

## Geomorphology, sedimentology and origin of the glacial Złota Góra hills near Konin (Central Poland)

Marek WIDERA



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The Złota Góra hills (Central Poland) have been variously interpreted as a kame, a sandur and as different types of moraine. Due to their morphology and internal structure, the Złota Góra hills differ, however, from typical depositional glacial landforms in the European lowlands. Morphologically, the Złota Góra hills consist of numerous asymmetrical and oval hills of various sizes. The deposits show a wide variety of lithofacies, which are diagnostic for debris flows, hyperconcentrated flows, sheetfloods, braided rivers, deltas and ephemeral lakes. The combination of such deposits is characteristic of an environmental setting including both an end moraine fan (debris flows, hyperconcentrated flows, sheetfloods and ephemeral lake deposits) and a sandur (braided river, sheetfloods, and delta or ephemeral lake deposits). Therefore, these hills must be interpreted as representing an end moraine/sandur massif. The hills were probably formed subaerially by meltwater in an interlobate area of the retreating Scandinavian ice sheet.

Marek Widera, Institute of Geology, Adam Mickiewicz University, Maków Polnych 16, PL-61-606 Poznań, Poland, e-mail: [widera@amu.edu.pl](mailto:widera@amu.edu.pl) (received: June 01, 2010; accepted: May 30, 2011).

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### INTRODUCTION

The maximum extent of the ice sheet in Poland during the Last Glacial Maximum (LGM) has been discussed since the 1920s, when Lencewicz (1927) distinguished the youngest Scandinavian glacial deposits in Central Poland. Since then, the maximum extent has frequently been revised (Rotnicki, 1963; Kozarski, 1981, 1986, 1990; Stankowska and Stankowski, 1988; Rotnicki and Borówka, 1990; Karczewski, 1994; Stankowski *et al.*, 1995; Morawski, 1999, 2009; Wysota, 1999; Krzywicki, 2002; Petera and Forsytek, 2003; Przybylski, 2008). Marks (2002, 2005) and Marks *et al.* (2006) have reviewed the previous opinions and the most recent concepts concerning the maximum extent of the ice in Poland during the LGM.

In the vicinity of Konin (Central Poland), however, the LGM maximum ice extent is still under discussion. Some researchers have argued that the Złota Góra hills are of Weichselian (Vistulian) age (e.g., Berendt and Keilhack, 1894; Łyczewska, 1960; Krygowski, 1974; Gogołek and Mańkowska, 1989; Szałamacha and Skompski, 1999; Marks, 2005; Marks *et al.*, 2006). Other authors date the Złota Góra

hills as Wartanian (Late Saalian; e.g., Lencewicz, 1927; Mikołajski, 1927; Woldstedt, 1931; Majdanowski, 1950; Rotnicki, 1963; Stankowska and Stankowski, 1988; Stankowski *et al.*, 1995; Widera, 1993, 2000; Petera and Forsytek, 2003). Petera and Forsytek (2003) have reviewed in detail the evolution of ideas on the of LGM ice extent in the study area.

The hypotheses concerning the Złota Góra genesis can be divided into three groups. First, based on geomorphological criteria only, the hills have been regarded as an end moraine and ground moraine of various ages (*cf.* Petera and Forsytek, 2003). Secondly, the Złota Góra hills have been identified as a kame of Wartanian age on the basis of geomorphological criteria in combination with sedimentological data (Kłysz, 1981, 1985). Thirdly, taking the internal structure and geomorphological features as the most important criteria, the present author has interpreted it as an “interlobate sandur fan” dating from the Wartanian Glaciation (Widera, 1993).

The main objective of the present contribution is to define the glacial landforms and to discuss the origin of the Złota Góra hills. This work is a continuation of earlier studies by the present author (Widera, 1993).

## STUDY AREA

The study area (52°010' N, 18°018' E) is located in the vicinity of Konin, Central Poland (Fig. 1). The area under investigation is 324 km<sup>2</sup>, but the area of the Złota Góra hills only is less than 63 km<sup>2</sup> (approx. 9 km long and 7 km wide). The altitude ranges between 79.9 and 191.0 m a.s.l. The lowest point lies in the Warta Valley west of Konin, whereas the highest one is the top of the Złota Góra (Fig. 2).

According to the latest opinions, this area belongs to the glaciomarginal zone of the Weichselian Glaciation. The LGM is represented here by the Leszno and Poznań phases, which correspond to the Brandenburg and Frankfurt phases in Germany, respectively (Woldstedt, 1931). Their end moraines are quite close together and even overlap 30 km NE of Konin (Fig. 1B). Therefore, on the 1:500 000 geological map of Poland (Marks *et al.*, 2006), the Złota Góra hills represent the end moraine of the Leszno Phase (Fig. 1C).

The fieldwork for the present study was carried out in three sand pits, i.e. Gołabek I, Gołabek II and Gołabek III, located 5–7 km ESE of Konin, in the northern part of the study area (Fig. 2).



Fig. 1. Location map

A – maximum extent of the Weichselian ice sheet in Poland and neighbouring areas, modified after several authors; B – major phases of the Late Weichselian Glaciation in Central Poland, compiled from Kozarski (1981) with modification after Marks (2005) and Marks *et al.* (2006); C – part of the 1:500 000 geological map of Poland at Konin, after Marks *et al.* (2006). Most relevant symbols: 14 – outwash sand and gravel; 17 – terminal-moraine sand, gravel, boulder and till; 18 – meltout or lodgement till, weathered till, sand and gravel

## METHODS

The landforms were mapped for the present study from 1:25 000 and 1:50 000 topographic maps, yielding the morphological sketch of Figure 2. Six W–E and four N–S morphological cross-sections are shown in Figure 3.

Twelve sedimentological profiles were analysed in the three sand pits for their texture, structure, deformations and palaeocurrent directions. The sediment architecture was recorded using a combination of digital photographs, sketches and sedimentary logs. The palaeocurrent data were collected from planar and trough cross-stratified layers only.

For the sediment texture and structure, a lithofacies code, based on Miall (1977, 1985) and Eyles *et al.* (1983), was used (Table 1). The original codes established by Miall (1977, 1985) for fluvial deposits only, with additions made by Eyles *et al.* (1983) for diamicts, was slightly modified. The structural code notation “d”, i.e. deformed, is used for all investigated deposits (Table 1). For example, lithofacies GDmd and Thd indicate a massive and deformed gravelly diamicton, and a horizontally stratified and deformed silt, respectively.

## RESULTS

## MORPHOLOGY

The hills of Złota Góra, culminating 191 m a.s.l., are bordered by hummocky ground moraine at ~110–160 m a.s.l. to the south. To the west and east, the hills are flanked by shallow depressions of the Powa and Topiec rivers, respectively, which both drain to the north. These valleys change in altitude from more than 100 m to less than 90 m a.s.l. In contrast, the northern landscape is 2–5 km wide and relatively flat. It is the Warta Valley, which is a well-defined remnant of the Warszawa–Berlin ice-marginal streamway, reaching an altitude of ~80–85 m a.s.l. (Figs. 2 and 3).

Based on morphological criteria, the Złota Góra hills can be divided into the following three segments.

Table 1

Codes of the textural and structural elements of the various lithofacies (modified after Miall, 1977, 1985; Eyles *et al.*, 1983)

Code	Granulometry
D	diamicton
G	gravel
S	sand
T	silt
C	organic deposit
Code	Sedimentary structure
m	massive
p	planar cross-stratification
t	trough cross-stratification
r	ripple cross-lamination
h	horizontal lamination
d	deformed

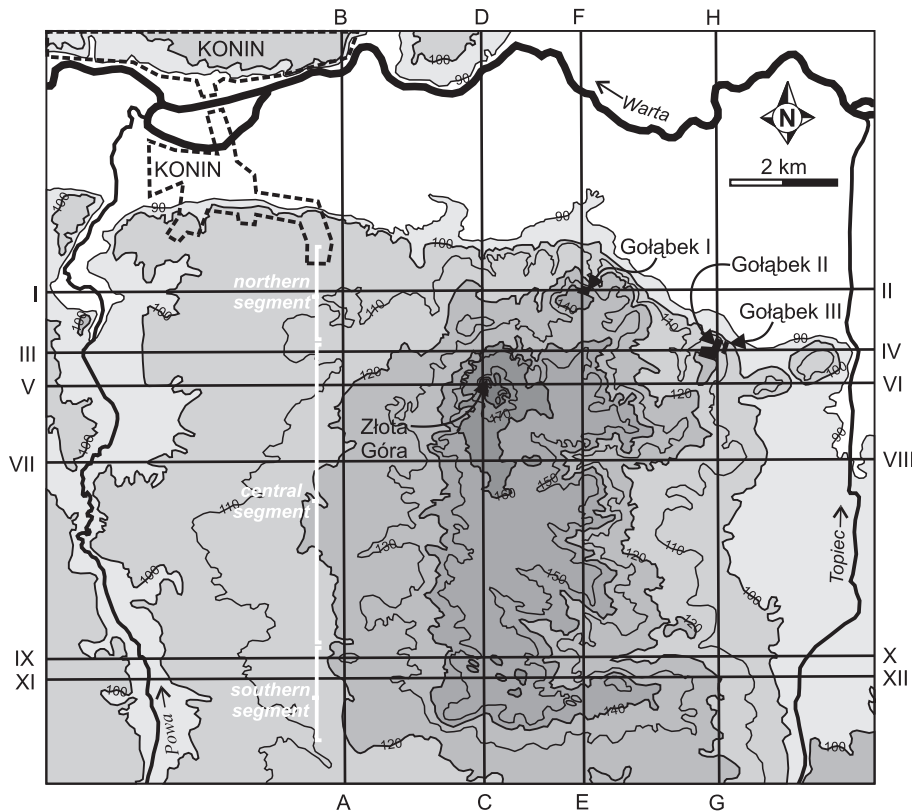


Fig. 2. Simplified morphology of the Złota Góra Massif and surrounding area, with location of the sand pits under study and cross-sections (A–H, I–XII)

Altitudes are between 79.9 and 191.0 m a.s.l.; contour intervals 10 m (90–190 m a.s.l.)

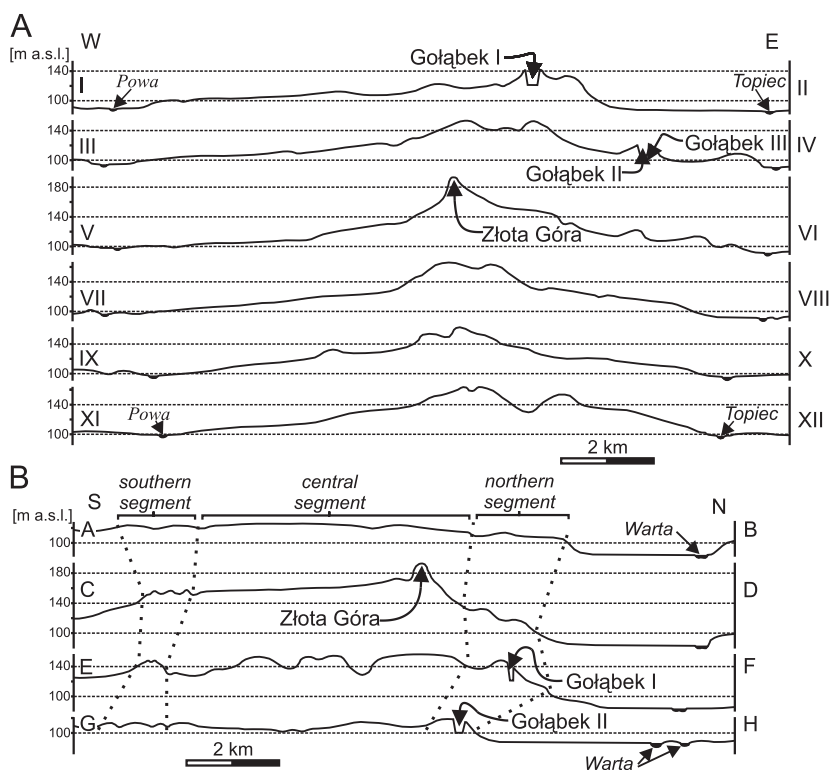


Fig. 3. Morphological cross-sections through the Złota Góra Massif

A – W–E cross-sections; B – N–S cross-sections; for location see Figure 2

1. The southern segment, which is 7 km long and 2 km wide, has an W–E orientation. This segment consists of numerous small mounds (Fig. 2) that occur sporadically more than 10 m above the surrounding area, which has an altitude of ~140–150 m a.s.l. The southern flank of this segment is steep (Figs. 2 and 3).

2. The highest point of the study area, i.e. the Złota Góra, forms part of the central segment (Fig. 2). The axial part of this segment, reaching an altitude of over 140 m a.s.l., is, like the southern segment, 7 km long and 2 km wide. Three flanks (the southern flank is different), are relatively steep and deeply eroded between 130 and 150 m a.s.l. (Fig. 3).

3. The most important area for the present study is the northern segment of the Złota Góra hills, which lies close to the Warszawa–Berlin streamway in the north. There are at least five hills, but the constituent deposits are exposed in two of them only. Their morphology is similar to the above-mentioned central segment. The relative height of the hill with the Gołabek I sand pit is ~30–45 m and the hill with the Gołabek II and Gołabek III sand pits is ~10–25 m high (Figs. 2 and 3).

## SEDIMENTOLOGY

### GOŁABEK I

The Gołabek I sand pit is 200 m long, 150 m wide and located at 124–138 m a.s.l. (Fig. 4). Four sedimentological profiles have been selected for detailed examination. They contain ten lithofacies, which are grouped into four associations (Figs. 5–7).

**Description.** – Four lithofacies associations have been distinguished, with the following characteristics.

Lithofacies association 1 (SGt, SGp, St, Sp, Sh, Sr) is composed of gravelly sand, sandy gravel and sand with various types of stratification: trough, planar, horizontal and ripple. These lithofacies are more common in the lower part of the exposure (Figs. 5 and 6). The individual layers are between 3 cm and 1.5 m thick and their bases are predominantly erosional. All these lithofacies are characterized by a matrix-supported texture and, usually, normal grading. Moreover, the cross-stratified units generally dip towards the south (Fig. 5B, D).

Lithofacies association 2 consists of horizontally stratified or massive and deformed silts (Th, Tmd) together with horizontally stratified sand (Sh). These lithofacies are lenticular in shape, 20–30 m long and up to 1–2 m thick (Figs. 6A and 7A).

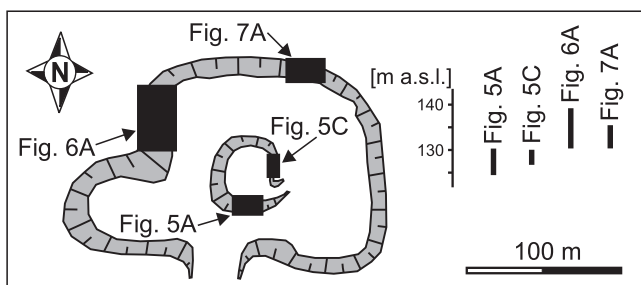


Fig. 4. Outline of the Gołabek I sand pit with location of the sedimentary profiles shown in Figures 5–7

In one case, lithofacies Th and Sh, i.e. silt and sand, are stratified horizontally and undisturbed (Fig. 7B). In another case (lithofacies Tmd), initially massive silt is now deformed (Fig. 6B, C).

Lithofacies association 3 is composed of massive and deformed gravelly diamicton (DGmd), massive and deformed diamicton (Dmd) as well as massive and deformed diamictic gravel (DGmd). This association is common in the upper parts of the western and northern profiles in the Gołabek I sand pit. These lithofacies are deformed and their basal contacts are always sharp (Figs. 6A, C and 7A, D). The total thickness of the massive and deformed gravelly diamicton (DGmd), and of the massive and deformed diamictic gravel (GDmd) reaches 4–6 m (Fig. 7A). These lithofacies consist of a mixture of matrix-supported gravels and boulders, which can exceed 0.5 m in diameter (Fig. 7D). However, in the case of massive and deformed diamicton (Dmd), the thickness decreases from 4–6 m to less than 1 m towards the south (Fig. 6A). Lithofacies Dmd is predominantly fine-grained (i.e. clay, silt, sand) with sparsely isolated pebbles. The fold axes of the deformed diamictons are roughly orientated E–W.

Lithofacies association 4 consisting of gravelly sand with planar stratification (SGp), only seen at the top of the exposure (Figs. 6A, D and 7A), contains a matrix with a relatively high amount of clay and silt (Fig. 6D). One or two sets of strata dipping to the south can be distinguished. Their combined thickness ranges between 2 and 3 m and their lower bases are always sharp (Figs. 6A and 7A).

**Interpretation.** – The four lithofacies associations are genetically interpreted as follows.

Lithofacies association 1 is characteristic of a braided-river environment (Maizels, 1993; Krüger, 1997; Krzyżkowski and Zieliński, 2002; Zieliński and van Loon, 2003; Kjær *et al.*, 2004). The lithofacies SGt, St, SGp, Sp and Sr represent bedforms migrating in braided channels (Allen, 1965; Miall, 1977, 1985). They are typical of 2-D and 3-D dunes (megaripples) and ripples. According to Maizels (1993), sandurs are prototypes of landforms built up by braided-river lithofacies assemblages. Lithofacies Sh shows that meltwater ran over the entire depositional area. The horizontal stratification of the sands was produced under conditions of lower flow regime. This unit has a relatively flat top, which is interpreted as the topset and steeply sloping foreset of a delta (Fig. 5C, D). This lithofacies assemblage thus records a glaciofluvial delta entering a sandur, which was covered at the time by deposits of a braided river (*cf.* Smith and Ashley, 1985).

The second, fine-grained, lithofacies assemblage is composed of facies Th, Tmd and Sh. This association is interpreted as formed in ephemeral lakes. The sediments were mainly deposited from suspension in almost stagnant water or under conditions of very low-energy water currents. The silty and sandy beds form rhythms reflecting changes in ablation (Mokhtari Fard and Gruszka, 2007). They can be attributed to long-lived seasonal (rather than daily) fluctuations in water supply. The sediments are usually disturbed in their top parts, most probably during rapid deposition of the overlying flow tills (*cf.* van Loon, 2009). Similar deposits have been described by Gruszka and Zieliński (1996) and Gruszka (2001, 2007) and as glaciolacustrine deposits in the Bełchatów lignite mine in Central Poland.



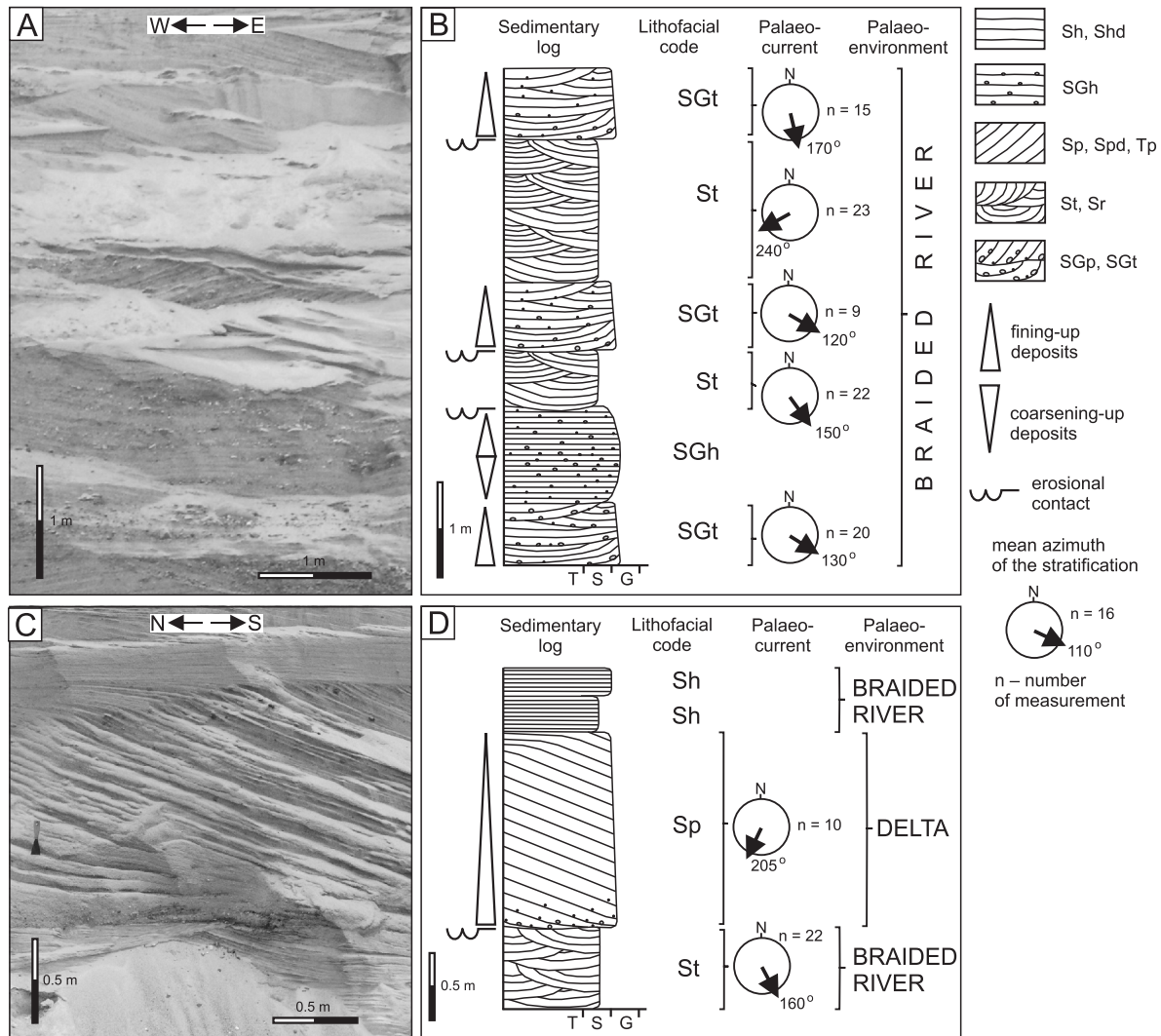


Fig. 5. Section in the central part of the Gołabek I sand pit

A and C – photographs of the section; B and D – corresponding sedimentary logs; for location see Figure 4; for explanation of the lithofacies codes see Tables 1 and 2

Association 3 is built of diamictic lithofacies, which are either underlain by sand and gravel deposits or occur on top of the sedimentary succession. Moreover, all of them are deformed with clearly visible folds, indicating fluidization during deposition by cohesive mass flows, i.e. debris flows (Nemec and Steel, 1984; Pisarska-Jamroży, 2006). These features are characteristic of flow tills derived from the ice sheet (Krüger and Marcussen, 1976; Ruszczynska-Szenajch, 1982; Eyles *et al.*, 1983; Brodzikowski and van Loon, 1987; Krüger, 1994; Zieliński and van Loon, 1996; Krüger, 1997; Huddart *et al.*, 1999; Krüger *et al.*, 2010). The occurrence of flow tills composed of lithofacies DGmd, Dmd and GDmd is evidence of deposition relatively close to the ice sheet margin (Krüger and Marcussen, 1976; Kasprzak and Kozarski, 1984, 1989; Paul and Eyles, 1990; Evans *et al.*, 1999; Zieliński and van Loon, 2000; Evans and Twigg, 2002; Krzyszkowski and Zieliński, 2002). This explains why this lithofacies association is exposed less than 50–70 m from the northern wall of the Gołabek I sand pit. The general ice-flow direction was from north to south. This is supported by the position of the flow tills and their ar-

chitecture, as well as by the fold axes that have an E–W direction. The fourth thick, lithofacies association, consisting of only one lithofacies (large-scale planar stratified gravelly sand, SGp) occurs at the top of the exposure. The sands contain a significant amount of clay and silt, which indicates that this succession is fairly similar to the “dirty gravels”, but finer. Zieliński and van Loon (2000) have interpreted such poorly sorted, matrix-supported gravelly sands as typical of the proximal zone of end moraine fans. They are transitional between gravel and sand/silt sheetfloods, and show a decreasing grain size towards the south. The sediments were probably deposited under high-energy conditions, where the fan surface was relatively steep and transport was not channelized (*cf.* Zieliński and van Loon, 2000).

#### GOŁABEK II

The Gołabek II sand pit is more than 500 m long and 350 m wide. It is at 105–115 m a.s.l. (Fig. 8). Six sedimentological

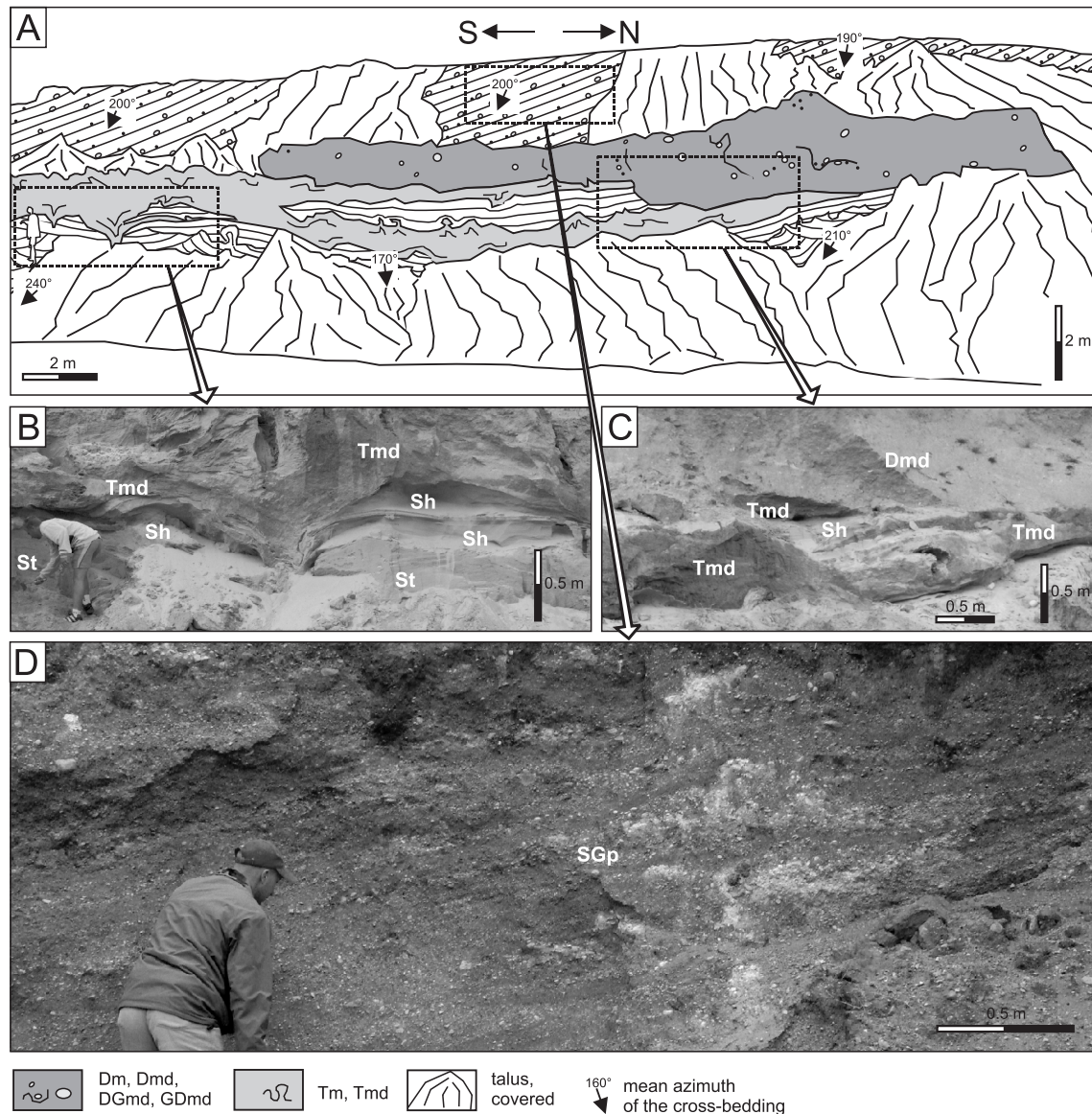


Fig. 6. Section in the western part of the Gołabek I sand pit

A – general architecture; B–D – lithofacies described in detail in the text and in Table 2; photo D shows the so-called “dirty gravels”; for location see Figure 4; for explanation of the lithofacies codes see Tables 1 and 2; other explanations as in Figure 5

profiles have been studied. They include twenty lithofacies, which have been grouped into seven associations (Figs. 9–13).

**Description.** – The seven lithofacies associations in this pit have the following characteristics.

Lithofacies association 1 consists of massive diamicton (Dm), which may be deformed (Dmd). These deposits are the highest ones in the profiles located in the northernmost parts of the Gołabek II sand pit (Figs. 9 and 10). Their thickness is up to 3.5 m, their horizontal extent reaches 15 m, and the base is sharp. Moreover, the interior structure of these lithofacies is locally folded (Fig. 9A, C).

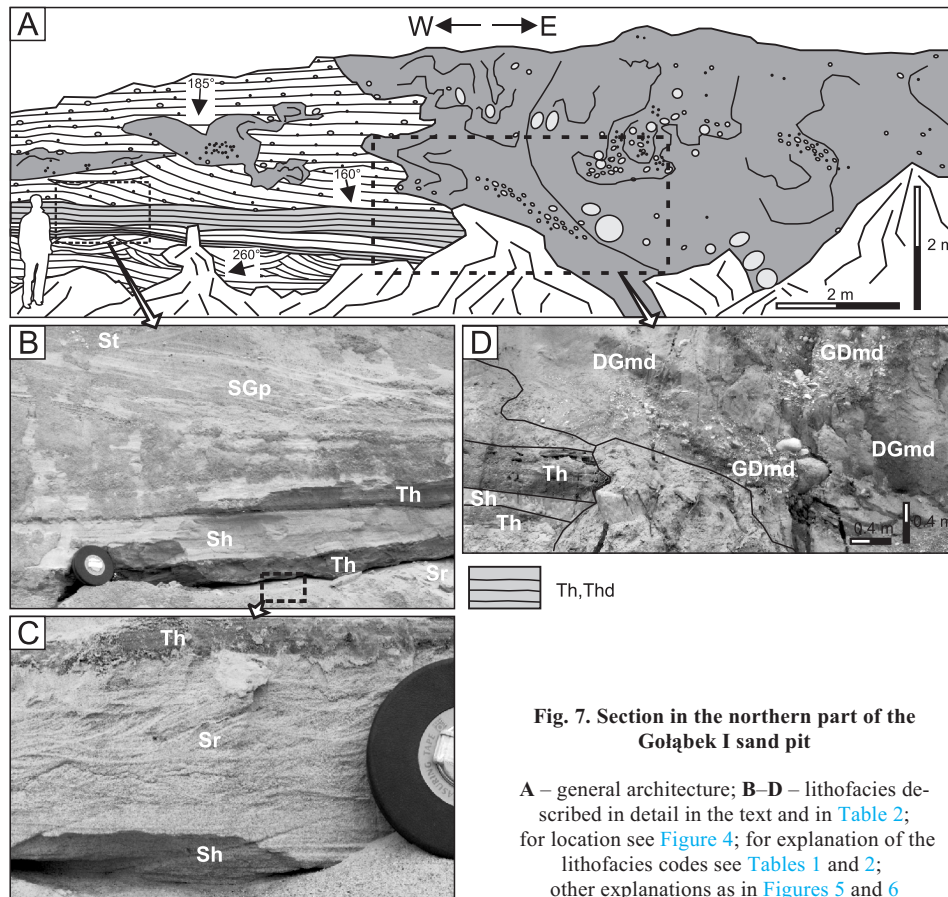
Lithofacies association 2 consists of massive deposits, *viz.* gravel (Gm), sandy gravel (GSm), diamictic gravel (GDm) and sand (Sm). All lithosomes are lenticular in shape and their thicknesses range from 0.3 to 2.5 m (Figs. 9, 10 and 13). Their basal contact is always erosional. Apart from lithofacies Sm,

this association consists of matrix-supported to clast-supported well-rounded gravels (so-called “egg gravels”) with finer admixtures. These gravels contain gneisses, granites, marls and diamictons (Fig. 10).

Both the large-scale planar stratified (Sp) and the deformed equivalents (Spd) of lithofacies association 3 are more than 0.3 m thick, reaching up to 3 m (Figs. 9, 12 and 13). The strata overlain by diamictons are usually faulted with a throw of less than 10 cm (Fig. 9A, B, D).

The fourth association consists of only one lithofacies: planar-stratified gravel (Gp), which is characterized by two pseudo-imbricated sets of strata. Both sets dip to the SSW (Fig. 11). The length of these sets is more than 15 m and their thicknesses range from 1 to 2 m (Fig. 11A). The base of the sets is slightly erosional, so that the contact between both sets is sharp. The lower set consists mainly of granules and fine peb-





**Fig. 7. Section in the northern part of the Gołębek I sand pit**

A – general architecture; B–D – lithofacies described in detail in the text and in Table 2; for location see Figure 4; for explanation of the lithofacies codes see Tables 1 and 2; other explanations as in Figures 5 and 6

bles. It is clast-supported with a matrix of coarse sand and fine gravel. In contrast, the upper set consists of medium-sized and coarse pebbles, and it is clast-supported with a matrix of fine gravel (Fig. 11B).

Lithofacies association 5 is composed of planar-stratified gravelly sand and sand (SGp, Sp) with, in general, admixtures of gravel. This association is exposed at the top of the profile in the eastern part of the Gołębek II sand pit (Fig. 8). Its lateral extent is more than 20 m and its thickness ranges from 1 to 3 m (Figs. 10 and 12). The sands belong to the medium and coarse sand fractions. The gravel clasts are up to 20–40 cm across and they occur close to the base of this succession (Fig. 12A, B, E), which dips towards the SE (Fig. 10A) or to the SW (Fig. 12B).

Lithofacies association 6 (St, Sp, Sh, SGt, SGh) consists of trough, planar and horizontally stratified sand and gravelly sand. The sets of this association, which range in thickness from 0.6 m (Fig. 12C) to more than 6 m (Fig. 13C, D), contain crude (>5 cm) stratification (Figs. 10A, 12C, D and 13C, D), whereas the individual strata are 0.2–1 m thick. The sets consist of sands with sporadic admixtures of gravel. All lithofacies of this association are characterized by normal grading. The cross-stratified units generally dip towards the SE–SW (Figs. 10A, 12B and 13D).

Lithofacies association 7 consists of horizontally stratified silt and sand (Th, Sh) as well as horizontally stratified and deformed silt and sand (Thd, Shd). These deposits are limited laterally to ~20–30 m and vertically to 5–7 m. Most common are sets of horizontally stratified silts (Th) and horizontally stratified sands (Sh). Co-sets of these two lithofacies, i.e. horizon-

tally stratified sands with intercalations of horizontally stratified silts (Sh, Th) are also characteristic (Fig. 13A, B). The succession contains massive gravel (Gm) and planar stratified sands (Sp) that are less than 10 m long and 1 m thick. Massive gravels deform the underlying deposits (Fig. 13A, B). The large-scale planar cross-stratified sands dip towards the WSW (Fig. 13B).

**Interpretation.** – The seven lithofacies associations of this sand pit are interpreted as follows.

The diamictic lithofacies association 1 is similar to that in the Gołębek I sand pit. Consequently, it is interpreted as consisting of debris flow deposits, i.e. flow tills, which were deposited along the frontal ice slope, and their flow direction was from north to south.

Lithofacies association 2, which is characterized by massive structure, i.e. Gm, GSm, GDm, SGm and Sm, represents grain flows to hyperconcentrated flows. Relatively well-sorted deposits are commonly interpreted as the result of deposition by grain flows (Nemec and Steel, 1984; Costa, 1988; Huddart *et al.*, 1999). On the other hand, poorly sorted lithofacies without distinct grading, such as the diamictic gravels (GDm) of this association, are typical of “dirty gravels” (Mokhtari Fard and Gruszka, 2007). Such deposits result from hyperconcentrated flows (Nemec and Steel, 1984; Costa, 1988; Pisarska-Jamroży, 2007). The so-called “egg gravels” pose an interpretational problem. These gravels are composed of gneiss, granite, marl and diamicton clasts, in this case well-rounded (see Fig. 10). The origin of the “egg gravels” has been clarified by Glasser *et al.* (1999), who suggested that these

Characteristics of the lithofacies under study

Lithofacies code	General description	Characteristics
Dm, Dmd	massive or massive and deformed diamicton	matrix-supported diamicton with isolated gravels, 0.1–>5 m thick, sharp basal contact, usually folded, sometimes intercalated by other diamictic lithofacies, produced by mass flows
DGmd, GDmd, GDm	massive and deformed gravely diamicton or diamictic gravel	matrix-supported to clast-supported diamictic deposits, up to 1 m thick lens with clasts of 0.1–0.5 m, deformed with diamictons, formed by mass flows
GSm	massive sandy gravel	clast-supported gravel with sandy matrix, 2–3 m thick units, sharp basal contact, characteristically well-rounded clasts, i.e. “egg gravels”, up to 0.4 m in size, varying in lithology and age, associated with lithofacies GDm and GSm, derived from originally hyperconcentrated sub- and englacial water masses, finally resulting in mass flows
Gp	planar cross-stratified gravel	pebble and cobble gravel with granules and a coarse sand matrix, clast-supported, 0.7–1.1 m thick units, normally graded, sharp basal contact, pseudo-imbricated, deposited from high-energy currents with migrating 2-D dunes in deep braided channels
SGm, SGmd	massive or massive and deformed gravelly sand	coarse to medium sand and fine gravel, 0.2–0.7 m thick irregular beds, sharp basal contact, interpreted as mass-flow deposits
SGh	horizontally stratified gravelly sand	coarse to medium sand and fine gravel, i.e. granules and pebbles, more than 1 m thick and 100 m long units, deposited from sheetfloods
SGp, SGt	planar or trough cross-stratified gravelly sand	sand with admixtures of granules and pebbles, matrix-supported, 0.25–0.6 m thick beds formed by migration of 2-D and 3-D bedforms. Typically 1–>3 m thick units, planar cross-stratified, often normally graded, deposited in proximal part of fan
Sm, SCm	massive sand or massive sand with organic material	medium to fine sand with oxidized Fe in clay fraction, sometimes with organic content (SCm), 0.05–0.6 m thick units, modified by soil processes
Sh	horizontally stratified sand	fine sand, 0.1–0.2 m thick beds with not-erosional but sharp contact, representing glaciolacustrine deposition in standing water. Medium to fine sand, typically 0.5–1.5 m thick and more than 50–100 m long units, base and top lying parallel to each other, deposited from sheetfloods in the lower flow regime. Coarse to medium sand and fine gravel, i.e. granules and pebbles, deposited from sheetfloods
St	trough cross-stratified sand	coarse to fine sand, 0.06–0.45 m thick units, normally graded, evidently erosional top and basal contacts, typical for trough infilling of medium and thick (>5 cm) bedforms, formed by migrating 2-D and 3-D dunes in braided channels
Sr	ripple cross-stratified sand	medium to fine sand, individual units less than 0.06 m thick, sharp basal contact, typical for trough infilling of thin (<5 cm) bedforms, ripples
Sp, Spd	planar or planar and deformed cross-stratified sand	coarse to fine sand, 0.2–3 m thick layers, characteristic of positive medium and large 2-D bedforms, i.e. dunes, deformed close to the mass flow deposits; 0.5–3 m thick units typical for sheetfloods on delta and fan surface
Tm, Tmd	massive or massive and deformed silt	sandy silt to clayey silt, 0.1–0.8 m thick and up to 50 m long beds, deposited in standing water in ephemeral lakes, sometimes deformed by overlying mass flow deposits
Th	horizontally stratified silt	sandy silt to clayey silt with sandy intercalations, 0.1–0.4 m thick layers and 40–50 m long units, deposited in ephemeral lakes
Tp	planar cross-stratified silt	silt and sandy silt intercalating with thick planar cross-stratified sand, individual strata 0.001–0.05 m thick and more than 150–200 m long, typical for a glaciofluvial fan



gravels result from rotation and abrasion of large cobbles and pebbles by passing water within a debris-rich crevasse in the ice body. However, this interpretation does not explain the co-occurrence of very hard and very soft gravels. The present author therefore suggests that “egg gravels” came rather into existence in glacial tunnels or full-pipe channels in supra-, en-, or subglacial environments. Both the soft-rock clasts and the gneiss and granite clasts represent, in the present author’s view, material eroded from the substratum by the glacier.

The large-scale planar cross-stratified sand deposits (Sp, Spd) of association 3 are characteristic of an alluvial fan. They are interpreted as sheetflood deposits, where the water was thus not restricted to channels on the fan (*cf.* Zieliński and van Loon, 2000, 2003; Krzyszkowski and Zieliński, 2002; Shukla, 2009). This lithofacies originated under energy conditions ranging from high energy (SGp, more proximal fan) to low energy (Sp and Tp, more distal fan; *cf.* Zieliński and van Loon, 2000). These deposits show frequent normal faults. The displacement of these faults reaches 10 cm, their strike shows various orientations, and the maximum principal stress must have been almost vertical. The fault architecture thus probably reflects dewatering of the glaciofluvial fan deposits. It is evidence for syn- and/or postdepositional deformations caused by the melting of ice or small pieces of buried ice. A similar but significantly larger synsedimentary fault with a throw reaching ~1 m has been described from the Gołąbek II sand pit (Widera, 1993).

The large-scale planar cross-stratified gravels (Gp) of lithofacies association 4 are well-exposed and a pseudo-imbricated position of particles is perfectly visible. This lithofacies is typical of longitudinal bars in braided rivers with gravel-sized bedload (Allen, 1965; Miall, 1977). The axes of these bars are parallel to the prevailing transport direction and the pebbles accumulate on the down-current sides of the longitudinal bars. These bars are usually formed during in-

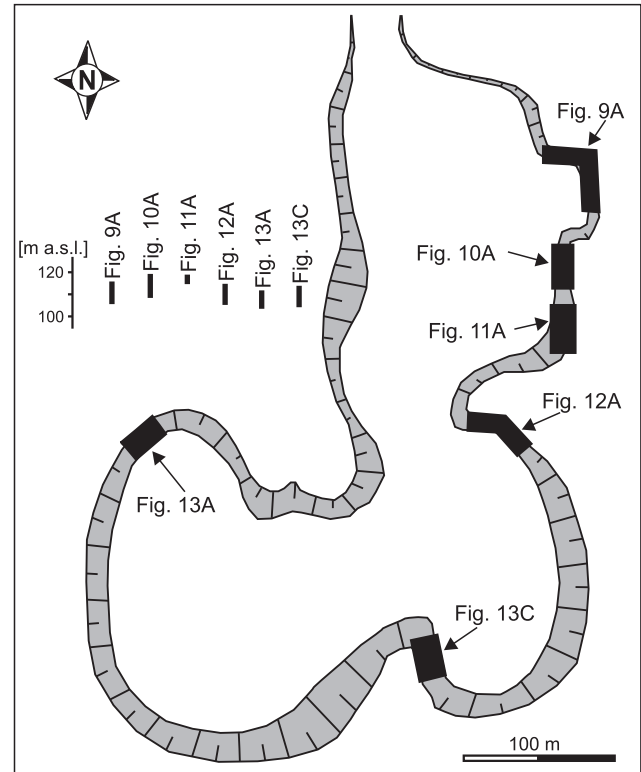


Fig. 8. Outline of the Gołąbek II sand pit with location of the sedimentary profiles shown in Figures 9–13

creasing discharge (Allen, 1970; Kleinhans, 2001). Inclined positions of gravel clasts are common in several proglacial environments (e.g., Knudsen and Marren, 2002; Pisarska-Jamroży, 2006). Thick (>5 cm) planar cross-stratified gravels are evidence of sedimentation by channelized currents under

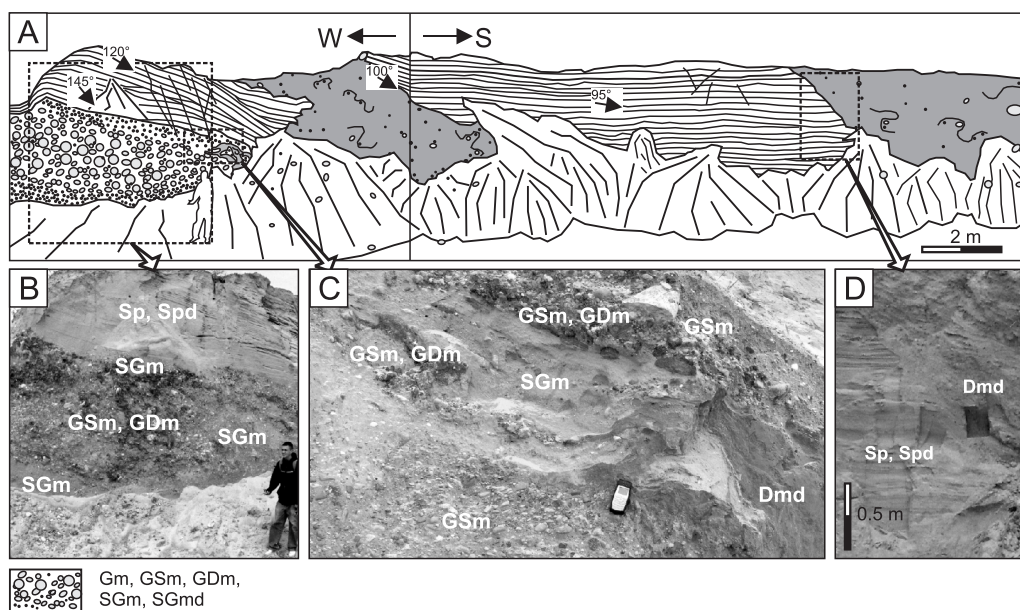
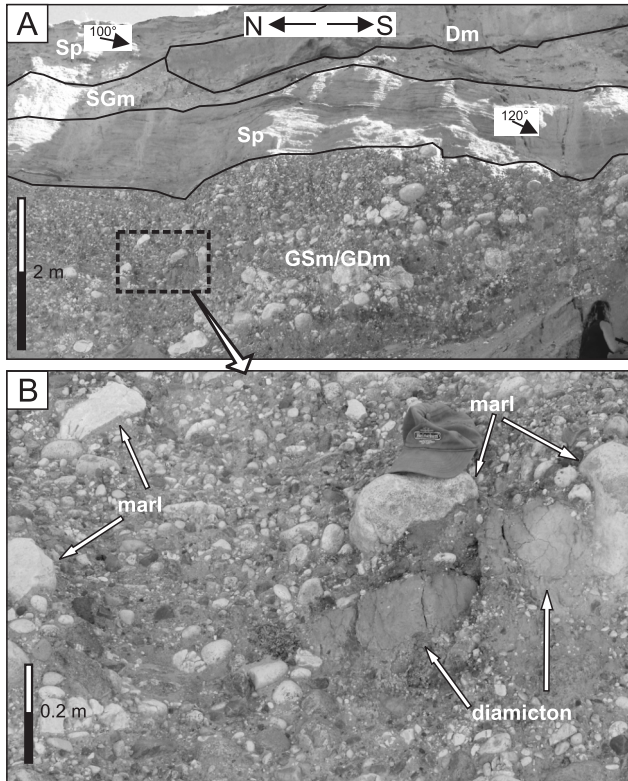


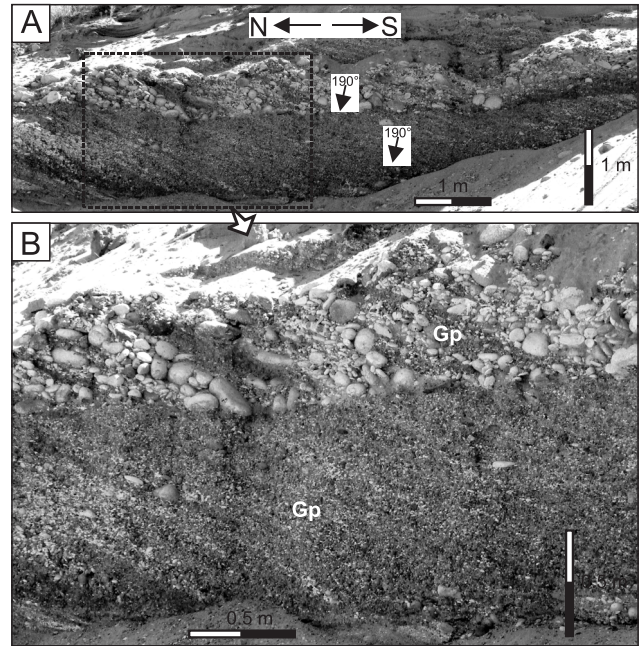
Fig. 9. Section in the northeastern part of the Gołąbek II sand pit

A – general architecture; B–D – lithofacies described in detail in the text and in Table 2; for location see Figure 8; for explanation of the lithofacies codes see Tables 1 and 2; other explanations as in Figures 5 and 6



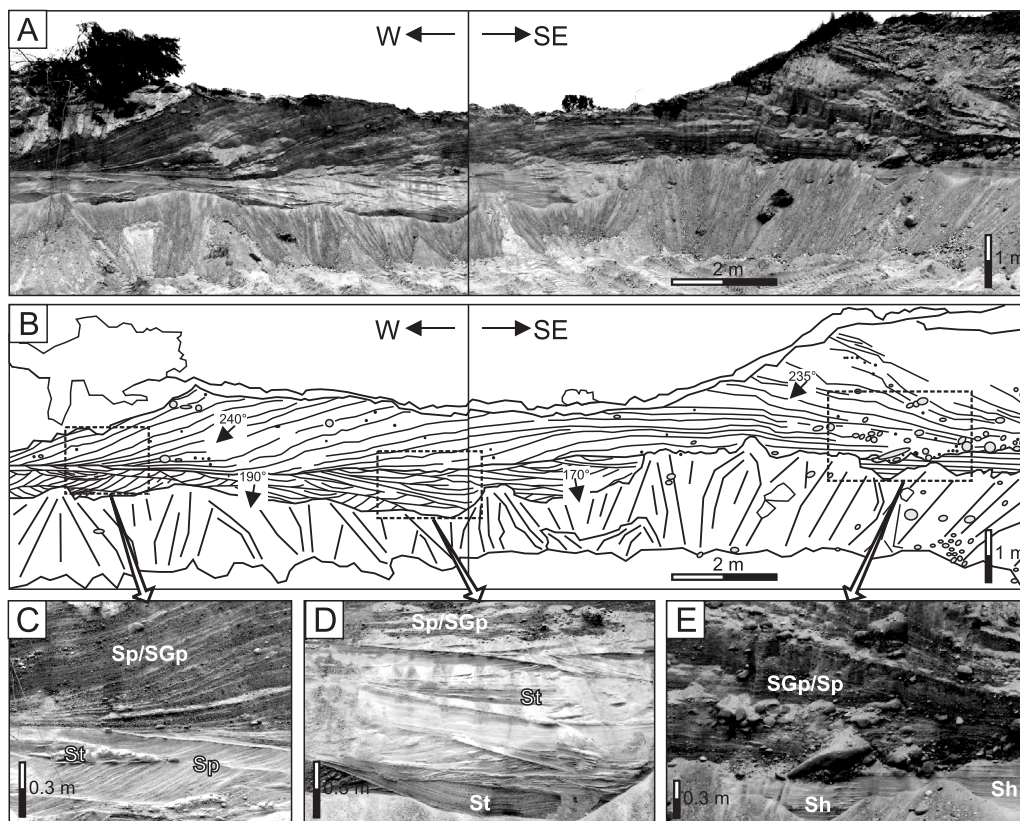
**Fig. 10. Mass-flow deposits in the eastern part of the Goląbek II sand pit**

A – general position of mass-flow deposits, consisting of clast-supported gravels in the profile; B – example of gravels including anomalously well-rounded, the so-called “egg gravels”, Cretaceous marls and Pleistocene diamictons; for location see [Figure 8](#)



**Fig. 11. Gravelly dune (megaripple) in the eastern part of the Goląbek II sand pit**

A – general view of dune deposits, clast-supported gravels; B – two sets of pseudo-imbriated gravels dipping in the same direction; for location see [Figure 8](#)



**Fig. 12. Section in the eastern part of the Goląbek II sand pit**

A – general view; B – general architecture; C–E – lithofacies described in detail in the text and in [Table 2](#); for location see [Figure 8](#); for explanation of the lithofacies codes see [Tables 1 and 2](#); other explanations as in [Figure 5](#)



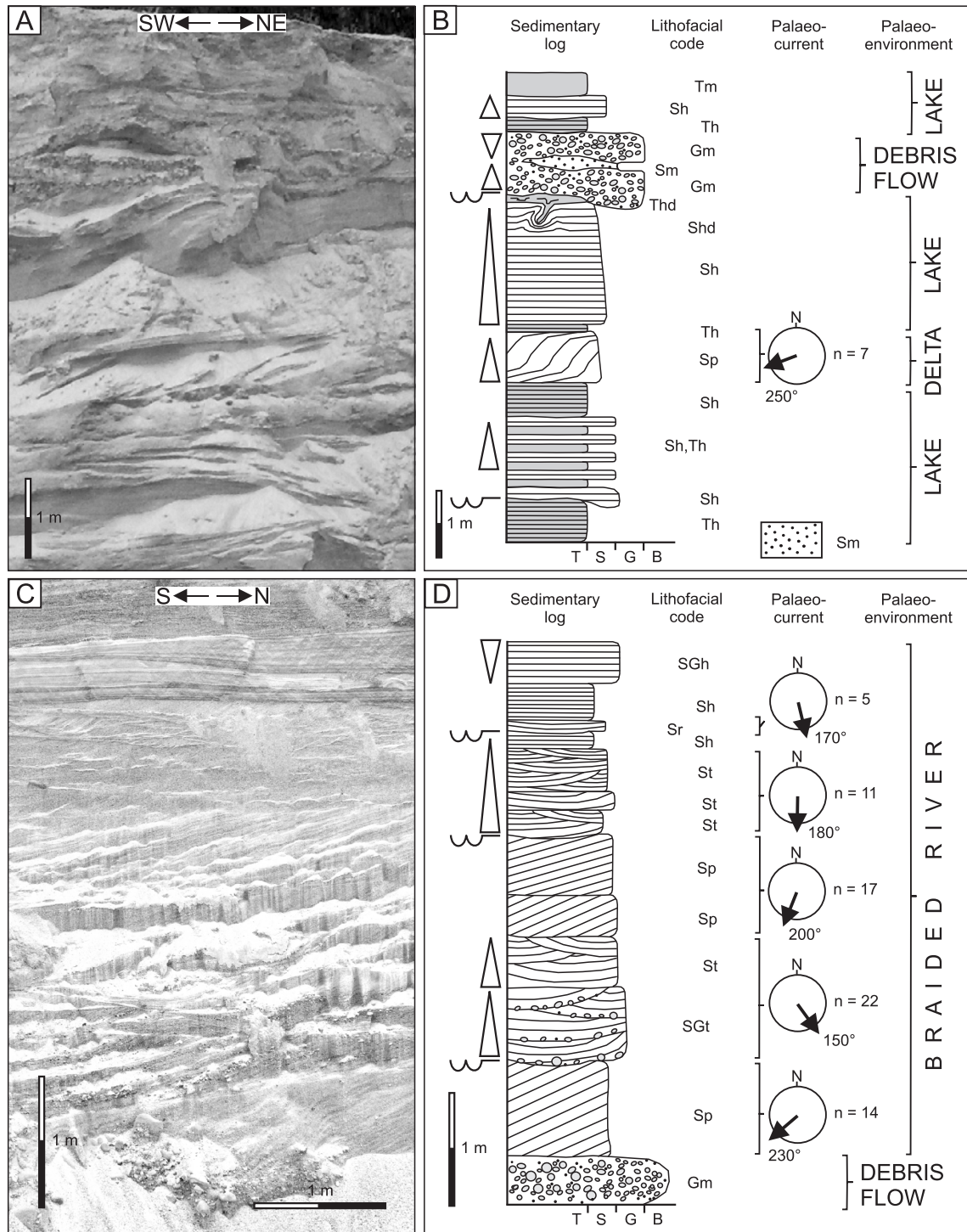


Fig. 13. Section in the southern and western parts of the Goląbek II sand pit

A and C – photographs of the section; B and D – corresponding sedimentary logs; for location see Figure 8; for explanation of the lithofacies codes see Tables 1 and 2; other explanations as in Figures 5–7 and 9

very high-energy conditions and they can be regarded as characteristic of the most proximal parts of sandur fans (Brodzikowski and van Loon, 1987; Maizels, 1993; Zieliński and van Loon, 2003).

In lithofacies association 5, the lithofacies SGp and Sp, with thicknesses reaching up to 3 m, can be interpreted, as for lithofacies association 4 from the Goląbek I sand pit, as result-

ing from sheetfloods in the proximal zone of a glaciofluvial fan (cf. Zieliński and van Loon, 2000). By contrast, the deposits from the Goląbek II sand pit are both more sandy and better sorted and stratified. Thus, they can also be interpreted as deposited in the distal zone of so-called hochsander fans (Krüger, 1997; Evans and Twigg, 2002; Kjær *et al.*, 2004).

The thick trough, planar and horizontally stratified sands with admixtures of gravel, which form association 6, are characteristic of sandurs (Miall, 1977, 1985; Maizels, 1993; Krüger, 1997; Krzyszkowski and Zieliński, 2002; Zieliński and van Loon, 2003; Kjær *et al.*, 2004). These deposits are similar to the lowermost deposits in the Gołębek I sand pit (lithofacies association 1). It is noteworthy that the trough cross-stratified units are very well-developed in both the Gołębek I and the Gołębek II sand pits (Figs. 5, 12 and 13).

Lithofacies association 7, with its horizontally stratified silts and sands, was deposited in an ephemeral lake. These deposits are more distal than the glaciolacustrine deposits from the Gołębek I sand pit (lithofacies association 2). They, too, settled from suspension or in a low-energy water current during a season-dependent period of limited ablation of the ice sheet (*cf.* Gruszka and Zieliński, 1996; Gruszka, 2001, 2007; Mokhtari Fard and Gruszka, 2007). These glaciolacustrine deposits were deformed by the overlying flow tills and massive gravels. Both these flow tills and massive gravels are interpreted as debris flows (Nemec and Steel, 1984; Costa, 1988; van Loon, 2009). However, the glaciolacustrine deposits interfinger with glaciodeltaic deposits, which are represented by planar stratified sands. Such a situation is quite common in proglacial environments, where a delta prograded into a lake (e.g., Smith and Ashley, 1985; Hansen *et al.*, 2009).

#### GOŁĘBEK III

The Gołębek III sand pit is 200 m long and 110 m wide. It is located ~107–112 m a.s.l. (Fig. 14). The sedimentology of two

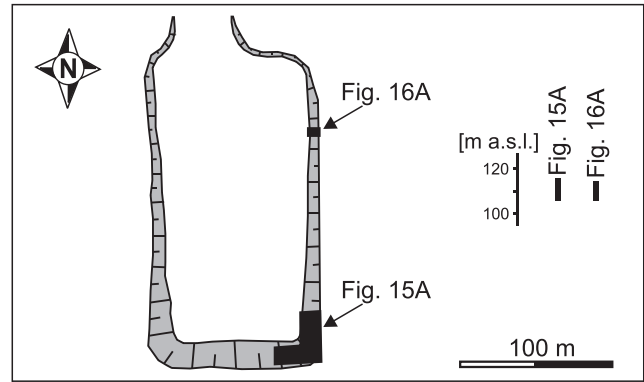


Fig. 14. Outline of the Gołębek III sand pit with location of the sedimentary profiles shown in Figures 15 and 16

profiles are described. They consist of only four lithofacies, which are grouped into two associations (Figs. 15 and 16).

**Description.** – As mentioned above, only two lithofacies associations are present in this sand pit.

Lithofacies association 1 is composed of large-scale planar cross-stratified sands and silts (Sp, Tp), which dominate the Gołębek III sand pit. The sands and silts alternate rhythmically. Their bases and tops are sedimentary (non-erosional, not deformed), running parallel to each other (Figs. 15A, B and 16A), but dip at about 10–15° towards the east in an E–W cross-section (Fig. 15A, C). The succession extends laterally for ~200 m and is 5 m thick. It is characterized by a pre-

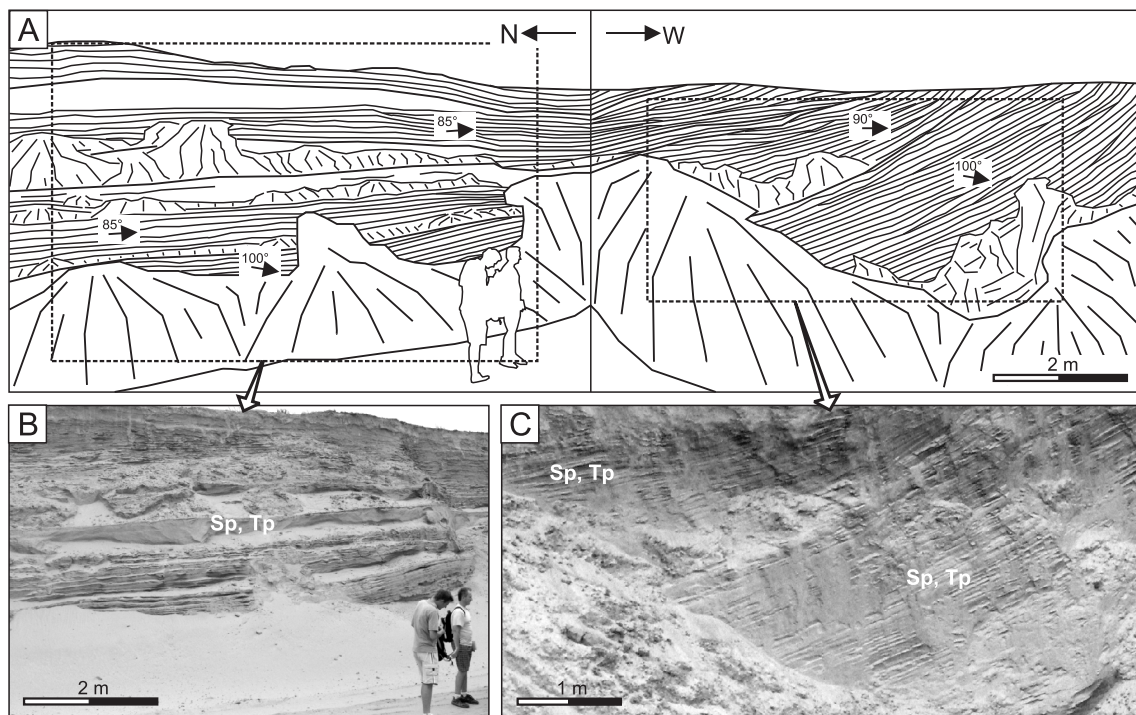


Fig. 15. Section in the southeastern part of the Gołębek III sand pit

A – general architecture; B and C – lithofacies described in detail in the text and in Table 2; for location see Figure 14; for explanation of the lithofacies codes see Tables 1 and 2; other explanations as in Figures 5 and 6



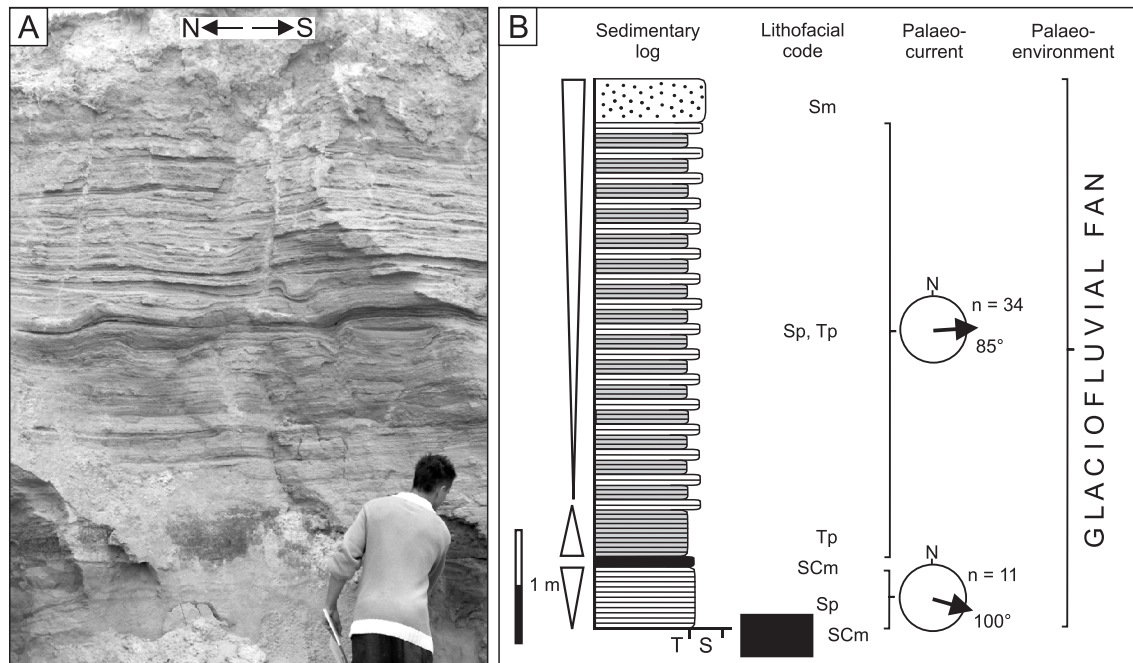


Fig. 16. Section in the eastern parts of the Gołębek III sand pit

A – photograph of the section; B – corresponding sedimentary log; for location see Figure 14; for legend see Figure 7; for explanation of the lithofacies codes see Tables 1 and 2; other explanations as in Figure 5

dominance of inverse grading, and the preferred palaeocurrent direction is towards the east (Fig. 16B).

Lithofacies association 2 consists of massive sands, locally with organic material (Sm, SCm). These two lithofacies are found at the top of each co-set described above, i.e. Sp and Tp (Fig. 16). Individual strata are less than 0.6 m thick, but their horizontal extent reaches up to 200 m. It is noteworthy that this succession contains an admixture of organic matter (Fig. 16B).

**I n t e r p r e t a t i o n.** – The two lithofacies associations are interpreted as follows.

Association Sp, Tp is used as a prototype of alluvial-fan lithofacies assemblages (Blair and McPherson, 1994; Blair, 1999; Shukla, 2009). Taking its palaeogeographical position into consideration, this association represents a terminoglacial fan (Zieliński and van Loon, 2000, 2003; Krzyszkowski and Zieliński, 2002). These large-scale deposits are a continuation, several tens of metres to the east, of the deposits in the Gołębek II sand pit described as large-scale sands with a planar structure (lithofacies association 3). The deposits are structurally the same, but they differ in grain size, i.e. they contain equal proportions of sand and silt. Therefore, this lithofacies association (Sp, Tp), can be considered to be a result of deposition by sheetfloods. The water was not channelized and the current conditions were rhythmically changing from low-energy to very low-energy (*cf.* Zieliński and van Loon, 2000). On the other hand, the rhythms can reflect changing influxes of sediments, which in turn must be ascribed to processes in the supraglacial source area such as ablation, influx of rainwater, sudden drainage of pockets of water or reworking of debris (e.g., Krüger, 1994, 1997; Kjær *et al.*, 2004). Thus, the deposits likely formed in the proximal part of a middle glaciofluvial fan (*cf.* Zieliński and van Loon, 2000) or in the distal zone of a

hochsander fan (Krüger, 1997; Evans and Twigg, 2002; Kjær *et al.*, 2004). It is noteworthy that the large-scale planar stratification dips 10–15°, although the slope gradient (= large-scale planar stratification) ranges, in the case of an ordinary hochsander fan, from 1 to 5° (Krüger, 1997; Kjær *et al.*, 2004).

The second association, with massive sands, either with or without organic material, is characteristic of palaeosoils, which indicate a hiatus in the development of the glaciofluvial fan. It is possible to distinguish, in a vertical profile, at least four generations of the fan in the Gołębek III sand pit (Zieliński *et al.*, 2009). The massive structure is probably a result of sandy sheetfloods and/or bioturbation (Shukla, 2009; van Loon, 2009). In the latter case the plant roots create, according to these researchers, special redox conditions, and can affect the original stratification. Moreover, the resulting organic matter from decomposed plants can be found if they were rapidly covered with new deposits (van Loon, 2009).

#### SEDIMENTOLOGICAL MODEL

On the basis of the above geomorphological and sedimentological considerations, a new conceptual model of the Złota Góra Massif evolution is proposed (Fig. 17). It is obviously more representative and realistic for the northern segment, where the detailed sedimentological investigations were carried out. In contrast, this model is more conceptual for the central and southern segments of the Złota Góra Massif, where it is mainly based on geomorphology, surface observations as well as geological mapping (Gogolek and Mańkowska, 1989). The present model distinguishes four main phases, during which the landforms under study with their lithofacies were formed (Table 2).

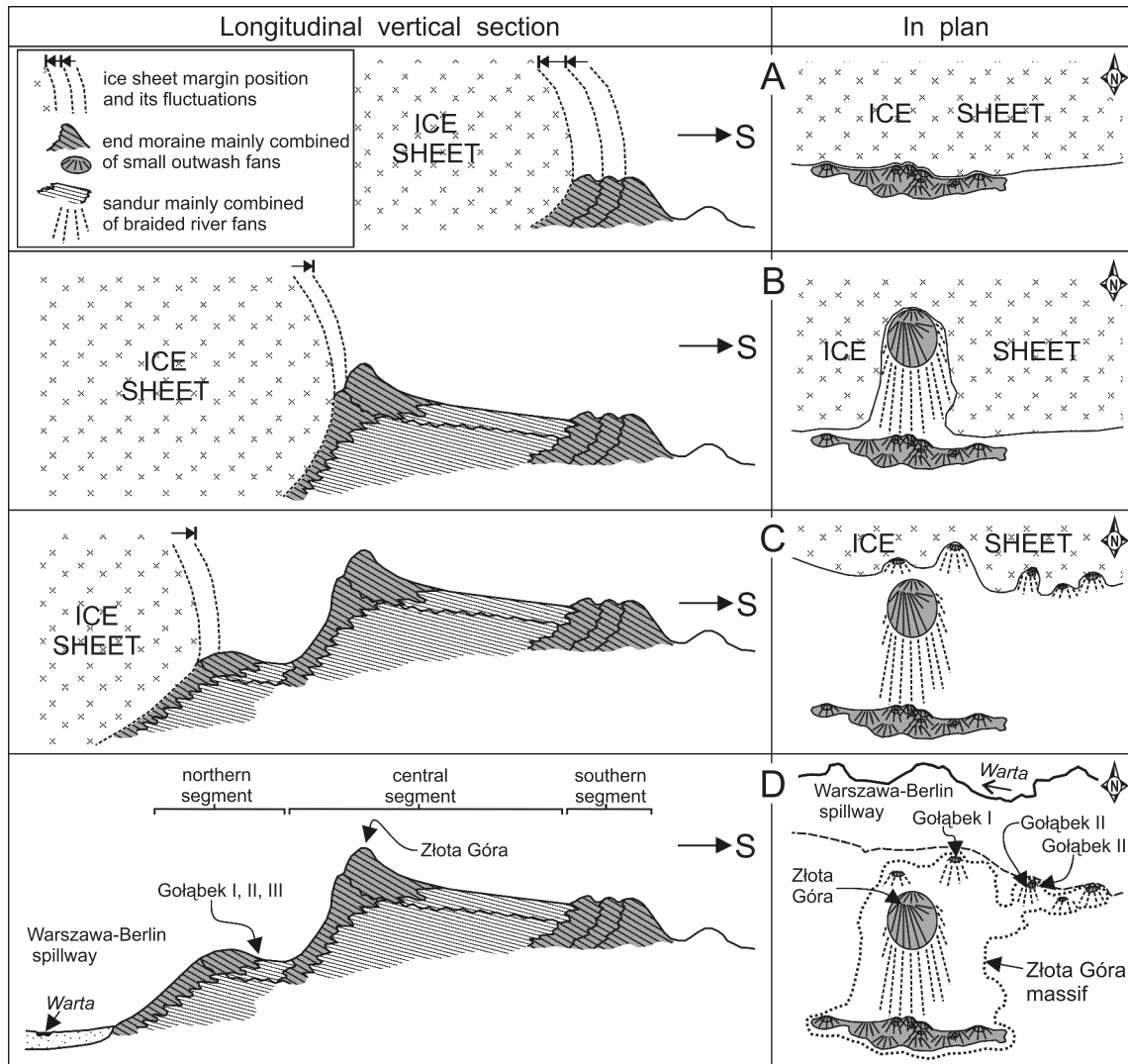


Fig. 17. Conceptual model for the geomorphological development of the Złota Góra Massif

The southern part of the study area was formed during the first phase. Several small terminal-moraine fans, with relatively steep southern slopes, were built along the ice front, with their apexes touching the ice margin (Fig. 17A). These fans were situated parallel to each other, what suggests active ice retreating for a few hundred metres. In this way, a belt of terminal moraines, consisting of stacked glaciofluvial and glacial deposits, was created. The southern part of the Złota Góra Massif thus represents a terminal moraine of mixed glaciofluvial/glacial type (Fig. 17A).

During the second phase, deposition took place between two major ice sheet lobes, probably above a pre-existing high in the substratum (Fig. 17B). Złota Góra was then formed. Its surface is covered by diamictons, “egg gravels” and sands and “normal” gravels. The top of Złota Góra can thus be considered as a terminal-moraine fan. Conversely, the huge and flat-topped area south of Złota Góra can be interpreted as an elongated sandur fan (Fig. 17B). Its shape, with steep western and eastern slopes, suggests that fluvio-glacial deposition took place in an ice-walled accumulation space, i.e. in an interlobe area.

The third phase is a repetition of the second one, but at a smaller scale. During this stage of deglaciation, at least five

small hills were formed (Fig. 17C). The lithofacies architecture indicates some oscillations of the ice sheet margin. In general, the hills must be considered to form a combination of the terminal moraine and sandur fans (Fig. 17C).

The last phase is connected with the deglaciation of the study area. Erosion of the steep slopes occurred, and the Warszawa–Berlin ice-marginal streamway came into existence simultaneously (Fig. 17D). Finally, the present-day drainage network was formed (see Fig. 2).

## DISCUSSION

In general, most depositional glacial landforms are composed of similar deposits in varying proportions, but each is characterized by an individual morphology and interior architecture (Evans *et al.*, 1999; Evans and Twigg, 2002). The size, shape, lithology, depositional conditions, palaeocurrent patterns and deformations of these landforms are, therefore, discussed below in the following order: kame, sandur and terminal moraine.

The basis of a kame may be circular, lenticular, irregular, *etc.* Taking into consideration kame formation in a lowland area, it can be concluded that deposition must have taken place in crevasses or depressions surrounded by dead-ice (Bartkowski, 1967) or between ice-cored moraines (Boulton, 1972). In most cases, the palaeocurrent pattern is centripetal, i.e. the kame material was deposited by water running towards the central zone of the crevasses or depressions (Klajnert, 1984). However, in the case of the Złota Góra Massif, measurements do not indicate transport directions towards the N, NW and NE. Similar observations were made during construction of the A2 highway (Poznań–Konin–Warszawa), which cuts the study area south of the Złota Góra top. These preliminary observations provided similar results to the above-mentioned, i.e. the transport predominantly was directed towards the south in the central segment of the Złota Góra Massif. Thus, taking all information into consideration, the investigated landforms cannot be regarded as kames, as was suggested by Kłysz (1981, 1985).

The term “sandur” or “interlobate sandur fan” cannot be used for the hills and for the entire Złota Góra Massif, as did Widera (1993). It is true that most of the sediments in the Gołębek I and Gołębek II sand pits represent lithofacies typical of sandurs, *viz.* the (glaciofluvial) braided-river environment (Krüger, 1997; Zieliński and van Loon, 2000; Kjær *et al.*, 2004). The morphology of the above landforms, where the western, northern and eastern slopes are very steep, indicates also sedimentation between ice sheet lobes (see Figs. 2 and 17). However, the lithofacies that were distinguished are characteristic of end moraines: flow tills and glaciofluvial-fan deposits. Moreover, the presence of so-called “egg gravels” on the top of Złota Góra indicates that the entire massif cannot be interpreted as a sandur or an “interlobate sandur fan”.

For geomorphological and sedimentological reasons the Złota Góra Massif, including the hills in its northern segment, cannot be considered as a terminal moraine (Peters and Forysiak, 2003; Marks *et al.*, 2006; and references therein). Only the southern, the northern and the north-central parts of the Złota Góra Massif may be considered as a terminal moraine (see Fig. 17). Deposits characteristic of terminal moraines have been described in detail from the northern and upper parts of the Gołębek I and Gołębek II sand pits. However, all deposits from the Gołębek III sand pit are characteristic of an alluvial (glaciofluvial) fan. In contrast to sandur sediments dominated by deposition in a braided river, these terminal-moraine deposits result from debris flows, sheetfloods and/or hyperconcentrated flows. Generally, they represent a glaciofluvial/glacial type of terminal-moraine fan. Zieliński and van Loon (2000) stated: “...Pleistocene sandur deposits represent braidplains, not alluvial fans...”. Here, it is suggested that the glaciofluvial fan represents a terminal moraine, whereas the braidplain deposits represent a sandur. The Złota Góra Massif can consequently not be considered in its entirety as a terminal moraine, as is done on the most recent geological map of Poland at 1:500 000 scale (Marks *et al.*, 2006).

It seems that the Złota Góra Massif results from a combination of factors. The data indicate that the entire massif is composed of terminal moraines and sandurs, which were formed between ice sheet lobes. Such a situation probably took place along a contact zone of the Odra lobe (Marks, 2002; Przybylski, 2008)

and the Vistula lobe (Marks, 2002; Morawski, 2009). The Złota Góra Massif should, therefore, be regarded as a triple terminal-moraine/sandur complex. Partly similar ice-marginal landforms are described from the Kötlujökull by Krüger (1997), and from the Breijamerkurjökull and Fjallsjökull (all in Iceland) by Evans and Twigg (2002).

## CONCLUSIONS

The origin of the Złota Góra Massif in Central Poland was investigated on the basis of its geomorphology and sedimentology. The massif consists of three parts, each consisting of asymmetrical and oval-shaped hills which differ in shape and size. They have three flanks that are relatively steep, which was interpreted as the effect of accumulation between lobes of the retreating Scandinavian ice sheet.

The origin of the interlobate landforms is explained on the basis of sedimentological analyses in three sand pits, i.e. Gołębek I, II and III. The results show a diversity of lithofacies, which can be recognized as characteristic of a sandur or a terminal moraine. Additionally, some lithofacies indicate deposition in ephemeral lakes.

The sandur-related lithofacies were formed in braided rivers. These deposits are dominant in the central and southern parts of the Gołębek I and Gołębek II sand pits. The lithofacies related to a terminal moraine were deposited mainly by debris and hyperconcentrated flows and/or sheetfloods. Both the debris-flow and sheetflood lithofacies are present in the most northern and upper parts of the Gołębek I and Gołębek II sand pits. It must be noted in this context that all lithofacies in the Gołębek III sand pit were produced by sheetfloods. The ephemeral lake-related lithofacies occur in both the sandur and the terminal-moraine areas. These glaciolacustrine deposits are often deformed at their top by the overlying debris-flow deposits. Lithofacies characteristics of a delta are also present. They are spatially related to both the ephemeral lakes and the sandur.

A large number of measurements indicate that the palaeocurrent direction was directed predominantly towards the south. Taking the geomorphology and sedimentology into account, the hills of the Złota Góra thus represent a moraine/sandur massif. It was built in the area where the Odra and Vistula ice lobes probably met. The “fresh” morphology and the lack of ventifacts support a Weichselian age of the landforms. However, an older age of the Złota Góra Massif cannot be rejected definitely and, therefore, further investigations are recommended.

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