

The assemblages of transparent heavy minerals in Quaternary sediments of the Kielce-Łagów Valley (Holy Cross Mountains, Poland)

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Abstract

The composition of the transparent heavy-mineral assemblages (0.25–0.1 mm) in Quaternary slope, karst, glacial, fluvio-glacial and fluvial deposits with different parent material was investigated in the Kielce-Łagów Valley (the central part of the Palaeozoic core of the Holy Cross Mountains). For the purpose, 93 samples of mostly sandy sediments were examined. Some marker and some supporting minerals can be distinguished. Slope and karst deposits are dominated by the abrasion-resistant minerals zircon, tourmaline, staurolite and rutile. This assemblage points at a source consisting of strongly weathered pre-Quaternary bedrock. Glacial and fluvioglacial deposits are dominated by medium-resistant and non-resistant minerals (garnet, amphibole, pyroxene and biotite). The two types of parent material of the heavy minerals are typical of the Quaternary deposits in the Polish uplands. The two sources are most clear in the younger (Vistulian and Holocene), mostly fluvial sediments. The results of the analysis imply that the impact of Pleistocene glaciers on the central part of the Holy Cross Mountains was neither large enough to hide the local mineralogical background, nor sufficient to dominate over the main processes transforming the mineral composition under the variable climatic conditions of the Quaternary, including aeolian processes and chemical weathering.

Key words: heavy-mineral analysis, Quaternary deposits, Holy Cross Mountains

1. Introduction

The Holy Cross (Świętokrzyskie) Mountains are located in the morphogenetic zone of Polish uplands and old mountains (Gilewska, 1991; Starkel, 2008), where Palaeozoic outcrops are locally covered by unconsolidated sediments. This cover comprises deposits that accumulated under various climatic conditions during the Palaeogene-Neogene, the Pleistocene glacials and periglacial phases, and the Holocene (Łyczewska, 1971; Linder, 1984; Mojski, 2005). Thus, the Quaternary of the Holy Cross Mountains contains material from reworked, weath-

ered bedrock, as well as from older glacial and fluvioglacial deposits, as a consequence of the cover by Pleistocene ice sheets (Lindner, 2004; Marks, 2011).

Under periglacial conditions, the relief of the Holy Cross Mountains affected the sediments, which underwent modifications, mostly due to denudation, fluvial activity, weathering and aeolian processes. Deposits accumulated in several sedimentary environments can consequently be found side by side, also at similar elevations. This complex character was thus far insufficiently discussed in the literature dealing with the region.

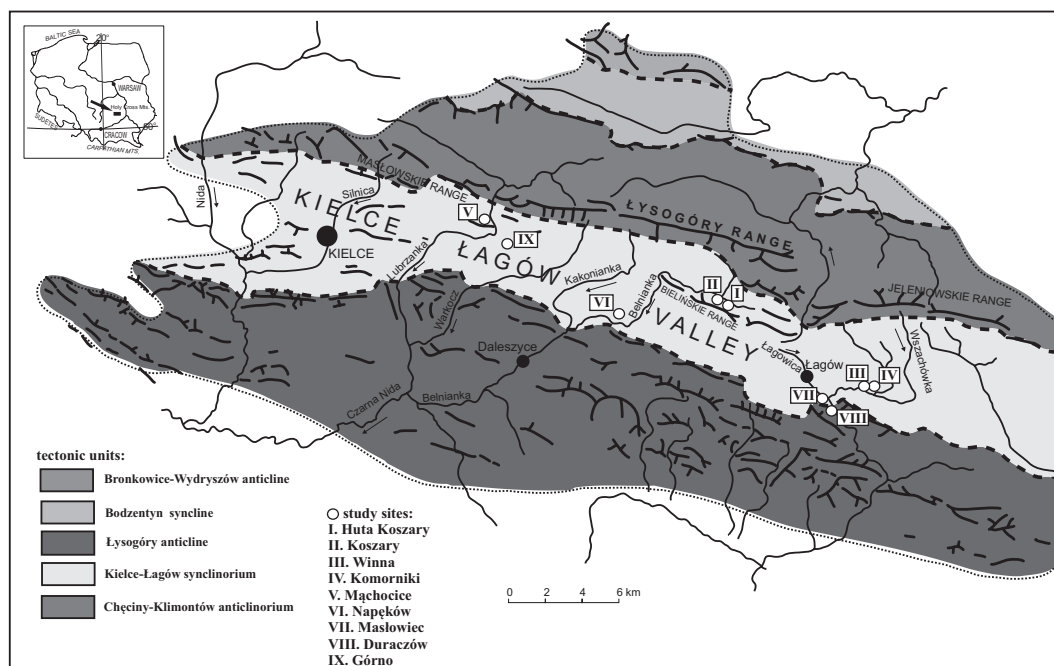


Fig. 1. Location of the study area and of sites I-IX in the Kielce-Łagów Valley, also showing the tectonic units of the Holy Cross Mountains (from Wróblewski, 1977, and Czarnocki, 1957).

It was therefore decided to investigate the Quaternary deposits of a specific stratigraphic position in the central part of the mountain range; the deposits represent various sedimentary environments, viz. slope, glacial, fluvioglacial and fluvial sediments, in combination with older deposits that are considered as parent material for the Quaternary cover, i.e. Miocene deposits filling karst pits, and weathered material of the Palaeozoic rocks. The latter aspect has so far hardly been dealt with in the literature (Radłowska & Mycielska-Dowgiałło, 1972; Kowalski et al., 1979; Ludwikowska-Kędzia, 2000, 2007; Ludwikowska-Kędzia et al., 2006).

The objective of the study was to identify the characteristic qualitative and quantitative features of the heavy-mineral composition of these Quaternary deposits, taking the mineralogical features of the possible or probable parent material into consideration. The study should thus lead to identification of the local and regional parent material of the Quaternary deposits in the central part of the Holy Cross Mountains. This, in turn, should result in data that are useful for establishing a better lithostratigraphy of the Holy Cross Mountains. The Kielce-Łagów Valley was chosen for the study because it forms a vast, structural depression

in the central part of the Holy Cross Mountains (Fig. 1).

2. Study area and locations of the study sites

The depression of the Kielce-Łagów Valley (300 m above sea level – a.s.l.) coincides with the structural boundaries of the Kielce-Łagów synclinorium in the Palaeozoic core of the mountain range (Fig. 1). In the North and the South, the valley is bordered by mountain ranges with a maximum elevation of 612 m a.s.l., built by Cambrian quartz sandstones, shales and greywackes.

The bottom of the valley consists of Silurian, Devonian (mainly limestones, dolomites, sandstones and greywackes), and locally of Carboniferous shales. In the area with carbonate rocks, the bedrock shows a fossil karst relief (Urban, 2001; Rzonca & Urban, 2009), buried under a cover of Quaternary deposits of various types and ages. Due to the karst relief, the thickness of the Quaternary in the valley bottom varies from 30 to 40 m; it decreases from NW to SE. The selection of the various sites was based on the relationship between the Quaternary and

the area's relief. The study concerned deposits representing different forms of relief (fossil or contemporary) and different environments: slope, glacial and fluvial.

Samples from nine study sites of different ages were collected for the heavy-mineral analysis. Two are located on the north-eastern slope of the Bieliny range, near Huta Stara Koszary (site I) and near Koszary (site II) (Fig. 1). At both sites the analysis concerned debris of the Devonian sandstone building the Bieliny range. The heavy-mineral composition of the deposits filling the karst pits was studied in the Winna quarry (site III) and in the Komorniki quarry (site IV). Glacigenic deposits were analysed at the sites Mąchocice (site V) and Napęków (site VI). Periglacial fluvial-slope deposits were examined at Masłowiec (site VII) and fluvial deposits were sampled at Duraczów (site VIII) and Górno (site IX).

3. Methods

The textural and structural features are described through the lithofacies codes proposed by Miall (1978, 1985), as modified by Zieliński & Pisarska-Jamroży (2012). The stratigraphic position of the deposits was established by TL and OSL datings, and named in accordance

with the general stratigraphical subdivision of the Quaternary of Poland; correlation with the Western European stratigraphy follows Marks (2011) and Lindner & Marks (2012) (Fig. 2).

The various units are indicated with a code that is based on the type of deposit, its lithology, its age and the number of the study site. As an example, unit Ss-O₁ refers to a slope deposit (S), which is sandy (s) and of Odranian age (O) at study site I. Regarding the type of deposit, 6 types are distinguished: slope (S), weathered bedrock (W), karst infilling (K), glacial (G), glaciofluvial (FG) and fluvial (F). Three types of lithology are distinguished: sand (s), till (t), and debris or scree (d). Sediments of the following ages are studied: Devonian (D), Miocene (M), Odranian (O), Krznanian (K), Lublinian (L), early Vistulian (EV) and Pleniglacial (P). The various sites are coded according to their number (I-IX).

The heavy minerals from 93 samples of sand, sandy gravel, till and weathered debris of Devonian sandstones were analysed for the 0.10–0.25 mm size fraction. The results of the various deposits are presented in Tables 1–6, also classified according to their resistance to chemical weathering and mechanical abrasion following Racinowski (1995). The group of resistant minerals consists of tourmaline (tou, T), zircon (zir, Z), rutile (rut, R), titanite

Fig. 2. General stratigraphical subdivision of the Quaternary of Poland and its correlation with Western Europe (after Marks, 2011). The glacial episodes in Poland are indicated in bold.

SYSTEM	SERIES	SUBSERIES	WESTERN EUROPE				POLAND		Age (Ma)
QUATERNARY	PLEISTOCENE	HOLOCENE	HOLOCENE				HOLOCENE		0.01
		LATE PLEISTOCENE	WEICHSELIAN				NORTH POLISH COMPLEX	Vistulian	0.1
			EEMIAN					Eemian	
		MIDDLE PLEISTOCENE	SAALIAN		Warthe	MIDDLE POLISH COMPLEX	Wartanian	0.2	
					Drenthe		Odranian		
					Schoningen		Lublinian		
					Reinsdorf		Krznanian		
					Fuhne		Zbójnian		
			HOLSTEINIAN		Liwiecian				
			ELSTERIAN		Mazovian	0.4			
			CROMERIAN COMPLEX		Interglacial IV	SOUTH POLISH COMPLEX	Sanian 2	0.6	
					Glacial C		Ferdynandowian		
					Interglacial III		Sanian 1		
				Glacial B	Kozi Grzbiet				
				Interglacial II					
		EARLY PLEISTOCENE	BAVELIAN		Glacial A	SOUTH POLISH COMPLEX	Nidanian	0.8	
					Interglacial I				
					Dorst				
					Leerdam		Augustowian		1.0
					Linge				
				Bavel					
			MENAPIAN			PREGLACIAL COMPLEX	Narewian	1.5	
			WAALIAN		Celestynowian				
			EBURONIAN		Ottockian				
			TIGLIAN		Ponurzcian				
PRAETIGLIAN		Różcian	2.6						

(tit, TI), kyanite (kya, K), staurolite (stau, ST), andalusite (and, AN) and topaz (top, TO). The semi-resistant minerals are epidote (epi, E), garnet (gar, G), sillimanite (sil, S) and apatite (apa, AP). The non-resistant minerals are amphibole (amp, AM), pyroxene (pyr, P), glaucophane (gla, GL), biotite (bio, B), muscovite (mus, M), and chlorite (ch, CH).

The weathering index (W) was calculated for the analysed sediments after Racinowski & Rzechowski (1969), as defined by the formula $W = (SR/R) NR$ (percentage of semi-resistant minerals (SR) divided by the percentage of resistant minerals (R), multiplied by the percentage of non-resistant minerals (NR)). The calculation is based on the proportion of transparent minerals of different resistance in the deposit. The group of transparent minerals (T) is taken as 100% ($T = 100\%$) and acts as the basis for the calculations.

The analog weathering index (aW) proposed by the present author, is based on the same formula, but the difference is that the total sum of transparent (T) and opaque (O) minerals, i.e. the whole group of heavy minerals from the sample ($T + O = 100\%$) is taken as the starting point for the calculations. The methodology using aW calculations results from adopting the following assumptions:

- 1) the assemblage of transparent heavy minerals (T) is an integral part of the total heavy-mineral assemblage, and should not be analysed without also analysing the opaque mineral group (O);
- 2) the relationship between the proportion of the transparent mineral (T) and the opaque minerals (O), i.e. the proportionality index ($P = T/O$), defines specific conditions of the sedimentary environment (Marcinkowski, 2007); the lower the proportionality index, the higher the proportion of opaque minerals in a sediment; in the mineral analysis of a sediment, the characteristics of the opaque heavy minerals are then consequently more important for interpretations (the characteristics being increasingly better recognisable with a decreasing proportionality index; see, e.g., Barczuk & Nejbert, 2008);
- 3) In both W and aW, the ratio SR/R (semi-resistant to resistant) is the same. The ultimate val-

ue of these indexes is affected by the proportion of non-resistant transparent minerals.

The heavy-mineral composition of the transparent minerals can, as suggested by Racinowski (2008), be subdivided into dominant and supporting minerals. The dominant minerals are the most frequent species that jointly make up more than 50%; they are indicated with capital letters. Supporting minerals are the species that are quantitatively similar to the least frequent dominant mineral; they are indicated with lower-case letters between brackets.

4. Geomorphology, lithology and age of the deposits

4.1. The Huta Stara Koszary site (I)

The slope deposits at the Huta Stara Koszary site constitute the higher part of the less inclined slope under the steeper north-eastern rocky slope of the Bieliny range; the steep rocky slopes are built of Devonian quartz sandstones (Fig. 3A). The less inclined slopes, consisting of slope material are located between 350 and 355 m a.s.l. Two successions of different lithology and age are distinguished (Fig. 3B) (Ludwikowska-Kędzia, 2007, Ludwikowska-Kędzia & Olszak 2009): (1) a sandy, gravelly/sandy and gravelly unit ($Ss-O_l$), dating from the Odranian glaciation (MIS 6, Drenthian glaciation of the Saalian, Fig. 2), accumulated due to the denudation of sandy and gravelly sandy covers of local weathered material from the Devonian bedrock ($Wd-D_l$), and of fluvioglacial deposits; and (2) a periglacial till unit ($St-P_l$) and a sandy unit ($Ss-P_l$) dating from the early and middle Pleniglacial (= Weichselian, MIS 3, MIS 2; Fig. 2). In the lower part of the till unit, the tills are massive, whereas they become layered higher up. These deposits originated by denudation of the coarse-grained weathering covers of the Palaeozoic bedrock, of Odranian deposits and loess, but mostly as a result of solifluction of unsorted material with different densities, which started moving due to ablation.

The heavy minerals of 24 samples (numbers 1–24) from deposits at the Huta Stara Koszary site have been analysed (Table 1).

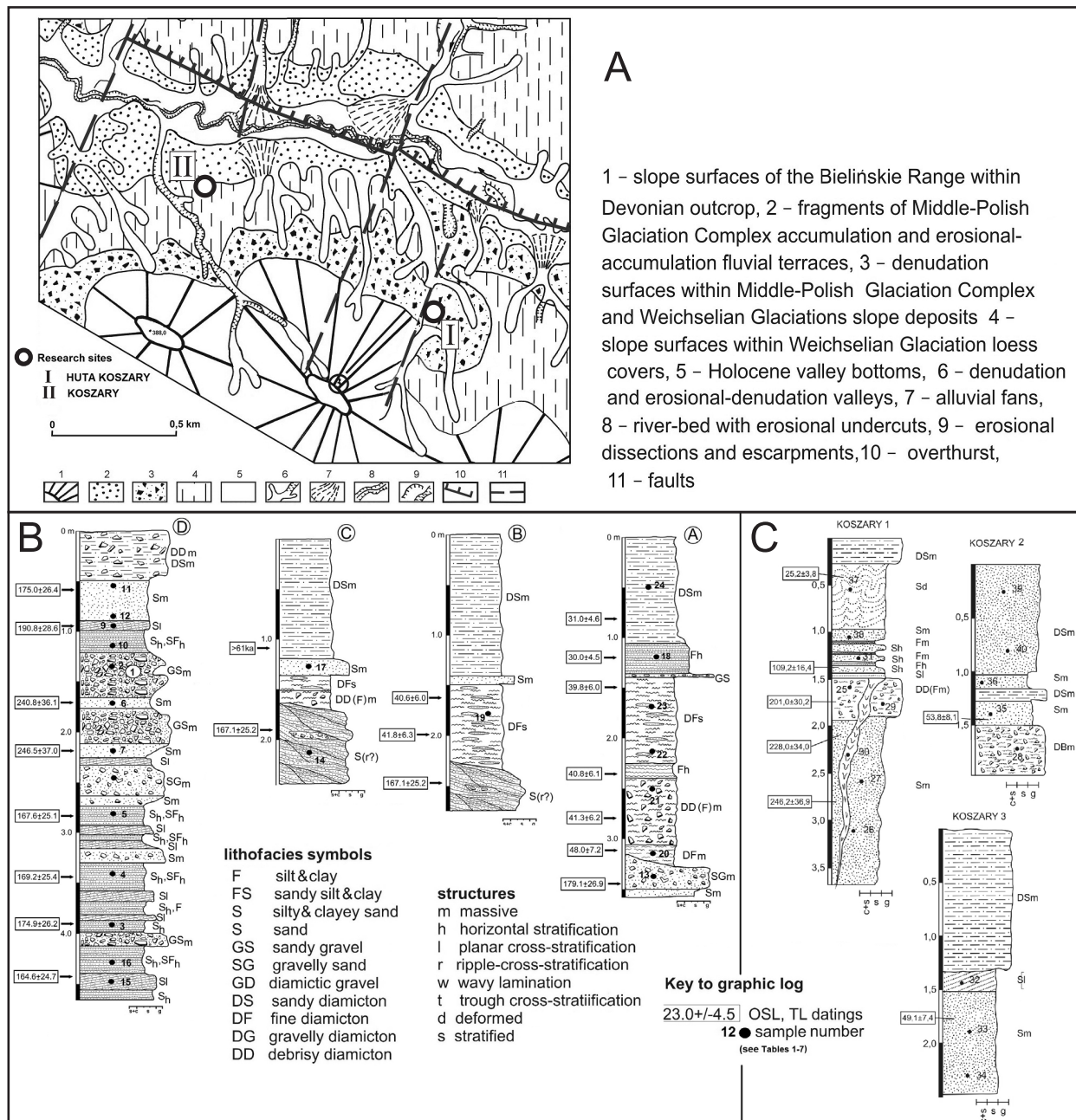


Fig. 3. Study sites Huta Koszary (site I) and Koszary (site II).

A: The sites in their (schematic) geomorphological context of the northern slopes of the Bieleńskie Range.

B: Sedimentological logs of the slope deposits at site Huta Koszary (modified after Ludwikowska-Kędzia, 2007; Ludwikowska-Kędzia & Olszak, 2009).

C: Sedimentological logs of the slope deposits at site Koszary (modified after Ludwikowska-Kędzia, 2007; Ludwikowska-Kędzia & Olszak, 2009).

4.2. The Koszary site (II)

The Koszary site is located where the erosion and denudation processes gradually pass into the lower level of the less inclined slope under the steeper slope with Devonian

rocks in the Bieleńskie range, ending at the bottom of the Belnianka river (Fig. 3A). Just like at site I, two units of slope deposits with different age and lithology are distinguished: (1) a complex dating from the Middle Polish complex (= Saalian), and (2) a complex dating

Table 1. Heavy-mineral composition of the slope deposits and the weathered Devonian sandstone at Huta Koszary (site I).

Site of study	I - Huta Koszary																							
	weathered Devonian material	slope deposits Odra glaciation (MIS 6)																slope deposits middle and late Pleniglacial (MIS 3, MIS 2)						
		Wd-D ₁	Ss-O ₁																Ss-P ₁					
unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
sample number	transparent and opaque heavy minerals calculated as 100%																							
O - opaque heavy minerals (%)	75.7	41.8	68.4	51.2	41.0	45.5	41.0	37.0	49.5	48.6	79.7	40.2	46.6	42.6	53.9	54.6	27.0	43.1	51.0	60.3	75.2	53.8	41.9	35.3
T - transparent heavy minerals (%)	24.3	58.2	31.6	48.8	59.0	54.5	59.0	63.0	50.5	51.4	20.2	59.8	53.4	57.4	46.1	45.4	73.0	56.9	49.0	39.7	24.8	46.2	58.1	64.5
P (=T/O ratio)	0.32	1.39	0.46	0.95	1.43	1.19	1.44	1.70	1.02	1.06	0.25	1.48	1.15	1.35	0.86	0.83	2.70	1.32	0.96	0.66	0.33	0.86	1.39	1.83
amphibole	0	0.4	0.5	1	0.9	1.2	0.3	0.3	0.4	0.3	0	1.8	0	0	0	0.9	0.4	0.3	0.5	0.4	0	0.7	0.7	0.8
pyroxene	0.1	0	0	1	0.9	0.9	0.8	0.9	0.4	0.5	0	0.9	0	0	0	0.2	0.4	0.3	0.2	0.2	0	0.7	0.2	0.5
glauconite	0.1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
biotite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
muscovite	6.7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
chlorite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
epidote	1.7	11.2	2.8	5.2	2.3	9.8	8.1	4.8	6.2	3.2	1.0	5.3	6.0	2.8	1.2	3.3	4.6	2.8	4.3	3.0	0.8	3.3	4.3	4.4
garnet	0	9.6	6.5	10.9	16.8	13.4	12.8	19.4	21.1	9.1	5.4	22.9	20.4	27.5	8.4	5.5	17.7	29.6	16.8	11.7	10.9	5.4	21.5	20.0
sillimanite	0	1.9	0.4	0.5	0.8	0.5	0.6	0	0	0.3	0	0.4	0	0.8	0	0.2	0	0	0.3	0.2	0	0	0	0
apatite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
tourmaline	6.0	12.5	3.2	4.7	3.5	4.6	3.9	7.1	1.9	2.1	0	4.4	1.0	4.0	0.6	4.4	7.0	1.0	3.1	3.1	0.3	1.8	2.1	2.5
zircon	8.3	9.8	9.7	14.6	22.8	12.2	23.3	17.1	13.2	26.2	12.8	13.2	14.5	13.2	30.5	15.5	18.5	15.0	12.3	11.3	11.6	24.3	17.5	31.1
rutile	0.8	0.8	0	0	0	0.2	0.3	0.6	0	0.3	0	0	1	0	0	0.6	0.7	0.3	0.5	0	0	0.3	0	0
titanite	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
kyanite	0.1	3.3	0.8	2.1	0.5	1.5	1.6	0.9	1.9	0.5	0	1.3	1.3	0.2	0.9	1.1	2.9	1.0	0.2	0.6	0.6	1.4	0.8	0.8
staurolite	0	7.9	6.5	6.2	9.3	5.9	5.4	9.7	3.1	6.8	1.0	7.0	7.9	8.9	3.6	11.9	20.1	5.6	9.8	8.2	0.6	6.5	9.6	3.5
andalusite	0	0.6	1.2	2.6	1.2	4.3	1.9	2.2	2.3	1.7	0	2.6	1.3	0	0.9	1.8	0.7	1.0	1.0	1.0	1.8	1.4	0.9	0
topaz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
non-resistant (%)	6.9	0.6	0.5	2.0	1.8	2.1	1.1	1.2	0.8	0.8	0	2.7	0	0	0	1.1	0.8	0.6	0.6	0.6	0	1.4	0.9	1.3
semi-resistant (%)	1.7	22.7	9.7	16.6	19.9	23.7	21.5	24.2	27.3	13.0	6.4	28.6	26.4	31.1	9.6	9.0	22.3	32.4	21.4	14.9	11.7	8.7	25.8	24.4
resistant (%)	15.7	34.9	21.4	30.2	37.3	28.7	36.4	37.6	22.4	37.6	13.8	28.5	27.0	26.3	36.5	35.3	49.9	23.9	26.9	24.2	13.1	36.1	31.4	38.8
analog weathering index (aW)	0.75	0.39	0.23	1.10	0.96	1.73	0.65	0.77	0.98	0.28	0.46*	2.71	0.98*	1.18*	0.26*	0.28	0.36	0.81	0.48	0.37	0.89*	0.34	0.74	0.82
transparent heavy minerals calculated as 100%																								
non-resistant (%)	28.8	1.2	1.7	4.2	3.0	3.9	1.9	2.0	1.5	1.7	0	4.4	0	0	0	2.2	1.1	1.2	1.3	1.6	0	3.2	1.5	2.1
semi-resistant (%)	6.8	38.8	30.8	33.9	33.8	43.6	36.4	38.4	54.2	25.4	31.7	48.0	49.4	54.2	20.8	19.9	30.7	56.9	43.8	37.6	47.1	18.8	44.5	37.8
resistant (%)	64.4	60.0	67.5	61.9	63.2	52.5	61.7	59.6	44.3	72.8	68.3	47.6	50.6	45.8	79.2	77.9	68.2	41.9	54.9	60.8	52.9	78.0	54.0	60.1
weathering index (W)	3.03	0.78	0.78	2.36	1.60	3.24	1.12	1.29	1.84	0.60	0.46*	4.44	0.98*	1.18*	0.26*	0.56	0.49	1.63	1.04	0.99	0.89*	0.77	1.24	1.32

* The analog weathering index, aW, and the weathering index, W, are unidentified, or the same, because non-resistant transparent minerals are lacking.

Table 2. Heavy-mineral composition of the sandy slope deposits and the weathered Devonian sandstone at Koszary (site II).

Site of study		II - Koszary															
depositional environment - age		slope deposits															
		Devonian	Krznanian glaciation (MIS 8)		Lublinian interglacial (MIS 7)		early Vistulian MIS 5d		middle Pleniglacial MIS 3, MIS 2								
			Wd-DII	Ss-KII	St-LII	28	29	Ss-EVII	30	31	32	33	34	35	36	37	38
unit	sample number	transparent and opaque heavy minerals calculated as 100%															
O - opaque heavy minerals (%) T- transparent heavy minerals (%) P (= T/O ratio) amphibole pyroxene glauconite biotite muscovite chlorite epidote garnet sillimanite apatite tourmaline zircon rutile titanite kyanite staurolite andalusite topaz non-resistant semi-resistant resistant analog weathering index (aW)	47.9	53.4	54.2	60.8	56.1	53.9	61.0	43.1	47.3	34.1	55.7	47.7	52.9	48.4	33.8	57.1	
	52.1	46.6	45.8	39.2	43.9	46.1	39.0	56.9	52.7	66.0	45.0	52.3	47.2	51.6	56.2	42.9	
	1.08	0.87	0.84	0.64	0.78	0.85	0.63	1.32	1.11	1.94	0.81	1.10	0.90	1.07	1.28	0.75	
	0	0	0	0	0	0.6	2.7	0.6	0.8	2.9	0.6	2.8	1.4	0.7	0.5	0.8	
	0	0	0	0	0	0.2	0.3	0.9	0.4	1.3	0.2	1.4	0.4	0	0	0.2	
	0.1	0	0	0	0	0.4	0.2	0	0	0.4	0	0	0	0	0	0	
	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	0.5	2.4	1.6	1.1	2.3	3.3	4.5	3.3	2.6	3.7	2.2	3.5	4.0	4.2	4.1	3.0	
	0	2.8	1.6	5.4	5.2	14.6	5.0	28.8	24.0	31.2	10.1	7.0	4.4	7.5	16.2	9.5	
	0.1	0	0	0	0	0	0.6	0.2	0	0	0	0	0	0.4	0.2	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	34.2	2.0	4.3	2.2	2.3	4.8	3.3	3.0	2.6	2.2	3.7	4.9	8.8	5.1	2.5	3.5	
	11.8	26.2	24.0	24.7	27.7	10.4	13.4	13.3	17.5	20.6	26.3	19.5	13.1	19.4	27.8	17.1	
	2.3	2.8	1.1	0	0.3	0.2	0.2	0.3	0	0.4	0.7	0.7	0.4	0.5	0.5	0.8	
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
0.2	0.7	1.6	0.5	0.6	1.6	2.7	2.7	0.9	1.3	1.1	0.3	2.0	1.4	0.9	0.8	1.5	
0	9.4	10.8	5.0	5.2	8.6	4.6	4.6	5.0	3.1	1.5	0.8	9.8	11.1	12.4	3.0	5.3	
0.1	0.3	0.8	0.3	0.3	0.8	1.9	1.9	0.8	0.4	0.7	0.1	0.7	1.8	0.7	0.8	1.2	
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
2.4	0	0	0	0	1.2	3.2	3.2	1.5	1.2	4.6	0.8	4.2	1.8	0.7	0.5	1.0	
0.6	5.2	3.2	6.5	7.5	18.5	9.7	32.1	26.6	34.9	12.3	10.5	8.8	11.9	20.3	12.5		
49.1	41.4	42.6	32.7	36.4	26.4	26.1	26.1	23.3	24.9	26.5	31.9	37.6	36.6	39.0	35.4	29.4	
0.03	0.13*	0.08*	0.20*	0.21*	0.84	1.19	2.07	1.28	6.06	0.31	1.17	0.43	0.21	0.29	0.43		
transparent heavy minerals calculated as 100%																	
non-resistant	4.5	0	0	0	0	2.7	8.2	2.6	2.3	7.1	1.8	8.0	3.7	1.5	0.9	2.4	
semi-resistant	1.3	11.2	7.0	16.7	17.1	40.0	25.0	56.3	50.5	52.8	27.3	20.0	18.6	23.0	36.0	29.3	
resistant	94.1	88.8	93.0	83.3	82.9	57.3	66.8	41.1	47.2	40.1	70.9	72.0	77.7	75.5	63.1	68.3	
weathering index (W)	0.06	0.13*	0.08*	0.20*	0.21*	1.88	3.07	3.56	2.46	9.35	0.69	2.22	0.88	0.46	0.51	1.03	

* The analog weathering index, aW, and the weathering index, W, are unidentified, or the same, because non-resistant transparent minerals are lacking.

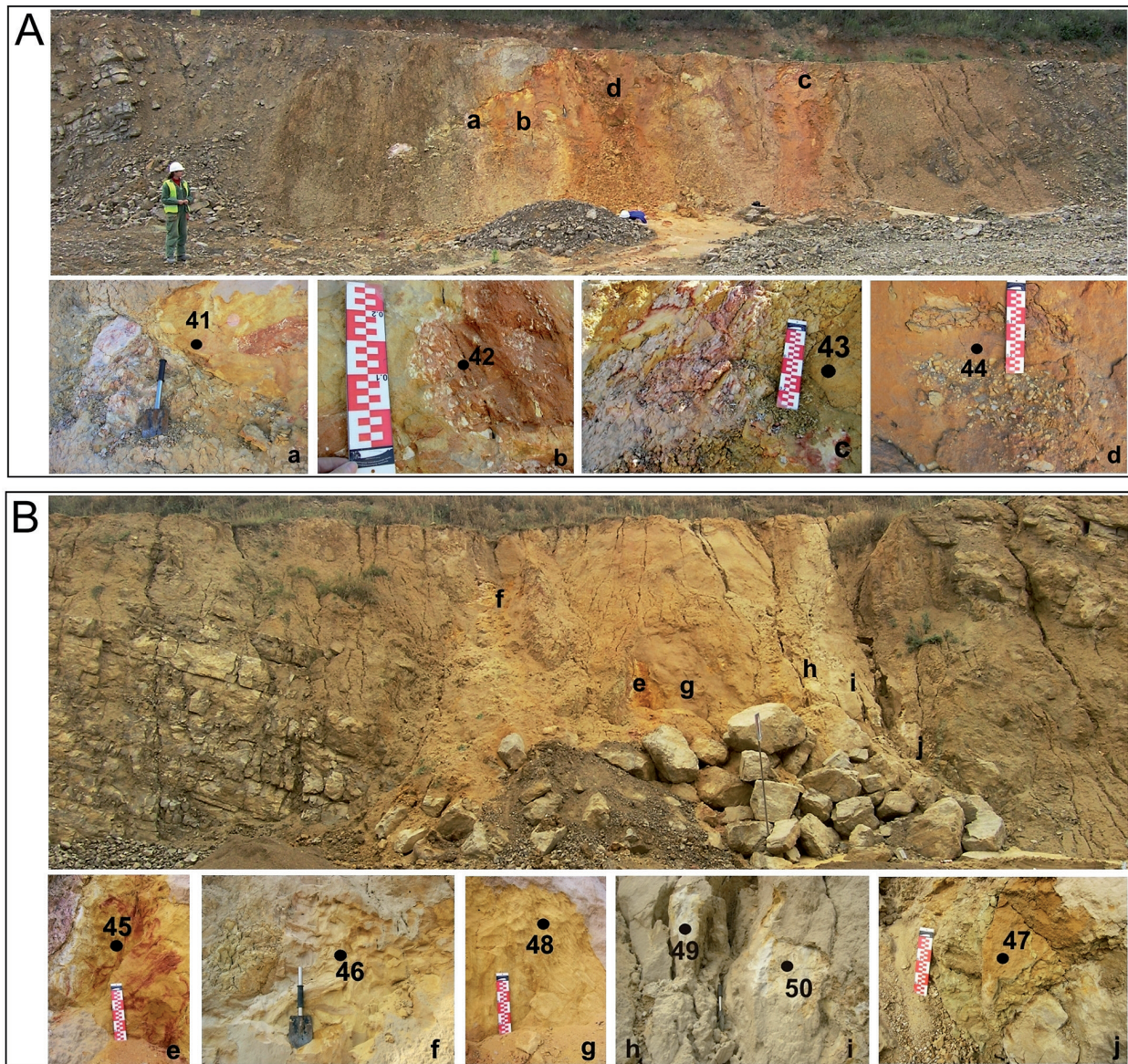


Fig. 4. Karst pits and their infillings, with sampling sites. Numbers of samples are indicated (see Table 3).

A: The dolomite quarry at Winna (site III).

B: The dolomite quarry at Komorniki (site IV).

from the North-Polish complex (= Vistulian = Weichselian) (Fig. 3C).

The periglacial, Middle-Polish complex of slope deposits is represented by (a) a unit (Ss-K_{II}) that is sandy/silty in its lower part and sandy in its upper part, dating from the Krznianian glaciation of the Saalian (MIS 8, a glacial episode in Poland; Fig. 2), with locally lenses of debris from heavily weathered local Devonian quartz sandstones (Wd-D_{II}); and (b) a till unit (St-L_{II}), consisting of clast-rich diamictos and sandy diamictos dating from the Lublinian

interstadial (Saalian, Schoninghen, MIS 7) (Fig. 2) formed by solifluction.

The Vistulian periglacial complex is represented by (c) a sandy unit (Ss-EV_{II}) dating from the early Vistulian (= Weichselian, MIS 5d), with ice-wedge casts that were transformed by slope processes, (d) a sandy unit (Ss-P_{II}) dating from the middle Pleniglacial (MIS 3) with, in the upper part of the exposures, deformed sands with clearly visible ferruginous streaks, and (e) a till unit (St-P_{II}) consisting of a silty/clayey, locally

Table 3. Heavy-mineral composition of the sandy infillings in karst pits at Winna (site III) and Komorniki (site IV).

Site of study	III - Winna					IV - Komorniki				
depositional environment - age	infillings of karst pits Neogene-Palaeogene - Miocene?									
unit	Ks-M _{III}					Ks-M _{IV}				
sample number	41	42	43	44	45	46	47	48	49	50
transparent and opaque heavy minerals calculated as 100%										
O - opaque heavy minerals (%)	46.7	34.7	37.6	60.5	87.7	44.9	70.1	40.9	39.3	42.4
T - transparent heavy minerals (%)	53.3	65.3	62.4	39.5	15.3	55.1	29.9	59.1	60.7	57.8
P (= T/O ratio)	1.14	1.88	1.65	0.65	0.18	1.23	0.43	1.44	1.54	1.36
amphibole	6.7	10.5	3.6	3.6	4.0	5.5	1.6	12.8	12.6	6.9
pyroxene	0.8	0.8	0.5	0.6	0.3	0.7	0.2	1.2	0.7	0.8
glauconite	0.3	0	0.2	0	0	0	0	0	0	0.4
biotite	0	0	0	0	0	0	0	0	0	0
muscovite	0	0	0.1	0	0	0	0	0	0	0
chlorite	0	0	0.1	0	0	0	0	0.3	0	0
epidote	0	0	0	0.3	0	0	0	0	0.1	0.8
garnet	0.1	0	0	0.3	0.1	0	0	0.3	0	0.2
sillimanite	0	0.1	0.3	0	0	0.1	0.3	0	0.3	0
apatite	0	0.4	1.3	0.3	0	0.1	0	0.6	0.3	0.4
tourmaline	8.3	4.4	3.4	1.1	0.4	4.4	1.9	7.6	4.7	3.8
zircon	5.3	5.9	15.0	6.0	2.5	11.5	6.9	4.4	11.5	10.7
rutile	5.6	8.9	8.6	5.9	2.1	3.1	2.4	4.9	7.0	5.5
titanite	0	0.9	0.9	1.1	0	0.2	0.4	0.9	1.0	1.3
kyanite	10.2	20.7	18.0	11.6	0.3	14.4	6.1	6.4	6.7	4.2
staurolite	14.1	11.2	9.6	7.4	5.4	11.2	7.8	17.7	14.5	20.8
andalusite	1.4	1.3	0.6	1.3	0.1	2.5	1.4	2.0	0.7	1.0
topaz	0.5	0.2	0.2	0	0.1	1.4	0.9	0	0.6	1.0
non-resistant	7.8	11.3	4.4	4.2	4.3	6.2	1.8	14.3	13.4	8.1
semi-resistant	0.1	0.5	1.6	0.9	0.1	0.2	0.3	0.9	0.6	1.4
resistant	45.4	53.5	56.3	34.4	10.9	48.7	27.8	43.9	46.7	48.3
analog weathering index (aW)	0.02	0.11	0.13	0.11	0.04	0.03	0.02	0.29	0.17	0.23
transparent heavy minerals calculated as 100%										
non-resistant	14.7	17.3	7.2	11.8	27.9	11.2	5.9	24.1	22.2	14.1
semi-resistant	0.3	0.7	2.5	2.2	0.9	0.4	1.1	1.5	0.9	25.0
resistant	85.0	82.0	90.3	87.0	71.1	88.4	93.0	74.4	76.9	83.4
weathering index (W)	0.05	0.15	0.20	0.30	0.35	0.05	0.07	0.49	0.26	0.42

sandy, diamicton with clasts of local rocks, dating from the late Pleniglacial (MIS 2).

Heavy minerals of 16 samples (numbers 25–40) from deposits at the Koszary site have been analysed (Table 2).

4.3. The Winna (III) and Komorniki (IV) sites

Sandy Miocene sediments at both the Winna site (with unit Ks-M_{III}) (Fig. 4A) and the Komorniki site (with unit Ks-M_{IV}) (Fig. 4B) belong to the so-called ‘Tertiary land complex’ (an informal unit) (Fijałkowska & Fijałkowski,

1971); they form infillings of karst pits in the Devonian dolomites near Łagów (Fig. 1). The sediments comprise sandy and gravelly sediments, but primarily clayey/silty sediments, so-called ‘potter’s clays’. The sandy, massive, locally glaciectonically deformed sediments are regarded as the weathering products of various types of sandstone from the Holy Cross region (Fijałkowska & Fijałkowski, 1971).

The heavy minerals of 4 samples (numbers 41–44) from deposits at the Winna site and of 6 samples (numbers 45–50) from deposits at the Komorniki site have been investigated (Table 3).

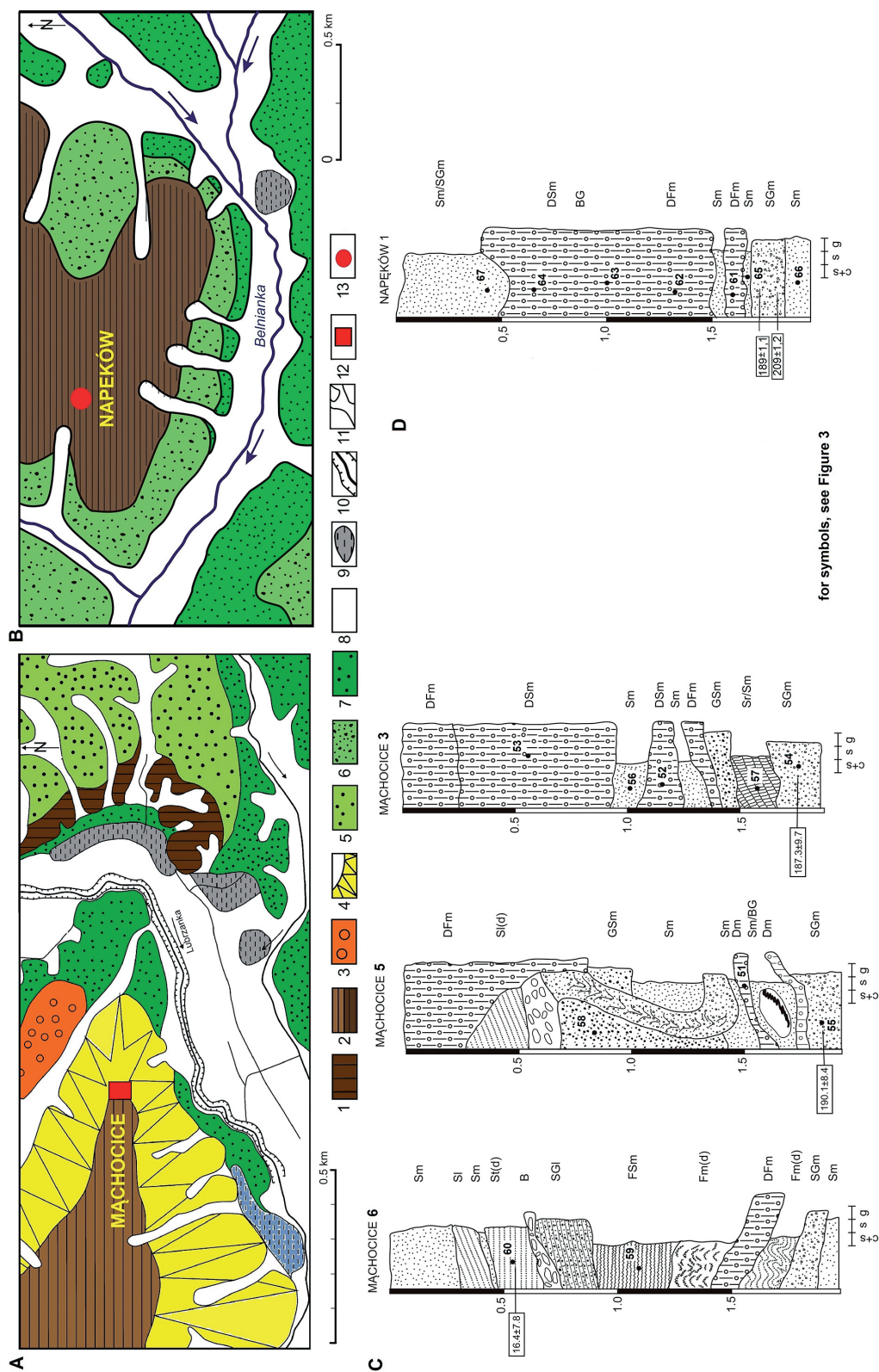


Fig. 5. The Mąchoć (V) and Napęk (VI) sites.

A-B: Location of the glacialic sediments at the Mąchoć (site V) and Napęk (site VI) sites within their (schematic) geomorphological context. 1 = denudation surface of the Palaeozoic bedrock; 2 = denudation surface tills of the Middle-Polish glaciations; 3 = accumulation surface of fluvio-glacial deposits of the South-Polish glaciation; 4 = slope surfaces of an erosional-denudation valley; 5 = accumulation-erosional fluvial terrace level from the Middle-Polish glaciation; 6 = denudation surface of fluvio-glacial deposits of the Middle-Polish glaciations; 7 = accumulation-erosional fluvial terrace level of the Vistulian glaciation; 8 = level of the Holocene fluvial accumulation terrace; 9 = accumulation zone of biogenic sediments; 10 = river bed with lateral erosion; 11 = erosional-denudation valleys; 12 = Mąchoć site; 13 = Napęk site.

C-D: Sedimentological logs of the glacialic deposits at the Mąchoć site (C) (according to Ludwikowska-Kędzia & Pawelec, 2011) and the Napęk site (D).

Table 4. Heavy-mineral composition of the glacial and fluvioglacial slope deposits at Napęków (site V) and Małochice (site VI).

Site of study depositional environment - age unit sample number	V - Małochice										VI - Napęków									
	glacial										Odranian glaciation (MIS 6)									
	Odranian glaciation (MIS 6)					MIS 2					Odranian glaciation (MIS 6)					MIS 2				
	Gt-O _V	51	52	53	54	55	56	57	58	59	Fs-P _V	60	61	62	63	64	65	66	67	
transparent and opaque heavy minerals calculated as 100%																				
O - opaque heavy minerals (%)	38.5	40.0	39.1		47.8	50.1	32.8	48.3	52.0	47.2	27.1		64.4	81.6	45.3	41.8	43.8	47.9		29.0
T - transparent heavy minerals (%)	61.5	60.0	60.9		52.2	49.9	67.2	51.7	48.0	52.8	72.9		35.6	18.4	54.7	58.2	56.2	52.1		71.0
P (=T/O ratio)	1.60	1.50	1.56		1.09	0.99	2.05	1.07	0.92	1.12	2.69		0.55	0.23	1.21	1.39	1.28	1.09		2.45
amphibole	14.3	14.1	15.5		13.3	12.1	37.4	15.3	9.6	18.2	7.8		10.4	6.1	12.7	6.7	9.0	6.8		8.7
pyroxene	2.2	1.8	1.4		1.5	1.3	3.6	1.9	1.2	1.7	1.2		0.5	0.6	0.7	0.7	1.3	1.1		0.7
glauconite	0	0	0		0.7	0	0	0.1	2.7	1.5	0		0.3	0	0.2	0	0	0.3		0
biotite	0.9	0	0		0	0	0	0	0	0	0		0	0	0	0	0	0		0
muscovite	0	0	0		0	0	0.3	0	0.3	0	0		0	0	0	0	0	0		0
chlorite	0.2	0	0		0	0	0.6	0	0	0	0		0	0	0	0	0	0		0
epidote	0.7	0.6	1.4		1.2	1.3	1.7	1.6	1.9	2.0	1.4		1.9	0.5	2.8	5.1	3.5	1.6		1.9
garnet	23.7	21.1	26.1		19.9	19.6	4.8	15.7	17.4	10.4	34.1		10.9	6.5	22.3	17.5	25.3	27.4		38.1
sillimanite	0.5	0.2	0		0	0	0.4	0.4	0.1	0.3	0.4		0	0	0.6	0	0.2	0		0.3
apatite	2.0	0.8	2.3		1.2	1.4	2.8	1.5	1.5	1.7	1.4		0.8	1.0	0	0.8	0.3	0.4		1.2
tourmaline	0.7	2.6	2.2		0.6	0.5	2.6	1.5	0.8	3.2	4.4		0.7	1.0	0.6	1.3	0.9	0.4		2.0
zircon	6.4	11.2	5.6		7.5	6.6	2.4	4.5	5.6	4.8	13.5		6.7	0.6	8.7	22.2	8.1	10.1		10.5
rutile	1.6	0.9	1.3		0.9	0.6	0.7	2.3	2.0	1.5	1.4		0.7	0.3	1.3	1.5	0.3	0.6		1.0
titanite	0.2	0.6	0.4		0.9	0.8	0.9	1.0	0.8	0.5	0.3		0.1	0	0.2	0.3	0.7	0.3		0.3
kyanite	3.1	2.9	2.1		1.7	1.6	3.7	2.5	1.5	3.8	0.7		1.6	0.3	1.6	0.7	1.7	0.4		1.4
staurolite	3.9	1.8	0.9		1.9	3.6	3.0	3.1	2.4	2.7	5.0		1.0	0.3	2.8	0.5	4.2	2.8		3.0
andalusite	1.2	0.3	1.4		0.5	0.3	1.3	0.3	0.3	0.5	0.3		0	1.0	0.2	0.8	0.3	0		0.3
topaz	0	1.1	0.3		0.4	0.2	1.0	0	0.1	0	1.0		0	0	0	0	0.4	0		1.6
non-resistant	17.6	15.9	16.9		15.5	13.4	41.9	17.3	13.8	21.4	9.0		11.2	6.8	13.6	7.4	10.3	8.2		9.4
semi-resistant	26.9	22.7	29.8		22.3	22.3	9.7	19.2	20.9	14.4	37.3		13.6	8.0	25.7	23.4	29.3	29.4		41.6
resistant	17.1	21.4	14.2		14.4	14.2	15.6	15.2	13.5	17.0	26.6		10.8	3.6	15.4	27.4	16.6	14.5		20.0
analog weathering index (W)	27.69	16.86	35.47		24.0	21.04	26.05	21.85	21.36	18.13	12.62		14.1	15.11	22.70	6.32	18.18	16.63		19.55
transparent heavy minerals calculated as 100%																				
non-resistant	28.5	26.6	27.8		29.7	26.9	62.3	33.5	28.6	40.5	12.3		31.5	36.9	24.8	12.8	18.3	15.7		13.2
semi-resistant	43.7	37.7	48.8		42.7	44.6	14.4	37.2	43.3	27.4	51.1		37.9	43.8	47.2	40.3	52.2	56.4		58.5
resistant	27.8	35.7	23.4		27.6	28.5	23.3	29.3	28.1	32.1	36.6		30.6	19.3	28.0	46.9	29.5	27.9		28.3
W - weathering index	44.80	28.09	57.98		45.95	42.1	38.5	42.5	44.07	34.57	17.17		39.0	83.74	41.80	11.0	32.38	31.74		27.29

4.4. The Mąchocie (V) and Napęków (VI) sites

Both the Mąchocie and Napęków sites are located within a denudation area of glacial sediments (Fig. 5A–B), at an elevation of 280–290 m a.s.l. The sediments were deposited during the Odranian glaciation (MIS 6, Drenthe glaciation of the Saalian) (Fig. 2). On the basis of preliminary facies, microfacies and petrographical analyses of the sediments (Ludwikowska-Kędzia & Pawelec, 2011; Kubala-Kukuś et al., in press), two units are distinguished: (Fig. 5C–D): (1) a sandy, sandy/gravelly unit ($Ss-O_v$, $Ss-O_{vi}$) underlying tills, and (2) a flow-till unit ($St-O_v$, $St-O_{vi}$).

The sediments were deposited in a glaciomarginal environment, in the direct neighbourhood of a stagnant or retreating head of the glacier lobe, presumably within an area of glaciomarginal fans. During the Vistulian they were modified by periglacial processes.

The heavy minerals of 10 samples (numbers: 51–60) from deposits at the Mąchocie site and of 7 samples (numbers 61–67) from deposits at the Napęków site have been investigated (Table 4).

4.5. The Masłowiec (VII) and Duraczów (VIII) sites

The deposits at Masłowiec, accumulated by a stream with admixtures of slope material from the valley walls and the fluvial deposits at Duraczów are situated in the upper Łagowica valley (Fig. 6A). From Łagów to Nowy Staw, the valley has the character of a karst gorge, incised into limestones and dolomites of the Middle Devonian (Walczowski, 1962, 1964, 1968; Łyczewska, 1971). Downstream of Nowy Staw and the Wszachówka river estuary, the valley bottom widens, and shows a flat bottom (Fig. 6A). Both study sites contain sediments typical of the Pleniglacial terrace level (Weichselian, MIS 3, MIS 2), which is situated at an elevation of 275–285 m a.s.l. (i.e. 8–10 m above the present-day floodplain). The Masłowiec site is situated in the deeply incised segment of the

valley, whereas the Duraczów site is located on the flat valley bottom.

On the basis of textual and structural features, the Masłowiec deposits can be subdivided into four genetic units: A, B, C (with sub-units C1 and C2) and D (Fig. 6B) (Ludwikowska-Kędzia et al., 2006). Unit A ($Fs-P_{vii}$) includes sandy, fluvial sediments, with sporadic gravelly/clayey packets of weathered Devonian sandstones. Large pieces of the Lower Devonian sandstone bedrock are present at the base of this unit. Unit B ($Ss-P_{vii}$), consisting of slope deposits, is built by sandy silts with a rhythmic character, with intercalated layers of massive sands. Unit C is built of sandy fluvial sediments with admixtures of slope material. The lower part of the unit, sub-unit C1 ($Fs-P_{vii}$), represents a fluvial environment, whereas the upper part, sub-unit C2 ($Ss-P_{vii}$), represents a slope environment. The unit contains post-depositional deformation structures, interpreted as a result of unstable density gradients (cf. Anketell et al., 1979), thus forming graviturbations sensu Van Loon (2009). Unit D ($Ss-P_{vii}$) has a slope origin and represents a solifluction process. The basal part of the unit contains silty clay with numerous masses of strongly weathered sandstone, underlain by irregular very fine laminae of sand and silt. Under this layer of clay, massive fine- and medium-grained sands are present that also contain fragments of sandstone. The upper part of the unit consists of loess that was reworked in a slope environment.

The Duraczów sediments come from two boreholes, ŁAG 1 and ŁAG 2, drilled in the Pleniglacial terraces (Fig. 6A). Both drillings reached the top of the Palaeozoic, at depths of 14.8 m and 22.5 m, respectively. The sandy fluvial unit ($Fs-P_{viii}$), from which the samples for mineralogical analyses were taken (at depths of 12.0 m and 19.8 m in drilling ŁAG1; and at 6.4 m and 12.4 m in ŁAG 2) overlies clays with fragments of the local Palaeozoic rocks (Fig. 6C).

The heavy minerals of 14 samples (numbers 68–81) from deposits at Masłowiec and of 4 samples (numbers 82–85) from deposits at the Duraczów site have been analysed (Table 5).

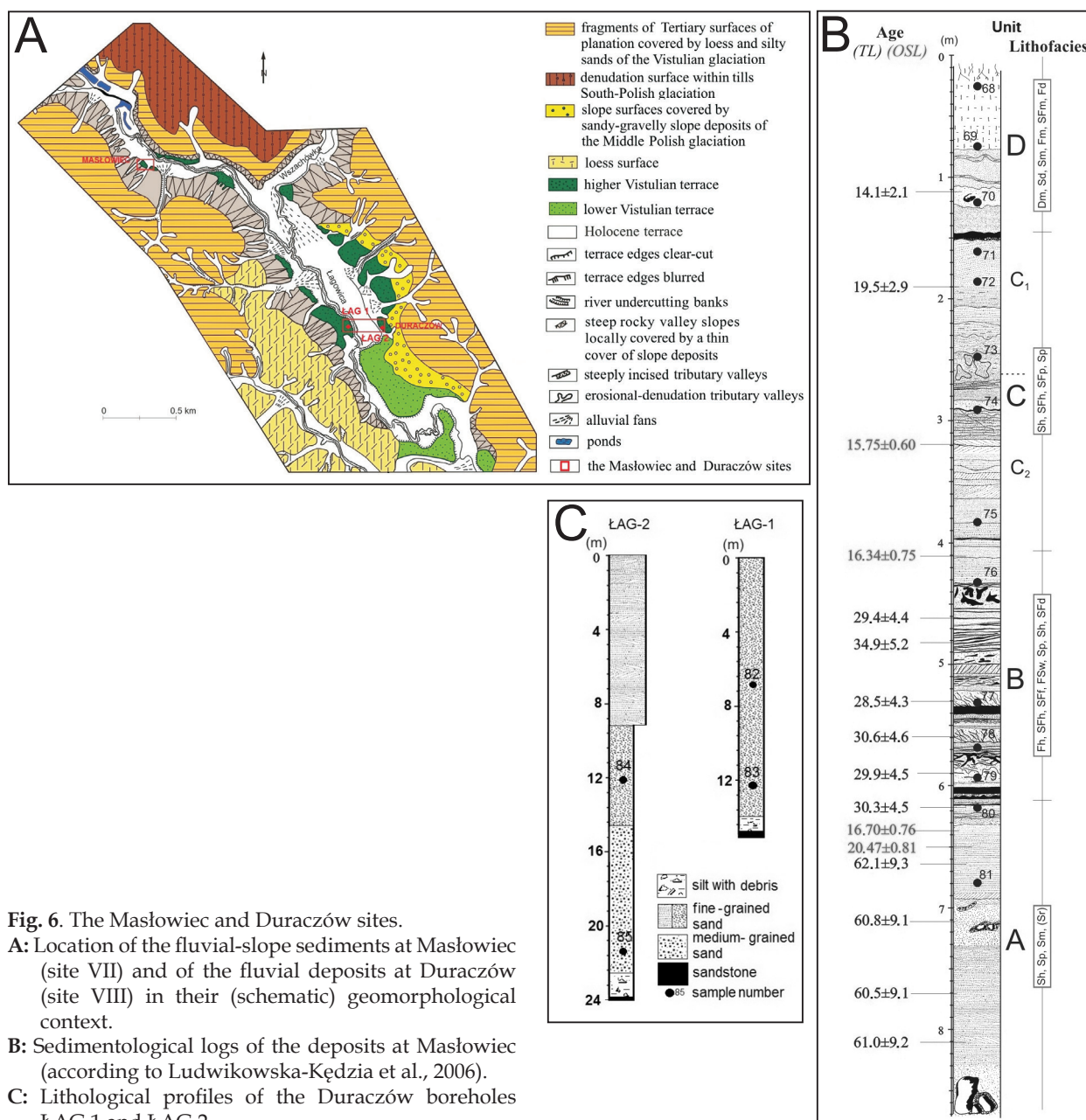


Fig. 6. The Masłowiec and Duraczów sites.

A: Location of the fluvial-slope sediments at Masłowiec (site VII) and of the fluvial deposits at Duraczów (site VIII) in their (schematic) geomorphological context.

B: Sedimentological logs of the deposits at Masłowiec (according to Ludwikowska-Kędzia et al., 2006).

C: Lithological profiles of the Duraczów boreholes ŁAG 1 and ŁAG 2.

4.6. The Górno site (IX)

This site is located within the area of fluvo-periglacial accumulation (at 260–265 m a.s.l.), incised by shallow, small streams (Fig. 7A). The analysis focused on the bottom part of the sandy unit (Fs-EV_{IX}), which fills a vast, shallow depression in the Palaeozoic bedrock (Fig. 7B). The sands overlie silts and at places also clays containing fragments of Palaeozoic sandstones. The age of the unit was determined, using OSL, as early Vistulian (Fig. 7C).

The heavy minerals of 8 samples (numbers 86–93) from deposits at the Górno site have been analysed (Table 6).

5. Heavy-mineral compositions

5.1. Weathered sandstone fragments (unit Wd-D_{I-II})

The heavy minerals in the weathered fragments of the Devonian sandstone at Huta Ko-

Table 5. Heavy-mineral composition of the fluvial deposits and the fluvial deposits with admixtures of slope material at Masłowiec (site VII) and Duraczów (site VIII).

Site of study depositional environment - age unit	VII – Masłowiec													VIII – Duraczów				
	late Pleniglacial (MIS 2)													fluvial				
	slope				fluvial				slope					fluvial				
sample number	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85
	transparent and opaque heavy minerals calculated as 100%																	
O – opaque heavy minerals (%)	53.0	38.4	38.6	33.3	41.3	38.6	36.6	37.5	42.5	36.2	31.2	30.2	31.7	31.5	19.4	24.0	20.9	17.2
T – transparent heavy minerals (%)	47.0	61.6	61.4	66.7	58.7	61.4	63.4	62.5	57.5	63.8	68.8	69.8	68.3	68.5	80.6	76.0	79.1	82.8
P (= T/O ratio)	0.86	1.44	1.52	1.92	1.31	1.48	1.60	1.58	1.16	1.60	2.07	2.14	2.02	2.03	4.15	3.17	3.78	4.81
amphibole	0.5	1.8	1.4	1.8	1.6	1.6	5.4	5.4	5.9	4.5	3.2	5.7	6.4	5.8	3.5	3.7	5.0	4.4
pyroxene	0.1	0.9	0.9	0.9	1.4	0.5	0.7	2.9	2.3	2.9	2.5	2.8	2.9	1.4	1.1	0.7	0.5	0.5
glauconite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
biotite	0	1.8	1.2	0.7	0.8	0.9	0.9	0.6	1.7	1.9	1.6	0.6	2.9	0.7	0	0	0	0
muscovite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
chlorite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
epidote	2.2	4.3	3.4	4.8	3.5	4.1	4.2	4.2	4.1	4.1	4.7	5.0	4.6	3.9	1.9	1.1	2.9	2.5
garnet	29.0	26.8	33.9	30.0	27.2	28.7	26.9	28.8	21.8	25.4	33.4	30.0	33.5	39.7	31.0	39.5	34.7	34.5
sillimanite	0.1	0	0.4	0.2	0	0.5	0.2	0.4	0.5	0.4	0	0.6	0	0.4	1.5	0.3	0.3	0.3
apatite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7	0.6	1.0	1.7
tourmaline	0.6	3.3	2.4	5.8	3.5	3.9	4.5	2.9	4.1	5.7	3.9	5.0	2.9	3.2	9.2	5.4	9.4	8.1
zircon	5.0	8.1	7.2	10.0	9.2	9.2	8.9	6.2	7.3	7.9	7.4	9.5	4.5	4.6	7.7	7.5	5.0	8.9
rutile	0.6	0.7	0.4	0.2	0.3	0.5	0.2	0.6	0.6	0.4	0.7	0	0.7	0.2	0.2	0.4	0.3	0
titanite	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0	0
kyanite	0.3	0.7	0.4	1.6	1.6	0.6	1.0	0.9	0.6	1.5	0.7	1.7	0.9	1.4	0.2	0.7	1.4	1.1
staurolite	5.5	9.6	7.6	8.5	6.5	7.6	8.1	7.4	3.6	5.4	8.1	5.6	6.7	4.6	18.9	10.9	11.8	12.8
andalusite	1.1	1.1	1.2	1.3	1.1	1.5	0.5	0.9	1.1	1.5	1.2	1.7	0.9	1.1	1.7	1.0	1.8	1.3
topaz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.0	3.9	5.0	6.7
non-resistant	0.7	4.5	3.5	3.4	3.8	3.0	7.0	8.9	9.9	9.3	7.3	9.1	12.2	7.9	4.6	4.4	5.5	4.9
semi-resistant	31.3	31.1	37.7	35.0	30.7	33.3	31.3	33.4	26.4	29.9	38.1	35.6	38.1	44.0	35.1	41.5	38.9	39.0
resistant	14.1	23.5	19.2	27.4	22.2	23.3	23.2	18.9	17.3	22.4	22.0	23.5	16.6	15.1	40.9	30.1	34.7	38.9
analog weathering index (aW)	1.55	5.96	6.68	4.85	5.25	4.29	9.44	15.73	15.11	12.41	12.64	13.79	28.00	23.02	3.95	6.07	6.17	4.91
transparent heavy minerals calculated as 100%																		
non-resistant	1.7	7.5	5.9	5.4	6.6	5.1	11.3	14.5	18.4	15.1	10.9	13.5	18.2	11.9	5.7	5.9	7.0	5.8
semi-resistant	67.9	52.6	62.2	53.0	54.1	55.9	50.9	54.7	49.2	48.5	56.5	52.1	57.1	65.5	43.6	54.6	49.2	47.2
resistant	30.4	39.9	31.9	41.6	39.3	39.0	37.8	30.8	32.4	36.4	32.6	34.4	24.7	22.6	50.7	39.5	43.8	47.0
weathering index (W)	3.80	9.89	11.50	6.88	9.09	7.31	15.22	25.75	27.94	20.12	18.89	20.45	42.07	34.49	4.90	8.15	7.86	5.82

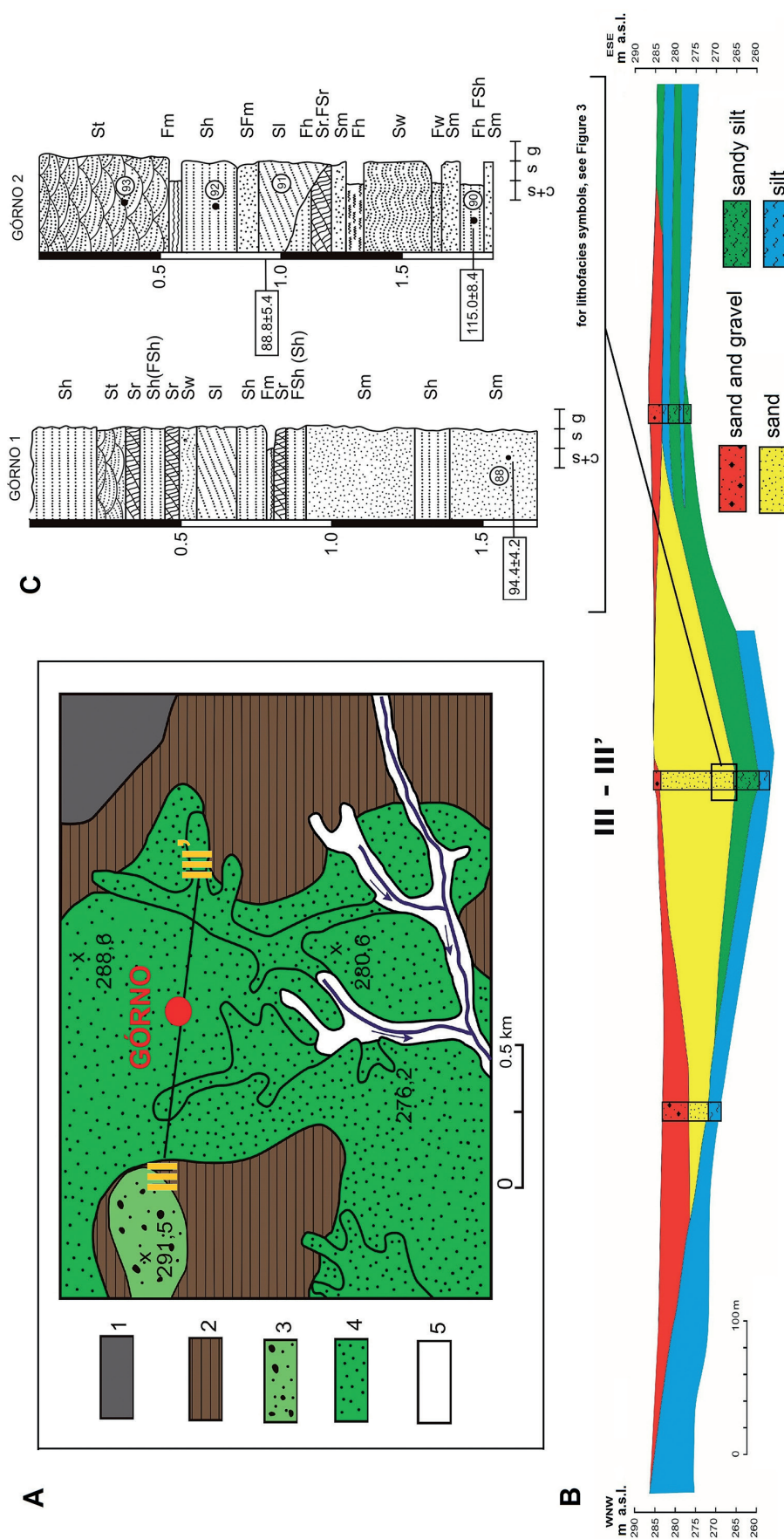


Fig. 7. The Górnó site.

A: Location of the fluvial sediments at Górnó (site IX) in their (schematic) geomorphological context. 1 = denudation surface of tills of the Middle-Polish glaciations; 2 = denudation surface of fluvio-glacial deposits of the Middle-Polish glaciations; 3 = accumulation-erosional fluvial terrace level of the Vistulian glaciation; 4 = fluvial accumulation terrace level of the Holocene; 5 = river bed.

B: Geological cross-section near Górnó (see location in A) and location of the sedimentological logs (C).
C: Sedimentological logs.

Table 6. Heavy-mineral composition of the fluvial deposits at Górnio (site IX).

Site of study	IX – Górnio							
depositional environment – age	fluvial deposits early Vistulian (MIS 5d-b)							
unit	Fs-EV _{IX}							
sample number	86	87	88	89	90	91	92	93
transparent and opaque heavy minerals calculated as 100%								
O – opaque heavy minerals (%)	33.9	41.7	40.4	46.1	39.1	22.0	21.7	33.1
T – transparent heavy minerals (%)	66.1	58.3	59.6	53.9	60.9	78.0	78.3	66.9
P (= T/O ratio)	1.95	1.40	1.48	1.17	1.56	3.55	3.61	2.02
amphibole	9.3	4.2	6.6	5.7	5.7	12.0	13.3	7.2
pyroxene	0.8	0.7	0.5	0.7	0.8	2.1	2.5	1.4
glauconite	0	0	0	0	0	0.2	0	0
biotite	0	0	0	0	0	0	1.1	0
muscovite	0	0	0	0	0	0	0	0
chlorite	0	0	0	0	0	0	0.2	0
epidote	2.3	3.7	3.3	1.8	1.6	5.4	3.1	3.1
garnet	3.6	3.3	4.7	6.1	3.5	2.1	1.6	4.4
sillimanite	0.3	0.6	1.2	0.3	0.4	1.3	2.5	1.0
apatite	3.0	1.9	2.1	2.3	2.2	2.5	2.5	1.4
tourmaline	11.2	4.3	3.5	5.5	6.6	9.3	13.6	6.2
zircon	13.7	23.5	23.1	16.8	23.1	22.1	18.1	18.6
rutile	2.6	3.9	1.2	2.0	1.7	1.3	1.6	2.4
titanite	0.3	0.6	0.6	0.6	0.3	0.4	0.4	0.5
kyanite	3.8	3.0	2.0	1.7	3.2	4.5	4.7	4.3
staurolite	10.9	7.0	8.6	8.8	8.8	11.4	9.5	12.8
andalusite	0.8	1.2	1.1	0.6	1.7	1.6	2.0	1.7
topaz	3.5	0.4	1.1	1.0	1.3	1.8	1.6	1.9
non-resistant	10.1	4.9	7.1	6.4	6.5	14.3	17.1	8.6
semi-resistant	9.2	9.5	11.3	10.5	7.7	11.3	9.7	9.9
resistant	46.8	43.9	41.2	37.0	46.7	52.4	51.5	48.4
analog weathering index (aW)	1.99	1.06	1.95	1.82	1.07	3.08	3.22	1.76
transparent heavy minerals calculated as 100%								
non-resistant	15.0	8.5	11.9	11.9	10.7	18.3	22.0	12.8
semi-resistant	14.3	16.2	19.0	19.5	12.7	14.4	12.3	14.8
resistant	70.7	75.3	69.1	68.6	76.6	67.3	65.7	72.4
weathering index (W)	3.03	1.83	3.27	3.38	1.77	3.92	4.12	2.62

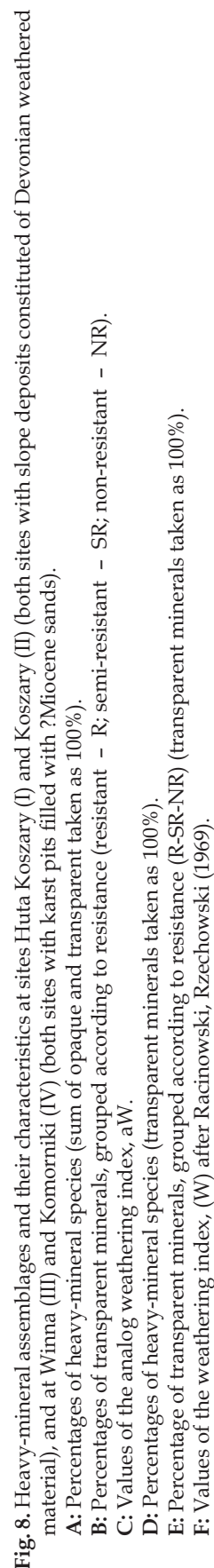
szary (site 1) contain three times more opaque (75.6%) than transparent (24.6%) minerals (Table 1, Fig. 8A). At Koszary (site 2), however, the proportions of transparent (52.1%) and opaque (47.8%) minerals are roughly the same (Table 2, Fig. 8A). The values of the proportionality index (T/O) are 0.32 and 1.08, respectively, for the sites (Tables 1–2).

The transparent minerals contain mainly resistant minerals, mostly tourmaline, zircon, rutile, titanite and kyanite (Tables 1–2, Fig. 8), forming Z>M>T (epi) and T>Z (rut,mus) assemblages. They contain a significant percentage of micas, as well as epidote, and trace amounts of pyroxene and glauconite, but no garnet. The values of the analog weathering

indexes are low (0.75 and 0.03, respectively) (Tables 1–2, Fig. 8C). For comparison: the calculated weathering indexes, W, are also low (3.03 and 0.06, respectively) (Tables 1–2, Fig. 8D–F).

5.1.1. Interpretation

The differences in the mineralogical composition of the weathered fragments of the Devonian sandstones may primary result from different conditions. The heavy minerals belong mainly to the group of resistant minerals, inset free during the weathering, they contributed to the weathered material that reworked and modified during successive sedimentation cycles. The analyses confirm the petrographical



studies of Devonian sandstones by Harapińska-Depciuch (1957) and Tarnowska (1971).

5.2. Karst pit (unit Ks-M_{III-IV})

The heavy minerals from ten samples of the sandy unit filling the karst pits in the Devonian dolomites at Winna (III) and Komorniki (IV) were identified. The transparent minerals range from 15.3% to 39.5%, and from 53.3% to 65.3%, respectively (Table 3, Fig. 8A). The values of the proportionality index (T/O) are 0.18–0.65 and 1.14–1.88, respectively, for both sites (Table 3). They mostly consist of resistant minerals, i.e. staurolite, kyanite, zircon, tourmaline, rutile and andalusite (Table 3, Fig. 8B). Among the non-resistant minerals (1.8–11.3%), the most important are amphiboles and pyroxenes. Semi-resistant minerals are insignificant. The values of the analog weathering index, aW, are very low and range from 0.02 to 0.29 (Table 3, Fig. 8C), whereas those of the weathering index, W, are 0.05–0.49 (Table 3, Fig. 8D–F). The minerals form K>ST>Z (rut,amp,tou) and ST>AM>Z (kya,tou,rut) assemblages.

5.2.1. Interpretation

The deposits include two prominent groups of minerals; one includes almost exclusively minerals with a high resistance to chemical weathering, whereas the other contains mainly non-resistant ones, like in sandy deposits of karst pits in the SE part of the Sandomierska Upland (Mycielska-Dowgiałło, 1965). The first mineral group is an indicator of a warm and moist climate (Barcicki et al., 1988). It may be assumed that denudation and erosion of the sedimentary cover provided only a very small number of heavy-mineral species. The second group of minerals is ascribed to the denudation of the cover of the glacial deposits which topographically mask the karst pits.

5.3. Glacial deposits (unit Gt-O_{V-VI})

Transparent minerals (60.0–61.5%) prevail in the samples of tills at Mąchocice (site V) and

in the two till samples (54.7–58.2%) collected at Napęków (site VI) (Table 4, Fig. 9A), whereas opaque minerals predominate (64.4–81.6%) in the two till samples from Napęków (site VI). The values of the proportionality index (P) are 1.5–1.65 at the Mąchocice site and 0.23–1.39 at the Napęków site (Table 4).

Semi-resistant minerals (8.0–29.8%) prevail in the group of transparent minerals (Table 4, Fig. 9B). The proportion of non-resistant minerals (6.8–17.6%) is comparable with that of the resisting ones, especially at the Mąchocice site. Qualitatively, the deposits are dominated by garnet and amphibole, accompanied by zircon, kyanite, staurolite and pyroxene; they form the following order: G>AM>Z (epi,sta,kya), Z>G>AM (epi,rut), G>AM (zir,kya,sta,pyr). The values of the analog weathering index, aW, are in the range of 14.10–35.47 (Table 4, Fig. 9C), and the weathering index, W, is 39.0–83.74 (Table 4, Fig. 9D–F).

5.3.1. Interpretation

The mineral assemblage is characteristic of glacial tills, with the dominant minerals form the order G>AM>Z (Racinański, 2008). Biotite, regarded in this region as typical of glacial tills (Racinański, 2008), occurs nevertheless only sporadically in the deposits. However, the enrichment with some resistant minerals (zir, kya, sta), typical of older bedrock, indicates a local (i.e. inside the Holy Cross Mountains) source of weathered material. The mineralogical composition of the clays resembles the clay composition in the nearby Wilkowska Valley (Kowalski et al., 1979), but it lacks biotite and contains a significant amount of kyanite.

5.4. Slope deposits (till succession)

5.4.1. Unit St-L_{II}

Opaque minerals prevail (55.3–60.3%) in the two samples of from Koszary (site II) (Table 2, Fig. 9A) and the value of the proportionality index, P, is 0.64–0.78 (Table 2). The transparent minerals are dominated by zircon (24.7–27.7%) and staurolite (5.0–5.2%). They are accompanied by other resistant minerals, viz. tourmaline, kyanite and andalusite. The semi-resistant

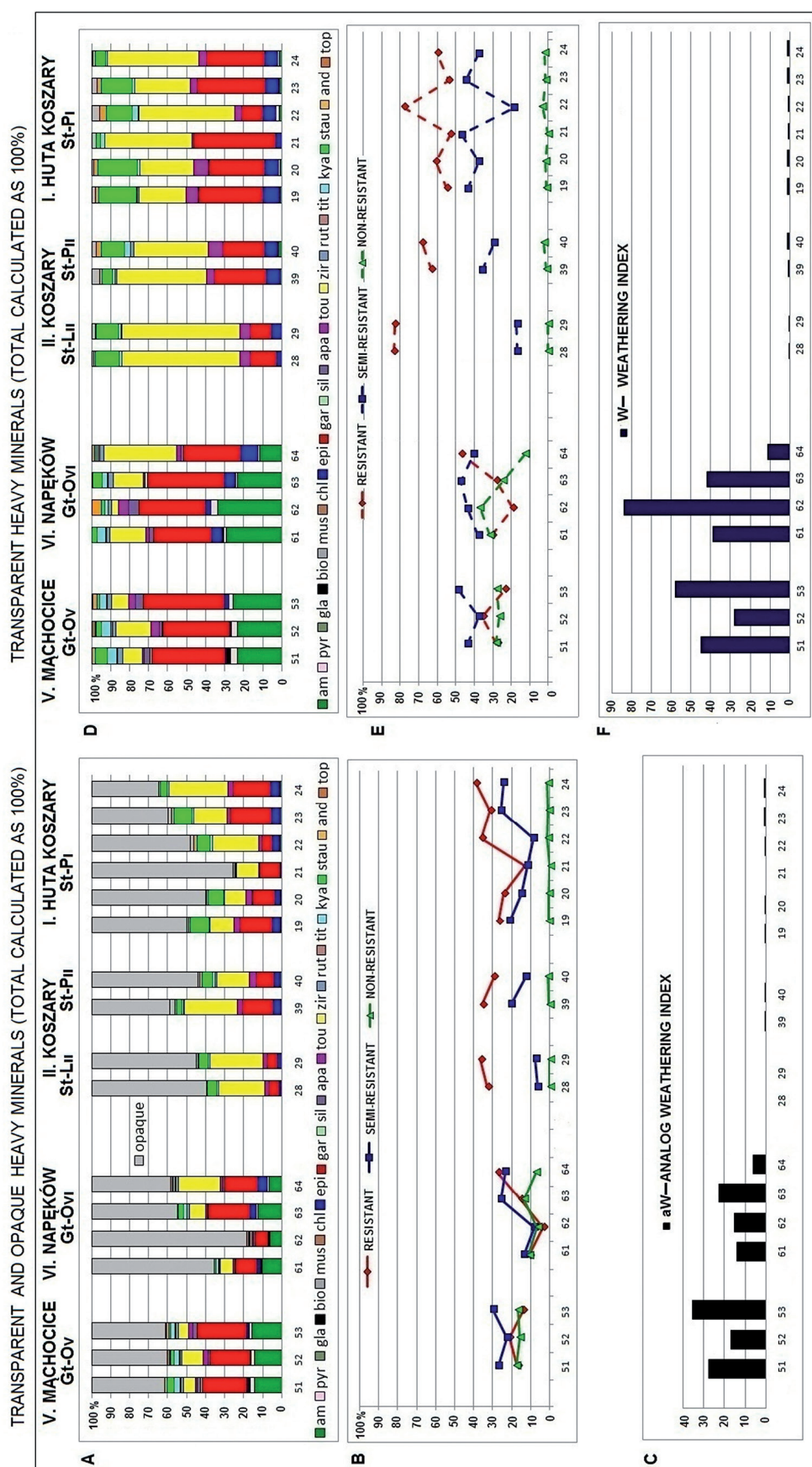


Fig. 9. Heavy-mineral assemblages of the slope deposits at sites Huta Koszary (I) and Koszary (II), and of the Lublinian, Odranian and Pleniglacial tills at sites Machocice (V) and Napęków (VI). For legend, see Figure 8.

minerals include garnet (5.2–5.4%) and epidote (1.1–2.3%) (Table 2, Fig. 9B). Non-resistant minerals are absent, so the analog weathering index, aW, and the weathering index, W, cannot be calculated (Table 2, Fig. 9D–F). The dominant minerals occur in the order Z (gar,sta,tou).

5.4.1.1. Interpretation

The mineral composition resembles that of the Ss-K_{II} (Table 2) unit underneath. Unit Ss-K_{II} was formed by solifluction of material that must have included not only sands from this unit, but also loess.

5.4.2. Unit St-P_{I-II}

Six samples of Pleniglacial diamictos sampled at Huta Koszary (site I) and two samples from Koszary (site II) were analysed (Tables 1–2, Fig. 9A). Opaque minerals (51.0–75.32%) prevail in the five samples of the periglacial clays, whereas transparent minerals (56.2–64.5%) predominate in the three samples (Tables 1–2). The values of the proportionality index, P, are 0.33–0.96 and 1.28–1.83, respectively (Tables 1–2). Resistant minerals (13.1–38.8%), represented by zircon, staurolite and tourmaline, prevail among the transparent minerals (Tables 1–2, Fig. 9A–B). The semi-resistant minerals are garnet and epidote. The dominant minerals form the assemblages Z>G (sta,epi,tou) and G>Z (sta,epi). The analog weathering index ranges from 0.29 to 0.82 (Tables 1–2, Fig. 9C), and the weathering index from 0.51 to 1.32 (Tables 1–2, Fig. 9D–F).

5.4.2.1. Interpretation

Compared with the clay from the Krznań interglacial, the Pleniglacial tills contain more epidote. The younger unit contains an increasing amount of non-resistant and of semi-resistant minerals (garnet). The slope deposits of the Bieliny range were isolated, and were not affected by the glacial processes connected with the Odranian glaciation that took place at the bottom of the Kielce-Łagów Valley. This explains their similar mineralogical composition.

5.5. Fluvioglacial deposits (unit FGs-O_{V-VI})

Six fluvioglacial samples from Mąchocice (site V) and two from Napeków (site VI) were analysed for their heavy minerals. The deposits of both sites have a diverse mineral composition, but a similar content of non-transparent (32.8–52.0%) and transparent minerals (48.0–67.2%) (Table 4, Fig. 10A). The values of the proportionality index, P, are 0.92–1.28 (Table 4). Only one sample is different: the transparent minerals prevail, and the proportionality index is 2.05. Among the transparent minerals, semi-resistant species dominate, i.e. garnet with epidote and apatite (Table 4, Fig. 10B). The heavy minerals contain a large proportion of non-resistant species (amphiboles and pyroxenes) and a smaller proportion of resistant minerals (mainly zircon, together with staurolite, tourmaline, and kyanite). They occur in the order G>AM (zir,sta), AM (gar,ky,pyr), G>Z (amp,sta). The analog weathering index ranges from 16.63 to 26.05 (Table 4, Fig. 10C), and the weathering index ranges from 31.74 to 45.95 (Table 4, Fig. 10D–F).

5.5.1. Interpretation

The mineral composition is typical of sandy/gravelly fluvioglacial deposits as present all over Poland (Racowski, 2008), i.e. G>AM, G>Z. These fluvioglacial deposits became undoubtedly a source material for younger fluvial sediments. The weathering value is similar to that of fluvioglacial deposits from the western part of the Holy Cross Mountains (Radłowska & Mycielska-Dowgiałło, 1972).

5.6. Slope deposits (sandy successions)

5.6.1. Unit Ss-K_{II}

The heavy minerals in the two samples of the periglacial unit consisting of sandy deposits at Koszary (site II) contain hardly more opaque than transparent minerals (53.4% vs. 46.6% for site I, and 54.2% vs. 45.8% for site II) (Table 2, Fig. 11A). The values of the proportionality index are 0.84–0.87 (Table 2). Non-resistant transparent minerals are lacking (Table 2, Fig. 11B), so the analog weathering index

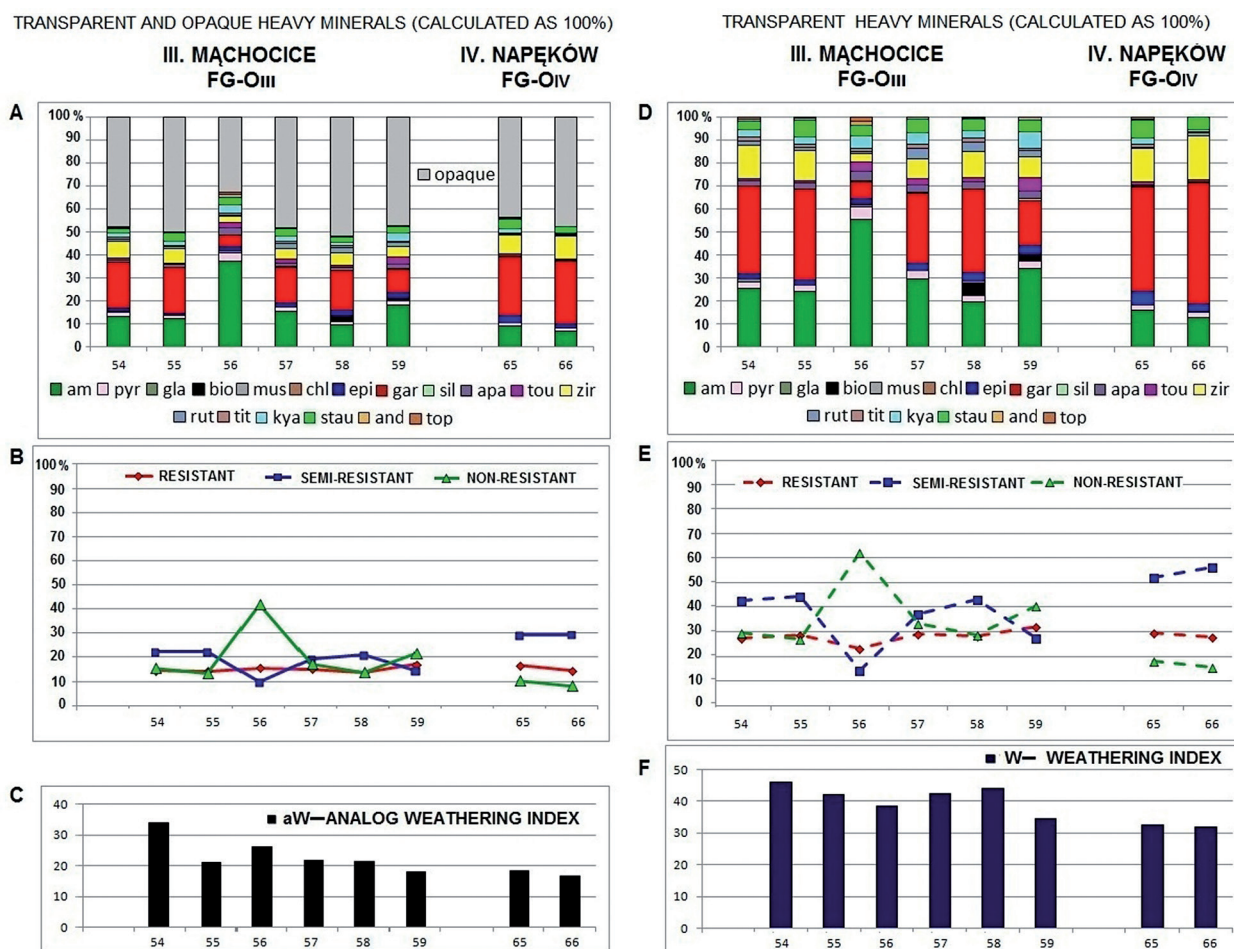


Fig. 10. Heavy-mineral assemblages of the Odranian fluvioglacial deposits at Mąchoć (V) and Napek (VI). For legend, see Figure 8.

and the weathering index cannot be calculated (Table 2, Fig. 11C–F). Resistant minerals are the most prominent, with zircon, followed by staurolite, rutile, tourmaline and kyanite. Garnet and epidote represent the semi-resistant minerals. The dominant minerals occur in the order Z (sta,gar,epi).

5.6.1.1. Interpretation

The mineral composition indicates that the deposit was strongly modified by secondary destructive processes, mostly chemical weathering but also washing. The presence of the zircon-staurolite-tourmaline assemblage implies that weathered Palaeogene-Neogene fragments were present in this unit (with properties as at the Winna and Komorniki sites).

5.6.2. Unit Ss-O₁

The heavy minerals from the Huta Koszary (site I) and Koszary (site II) sites were identified for 15 samples of Odranian slope sediments. The opaque minerals (68.4–79.7%) prevail in the five samples (Table 1). In the other samples, the transparent minerals (50.5–63.0%) dominate. The values of the proportionality index are 0.25–0.95 for the five opaques-dominated samples and 1.06–1.70 for the other samples (Table 1).

These slope deposits are characterised by a relatively low number of heavy-mineral species (Table 1, Fig. 11). The percentages of zircon and garnet are high. Staurolite and epidote are also common, but tourmaline, andalusite and kyanite occur only in low quantities. The content of the remaining heavy minerals, i.e. silli-

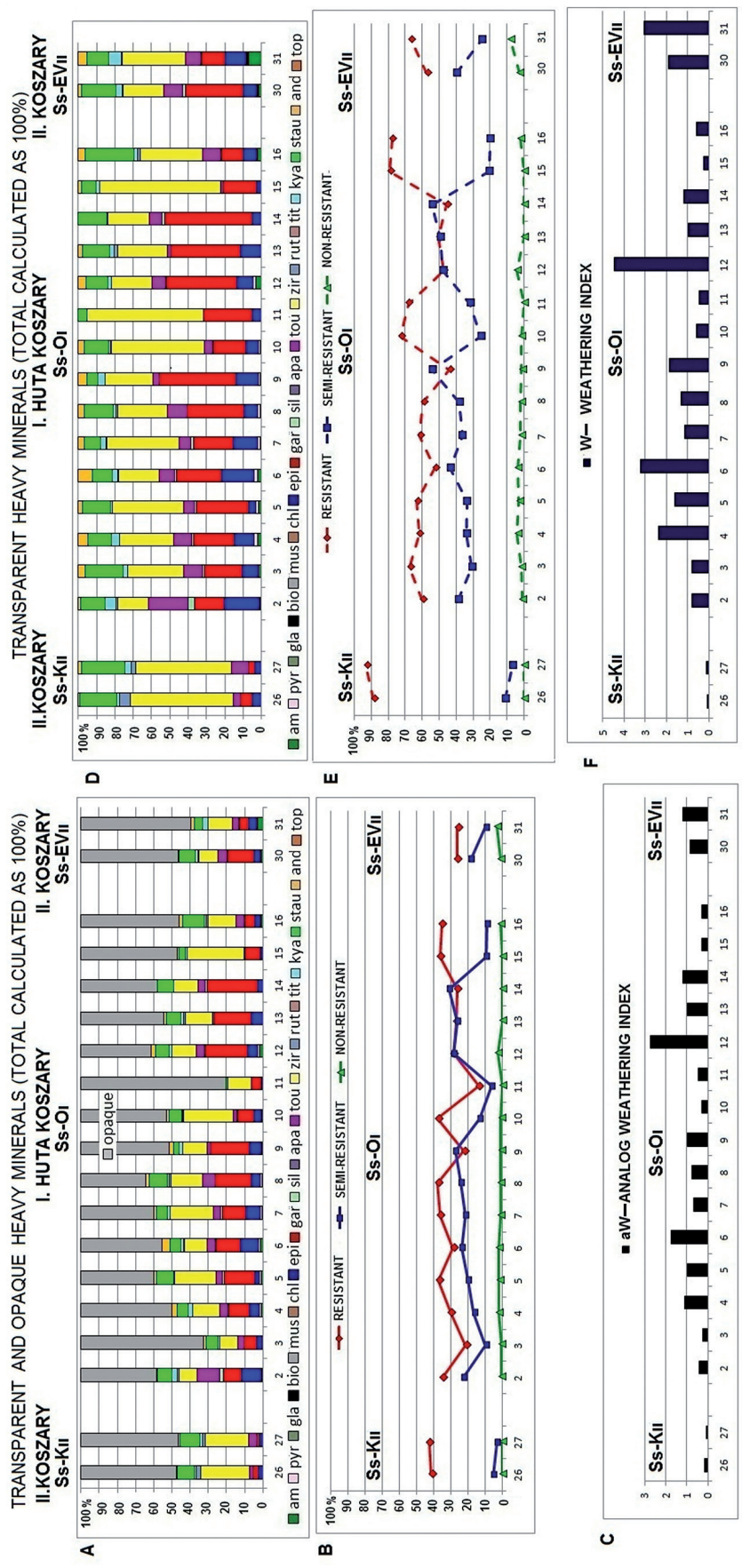


Fig. 11. Heavy-mineral assemblages of the Krzanian and early Vistulian sandy slope deposits at Huta Koszary (I) and Koszary (II). For legend, see Figure 8.

manite, rutile, amphibole and pyroxene, is low. Biotite and chlorite are absent.

With respect to the minerals' resistance to mechanical abrasion and chemical weathering, the sediments contain mostly resistant minerals (42.9–76.4%) (Table 1, Fig. 11). The semi-resistant minerals occur in only slightly lower percentages and are even more numerous in three samples. Non-resistant minerals make up only a few percent. The dominant minerals typically occur as $Z > G$, $G > Z$ (sta, epi, tou). The value of the analog weathering index is 0.23–2.71 (Table 1, Fig. 11C), and the weathering index is 0.56–4.44 (Table 1, Fig. 11D–F). The values of the weathering indexes in the four samples could not be calculated, because non-resistant transparent minerals are lacking (Table 1).

5.6.2.1. Interpretation

The material of this unit has a long history: it contains mainly minerals which are resistant and semi-resistant to mechanical abrasion and chemical weathering, and only a small proportion of non-resisting minerals; there are no minerals from the mica group, there is a high percentage of opaque minerals, and most grains show a well-developed coating. This indicates involvement in several depositional/erosional cycles, as well as intensive chemical weathering and physical attrition. This is supported by a low analog weathering index as well as a low weathering index. It is interesting that the deposits are dominated by a zircon/garnet assemblage, two minerals with a high mass.

The Cambrian rocks that surround the Kielce-Łagów Valley are also a possible source of minerals such as garnet, zircon, tourmaline and rutile (Radziszewski, 1928). This assemblage is also known from tidal environments, especially at the edge of the tidal range (Komar et al., 1989). A similar assemblage has been found in certain formations filling surface karst forms of the Cracow upland (Krysowska-Iwaszkiewicz, 1974), where they were interpreted as fluvioglacial. The relatively high content of garnet might be due to aeolian activity leading to relative enrichment with these minerals (Mycielska-Dowgiałło, 1995, 2001; Barczuk & Mycielska-Dowgiałło, 2001).

5.6.3. Units Ss-EV_{II} and Ss-P_{I-II}

The heavy-mineral composition of the sandy periglacial slope deposits at Huta Koszary (site I) and Koszary (site II) was analysed for 11 samples. Opaque minerals prevail in the early Vistulian deposit (53.9–61.0%) and in the three Pleniglacial samples (52.9–55.7%) (Tables 1–2, Figs 11–12). The value of the proportionality index is 0.63–0.90 (Tables 1–2). In the other Pleniglacial samples, the transparent minerals (52.70–66.0%) prevail. The assemblages are dominated by semi-resistant minerals, mostly garnet and, in smaller quantities, epidote; resistant minerals are represented by zircon, staurolite and tourmaline (Tables 1–2, Figs 11–12B). The dominant transparent minerals are present as $Z > G$; $G > Z$ (sta, epi, tou), G (zir, sta), $ST > Z$ (gar, tou). The analog weathering index ranges from 0.21 to 6.20 (Tables 1–2, Figs 11–12C) and the weathering index from 0.46 to 9.35 (Tables 1–2, Figs 11–12D–F).

5.6.3.1. Interpretation

The assemblage largely resembles that of the sandy Odranian glacial unit in the upper part of the less inclined slope under the steep-sloping Devonian sandstones of the Bieliny range; it is also similar to that of older Middle-Polish complexes at the study site. Thus it can be assumed that, in general, the Middle-Polish complex is the source of the Pleniglacial unit. The mineralogical composition of the older deposits was gradually modified, primarily as a result of periglacial denudation, weathering and aeolian erosion; the last process was responsible for the relative enrichment with garnet. The possibility that denudation transformed the older slope deposits into younger ones in the Holy Cross Mountains has earlier been put forward by Klatka (1962).

5.6.4. Unit Ss-P_{VII}

Ten samples of the slope deposits at Masłowiec (site VII) were analysed. The transparent minerals (58.7–69.8%) are more frequent than opaque species (30.2–41.3%), except for one sample (Table 5, Fig. 12A). The value of the proportionality index is 1.31–2.07; for one sample it is only 0.86 (Tables 1–2). Among the transparent minerals, semi-resistant species,

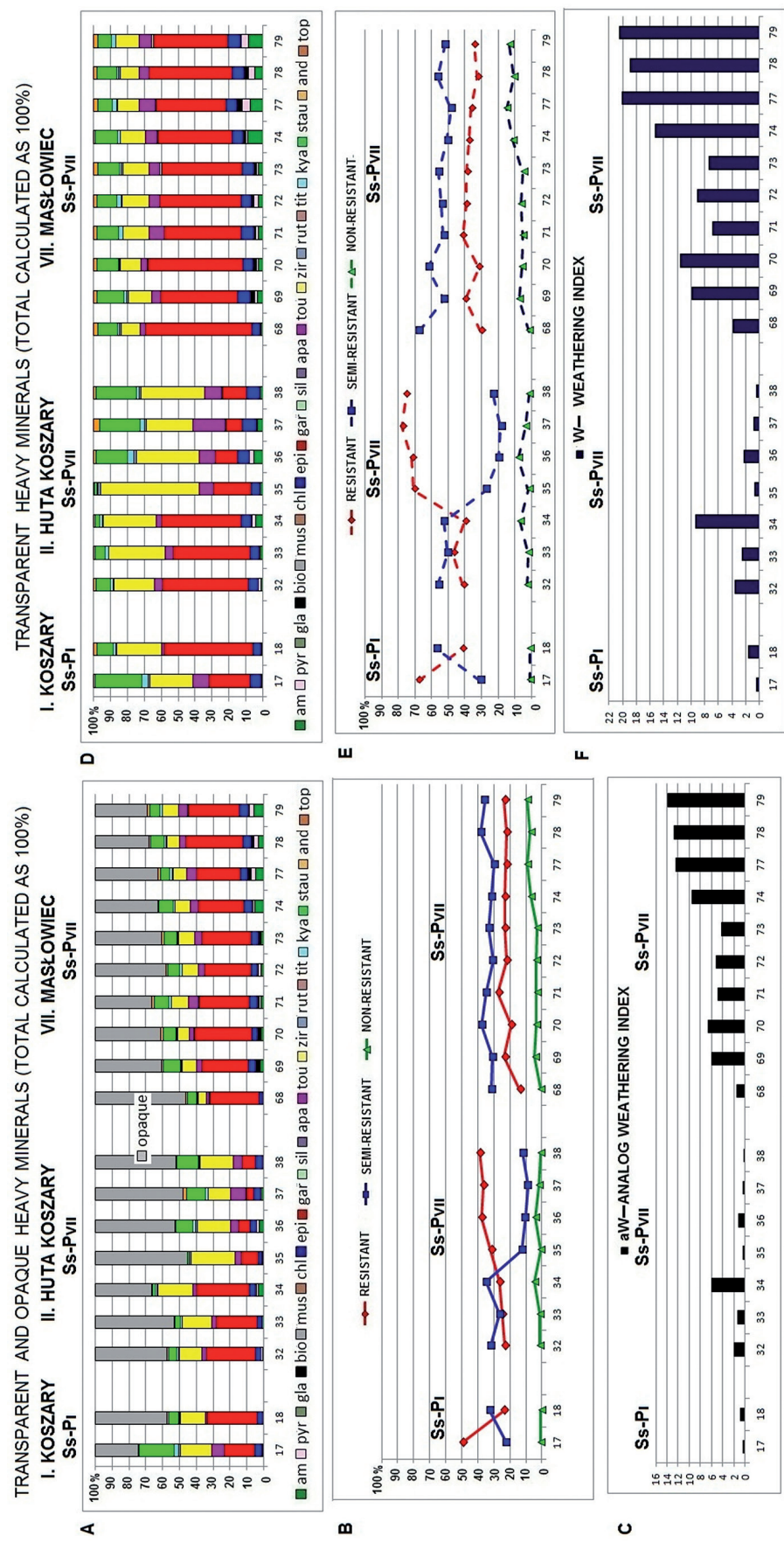


Fig. 12. Heavy-mineral assemblages of the Pleniglacial sandy slope deposits at sites Huta Koszary (I), Koszary (II) and Masłowiec (VII). For legend, see Figure 8.

mostly garnet, and to a lesser extent epidote, dominate, always with a large proportion of the resistant minerals zircon, staurolite and tourmaline, but also with amphibole, pyroxene and biotite (Table 5, Fig. 12). The analog weathering index ranges from 4.29 to 13.79 (Table 5, Fig. 12C) and the weathering index from 6.88 to 20.45 (Table 5, Fig. 12D–F). The deposits have a characteristic composition with few species: $G > ST$ (zir,epi) or $G > Z$ (sta,epi).

5.6.4.1. Interpretation

The exceptionally large proportion of garnets indicates strong aeolisation. The high percentage of resistant minerals, on the other hand, may indicate that the parent material was reworked numerous times and consisted mainly of weathered fragments of local Palaeozoic rocks (Michniak, 1969) and the Palaeogene-Neogene cover. One cannot exclude either the possibility of the glacial and fluvio-glacial cover as a source, as this cover occurs on the surface of hill tops and rocky slopes of the valley. These elements were strongly denudated and eroded under the periglacial conditions that persisted in this part of the Holy Cross Mountains for a long time-span. These deposits were repeatedly reworked, eventually becoming part of newly formed fluvial deposits. These fluvial processes led to a relative enrichment in garnet (cf. Mycielska-Dowgiałło, 1978; Florek et al., 1987; Mycielska-Dowgiałło & Rutkowski, 1995; Ludwikowska-Kędzia, 2000). A similar process of relative enrichment in garnet is known from the aeolian environment (Mycielska-Dowgiałło, 1995, 2001), which is also shown by a large content of garnet in the upper part of series D (Unit Ss-P_{vii}).

5.7. Fluvial deposits

5.7.1. Unit Fs-EV_{ix}

Transparent minerals prevail (53.9–78.3%); among them, minerals resistant to weathering dominate the fluvial deposits at Górno (site IX) (8 samples) (Table 6, Fig. 13A–B). The value of the proportionality index ranges from 1.17 to 3.61 (Table 6). They are represented by zircon,

staurolite, tourmaline, kyanite and apatite. The proportions of the non-resistant minerals and of the semi-resistant minerals are roughly the same. In the former group, amphibole is the most common, whereas garnet is the most common in the latter. The dominant minerals can be ranked as $Z > ST > T$ (amp,kya). The value of the analog weathering index is low and ranges from 1.06 to 3.22 (Table 6, Fig. 13C) and the weathering index is 1.77–4.12 (Table 6, Fig. 12D–F).

5.7.1.1. Interpretation

The mineral composition strongly resembles that of the slope covers of the Bieliny range, but most probably also that of other nearby slope deposits. The short transportation of the slope material did not significantly change the mineral composition, which is dominated by resistant minerals. The occurrence of staurolite and kyanite indicates that Palaeogene-Neogene material must be involved. The amphibole may be derived from glacial material.

5.7.2. Unit Fs-P_{v-vi}

Two samples of fluvial deposits were analysed, one from Mąchocice (site V) and a second from Napęków (site VI). The deposits are characterised by an uncommonly high proportion of transparent minerals (71.0–72.9%) and minerals from the semi-resistant group, mainly garnet (Table 4, Fig. 13A–B). The content of this mineral is so high that there are hardly any other heavy minerals; zircon, followed by staurolite, kyanite and tourmaline are the most important resistant minerals. The non-resistant minerals are represented by amphibole. The dominant minerals can be ranked as G (zir,amp,sta) $G > Z$ (amp,sta,tou). The analog weathering index ranges from 12.62 to 19.55 (Table 4, Fig. 13C) and the weathering index is 17.17–27.29 (Table 6, Fig. 12D–F).

5.7.2.1. Interpretation

The mineral composition resembles that of the fluvio-glacial deposits (unit FGs-O_{v-vi}). The latter most probably form the source material for these fluvial deposits, which were strongly affected by aeolian processes under periglacial conditions.

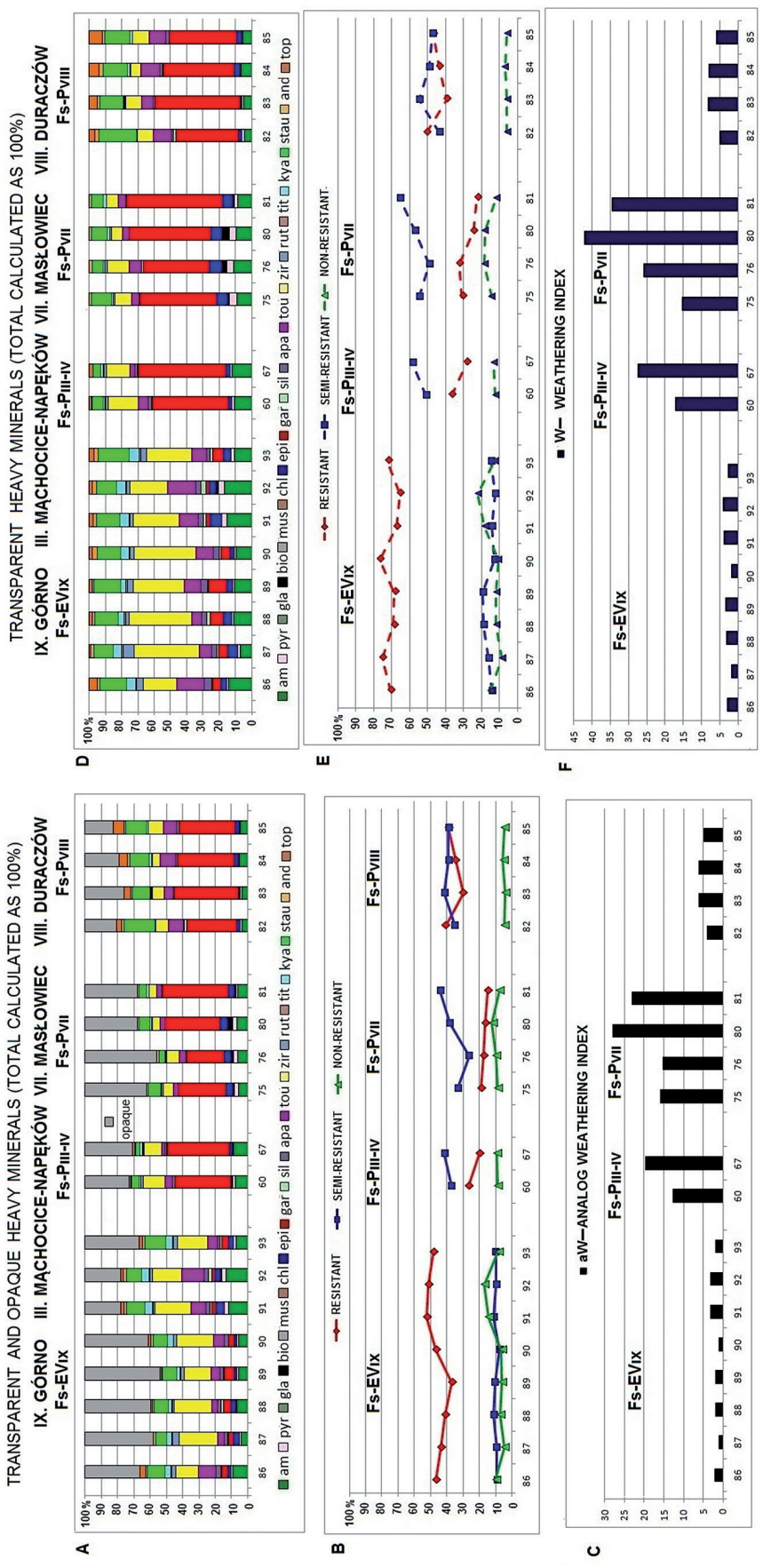


Fig. 13. Heavy-mineral assemblages of the early Vistulian and Pleniglacial fluvial deposits at sites Górnó (IX), Małchocice (V), Napėków (VI), Masłowiec (VII) and Duraczów (VIII). For legend, see Figure 8.

5.7.3. Unit Fs-P_{VII-VIII}

In the heavy-mineral composition of the fluvial deposits at Masłowiec (site VII) and Duraczów (site VIII) (four samples from each site), transparent minerals prevail (57.5–82.8%); their proportion is particularly high at the Duraczów site (76.0–82.8%). The values of the proportionality index range from 1.16 to 4.81 (Table 5). The heavy-mineral composition of the fluvial deposits is dominated by semi-resistant minerals, mainly garnet, with epidote as second (Table 5, Fig. 13A–B). The proportion of resistant minerals (mainly staurolite, zircon and tourmaline, with lesser amounts of andalusite, topaz and sillimanite) at Masłowiec is only half that of Duraczów, where the content of resistant minerals is also more diverse (with apatite and topaz). The unit contains a relatively small proportion of non-resistant minerals (amphibole, pyroxene and mica, and at Duraczów also biotite). The transparent dominant minerals can be ranked as G (zir,sta,amp) and G>ST (tou,zir). The analog weathering index of the deposits at Masłowiec ranges from 15.11 to 28.0, and at Duraczów from 3.95 to 6.17 (Table 5, Fig. 13C). The weathering index ranges from 25.75 to 42.07, and from 4.90 to 8.15, respectively, for both sites (Table 5, Fig. 13D–F).

5.7.3.1. Interpretation

The heavy minerals indicate a relatively high age of the fluvial deposits. The source material must consequently also be 'old', i.e. at least partly consisting of weathered local sedimentary rocks (Michniak, 1969) that were subsequently repeatedly reworked under periglacial conditions and thus became gradually part of 'new' fluvial deposits. The reworking resulted in a relative enrichment of garnet. A similar process has also been reported from an aeolian environment (Mycielska-Dowgiałło, 1995, 2001), where also minerals from the mica group can become enriched (Barczuk & Mycielska-Dowgiałło, 2001).

The differences in the mineral composition of the deposits from Masłowiec and Duraczów should be attributed to the relief of the Łagowica valley. At Masłowiec, the narrow gorge was more strongly affected by slope processes, initiated by the climate change. Consequently,

the valley bottom was covered with weathered material accumulated after denudation of glacial boulder clays. The deposits in Duraczów, in contrast, accumulated in a wide valley in which the stream also carried sediments from a tributary stream (the Wszachówka river) (Fig. 6).

6. Results and discussion

The heavy-mineral assemblages of the Quaternary sediments, deposited in different sedimentary environments in the Kielce-Łagów valley, have some characteristic features but is not very diverse (Table 7, Fig. 14).

6.1. Resistant minerals

Transparent resistant minerals prevail in the weathering debris of Palaeozoic rocks (Devonian sandstones) (at the Huta Koszary and Koszary sites), as well as in the infillings of karst pits (at the Winna and Komorniki sites) and in periglacial sandy (Komorniki) and soliflucted flowtill (Koszary, Huta Koszary) slope deposits. With respect to the age, these deposits are the oldest, formed before the Odra glaciations; they include also Vistulian deposits (at Koszary and Huta Koszary) but these were derived from 'old' sedimentary covers. The ranking of the dominant heavy minerals can be described as Z>M>T, T>Z, K>ST>Z, ST>AM>Z. These sediments form, in turn, one of the sources for later generations of deposits, which inherited their heavy minerals from this material. These younger deposits contain a high proportion of resistant heavy minerals, which results in a low analog weathering index (aW), ranging from 0 to 3.0 (Fig. 13). The values of the weathering index (W) values range from 3 to 27 (Fig. 14).

Resistant minerals, such as zircon, staurolite, tourmaline and kyanite, belong to the dominant minerals or complementary minerals in all types of deposit, regardless of age and origin (Table 7). They differ only with respect to their percentage in the heavy-mineral assemblage. Together with other resistant minerals, they provide the mineralogical

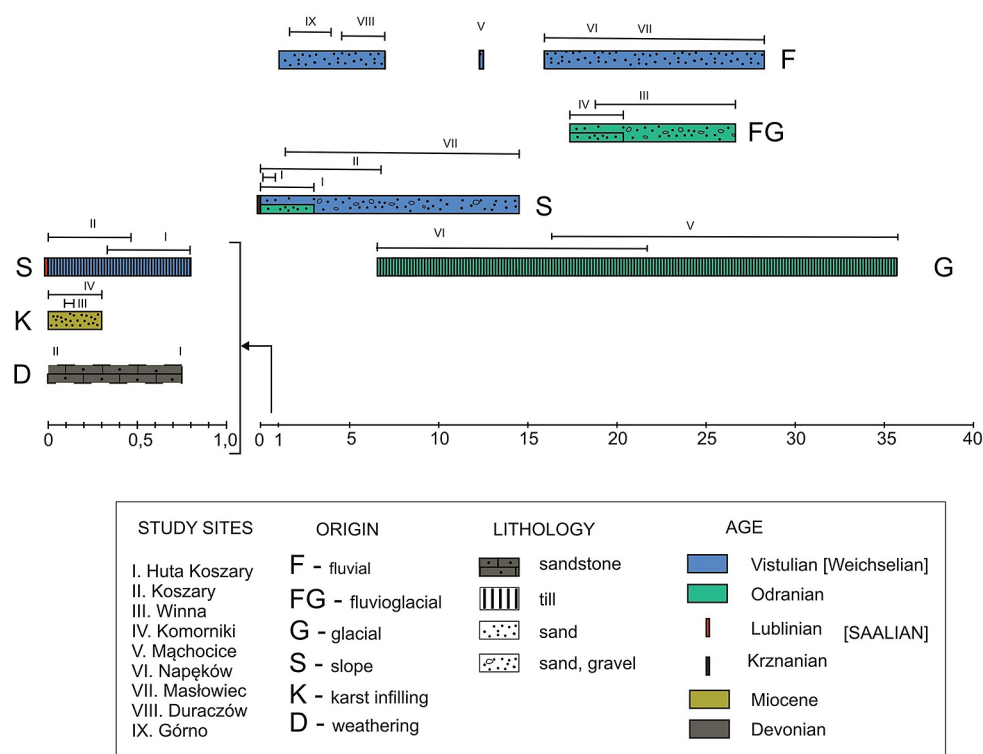


Fig. 14. The analog weathering index (aW) of the Kielce-Łagów Valley Quaternary deposits of different lithology, depositional environment and age.

background for all other sediments under study here. The non-resistant minerals became weathered and gradually disappeared with time, which led to the relative enrichment of resistant minerals. Where the mineral assembly of relatively young deposits (i.e. the early Vistulian deposits at Górnó) contains a truly large proportion of resistant minerals, it may be assumed, that 'old' deposits were reworked, for instance through erosion, denudation, or aeolian deflation. Thus it is possible to reconstruct the location that underwent erosion, the location of the source material, and the transport direction.

6.2. Semi-resistant minerals

Semi-resistant transparent minerals occur in large amounts in all sediments under study here. The early Vistulian fluvial deposits (Górnó), the infillings of karst pits (Winna, Komorniki) and the weathered debris of Devonian rocks (Huta Koszary, Koszary) con-

tain the lowest percentages of these minerals. They are represented mostly by garnet, and to a lesser extent by epidote. Garnet is one of the most dominant minerals in the periglacial slope deposits, the fluvial, the glacial and the fluvioglacial deposits (Table 7). The relative enrichment of garnet results from their repeated reworking and their gradual embedding in freshly formed fluvial sediments, which is particularly clear for relatively young deposits (e.g. at Masłowiec). This phenomenon is well known also from other fluvial and fluvioglacial areas (Mycielska-Dowgiałło, 1978; Florek et al., 1987; Mycielska-Dowgiałło & Rutkowski, 1995; Ludwikowska-Kędzia, 2000). A similar relative enrichment of garnet is also known from the aeolian environment (Mycielska-Dowgiałło, 1993, 1995, 2001). It is worth noting that Vistulian loesses in the area of the Middle-Polish uplands have an increased content of amphibole and epidote (Racinowski, 2008) and may be one of the sources of these minerals in the Quaternary deposits of the study area.

Table 7. Analog weathering index and weathering index values for the various Quaternary deposits, grouped according to their depositional environment, lithology and age.

depositional environment (with code used in units)	lithology (with code used in units)	age (with code used in units)	number of study site (with number used in units) [with sample numbers; see Tables 1–6]	unit	analog weathering index [weathering index]		Heavy-mineral assemblage
					value	range	
weathered material (W)	sandstone fragments (d)	Devonian (D)	I – Huta Koszary [1] II – Koszary [25]	Wd-D _I Wd-D _{II}	0.75 [3.03] 0.03 [0.06]	0.03–0.75 [0.06–3.03]	Z>M>T T>Z
karst infilling (K)	sand (s)	Miocene? (M)	III – Winna [41–45] IV – Komorniki [46–50]	Ks-M _{III} Ks-M _{IV}	0.02–0.13 [0.05–0.35] 0.02–0.29 [0.05–0.49]	0.02–0.29 [0.05–0.49]	K>ST>Z S>AM,Z
glacial (G)	till (t)	Odranian (O)	V – Małchoć [51–53] VI – Napeków [61–64]	Gt-O _V Gt-O _{VI}	16.86–35.47 [28.09–57.98] 6.32–22.70 [11.00–83.74]	6.32–35.47 [11.0–83.74]	G>AM Z>G>AM G>AM>Z
slope (S)	till (t)	Lublinian (L) Pleniglacial (P)	II – Koszary [28–29] II – Koszary [39–40] I – Huta Koszary [19–24]	St-L _{II} St-P _{II} St-P _I	[0.20–0.21*] [0.20–0.21*] 0.29–0.43 [0.51–1.03] 0.34–0.82 [0.77–1.32]	0.20*–0.82 [0.20*–1.32]	Z Z>G; G>Z Z>G
fluvioglacial (FG)	sand (s)	Odranian (O)	V – Małchoć [44–49] VI – Napeków [55–56]	FGs-O _V FGs-O _{VI}	18.13–26.05 [34.57–49.95] 16.63–19.55 [31.74–32.38]	16.63–26.05 [31.74–49–95]	G>AM; AM G>AM; G>Z
slope (S)	sand (s)	Krznanian (K) Odranian (O) early Vistulian (EV) Pleniglacial (P)	II – Koszary [26–27] I – Huta Koszary [2–16] II – Koszary [30–31] I – Huta Koszary [17–18] II – Koszary [32–38] VII – Masłowiec [68–74;77–79]	Ss-K _{II} Ss-O _I Ss-EV _{II} Ss-P _I Ss-P _{II} Ss-P _{VII}	[0.08–0.13*] [0.08–0.13*] 0.23–2.71 [0.56–4.44] 0.84–1.19 [1.88–3.07] 0.36–0.81 [0.49–1.63] 0.21–6.20 [0.46–9.35] 1.55–13.79 [3.80–20.45]	0–13.79 [0.46–20.45]	Z Z>G; G>Z Z>G; G>Z G; ST>Z G; G>Z; Z>ST G>ST; G>Z
fluvial (F)	sand (s)	early Vistulian (EV) Pleniglacial (P)	IX – Górnio [86–93] V – Małchoć [50] VI – Napeków [57] VII – Masłowiec [75–76; 80–81] VIII – Duraczów [82–85]	Fs-EV _{IX} Fs-P _V Fs-P _{VI} Fs-P _{VII} Fs-P _{VIII}	1.06–3.22 [1.77–3.92] 12.62 [17.17] 19.55 [27.29] 15.11–28.0 [25.75–42.07] 3.95–6.17 [4.90–8.15]	1.06–28.0 [1.77–42.07]	Z>ST>T G>Z G G G; G>ST

*The analog weathering index (aW) and the weathering index (W) are unidentified, or the same, because non-resistant transparent minerals are lacking.

6.3. Non-resistant minerals

The most significant minerals in the non-resistant group are amphibole and pyroxene. Their proportion is commonly low. Amphiboles are present in the ranking $G > Am > Z$ (epi,sta,tou), which is characteristic exclusively of glacial deposits (sites Małocice and Napęków) and of those formed as a result of the denudation of these deposits the Masłowiec site.

6.4. Source deposits and the role of reworking

Another issue worth dealing with is the degree of exposure of the possible source deposits, and the likelihood of their reworking, which is controlled by the relief of the Kielce-Łagów Valley. Reworked deposits occur in the sub-slope parts of the Palaeozoic hilly areas, away from the axis of the Kielce-Łagów Val-

ley. These are most frequently mature slopes, with a small gradient, so that the transportation of material to the valley bottom is not so easy. Only slight modifications of the mineral composition occur in increasingly younger deposits, because of the short time that was present for modification of the heavy-mineral assemblage, the low intensity of the modification processes, and the dominance of resistant minerals (which obscures slight modifications in the total assemblage. Consequently, garnet, amphibole and pyroxene, i.e. minerals of which the main source are glacial deposits, can be considered as diagnostic minerals. The relative enrichment in garnet results from their repeated reworking and from their gradual embedding in freshly formed fluvial sediments. The presence of amphibole and pyroxene must be ascribed to denudation of glacial deposits, which are common in the wide and flat bottom of the Kielce-Łagów Valley.

The influence of the second source of the heavy minerals, i.e. the glacial deposits that

sample number	transparent minerals T	opaque minerals O	TRANSPARENT+OPAQUE MINERALS = 100%					TRANSPARENT MINERALS = 100%					W aW	T O
			semi-resistant SR	resistant R	non-resistant NR	SR R	analog weathering index (aW)	semi-resistant SR	resistant R	non-resistant NR	SR R	weathering index (W)		
45	15.3	84.7	0.1	10.9	4.3	0.01	0.04	0.9	71.3	27.9	0.01	0.35	8.75	0.18
47	29.9	70.1	0.3	27.8	1.8	0.01	0.02	1.1	93.0	5.9	0.01	0.07	3.50	0.43
61	35.6	64.4	13.6	10.8	11.2	1.26	14.10	37.9	30.0	31.5	1.26	39.00	2.76	0.55
19	49.0	51.0	21.4	26.9	0.6	0.79	0.48	43.8	54.9	1.3	0.79	1.04	2.17	0.96
55	49.9	50.1	22.3	14.2	13.4	1.57	21.04	44.6	28.5	26.9	1.57	42.10	2.00	0.99
50	57.8	42.4	1.4	48.3	8.1	0.03	0.23	2.5	83.4	14.1	0.03	0.42	1.83	1.36
34	66.0	34.0	34.9	26.5	4.6	1.32	6.06	52.8	40.1	7.1	1.32	9.35	1.54	1.99
56	67.2	32.8	9.7	15.6	41.9	0.62	26.05	14.4	23.3	62.3	0.62	38.50	1.47	2.05
83	76.0	24.0	41.5	30.1	4.4	1.38	6.07	54.6	39.5	5.9	1.38	8.15	1.34	3.17
85	82.8	17.2	39.0	38.9	4.9	1.00	4.91	47.2	47.0	5.8	1.00	5.82	1.19	4.81

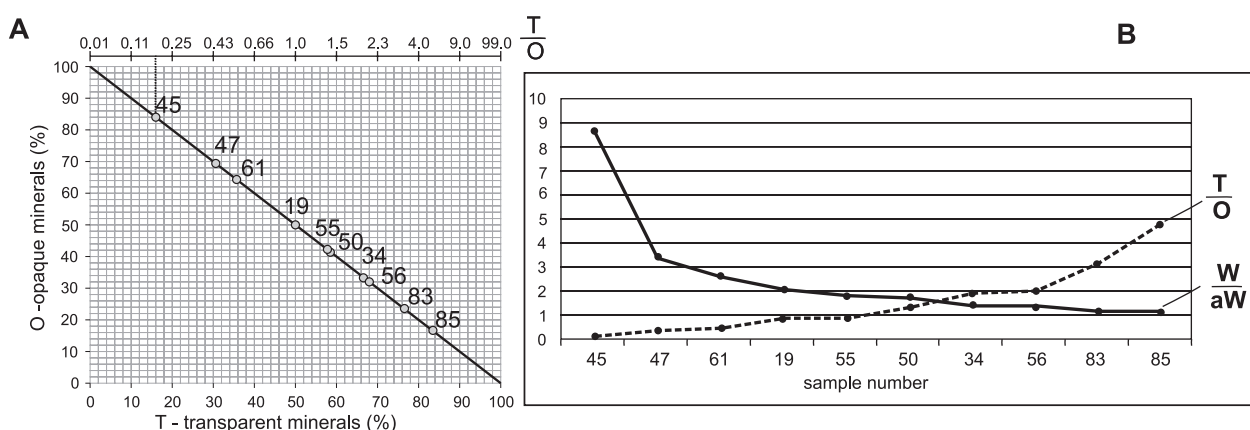


Fig. 15. Aspects of the proportionality index (P).

A: Relationship between the proportion of transparent minerals (T) in the various Quaternary deposits to that of the opaque minerals (O). The lower the value of P, the higher the proportion of opaque minerals in the sediment (and vice versa).

B: Changes in the proportionality index of the various Quaternary deposits and the W:aW ratio calculated for these deposits.

were denudated, is evident in the increasingly younger sediments, even against the background of the inherited assemblage of resistant minerals.

6.5. The analog weathering index (aW) and weathering index (W)

The dual character of the source material of the Quaternary deposits in the Kielce-Łagów Valley is typical of the zone of uplands and old mountains in Poland. This property is reflected in the value of the analog weathering index, aW and of the weathering index, W. The aW and W values for the source deposits (Wd-D, Ks-M, Ss-O), which are dominated by resistant heavy minerals, are exceptionally low and range from 0.02 to 2.71 for aW, and from 0.05 to 4.44 for W. In the glacial and fluvioglacial deposits (Gt, FGs), on the other hand, the aW ranges from 6.32 to 35.47, and W ranges from 11.08 to 83.74. Its value in younger, Vistulian deposits depends on the properties of the source deposits: it is lower in the case of a higher proportion of deposits with an assemblage dominated by resistant minerals (e.g. in the St-P Vistulian soliflucted till at the Huta Koszary, and Koszary sites, and in the Fs-P Vistulian fluvial sands at the Górno site), and higher in the case of a denudated glacial cover (e.g. at the the Masłowiec site). This relationship is also illustrated in the assemblages of the Holocene fluvial sediments in the Daleszyce profile (Ludwikowska-Kędzia, 2000), and of the Pleniglacial fluvial sediments in the Słopiec profile (Wachecka-Kotkowska & Ludwikowska-Kędzia, 2007) in the valley of the Belnianka river, in the central part of the Holy Cross Mountains.

When the values obtained for the weathering index and the analog weathering index are mutually compared (Fig. 15), two important conclusions can be drawn:

(1) the proportion of particular transparent mineral groups (with respect to their resistance) is lower if calculated with the use of the aW index than if calculated with W, and both values become increasingly lower with an increasing content of opaque minerals (i.e. the

values of the proportionality index [$P = T/O$] become lower).

(b) if the value of the proportionality index diminishes (i.e. if the proportion of opaque minerals increases), the value of $W/(aW)$ increases (i.e. the difference between the weathering index, W, and the analog weathering index, aW, increases). The values of both indexes will differ least from each other when the proportion of the transparent minerals reaches almost 100% ($T+O = T$).

These findings indicate that it is important for analysis of the environmental conditions under which the sediment was formed and transformed to know the proportions of the transparent and opaque minerals (e.g. Marcinkowski, 2007), as well as their relation to each other as defined by the proportionality index $P = T/O$, the weathering indexes W and aW, and the relationship between these two indexes.

7. Conclusions

The heavy-mineral analysis of the Quaternary deposits in the Kielce-Łagów Valley leads to the following five conclusions.

- 1) The mineral assemblages of the Quaternary deposits in the Kielce-Łagów Valley, which have different ages and which accumulated in different environments, are not truly diverse. The assemblages depend on the origin and location of the source material. The resistant minerals, among which zircon, staurolite and tourmaline, are largely inherited from the oldest source material: weathering products of Devonian and Palaeogene-Neogene rocks, as well as Pleistocene glacial and, in the case of loess, aeolian material dating from before the Odranian glaciation. The semi-resistant and non-resistant minerals, mainly garnet, amphibole and epidote, are derived from the denudation of the youngest glacial deposits in the study area, i.e. tills and fluvioglacial sands from the Odranian glaciation.
- 2) There is a clear relationship between the heavy-mineral assemblages of the Quaternary deposits and the relief of the Kielce-

Łagów Valley. The precise location of the deposits with regard to the relief controls, in combination with the nature of the local source material, the heavy-mineral assemblage. The oldest source deposits in which resistant minerals dominate, are found in the area of the sub-slope ranges of Palaeozoic hills. Their exposure to erosion decreased with time, because of the diminishing slope gradient and because they became gradually overlain by a younger sedimentary cover. The bottom of the Kielce-Łagów Valley, on the other hand, is covered with glacial deposits which, due to the low relief in the valley, were only slightly subjected to denudation and erosion, but more to aeolian activity. Consequently, the fluvial environment of the Kielce-Łagów Valley resulted in hardly varying mineral assemblages.

- 3) The heavy-mineral compositions of tills with a known stratigraphic position (and thus also a known age) in the glacial and periglacial slope environments are diagnostic, so that they can be used to distinguish between both types of tills. This is of great importance for the understanding of the regional Quaternary geology in this part of the Holy Cross Mountains. In this context, the weathering index also deserves attention. For glacial clays, the aW index ranges from 6.32 to 35.47, whereas it does not exceed 1 for periglacial soliflucted flowtills. The differences are also evident in the W values: for glacial tills, W amounts to 11–83.74 and for periglacial, soliflucted flowtills W is 0.51–1.32. W is especially low in comparison to the glacial deposits of northern Poland (where it ranges from 50 to over 200) (a.o. Racinowski & Rzechowski; 1969, Cichosz-Kostecka et al., 1991).
- 4) The heavy-mineral analysis is an additional tool in determining the age and origin of Quaternary deposits. In order to take full advantage of this possibility, it is important to obtain a good insight into the mineralogical background of the area at both a local and a regional scale (Racinowski & Rzechowski, 1969; Racinowski, 2008) before heavy-mineral analyses are carried

out. Only then is it possible to interpret the results of such an analysis in a reliable way.

- 5) The heavy-mineral analyses of the Quaternary sediments indicate an advanced weathering process. This implies that the Pleistocene land-ice mass did not affect the local and regional mineralogical background of sediments considerably. The flowing ice mass eroded mainly local material, consisting largely of resistant minerals from the weathered bedrock. Under the changeable climatic conditions of the Pleistocene, the deposits underwent aeolian processes and chemical weathering, which modified their original mineral composition.

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