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NEOFRACTURES VERSUS INHERITED FRACTURES IN STRUCTURAL ANALYSIS: A CASE STUDY FROM QUATERNARY FLUVIAL GRAVELS (OUTER CARPATHIANS, POLAND)

Antoni K. TOKARSKI & Anna ŚWIERCZEWSKA

Institute of Geological Sciences, Polish Academy of Sciences, Research Center in Kraków, Senacka 1, 31-002 Kraków, Poland; ndtokars@cyf-kr.edu.pl, ndswierc@cyf-kr.edu.pl

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Abstract: This paper presents the results of a detailed analysis of flysch-derived clasts within Quaternary fluvial gravels exposed close to a map-scale overthrust. These clasts are commonly fractured. For a given population of clasts, the number of fractured clasts is positively correlated with the clast size and negatively correlated with the grain size of clast-forming rocks. The fractures comprise both those inherited from earlier joints cutting source strata, and those formed *in situ* within the gravels (neofractures). These two groups of fractures show different diagnostic features. The inherited fractures are orientated at random in relation to geographic coordinates, whereas the neofractures show a well-organized architecture. The inherited fractures are mostly inclined 80–90° to the a-b planes of the host clasts, whereas the neofractures are usually inclined at 0–80° to these planes. The occurrence of neofractured clasts within the analysed gravels results from tectonic activity post-dating gravel deposition.

Key words: fractured clasts, neotectonics, Quaternary gravels, Outer Carpathians, Poland.

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INTRODUCTION

Since the pioneering paper by Kupsch (1955), fractured clasts in conglomerates and gravels have been studied in numerous areas and in very different geological settings, ranging from Caledonian orogens to Quaternary fluvial terraces. Two kinds of fracture architecture can be distinguished: (1) radial or radiating fractures, and (2) fractures arranged in one or more co-planar sets. The former are most likely to be found in the clast-supported media (Tyler, 1975; Jerzykiewicz, 1985; Harker & Giegengack, 1989; Harker, 1993; Ernston *et al.*, 2001) whereas the latter occur both in the clasts and matrix-supported strata (*e.g.*, Eidelman & Reches, 1992; Ernston *et al.*, 2001). Clasts cut by fractures of well organized co-planar sets have been used as palaeostress indicators (Ramsay, 1962, 1964; Ramsay & Sturt, 1970; Petit *et al.*, 1985; Bradley & Bradley, 1986; Tapponnier et al., 1986; Eidelman & Reches, 1992; Little, 1995; Decker & Peresson, 1996; Tokarski & Zuchiewicz, 1998; Cuong *et al.*, 2001).

In most of the studied cases, fractures cutting clasts are extension fractures (*e.g.*, Little, 1995; Eidelman & Reches, 1992; Tokarski & Zuchiewicz, 1998). Clasts cut by co-planar fracture sets tend to occur close to the map-scale and/or exposure-scale faults (Ramsay, 1962, 1964; Tanner, 1963, 1976; Tyler, 1975; Lamb & Bibby, 1989; Petit *et al.*, 1985; Bradley & Bradley, 1986; Tapponnier *et al.*, 1986; Owen, 1989; Eildelman & Reches, 1992; Carbon *et al.*, 1995; Little, 1995; Decker & Peresson, 1996; Tokarski & Zuchiewicz, 1998; Cuong *et al.*, 2001, Zuchiewicz *et al.*, 2004). The number of fractured clasts increases towards the faults (*e.g.*, Tanner, 1976). These relationships show that the origin of fractured clasts can be related to faulting. Therefore, these clasts can be used as fault-timing indicators (Tanner, 1976; Petit *et al.*, 1985; McCaffrey & McCann, 1992; Little, 1995; *cf.* also Hippolyte, 2001).

A model for the origin of fractured clasts has been proposed by Eidelman and Reches (1992). According to this model, the extension fractures in clasts can form at depths of at least a few hundred metres. This model, if valid, would seriously restrict the occurrence of fractured clasts in the Quaternary strata, since these strata are only exceptionally covered by such a thick overburden. However, the model is inconsistent with field observations of Tanner (1976), Arlhac *et al.* (1987), Owen (1989), Carbon *et al.* (1995), and Zuchiewicz *et al.* (2004). These observations show that

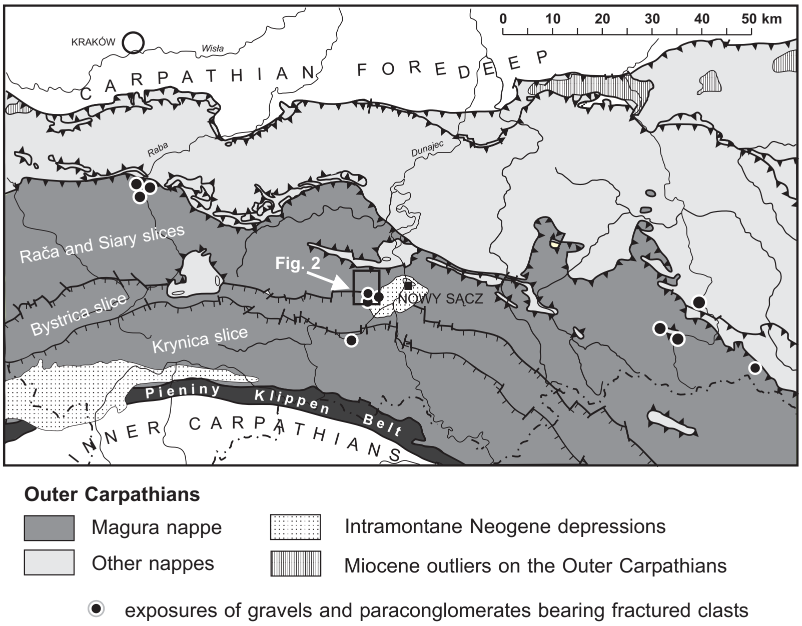

Fig. 1. Geological map of the Polish segment of the Outer Carpathians showing location of exposures of gravels and paracoglomerates bearing fractured clasts, and location of the study area (boxed). Geological setting after Żytko *et al.* (1989)

clasts may fracture under the overburden of few tens of metres or even 1 m or less below the top surface of the strata involved (Tanner, 1976). It follows that fractured clasts are an important tool for structural analysis, especially for Quaternary strata. Moreover, Quaternary gravel series are commonly found all over the world. Therefore, we believe that this tool is of universal character.

FRACTURED CLASTS IN THE OUTER CARPATHIANS

The Outer Carpathians are a thrust-and-fold-belt composed mostly of Lower Cretaceous through Lower Miocene flysch strata. The belt is north-verging in the Polish segment (Fig.1). The Outer Carpathians were formed due to Palaeogene–Neogene subduction, and comprise several nappes. The Magura Nappe is the innermost of these nappes within the Polish segment. This nappe is subdivided by overthrusts into four slices, named: Krynica, Bystrica, Rača, and Siary slices.

Within the Polish segment of the Outer Carpathians, mostly within the Magura Nappe, we have observed fractured clasts at 11 exposures of Quaternary and Neogene gravels and paraconglomerates which are located close to the map-scale overthrusts (Fig. 1). In these exposures, the amount of fractured clasts (more than 2 cm in diameter) is up to 63%. In some places, we have also observed exposure- and clast-scale faults. We infer, therefore, that at least some of the map-scale overthrusts cutting the Outer Carpathians have been active during Quaternary times, and that this activity can be reconstructed basing on an analysis of fractured clasts. The lithology of fractured clasts is similar at all studied sites, for most of the clasts were derived from the Outer Carpathian strata. In paraconglomerates, there also occur clasts from the Inner Carpathian rocks. However, fractured clasts show different features at particular exposures and their distribution is not uniform. In the majority of exposures, numerous clasts contain calcite veins, whereas at few exposures the clasts are devoid of these veins. The architecture of the fractures is either well- or poorly-organized. Patchy distribution of fractured clasts within unfractured gravels and paraconglomerates is very common. We believe that understanding of these differences is of crucial importance for regional tectonic analysis of fractured clasts. The aim of our case study has been to understand some of these differences.

OBJECT OF STUDY

In this paper, we present the results of a detailed analysis of fractured clasts within Quaternary fluvial gravels exposed at village Kwasowiec, close to the map-scale Bystrica overthrust, along which the Bystrica slice is thrust over the Rača slice (Figs 1, 2). The reasons for choosing this exposure as our case study are fourfold:

a) the number of fractured clasts is there larger than at other visited exposures,

b) in contrast to the majority of visited exposures, the fractured clasts at Kwasowiec are devoid of calcite veins,

c) the fractures show both well- and poorly-organized architecture, and

d) some of the clasts are cut by clast-scale faults.

Preliminary results of our analysis were presented at the Conference on Neotectonics of Poland (Tokarski & Świerczewska, 2003).

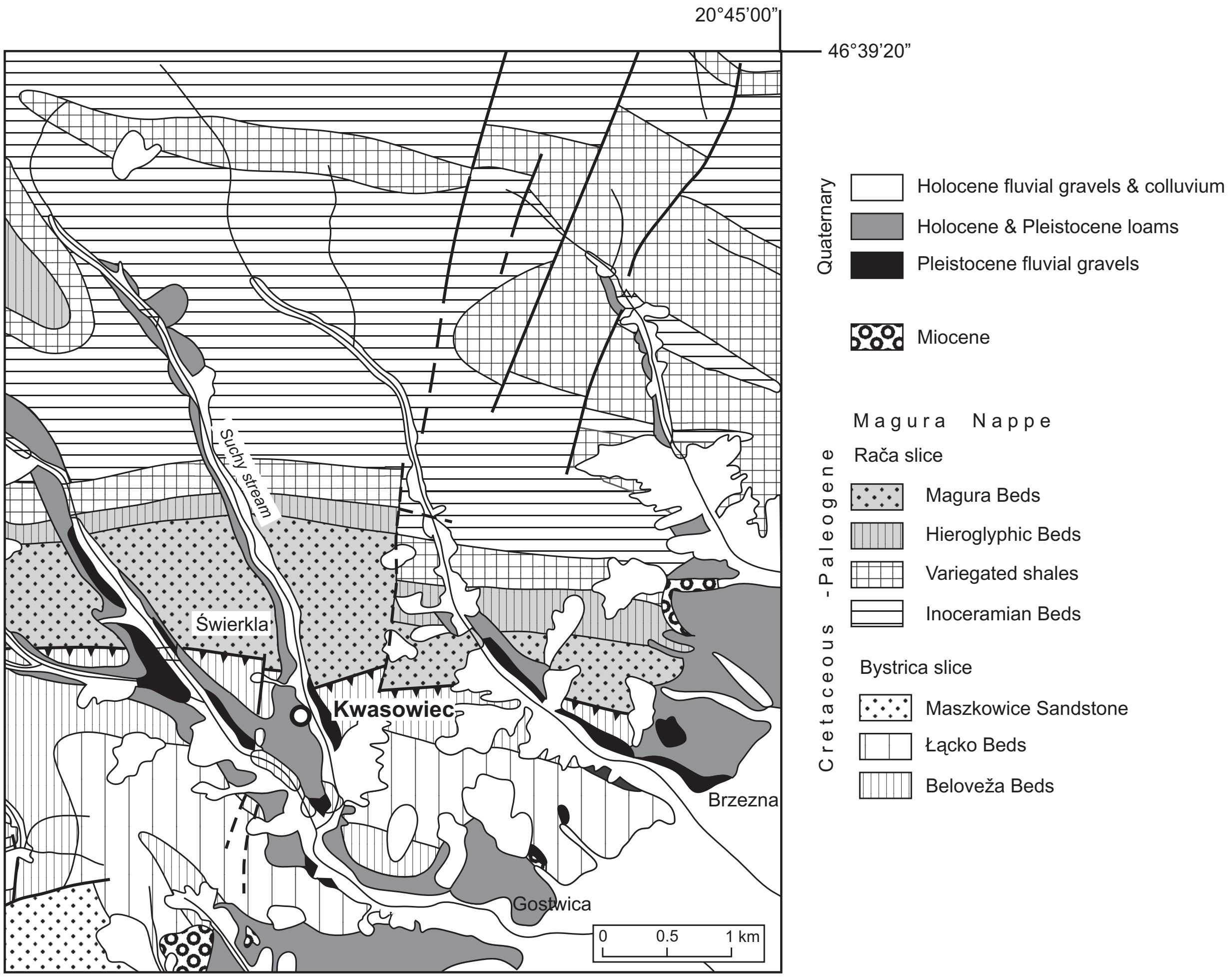

Fig. 2. Location of the Kwasowiec exposure (open circle). Geological setting after Oszczypko & Wójcik (1989); for location – see Fig. 1

METHODS

The fabric and composition of gravels were studied on the surface of *ca* 1m^2. This surface was covered by point-counting grid with mesh size of 10 x 10 cm or 10 x 5 cm. One hundred points were counted on traverses perpendicular to bedding, to determine the matrix and pebble percentages. Using the same counting method, 100 clasts were selected for detailed studies. The lithology, fracturing, roundness, size, and shape were taken into account. Roundness was expressed visually using a 5-grade scale. Maximum (a-axis), intermediate (b-axis), and minimum (c-axis) dimensions were measured to determine the clast shape, according to the Zingg's diagram. The clast size was expressed by volume. The estimated clast volume was obtained by calculating the three dimensions (a, b, c). Orientation of the a-axis and a-b plane (containing a and b axes) of some clasts were measured. The numbers of fractured clasts were determined for two size groups of 100 clasts each: a group of clasts with maximum dimension (a-axis) longer than 2 cm (2–20 cm), and that showing a-axis shorter than 2 cm (0.8–2 cm).

KWASOWIEC EXPOSURE

Fractured clasts are exposed in a river terrace on the right bank of the Suchy Stream (20°34'50''E, 49°36'00'' N), 5.5 km downstream of the headwaters (Fig. 2). The stream flows across outcrops of the Rača slice strata, truncating: (1) the Inoceramian beds cut by numerous calcite veins, and (2) variegated shales, the Hieroglyphic, and Magura beds almost devoid of these veins, as well as across outcrops of the Beloveža beds of the Bystrica slice, cut by few calcite veins.

The exposure is situated in the hanging wall of the Bystrica overthrust, 300 m away from the trace of the thrust surface. The 17-m-high terrace (Fig. 3) is either Saalian or Vistulian in age (*cf.* Zuchiewicz, 1984; Oszczypko & Wójcik, 1989). The 3-m-high strath of the terrace, is built up of tightly folded, thin-bedded sandstones and claystones of the Beloveža beds. The middle, 5 m thick, part of the terrace cover is composed of gravels, whereas the upper part is represented by loessial silts. Temporal springs seep from the exposure. At the foot of the discussed Quaternary terrace riser, the Suchy Stream bed is occupied by the present-day gravel bar.

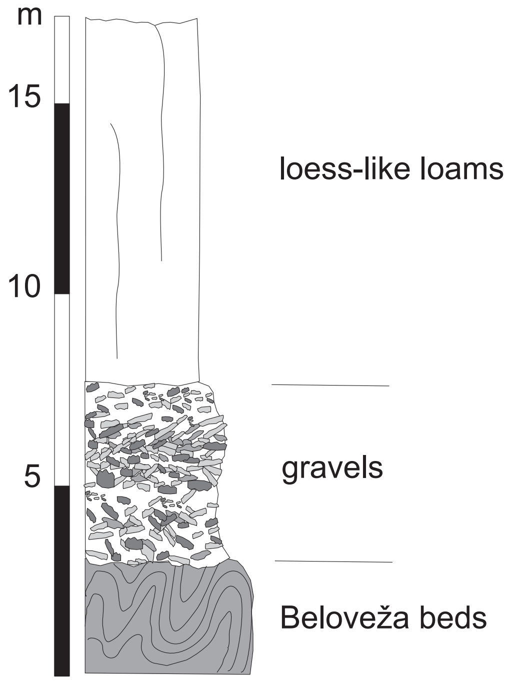

Fig. 3. Section of the Kwasowiec exposure

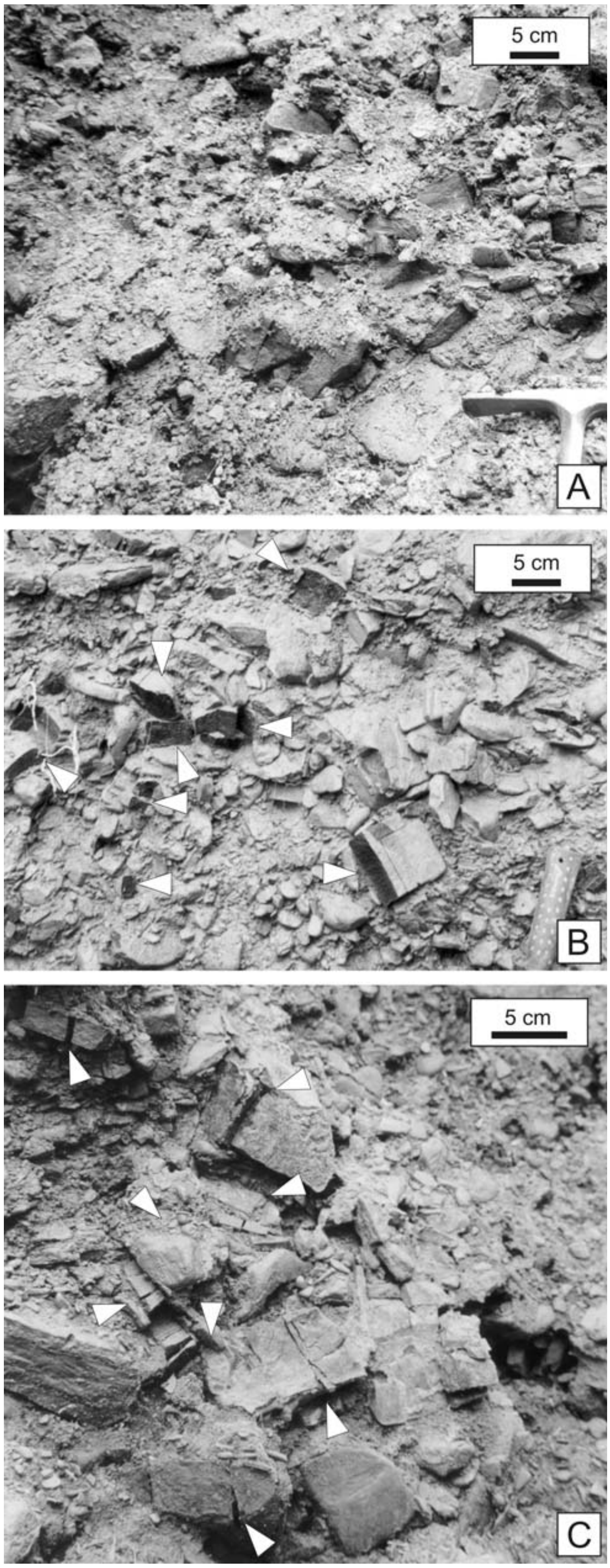

Fig. 4. Quaternary gravels at Kwasowiec: **A** – matrix-supported gravel; **B** – clast-supported gravel, numerous clasts are fractured, fracture walls are commonly coated by iron and manganese compounds (black, arrowed); **C** – part of gravels bearing numerous fractured clasts (arrowed

Gravels

Poorly sorted gravels exposed within the Quaternary terrace show different proportions between the clasts and sandy-clayey matrix. There occur both clast-supported and matrix-supported gravels (Fig. 4A, B). The matrix, composed of mud-sandy mass, builds up to 33% of the gravel body. The clasts are up to 20 cm across. They were derived exclusively from the Outer Carpathian flysch strata. The fabric and composition of gravels have been studied in a population numbering 100 clasts. The mudstone and fine-grained sandstone clasts are most common (Fig. 5). Some of these clasts are laminated, showing intercalated mudstone and sandstone laminae. Medium- and coarse-grained sandstone clasts are less common. The majority of these clasts are subangular to subrounded (Fig. 6), and discoidal and blade in shape (Fig. 7). The clast a-axes (the longest ones) plunge 0-30° towards WNW through NNE (Fig. 8). All clasts are devoid of calcite veins.

Fractures

Numerous clasts are fractured (Fig. 4B, C). The fractures were studied in two size groups. In the first group of 100 large clasts (2–20 cm; Fig. 9), 63 clasts cut by fractures, and 37 clasts devoid of fractures were counted. The number of fractured clasts in mudstone and fine-grained sandstone clasts of the same size are roughly equal. The medium- and coarse-grained sandstone clasts are not fractured. It follows that the number of fractured clasts is negatively correlated with their grain size. On the other hand, the number of fractured clasts is positively correlated with the clast size (Fig. 10). The number of fractured clasts is also dependent on shape. The spheroidal and blade-shape clasts tend to show larger numbers of fractured clasts (Fig. 7). In the second

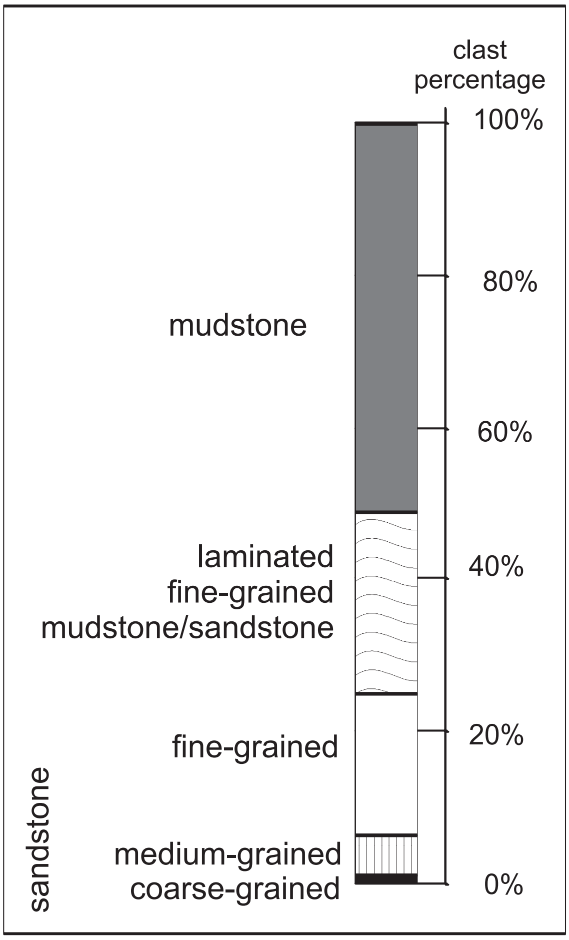

Fig. 5. Lithology of clasts within Quaternary gravels. See text for explanation

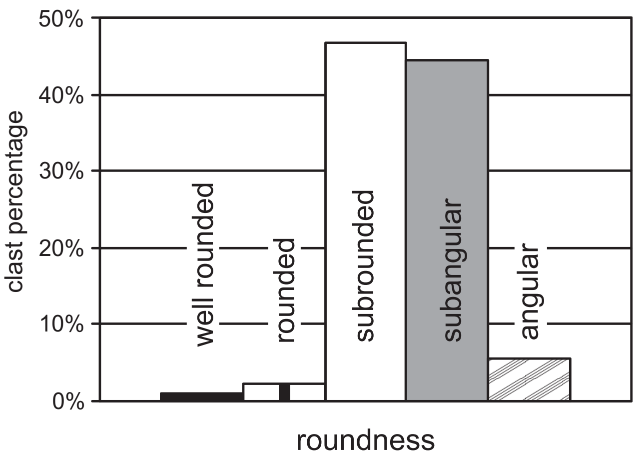

Fig. 6. Roundness of clasts within Quaternary gravels. See text for explanation

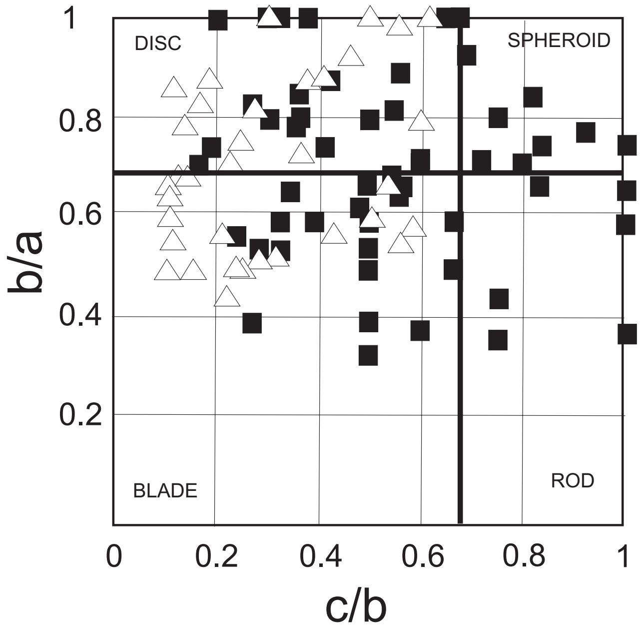

Fig. 7. Zingg's diagram of clast shape within Quaternary gravels. Full squares denote fractured clasts, empty triangles mark unfractured clasts; a, b, and c denote dimension of the longest (length), intermediate, and shortest (width) clast axes, respectively. See text for other explanations

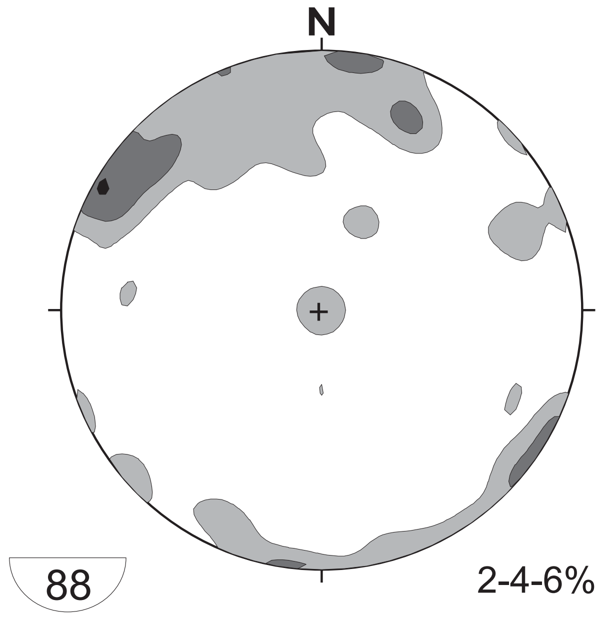

Fig. 8. Orientation of a-axes of clasts within Quaternary gravels

group of 100 small clasts (0.8–2 cm), 13 clasts cut by fractures, and 87 clasts devoid of fractures have been found. In both these groups, fractures are restricted to particular clasts, whereas the matrix is not fractured. Black and brownish-black varnish composed of iron and manganese compounds usually covers the fracture walls (Fig. 4B).

The architecture of fractures was studied in two populations of large clasts (I, II), located in different parts of the Kwasowiec exposure. In population (I), orientation of 50 fractures was measured. The majority (74%) of these fractures are inclined at 81–90° to the a-b planes of the host clasts (Fig. 11). These fractures are orientated at random in relation to the geographic coordinates (Fig. 12A). In population (II), orientation of 52 fractures was measured. In distinction to population (I), the majority (62%) of these fractures are inclined at 0–80° to the a-b planes of the host clasts (Fig. 11). The fracture architecture in population (II) is well organized (Fig. 12C). Few clasts are cut by normal or

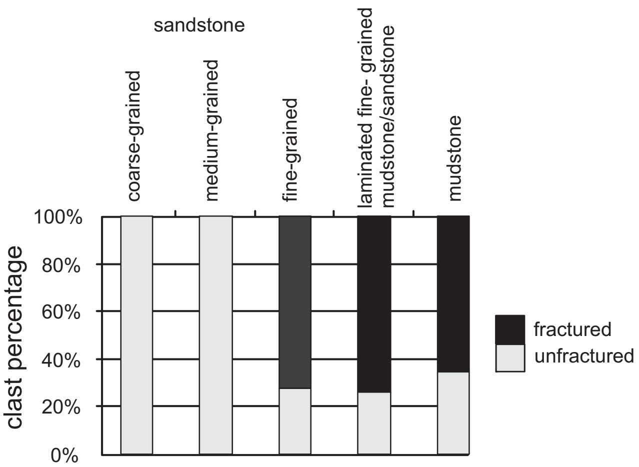

Fig. 9. The number of fractured clasts vs. clast lithology within Quaternary gravels presented for a group of 100 clasts, 2–20 cm in diameter

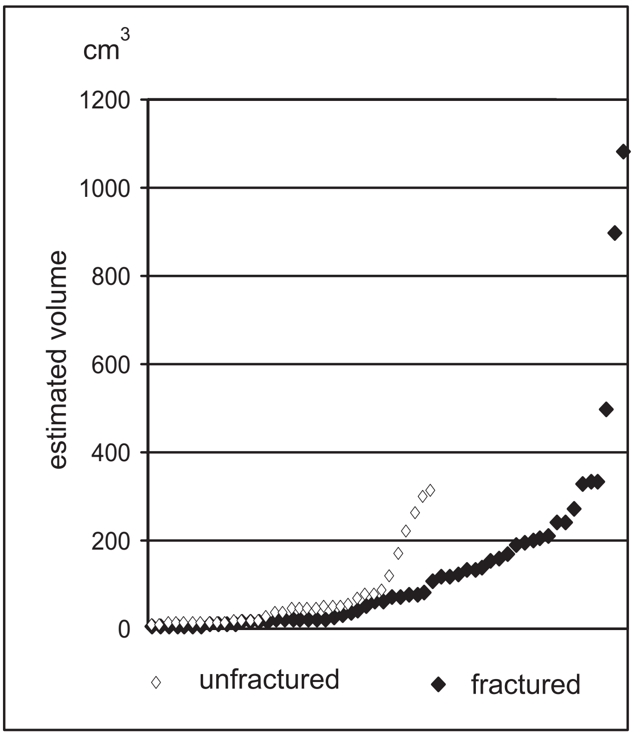

Fig. 10. Estimated volumes of fractured and unfractured clasts in Quaternary gravels presented for a group of 100 clasts, 2–20 cm in diameter. The clasts are arranged according to their increasing volume; each symbol denotes one clast

strike-slip faults (Fig. 14), showing offset up to 1.5 cm. Neither of the faults shows tectonic striae. The faults do not cut the matrix.

Present-day gravel bar

A group of 100 large clasts (2–20 cm) was studied in the present-day gravel bar in the Such Stream bed, at the foot of the discussed terrace riser. The lithological composition of clasts in this population is similar to that of the Qua-

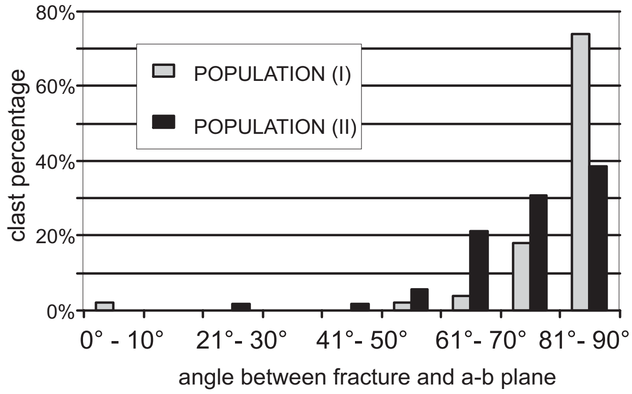

Fig. 11. Histogram illustrating the value of the dihedral angle between the fractures and a-b planes of the host clasts within Quaternary gravels. See text for explanation

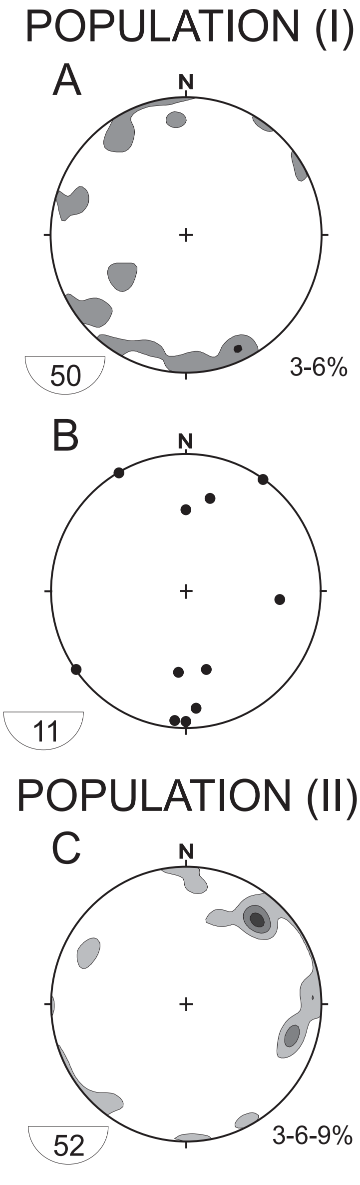

Fig. 12. Orientation of fractures cutting clasts within Quaternary gravels: **A** – all fractures of population (I); **B** – fractures of population (I) inclined at 0-80° to a-b planes of host clasts; **C** – all fractures of population (II)

Fig. 13. Veined clasts in the present-day gravel bar at the bottom of Suchy stream

ternary gravels. Within the present-day gravel bar, we have not observed any single fractured clast. However, 46% of the clasts are cut by calcite veins (Fig. 14). The calcite veins within clasts are randomly orientated in relation to geographic coordinates.

DISCUSSION

There are two distinct differences between fracture architecture of populations (I) and (II). They consist in: (1) the orientation of fractures in relation to geographic coordinates, and (2) values of angles between the fractures and a-b planes of the host clasts. In the following discussion we will try to show that the different architectures of fractures in particular clast populations (I, II) stem from different origin of the fractures.

The Outer Carpathian strata, which are the source rocks for the discussed Quaternary gravels, are commonly cut by joints orientated sub-perpendicularly (80–90°) to stratification. Within some formations, these joints are commonly healed by calcite veins, whereas other formations are devoid of such veins (Tokarski & Świerczewska, 2001). In the studied case, the source rocks contain both veined and unveined strata. During erosion and sedimentary transport, fragments of unveined strata disintegrate along the pre-existing joints. It follows that clasts in Quaternary gravels derived from the unveined strata are devoid of early joints. In contrast, fragments of veined strata have undergone differentiated rotations during transport and deposition, which resulted in random orientation of the early veined joints within Quaternary gravels and in the present-day gravel bar. Subsequent dissolution of calcite veins in the Quaternary gravels could have resulted in the formation of open fractures. It appears that discoidal and blade-shaped clasts represent disrupted fragments of beds, their a-b planes being orientated parallel to bedding surfaces of the source strata. Therefore, we infer that most of the fractures in population (I), which are randomly arranged and orientated 80-90° to the a-b planes of host clasts (Figs 11, 12A), could have been inherited from the early joints cutting the source strata and healed by calcite veins. The presence of numerous calcite veins in the present-day gravel bar clasts, as well as the occurrence of black varnish upon fracture walls supports this

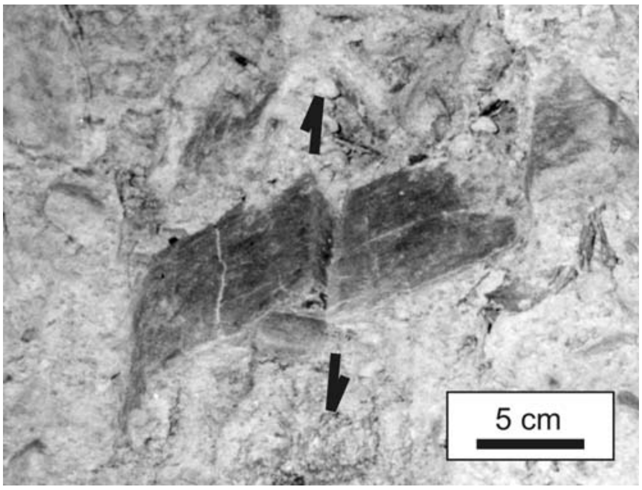

Fig. 14. Faulted clast within Quaternary gravels

conclusion. Fluctuations of ground water level in the Quaternary gravels, marked by temporary springs, involve changes of pH-Eh conditions within the terrace cover. Under such unstable pH-Eh conditions, dissolution of calcite is highly probable. This leads to a local increase in pH and, in consequence, to precipitation of Mn-oxides on walls of the inherited fractures (*cf.* Nimfopoulos *et al.*, 1997).

In contrast to mostly randomly orientated fractures in population (I), the fractures in population (II) show a well-organized architecture (Fig. 12C). Moreover, in distinction to fractures inherited from early joints cutting the source strata, the majority of these fractures are inclined at <80° to the a-b planes of the host clasts (Fig. 11). Therefore, we conclude that the majority of fractures in population (II) could have been formed *in situ* in Quaternary gravels. It follows that those fractures which are orientated 80–90° to the a-b planes of the host clasts were mostly inherited from early joints, whereas those which are orientated <80° to the a-b planes of the host clasts were largely formed *in situ*. This conclusion is confirmed by the architecture of those fractures in population (I) which are inclined at <80° to the a-b planes of the host clasts. Those fractures are orientated orderly in relation to geographic coordinates (Fig. 12B).

It appears, therefore, that the fractures cutting clasts within Quaternary gravels at Kwasowiec exposure comprise both fractures inherited from joints cutting source strata, and those formed *in situ* in the gravels (neofractures). This opinion is confirmed by the fact that the number of fractured clasts in the group of 100 large clasts within Quaternary gravels, which are cut by both inherited and neo-formed fractures, is larger (63%) than the number of veined clasts (46%) in the population of 100 large clasts in the present-day gravel bar, which are related exclusively to inherited fractures.

The numbers of inherited versus neo-formed fractures are different in individual parts of the discussed Quaternary gravels at Kwasowiec. In some parts of the exposure, the inherited fractures are more numerous (population I), whereas in other parts a reverse relationship is observed (population II). The origin for this differentiation is not yet understood.

Perhaps, the concentration of neo-fractures points to the zones of stress amplification.

To our knowledge, the only case where fractures in fractured clasts are arranged both in an orderly way and at random has hitherto been reported by Arlhac *et al.* (1987) from Quaternary fluvial terraces in southern France. However, in that area both groups of fractures have been interpreted to be formed *in situ* (Arlhac *et al.*, 1987).

Summing up, we conclude that diagnostic features of the inherited fractures are: (1) random orientation in relation to geographic coordinates, and (2) sub-vertical inclinations to the a-b planes of the host clasts. The equivalent features of the neo-fractures are: (1) well-organized architecture, and (2) prevailing inclinations <80° to the a-b planes of the host clasts. The discussed diagnostic features of the inherited fractures and neo-fractures are not definitive. Some of the inherited fractures may show inclinations <80° to the a-b planes of the host clasts, whereas some of the neo-fractures may be sub-vertical to the a-b planes. Therefore, separation into both the above groups is not possible for individual fractures. However, the discussed diagnostic features seem to be sufficient for separation of an assemblage of fractures into two sub-assemblages, one composed mostly of neo-fractures, and the second one composed mostly of inherited fractures.

The described neo-fractures cutting Quaternary gravels at Kwasowiec were formed during Quaternary times close to the map-scale Bystrica overthrust. Moreover, within the Polish segment of the Outer Carpathians, we have observed so far fractured clasts in Quaternary gravels and paraconglomerates only at those exposures that are located close to the map-scale overthrusts (Fig. 1). Therefore, it is likely that at least some of the overthrusts have been the loci of neotectonic activity. This conclusion corresponds well with the published data on the Quaternary tectonic activity within the Polish segment of the Outer Carpathians (Tokarski, 1978; Zuchiewicz *et al.*, 2002). However, the nature of this activity is unclear. We believe that the data from a single exposure are not sufficient for a valid kinematic analysis, especially as the architecture of neo-fractures is different in particular parts of the Kwasowiec exposure (Fig. 12B, C). Moreover, the observed minor faults are devoid of tectonic striae and, therefore, they are useless for kinematic considerations. Furthermore, the data on the present-day and Quaternary stress regime within the Polish segment of the Carpathians are rather scarce. The results of an analysis of breakouts in two boreholes (Jarosiński, 1998), and those of focal mechanism of a single earthquake (Wiejacz, 1994) point to the present-day strike-slip tectonic regime with σ_1 orientated roughly N–S. However, the results of analysis of small-scale structures (Tokarski, 1978) suggest a normal tectonic regime during Quaternary times, whereas borehole (Niedzielski, 1971) and gravity data (Pomianowski, 1995) point to both normal and strike-slip faulting during the same period. Summing up, there are not enough data to constrain the nature of Quaternary tectonic activity of the map-scale Bystrica overthrust.

CONCLUSIONS

(1) Within Quaternary fluvial gravels exposed at Kwasowiec, the number of fractured clasts is positively correlated with the clast size and negatively correlated with the clast grain size.

(2) The fractures cutting clasts within Quaternary gravels comprise both fractures inherited from early joints cutting source strata, and fractures formed *in situ* (neo-fractures) within the gravels.

(3) The inherited fractures show two diagnostic features: (a) most of the fractures are orientated at random in relation to geographic coordinates, and (b) most of the fractures are inclined at 80–90° to the a-b planes of the host clasts.

(4) The neo-fractures show a well-organized architecture, most of them being inclined at 0-80° to the a-b planes of the host clasts.

(5) The occurrence of neo-fractured clasts within the analysed gravels results from tectonic activity post-dating gravel deposition.

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Streszczenie

NEOSPĘKANIA A SPĘKANIA ODZIEDZICZONE W ANALIZIE STRUKTURALNEJ: PRZYKŁAD Z CZWARTORZĘDOWYCH ŻWIRÓW RZECZNYCH (POLSKIE KARPATY ZEWNĘTRZNE)

Antoni K. Tokarski & Anna Świerczewska

W czwartorzędowych żwirach rzecznych odsłoniętych w pobliżu regionalnego nasunięcia w polskich Karpatach Zachodnich powszechnie występują spękane klasty skał fliszowych. W analizowanym materiale klasty skał drobnoziarnistych są częściej spękane, niż klasty skał gruboziarnistych. Obserwuje się też dodatnią

korelację pomiędzy liczbą spękanych klastów a ich wielkością. Wśród spękań występują spękania odziedziczone po spękaniach ciosowych tnących skały macierzyste oraz neospękania, które powstały *in situ* w żwirach. Te dwie grupy spękań cechuje różna orientacja w stosunku do współrzędnych geograficznych oraz do powierzchni a-b klastów, tj. płaszczyzny zawierającej oś o maksymalnym (a) i pośrednim (b) wymiarze. Spękania odziedziczone są zorientowane chaotycznie w stosunku do współrzędnych geograficznych, podczas gdy orientacja neospękań jest uporządkowana. Spękania odziedziczone są zorientowane niemal pionowo (80-90°) względem powierzchni a-b klastów macierzystych, natomiast neospękania są zorientowane pod katami 0-80° do tych powierzchni. Pochodzenie neospękań jest wynikiem aktywności tektonicznej, która miała miejsce po osadzeniu analizowanych żwirów.