Geologia Sudetica, 1998, 31: 241–258.

Terraces of the Bystrzyca river valley, Middle Sudetes, and their deformation along the Sudetic Marginal Fault

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Key words: Fluvial terraces, neotectonics, fault scarps, Middle and Late Pleistocene stratigraphy

Abstract There are three stages in the evolution of the Bystrzyca river valley, dated to the Pliocene, the Early to late Middle Pleistocene, and the late Middle Pleistocene to recent. The Pliocene landscape was flat to hilly, with a weakly developed margin of the mountains. The valleys were shallow and wide, most probably with sinuous rivers, and are today represented by the 100–120 m high terrace. The scarp of the Sudetic Marginal Fault and the mountain landscape with deeply incised valleys were not formed until the Early Pleistocene tectonic phase, during which the uplift was about 60–70 m. The late Middle to Late Pleistocene stage of the valley development may be subdivided into several sub-stages, during each of which, one of three morphogenetic factors, namely fluvial activity, glacial erosion and sedimentation and tectonic uplift, prevailed. Five fluvial terraces have been found, one formed before glaciation and the other four during the post-glacial times. The valley was glaciated only once, during the early Saalian (Odranian) stage. The total postglacial uplift was about 40–50 m and fluvial activity that time was influenced by varying uplift rates. At first, erosion prevailed due to strong glacio-isostatic uplift. Then, it diminished quickly and was replaced by more localised tectonic uplift, which decreased with time. As a result, fluvial activity in the mountains and in the foreland became different, as is highlighted by the increased thickness of fluvial deposits in the foremoutain zone, the rapid change of terrace height, formation of a distinct, 25–30 m high, fault scarp along the Sudetic Marginal Fault, and the increased erodibility along the fault lines.

Manuscript received 15 April 1998, accepted 30 October 1998.

INTRODUCTION

The Bystrzyca is one of the biggest rivers in the Middle Sudetes Mts. Formed during the Late Cainozoic, it is one of only two entecedent valleys in the area, the other being the Nysa Kłodzka River valley. Its source area lies in the Central Sudetic Depression, with its Permian volcanic and Carboniferous sedimentary rocks, and then crosses the highland (Sowie Mts gneiss block), forming a narrow, 12 km long valley. The Bystrzyca river valley and its deposits were first described in the 19th century (Stapff, 1884, 1887, 1888, 1889). Berg (1909) described fluvial terraces in more detail and Finckh (1923) and Schwarzbach (1938, 1940, 1942) observed glacial and glaciolacustrine deposits. Later, Dumanowski (1961) and Jahn & Szczepankiewicz (1967) discussed the number of terraces and the origin and morphology of the valleys. Recent work emphasizes either the role of glaciation (Augustyniak, 1992) or of neotectonics (Krzyszkowski & Biernat, 1992, 1993; Biernat, 1994) in the formation of the valley.

This paper deals with the valley fragment adjacent to the highland margin (the Sudetic Marginal Fault scarp), between Zagórze Śląskie and Bystrzyca Górna in the mountainous region, and between Burkatów and Świdnica in the mountain foreland (Fig. 1). The aim of the paper is to discuss: 1. terrace stratigraphy and the characteristics of the fluvial deposits, 2. terrace deformation and its origin and age, and 3. the role of glaciation and neotectonics in the development of the valley.

BEDROCK AND SURFACE GEOLOGY

Geologically, the studied region is located entirely within the Sowie Góry gneissic block, which dates back to

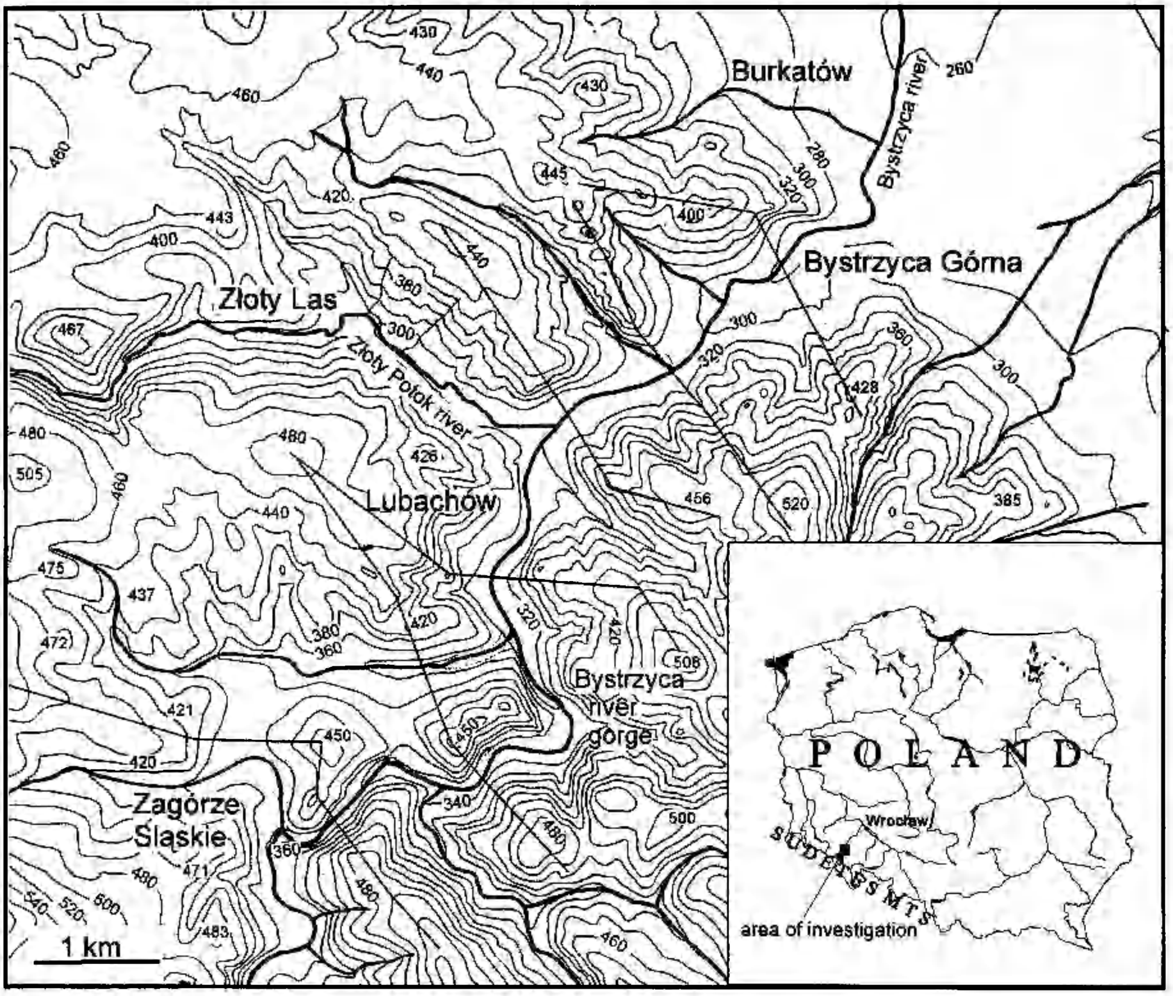


Fig. 1. Location of the Bystrzyca river valley in the Sudetes Mts and area of investigation. Cross sections at Bystrzyca Górna, Lubachów and Zagórze Śląskie are in Figures 3 and 4. Topography is based on Topographische Karte 1:25,000 – Blatt Charlottenbrunn, Königlich Preussische Landes, Aufnahme 1881, with valley morphology before construction of the artificial dam at Lubachów. Numbers indicate altitude in metres above sea level; contour lines every 20 m.

Upper Proterozoic–Lower Devonian (Gunia, 1981, 1985). This block now forms two parts, the strongly elevated (Sowie Mts) southwestern one, and the northeastern tectonic graben – the Roztoka-Mokrzeszów Graben (Dyjor & Kuszell, 1977; Grocholski, 1977). They are separated by a major regional fault line in the region – the Sudetic Marginal Fault (Fig. 2A). The local tectonic pattern consists of two systems of faults, one trending NW–SE, parallel to the Sudetic Marginal Fault, and the younger system, perpendicular or diagonal to the major fault (Zelaźniewicz, 1987). The main stage of fault activity has been referred to the late Neogene (Oberc & Dyjor, 1969; Oberc, 1977) or to the Early Pleistocene (Krzyszkowski *et al.*, 1998). The Bystrzyca river valley is located along one of the SW–NE trending fault lines, whereas its tributary valleys are located along the NW–SE faults (Stapff, 1885; Dathe & Finckh, 1924; Zelaźniewicz, 1987; Krzyszkowski & Bowman, 1997) (Fig. 2A).

The Sowie Mts are formed mainly of semipelitic or metagreywacke gneiss and migmatic gneiss (Zelaźniewicz, 1987), which contain inclusions of amphibolites, hyperites, granulites and serpentinites (Grocholski, 1965; Polański, 1955). Also, some patches of Upper Carboniferous conglomerates and sandstones overlie the gneiss, and these contain veins of kersantites, porphyrytes and pegmatites (Grocholski, 1967; Łapot, 1986, 1988) (Fig. 2B). Finally, Quaternary fluvial deposits are observed in valleys and glacial deposits both in the valleys and on the slopes. The glacial deposits are represented by till and glaciofluvial or glaciolacustrine deposits (Berg, 1909; Finckh, 1923; Dathe & Finckh, 1924; Arnold 1938; Schwarzbach, 1938, 1940, 1942; Krzyszkowski & Pijet, 1993; Pijet & Krzyszkowski, 1994).

The mountain foreland has a more complex stratigraphic sequence. The gneissic bedrock lies in the graben area about 100–200 m below the surface. The graben is 3–4 km wide and it is infilled with three main sedimentary series: ca 100–200 m thick Miocene clays or sands; *ca* 40–50 m of 'Preglacial' gravels (Dyjor & Kuszell, 1977); and up to 40 m of Quaternary deposits (Krzyszkowski, 1993). The Preglacial gravels are partly exposed at the surface (Fig. 2B). The Quaternary series contains glacial deposits from

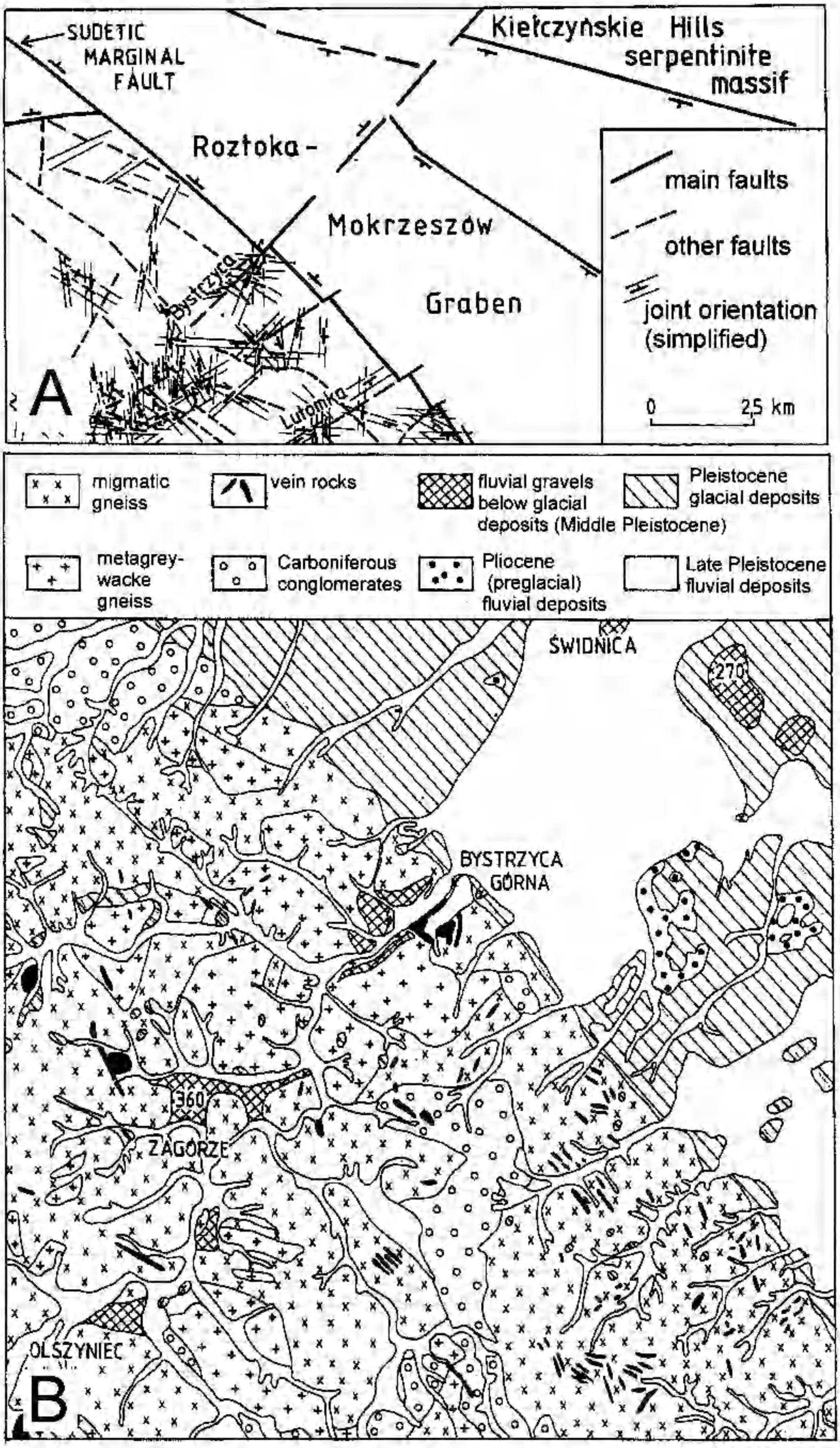


Fig. 2. Geology of the northern part of the Sowie Mts: **A** – tectonics; **B** – main types of rocks in the Bystrzyca river drainage basin and surficial geology.

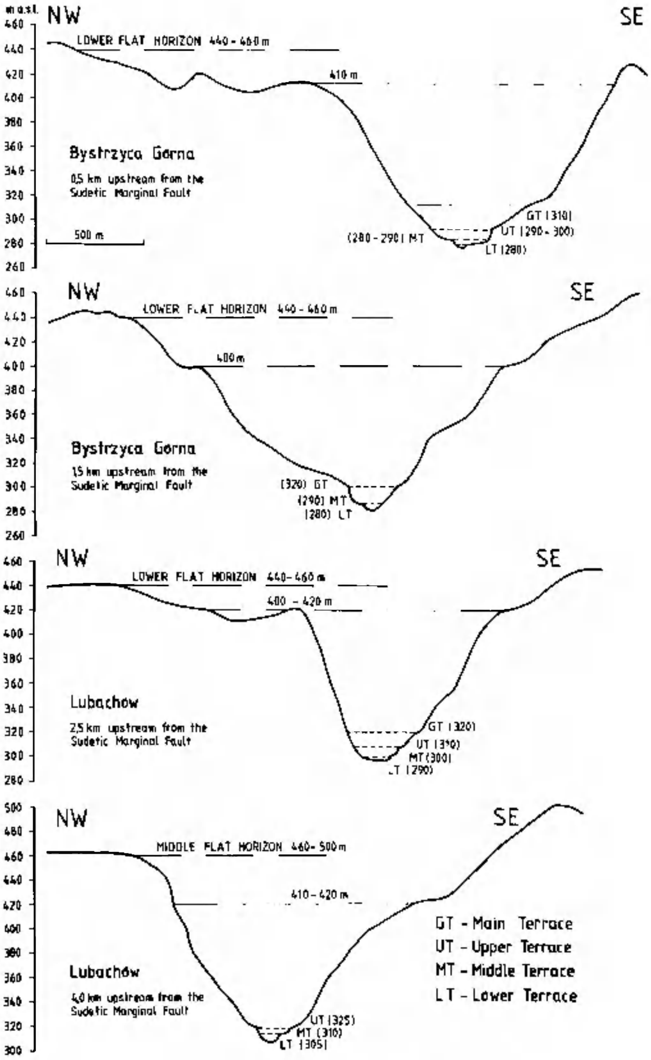


Fig. 3. Valley cross sections through the Bystrzyca river valley between Lubachów and Bystrzyca Górna; location of cross sections in Fig. 1. Note a continuous occurrence of the 400–420 m a.s.l. level (100–120 m high terrace) along the valley.

the last glaciation in the region (early Saalian) in the uplands and Late Pleistocene fluvial deposits in the valleys. Exposures of the Elsterian glacial deposits and the Middle Pleistocene fluvial gravels are limited (Krzyszkowski, 1993) (Fig. 2B). A thin cover of loess-like deposits has been observed throughout the region, including the mountain valleys.

GENERAL GEOMORPHOLOGY

The northern part of the Sowie Mts is a plateau lying 100–150 m higher than the mountain foreland, with summits varying between 420–560 m a.s.l. (Fig. 1). This plateau is dissected down to 280–360 m a.s.l. by the Bystrzyca river valley and its tributaries and is separated from the foremountain plain by the ca 120 m high scarp of the Sudetic Marginal Fault. The foremountain plain lies at 260–300 m a.s.l. The mountain plateau is generally formed of three distinct levels ('flat horizons', 'planation surfaces'), which are separated from one another by steep scarps. The highest flat horizon, at 560–700 m a.s.l., does not occur in the Bystrzyca river valley region (Krzyszkowski & Pijet, 1993; Pijet & Krzyszkowski, 1994). The middle flat horizon, which forms the extensive highland plateau in the region, is at 480–560 m a.s.l., whereas the lowest one (420–460 m a.s.l.) occurs in small fragments along the river valley and along the scarp of the Sudetic Marginal Fault. The flat relief of the highland is well visible in the field and on morphometric maps (Pijet & Krzyszkowski, 1994). The valley slopes and scarps are usually 10–30° steep, whereas the highland summits and the valley bottoms indicate slope inclinations below 10°, and very often only 0–5°.

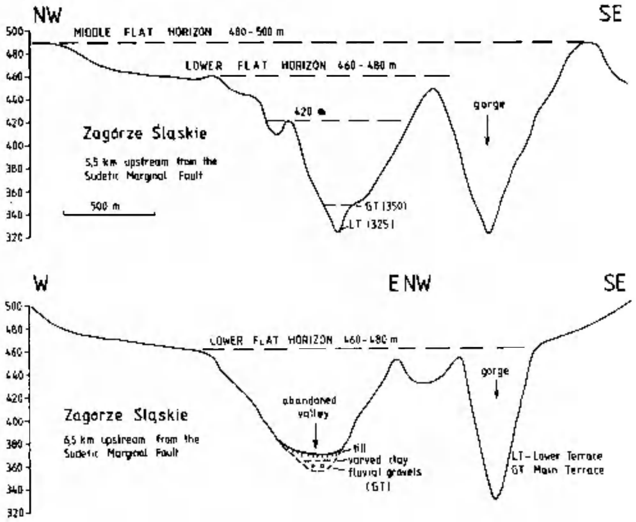


Fig. 4. Valley cross sections through the river gorges and abandoned valleys near Zagórze Śląskie; location of cross sections in Fig. 1. Sediment sequence in the abandoned valley after Berg (1909).

The cross-section of the mountain stretch of the Bystrzyca river valley may be subdivided, in vertical sequence, into two components that are likely to reflect valley morphology from two different stages of its morphological development. Its upper part is formed by laterally restricted shelves on both side of the valley, at an altitude of 400–420 m a.s.l.. Their position and continuity along the river suggests that they are remnants of an old, 0.7–1.6 km wide and 20–40 m deep, box-shaped valley incised into the lower or, in part, directly into the middle flat horizon (Fig. 3, 4, 5). By contrast, the lower part represents a 100–120 m deep incision, with steep slopes and a flattened bottom, whose width is 0.4–1.0 km. The most recent stages of development of this incision are marked by alternating terrace levels and intervening scarps and the valley bottom is occupied by the present-dat Bystrzyca river (Fig. 3). In addition, in some places V-shaped gorges have formed and these are characterised by very steep slopes (20–45°), subvertical rock walls, and a reduced floodplain width. The longest gorge-like segment occurs at Zagórze Śląskie and is 100–200 m wide and 130 m deep (Fig. 4, 5). This gorge runs parallel to an abandoned valley segment

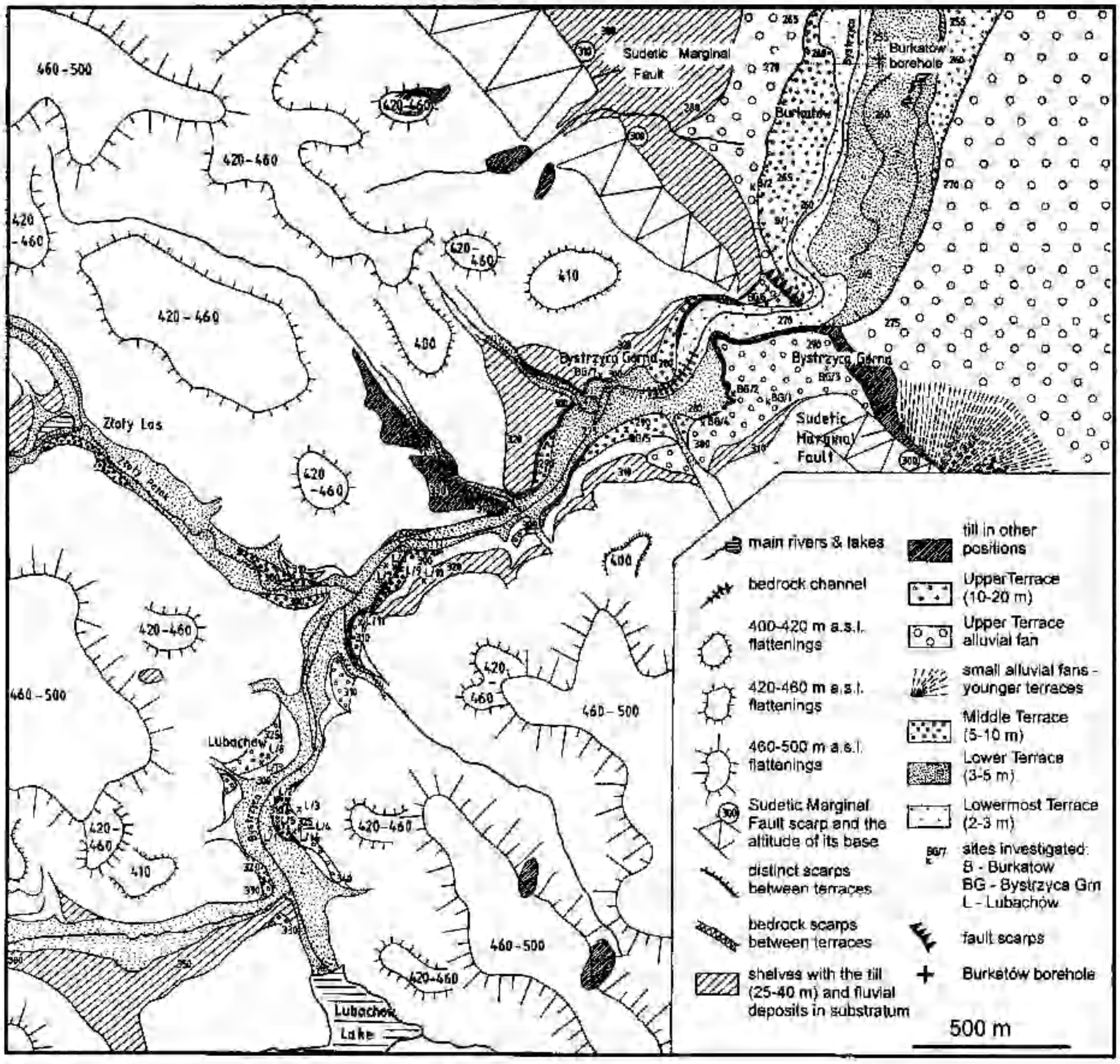


Fig. 5. General morphology and terrace distribution in the Bystrzyca river valley near the Sudetic Marginal Fault.

(Fig. 4), now left hanging 40–45 m above the gorge floor.

The longitudinal profile of the valley is irregular. Three breaks occur in the investigated part of the valley, marked by increased channel slopes and bedrock channels (Fig. 6). The first break zone occurs in the narrow river gorge at Zagórze. The other two occur further downstream, at Lubachów and at Bystrzyca Górna. In the latter case, the break coincides closely with the position of the Sudetic Marginal Fault zone (Fig. 6). The valley slope in the gorge varies from 1.5 to 2.0%, in the other break zones it is from 0.8 to 1.2%, whereas beyond them is only 0.5–0.8%. Except for the river gorge at Zagórze, the valley fragments with increased channel slopes are not distinctly narrower than the reaches up- and down-stream. However, at least one side of these valley fragments is formed of a rock wall and the river changes its pattern, from an almost straight or slightly sinuous course to a distinctly meandering one (Fig. 5).

TERRACES

The Bystrzyca river valley has six terraces. The uppermost one is equivalent to the oldest part of the valley, hanging at 400–420 m a.s.l. (Fig. 5). This 100–120 m high terrace may represent the oldest fluvial phase in the valley, although fluvial sediments have not yet been found. The other five terraces definitely represent fluvial surfaces, comprising alluvial gravels. Moreover, one of them, forming 30–45 m high shelves on both sides of the valley, is covered by a till (Fig. 5). This terrace, the Main Terrace, forms one fluvial system together with the abandoned valleys. Fluvial deposits of the same age have also been documented in the foremountain zone (Krzyszkowski, 1993)

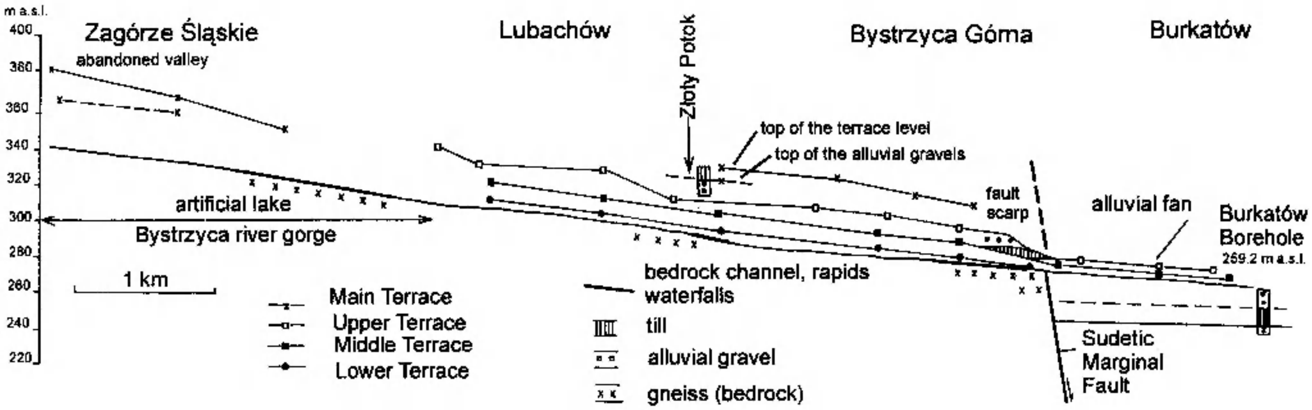


Fig. 6. Longitudinal profile and terrace heights along the Bystrzyca river near the Sudetic Marginal Fault; note a displacement of the Upper Terrace gravels and till along the fault line.

(Fig. 2B). The remaining fluvial surfaces of the mountainous valley are the Upper Terrace (20–25 m), Middle Terrace (10 m), Lower Terrace (3–5 m) and the Lowermost Terrace (2–3 m). The latter one only occurs in the zone adjacent to the Sudetic Marginal Fault (Fig. 5).

The foremountain fluvial system of the Bystrzyca river is generally formed of a set of alluvial fans (Krzyszkowski, 1993). Near the mountain margin, four distinct terrace levels have been found: Upper (10 m), Middle (5 m), Lower (2–3 m) and the Lowermost Terrace (1–2 m). However, only the Upper Terrace has fan morphology in this zone (Fig. 5). The other fluvial surfaces form relatively narrow, cut and fill terraces, which develop into fans further north (Krzyszkowski, 1993). The terrace downstream slope varies from 0.2–0.4% in the youngest terraces to 0.5–1.0% in the Upper Terrace (fan). The Main Terrace fluvial deposits occur in the foremountain zone about 20–40 m above the recent river channel and they are partly covered by a till (Fig. 2B).

TERRACE DEPOSITS

MOUNTAINOUS ZONE

Main Terrace. The top surface of the Main Terrace lies 40–45 m above the recent river channel in the mountain interior (abandoned valleys). Downstream, its height is lowered to 35 m at Lubachów and 30 m at Bystrzyca Górna (Fig. 6). However, this level does not represent the fluvial terrace, but its surficial, glacial cover.

This terrace forms a 100–300 m wide shelf with limited lateral extent on the left side of the river near the Sudetic Marginal Fault scarp at Bystrzyca Górna (Fig. 5, 7). The shelf is covered by at least 1.4 m of till, as indicated in trench BG/7. The till is partly re-worked by slope processes, as it contains both sub-rounded clasts and angular debris of local gneiss. Fluvial gravels have not yet been found, but they probably occur below the glacial cover (Fig. 7). On the right side of the river, this terrace forms a more continuous shelf, albeit only 50–100 m wide (Fig. 5). The complete profile has been discovered in trench L/10 (Fig. 8). Below slope debris (0.0–0.4 m), containing angular clasts, and till (0.4–1.2 m), there is a fluvial gravel (1.2–2.0 m). This is a matrix supported, well rounded gravel with maximum clast size of about 5 cm and a sandy matrix. The till is matrix-supported and contains sub-rounded to rounded clasts, up to 0.5 m in diameter.

The abandoned valley near Zagórze has a more complex sediment sequence. The trench made by the authors (ZG/2) indicated an at least 1.4 m thick till on the valley surface, whereas that made by Augustyniak (1992) indicated at least 9.0 m of till and slope deposits (ZG/1). Berg (1909), however, described a sequence of more than 10 m thickness in the Zagórze (Kynau) brickyard (ZG/1). It contained, from the bottom to top: fluvial gravels of unknown thickness; glaciolacustrine, finely laminated clay and silt (5 m); glacial till (1–5 m thick); and a slope deposit with angular debris (2 m thick). The top of the fluvial gravel lies at about 365 m a.s.l., *i.e.* about 30 m above the channel, which represents the same level as the gravels at Lubachów (Fig. 8). Schwarzbach (1940) presented fabric measurements from the Zagórze till, indicative of glacial transport from NE to SW, parallel to the valley. Similar profiles, with old fluvial gravels covered by glaciolacustrine clays and/or till have also been described further upstream, near Olszyniec (Erlenbusch) (Berg, 1909; Schwarzbach, 1938, 1940). Augustyniak (1992) described glaciofluvial sandy deposits in the abandoned valley near Jugowice.

Berg (1909) pointed out that the fluvial gravels found in the abandoned valleys do not contain the northern (Scandinavian) component. This is confirmed at site L/10, where the fluvial gravels are dominated by local gneiss (45%) and porphyry (41%), with a minor portion of quartz, quartzite and conglomerates. On the other hand, the till beds contain 86–98% local gneiss and porphyry var-

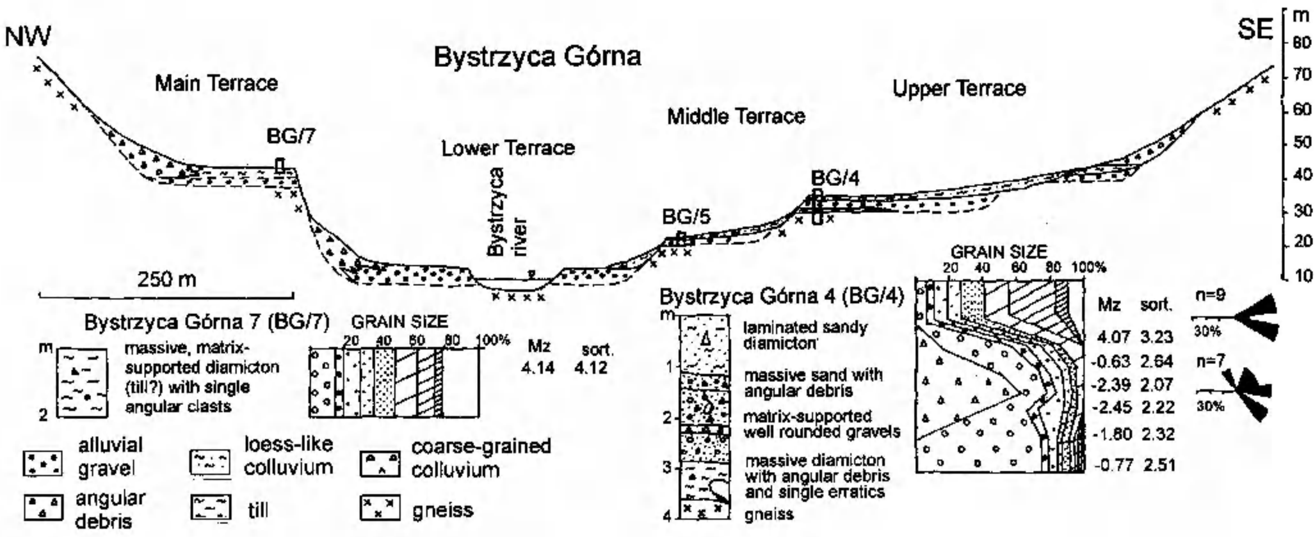


Fig. 7. A sequence of terraces and characteristics of their deposits at Bystrzyca Górna.

ies only from 0 to 5%; Scandinavian rocks have also not been found at this site.

Upper Terrace. This is a rock terrace forming usually more or less continuous, 50–150 m wide shelves on both sides of the river. Near the Sudetic Marginal Fault scarp, the right-side shelf reaches up to 400 m width (Fig. 5). The terrace is about 20–25 m high, although the height differences along the river result rather from the varying thickness of the surficial, non-fluvial cover (Fig. 6).

The most complete sediment sequence of the Upper Terrace has been recognized in trench BG/4 (Fig. 7). The sequence consists of, from bottom to top: gneiss bedrock; massive, clast supported diamicton with mainly angular (small) clasts and a few sub-rounded cobbles (one red granitoid boulder up to 40 cm in diameter); matrix supported, well to sub-rounded, imbricated gravels with clasts up to 30 cm in diameter and a sandy matrix (2.25–2.75 m); angular debris with clasts up to 15 cm (2.0–2.25 m); matrix supported gravel containing both sub-rounded and angular clasts up to 30 cm in diameter (1.5–2.0 m); coarse-grained sand with single angular and sub-rounded clasts with diameters of up to 10 cm (1.15–1.5 m); and a loess-like deposit with single angular clasts (0.0–1.15 m). The lower diamicton most probably represents a till, as indicated by

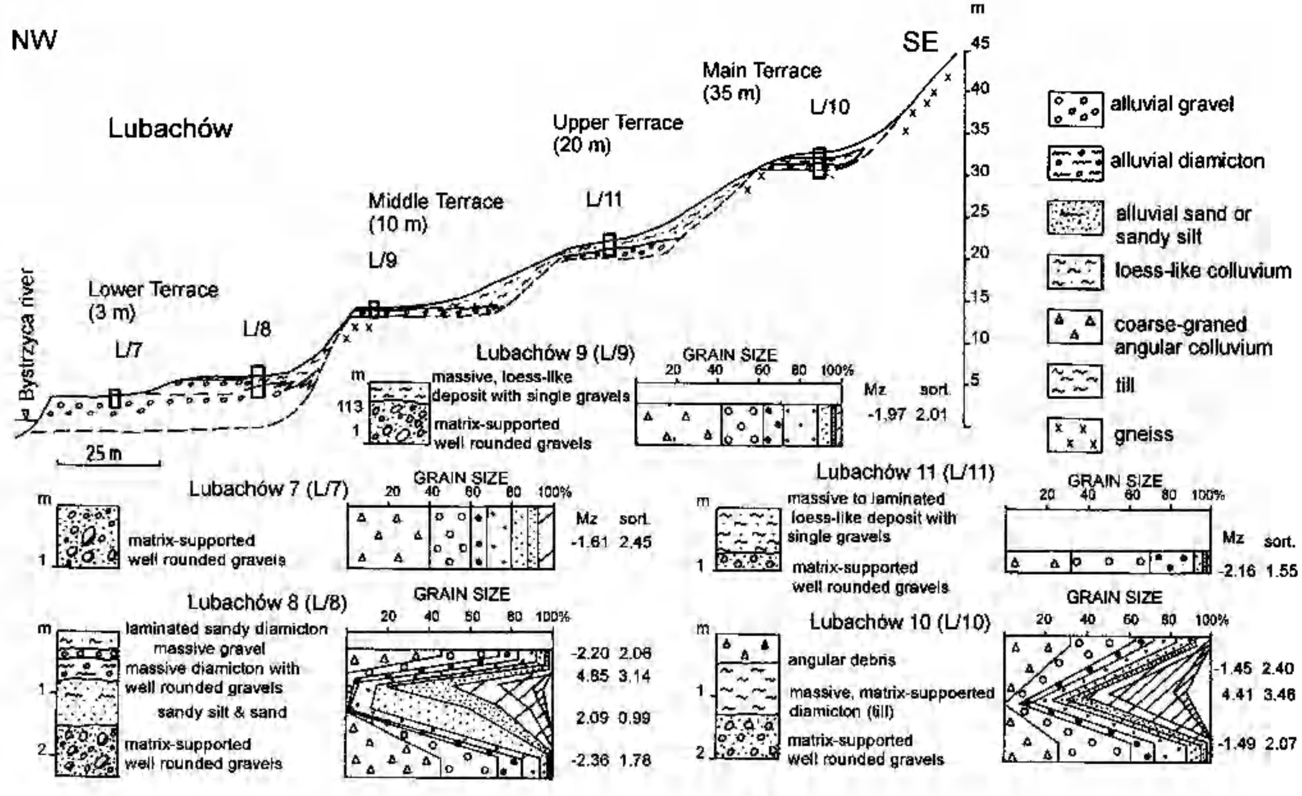


Fig. 8. A sequence of terraces and characteristics of their deposits at Lubachów (East).

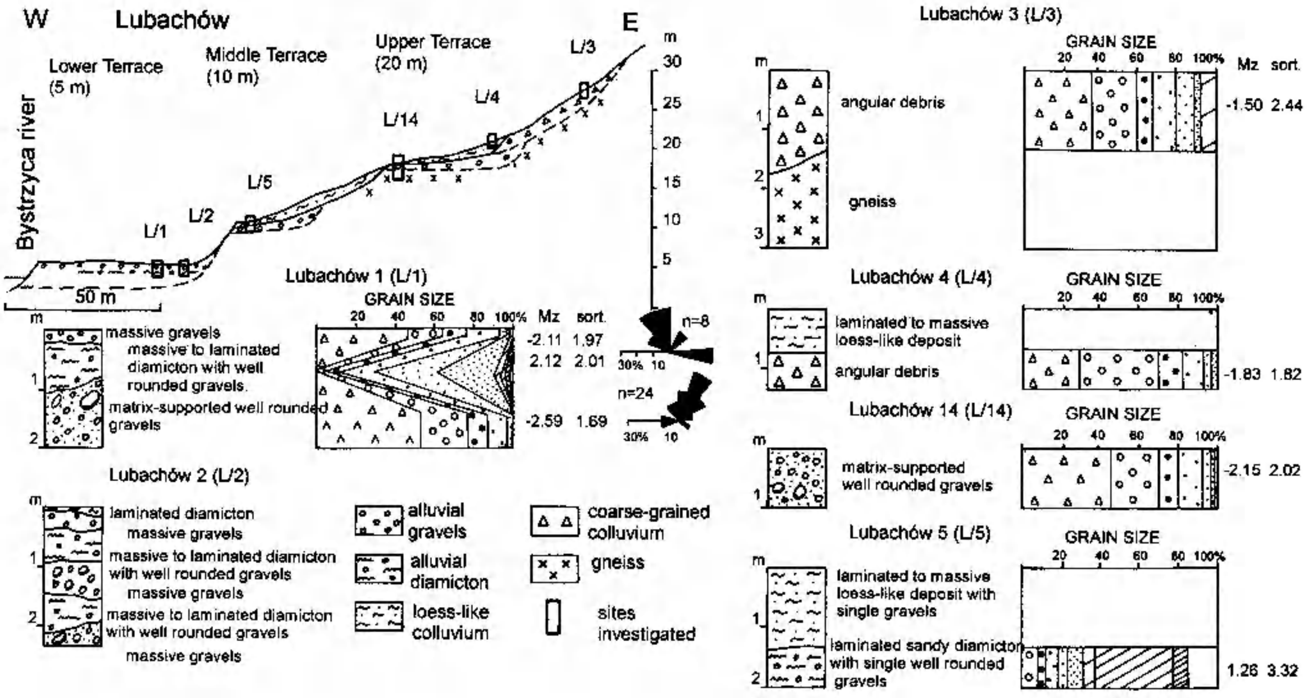


Fig. 9. A sequence of terraces and characteristics of their deposits at Lubachów (West).

occasional northern erratics. The lowermost gravels can undoubtedly be interpreted as fluvial deposits. The remaining part of the profile contains slope cover, either coarse-grained slope colluvium (2.0–2.25 m) or mixed fluvial and slope debris (1.15–2.0 m) or fine-grained colluvium (redeposited loess, 0.0–1.15 m).

Other trenches within the Upper Terrace revealed only fluvial gravels and overlying colluvium. The latter is either coarse-grained (L/3 and L/4, Fig. 10) or fine-grained (L/6, L/13, L/14, L/4, L/11, BG/6, BG/2 and BG/1, Fig. 7, 9). Except at the BG/4 site, the fluvial gravels lie, most probably, directly on the gneiss bedrock (Fig. 8, 9, 10).

The Upper Terrace gravels are usually dominated by local gneiss (37–65%) and porphyry (20–42%) , with a lesser content of quartz (6–12%), quartzite (3–8%), other local crystalline rocks (0–5%) and conglomerates (0–1%). The exception is a sample from trench L/6, where quartz dominates (42%) and gneiss is rare (10%). Moreover, all the samples contained a small, although stable admixture of northern rocks (0.2–1.6%, at L/6 up to 6.3%), mainly red graitoids and red quartzites and, in one case, Baltic limestone. The till at BG/4 comprises, in the 5–10 mm fraction, only local gneiss; northern erratics have been recognized only in cobble and boulder fractions. The coarse-grained colluvium is gneiss-dominated, with a 1–12% porphyry admixture.

Middle Terrace. This is a 10 m high rock terrace that forms isolated benches on both sides of the valley (Fig. 5). The terrace benches are up to 50 m wide and not more than 400 m long. The terrace usually consists of 1–2 m of matrix-supported, well rounded gravels, lying directly on bedrock, with a loess-like colluvium at the surface (Fig. 7, 8, 9).

The fluvial gravels are porphyry-dominated (40–60%) with less local gneiss than in the Upper Terrace gravels (21–45%). The proportions of other types of rocks are similar in both terraces, including the northern component (0.4–1.8%). The colluvium lying on the Middle Terrace gravels contains 84–96% of local gneiss and only 0–4% of porphyry.

Lower Terrace. This terrace forms a continuous alluvial level at a height of 3–5 m above the river channel (Fig. 7, 8, 9). The terrace forms 50–100 m wide benches in the mountain interior, which widen downstream to 200 m at Bystrzyca Górna (Fig. 5). The terrace sedimentary sequence is formed of alternating beds of gravels, sands and diamictons (Fig. 8, 9). The fluvial gravels are massive, matrix-supported, well rounded and imbricated. The maximum size of clasts is up to 0.5 m and the matrix is usually sandy. The thickness of the gravel beds varies from 0.2 to more than 1 m. The alluvial sands are moderately sorted and fine grained; sedimentary structures have not been observed. Their thickness reaches up to 0.8 m. Alluvial diamictons represent poorly sorted, massive to crudely laminated sandy silt with single well rounded clasts (up to 15 cm in diameter). The diamicton beds are 0.20–0.55 m thick.

Fluvial gravels are gneiss dominated (50–65%), with much less porphyry (23–39%) and a relatively large admixture of quartz (2–7%) and local quartzite (3–10%). Northern rocks may reach up to 2.5%, and among them, only red granitoids and red quartzites have been found. The clasts in the diamicton beds are represented mainly by gneiss and only occasionally by porphyry, quartz or quartzite.

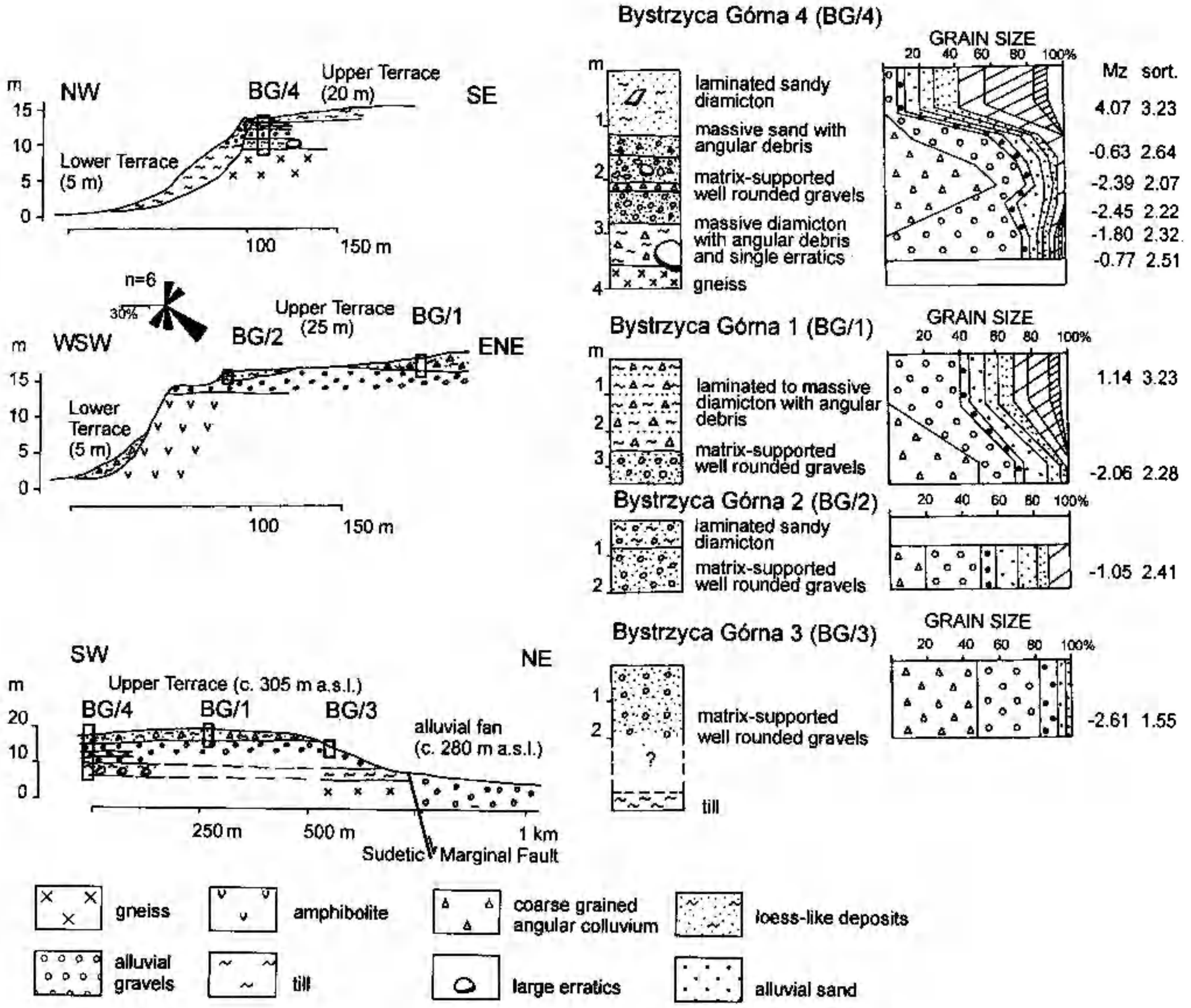


Fig. 10. A sequence of terraces and characteristics of their deposits in the zone of Sudetic Marginal Fault; note that the till exposures are at the base of fluvial gravels at site BG/4 and in the fault scarp as indicated in the lowest section.

FOREMOUNTAIN ZONE

The terraces of the foremountain zone are only half the height, but much wider than the equivalent terraces in the mountainous region (Fig. 5, 6, 11). The Lower and Middle Terraces are 200–400 m wide. The Upper Terrace forms a 200–300 m wide shelf on the left side of the river. On the opposite side of the river, this alluvial surface (fan) covers of about 20 sq. km, being about 3–4 km wide (Fig. 12A). The Lowermost Terrace is restricted to the near-channel zone and it is only about 50–100 m wide.

From among four terraces, deposits from only two, the Upper and Middle one, have been investigated in detail in the foremountain zone (Fig. 11). The Upper Terrace (fan) deposits are exposed in a small outcrop at Burkatów (B/2) and are represented by massive, matrix-supported, well rounded and imbricated gravels. The largest clasts are up to 0.5 m. The matrix is sandy. The fluvial gravels are overlain by 0.5–1.0 m of a loess-like sediment. The Middle Terrace deposits have been described within a 5 m deep well-pit (B/1). The sequence contains mainly massive, imbricated, matrix-supported or matrix-free well rounded gravels (pebbles to boulders). These massive sediments form alternating beds of matrix-free pebbles and matrix-supported cobbles and boulders. The maximum size of the gravels is about 0.5 m. Occasionally horizontally bedded sandy gravel and trough cross bedded gravel have been observed.

The gravel petrography in both described terraces is very similar and comparable with that from the montainous area. Porphyry (25–55%) and local gneiss (30–70%) dominate, with smaller contents of quatrz, quartzite and other local crystalline rocks (each group about 3–11%). The northern component is up to 2.6%.

The thickness of the fluvial deposits in the mountain foreland is not precisely established for the Upper and Middle Terraces. The first may reach 20–30 m and the latter up to 10–15 m (Fig. 11). The thickness of the gravels

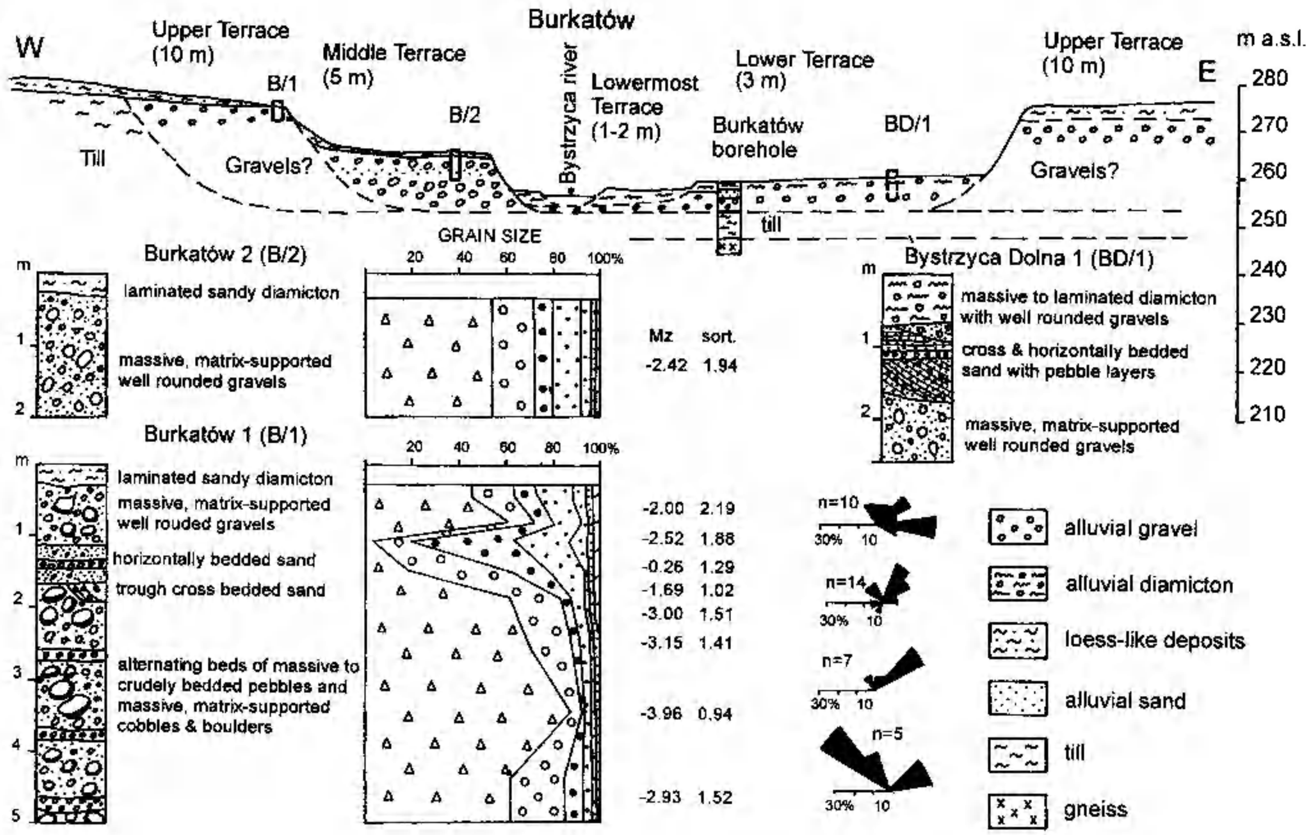


Fig. 11. A sequence of terraces and characteristics of their deposits in the foremountain zone at Burkatów.

along the Lower Terrace, which is known from boreholes, varies from about 5 m near the mountain margin to 20 m five kilometres downstream (Fig. 13). Thus in all the terraces, there is a synsedimentary increase of thickness of fluvial gravels in the foremountain zone, which coincides well with its position in the tectonic graben. The alluvial deposits are underlain by till or, in places, by Preglacial gravels (Fig. 11, 13) (Krzyszkowski, 1993).

SUDETIC MARGINAL FAULT ZONE

Three features are characteristic for the Bystrzyca river valley in the Sudetic Marginal Fault zone:

1. Terrace height is halved crossing the fault zone; this is especially well indicated for the Upper and Middle Terraces, with their jump from 20 to 10 m and from 10 to 5 m, respectively, above the valley floor (Fig. 6),
2. A distinct scarp is formed along the fault zone truncating the Upper Terrace level (Fig. 5, 6, 12B),
3. Erosion rates were substantially greater along the fault zone during the formation of the younger terraces.

The uniform alluvial surface of the Upper Terrace on the right side of the valley is truncated by a SE-NW stretching, 20-25 m high, scarp (Fig. 6, 12B). The terrace surface in the mountain zone lies here at 295-300 m a.s.l., and that of the foremountain fan is at 275 m a.s.l. The scarp has an inclination of 10-15°, whereas the adjacent alluvial surafces are flat (0-2°) (Fig. 14). Such a scarp can be easily interpreted as a degraded fault scarp (Bull & McFadden, 1977), where scarp degradation caused a decrease in the inclination of an originally much steeper scarp. Moreover, Dathe & Finckh (1924) found that the till is exposed along this scarp within an altitude range of 280-285 m a.s.l. (Fig. 5). It seems that this till forms a uniform bed together with the till found about 1 km upstream at site BG/4. The latter lies directly on the bedrock at about 290 m a.s.l. (Fig. 10). The till bed has also been found in the foremountain zone in the Burkatów borehole, about 1 km downstream from the Sudetic Marginal Fault zone (Fig. 5). This bed, which is 5.2 m thick, lies at in the altitude range 249.3-254.5 m a.s.l. If we assume that the till at the base of Upper Terrace and that one from the Burkatów borehole represent the same stratigraphic unit, the displacement value along the fault scarp can be precisely established. It is about 30 m, as indicates from the height difference between the base of till beds (Fig. 6, 13). A similar scarp is observed within the Upper Terrace level on the left side of the river, although here it is not as clear, as the till is not exposed.

The increased erosion in the Sudetic Marginal Fault zone during the formation of the youngest terraces is confirmed by several facts. First, besides the Upper Terrace, only the youngest, the Lowermost Terrace occurs in this

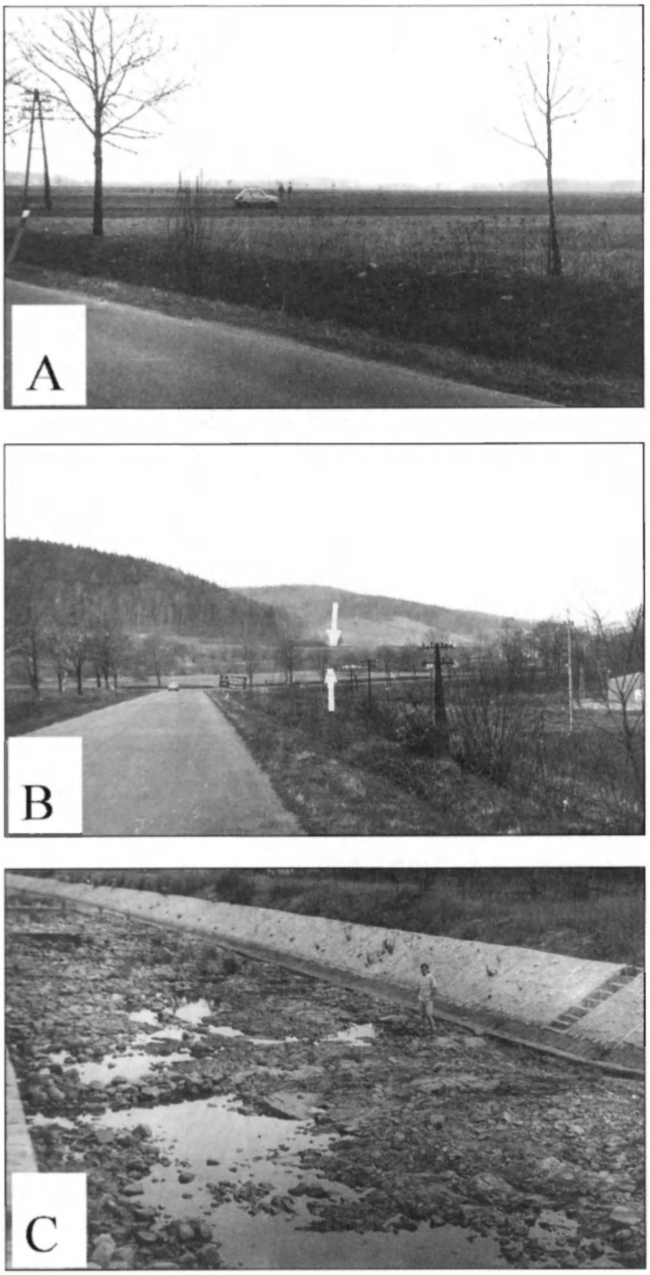


Fig. 12. The Bystrzyca river valley near the Sudetic Marginal Fault: **A** – the foremountain alluvial fan of the Upper Terrace; **B** – the fault scarp truncating the Upper Terrace surface, arrows indicate the base and top of the scarp, which is about 20–25 m high; **C** – bedrock channel in the Sudetic Marginal Fault zone of the valley.

zone. The Middle and Lower Terrace deposits have been eroded from this zone (Fig. 5). The Lowermost Terrace fills a narrow and shallow channel cut directly in the bedrock. The bedrock channel, with rapids and small waterfalls, has been observed frequently (Fig. 12C). Moreover, the increased sinuosity of the river is clearly visible, with the largest meander just on the fault line (Fig. 5).

AGE OF TERRACES

The 100–120 m terrace level is probably of Pliocene age. This is a highly speculative conclusion. However, the fluvial system of this age has been proposed in other large valleys of the Sudetes (Krzyszkowski *et al.*, 1998) and Pliocene fluvial deposits are common in the Sudetic Foreland (Przybylski *et al.*, 1998), including the foremountain part of the Bystrzyca river valley (Krzyszkowski & Bowman, 1997). The Preglacial fluvial series that overlies the Miocene clays consists of two stratigraphic units in the Sudetic Foreland. The lower unit, presumably of Pliocene age and deposited by sinuous rivers, is mainly formed of gravel and sand, with numerous silt/clay beds. In turn, the upper unit, presumably of Early Pleistocene age, is gravel-dominated and represents the alluvial fan and/or braided river sedimentary sequences. This two-fold division is also visible in the Preglacial series in the borehole at Swidnica-Kraszowice (Fig. 13) and in outcrops at Bojanice (Fig. 2) (Krzyszkowski & Bowman, 1997). Hence, it seems that the sediments of the lower unit of the Preglacial series may represent an age equivalent series to the oldest terrace in the mountainous valley (400–420 m a.s.l. shelves). Consequently, the upper unit of the Preglacial series represents an age equivalent series to the erosion phase that formed a major part of the Bystrzyca river valley (alluvial fan deposits) (Fig. 15). During that time and during the forthcoming glaciation, Pliocene fluvial gravels might have been completely eroded in the mountainous zone.

The Pleistocene terraces can be subdivided into two groups, depending on their relationship to the glacial deposits in the valley. The Main Terrace is covered by till, whereas all other terraces are younger than the glaciation. In one case, the fluvial gravels of the Upper Terrace lie directly on this till (Fig. 6).

We assume that all glacial deposits in the Bystrzyca river valley were deposited during one glacial episode, presumably during the latest advance of the Scandinavian ice sheet in the region – during the early Saalian (Odranian) stage (Schwarzbach, 1942; Jahn 1960; Jahn & Szczepankiewicz, 1967; Krzyszkowski *et al.*, 1995). Augustyniak (1992) assumed two glacial episodes, during the Elsterian and the early Saalian, based on lithological changes between the lower, clayey, and upper, sandy till at Zagórze (ZG/1). However, the clay increase in the basal till can be easily explained by the nature of subglacial processes and the redeposition of underlying varved clays. Moreover, the fluvial gravels of the Main Terrace in the mountaineous region do not contain northern rocks (Fig. 16). This suggests that no older glacial cover existed in the mountain valley prior to the formation of the Main Terrace fluvial gravels. Krzyszkowski (1993) suggested that the Main Terrace fluvial deposits lie in between the Elsterian and early Saalian tills in the foremountain zone. However, these deposits contain northern rocks.

The precise age of the terraces cannot be established, as the fluvial deposits do not contain any palaeobotanical or palaeontological evidence. Also, all the younger fluvial deposits have very similar gravel assemblages, preventing

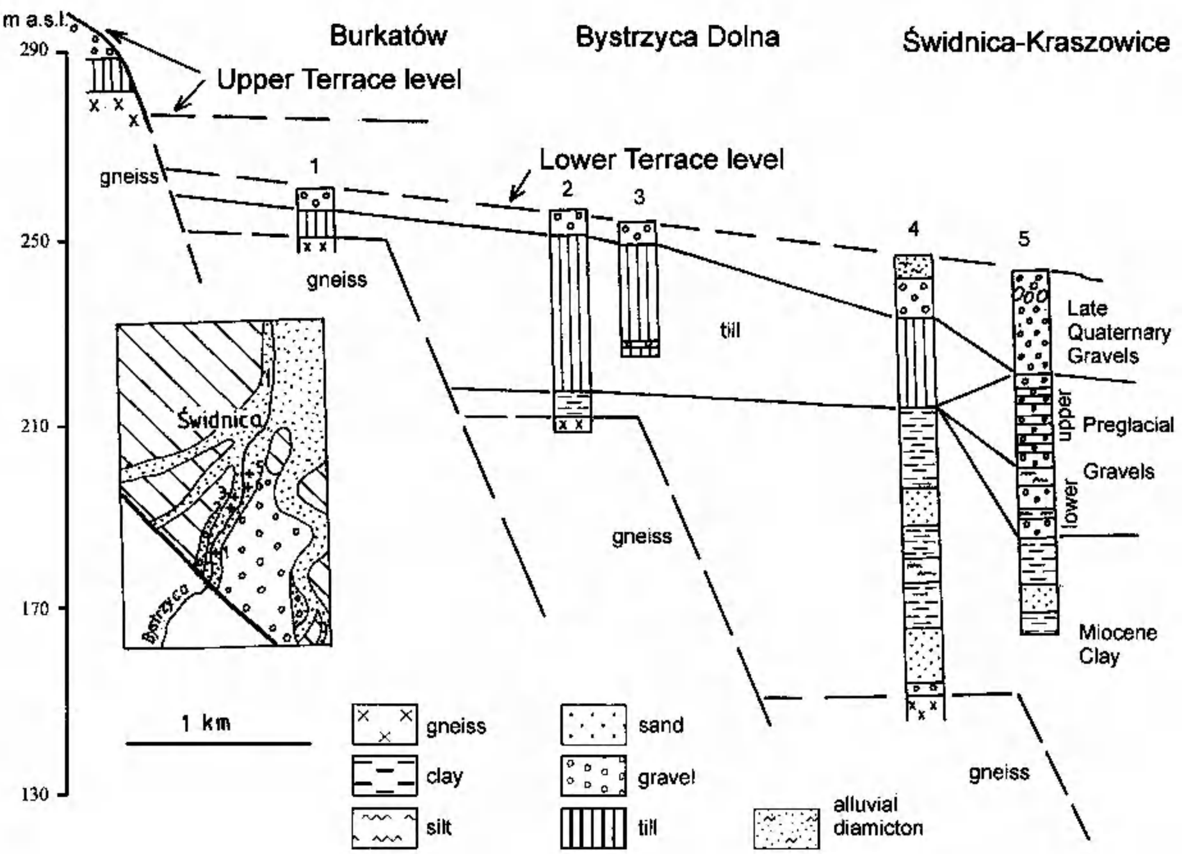


Fig. 13. Geological cross section throughout the foremountain graben between Burkatów and Świdnica-Kraszowice; note that the Preglacial series consists of two lithological units and that the thickness of the Pleistocene gravels increases downstream. Location of boreholes in the insert-map.

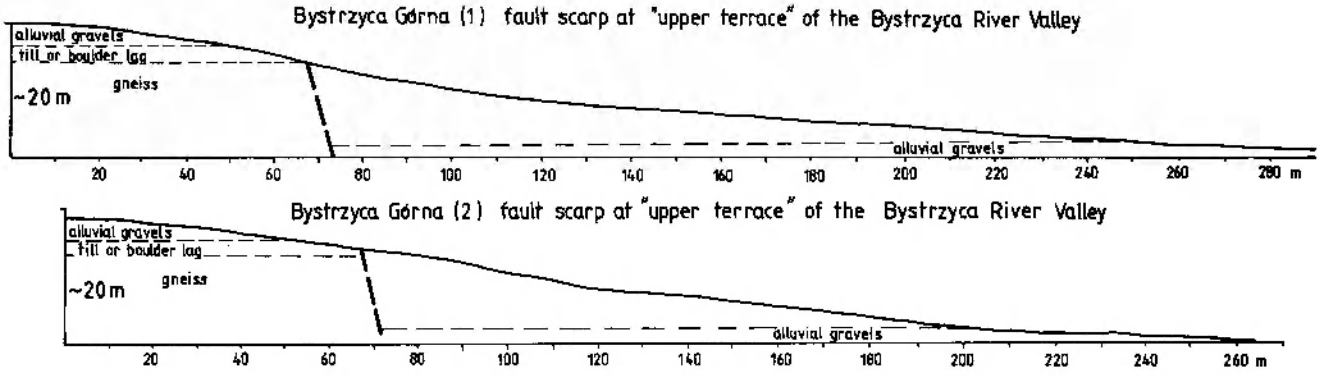


Fig. 14. Tha fault scarp indication as evidenced in the field (measurements have been taken every 1 m using the compass inclinometer); the maximum slope inclination is 15°.

their lithostratigraphic subdivision (Fig. 16). Thus, only terrace morphology and their position in the sequence define their possible ages. The Main Terrace is roughly correlated with the Elsterian/Saalian ice-free period, being, most probably, initiated during the Holsteinian. The younger terraces in the Sudetes are conventionally attributed to the late Saalian/Eemian (Upper Terrace), Middle Weichselian (Middle Terrace), Lateglacial/early Holocene (Lower Terrace) and medieval times to recent (Lowermost Terrace) (Krzyszkowski & Pijet, 1993; Krzyszkowski *et al.*, 1995; Krzyszkowski & Stachura, 1998; Krzyszkowski *et al.*, 1998).

PHASES OF EROSION AND NEOTECTONIC ACTIVITY

Three phases of increased erosion, which most probably coincide with tectonic uplift, can be recognized within the Bystrzyca river valley. The main valley and the 100–120 m terrace were formed during the first erosion phase. This was probably connected with the Early Pleistocene uplift of the Sudetes. If erosion directly followed uplift, the total uplift at that time can be assumed to be 60–70 m This gives a minimum uplift rate of around 0.03–0.04 mm/yr, if the tectonic movement was continuous throughout the Early Pleistocene (Fig. 15).

The next distinct erosion took place after glaciation, when the level of the Upper Terrace and the river gorges were formed. At that time processes of erosion and sedimentation were very similar in the mountainous and in the foremountain regions. This was connected with postglacial glacio-isostatic rebound and the lowering of the base level. In the mountainous region, the old valley was to a major extent exhumed, but several new, epigenetic valley sections were incised directly into the bedrock (Fig. 4). The formation of the postglacial valleys was very fast, giving erosion rates in the bedrock gorge of up to 2 mm/year. The exhumed and new valleys are about 10–20 m deeper than the older fluvial level (the height difference between the Main and Upper Terraces), which may also indicate the relative uplift of the mountainous region at that time. Similar, 20–30 m deep erosion was observed in the foremountain region (Krzyszkowski, 1993).

At the end of the postglacial period (late Saalian/early Eemian), the isostatic rebound was supplied by tectonic activity. The foremountain zone become relatively stable, whereas the mountain zone was uplifted some 30 m, as indicated by the truncation of the Upper Terrace along the Sudetic Marginal Fault. This tectonic movement, although most probably reactivated due to glacio-isostatic movements, represents endogenic processes. The total postglacial uplift in the Bystrzyca river valley, including the glacio-isostatic and tectonic components, is about 40–50 m.

The last phase of erosion led to the formation of a set of younger terraces. Their formation was undoubtedly connected with changes of climate and base level during the Late Pleistocene (Eemian, Weichselian, Holocene). The erosion rates at that time were quite high (about 0.2 mm/yr). Moreover, many features, such as the formation of a narrow bedrock channel and its increased sinusosity on the fault line may suggest that fluvial erosion since the beginning of the Upper Pleistocene has been partly driven by localised tectonic movements (Ouchi, 1983; Schumm, 1986). This tectonic activity was, however, much lesser than during the postglacial period, and it diminished in time, as marked by the terrace heights (Fig. 15).

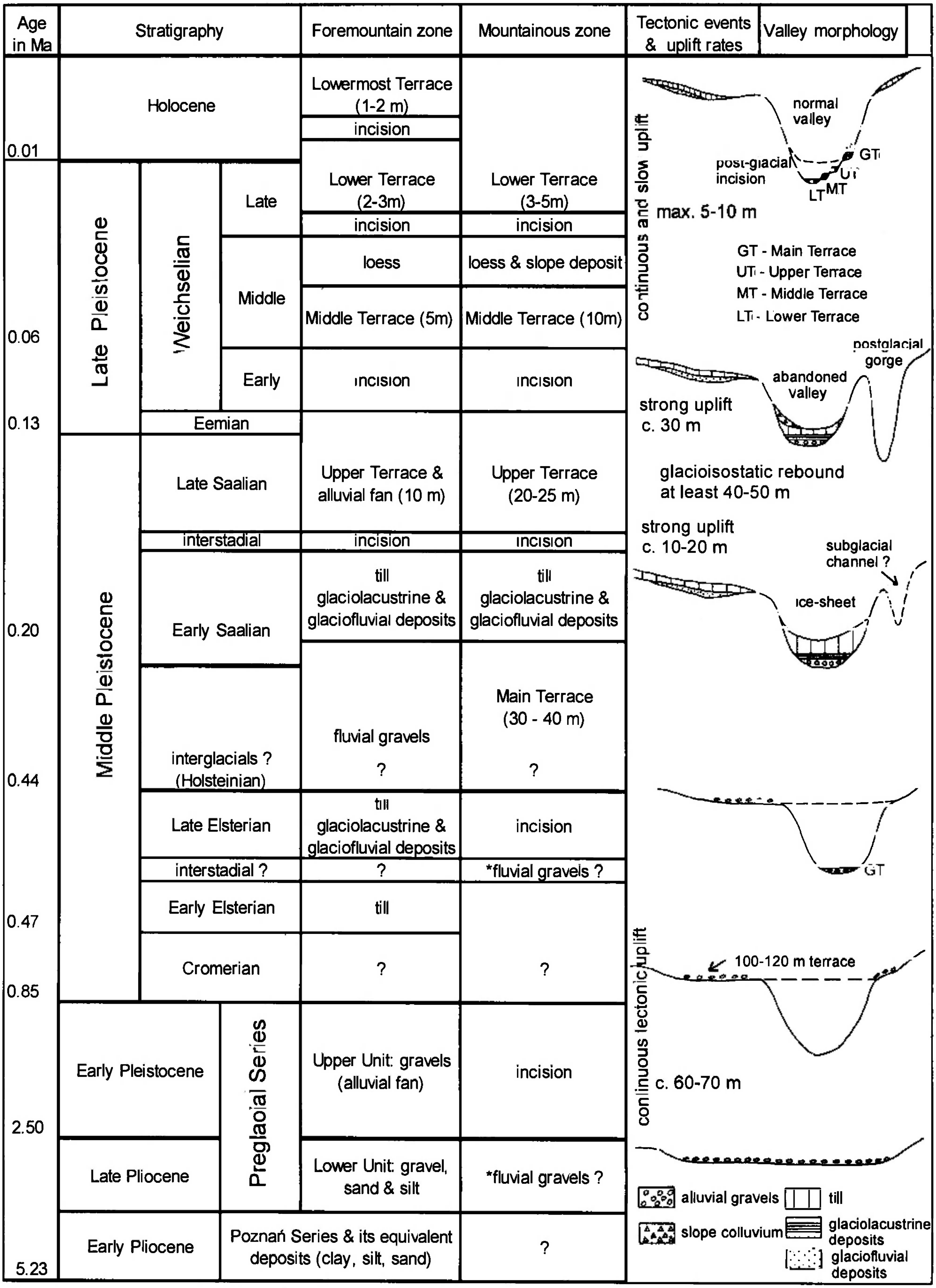
From the above it follows that the Sudetic Marginal Fault zone was tectonically active during at least three different episodes during the Pleistocene. The tectonic displacement during the first, Early Pleistocene phase, was about 60–70 m. The next stage of tectonic activity, connected with glacio-isostatic rebound after the early Saalian glaciation, was supplied by endogenic forces, and gave a total displacement of about 40–50 m. Later, during the Upper Pleistocene, tectonic activity was much less pronounced, providing less distinct fault scarps and increased erosion rates along the fault zone. Tectonic displacement during or after the formation of the Middle and Lower Terraces might have been about 5 m and 2–3 m, respectively, taking into account the height differences between equivalent terraces in the mountain zone and its foreland (Fig. 15).

EVOLUTION OF THE BYSTRZYCA RIVER VALLEY: DISCUSSION AND CONCLUSIONS

There are three stages in the evolution of the Bystrzyca river valley. They can be dated back to the Pliocene, the Early to late Middle Pleistocene, and the late Middle Pleistocene to Recent. Each of them was characterized by specific landscapes, fluvial processes and neotectonic activity.

The Pliocene landscape around the Bystrzyca river valley was rather flat to hilly, with a weakly developed margin of the mountains. The valleys were shallow and wide, both in the present-day mountainous region as well as in its foreland, most probably with sinuous rivers. The 100–120 m terrace, if it really represents the Pliocene surface, is the best developed feature of this age in the Middle Sudetes. The scarp of the Sudetic Marginal Fault, did not exist or was very low that time. This tectonic line was probably marked by the occurrence of small hills with exposed bedrock. The scarp of the Sudetic Marginal Fault and the mountain landscape with deeply incised valleys were formed in this region only during the Early Pleistocene tectonic phase. This may be inferred from data from the Nysa Klodzka river valley (Krzyszkowski *et al.*, 1998), where the upper age boundary of preglacial fluvial deposits inside the mountainous region was dated palaeobotanically to the late Pliocene. During the Early Pleistocene, the mountainous region was continuously eroded, with the formation of alluvial fans in the mountain foreland (Krzyszkowski & Bowman, 1997; Krzyszkowski *et al.*, 1998). A more precise interpretation of events during the early stages is impossible, as, in fact, there are no deposits of this age in the Bystrzyca river valley and those of the foremountain region are very homogenous (gravels). There is a hiatus until the Middle Pleistocene, when the valley was filled with the gravels of the Main Terrace.

The last stage of the valley development is the most complex one. It may may be subdivided into several substages, during each of which one of three general morpho-



Age in Ma	Stratigraphy			Foremountain zone	Mountainous zone	Tectonic events & uplift rates
	Holocene			Lowermost Terrace (1-2 m) incision		continuous and slow uplift max. 5-10 m
0.01	Late Pleistocene	Weichselian	Late	Lower Terrace (2-3m) incision	Lower Terrace (3-5m) incision	
			Middle	loess Middle Terrace (5m)	loess & slope deposit Middle Terrace (10m)	
0.06			Early	incision	incision	strong uplift c. 30 m
0.13		Eemian				
	Middle Pleistocene	Late Saalian		Upper Terrace & alluvial fan (10 m)	Upper Terrace (20-25 m)	glacioisostatic rebound at least 40-50 m
		interstadial		incision	incision	strong uplift c. 10-20 m
0.20		Early Saalian		till glaciolacustrine & glaciofluvial deposits	till glaciolacustrine & glaciofluvial deposits	
0.44		interglacials ? (Holsteinian)		fluvial gravels ?	Main Terrace (30 - 40 m) ?	
		Late Elsterian		till glaciolacustrine & glaciofluvial deposits	incision	
		interstadial ?		?	*fluvial gravels ?	
0.47		Early Elsterian		till		continuous tectonic uplift
0.85		Cromerian		?	?	
2.50	Early Pleistocene	Preglacial Series		Upper Unit: gravels (alluvial fan)	incision	c. 60-70 m
	Late Pliocene			Lower Unit: gravel, sand & silt	*fluvial gravels ?	
5.23	Early Pliocene	Poznań Series & its equivalent deposits (clay, silt, sand)			?	

Fig. 15. The fluvial and glacial stratigraphy in the Bystrzyca river valley.

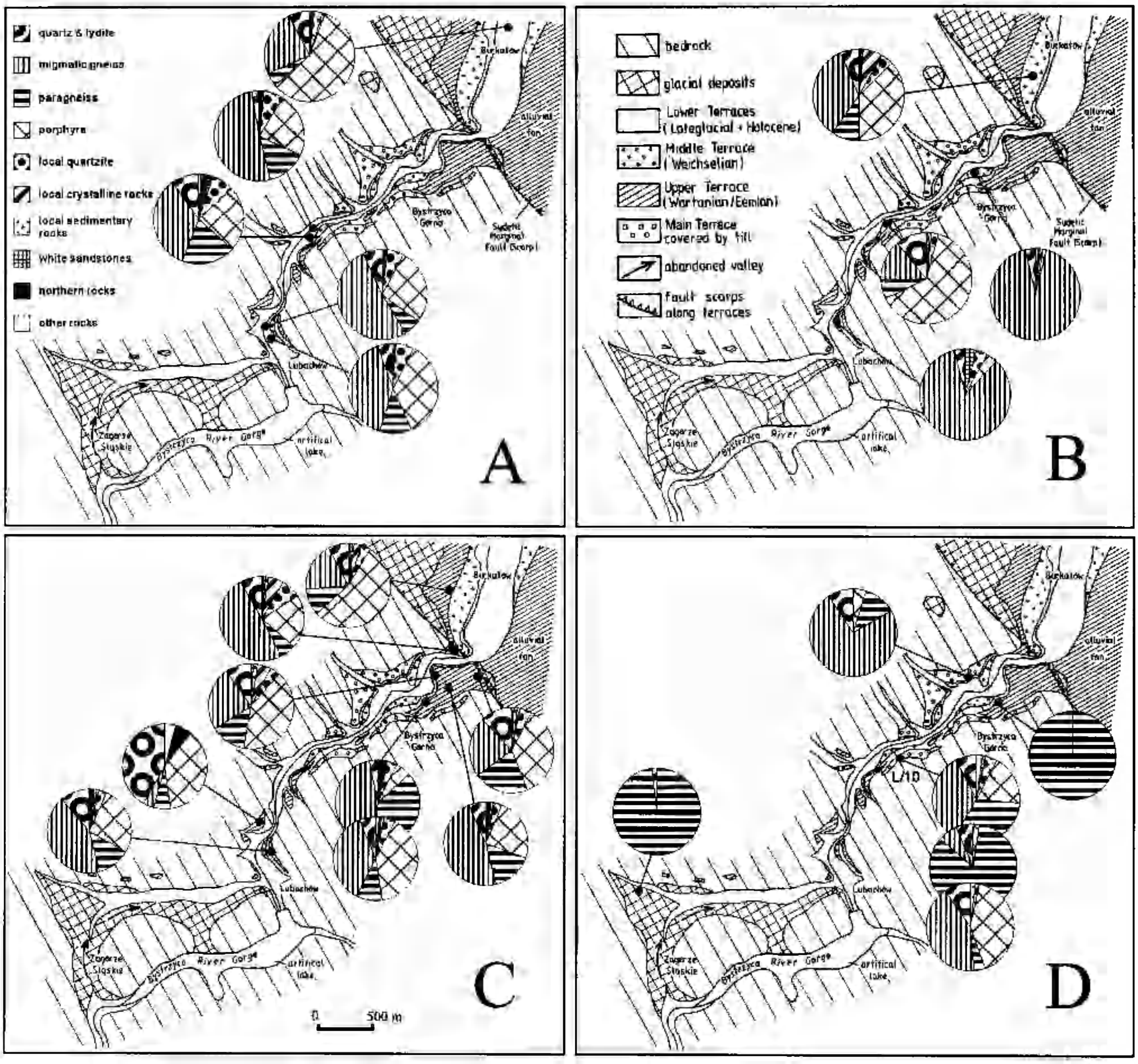


Fig. 16. Petrography of fluvial gravels and the till of the Bystrzyca river valley: **A** – Lower Terrace, **B** – Middle Terrace, **C** – Upper Terrace, **D** – Main Terrace gravels (L/10) and tills.

genetic factors, namely fluvial activity, glacial erosion and sedimentation and tectonic uplift, prevailed.

Badura *et al.* (1992, 1998) have stated that three Scandinavian ice-sheets advanced to the margin of the Sudetes Mts, including two advances during the Elsterian stage. The Elsterian ice sheet entered into the mountain interior in the Klodzko Basin in the south (Krzyszkowski *et al.*, 1998) and at least into the marginal part of the Wałbrzych Upland in the north (Krzyszkowski & Stachura, 1998). However, there are no data that confirm the occurrence of Elsterian glacial deposits in the mountainous part of the Bystrzyca river valley. This suggests that prior to the Elsterian ice-sheet advance, the Bystrzyca valley could only have been blocked by the ice and, probably filled with sediments. However, such sediments are not preserved, possibly became of extensive post-Elsterian erosion. The latter could have been induced either by glacio-isostatic rebound or by base level lowering. The early Saalian ice sheet advanced into the mountain interior from the northeast, forming at first deep proglacial lakes (varved clays), and later, during its final advance, leaving till (Berg, 1909; Schwarzbach, 1938, 1940). Till fabric at Zagórze (Schwarzbach, 1940) indicates that the local ice sheet advance along the valley follows the regional advance (Krzyszkowski & Czech, 1995; Badura *et al.*, 1998). The till mainly contains local gneiss and some quartz and porphyry, with the northern component limited to boulders only. This may suggest that the older fluvial series (Main Terrace deposits) was only a limited source of the material in the till, and that the major glacial erosion took place in the gneissic bedrock. Again, this is in good agreement with the northeasterly advance; in the case of an advance from the north

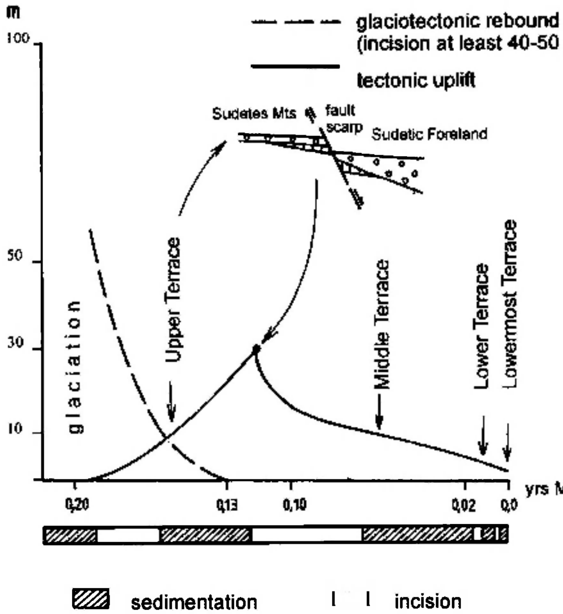


Fig. 17. Possible rates of glacio-isostatic and tectonic displacement in the Bystrzyca river valley and position of Late Pleistocene stages with fluvial erosion and sedimentation.

or northwest amounts of material from the Central Sudetic Depression (porphyry, quartz, conglomerates, spilites and metamorphic schists) would have been higher.

The post-glacial history of the Bystrzyca river valley, and especially the formation of narrow gorges, has been something of a mystery since Berg's (1909) time. Post-glacial erosion, at least in the Zagórze gorge, started from the new, initial level of 420–440 m a.s.l.. This erosion cannot be explained by drainage of the proglacial lake, as lacustrine deposits were formed during the ice sheet advance and are covered by the till. This suggests that glacial deposits, including those from the retreat phase, filled the valley up to the level 420–440 m a.s.l., enabling post-glacial rivers to shift away from the main valley to the adjacent bedrock plains. However, there are no field data that suggest that the glacial cover could have been 100 m thick in the mountain valley. It may be that the new valley started from a substantially lower initial level, using a former subglacial channel (Augustyniak, 1992).

The post-glacial fluvial erosion and sedimentation have been influenced by varying uplift rates. At first, erosion prevailed due to strong glacio-isostatic uplift. As a result, the old valley was completely exhumed, except for the abandoned fragments, and a major part of the glacial deposits removed. This uplift probably diminished quickly (Fig. 17), and fluvial sedimentation started, forming the level of the Upper Terrace. At this stage, tectonic uplift became greater than that caused by glacio-isostasy, and as a result, different shapes of fluvial activity prevailed in the mountains and in its foreland. The slow uplift in the mountainous zone led to the formation of only thin alluvial sequences (1–5 m), characteristic of rivers with balanced erosion and sedimentation. At the same time, 20–30 m thick alluvial sequences (alluvial fan) were deposited in the mountain foreland. Finally, the uplift rate increased, ending the fluvial sedimentation on the Upper Terrace level and beginning a new erosion stage. The fault scarp along the Sudetic Marginal Fault at Bystrzyca Górna was formed (Fig. 5, 6, 12B). This is the best example of a fault scarp in the Sudetes Mts, and is not only morphologically well developed, but also gives rise to a distinct index layer (till) that has been displaced by the fault. Other fault scarps in the Sudetes Mts have only been defined by morphological criteria (Krzyszkowski *et al.*, 1995). The features indicating a tectonic influence on fluvial processes during the formation of the Late Pleistocene terraces, such as the increase of the thickness of fluvial deposits in the foremountain zone, the rapid change of terrace height (and the formation of fault scarps) and the increased erodibility along fault lines, are similar to those of the Upper Terrace. The differences are only in the scale of the response, as the uplift was substantially less during the Late Pleistocene (Fig. 17).

The type of fluvial sedimentary environments probably does not coincide with changes of uplift rates. The deposits of the Lower Terrace were deposited by a sinuous to meandering river, with well developed channel and overbank facies. The Middle and Upper Terrace sequences are thin, and formed only of gravels. This may suggest a braided river system, although the small thickness of fluvial deposits makes a final conclusion almost impossible. The same problem occurs within the sediments of the Main Terrace. The sequences of the mountain foreland were deposited on fluvial processes-dominated alluvial fans.

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