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PLEISTOCENE EVOLUTION OF FAULT-LINE SCARPS IN THE NORTHERN MARGIN OF THE KRZESZOWICE GRABEN, SOUTH POLAND

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Abstract

The paper aims at reconstructing Pleistocene slope processes and transformation of tectonic relief in two sections across the northern margin of the Krzeszowice Graben. The investigations are based on the analysis of deposits present on the slopes of fault-line scarps. The lithology and stratigraphy of these deposits was reconstructed based on analysis of outcrops and boreholes. Detailed lithological logs were prepared, along with grain size analyses, and determination of $CaCO_3$, Fe_2O_3 and C_{org} contents in fine-grained sediments.

The studied fault-line scarps were transformed by Pleistocene denudation. The type and intensity of these processes were different in the sections studied. In the Będkowice area, accumulation prevailed; the fault-line scarp became covered with sediments. In the Karniowice area, in turn, periglacial processes caused degradation of the fault-controlled slope. In the lower part of the fault-line scarp, the intensity of degradation processes was limited by repeated presence of sediment cover which preserved the substratum.

Differences in the intensity and type of Pleistocene denudation can be explained by different heights of fault-line scarps, controlled by tectonic structure and neotectonic movements.

Key words: fault-line scarp, slope deposits, periglacial processes, neotectonics, Krzeszowice Graben, South Poland

INTRODUCTION

A fault scarp is a steep slope present on the surface upon a fault (Zuchiewicz 2004). Since its origin, the fault slope is transformed by weathering and slope processes. The relief of fault escarpments is therefore a result of interaction between tectonics and denudation processes.

The development of denudation processes modelling fault escarpments is controlled by tectonic structure (slope height and inclination), rock resistance and climate (*e.g.* Cotton 1950, Goldsworthy, Jackson 2000). The type and intensity of denudation processes determine evolution of a tectonic relief. Models of fault escarpment transformation were produced (Wallace 1977, Mayer 1986, Nash 1986, Carretier *et al.* 2002) as a result of analysis of depositional and erosional processes.

The results of investigations on the evolution of fault scarp topography provide valuable data to interpretation of its origin. Reconstruction of original morphology helps to investigate tectonic structure. The rate of degradation of fault and fault-line scarps can suggest the lack of tectonic stability in the area. Neotectonic movements led to changes of denudation base and influence upon the intensity of erosion and exposition of the bedrock to weathering processes, which consequently control the intensity of degradation processes.

In a study of denudation processes modelling fault escarpments, grain-size analysis plays an essential role. This is confirmed by investigations of both marine (deep-sea) (*e.g.* Fielding *et al.* 1997, Kim *et al.* 2003) and terrestrial slope deposits (*e.g.* Postma 1998, Nelson 1992).

The results of investigations of slope deposits in the southern part of the Ojców Plateau and in the northern margin of the Krzeszowice Graben (Fig. 1) encouraged the author to take up research on the evolution of fault-line scarps. An attempt was made to reconstruct the development of their relief during the Pleistocene. The results of these investigations may contribute to the interpretation of tectonic structures of the Krzeszowice Graben.

STUDY AREA

The area studied includes the southern part of the Ojców Plateau and the northern margin of the Krzeszowice Graben (Fig. 2). Within the Ojców Plateau, Pleistocene sediments overlie Upper Jurassic limestones and locally Upper Cretaceous strata (Dżułyński 1952, Matyszkiewicz 1997), as well as residua of Tertiary karst weathered deposits (Felisiak 1992). In the Krzeszowice Graben, Mesozoic rocks are covered by marine Miocene strata (Rutkowski 1993). Pleistocene sediments in the study area include glaciogenic residua connected with the South-Polish (Elsterian) glaciation (Walczak 1956, Rutkowski 1993) and periglacial sediments represented by loess and scree debris slope deposits (Walczak 1956, Alexandrowicz 1995, Pawelec 2004, 2005, 2006). The

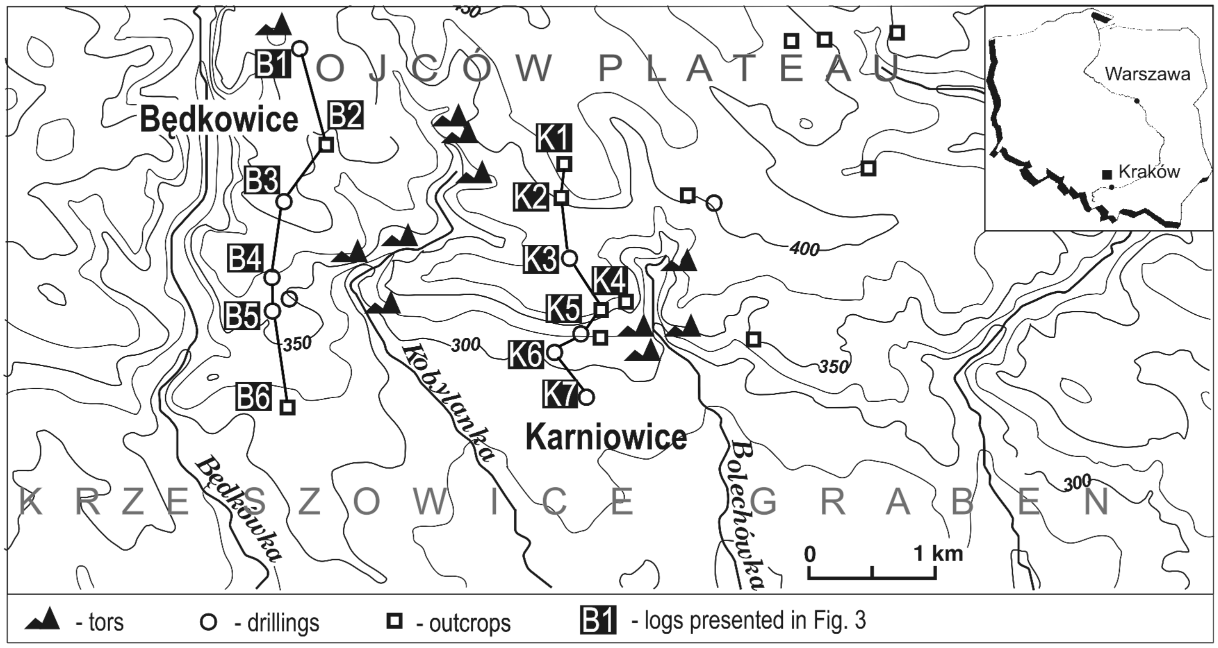

Fig. 1. Location of the study area between the Ojców Plateau and the Krzeszowice Graben.

northern margin of the Krzeszowice Graben is composed of a system of Palaeogene and Neogene, WNW–ESE oriented, fault steps whose surfaces are steeply inclined towards the graben axis (Dżułyński 1953, Bogacz 1967, Rutkowski 1986,1989, Felisiak 1992) (Fig. 2B).

A typical feature in the relief of the southern part of the Ojców Plateau is an undulating (locally flat) surface overtopped by limestone rocky hills. River valleys of general N–S orientation dissect the area. The upper parts of the valleys represent shallow, trough-like morphology. In their lower courses, they change into V-shaped valleys that, near the margin of the Krzeszowice Graben, turn into deep ravines with rocky slopes. The fault zone is clearly visible in the landscape in the form of a scarp, 30 to 100 m high.

Some data indicate that after the Miocene, periods of reactivation of vertical movements occurred in the northern margin of the Krzeszowice Graben. Neotectonic activity in this area is also confirmed by observations of modern relief

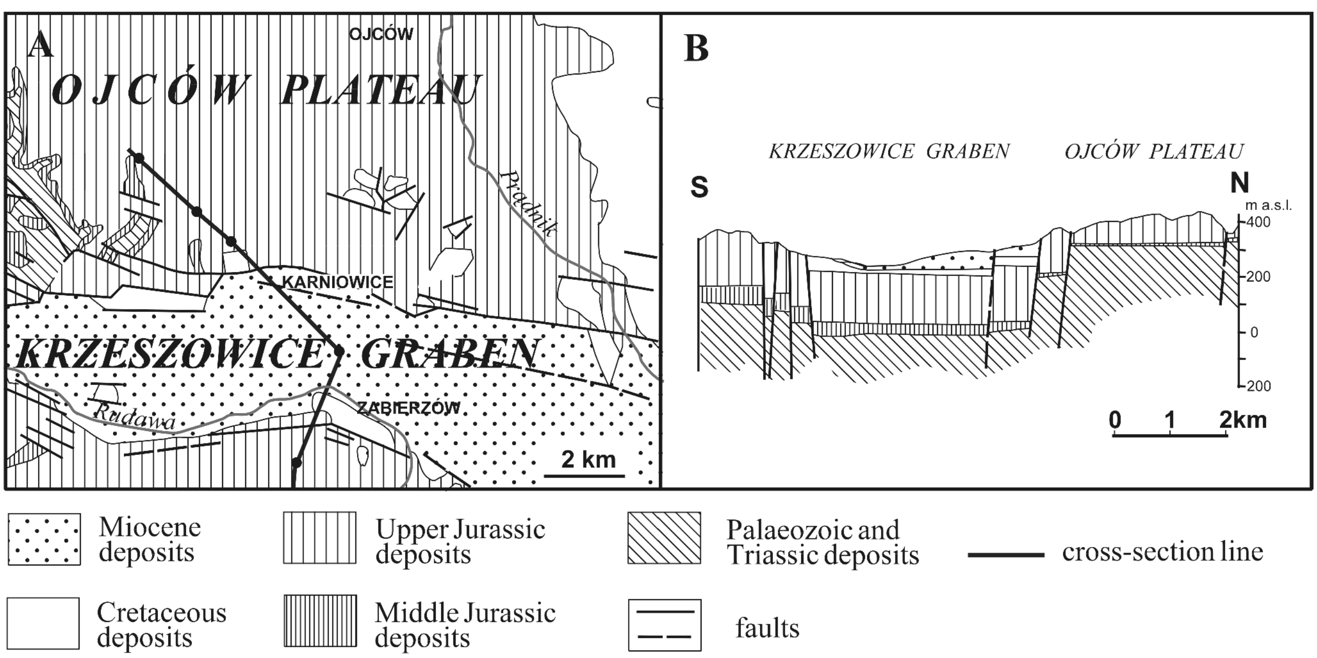

Fig. 2. **A** – Geological map of the Cracow Upland, without Quaternary; **B** – Cross-section (after Rutkowski 1986, simplified and modified).

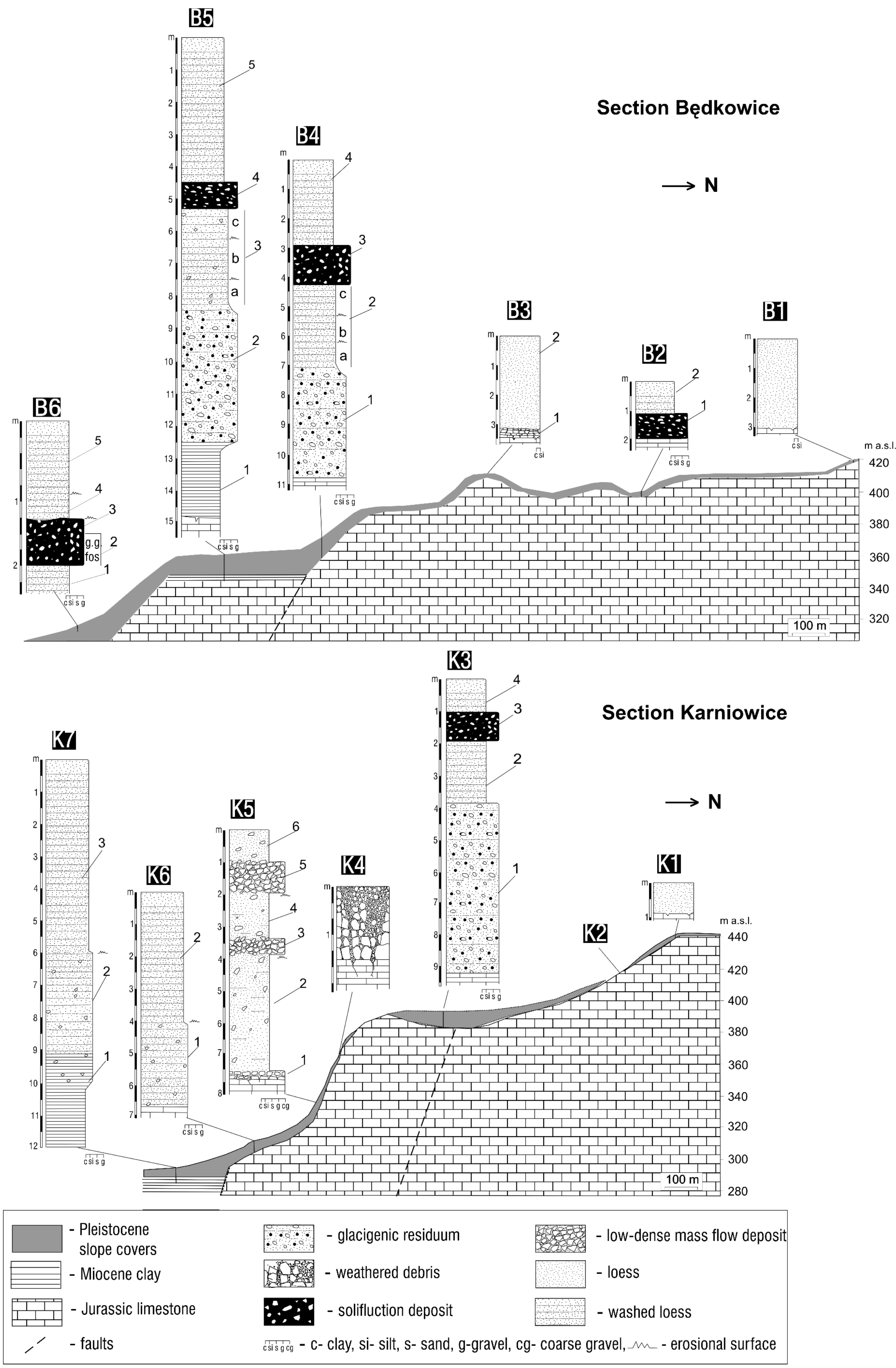

Fig. 3. Lithology of slope covers in the northern margin of the Krzeszowice Graben.

in the southern part of the Ojców Plateau, as well as by research results concerning relief evolution in the Pliocene and Pleistocene. The main morphological features pointing to neotectonic activity of the area include breaks in longitudinal valley profiles, as well as hanging valleys (Blackwelder 1928, Migoń 1995). The presence of flat hilltops and deep valleys, according to theoretical models of landscape development (Kennedy 1962, Hovius 1999), points to relief development proceeding during uplift dominating over fluvial erosion and, simultaneously, the latter dominating over slope processes.

The studies focusing on relief evolution of the southern part of the Ojców Plateau revealed intensive erosion and denudation during the Pliocene and Pleistocene. These processes resulted in considerable reduction of karstic Tertiary eluvial covers (Felisiak 1992) and sediments of Early and Middle Pleistocene age (Alexandrowicz 1995, Rutkowski 1996, Pawelec 2005). During the Pleistocene, according to Madeyska (1977), valley bottoms in the southern part of the Ojców Plateau were dissected to a depth of 50 m. Lewandowski (1993, 1995), basing on investigations of buried river valleys in the Carpathian Foredeep, distinguished two phases of tectonic rejuvenation during the Pleistocene; the Early and the Middle Pleistocene ones.

The studies of slope deposits were based on an analysis of outcrops and boreholes distributed in two N–S oriented cross-sections, along the Będkowice-Karniowice line (Fig. 1). Detailed lithological sections were constructed, grain-size analyses were made, and the $CaCO_3$, Fe_2O_3 and C_{org} contents within fine-grained sediments were determined.

SLOPE DEPOSITS

The description of slope deposits concentrates on distribution of individual types of sediments in relation to the fault scarp morphology. The detailed sedimentological analysis of slope deposits present in the southern part of the Ojców Plateau has been already published elsewhere (Pawelec 2004, 2006).

Będkowice cross-section

The Będkowice cross-section runs along a watershed zone between the Będkowska Valley and Kobylańska Valley (Fig. 1). This zone contains shallow, trough-like initial segments of lateral valleys. In this area, the plateau surface lowers with gentle steps towards the Krzeszowice Graben.

In the northern part of the cross-section, the thickness of slope covers is small. Gently inclined watershed areas built up of Upper Jurassic limestones are overlain by up to 3 m thick loess, showing lithological features of the youngest loess horizon (Fig. 3 – B1). In flat areas, the lower part of loess contains angular limestone debris, which originated due to frost weathering (B3, **1** and **2**). In the initial, trough-like parts of the valleys, the Jurassic limestones are covered by solifluction deposits (massive, matrix-supported diamictons), which are overlain by loess deluvia (laminated silts), originated due to washing of the youngest loess horizon (B2, **1** and **2**).

In the southern part of the cross-section, along the margin, a continuous cover of slope deposits of considerable thickness (up to 13 m) occurs. The cover consists of the following sediment types (listed in stratigraphic order):

– **glaciogenic residuum** – sands with gravels of Scandinavian rocks, up to 4.5 m thick. It occurs directly above the Jurassic substratum (B4, **1**) or above the Badenian clay (B5, **2**);

– **washed loess** – laminated silt (B4, **2**; B5, **3**; B6, **1**). Three horizons of loess deluvia (a, b, c) of total thickness up to 4 m were found above glaciogenic residuum. These sediments differ from deluvium of the youngest loess horizon in the content of colloidal clay, Fe_2O_3, C_{org} and colour, showing also differences in individual deluvium horizons. It may be assumed that these sediments originated as a result of an older phase of washing (preceding accumulation of the youngest loess horizon). They contain material derived from the washed-out older loess horizons. They became transformed by soil processes. Deluvia represent a product of soil denudation, which originated from loess deposits in warm stages of the Pleistocene. They point to a cyclic degradation of loess covers, influenced by wet climatic phases (Jersak *et al.* 1992);

– **solifluction deposit** – massive, matrix-supported diamictons with loess matrix (B4, **3**; B5, **4**; B6, **2** and **3**). At the escarpment foot, two horizons of solifluction deposits were recognised (B6, **2** and **3**). They are divided by a gley soil (developed on the substratum of the lower horizon). This soil is 0.4 m thick and shows features of a typical pseudogley soil the Komorniki Complex (Jersak 1973). It contains ferruginous, columnar (vertical, up to 20 cm high) or spherical (up to 5 cm in diameter) concretions and also concretions of the “pepper” type. This horizon consists of silty clay (17% of colloidal clay), up to 0.27% of C_{org} and 2.2% of Fe_2O_3. It is carbonate free. Pseudogley conditions of soil formation are suggested by the lack of gleying traces in the deluvia present under the soil. The soil of the Komorniki type marks the last (Grudziądz) interstadial stage (Jersak 1973). Section B6 documents development of solifluction processes before and after soil formation. Slope deposits of the Komorniki Horizon were found in loess sections of the Kraków area. At Odonów II (Dwucet, Śnieszko 1996), washing phases at the beginning and end of the Komorniki Horizon were documented, along with activity of slope processes during the formation of gley soil. Slope deposits older than gley soil occur in the Kraków-Zwierzyniec section (Konecka-Betley, Madeyska 1985), at Spadzista (Kozłowski, Sobczyk 1987), and at Szczyglice (Racinowski *et al.* 1994);

– **washed loess** – laminated silts. In the study area they form a continuous cover, up to 4.6 m thick (B4, **4**; B5, **5**; B6, **5**). These sediments record the development of washing-out after the sedimentation of the youngest loess horizon. At the escarpment foot, two horizons of loess deluvia divided by erosion surface overlie solifluction sediments. The lower horizon (B6, **4**) consists of deposits considerably transformed by gley processes. This deluvium resulted from washing-out of loess deposits, which had been transformed earlier by gley processes. Probably, they may be correlated with the upper part of the Komorniki Horizon – the decline of the Grudziądz interstadial stage.

Karniowice cross-section

The Karniowice cross-section runs along the watershed zone between the Kobylańska Valley and Bolechowicka Valley (Fig. 1). In this area, the plateau surface passes in a few steep steps to the Krzeszowice Graben.

In the northern part of the cross-section, the youngest loess horizon occurs as a discontinuous cover upon Upper Jurassic limestones (Fig. 3 – K1, K2). Only in flat areas with shallow trough-like initial valleys (K3), slope deposits do show considerable thickness (9.5 m). Their lithology and stratigraphy are similar to those present in sections B4 and B5.

In the southern part of the cross-section, a steep, *ca.* 100 m high, fault-line scarp occurs, whose upper part is dominated by exposures of Upper Jurassic limestones. Locally, in flat areas on top of the limestones, scree deposits (resulting from frost weathering) are present (K4). The lower part of the escarpment is built up of the youngest loess horizon (K5, **2**), which overlies scree deposits (K5, **1**). The loess deposit contains rare fragments of limestones and flints, and debris intercalations (massive, clast-supported diamictons with loess matrix), interpreted as flow deposits of small density (K5, **3** and **5**). At the foot of the escarpment, Jurassic limestone (K6) or Badenian clay (K7) is overlain by washed loess (laminated silts). Two horizons of loess deluvium were found, of total thickness up to 9 m. The lower horizon (K6, **1**; K7, **2**) consists of considerably gleyed silty clay (blue-grey sediment containing numerous ferruginous-manganese concretions). Probably, these sediments can be correlated with the end of the Komorniki Horizon (the last interstadial stage). The upper horizon (K6, **2**, K7, **3**) is represented by deluvia, originated due to slopewash in the upper part of the youngest loess horizon (at the end of the Vistulian).

RECONSTRUCTION OF DEVELOPMENT OF SLOPE PROCESSES

The occurrence of the youngest loess horizon directly on Upper Jurassic limestones in the northern part of the area studied confirms the results of previous studies (Madeyska 1977, Alexandrowicz 1995, Rutkowski 1996) and points to intensive erosion and denudation processes in the period preceding sedimentation of the youngest loess horizon.

In periglacial conditions, the processes of frost weathering and loess sedimentation occurred on gently inclined hilltops. Debris and loess materials were transported by slope processes down the valleys to the Krzeszowice Graben. The type and intensity of slope processes were climatically controlled (Pawelec 2005). These processes are recorded in solifluction and deluvial deposits preserved in shallow, trough-like and hanging initial parts of the valleys. In the area of fault-line scarps, the analysed cross-sections show different structure of slope deposits. This proves that in the two studied scarp sections, the type and intensity of denudation processes were different.

In the area of Będkowice, sediment cover overlies the fault-line scarp. This cover consists of glaciogenic residuum, deluvium and solifluction sediments, which record cyclic intensification of denudation processes in the Pleistocene, influenced by climate. Apart from the youngest deluvium (originated as a result of washing of the youngest loess horizon), there are also deposits correlated with the last interstadial stage (Komorniki Horizon; Jersak 1973), and older deluvial deposits (originated from the washing of older loess horizons). At the escarpment foot, a fossil interstadial soil is preserved. Such a structure of deposits covering the slopes of the fault-line scarp shows that during the Pleistocene accumulation predominated over denudation (negative denudation balance; cf. Jahn 1968). The successive phases of denudation processes did not reach the bedrock, thereby preserving the fault scarp.

In the area of Karniowice, the deposits similar to those of the Będkowice area were found only in borehole located in the bottom of a trough-like initial part of the valley. The fault scarp, before sedimentation of the youngest loess deposit, was not covered by sediments. At the beginning of loess deposition, frost weathering developed on the bedrock, leading to deposition of scree layers at the base of the loess. In the upper part of the fault scarp, weathering processes still proceeded during loess sedimentation. Debris material was deposited by fall processes (individual fragments in the loess section) and by mass flows (diamictons layers intercalated with loess deposits). Following loess deposition, a phase of intensive slopewash occurred, being connected with climatic warming and permafrost thawing. This is recorded in reduction of the loess cover and deposition of deluvium at the foot of the scarp. At the base of the deluvium of the youngest loess horizon, only one older deluvial horizon was recognised which was correlated with the end of the last interstadial stage.

The above analysis shows that in the Karniowice area, development of periglacial processes resulted in degradation of the initial surface of the fault. The intensity of degradation in individual sections of this surface was different. The upper part of the fault scarp was degraded most intensively (by lateral retreat), as a result of frost weathering and mass flows. This led to the development of a steep slope. In the middle part of the escarpment, degradation processes were controlled by periodically occurring sediment cover. The smallest intensity of degradation was confined to the lower part of the scarp. In this area, the sediment covers preserved the limestone bedrock against weathering for the longest period of time. This resulted in development of a gently inclined slope of the pediment type (Penck 1953). Its development was controlled by slopewash and deposition of deluvial material. A similar model of degradation of a fault scarp was documented by Wallace (1977) – piedmont scarp, Nash (1986) – retreating, loosening-limited scarp, and Mayer (1986) – slope replacement.

The present-day location of the northern margin of the Krzeszowice Graben does not follow the fault surface, which became laterally retreated by about several tens of meters. Denudation retreat of the northern margin of the Krzeszowice Graben (by about 60 m) was already documented by Bogacz (1967). It should be underlined that the above results allow one to conclude about denudation processes proceeding during periglacial periods only. According to the published data, in the area of the southern part of the Ojców Plateau, denudation processes have been active since the

Pliocene (Dżułyński *et al.* 1966). At present, it is not possible to estimate quantitatively the rates of Pliocene and Pleistocene denudation in degradation of tectonic scarps.

Different types and intensity of denudation processes in the studied sections were controlled by slope morphology (mainly height). The lithological factor can be excluded, since both sections are built up of Jurassic limestones. Moreover, some data indicate that the height of fault scarps is mainly a function of tectonic uplift and not lithological differences (Zuchiewicz, McCalpin 2000). This shows that height differences of the fault scarps studied can be explain by tectonic structure. Tectonic studies (Bogacz 1967) and facies analysis of Upper Jurassic limestones in the northern margin of the Krzeszowice Graben (Matyszkiewicz, Krajewski 1996) revealed the presence of hinge faults, which show changeable heights of fault scarps.

The northern margin of the Krzeszowice Graben became rejuvenated in the Pleistocene (Felisiak 1992, Lewandowski 1993). It is probable that neotectonic movements (commonly understood as continuation of earlier tectonics) differentiated structural-morphological levels.

CONCLUSIONS

1. Pleistocene denudation processes modified tectonic relief of the northern margin of the Krzeszowice Graben.

2. The type and intensity of these processes in the studied sections of the margin were different. In the Będkowice area, accumulation processes predominated, and the tectonic margin was preserved by a sediment cover. In the Karniowice area, in turn, periglacial processes led to degradation of the fault surface. Lateral slope retreat was the main geomorphic factor. In the lower part of the fault-line scarp, the intensity of denudation was limited by periodical occurrence of sediment covers.

3. Different heights of fault-line scarps, controlled by tectonic structure and neotectonic movements, can be explained by differences in the type and intensity of Pleistocene denudation processes.

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