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 – Meso-Holocene (Neo-Holocene?) 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 Prererozoic–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 Zg³obice Unit (Kotlarczyk 1985), where map-scale fold axes and thrust faults trend W–E to WNW–ESE (Kirchner, Po³towicz 1974, Po³towicz 1991, 1998, Krzywiec 2001).

Normal and strike-slip faults were recognised in the basement of the central Carpathian Foredeep (Doktór, Grańczy 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 Słowinki 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 Kurdanów-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 Kurdanów-Zawichost Fault Zone was reactivated during the Miocene.
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 recognized 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 (Sanatorium 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 solifluxion 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,
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 Podleżeówka (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 gleiyed loess deposits. These are silts (Mz = 5.53 $\phi$), poorly sorted ($\delta$ = 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 $\phi$, $\delta$ = 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 $\phi$, $\delta$ = 1.52), with angular blocky structures. The lower part, in turn, consists of grey, poorly sorted ($\delta$ = 1.56), silts (Mz = 5.96 $\phi$). 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 (Haplustalf). Dark-greyish and brown (10RY 3/2) humic horizon A is very
well decomposed, and the average diameter of mineral grains is 6.22 \( \phi \), whereas sorting is poor (\( \delta = 1.58 \)). 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), argilllic 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 (\( \delta = 1.57 \)) silts (\( M_z = 6.08 \phi \)). The buried soil developed probably within the Late Glacial and Eoholocene (before the Neolithic or even Bronze Age, according to artefacts).

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 (\( \phi > 2 \)), 2 – coarse and medium silt (\( \phi = 4–6 \)), 3 – fine silt (\( \phi = 6–8 \)), 4 – clay (\( \phi > 8 \)); \( S_k \) – skewness, \( K_g \) – kurtosis, \( s_1 \) – standard deviation, \( M_z \) – mean size diameter.
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. 4. Outline of the graben: A – plan view; B – detailed photograph of the graben boundary showing differently oriented faults.

Fig. 5. Photographs of the graben in plan view (A, B), showing faults and fractures, mostly joints (by Marek Mularczyk).
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 ($\sigma_1$) in subvertical position and the horizontal minimum principal stress ($\sigma_3$) 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.

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.
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 Pod³ê¿anka 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 Kardwanów-Zawichost Fault Zone (Fig. 1). Some pieces of evidence imply that this fault zone was reactivated as a sinistral fault even in the Late Mio- cene and later (Rauch-Wlodarska 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 sedimen-
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