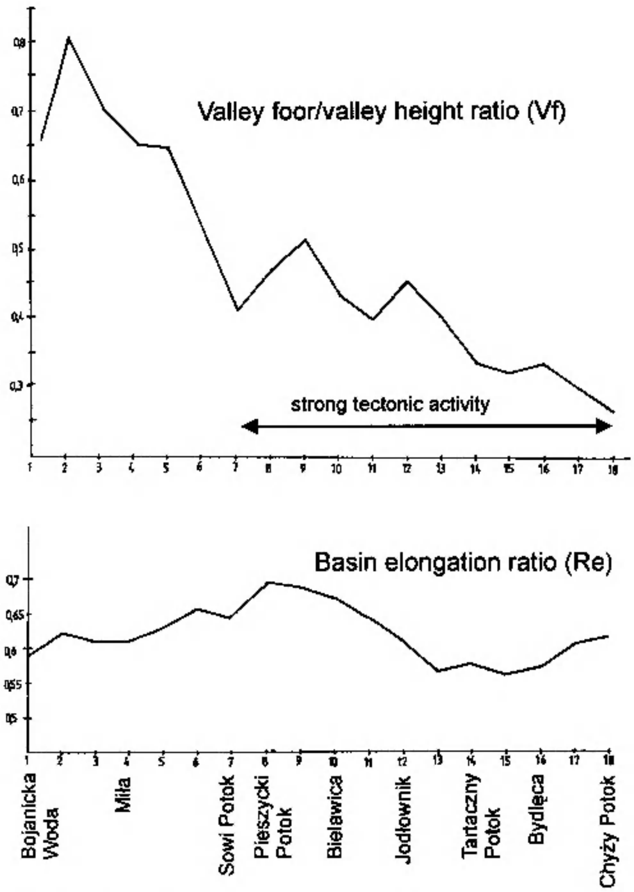

Fig. 16. Changes of the valley floor width/valley height ratio (V_f) and basin elongation ratio (R_e) (Bull & McFadden, 1977) along the Sowie Mts range (see discussion in the text).

the valley floor width/valley height ratios (V_f) (Table 3). The latter parameter describes the interaction of the fluvial system and tectonic uplift, and as all values calculated for the Sowie Mts range are below 1, the Sudetic Marginal Fault may be included in first category of faults, *i.e.* recently tectonically active faults (Bull & McFadden, 1977). An interesting feature is that this parameter suggests less active tectonics in the northern part of the Sowie Mts in comparison to the central and southern areas (Fig. 16). The basin elongation ratio (R_e) is, however, more ambiguous as the R_e values range between 0.55–0.70 (Table 3). This indicates weak tectonic fault activity.

The height of fault scarps and basal scarplets along the Sudetic Marginal Fault show that its latest movement was between 10–20 m. The height difference between the valley segments above and below knickpoints vary from a few metres to 40 m, which suggests the similar or little bit greater uplift along P1 and P2 faults in the mountain interior. The fault scarps interveining the flat sufaces are, however, 100–300 m high, which suggest an occurrence of the older phase of tectonic activity in the Sowie Mts.

The age of the younger tectonic phase may be inferred from the age of the terraces. As the oldest truncated terrace (Upper Terrace) dates back to late Saalian, it seems that the uplift phase may have been connected with glacio-isostatic rebound after the early Saalian glaciation. The ice thickness in the range front was at least 150 m (Schwarzbach, 1942; Szczepankiewicz, 1969), which seems to be enough to create 10–40 m uplift (Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski, 1994; Krzyszkowski & Biernat, 1998). The glacio-isostatic rebound must have been quite fast, as finally the Upper Terrace was truncated along the

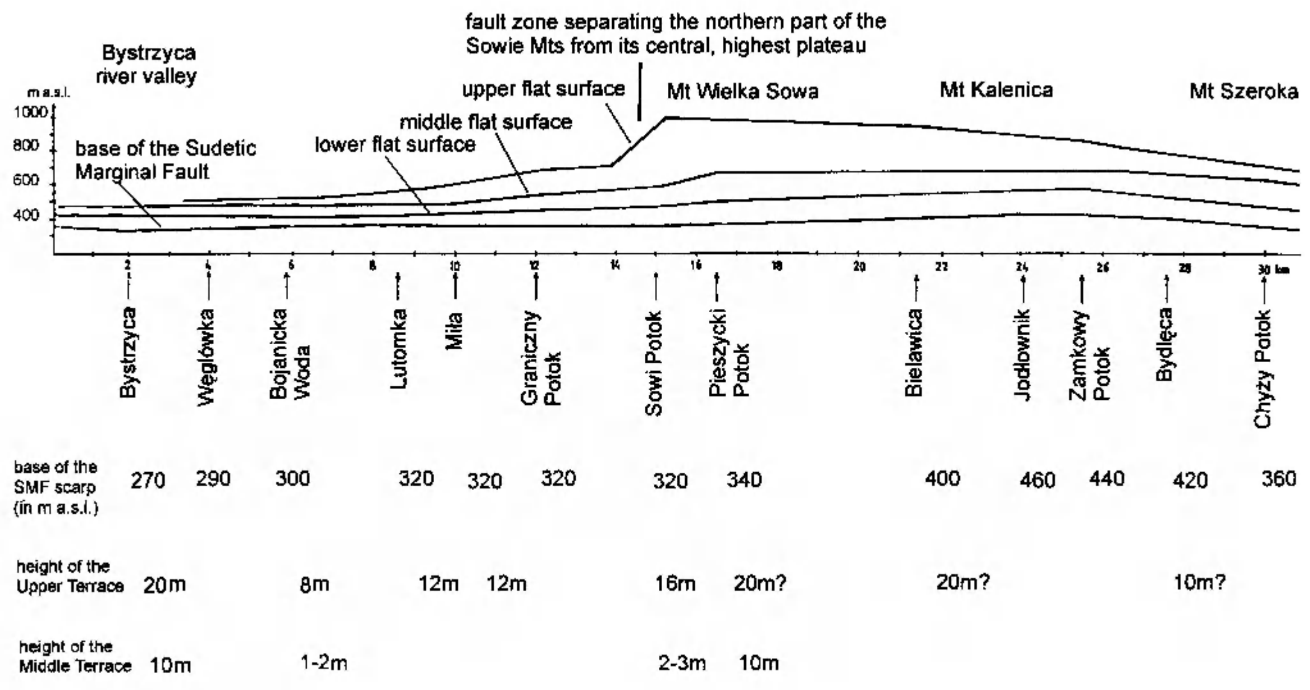

Fig. 17. Changes of altitudinal position of the flat surfaces, base of the Sudetic Marginal Fault scarp and changes of the terrace heights along the Sowie Mts range; note that the highest values are located between the Sowi Potok and Jodłownik valleys; this zone presumably represents the permanently uplited block, which is roughly coincident with the tectonic zones in the mountain foreland.

fault scarps (displacement 6–10 m), with simultaneous offlap of fans and formation of deep valleys in the mountainous area. The relatively small ammount of glacially-derived material in the deposits of the Upper Terrace/fan system was probably due to deep down-cutting, when the local gneiss was eroded, while the glacial cover survived on divides. Later, the tectonic activity probably slowly diminished and a major part of the glacial deposits was removed due to lateral erosion and deposited in the valleys and erratic material was incorporated into younger fluvial material. However, the tectonic activity that time was still enough great in the central part of the Sowie Mts, as the Middle Terrace is truncated by a fault scarp in the Pieszycki Potok valley (displacement about 10 m). The regional differentiation of uplift rates, marked by different heights of the fault scarps and terraces along the Sudetic Marginal Fault scarp (Fig. 17), may suggests that the youngest uplift phase was not a simple rebound, but was influenced by localised endogenic forces.

The age of the older uplift phase remains open. The tectonic movements could have been initiated during the Neogene, but it seems that the last large tectonic uplift phase dates back to the Early Pleistocene, analogous with adjacent regions (Krzyszkowski *et al.*, 1998; Krzyszkowski & Biernat, 1998). The formation of large-scale stepped landscape of the Sowie Mts range may relate to this tectonic phase. As a consequence, the Sowie Mts range prior this uplift phase would have been from 100–300 m lower than present-day. The possible Early Pleistocene tectonic activity in the Sowie Mts was also regionally variable, which is evident from different altitudes of the coeval flat surfaces and the changing altitude of the base of the Sudetic Marginal Fault (Fig. 17). Generally, three main tectonic blocks can be recognized, including the northern part of the range (beyond the studied area; *vide* Krzyszkowski & Pijet, 1993a; Pijet & Krzyszkowski, 1994). The northern and the southern regions are characterized by much less uplift (60–100 m) whereas the central block is charracterised by large uplift (160–300 m). The last zone also coincides with the uplifted block in the mountain foreland (Bielawskie Hills horst), whereas less uplifted blocks are adjacent to tectonic grabens (Fig. 2A). It seems, that the central part of the Sowie Mts was characterised by greater uplift rates from the first Neogene offset and simply continued this pattern during the Early and Late Pleistocene.

CONCLUSIONS

1. The Sowie Mts comprises distinct morphological features that can be related to active tectonics. These are large-scale features such as: 100–200 m high morphological scarp with triangular facets formed along the Sudetic Marginal Fault, stepped morphology in the mountain interior with 100–300 m high scarps intervening flat horizons, and straight, asymmetric valleys related to differently oriented faults. The meso-scale tectonically induced features occur as knickpoints in longitudinal valley profiles at the fault lines, distinct downstream divergence of the Upper Terraces, offset of the Upper and Middle Terraces and formation of the fault scarps, basal scarplets beyond the valleys, common occurrence of alluvial fans and their onlap, and stream deflections at the Sudetic Marginal Fault.

2. Besides the first Neogene offset, two further phases of the tectonic uplift have been recognized that date back to Early and Late Pleistocene. The total Quaternary uplift of the Sowie Mts range was between 100–300 m, with the major tectonic activity taking place during the Early Pleistocene and while the last phase was minor (uplift 10–40 m).

3. The late Pleistocene tectonic activity is most probably related to post-glacial (post-early Saalian) isostatic rebound, as the mountain range was partly covered by the Scandinavian ice-sheet. The glacio-isostatic rebound was influenced by localised tectonic movements created by endogenic forces.

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