Acta Geologica Polonica, Vol. 71 (2021), No. 2, pp. 199–218
DOI: 10.24425/agp.2020.132264

The maximum ice sheet extent and its retreat in the western part of the Holy Cross Mountains, Poland, during the Sanian 2 Glaciation/MIS 12 based on geological data and analysis of karst phenomena

JAN DZIERŻEK[1*], LESZEK LINDNER[1], KRZYSZTOF CABALSKI[1], JAN URBAN[2] and MICHAŁ CYGLICKI[3]

[1] *Faculty of Geology, University of Warsaw, Żwirki i Wigury 93, PL-02-089 Warszawa, Poland.*
E-mails: j.dzierzek@uw.edu.pl, l.lindner@uw.edu.pl, krzysztof.cabalski@uw.edu.pl
[2] *Institute of Nature Conservation, Polish Academy of Sciences, Adama Mickiewicza 33, PL- 31-120, Kraków, Poland. E-mail: urban@iop.krakow.pl*
[3] *Polish Geological Institute-National Research Institute, Rakowiecka 4, PL-00-975, Warszawa, Poland.*
E-mail: mcyg@pgi.gov.pl

ABSTRACT:

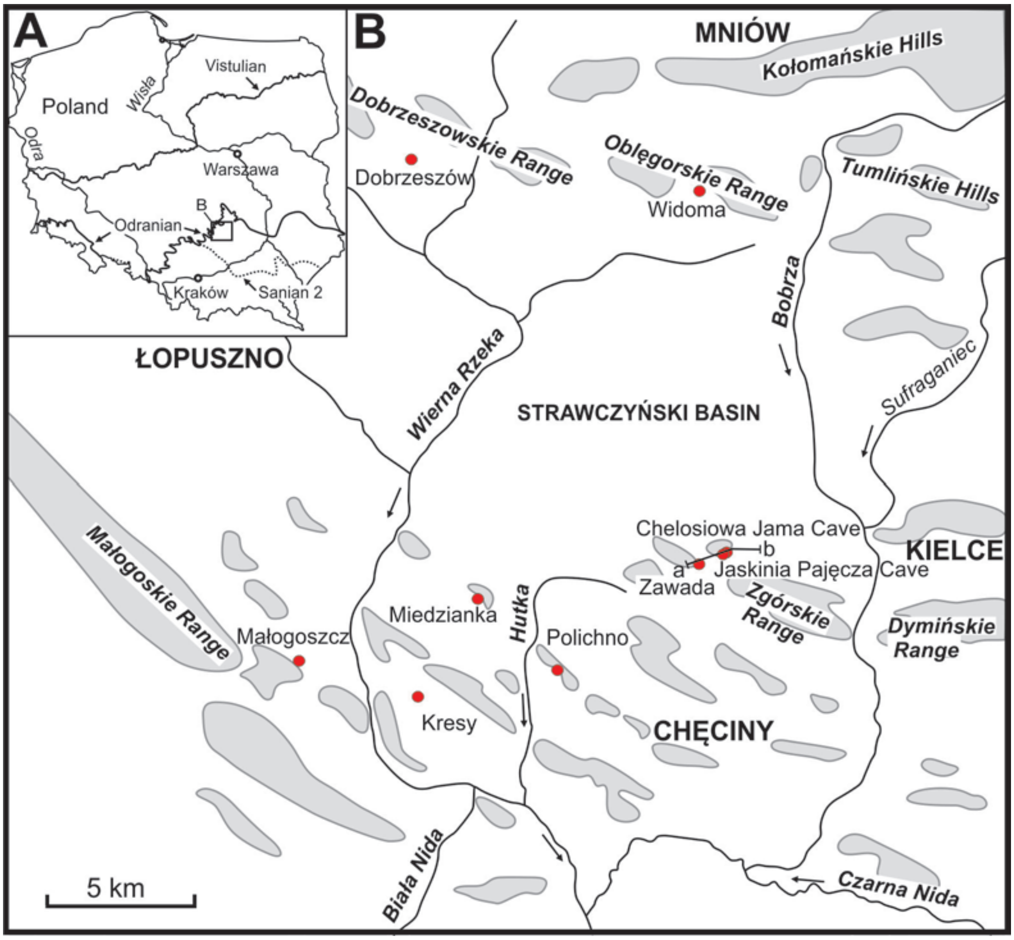
Dzierżek, J., Lindner L., Cabalski, K., Urban, J. and Cyglicki, M. 2021. The maximum ice sheet extent and its retreat in the western part of the Holy Cross Mountains, Poland, during the Sanian 2 Glaciation/MIS 12 based on geological data and analysis of karst phenomena. *Acta Geologica Polonica*, **71** (2), 199–218. Warszawa.

The paper is focused on the palaeographic development of the western part of the Holy Cross Mountains, Poland, during the maximum extent of the Sanian 2 (MIS 12) ice sheet and its retreat. The studies were based on archival cartographic data, coupled with new lithological and petrographic analyses of limni- and fluvioglacial sands, i.e., grain-size composition, quartz grain morphology and heavy mineral analysis, as well as analysis of the erratic material of tills. The results confirm the regional variability of the erratic material in the Sanian 2 tills and point to the long-term development of fluvioglacial sands cover documenting cold climate conditions. They also evidence that the western part of the Holy Cross Mountains was the area where two oppositely directed ice sheet lobes (Radoszyce and Sandomierz) advanced during the Sanian 2 Glaciation and that deglaciation of the area took place in two stages. Huge quantities of meltwater released at that time contributed to the intensification of earlier initiated karst phenomena, as well as filling of the existing caves by fluvioglacial sands.

Key words: Central Poland; Glacial deposits; Cave deposits; Palaeogeography; Middle Pleistocene.

INTRODUCTION

One of the unsolved issues in the studies of the Pleistocene in the Holy Cross Mountains (Text-fig. 1) is the maximum ice sheet extent and deglaciation of the mountains during the last Scandinavian glaciation in the area, i.e., the Sanian 2 Glaciation (see Lindner 1984; Lindner and Dzierżek 2013). So far, this topic was only briefly discussed in the reconstructions of the number and age of Scandinavian ice sheets that covered the western part of the Holy Cross Mountains (Lindner 1977a). Moreover, the subject remained almost unnoticed in the characteristics of Pleistocene strata from the central part of the mountains (compare Ludwikowska-Kędzia 2018a, b). The Sanian 2 Glaciation is the youngest glacial episode within the South Polish Complex, correlated with MIS 12 (Marks *et al.* 2016; Text-fig. 2). After reaching the Holy Cross Mountains, the Sanian 2 ice sheet surrounded their main ranges both from the west and



Text-fig. 1. A – Location of the study area with regard to the maximum extents of the Sanian 2, Odranian and Vistulian glaciations in Poland. B – Study area with location so the study sites (red dots) with regard to the main hill ranges in the western part of the Holy Cross Mountains; a–b line of schematic cross-section (see Text-fig. 9).

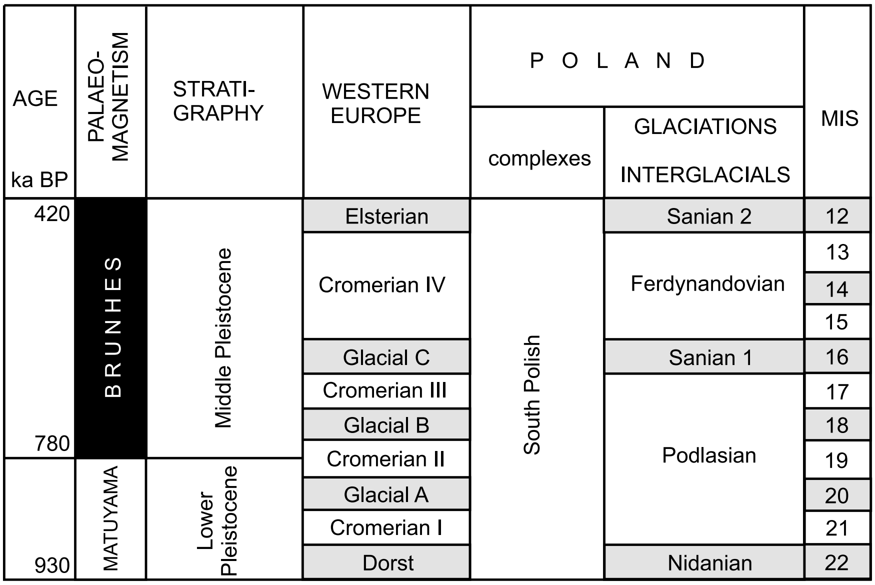
from the east, but did not cover them completely, extending to the Wierna Rzeka river catchment (Lindner 1977a, b). Existing data point to the rather complex and so far incompletely recognised ice sheet advance in the study area.

This paper is aimed at reconstructing the maximum ice sheet extent and the deglaciation mode in the western part of the Holy Cross Mountains during the Sanian 2 Glaciation, with regard to analysis of till and selected kame-type deposits, as well as analysis of karst phenomena and sandy sediments filling the karst forms (compare Urban 2013; Urban *et al.* 2019). The largest focus is posed on the analysis of sandy and sandy-silty sediments from that stratigraphic interval, which occur at higher elevations than the recently described surfaces of valley burial from the Odranian Glaciation (see Dzierżek *et al.* 2019a).

The reconstructed maximum extent and retreat of the Sanian 2 ice sheet was verified by analysis of the Pleistocene strata distribution from detailed geological mapping in the western part of the Holy Cross Mountains (see Hakenberg 1973; Filonowicz and Lindner 1986), as well as MSc projects conducted in the Faculty of Geology of the University of Warsaw in the frame of the Quaternary geology specialization (Pogorzelski 1972; Adaszewski 1973). The lithological-petrographic characteristics of till and fluvioglacial sands are based on newly collected samples.

GEOLOGICAL SETTING

The study area is located in the western part of the Holy Cross Mountains between Kielce to Małogoszcz and between Chęciny and Mniów. The



AGE	PALAEO-MAGNETISM	STRATI-GRAPHY	WESTERN EUROPE	POLAND		MIS
ka BP				complexes	GLACIATIONS INTERGLACIALS	
420	BRUNHES	Middle Pleistocene	Elsterian	South Polish	Sanian 2	12
			Cromerian IV		Ferdynandovian	13
						14
						15
			Glacial C		Sanian 1	16
			Cromerian III		Podlasian	17
			Glacial B			18
780	MATUYAMA	Lower Pleistocene	Cromerian II			19
			Glacial A			20
			Cromerian I			21
930			Dorst		Nidanian	22

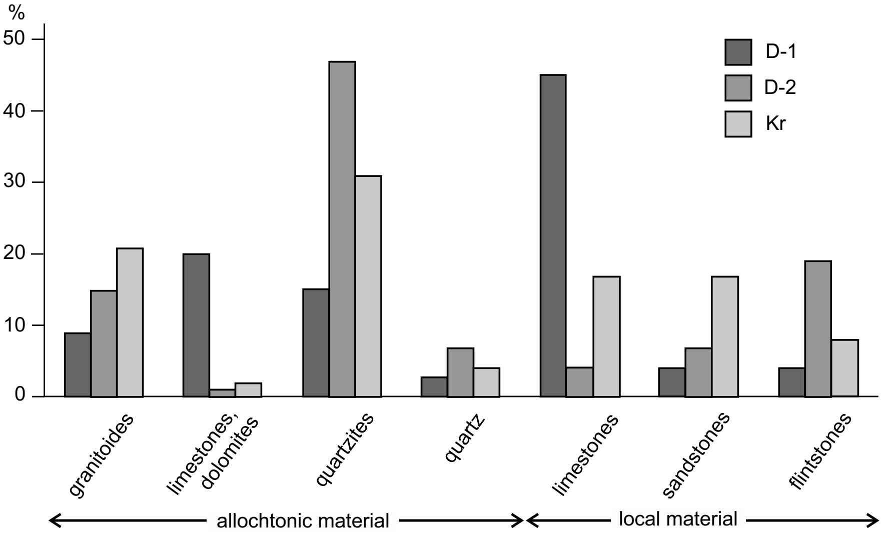
Text-fig. 2. Stratigraphic position of the Sanian 2 Glaciation with regard to the subdivision of the South-Polish Complex, after Marks *et al.* (2016).

area covers the Wierna Rzeka and Bobrza catchments, extending along the Dobrzeszowskie Range, Oblęgorskie Range, Strawczyński Basin, Zgórskie Range and Dymińskie Range, and a series of culminations built of pre-Quaternary rocks in the southern part of this area (Text-fig. 1). The southern limit of the study area encompasses the lower stretch of the Czarna Nida river valley. Pre-Quaternary rocks in this area belong to the Palaeozoic and Mesozoic of the Holy Cross Mountains (Czarnocki 1938; Konon 2008; Konon and Sidorczuk 2015; Skompski 2015). The pattern of geological structures, fault zones and lines, and the lithology of basement rocks largely influenced the course of Quaternary geological processes and the distribution of Quaternary strata (Klatka 1976; Lindner 1977a; Lindner and Mastella 2002). The western part of the Holy Cross Mountains is characterised by the occurrence on the surface, or at small depths below the surface, of tills (or their residua) and sandy sediments forming fluvioglacial plains or morphological horizons in the Wierna Rzeka and Bobrza river valleys (Dzierżek *et al.* 2019). Loess covers were observed near Oblęgorek, Grzywy Korzeczkowskie Range and Zgórskie Range (Hakenberg 1973; Filonowicz and Lindner 1986). The lowermost horizons in river valleys are composed of sands and gravels of ancient river terraces from the Vistulian Glaciation and the Holocene (Krupa 2015; Kalicki *et al.* 2018; Lindner and Dzierżek 2019).

MATERIAL AND METHODS

The studies are based mainly of earlier detailed mapping surveys (Hakenberg 1973; Filonowicz and Lindner 1986) and field studies (Lindner 1977a, 1984; Lindner and Braun 1974; Lindner and Kowalski 1974), supplemented with the most recent reports on earlier unrecognised geological exposures (Lindner and Dzierżek 2013, 2019; Cabalski *et al.* 2018; Lindner *et al.* 2019).

Analysis of archival data was followed by field work enabling the collection of new material for laboratory analysis. Six sites with surface sediments: Widoma, Dobrzeszów, Zawada, Miedzianka, Polichno, Kresy, and two sites with cave sediments: Chelosiowa Jama cave, belonging to the cave system of Chelosiowa Jama–Jaskina Jaworznicka caves, and Jaskinia Pajęcza cave in Jaworznia Quarry (Kopaczowa Hill), were selected for the analysis (Text-fig. 1; compare Urban 1996; Kasza and Urban 2016). The sites were chosen in areas where the Sanian 2 sediments are well preserved and have a well defined stratigraphic position. The spread of sites in the studied area (see Text Fig. 1) gave a more chance to find regional differences in the characteristics of the studied sediments. The cave sites were chosen because of the relatively easy accessibility of the Chelosiowa Jama–Jaskinia Pajęcza caves and the presence of alluvial material in them. The characteristics of sediments were determinate based on the



Text-fig. 3. Petrographic composition of the 5-10 mm fraction in tills from the Dobrzeszów (D-1 and D-2) and Kresy (Kr) sites.

following methods: grain size analysis, analysis of heavy minerals, analysis of quartz grains and petrographic analysis of glacial erratics. The type of analysis was adapted to the type of deposits and quality of the obtained material.Therefore, the descriptions of the results for individual sites differ.The samples were collected from core samplers, exposures and excavations (in the caves). Grain-size analyses and grain-size indexes were prepared after Folk and Ward (1957) for 34 samples (Appendix 1); analysis of the roundness and matting of quartz grain surfaces was prepared for 22 samples (Table 1) according to the methodology of Mycielska-Dowgiałło and Woronko (1998). Petrographic analysis was made for 5–10 mm fraction grains from three till samples (Text-fig. 3). Macroscopic identification of the lithological types was conducted after Lisicki (2003). Particular focus in the petrographic analysis was drawn on the identification of fragments of Lithothamnium limestones (see Text-fig. 4), exposed to the south of the study area (Głazek *et al.* 1976a).

Heavy mineral analysis was conducted for 10 sand samples collected at the cave sites (Chelosiowa Jama and Jaskinia Pajęcza caves, see Text-fig. 5) and at the Zawady site located in the vicinity of Jaworznia. The samples were etched in 10% acetic acid to remove calcium carbonate, and then sieved to obtain the 63–250 µm fraction and washed in an ultrasonic washer. The heavy minerals were separated by centrifuging in sodium tungstate (2.9 g/cm^3) and retrieved by partial freezing with liquid nitrogen. A total of 200–300 grains was determined in each sample. The grains were counted using the ribbon method (Galehouse 1971) and presented as percentage contributions (Table 2). The degree of rounding was determined based on the scale suggested by Powers (1953). The weathering degree was established following the criteria proposed by Andò *et al.* (2012). The ZTR index, known as the maturity index (Hubert 1962), is expressed by the following formula:

$$ZTR = \frac{\%Zircon + \%Toutmaline + \%Rutile}{\%Transparent\ Heavy\ Minerals}$$

The GZi index (a provenance-sensitive parameter; Morton and Hallsworth 1994) is expressed by the following formula:

$$GZi = \frac{\%Garnet}{\%Garnet + Zircon}$$

The values of these indexes for the analysed heavy mineral samples are presented in Table 3 and Text-fig. 6. A more favourable interpretation of the variability of cave and surface mineral associations was achieved by the Z index, which calculates the number of standard deviations from the mean content of a given mineral phase in the sediment (Text-fig. 7). The Z index is expressed by the following formula:

$$score_{i,z} = \frac{x_{i,z} - mean_i}{sdev_i}$$

where:
$x_{i,z}$ – number of minerals of type *i* from sample *z*,
$mean_i$ – mean content of minerals of type *i*,
$sdev_i$ – standard deviation for minerals of type *i*.

Site	Sample place and depth	NU	EL	RM	EM/RM	EM/EL	Other	C
		fresh, angular	well-rounded, shiny	well-rounded, frosted	partially rounded, frosted	partially rounded, shiny		fractured
Widoma	W-1 0.5-0.8	30	0	3	57	0	8	2
	W-2 0.5-0.8	22	0	9	53	0	13	3
Dobrzeszów	D-3 1.2-1.5	2	3	7	40	27	15	6
	D-4 1.2-1.4	8	2	12	46	11	14	7
	D-4 1.8-2.1	4	2	19	42	15	12	6
Miedzianka	Mi 0.8-1.0	0	0	30	60	3	6	2
	Mi 2.8-3.0	1	0	33	56	4	5	1
	Mi 3.6-3.8	2	0	23	61	4	8	2
Polichno	P-1 0.5-0.6	0	0	27	63	3	6	1
	P-1 2.0-2.2	0	0	33	60	1	5	1
	P-1 3.6-3.7	0	0	29	64	1	5	1
	P-2 0.6-0.7	0	0	27	62	2	8	1
Zawada	Z-1 1.0-1.2	1	0	36	47	7	5	4
	Z-1 1.7-1.8	2	0	37	49	4	6	2
	Z-2 0.5-0.6	1	0	23	71	2	3	0
	Z-2 1.2-1.6	2	0	25	61	5	5	2
Chelosiowa Jama Cave	Chel-1 0.2-0.3	2	0	15	69	3	9	2
	Chel-1 0.5-0.6	3	0	16	64	2	14	1
	Chel-2 0.4-0.5	1	0	11	73	4	11	0
Pajęcza Cave	Paj-1 0.3-0.4	1	0	10	77	2	9	1
	Paj-1 0.7-0.8	0	0	15	76	1	7	1
	Paj-1 1.1-1.2	2	0	10	78	3	7	0

Table 1. Quartz grains characteristics in selected sites of the western part of the Holy Cross Mountains. See Text-fig. 1 for location of sites.

Sample place and depth	Olivine	Apatite	Augite	Hornblenda	Garnet	Andalusite	Sillimanite	Kyanite	Staurolite	Zoisite	Clinozoisite	Epidote	Zircon	Tourmaline	Rutile	Others
Chel-1, 0.2-0.3	2.9	1.9	2.9	22.1	2.9	4.8	1.9	2.9	9.6	1.0	5.8	4.8	12.5	18.3	0.0	5.8
Chel-1, 0.5-0.6	4.1	3.2	0.5	10.6	10.1	13.4	1.4	2.3	12.9	0.9	2.8	3.7	8.3	21.7	2.8	1.4
Chel-2, 0.4-0.5	0.8	5.5	0.8	3.9	10.9	13.3	2.3	0.8	18.0	0.8	3.1	3.9	9.4	21.1	0.8	4.7
Paj-1, 0.3-0.4	2.9	0.5	1.0	5.3	15.0	7.7	2.4	1.4	15.5	1.0	3.9	1.0	18.8	14.5	1.0	8.2
Paj-1, 0.7-0.8	2.2	2.5	1.8	4.0	22.9	0.7	0.0	1.8	11.6	1.8	3.3	3.3	22.5	12.0	3.6	5.8
Paj-1, 1.1-1.2	0.6	2.6	1.3	11.7	11.7	5.2	0.6	3.2	16.9	0.6	1.9	3.9	11.7	20.1	2.6	5.2
Z-1, 1.0-1.2	1.5	0.0	3.8	0.8	45.9	8.3	1.5	0.8	9.8	0.0	2.3	6.8	5.3	12.0	0.0	1.5
Z-1, 1.7-1.8	4.4	1.8	4.0	4.9	32.4	4.9	0.4	0.4	8.9	0.0	1.8	5.3	15.6	12.4	0.0	2.7
Z-2, 1.2-1.6	0.0	2.4	2.0	9.3	24.4	3.9	2.0	2.4	9.3	0.5	7.8	7.3	14.6	10.2	2.0	2.0
Z-2, 0.5-0.6	1.5	1.0	0.5	1.5	39.1	3.0	3.0	1.5	16.3	1.5	1.0	3.5	7.9	12.9	3.0	3.0

Table 2. Percentage contribution of heavy minerals in the sand sediments of Chelosiowa Jama cave (Chel-1, Chel-2), Jaskinia Pajęcza cave (Paj-1) and Zawada (Z-1, Z-2).

Grain size analysis, analysis of quartz grains and petrographic analysis were performed by Krzysztof Cabalski; analysis of heavy minerals – Michał Cyglicki, analysis of carst phenomena Jan Urban, the field work – Krzysztof Cabalski, Jan Dzierżek, Jan Urban; the concept, interpretation of archival materials – Leszek Lindner; all authors took part in the discussion and interpretation of the results.

RESULTS AND DISCUSSION

Features of subsurface sandy sediments

Widoma (Text-fig. 1)

The Widoma site is situated on the southern slope of Barania Hill in the Oblęgorskie Range. Two short

Sample place and depth	ZTR	GZi
Chel-1, 0.5-0.6	30.8	19
Chel-1, 0.2-0.3	32.7	55
Chel-2, 0.4-0.5	31.3	54
Paj-1, 0.3-0.4	34.3	44
Paj-1, 0.7-0.8	38.2	50
Paj-1, 1.1-1.2	34.4	50
Z-1, 1.0-1.2	17.3	90
Z-1, 1.7-1.8	28.0	68
Z-2, 1.2-1.6	26.8	63
Z- 2, 0.5-0.6	23.8	83

Table 3. Relationship of the maturity index (ZTR) and the provenance-sensitive parameter (GZi) for samples collected in Chelosiowa Jama cave (Chel-1, Chel-2), Jaskinia Pajęcza cave (Paj-1) and Zawada (Z-1, Z-2). For further explanations, see text.

cores were drilled here with a hand core sampler in medium-grained and silty sands: W-1 at the elevation of 385 m a.s.l. and W-2 at the elevation of 380 m a.s.l. In both cores, light yellow fine-grained Triassic sandstones were encountered at the depth of about 0.8 m. Grain-size analysis indicated poor sorting and a normal distribution. Partially-rounded, frosted grains (EM/RM) dominate (57%), with a considerable admixture (over 30%) of fresh angular grains (NU) (Table 1). These features indicate long-term weathering of rocks in surface conditions.

Dobrzeszów (Text-fig. 1)

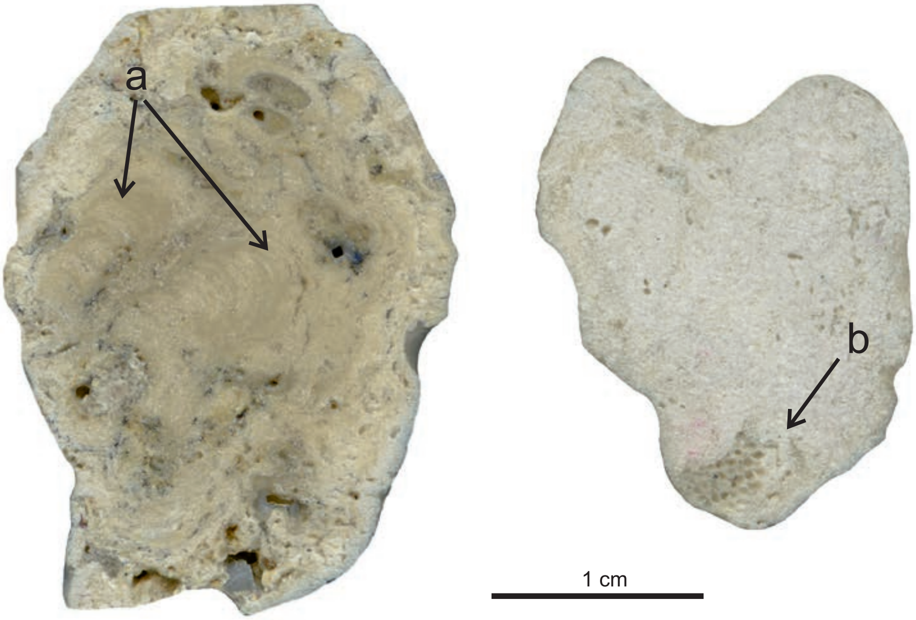
Four cores were abtained at about 2 km to the SE of Dobrzeszowska Hill in the Dobrzeszowskie Range. Samples for petrographic analysis of the gravel fraction from till (see below) were collected from cores D-1 (268 m a.s.l.) and D-2 (270 m a.s.l.) located on a flat surface built of till located below a moraine hill (for results description see next paragraph). Drilling D-3 was located at an elevation of 275 m a.s.l. directly beneath the moraine hill from the east, and drilling D-4 was situated on the peak of this hill at an elevation of 278 m a.s.l. Fine-grained sand with moderate sorting (σ – 0.80) and a normal grain-size distribution (Appendix 1) occurs in depth interval 1.2–1.5 m in drilling D-3. It is dominated by EM/RM quartz grains (40%), at high contribution of EM/EL grains (27%). Medium-grained sand, poorly or moderately sorted with a normal and slightly positive grain-size distribution (Appendix 1) prevails in drilling D-4. Partially-rounded, frosted grains (EM/RM over 40%) dominate, and the contribution of well-rounded, frosted (RM) and partially-rounded shiny (EM/EL) grains varies at the level of over a dozen percent for each grain type. Fresh angular grains (NU) also occur (8%). Fractured grains (C) contribute to about 7% (Table 1). The substantial content of shiny and sub-angular grains points to admixture of local material from the weathering covers of local Lower Triassic sandstones.

Miedzianka (Text-fig. 1)

A 3.8 m section was measured above the northern margin of a sand pit located at about 301 m a.s.l. on the southern slope of Miedzianka Hill. The results of grain-size, roundness and matting analysis of quartz grains supplement earlier data on this site (Lindner 1977b; Lindner and Kowalski 1984). Sands covering the slope of Miedzianka Hill, studied in 7 samples, are usually fine-grained (being medium-grained at the level of c. 1 m) and moderately sorted (σ at 0.73–0.84; Appendix 1). Quartz grains analysed in 3 samples are dominated with partially-rounded, frosted grains (c. 60%), at a significant admixture of well-rounded, frosted grains (RM) at the level of 23–30% in the upper part of the section. The content of partially-rounded shiny grains (EM/EL) is at 3–4% (Table 1). Features of these deposits point to calm sedimentary conditions in an aqueous regime and the significant influence of eolian processes during their deposition.

Polichno (Text-fig. 1)

Fine- and medium-grained sands, in places with silty interbeds, are exposed in a 5 m high sand pit wall in Polichno (behind the school). The sand pit margin is located at c. 265 m a.s.l. Five samples (P-2 and P-3) were collected from the upper part of the exposure from depths between 0.5 and 1.5 m (Appendix 1). The grain-size indexes indicate moderately to poorly sorted sediments (σ at 0.83–1.11), with a slightly to strongly positive distribution (Appendix 1). Partially-rounded, frosted grains (EM/RM – 63%) and well-rounded, frosted grains (RM – 27%) dominate in the subsurface layer, which indicates strong influence of eolian processes (Table 1). A hand probe was drilled down to 3.9 m (P-1) in the floor of the sand pit (c. 260 m a.s.l.). Sands occur to the depth of 3.6 m, whereas sandy silt and a brown silty till with sand and debris of Muschelkalk limestones were noted below. The sandy sediment is composed of fine grains and is usually poorly sorted (σ at 1.15–1.45). Silty sand occurs at the depth of 2.7 m. The downwards decreasing grain diameter is marked in grain-size parameters at the depth of 3.7 m, where the sandy silt is characterised by very poor sorting (σ at



Text-fig. 4. Fragments of Lithothamnium limestone from tills in Kresy, a – rodoids; b – textures after bryozoans.

2.68) and a strongly negative grain-size distribution (Appendix 1). The quartz grain features are similar as in the sand pit wall; partially-rounded, frosted grains (EM/RM – 64%) dominate, with a significant content of rounded, matted grains (above 30%) also in the lower part of the section (Text-fig. 1).

Zawada (Text-fig. 1)

The analysed sections were located on a hill pass (c. 300 m a.s.l.) on the SE side of Plebańska Hill being the extension of the Zgórskie Range. The sandy deposits were analysed in two short sections Z-1 and Z-2, from which 4 samples were collected. Close to the surface occurs medium-grained, moderately sorted sand (σ at 0.95). Below, the sand is poorly sorted and in section Z-2 the grain size decreases (Appendix 1). Partially-rounded, frosted grains dominate (47–71%), but the content of RM grains is considerable, up to 37% particularly in section Z-1 (Table 1).

Petrographic composition of the tills

Dobrzeszów (Text-fig. 1)

The till building the surface to the SE from the moraine hill in Dobrzeszów was analysed in two sections, up to 2.1 m long (D-1 and D-2), for the petrographic composition of the gravel fraction (5–10 mm). Due to low content of gravel material, the samples were taken from 70–100 cm manually drilled cores. The petrographic composition of sample D-1 is dominated by fragments of local limestones and marls of Mesozoic age (48%), at the contribution of crystalline rocks below 10% (Text-fig. 3). Till from sample D-2 is dominated by allochtonic sandstones and quartzites (47%) at insignificant contribution of local rocks. Crystalline rocks contribute to 15% of the gravel fraction.

Kresy (Text-fig. 1)

The Kresy site (244 m a.s.l.) is situated in the floor of a vast depression built of till located to the SW of the Grząby Bolmińskie Range. Material for petrographic analysis of the gavel fraction (5–10 mm) was taken from the depth of 1.2–2.1 m from a manually drilled core. The samples are dominated by quartzites (c. 30%), and the contribution of crystalline rocks and Mesozoic limestones is similar, at c. 20%. Worth emphasising is the presence of fragments of Lithothamnium limestones (2–3 cm in size) in the till (Text-fig. 4).

Analysis of karst phenomena

Substantial parts of the southern and south-eastern segment of the study area are built of Middle and Upper Devonian carbonate rocks, in which karst forms developed during the terrestrial stages of the Cenozoic. Fragments of the oldest, probably Palaeogene karst systems include the caves of Miedzianka and Milechowska hills located at the highest elevations (305–325 m a.s.l.). These systems, which by the end of the Neogene were preserved only fragmentarily and mostly filled with sediments, did not play a significant role in the Pleistocene geological and morphological evolution of the area (Urban 1996, 2002). The Kozi Grzbiet palaeontological site, which was washed out and infilled during the oldest glaciations covering the Holy Cross Mountains area, is the example of the lower karst system of Miedzianka Hill (c. 275 m a.s.l.) (e.g. Głazek *et al.* 1976b, 1977, 1978; Kowalski 1989; Urban *et al.* 2019).

In turn, the Neogene karst system that developed within the zone of Devonian dolomite and limestone exposures building the southern limb of the Kielce Syncline, to the north of the Zgórskie Range, played a significant hydrogeological role in the Pleistocene. This maze karst system developed horizontally at the elevation of 250–260 m a.s.l., connecting with the upper and lower systems along steep conduits. By the end of the Neogene, the system was filled mostly with sediments; in turn, in the Pleistocene intervals of intense water flow during ice sheet development and retreat, it constituted an underground channel transporting water eastwards, to the Bobrza valley and Słowik gap, or westwards, to the Hutka and Wierna Rzeka river valleys (Urban *et al.* 2019). The latter is evidenced by numerous karst sinkholes and ponors preserved between Miedzianka and Jaworznia, particularly the caves Jaworznia (Kopaczowa Hill) which are fragments of this system partially devoid of sediments, i.e. the Chelosiowa Jama–Jaskinia Jaworznicka cave system with a length of 3670 m and height difference of 61 m, and the Jaskinia Pajęcza cave with a length of 1183 m and height difference of 26 m (Text-figs 5 and 9; Urban and Rzonca 2009; Urban 2013; Kasza and Urban 2016).

Characteristics of cave sediments

Two excavations were made in the alluvial sediments of Chelosiowa Jama cave (SW part of the Chelosiowa Jama–Jaskinia Jaworznicka cave system; Urban 1996, 2013; Kasza and Urban 2016) in the Trójkąt gallery (Text-fig. 5). Excavation Chel-1 was localised at the mouth of Piaskowa Szczelina fissure, at the elevation of about 244 m a.s.l. The samples were collected from depth intervals 0.2–0.3 m and 0.5–0.6 m below the cave floor. The second excavation was localised close to the sinkhole margin near the line of periodical water flow, at an elevation of about 243 m a.s.l. One sample (Chel-2) was collected from a depth interval 0.4–0.5 m, below the cave floor.

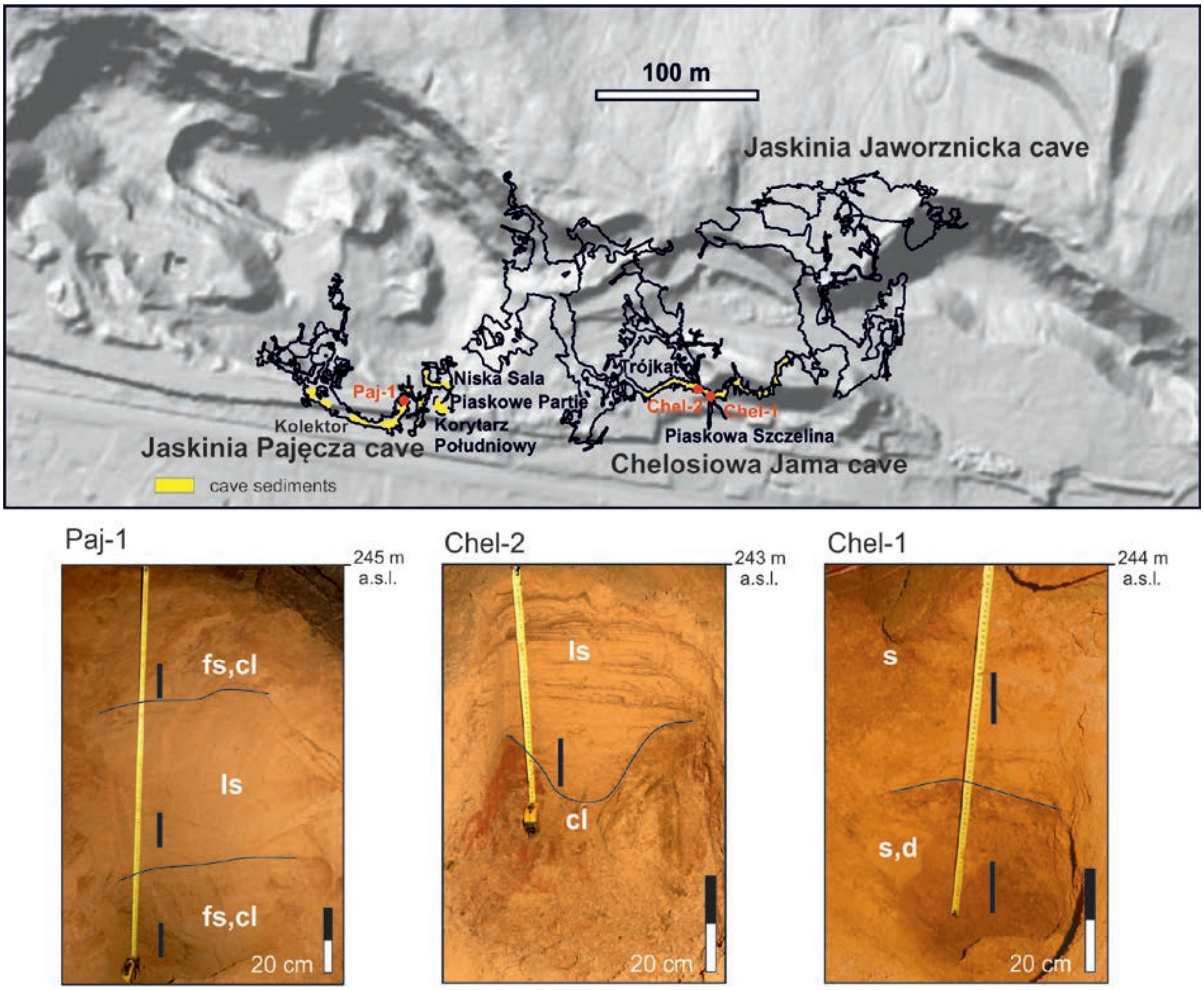
The Chel-1 section is dominated by light yellow fine-grained sand to the depth of 0.4 m. Below occur irregular intercalations of grey-brown silt with calcite debris, which begin to dominate at 0.6 m, hampering deeper excavation (Text-fig. 5). Sorting is from moderate (σ at 0.83) at the depth of 0.2–0.3 m to poor (σ at 1.23) at the depth of 0.5–0.6 m, and the grain-size distribution is symmetrical and slightly positively skewed, respectively (Appendix 1).

The Chel-2 section (Text-fig. 5) is characterised by light yellow medium-grained sand with lamines of brown silt to the depth of 0.5 m, and pink clay below. Sorting is moderate (σ at 0.88) and the grain-size distribution is symmetrical (Appendix 1).

In Jaskinia Pajęcza cave, the samples (Paj-1) were collected from an excavation localised at the beginning of the Kolektor gallery at an elevation of about 245 m a.s.l. Three samples were collected from the depths of 0.3–0.4 m, 0.7–0.8 m and 1.1–1.2 m. The artificially oucropped succession starts at a depth of 1.3 m with light yellow sand bearing irregular intercalations (zones and stains) of light brown clayey sand (Text-fig. 5). Sorting in the lowermost part is poor (σ at 1.02) and the grain-size distribution is slightly positively skewed (Appendix 1). Above, from a depth of 0.9 m occurs light yellow sand with thin lamines of light brown clayey sand. The lamines dip at 23° to the south, in an opposite direction than the gallery slope, i.e., towards its entrance into the larger chamber. The uppermost part of succession is represented by a 0.5 m thick layer of light yellow fine-grained sand with irregular intercalations of light brown clayey sand. Sorting is moderate (σ at 0.76–0.78) and the grain-size distribution is slightly positively skewed. Larger intercalations of clayey sand occur at the base of this layer. Analysis of quartz grains (Table 1) indicates that partially-matted grains occur in sands of both caves (60–70%), with the contribution of rounded, matted grains at the level of c. 15%.

Development and origin of sandy cave alluvia

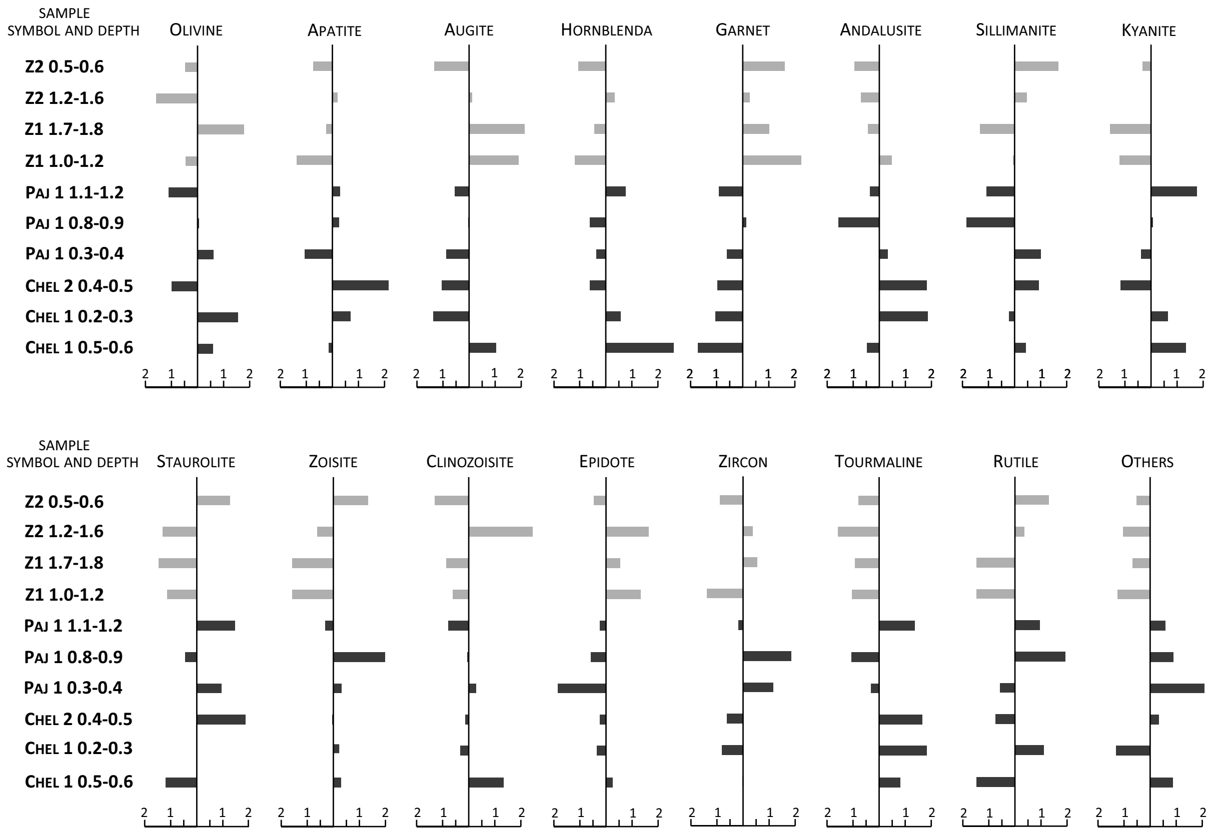
The upper (accessible for observations) part of the alluvia in Chelosiowa Jama cave is dominated by cherry-red clay and clay-debris deposits. This is caused by the fact that the cave is located in the northern part of a Devonian limestone massif of Kopaczowa Hill, close to the fault separating this massif from the Lower Triassic clay-silty depos-



Text-fig. 5. Selected lithological columns of cave sediments with regard to the corridors of the Chelosiowa Jama (Chel-1, Chel-2) and Jaskinia Pajęcza (Paj-1) caves near Jaworznia. Lithological symbols: s – sand; fs – fine-grained sand; ls – laminated sand; cl – clay, d – calcite debris. Black line indicates sample locality.

its that initially covered this massif (forming the peak of Kopaczowa Hill). In the southern part of Chelosiowa Jama cave, in the Trójkąt gallery, beige sands occur at an elevation of about 142–145 m a.s.l. (Text-fig. 5); they seem to be fairly recently (in the Holocene) washed out from lateral fractures, probably reaching to the ancient valley near Jaworznia village. The Chelosiowa Jama cave samples were collected from these sands, which cover the loam or debris deposits (with dripstone debris from the Middle Polish Glaciations). Older Chelosiowa Jama cave deposits were washed out during the Middle Polish Glaciations, as evidenced by the undercutting of dripstones of this age (Urban *et al.* 2019). Their relicts are probably preserved in the lower part of the alluvium.

Jaskinia Pajęcza cave represents part of a karst system developed more to the south compared to the Chelosiowa Jama cave (Text-fig. 5) and therefore it contains less deposits linked with the weathering of Triassic claystones and siltstones, being dominated by beige brown sandy-loamy and sandy alluvia. The occurrence of these alluvia in a wider range (243–255 m a.s.l.) of elevation and variable contexts (e.g., below boulder fields) points to their variable age. However, mechanical destruction of dripstones from the Middle Polish Complex suggests significant washing out also of this system. The sand succession from which samples were collected seems older than the last mechanical transformations of the cave, because it does not match the morphology of the surroundings: the dip of sand lamines is opposite to the dip of the gallery



Text-fig. 6. Vertical bar chart of standardised percentage scores for each heavy mineral species in Chelosiowa Jama cave (Chel-1, Chel-2), Jaskinia Pajęcza Cave (Paj-1) and Zawada (Z-1, Z-2). The Z index points to the number of standard deviations from the mean content of particular mineral species in the sediment. For further explanations, see text.

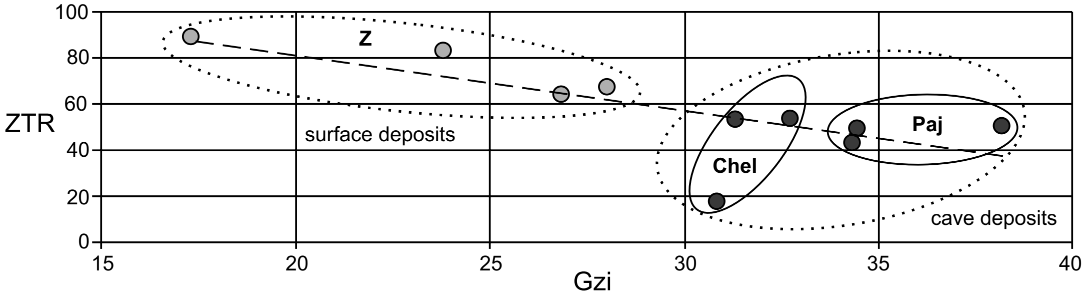
floor, but also opposite to the present-day morphology of the alluvial sediments. The laminated deposit may represent a micro delta located in the mouth of an underground stream to an underground palaeolake.

The underlying deposits in Jaskinia Pajęcza cave are poorly sorted. The morphological features and mineral composition (Text-fig. 6) of the cave sand grains (Chel-1, Chel-2 and Paj-1) are generally similar to the surface sediments from the nearby Zawady (Z) site. The Pearson's correlation coefficient calculated from the ZTR and GZi indexes is 0.7 and shows a strong negative correlation between these indexes (Text-fig. 7; Table 2). Differences between these two sediment types most probably result from initial (surface) transformation of the heavy mineral association, during transport to the karst system, and as a result of chemical weathering during deposition in this system in a karst setting. Garnet grains are generally better rounded in the cave sediments than in the surface sediments from Zawada. Another difference is the presence of structures indicating eolian activity in the surface sediments. The relatively lower contribution of rounded, matted grains in cave sediments at slightly over 10% indicates a lower impact of the eolian factor in their transport and shorter frost weathering influenced by diurnal and seasonal changes, because cave sediments were not affected by such processes after being washed into the karst system.

The reason for a similarly lower (as in the caves) contribution of rounded, matted grains in the Dobrzeszów and Widoma sands is completely different, as indicated by the relatively high contribution of shiny, angular and partially-rounded grains in samples from these localities. Such roundness results from a local source of part of the material, i.e., Lower Triassic sandstones.

Heavy mineral composition

The analysed mineral associations in the sediments from Chelosiowa Jama and Jaskinia Pajęcza



Text-fig. 7. Relationship between the maturity (ZTR) index and the provenance-sensitive parameters (GZi) for minerals from cave sediments in Chelosiowa Jama (Chel-1, Chel-2) and Jaskinia Pajęcza (Paj-1) caves, and surface sediments in Zawada (Z-1, Z-2). For further explanations, see text.

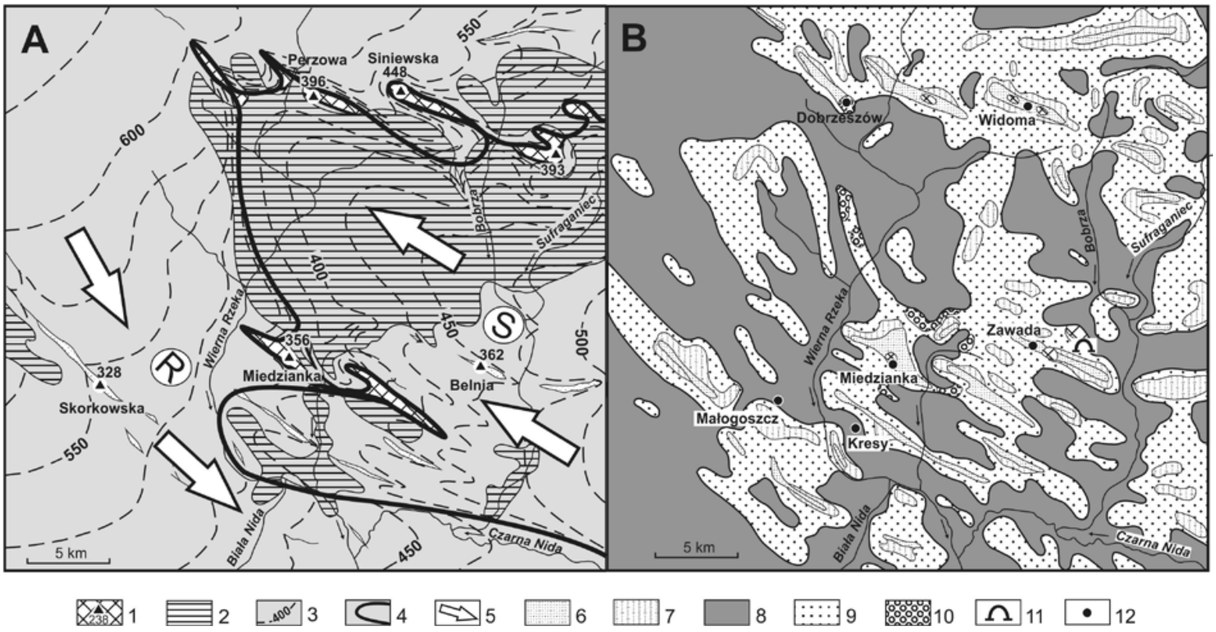
caves, and Zawada site contain all 15 types of distinguished heavy minerals (Table 2), which are moderately to well rounded. Some minerals occur in similar proportions both in cave and surface sands, e.g., sillimanite, zoisite and augite. Differences appear in the degree of weathering of the unstable mineral grains. Samples from the Chelosiowa Jama and Jaskinia Pajęcza caves are characterised by numerous weathering structures on amphibole and pyroxene grains. The garnet content decreases distinctly (Text-figs 6 and 7; Table 2); numerous mammals-type structures that formed due to chemical weathering can be observed on their surfaces. Moreover, the samples are dominated by non-transparent iron oxides and hydroxides, which could be formed at the expense of garnets (Hansley and Briggs 1994; Mange and Wright 2007). The ZTR maturity index is higher (at 30–38) in the cave samples. In turn, the GZi index decreases to 19–50 (Text-fig. 6; Table 3). Considerable drop of garnet abundance is coupled with the increased abundance of zircon, tourmaline and rutile grains, which are ultrastable during chemical weathering. An opposite trend may be observed among the mineral associations from the Zawada site. Transparent minerals dominate, among which the prevailing ones are garnets (Text-fig. 7; Table 2). Traces of chemical corrosion of the grains are rare. The ZTR index is at 17–28 and the GZi index – at 60–90 (Text-fig. 6; Table 3).

PALAEOGEOGRAPHIC EVOLUTION

In the stratigraphic scheme for the Pleistocene of Poland (Text-fig. 2), the Sanian 2 Glaciation separates the Ferdynandovian Interglacial (MIS 15–13) from the Mazovian Interglacial (MIS 11). Its equivalents are the Elsterian Glaciation in western Europe and the Okanian Glaciation in eastern Europe (Gozhik *et al.* 2012). In Poland the ice sheet of this glaciation had a smaller extent than the older ice sheet of the Sanian 1 Glaciation (MIS 16) which reached the Carpathians (Marks *et al.* 2016). The Sanian 1 deposits, earlier referred to as the older stage of the South Polish Glaciation (Lindner 1977a), are fragmentarily preserved in the study area. They have been determined in deep drillings and a few exposures (in the upper section of the Bobrza river valley). Both in the Wierna Rzeka and Bobrza catchments, patches of till from this glaciation underlie thick silty-sandy deposits of ice-dammed accumulation preceding the advance of the Sanian 2 ice sheet. These deposits, as well as the strata of the older Nidanian Glaciation (Text-fig. 2), are not the scope of this paper.

The presence of large amounts of glacial erratics of local origin (Lithothamnium limestones, Sarmatian sandstones, and fragments of Devonian sandstones and Cambrian quartzites) is characteristic for the tills of the Sanian 2 Glaciation occurring in the western part of the Holy Cross Mountains, uptaken by the contemporary ice sheet from the southern foreland and central part of the Holy Cross Mountains. This fact was observed for the first time by Siemiradzki (1888) and Michalski (1888), and their successors, e.g., Czarnocki (1931), Różycki (1967), Głazek *et al.* (1976a) and Lindner (1977a, 1995). The presence of Lithothamnium limestones in the gravel fraction of the till was noted in Kresy, in the SW part of the study area (Text-figs 1 and 4).

Detailed mapping and geological surveys in the area, conducted by Hakenberg (1973) and Filonowicz and Lindner (1986), allowed for a precise recognition of the Sanian 2 till extent and of the sand and gravel occurrence marking the deglaciation in the western part of the Holy Cross Mountains. These deposits not only enabled the reconstruction of the maximum extent of the ice sheet in the area but also recognition



Text-fig. 8. Palaeogeographic sketch-map of the western part of the Holy Cross Mountains (A) during the maximum extent of the Sanian 2 ice sheet and (B) during the second deglaciation stage (after Lindner 1977a, substantially changed). Explanations: 1 – elevations built of pre-Quaternary rocks and their altitude in m a.s.l.; 2 – sub-till ice-dammed reservoirs; 3 – surface of ice sheet lobes: R – Radoszyce and S – Sandomierz in m a.s.l.; 4 – extent of ice sheet lobes; 5 – directions of ice sheet propagation; 6 – areas of kame accumulations during the first deglaciations stage; 7 – till surfaces; 8 – dead glacial ice; 9 – areas of kame accumulation during the second deglaciation stage; 10 – dead ice moraines; 11 – Chelosiowa Jama–Jaskinia Jaworznicka cave system; 12 – sites mentioned in text.

of two deglaciation stages in the western part of the Holy Cross Mountains

Maximum extent of the ice sheet

Earlier collected data (Lindner 1977a, b), mapping and geological surveys (Hakenberg 1973; Filonowicz and Lindner 1986) and recent field studies, coupled with the palaeogeomorphological analysis of the ice-dammed series underlying the Sanian 2 till and the extent of this till, were used to reconstruct the maximum extent of the Sanian 2 ice sheet (Text-fig. 8). The till preserved in the western and north-western part of the study area clearly differs in the petrographic composition of the gravel-cobble fraction from till of contemporary age in the central-eastern part of the study area. This till does not contain rocks representing the marine Neogene or the Palaeozoic of the Holy Cross Mountains. Apart from Scandinavian material, the fine gravel and rubble fraction of the till contains fragments of silicified Jurassic limestones, Cretaceous decalcified sandy spongiolites and silicified limestones, a well as a considerable content of Lower Triassic sandstones. The 5–10 mm fraction in Dobrzeszów (Text-fig. 3) is dominated by local limestones, followed by quartzites and quartzitic sandstones. Section D-2 is dominated by quartzite, quarzitic sandstones and flintstones, with a contribution of crystalline rocks at the level of 15%.

Till marking the maximum extent of the Sanian 2 ice sheet in the eastern and south-eastern part of the study area, beside Scandinavian material contains erratics of Neogene (Lithothamnium limestones and Sarmatian marls) and Palaeozoic rocks (Devonian sandstones and limestones, and Cambrian quartzites). Neogene erratics have been recognised e.g., in till on Sitki Hill near Chęciny (Głazek *et al.* 1976a), in deep excavations cutting this till in Kielce–Cegielnia (Łyczewska 1971), in numerous drillings made near Karczówka, Skiby and Wolica (Pogorzelski 1972; Lindner 1977a), and presently also in Kresy (Text-fig. 4), which is an important data for palaeogeographic interpretations. Tills with Neogene erratics cover the culminations of the Piekoszów Elevation (Strawczynek, Promnik, Micigózd) and reach westwards to the Korczyn–Piotrowiec line (Czarnocki 1931; Lindner 1977a; Filonowicz and Lindner 1986).

As indicated by mapping and geological surveys

(Hakenberg 1973; Filonowicz and Lindner 1986), the extent of the Sanian 2 glacial till is much larger in the study area compared to the extent of older tills (Lindner 1977a). The till occurs in almost all depressions separating the main morphological elevations, and even covers their slopes and lower elevations, which earlier were not within the range of the Sanian 1 Glaciation (Lindner and Dzierżek 2013). Following the opinion of Czarnocki (1927), the elevations at which this till occurs do not exceed 300–320 m a.s.l. Above, till gradually passes into muddy-cobble or cobble-sandy deposits with Scandinavian material displaced by the upper parts of the ice sheet (slopes of Dymińskie Range, Dobrzeszowska and Kamień hills). After Czarnocki (1927), these sediments may represent residua of this till. Our observations have shown that in several contexts these deposits gradually pass into reworked weathering debris-loam covers with local rocks and sporadic fragments of red granites (eastern part of the Dymińskie Range). Therefore, it seems possible that these deposits, as well as part of the overlying reworked weathering debris-loam covers (up to 350 m a.s.l.), may be traces of the exaration-accumulative activity of the highest parts of the ice sheets, minimally loaded with basal moraine material. Similar cases of lateral transition of a typical till into a chaotic loamy-debris material are known from the marginal parts of the Sanian 1 ice sheet extent in the Carpathians (Łoziński 1909; Wójcik 2003) and the Odranian ice sheet extent in the north-western Mesozoic margin of the Holy Cross Mountains (Lindner 1971).

In the western part of the Holy Cross Mountains, tills of the Sanian 2 Glaciation are preserved at the elevations of 320–270 m a.s.l. and usually are thinner (1–3 m) than tills of the same age within valley depressions (250–210 m a.s.l.), where their thickness reaches up to 10 m. The distribution and petrographic composition of the gravel fraction of this till in the north-western and south-western part of the study area confirm the opinion of Różycki (1972) on the sub-division of the Radoszyce lobe into a northern part, passing above the pre-Quaternary basement elevations near Mniów and the main culminations of the Oblęgorskie Range (Perzowa, Siniewska, and Kamień hills), and the southern part rather smoothly moving towards the south-east (to the south of Miedzianka; Text-fig. 8A). In turn, the distribution and petrographic composition of the tills from the central and eastern part of the study area point to the earlier suppositions (compare Siemiradzki 1988; Czarnocki 1931; Łyczewska 1971; Różycki 1972; Lindner 1977a, 1995) about the advance of the Sandomierz lobe carrying Neogene and Palaeozoic material from the south-eastern foreland and central part of the Holy Cross Mountains. In the frontal part, this lobe could have been sub-divided into two smaller parts (Text-fig. 8A).

The presence of ice-dammed deposits underlying till in the central part of the study area – particularly in the Wierna Rzeka catchment and the northern part of the Bobrza catchment (Text-fig. 8A) – seems to suggest an earlier advance of the marginal part of the Radoszyce lobe onto this area and thus hamper further westward shift of the sub-till ice-dammed reservoir forming in front of the slightly younger Sandomierz lobe advancing from the south-east.

The reconstructed maximum extent of these glacial lobes may be used to determine the elevation of their top surface (Text-fig. 8A). Overall data seem to suggest that the surface of the Radoszyce lobe advancing from the north-west could have reached to 600–550 m a.s.l. near the Oblęgorskie Range and 550–500 m a.s.l. in the southern part of the Małogoszcz Range and southern slope of Miedzianka Hill. In the marginal part of the Sandomierz lobe its top surface must have been located lower, at 450–400 m a.s.l. The presented interpretation suggests a larger ice thickness in the Radoszyce lobe (about 300–350 m) than in the Sandomierz lobe (about 150–200 m).

These facts, particularly the distribution of the Sanian 2 till, seem to evidence the presence of the ice sheet foot reaching only to the elevation of 320–350 m a.s.l. During the maximum extent of this glaciation, higher culminations built of pre-Quaternary rocks represented nunataks elevated above the ice sheet surface or depressed nunataks being landlocked oases (compare Różycki 1960). The presence of two nunatak types does not exclude the possibility of Scandinavian material presence to the height of about 500 m a.s.l. (compare e.g., Kotański 1959; Łyczewska 1971). This material is mostly represented by fragments of crystalline rocks, deposited during ice sheet retreat when slopes of proper nunataks as well as landlocked oases were areas of kame-type fluvioglacial accumulation (Radłowska and Mycielska-Dowgiałło 1972, 1974; Lindner and Kowalski 1974; Lindner 1977a).

Detailed mapping and geological surveys in the study area have shown the presence of sands, silts and gravels in elevated areas, including those covered by till. Their structural and lithological features, and morphological setting allow to assume that they are remains of limni- and fluvioglacial forms developed during two deglaciation stages in the western part of the Holy Cross Mountains.

First deglaciation stage

The maximum height at which fine-grained sandstones and silts occur is from 420–415 m a.s.l. (pass between Sieniawska and Barania hills) to 320–270 m a.s.l. (between Miedzianka and Sowa hills, and between Plebańska and Kopaczowa hills). With regard to the classical papers about ice sheet retreat in mountainous areas (compare Jahn 1969; Flint 1971), these deposits should be considered as relicts of kame terraces on hill passes or kame plains marking the first deglaciation stage of the Holy Cross Mountains during the Sanian 2 ice sheet retreat. In hill pass contexts (Widoma and Zawada), these deposits are represented by fine- and medium-grained sands, as well as silty sands and silts (Table 1; Appendix 1) with admixture of local sandy material. They occasionally contain cobbles of local or Scandinavian rocks and interbeds of colluvium flows of loamy-debris material, as well as relatively thin lenses of gravel pointing to enhancement of water flow. The mean thickness of these deposits is about 4 m, maximally reaching 15 m (Lindner 1977a). In the studied successions the deposits are much thinner and represented by fine- and medium-grained, poorly sorted sands. Fine faults cutting the sandy layers were observed in an exposure on the pass between Miedzianka and Sowa hills. In a new section on Miedzianka (Table 1; Appendix 1), fine-grained sands mainly contain rounded, matted and partially-rounded, matted grains (a total of 90%). The morphological context of these deposits as well as their features clearly indicate the long-term eolization process of primarily kame deposits.

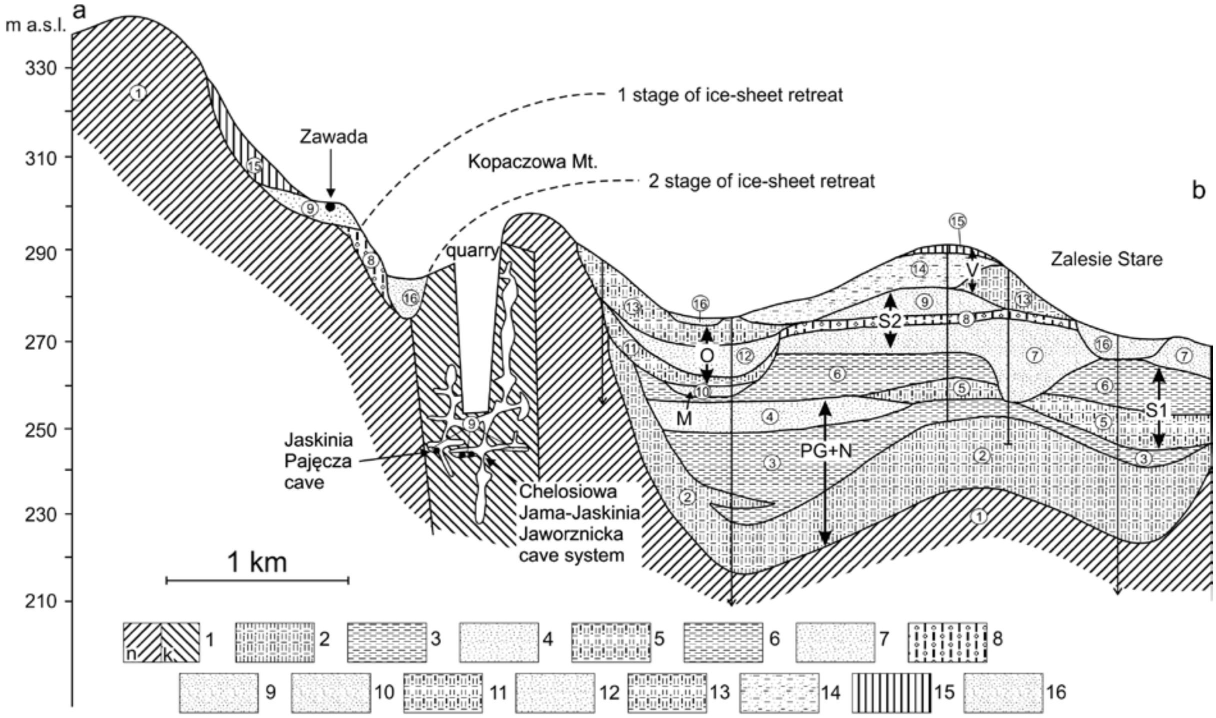
Areas of limni- and fluvioglacial accumulation during the first deglaciation stage of the western part of the Holy Cross Mountains are schematically presented on a palaeogeomorphological map of the study area during the second deglaciation stage (Text-fig. 8B). Basement culminations exposed from beneath the sandy-silty deposits being relicts of hill pass kame terraces and kame plains, due to graphic reasons have been presented only in a few localities (Perzowa, Siniewska, Barania, Miedzianka and Kopaczowa hills).

Second deglaciation stage

Relicts of the second (younger) deglaciation stage of the study area (Text-fig. 8B) include hill pass sands preserved at lower elevations and several metres high gravel-sandy hillocks accompanying these deposits, as well as lower ledges of sandy and sandy-silty material covering slopes built of pre-Quaternary rocks. These deposits usually cover Sanian 2 till and are preserved at elevations between 280 and 250 m a.s.l. In relation to the classical papers of Jahn (1969), Baraniecka (1969) and Walczak (1969), it should be assumed that these deposits represent relicts of slope (external) kame terraces and plains. They were accumulated between gradually deteriorating dead-ice patches and slopes of elevations exposed during the deglaciation. These sediments are represented by sandy ledges, which as detached fragments reach up to 280 m a.s.l. and run along the entire northern slope in the eastern part of the Małogoszcz Range. In the exposure near Małogoszcz they occur at 40–50 m above the bottom of the present-day valley and are represented by fine- and variable- grained sands with traces of cross-stratification and interbeds of silts and colluvium flows of limestone debris (Lindner 1977a; Filonowicz and Lindner 1986). Within this exposure, the thickness of kame sands reaches 9 m, whereas averagely it does not exceed 2–3 m. In Polichno these deposits are about 8 m thick and poorly sorted, with dominating partially-rounded, matted or rounded, matted quartz grains, which is a typical feature of old sediments deposited in close periglacial conditions.

On the eastern slope of Kopaczowa Hill in Jaworznia, the sands overlie till at an elevation of 270–280 m a.s.l. and are covered by younger sediments of solifluxion flows of local weathering covers of pre-Quaternary material, followed by thin loess layers (Text-fig. 9). During the second deglaciation stage of the study area, these deposits could be washed into the karst system developed at 250–260 m a.s.l. in a parallel belt of Devonian limestone and dolomite outcrops to the north of Zgórskie Range, partly infilling the karst cavities. Linkage of the cave sediments with sandy sediments occurring in the area where the karst system was in contact with the surface was confirmed by sand analysis (Tables 2 and 3; Appendix 1). Near Jaworznia, the sands were recognised in a depression in Zawada and in drilling cores between Jaworznia and Zalesie Stare, where they overlie till, and are covered by younger slope deposits and a thin loess patch (Text-fig. 9). It is worth noting that during the second deglaciation stage, surface waters released from melting snow and dead-ice patches favoured the development of sand covers in the form of kame sands at 270–280 m a.s.l.

In the middle part of the study area, the sands and silts cover the slopes of most elevations built of pre-Quaternary rocks (e.g., Milechowska, Ostrówka and Zelejowa hills, western slope of Rzepka Hill, and Grząby Bolmińskie Range). Such sediments include also sands containing cemented sandstones and limestone debris preserved on the northern slope of



Text-fig. 9. Schematic geological cross-section through Quaternary deposits near Jaworznia (after Lindner 1977a, substantially changed). Explanations: 1 – non-karstifying (n: Cambrian, Ordovician, Silurian, Lower Devonian and Lower Triassic) and karstifying (k: Middle and Upper Devonian) rocks of the pre-Quaternary basement; PG + N – preglacial + Nidanian Glaciation: 2 – weathering rubble and clays; 3 – ice-dammed silts; 4 – fluvial sands; S1 – Sanian 1 Glaciation: 5 – weathering rubble and clays; 6 – ice-dammed silts; S2 – Sanian 2 Glaciation: 7 – sub-till fluvioglacial sands; 8 – till; 9 – sands of kames and kame terraced, including sands from Chelosiowa Jama and Jaskinia Pajęcza caves; M – Mazovian Interglacial: 10 – fluvial gravels and sands; O – Odranian Glaciation: 11 – weathering rubble and clays; 12 – sands and silts of slope accumulation; V – Vistulian Glaciation: 13 – weathering rubble and clays; 14 – sands and silts of slope accumulation; 15 – loesses; 16 – valley sands and gravels. The black dots indicate the sampling localities in Zawada, Chelosiowa Jama and Jaskinia Pajęcza caves. See Text-fig. 1 for location of cross-section a–b.

the Korzeczkowskie Range (compare Kaźmierczak and Pszczółkowski 1967). Near the Piekoszów Ridge, they form some of the vastest plains in the water divide between Wierna Rzeka and Bobrza rivers. Within the Wierna Rzeka catchment the described sand plains are limited in some places by gravel-sandy hillocks. Near Dobrzeszów, such hillock is built of sands with gravel and thin interbeds of runoff (?) till, evidencing that its accumulation must have taken place in close vicinity of the disappearing ice patch, resulting in a dead-ice moraine. Beside Scandinavian material, local Triassic sandstones and limestones dominate in the petrographic composition of the gravel fraction of this hillock, whereas Lithothamnium limestones and Palaeozoic sandstones from the Holy Cross Mountains are relatively rare (Adaszewski 1973; Lindner 1977a). The 5–10 mm fraction is dominated by fragments of local limestones and marls (about 50%), with crystalline rocks below 10%. Locally, the contribution of allochtonic material may significantly increase (Text-fig. 3). The source of the gravel material could have been the shrinking ice of the Sandomierz lobe. Similar sandy-gravel sediments build small hillocks in the south-eastern part of the study area. According to Radłowska and Mycielska-Dowgiałło (1972, 1974) they may represent relicts of fissure forms.

The karst system in the Devonian carbonates of the southern limb of the Kielce Syncline was hydrogeologically active both in the anaglacial period and during the Sanian 2 ice sheet retreat. During the second deglaciation stage of this area, intense water flow occurred along underground karst waterways. Polar observations of the dissolution of carbonate rocks by water from melting snow and ice (compare Pulina 1977; Lindner and Kłysz 1989), as well as proglacial cave studies in the neighbouring Kraków–Wieluń Upland (Głazek *et al.* 1978) suggest that the karst forms could be both drained and expanded. By the end of this period, sands partly infilled the karst system. Large stalagmites, dated at 6–10 MIS (350–150 ka) in the Chelosiowa Jama–Jaskinia Jaworznicka cave system (Urban *et al.* 2019) developed on these sands. The sands were later washed out (5–6 MIS, locally to 1 MIS, i.e. the Holocene), which caused mechanical, gravitational destruction of some of these dripstones, but they are preserved or secondarily washed into the southern part of the karst system in Jaskinia Pajęcza cave and partly in Chelosiowa Jama cave, where their samples were analysed. The sands are typically fine-grained, moderately sorted (Appendix 1), and contain mainly well-rounded, matted quartz grains, which allows to relate them to Pleistocene burial. Therefore, the distribution of sediments around the Kopaczowa Hill massif as well as the infilling of the karst system in this massif by Pleistocene (kame) sands documents the course of areal deglaciation of the western part of the Holy Cross Mountains during the last Sanian 2 ice sheet in the area, although the supply of this sandy material from the surroundings to the caves took place also during the Odranian Glaciation and later times, till present.

Of the same age as the karst system represented by the Chelosiowa Jama–Jaskinia Jaworznicka caves and the Jaskinia Pajęcza cave may be the karst system developed in Devonian carbonates of the Gałęzice–Bolechowice Syncline on the opposite, southern side of the Zgórskie Range, whose fragment is the Raj Cave with an upper Pleistocene palaeontological and archaeological site (Madeyska 1972, 1974; Urban *et al.* 2019).

The collected data indicate that both during the first and second deglaciation stage, the disappearance of the Sanian 2 ice sheet in the western part of the Holy Cross Mountains was areal-type. Ice sheet retreat depended not only on the rapidly improving climate conditions and relatively small thickness of the ice sheet, but most of all on the much diversified relief of the mountains. Some analogues to processes taking place during the Sanian 2 Glaciation in the study area can be found in polar and circum-polar areas, where glaciers fill mountain valleys reaching closely to their culminations (Dzierżek and Nitychoruk 2013; Dzierżek *et al.* 2019b). This refers not only to postglacial sediments and forms, but also cases when deglaciation processes commenced in areas, where carbonate rocks occur in the basement or vicinity of the glaciers. The carbonate rocks were prone to strong karstification under the influence of aggressive waters released from the disappearing ice masses and snow covers (Pulina 1977; Lindner 1985; Lindner and Kłysz 1989).

CONCLUSIONS

- Two main lobes (Radoszyce and Sandomierz) of the Scandinavian ice sheet, advancing from opposite directions, coalesced in the western part of the Holy Cross Mountains during the Sanian 2 Glaciation. Partial evidence comes from the results of lithological and petrographic analyses of tills.
- The surface of the Radoszyce lobe advancing from the NW probably reached to 600–500 m a.s.l., whereas the surface of the Sandomierz lobe advancing from the SE, was located lower and reached to about 400–450 m a.s.l.
- During the maximum extent of these lobes, the main elevations built of pre-Quaternary rocks were exposed above their surface forming concave nunataks.
- During the first areal deglaciation stage of the western part of the Holy Cross Mountains, these nunataks were subject to sandy-silty accumulation of deposits building kames and kame terraces.
- During the second areal deglaciation stage, the western part of the Holy Cross Mountains was largely covered by dead-ice blocks, between which accumulation of sandy-silty deposits of kames, kame terraces and kame plains took place, in many cases limited by gravel-mud and sandy-gravel dead-ice moraines.
- Release of huge amounts of meltwater – aggressive in relation to Devonian limestones – during the deglaciation process, favoured the drainage of earlier karst systems and their karst-related extension, followed by partial infilling by contemporary kame sands and silts. The sands are preserved in the Jaskinia Pajęcza cave and in the southern part of the Chelosiowa Jama–Jaskinia Jaworznicka cave system, the longest (3670 m) karst system in the Holy Cross Mountains area and in the Polish Uplands.

Acknowledgements

The authors are grateful for patient and constructive reviews of Prof. Teresa Madeyska and Prof. Małgorzata Roman. Thanks for Andrzej Kasza from the Świętokrzyski Speleoclub in Kielce for help in collection and descriptions of samples from the Chelosiowa Jama and Jaskinia Pajęcza caves in Kopaczowa Hill, Jaworznia. We would like to thank Danuta Olszewska-Nejbert for help in the recognition of limestone microstructures and Krzyszof Nejbert for thin section preparation, photography of the specimen and a fruitful discussion.

REFERENCES

Adaszewski, M. 1973. Stratygrafia osadów czwartorzędowych w górnym odcinku dorzecza Wiernej Rzeki (na NW od Kielc), 89 pp. Praca magisterska, Archiwum Instytutu Geologii Podstawowej Uniwersytetu Warszawskiego; Warszawa.

Baraniecka, M.D. 1969. Classification of kame forms in the light of types and of dynamic stages of deglaciation. *Geological Quarterly*, **13** (2), 442–458. [In Polish with English summary]

Cabalski, K., Dzierżek, J. and Kowalczyk, S. 2018. Pleistocene periglacial structures in the Mosty site, near Chęciny (The Holy Cross Mountains). In: Ludwikowska-Kędzia, M. and Wiatrak, M. (Eds), Materiały XXV Konferencji Stratygrafia Plejstocenu Polski „Plejstocen Gór Świętokrzyskich", Huta Szklana, 3–7.09.2018, 78–80. Politechnika Świętokrzyska, Uniwersytet Jna Kochanowskiego; Kielce [In Polish with English summary].

Czarnocki, J. 1927. O zlodowaceniach środkowej części Gór Świętokrzyskich. *Posiedzenia Naukowe Państwowego Instytutu Geologicznego*, **17**, 18–21.

Czarnocki, J. 1931. Diluvium der Święty Krzyż Gebirge. *Rocznik Polskiego Towarzystwa Geologicznego*, **7**, 85–105.

Czarnocki, J. 1938. Ogólna mapa geologiczna Polski 1 : 100 000. Arkusz 4, Kielce. Państwowy Instytut Geologiczny; Warszawa.

Dzierżek, J. Lindner, L. and Cabalski, K. 2019. Quaternary valley levels and river terraces in the western part of the Holy Cross Mountains. *Studia Quaternaria*, **36** (2), 109–118.

Dzierżek, J. and Nitychoruk, J. 2013. Orography and slope processes. In: Zagórski, P., Harasimiuk, M. and Rodzik, J. (Eds), The Geographical Environment of NW Part of Wedel Jarlsberg Land (Spitsbergen, Svalbard), 120–135. Wydawnictwo UMCS; Lublin.

Dzierżek, J., Szymanek, M. and Nitychoruk, J. 2019. Slope processes in the High Arctic: a 30-year-long record from Spitsbergen. *Boreas*, **48**, 856–866.

Filonowicz, P. and Lindner, L. 1986. Detailed Geological Map of Poland, sheet Piekoszów (Szczegółowa mapa geologiczna Polski, arkusz Piekoszów). Wydawnictwa Geologiczne; Warszawa. [In Polish]

Flint, R.F. 1971. Glacial and Quaternary geology. 892 pp. J. Wiley and Sons; New York–London–Sydney–Toronto.

Folk, R.L. and Ward, W.C. 1957. Brazos River bar: a study in the significance of grain size 446 parameters. *Journal of Sedimentary Petrology*, **27**, 3–26.

Galehouse, J.S. 1971. Point counting. In: Carver, R.E. (Ed.), Procedures in Sedimentary Petrology, 385–407. Wiley Interscience; New York.

Głazek, J., Bednarek, J., Szynkiewicz, A. and Wierzbowski, A. 1978. Origin of the Szacownica cave – the grates cave system in the Kraków–Wieluń Upland. *Kras i Speleologia*, **2**, 38–50.

Głazek, J., Kowalski, K., Lindner, L., Młynarski, M., Stworzewicz, E., Tuchołka, P. and Wysoczański-Minkowicz, T. 1977. Cave deposits at Kozi Grzbiet (Holy Cross Mts., Central Poland) with vertebrate and snail faunas of the Mindelian I/Mindelian II Interglacial and their stratigraphic correlations. *Proceedings 7th International Speleological Congress*, 211–214, Sheffield.

Głazek, J., Kutek, J. and Lindner, L. 1976a. Okruchy wapieni mioceńkich w osadach morenowych na górze Sitki pod Chęcinami. *Przegląd Geologiczny*, **24** (8), 459–463. [In Polish with English summary]

Głazek, J., Lindner, L. and Wysoczański-Minkowicz, T. 1976b. Interglacial Mindel I/Mindel II in fossil-beaving karst at Kozi Grzbiet in the Holy Cross Mts. *Acta Geologica Polonica*, **26** (3), 377–393.

Gozhik, P., Lindner, L. and Marks, L. 2012. Late Early and early Middle Pleistocene limits of Scandinavian glaciations in Poland and Ukraine. *Quaternary Internationl*, **271**, 31–37.

Hakenberg, M. 1973. Detailed Geological Map of Poland, sheet Chęciny. Wydawnictwa Geologiczne; Warszawa. [in Polish]

Hansley, P. L. and Briggs, P. H. 1994. Garnet dissolution in oxalic acid – a possible analog for natural etching of garnet by dissolved organic matter. *U.S. Geological Survey Bulletin*, **2106**, 241–256.

Hubert, J. F. 1962. A Zircon–Tourmaline–Rutile maturity index and the interdependece of the composition of heavy mineral assemblages with the gross composition and texture of sandstiones. *Journal of Sedimentary Petrology*, **32**, 440–450.

Jahn, A. 1969. Kame terraces in the Sudetes. *Folia Quaternaria*, **30**, 17–22. [In Polish with English summary]

Kasza, A. and Urban, J. 2016. Przedsympozjalna sesja terenowa – rezerwat „Chelosiowa Jama", system jaskiniowy Chelosiowa Jama–Jaskini Jaworznicka oraz Jaskinia Pajęcza w Jaworzni. In: Urban, J. (Ed.), Materiały 50. Jubileuszowego Sympozjum Speleologicznego, Kielce–Chęciny 20–23.10.2016, 13–17. Sekcja Speleologiczna PTP im. Kopernika; Kraków.

Kaźmierczak, J. and Pszczółkowski, A. 1967. Breccia and sandstone of the Quaternary age from the vicinity of Chęciny, Holy Cross Mts. *Biuletyn Geologiczny Uniwersytetu Warszawskiego*, **9**, 289–300. [In Polish with English summary]

Kalicki, T., Frączek, M., Przepióra, P., Kusztal, E., Kłusakiewicz, E. and Malęga, E. 2018. Late Quaternary geomorphology and geoarchaeology in the rivers of the Holy Cross Mountains region, central Europe. *Quaternary Research*, **91** (2), 584–599.

Klatka T. 1976. Niektóre problemy czwartorzędowego rozwoju dolin centralnej części Gór Świętokrzyskich. *Acta Geographica Lodziensia*, **37**, 73–89.

Konon, A. 2008. Tectonic subdivision of Poland: Holy Cross Mountains and adjacent areas. *Przegląd Geologiczny*, **56**, 921–926.

Konon, A. and Sidorczuk, M. 2015. Tectonic structures and karst phenomena in the dolomites of Rzepka Hill. In: Skompski, S. and Żylińska, A. (Eds), The Holy Cross Mountains. 26 journeys through Earth history, 98–101. Univeristy of Warsaw Faculty of Geology; Warszawa.

Kotański, Z. 1959. Przewodnik geologiczny po Górach Świętokrzyskich. T. 1 i 2, 447 pp. Wydawnictwa Geologiczne; Warszawa.

Kowalski, K. 1974. Animal remains in the Raj Cave deposits. In: Rubinowski, Z. (Ed.), Badania i udostępnienie jaskini Raj, 101–128, Wydawnictwa Geologiczne; Warszawa. [In Polish with English summary]

Kowalski, K. 1989. Historia i ewolucja lądowej fauny Polski. *Folia Quaternaria*, **59/60**, 1–278.

Krupa, J. 2015. Natural and anthropogenic channel pattern changes in the mid-mountain valley during the Late Glacial and Holocene, Polish Uplands. *Quaternary International*, **370**, 55–65.

Lindner, L. 1971. Loess deposits at Oblęgorek near Kielce, Holy Cross Mts. *Acta Geologica Polonica*, **21** (2), 265–278. [In Polish with English summary]

Lindner, L. 1977a. Pleistocene glaciations in the western part of the Holy Cross Mountains, central Poland. *Studia Geologica Polonica*, **53**, 1–143. [In Polish with English summary]

Lindner, L. 1977b. Miedzianka – Origin and age of sands occuring on slopes and passes of Miedzianka Mountain. In: Lindner, L. and Michalska, Z. (Eds), Czwartorzęd zachodniej części regionu świętokrzyskiego – Przewodnik Sympozjum Terenowego, Warszawa–Kielce, 6–10 czerwca 1977, 25–31, Wydawnictwa Geologiczne; Warszawa. [In Polish with English summary]

Lindner, L. 1984. The Holy Cross Mts. Region (Region Świętokrzyski). In: Sokołowski, S. and Mojski, J.E. (Eds), Budowa geologiczna Polski, T. 1, Stratygrafia, część 3b, Kenozoik – czwartorzęd Sokołowski, 34–35; 63–73; 113–145; 255–286; 326–330. Wydawnictwa Geologiczne; Warszawa. [In Polish]

Lindner, L. 1985. Origin and age of the Cracow Canyon, western Tatra Mts. *Acta Geologica Polonica*, **35** (1–2), 189–202.

Lindner, L. 1995. Till sequences and local moraines in the Holy Cross Mountains area in Central Poland. In: Ehlers, J., Kozarski, S. and Gibbard, P.L. (Eds), Glacial Deposits in North-East Europe, 329–337. A.A. Balkema; Rotterdam.

Lindner, L. and Dzierżek, J. 2013. Zlodowacenia i interglacjały w plejstocenie regionu świętokrzyskiego (nowe ujęcie). In: Bąbel. M., Dzierżek J. and Olszewska-Nejbert D. (Eds), Od Czarnohory po Góry Świętokrzyskie – geologiczne peregrynacje, Polsko-Ukraińska Sesja Naukowa, Warszawa–Bocheniec, 15–19 października 2013, 39–44. Instytut Geologii Podstawowej Wydziału Geologii Uniwersytetu Warszawskiego; Warszawa.

Lindner, L. and Dzierżek, J. 2019. Pleistocene deposits in the western part of the Holy Cross Mts. *Studia Quaternaria*, **36** (2), 75–85.

Lindner, L. and Kłysz, P. 1989. Surface karst features at a southern slope of Stupryggen (Sorkapp Land, Spitsbergen). *Kras i Speleologia*, **6**: 58–65. [In Polish with English summary]

Lindner, L. and Kowalski, W.R. 1974. Quaternary cover around Mt. Miedzianka in the Holy Cross Mts. *Acta Geologica Polonica*, **24** (2), 415–424. [In Polish with English summary]

Lindner, L. and Mastella, L. 2002. Origin and age of the Wierna River (Łososina) gorge in the vicinity of Bocheniec (SW Mesozoic margin of the Holy Cross Mts). Geologia i geomorfologia gór i wyżyn w Polsce. *Prace Instytytu. Geografii Akademii Świętokrzyskiej*, **6**, 21–46. [In Polish with English summary]

Lisicki, S. 2003. Lithotypes and lithostratigraphy of tills of the Pleistocene in the Vistula drainage basin area Poland. *Prace Państwowego Instytutu Geologicznego*, **177**, 1–105. [In Polish with English summary]

Ludwikowska-Kędzia, M. 2018a. Wpływ rzeźby strukturalnej Gór Świętokrzyskich na przebieg procesów morfogenetycznych w plejstocenie i ich zapis w cechach sedymentologicznych osadów. In: Ludwikowska-Kędzia, M. and Wiatrak, M. (Eds), Meteriały XXV Konferencja naukowa Stratygrafia Plejstocenu Polski „Plejstocen Gór Świętokrzyskich", Huta Szklana, 3–7 września 2018 r., 38–46. Politechnika Świętokrzyska, Uniwersytet Jan Kochanowskiego; Kielce.

Ludwikowska-Kędzia, M. 2018b. Litologia, geneza i stratygrafia osadów czwartorzędowych w południowej części Gór Świętokrzyskich, 203 pp. Instytut Geografii UJK; Kielce.

Łoziński, W. 1909. Über die mechanische Verwiterung der Sandsteine im gemässigten Klima. *Biuletyn Polskiej Akademii Umiejętności*, **2**, 1–25.

Łyczewska, J. 1971. The Quaternary of the Góry Świętokrzyskie Region. *Prace Instytutu Geologicznego*, **64**, 5–108. [In Polish with English summary]

Madeyska, T. 1972. A stratigraphical and sedimentological study of the deposits. In: Studies on Raj cave near Kielce (Poland) and its deposits. *Folia Quaternaria*, **41**, 17–44.

Madeyska, T. 1974. Lithologie and stratigraphie des sediments dans la grotte de Raj. In: Rubinowski, Z. (Ed.), Badania i udostępnienie jaskini Raj, 61–92. Wydawnictwa Geologiczne; Warszawa. [In Polish with French summary]

Mange, M.A. and Wright, D.T. 2007. Heavy minerals in use. *Developments in Sedimentology*, **58**, 1–1284.

Marks, L., Dzierżek, J., Janiszewski, R., Kaczorowski, J., Lindner, L., Majecka, A., Makos, M., Szymanek, M., Tołoczko-Pasek, A. and Woronko, B. 2016. Quaternary stratigraphy and palaeogeography of Poland. *Acta Geologica Polonica*, **66** (3), 403–427.

Michalski, A. 1888. Aperçu géologique de la partie sud-ouest de gouvernement de Piotrków (en Pologne). *Pamiętnik Fizjograficzny*, **8** (2), 19–35. [In Polish with French summary]

Morton, A. C. and Hallsworth, C. 1994. Identifying provenance-specific features of detrital heavy mineral assemblages in sandstones. *Sedimentary Geology*, **90**, 241– 256.

Mycielska-Dowgiałło, E. and Woronko, B. 1998. Rounding and frosting analysis of quartz grains of sand fraction, and its interpretative value. *Przegląd Geologiczny*, **46** (4), 1275–1281. [In Polish with English summary]

Pogorzelski, M. 1972. Stratygrafia osadów czwartorzędowych w widłach Bobrzy i Sufragańca (na W od Kielc), 75 pp. Praca magisterska, Archiwum Instytutu Geologii Podstawowej Uniwersytetu Warszawskiego, Warszawa.

Powers, M.C. 1953. A new roundness scalefor sedimentary particles. *Journal of Sedimentary Petrolog*y, **23**, 117–119.

Pulina, M. 1977. On karst phenomena occurring in the southern part of Spitsbergen. *Kras i Speleologia*, **1**, 104–129. [In Polish with English summary]

Radłowska, C. and Mycielska-Dowgiałło, E. 1972. Comments on deglaciation in W part of Święty Krzyż Mountains – near Chęciny. *Przegląd Geograficzny*, **44** (4), 649–672. [In Polish with English summary]

Radłowska, C. and Mycielska-Dowgiałło, E. 1974. Deglaciation in the Świętokrzyskie Mts. *Geographia Polonica*, **28**, 19–48.

Różycki, S.Z. 1960. Czwartorzęd regionu Jury Częstochowskiej i sąsiadujących z nią obszarów. *Przegląd Geologiczny*, **8** (8), 424–429.

Różycki, S.Z. 1967. Plejstocen Polski środkowej na tle przeszłości w górnym trzeciorzędzie, 251 pp. Państwowe Wydawnictwa Naukowe; Warszawa.

Różycki, S.Z. 1972. Pleistocene of the middle Poland, Wydanie II, 315 pp. Państwowe Wydawnictwa Naukowe; Warszawa. [In Polish with English summary]

Siemiradzki, J. 1888. Sprawozdanie z badań geologicznych z okolicy Kielc i Chęcin. *Pamiętnik Fizjograficzny*, **8** (2), 4–18.

Skompski, S. 2015. Geological history of the Holy Cross Mountains. Palaeozoic. In: Skompski, S. and Żylińska, A. (Eds), The Holy Cross Mountains. 26 journeys through Earth history, 185–189. Univeristy of Warsaw Faculty of Geology; Warszawa.

Urban, J. 1996. Jaskinie regionu świętokrzyskiego, 322 pp. Polskie Towarzystwo Przyjaciół Nauk o Ziemi; Warszawa.

Urban, J. 2002. Kras kopalny trzonu paleozoicznego Gór Świętokrzyskich. *Streszczenia Polskiego Towarzystwa Geologicznego* Oddział w Poznaniu, Uniwersytet im. A. Mickiewicza, **11**, 53–69.

Urban, J. 2013. Zapis lądowych etapów historii geologicznej Gór Świętokrzyskich w osadach i formach krasowych – wybrane przykłady. *Biuletyn Państwowego Instytutu Geologicznego*, **454**, 77–102.

Urban, J., Hercman, H., Ochman, K. and Kasza, A. 2019. Record of the Pleistocene in karst sites of the Świętokrzyskie (Holy Cross) Mountains region – a review. *Studia Quaternaria*, **36**, 87–108.

Urban., J. and Rzonca, B. 2009. Karst system analyzed using borehole logs – Devonian carbonates of the Świętokrzyskie (Holy Cross) Mountains, Central Poland. *Geomorpholog*y, **112**, 27–47.

Walczak, S. 1969. Kame terraces in the Bardzkie Montains. *Folia Quternaria*, **30**, 23–32.

Wójcik, A. 2003. Quaternary of the western part of the Jasło–Sanok Depression, Polish Outer Carpathian. *Prace Państwowego Instytutu Geologicznego*, **178**, 1–148.

Manuscript submitted: 11th May 2020
Revised version accepted: 14th September 2020

Appendix 1

Grain-size parameters (after Folk and Ward 1957) in selected sites in the western part of the Holy Cross Mountains. W – Widoma; D – Dobrzeszów; Mi – Miedzianka; P – Polichno; Z – Zawada; Paj – Jaskinia Pajęcza cave; Chel – Chelosiowa Jama cave.

Widoma	W-1 0.5–0.8	W-2 0.5–0.8
lithology	medium sand	very coarse silt
mean grain size	1.74	3.41
standard deviation	1.67	1.98
skewness	-0.17	0.09
kurtosis	1.99	0.83
sorting	poor	poor

Dobrzeszów	D-3 1.2–1.5	D-4 1.2–1.4	D-4 1.8–2.1
lithology	medium sand	medium sand	medium sand
mean grain size	2.05	1.32	1.85
standard deviation	0.80	1.25	0.88
skewness	0.04	-0.04	0.14
kurtosis	0.80	1.30	1.08
sorting	moderate	poor	moderate

Miedzianka	Mi 0 5–0.7	Mi 0.8–1.0	Mi 1.5–1.7	Mi 1.9–2.1	Mi 2.5–2.7	Mi 2.8–3.0	Mi 3.6–3.8
lithology	fine sand	medium sand	fine sand	fine sand	fine sand	fine sand	fin sand
mean grain size	2.38	2.05	2.23	2.25	2.34	2.14	2.48
standard deviation	0.81	0.73	0.79	0.85	0.84	0.84	0.76
skewness	-0.09	0.20	0.02	0.06	-0.03	-0.09	-0.09
kurtosis	1.03	0.75	0.79	0.86	0.95	0.83	1.14
sorting	moderate	moderate	moderate	moderate	moderate	moderate	moderate

Polichno	P-1 0.5-0.6	P-1 1.6-1.7	P-1 2.0-2.2	P-1 2.5-2.7	P-1 3.0-3.2	P-1 3.6- 3.7	P-2 0.6-0.7	P-2 1.2-1.4	P-3 0.4-0.5	P-3 0.8- 1.0	P-3 1.4- 1.5
lithology	fine sand	fine sand	fine sand	very fine sand	medium sand	very coarse silt	medium sand	medium sand	medium sand	fine sand	medium sand
mean grain size	2.52	2.32	2.40	2.79	2.02	4.04	2.01	1.98	2.13	2.14	1.93
standard deviation	1.15	1.22	1.15	1.45	0.75	2.68	0.88	0.94	1.09	1.11	0.83
skewness	0.15	0.32	0.18	0.29	0.22	-0.47	0.34	0.26	0.35	0.22	0.21
kurtosis	1.16	1.12	1.17	1.11	0.75	1.43	0.93	1.02	1.13	1.08	0.77
sorting	poor	poor	poor	poor	moderate	very poor	moderate	moderate	poor	poor	moderate

Zawada	Z-1 1.0-1.2	Z-1 1.7-1.8	Z-2 0.5-0.6	Z-2 1.2-1.6
lithology	medium sand	medium sand	medium sand	versy coarse
mean grain size	1.64	1.83	1.58	2.37
standard deviation	0.95	1.59	0.94	1.56
skewness	0.10	-0.20	0.10	0.20
kurtosis	1.08	1.50	1.17	1.21
sorting	moderate	poor	moderate	poor

Chelosiowa Jama Cave	Chel-1 0.2-0.3	Chel-1 0.5-0.6	Chel-2 0.4-0.5
lithology	fine sand	fine sand	medium sand
mean grain size	2.27	2.69	2.02
standard deviation	0.83	1.23	0.88
skewness	-0.01	0.23	0.06
kurtosis	0.86	1.59	0.89
sorting	moderate	poor	moderate

Pajęcza Cave	Paj-1 0.3-0.4	Paj-1 0.7-0.8	Paj-1 1.1-1.2
lithology	fine sand	fine sand	medium sand
mean grain size	2.18	2.08	1.89
standard deviation	0.78	0.76	1.02
skewness	-0.03	0.12	0.24
kurtosis	0.74	0.74	1.14
sorting	moderate	moderate	poor