Studia Quaternaria, vol. 24: 37–45.

YOUNG QUATERNARY FOSSIL GRABEN IN THE VISTULIAN LOESS AT BRZEZIE NEAR KRAKÓW (CARPATHIAN FOREDEEP, SOUTH POLAND)

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Abstract

In this paper we describe a fossil graben and associated normal faults and joints. The graben is situated in the section of the Vistulian (Weichselian) and Holocene sediments in an archaeological excavation site at Brzezie, in the central part of the Polish Carpathian Foredeep (Wieliczka-Gdów Upland, western part of the Sandomierz Basin). Normal faults strike mostly NNE–SSW and dip steeply about 65–85°. Some of them, namely master normal faults, bound the fossil graben. The joints form orthogonal pattern and are closely spaced close to the faults. They developed simultaneously with faulting. Normal faulting took place during the Vistulian – Mesoholocene (Neoholocene?) time, according to the age of archaeological artefacts which were found in the faulted sediments. The faulting was probably finished during the Neolithic or even later, during the Bronze Age. The NNE-striking normal faults connected with graben formation could have been produced by reactivation of a NE-striking sinistral regional fault in the basement.

Key words: loess, normal faults, joints, Carpathian Foredeep, South Poland

INTRODUCTION

The aim of our study is to recognise the origin of a fossil graben situated in the section of Vistulian (Weichselian) and Holocene sediments at Brzezie near Cracow (Carpathian Foredeep, south Poland). The fossil graben was discovered during archaeological rescue research on the A-4 highway, performed by the Institute of Archaeology and Ethnology of the Polish Academy of Sciences, the Archaeological Museum in Cracow, and the Jagiellonian University: Cracow Team for Motorway Survey, Registered Partnership. The detailed sedimentological and mesostructural data obtained from an archaeological excavation site at Brzezie were the base for our study.

GEOLOGICAL SETTING

The study area is situated in the folded part of the central Carpathian Foredeep, directly in front of the Polish Outer Carpathians (Fig. 1). The Carpathian Foredeep is a syntectonic basin, which developed on the Proterozoic–Mesozoic basement, a part of the European Platform (Oszczypko 1998, Olszewska 1999, Krzywiec 2001). This basin is filled mainly with fine-grained clastic strata, which are Early to Middle Miocene in age. Throughout most of the Carpathian Foredeep area, these strata lie mostly sub-horizontally. However, close to the front of the Outer Carpathians, the Early to Middle Miocene strata are strongly folded and thrust to the north. These deformed strata form a narrow belt, called the Zgłobice Unit (Kotlarczyk 1985), where map-scale fold axes and thrust faults trend W–E to WNW–ESE (Kirchner, Połtowicz 1974, Połtowicz 1991, 1998, Krzywiec 2001).

Normal and strike-slip faults were recognised in the basement of the central Carpathian Foredeep (Doktór, Graniczny 1983, Oszczypko *et al.* 1989, Krzywiec 2001, Krysiak 2000, and references therein) (Fig. 1). These faults are probably mostly Early Paleocene in age, although some evidence for their younger activity is also available. The NW–SE striking normal faults bound several horsts and grabens (called depressions). The study area is located within the Słomniki Horst, close to its SW boundary normal fault. According to Krysiak (2000), the NE–SW to NNE–SSW-trending faults are predominantly sinistral strike-slip and oblique-slip. In the central part of the Carpathian Foredeep, such faults are arranged en-échelon forming the so-called Kurdwanów-Zawichost Fault Zone with a known width of *ca*. 40 km. According to Oszczypko *et al.* (1989), one of such NE–SW-trending faults is located to the west of Brzezie (Fig. 1). There are some pieces of evidence that the Kurdwanów-Zawichost Fault Zone was reactivated during the Miocene.

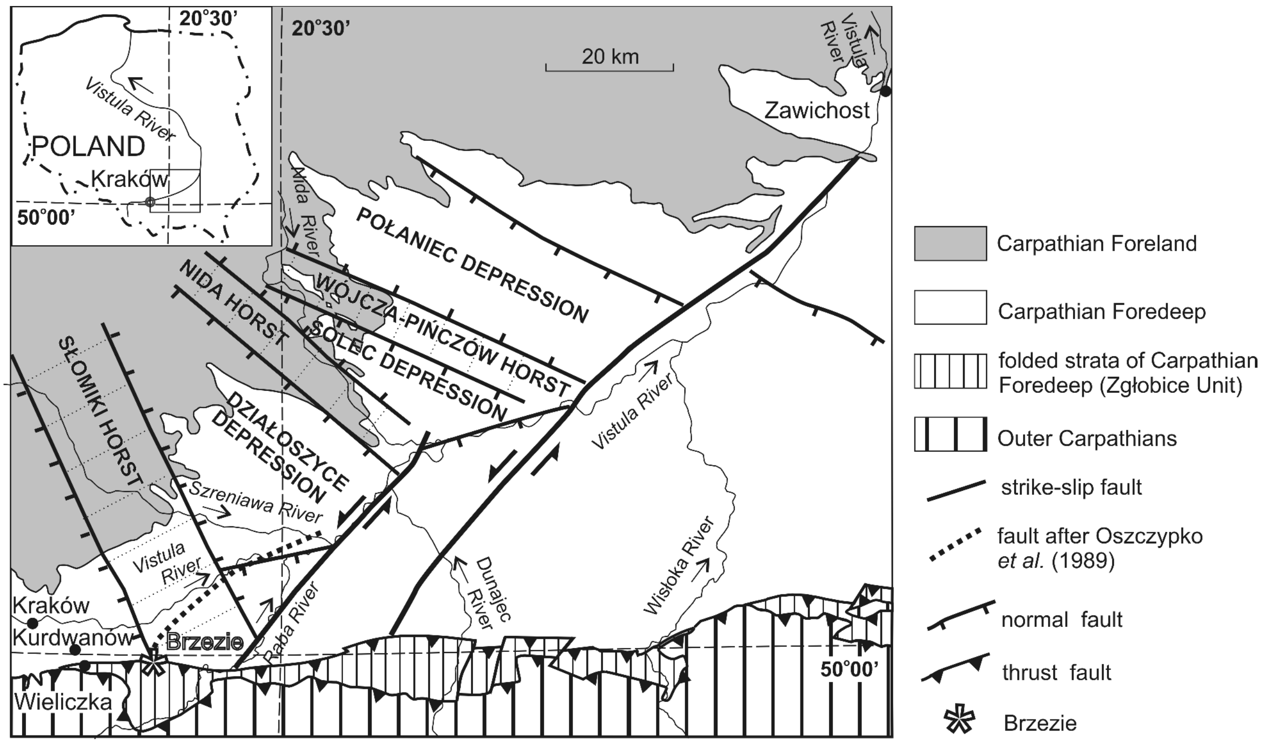

Fig. 1. Tectonic sketch of the central part of the Polish Carpathian Foredeep (after Krysiak 2000) showing location of Brzezie. The Zgłobice Unit after Połtowicz (1991, simplified).

Osmólski *et al.* (1978) suggested a sinistral reactivation of this fault zone in the Middle Miocene, while Jarosiński (1992) inferred a late Middle to early Late Miocene age (or later up, to 11.5–9? Ma). On the other hand, Krysiak (2000) concluded about Late Miocene, and Rauch-Włodarska *et al.* (2006) – Late Miocene and probably Pliocene ages. Such reactivation of the Kurdwanów-Zawichost Fault Zone was caused by horizontal compression oriented about N–S (Jarosiński 1992, Rauch-Włodarska *et al.* 2006). These authors noticed that normal faulting either preceded or post-dated sinistral reactivation of the Kurdwanów-Zawichost Fault Zone in the late Middle Miocene (Krysiak 2000), after the early Late Miocene (Jarosiński 1992), and after the Pliocene (Rauch-Włodarska *et al.* 2006).

Structural evolution of the Miocene strata in the Carpathian Foredeep as well as Miocene reactivation of the faults within its basement were influenced by the stress field generated within the Outer Carpathians at this time. Two stages of horizontal compression oriented NNW–SSE and NE–SW, respectively, have been recognised in the Carpathians (Aleksandrowski 1989, Decker *et al.* 1999a). The first stage occurred during the Paleocene–Early Miocene (cf. Świerczewska, Tokarski 1998, Decker *et al.* 1999a, Świerczewska *et al.* 2001), whereas the second one from the Early Miocene to, probably, the early Late Miocene (Decker *et al.* 1999b, see also Wójcik *et al.* 2001). Folds and thrust faults did develop during both these stages, but the structures connected with the first stage are overprinted by those formed during the second stage.

Normal faults observed within the Polish Outer Carpathians and in the Carpathian Foredeep appear to be connected with the youngest stage of faulting (Decker *et al.* 1997, Jarosiński 1992, Krysiak 2002, Zuchiewicz *et al.* 2002, Rauch-Włodarska *et al.* 2006). Considerable differences in the orientation of normal faults within the Polish Outer Carpathians suggest that they can be a result of either a single stage of multidirectional extension (collapse) or few successive stages of differently oriented extension (Zuchiewicz *et al.* 2002). It is assumed that this extensional episode might have occurred since the Late Miocene till the Pleistocene. The WNW–ESE to NW–SE-striking normal faults seem to be the youngest ones in the Polish Outer Carpathians (Decker *et al.* 1997) and in the Polish Carpathian Foredeep (Rauch-Włodarska *et al.* 2006).

The present-day maximum horizontal stress is oriented N–S to NNE–SSW in the central and eastern parts of the Carpathian Foredeep (Jarosiński 1998, Klek *et al.* 2003).

The relief of this part of the Carpathian Foredeep (Sandomierz Basin), which developed on the Miocene strata, has a Pliocene background but it was strongly transformed and covered by loess (a few metres thick) during the Pleistocene (Burtan 1954). The loess lies unconformably upon Middle Miocene (Badenian) strata and plays a minor role within intra-basinal sequence of the Carpathian Foredeep. The widespread solifluction covers, predating the Alleröd, are overlain by Holocene deluvia connected with agricultural activity that has been proceeding since the Neolithic (Kalicki 1997).

In the Polish Carpathian Foredeep, tectonic structures within Quaternary sediments, and particularly within the loess cover have been poorly investigated. Joints, which are best developed within the Miocene strata of the Foredeep,

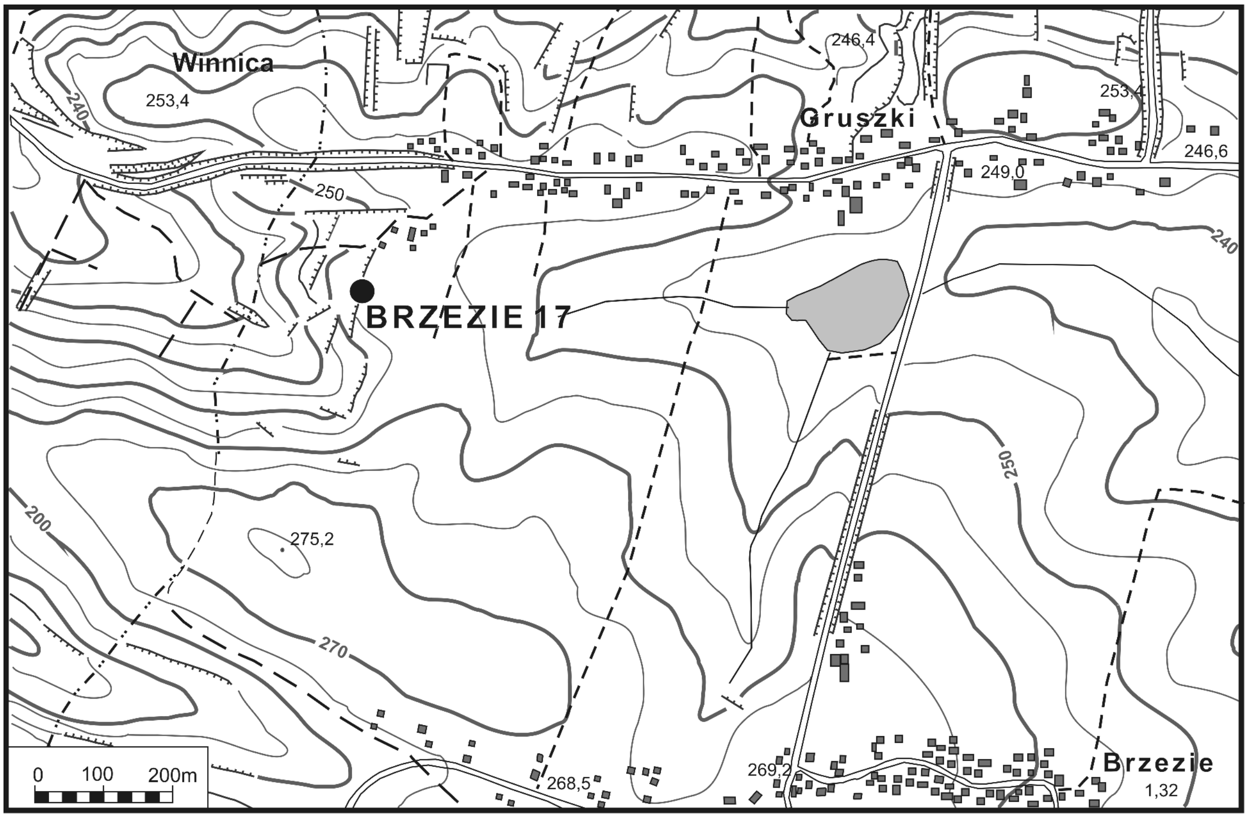

Fig. 2. Study area showing the graben location (black full circle).

also appear in loess cover. Recent studies in the central part of the Carpathian Foredeep (Brud 2002) reveal that joints in the loess cover tend to show different orientations. Nevertheless, the NE–SW-trending joint set predominates, whilst the ENE–WSW to ESE–WNW-trending sets are subsidiary ones.

As far as the Polish Outer Carpathians are concerned, only two normal faults within the loess cover have been documented from the Nowy Sącz Basin (Tokarski 1978). These faults strike N30E and N40E.

GEOMORPHOLOGY AND STRATIGRAPHY OF THE STUDY AREA

Physiographically, the study area represents the western part of the Sandomierz Basin, namely the Wieliczka-Gdów Upland. The morphological level at about 225 m a.s.l. of the Wieliczka-Gdów Upland is dissected by systems of small dry valleys that belong to the Podłężówka (to the west) and Tusznica rivers (to the east) drainage basins. Therefore, this level forms individual hills, which are connected southward by meridional elevations with the higher part (275 m a.s.l.). The study area is located on one of these elevations, near its top, where an open archaeological site occurs.

The fossil graben was found on the western slope of the elevation during archaeological excavations (Fig. 2). This is a N–S oriented structure with a depth of 4 meters. This graben was probably connected with a dry valley limiting the study area from the north, and therefore the fossil graben is deeper near the junction with the main dry valley and shallower upstream. The analysed landform, in its uppermost part, nearly joins with an analogical dry valley (dellen), belonging to a system of valleys that bound the site from the south.

The fossil graben occurs in the Vistulian gleyed loess deposits. These are silts (Mz = 5.53 ϕ), poorly sorted (δ = 1.63), bearing traces of oxidoreduction processes. Three main members can be distinguished within the fossil graben: slope wash sediments (deluvium), buried soil, and laminated loess (Fig. 3).

Deluvium

The upper part of deluvium has a mosaic pattern with dominating dark-greyish colour 10 YR 4/2. Illuviation processes are in initial stage. These are poorly sorted silts (Mz = 6.1–6.15 ϕ, δ = 1.6). An initial soil horizon is developed in the middle part of these sediments.

The middle part of deluvium is black. These are poorly sorted silts (Mz = 5.96 ϕ, δ = 1.52), with angular blocky structures. The lower part, in turn, consists of grey, poorly sorted (δ = 1.56), silts (Mz = 5.96 ϕ). Artefacts and lumps of daub were found in all deluvium layers. These are Neolithic and early Bronze Age artefacts in the lower part, and Lusatian culture artefacts in the upper part.

Buried soil

The deluvium overlies a buried soil, which is preserved *in situ* only in the western part of the outcrop. Three horizons can be distinguished in the section of luvisol (Hapludalf). Dark-greyish and brown (10RY 3/2) humic horizon A is very

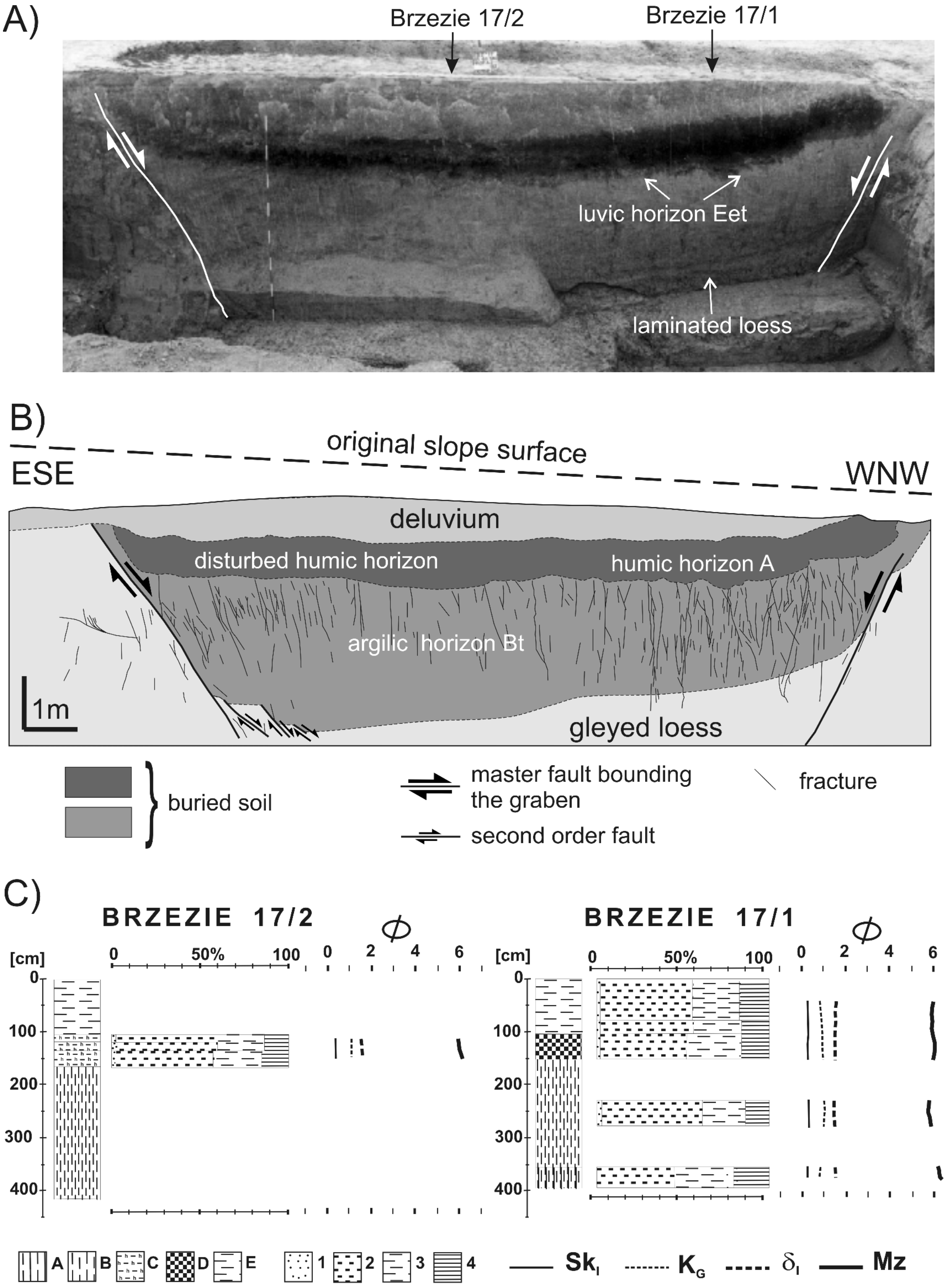

Fig. 3. Cross-section through the graben: **A** – photograph (by Marek Mularczyk); **B** – drawing from detailed photographs; **C** – grain-size composition and Folk-Word grain-size distribution parameters of Brzezie 17/1 and Brzezie 17/2 sections. (C): Sediments: *A* – gleyed loess, *B* – loess, *C* – grey organic silts , *D* – black organic silts (deluvium?), *E* – silty deluvium. Fraction: *1* – sands (ϕ >2), *2* – coarse and medium silt (ϕ = 4–6), *3* – fine silt (ϕ = 6–8), *4* – clay (ϕ> 8); Sk_I – skewness, K_G – kurtosis, σ_I – standard deviation, Mz – mean size diameter.

well decomposed, and the average diameter of mineral grains is 6.22 ϕ, whereas sorting is poor (δ = 1.58). Directly under the humic horizon, a *ca*. 6 cm thick luvic horizon Eet (colour 10RY 6/4) occurs. This horizon is underlain by a yellowish-brown (10YR 5/8), argillic Bt horizon. Irregular glossic structures are present. Concretions of iron oxides, resulting from diagenetic processes, are common. Soil *in situ* is weakly preserved in the eastern part of the depression, bearing only luvic horizon. These are poorly sorted (δ = 1.57) silts (Mz = 6.08 ϕ). The buried soil developed probably within the Late Glacial and Eoholocene (before the Neolithic or even Bronze Age, according to artefacts).

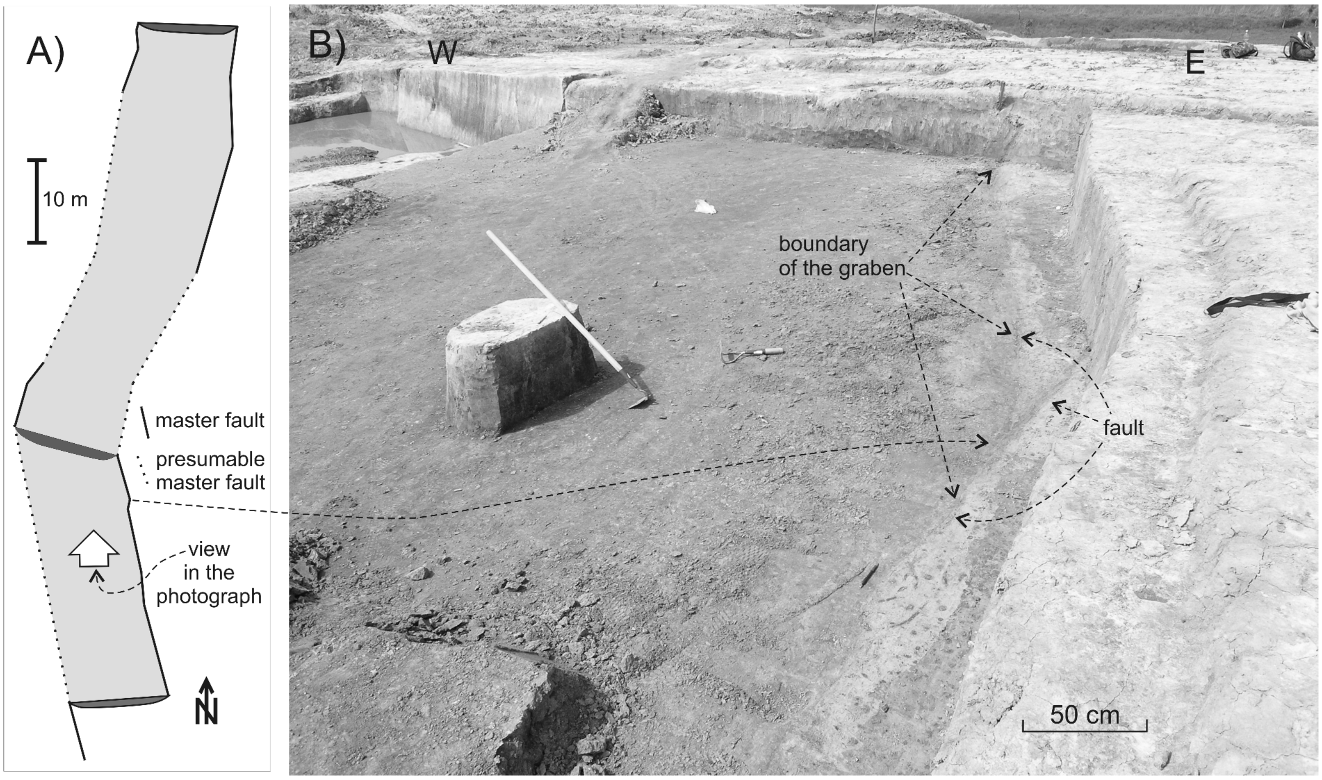

Fig. 4. Outline of the graben: **A** – plan view; **B** – detailed photograph of the graben boundary showing differently oriented faults.

Laminated loess

Laminated sediments occur in the western part of the graben, below Bt horizon of the buried soil. These reflect fluvial transport in the graben during the first stage of its filling. It is not possible to evaluate the detailed time interval for accumulation of these sediments.

SMALL-SCALE TECTONIC STRUCTURES AT BRZEZIE – OBSERVATIONS

Our work focused on detailed structural studies of joints and normal faults, which occur in the section of Vistulian and Holocene sediments in the archaeological excavation site at Brzezie (Fig. 2), as well as along steep natural escarpments in the vicinity of the latter. The obtained results of orientation analyses were plotted on equal-area, lower hemisphere stereographic projections using the TectonicsFP software for Windows (Reiter, Acs 1999; Ortner *et al.* 2002).

Normal faults

The Vistulian and Holocene sediments at Brzezie are cut by numerous normal faults, including a few master faults and related small-scale, second-order faults. The master faults are conjugated and bound a single graben (Fig. 3A and B). The strikes of these master faults observed in plan view show minor changes in orientation: from N16W to N15E (Fig. 4). Hence, the graben is a composite multi-segmented structure, zigzag in shape. Small-scale second-order faults were observed both in hanging walls and footwalls of master faults; the latter being predominant (Figs. 3A, 3B, 5). Vertical off-

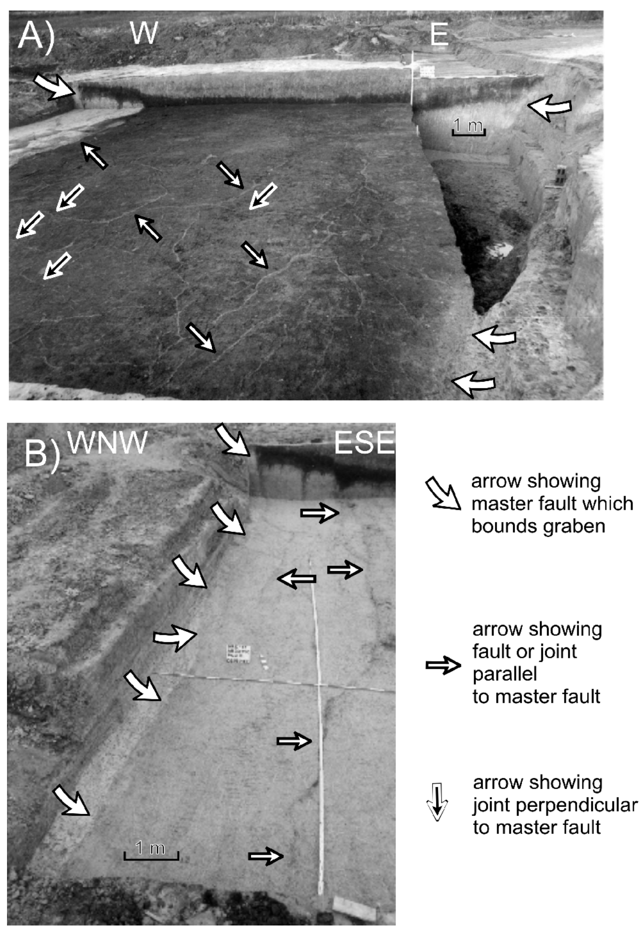

Fig. 5. Photographs of the graben in plan view (**A**, **B**), showing faults and fractures, mostly joints (by Marek Mularczyk).

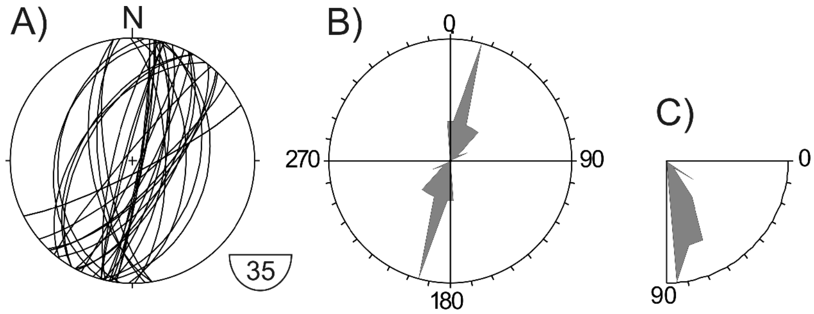

Fig. 6. Orientation of small-scale normal faults: **A** – lower-hemisphere equal area stereographic projection of fault planes (great circles); **B** – rose-diagram of fault plane strikes; **C** – rose-diagram showing dip angles of fault planes.

sets on the normal faults were calculated from changes of elevation of the bottom or upper surfaces of the humic horizon of buried soil and the Neolithic, lower part of the deluvium. Decimetric-scale displacements along these faults were measured.

We measured orientation of 35, steeply dipping (65–85°) fault surfaces (Fig. 6). The strike of normal faults changes from N–S to NE–SW, although the NNE–SSW orientation predominates (Fig. 6B). Some normal fault gouges are enriched in dark-grey, fine-grained material. This material is macroscopically similar to the humic horizon of the buried soil, which occurs in the upper part of the intra-graben sedimentary sequence. The surfaces of such normal faults are slightly striated. High cohesion of the analysed loess cover prevented successful precise separation of these fault surfaces. Nevertheless, we separated 9 fault surfaces bearing lineation necessary for fault-slip analysis. Using the "numeric dynamic method" of Spang (1972), we calculated the reduced palaeostress tensor (Fig. 7), which shows the maximum principal stress (σ_1) in subvertical position and the horizontal minimum principal stress (σ_3) trending WNW–ESE. Normal faults cut gleyed loess, loess, buried soil and the lower part of deluvium (Fig. 8). Within the middle and upper parts of deluvium, these faults die out.

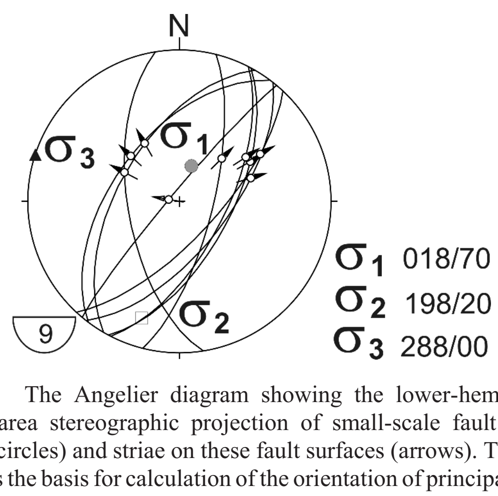

Fig. 7. The Angelier diagram showing the lower-hemisphere equal area stereographic projection of small-scale fault planes (great circles) and striae on these fault surfaces (arrows). This diagram is the basis for calculation of the orientation of principal stress axes σ_1, σ_2 and σ_3.

Joints

The Vistulian and Holocene sediments at Brzezie are cut by numerous joints, which are particularly frequent within the graben. The joint spacing slightly increases in the direction of the master (Fig. 3B) and the second-order faults. Like normal faults, some of the joints are enriched in dark-grey, fine-grained material that is macroscopically similar to the humic horizon of the buried soil. 39 joint surfaces (Fig. 9) were measured. These are steeply dipping, with the modal dip of 85° (Fig. 9D). The strike of joint surfaces is variable, however, they tend to cluster into three sets: set 1 corresponds to NNE–SSW-trending joints which are parallel to normal faults; set 2 corresponds to WNW–ESE-trending joints being perpendicular to normal faults; and set 3 corresponds to WSW–ENE-trending joints which are oblique to normal faults (Fig. 9C). Joints of sets 1 and 2 predominate.

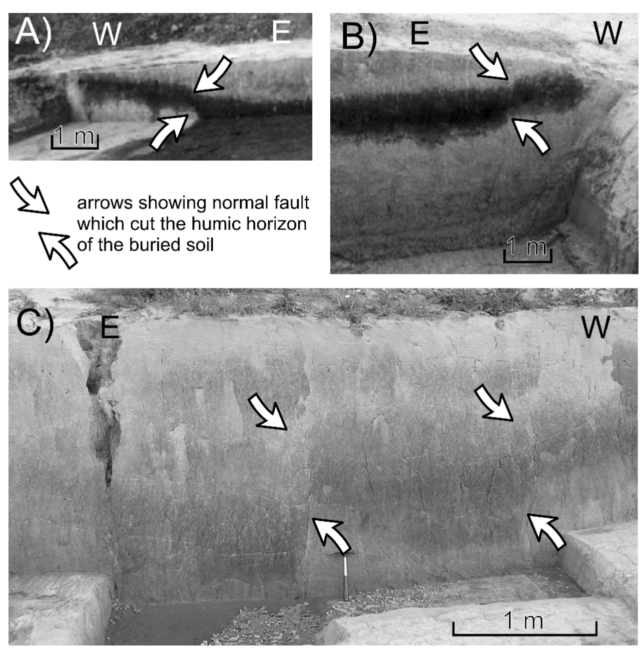

Fig. 8. Photographs showing humic horizon of the buried soil cut by normal small-scale faults (**A–C**) (photographs A and B by Marek Mularczyk).

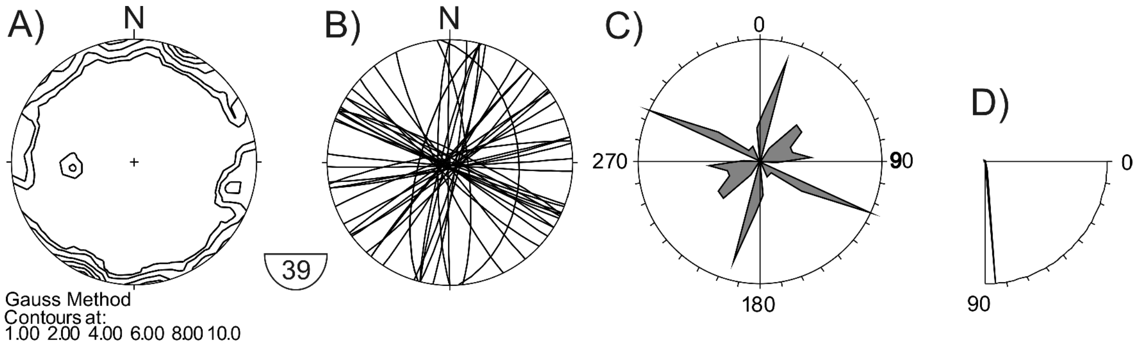

Fig. 9. Architecture of joints: **A** – lower-hemisphere equal area stereographic projection of poles to joint planes (contour diagram); **B** – lower-hemisphere equal area stereographic projection of joint planes (great circles); **C** – rose-diagram of joint plane strikes; **D** – rose-diagram showing dip angles of joint planes.

FOSSIL GRABEN AT BRZEZIE – INTERPRETATION AND DISCUSSION

The analysed fossil graben occurs within the section of Vistulian and Holocene sediments at Brzezie. Some of these sediments fill the graben. These are represented by different lithological-pedological members of laminated loess, as well as buried soil and deluvium. The laminated loess and disturbed A horizon in the eastern part of the graben document that the latter was periodically included in the hydrographical system of the Podłężanka River as a dry dellen with episodic fluvial transport. The humic horizon of the buried soil and the lower part of the deluvium including archaeological artefacts are the youngest faulted sediments within this intra-graben sequence. Therefore, tectonic activity of the graben must still have occurred during the Neolithic or even Bronze Age.

Normal faults observed in the section of Vistulian and Holocene sediments at Brzezie form the single system, which comprises two opposite dipping fault sets. The master faults bound the fossil graben that has the zigzag shape. The strike of these faults is changeable, oscillating around NNE—SSW orientation.

Joints within both the intra-graben sequence and the loess in the vicinity of Brzezie, strike NNE–SSW (set 1), WNW–ESE (set 2), and rarely ENE–WSW (set 3). Joints of the two first sets form an orthogonal joint pattern, which is typical of joints associated with normal faults (Stewart, Hancock 1990, Kattenhorn *et al.* 2000). According to the conceptual model of these authors, the strike of the first joint set is perpendicular to normal faults, and the bearing of the second joint set is parallel to the strike of normal faults (Fig. 10). In addition, the irregular joint spacing and the occurrence of closely spaced joints only close to normal fault surfaces also suggest a connection between development of joints and normal faulting. Therefore, we infer that jointing was simultaneous with faulting.

In the basement of the study area, a NE-striking fault occurs, which belongs to the Kurdwanów-Zawichost Fault Zone (Fig. 1). Some pieces of evidence imply that this fault zone was reactivated as a sinistral fault even in the Late Miocene and later (Rauch-Włodarska *et al.* 2006). According to the conceptual model proposed by Wilcox *et al.* (1973), the reactivation of this sinistral basement fault in the study area could have led to formation of normal faults in the sedimentary cover, including the Vistulian and Holocene sediments at Brzezie (Fig. 11). The present-day maximum stress axis in the central part of the Polish Carpathian Foredeep is oriented about NNE–SSW (Jarosiński 1998, Klek *et al.* 2003). This direction is parallel to the most frequent fault strike in the study region. Normal faults in loess deposits from the Nowy Sącz Basin in the Polish Carpathians strike N30E and N40E (Tokarski 1978). It is possible, that the stress field in the medial segment of the Polish Outer Carpathians and Carpathian Foredeep during the Late Pleistocene, Eoholocene, and Neolithic times had the same orientation as today.

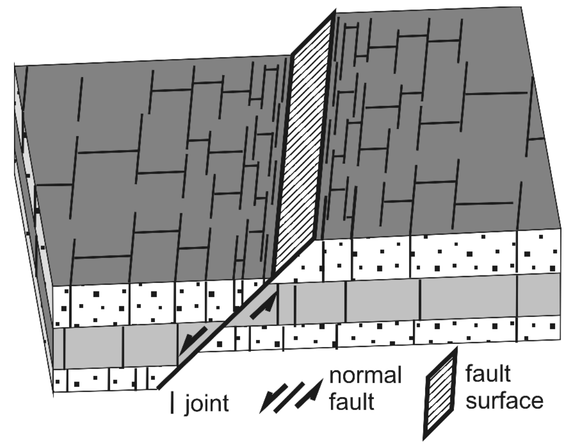

Fig. 10. Block-diagram showing orientation of joints associated with normal faulting (after Stewart, Hancock 1990, modified).

CONCLUSIONS

A fossil graben was recognised within the section of Vistulian and Holocene sediments at Brzezie, in the central part of the Polish Carpathian Foredeep. Tectonic activity of this graben took place during the Vistulian – Mesoholocene (Neoholocene?). The faulting was probably finished during the Neolithic or even later, during the Bronze Age, according to age of the archaeological artefacts found in some of faulted sediments. The NNE–SSW-striking normal faults connected with the graben formation could have been produced due to reactivation of a regional sinistral fault in the basement.

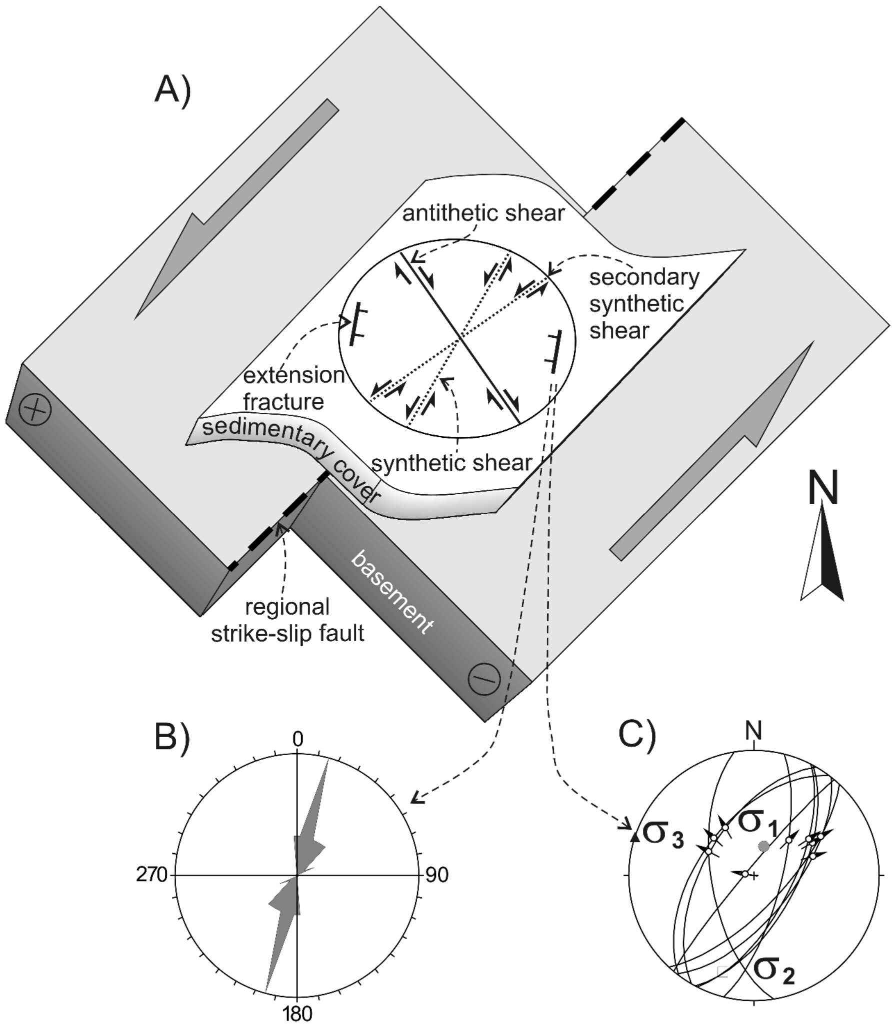

Fig. 11. Kinematic interpretation of small-scale tectonic structures. (**A**) Conceptual model of Wilcox *et al.* (1973) showing the influence of the reactivated regional sinistral strike-slip fault in basement on the local strains within overlaying sedimentary cover. Note that this model correctly predicts the spatial arrangement of the analysed faults (B and C). (**B**) Stereographic projection of small-scale normal faults (rose diagram of fault plane strikes). (**C**) The Angelier diagram showing orientation of fault planes (circles) and striae on fault surfaces (arrows) as well as the orientation of reconstructed principal stress axes.

Acknowledgements

We would like to thank the Institute of Archaeology and Ethnology of the Polish Academy of Sciences, the Archaeological Museum in Kraków, and the Jagiellonian University: the Kraków Team for Motorway Survey, Registered Partnership, and especially Msc. Agnieszka Czekaj-Zastawny for permission to publish data and photographs from the archaeological site. Structural research was supported by the Polish Committee for Scientific Research (KBN), grant project no. 2 P04D 03328.

Preliminary version of this paper was presented at the 6th National Conference "Neotectonics of Poland", organized in 2005 by the Commission on Neotectonics, Committee on Quaternary Research of the Polish Academy of Sciences, Lower Silesian Branch of the Polish Geological Institute, Institute of Geological Sciences of the Jagiellonian University, and the Galicia T. Group.

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