

Mineralogy and abrasion of sand grains due to Vistulian (Late Pleistocene) aeolian processes in central Poland

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Abstract

The Eemian and Vistulian (= Weichselian) sedimentary fill of a closed depression and the glacial Saalian substratum at Kalinko as well as the Late Vistulian (= Late Glacial) dune deposits at Zamęty were studied as representative periglacial sequences for central Poland. Heavy minerals and feldspars were examined by optical methods and by coloration with cobalt nitrite of sodium. Quartz grain abrasion was investigated by applying a modified Cailleux morphoscopic method and Krygowski's mechanical graniformametry. Mineralogical changes, especially a decrease in frequency of amphiboles and an increase of garnets, along with an increase of wind-abraded elements, suggest that these changes have an aeolian origin. The frequency of features which are due to aeolian activity increases progressively in Early Vistulian and Plenivistulian lake and slope deposits. The degree of transformation is highest in the sands with gravels deposited by slopewash waters and in the sands filling the Late Plenivistulian frost wedges. The degree of transformation increases markedly from about 30 000 BP onward and reaches a maximum between 20 000 and 14 000 BP. The Late Vistulian coversands and dunes consist of material that was formerly strongly transformed by wind. They do not contain more wind-abraded grains than the Late Plenivistulian non-aeolian deposits.

Introduction

Aeolian processes play a great role in periglacial lithogenesis. This is proved by the common occurrence of periglacial aeolian sediments, such as loess, dune and coversands and wind-worn stone pavements, and by the indications for aeolian abrasion of sand grains, which indications may occur also within non-aeolian deposits. These phenomena are common in the Vistulian (= Weichselian) periglacial zone of central Poland, situated not far from the southernmost extent of the last ice sheet.

The content of wind-abraded grains in the aeolian and non-aeolian deposits of the region has been studied by many authors (Dylik 1969, Dylikowa 1969, Goździk 1981, 1986, Klatkova 1985, Krajewski

1977, Manikowska 1977, 1985, 1990, 1991, Nowaczyk 1986, Rotnicki 1970) but the researches on mineralogical changes caused by aeolian processes are relatively few (Goździk 1980, Kamińska et al. 1986, Krzyszkowski 1990, Manikowska 1985, Urbaniak-Biernacka 1976). This paper presents the results of a detailed study of the Kalinko site. Some data from the Zamęty site (Manikowska 1985) are also dealt with. The conclusions of this paper will also include the results from other localities in central Poland. The general stratigraphy of the Late Pleistocene in central Poland is shown in Fig. 1.

The village of Kalinko is situated SE of Łódź city (Fig. 2). At this site, a fully developed succession of Eemian to Late Plenivistulian sediments was exposed in a long excavation at the margin of a closed

V i s t u l i a n	Late Vistulian	Younger Dryas Allerød Older Dryas Bølling Oldest Dryas
	14 000 BP	Late Middle Early
	P l e i s t i v i s t u l i a n	
	30 000 BP	
	55 000 BP	
Early Vistulian		
Eemian		
Saalian		

Fig. 1. Stratigraphic table of the Late Pleistocene in the study area.

depression (Fig. 3). The substratum consists of Saalian glacial deposits. At the Zamęty site, north of Kalisz and located within the area of the same glaciation, Late Vistulian dune sediments were exposed, containing three sandy series of which the youngest is underlain by an Allerød soil horizon (Fig. 4).

At both sites, deposits were sampled for mineralogical and textural analysis. For the heavy mineral analysis a minimum of 300 transparent grains from the 0.10–0.25 mm fraction was identified but only indicator minerals were considered: zircons, tourmalines, rutiles and garnets as stable minerals and amphiboles, pyroxenes and epidotes as relatively unstable ones. From these analyses weathering ratios were calculated. The feldspar contents of the 0.5–0.8 mm fraction were established using the method of HF treatment and coloration by cobalt nitrite of sodium. The percentages of the sum of K-feldspars and plagioclases were calculated in relation to quartz-grain amounts.

The quartz grains were analysed morphoscopically, using the modified Cailleux method (Cailleux & Tricart 1959), to obtain information about the type and degree of mechanical abrasion. Within the

0.5–0.8 mm fraction, the contents of four morphoscopic grain categories were determined: RM (round mat, wind-abraded), EL (rounded shiny, water-abraded), NU (angular, unabraded) and M (intermediate grains, without the fully developed characteristics indicated above). M-grains in Pleistocene deposits of central Poland were as a rule produced by slight aeolian abrasion of grains which before were unabraded or abraded by flowing water; they will be considered as partly wind-abraded grains. Grains of the C-category (split after strong wind or water abrasion) are excluded from the calculations.

The grains of the 0.8–1.0 mm fraction were studied on the grain-roller using the graniformometric method (Krygowski 1964) which enables their subdivision into three classes: α and β and γ . Experiments demonstrated that the amount of grains of the γ -class, i.e. the most spherical ones, turns out to be proportional to the degree of aeolian abrasion.

Stratigraphy and age of the deposits

Figure 3 shows a stratigraphic column of the deposits in the Kalinko closed depression as they were exposed in a 2–3 m-deep and 25 m-long excavation. Glaciofluvial sands occur on the surrounding slopes. The glacial substrate is made up of: (unit 1) glaciofluvial sands, (2) older glacial till, (3) intermorainic sands with silt admixture and (4) younger glacial till. The tills represent the older and younger Saalian stadials. The younger of these tills is Wartanian. All these sediments could be the source of the deposits filling the depression, but the contribution of the younger till was relatively small because of its low topographic position. The same holds for the influence of the glaciofluvial sands because of their relatively large distance from the bottom of the depression. Figure 3 shows only those substratum sediments which were the main source of the deposits filling the depression (units 2 and 3). Table 1 contains the mineralogical results for all possible source deposits (units 1, 2, 3 and 4).

The Eemian in the Kalinko section is represented by: (5) sand with plant detritus and humus streaks,

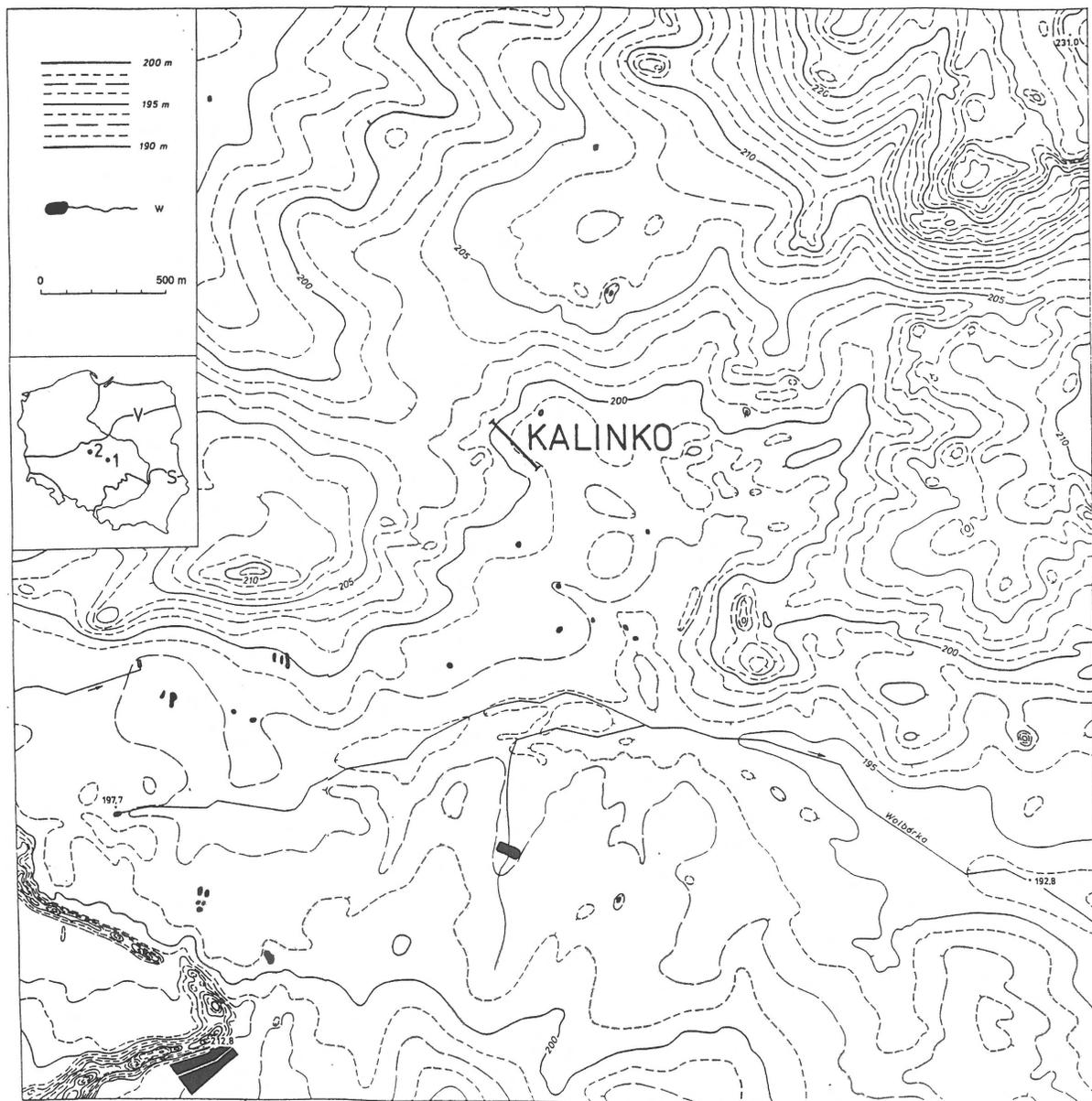


Fig. 2. Location map. Bar indicates excavated section at Kalinko. W – surface water, V – maximal extent of Vistulian ice sheet, S – maximal extent of Saalian ice sheet; 1 – Kalinko, 2 – Zamęty.

deposited in a lake near the shore, and (6) peat with a very small admixture of mineral grains.

The Vistulian deposits comprise: (7) clayey-sandy gyttja, (8) sand with interlaminated redeposited organic material, considered to be a slope-wash deposit, (9) massive silt with a small admixture of organic substance, representing stagnant water conditions, (10) parallel or cross-stratified

sand, representing seasonally flowing water conditions, (11 and 13) sands and silts with an intercalated (12) humic silty bed, representing slope-wash deposits separated by a bog soil, (14) sand filling a frost wedge, (15) sand and gravel with cobbles, deposited by seasonally flowing waters. The successive sediments filling the depression gradually decrease in areal extent except for the youngest sand and gravel

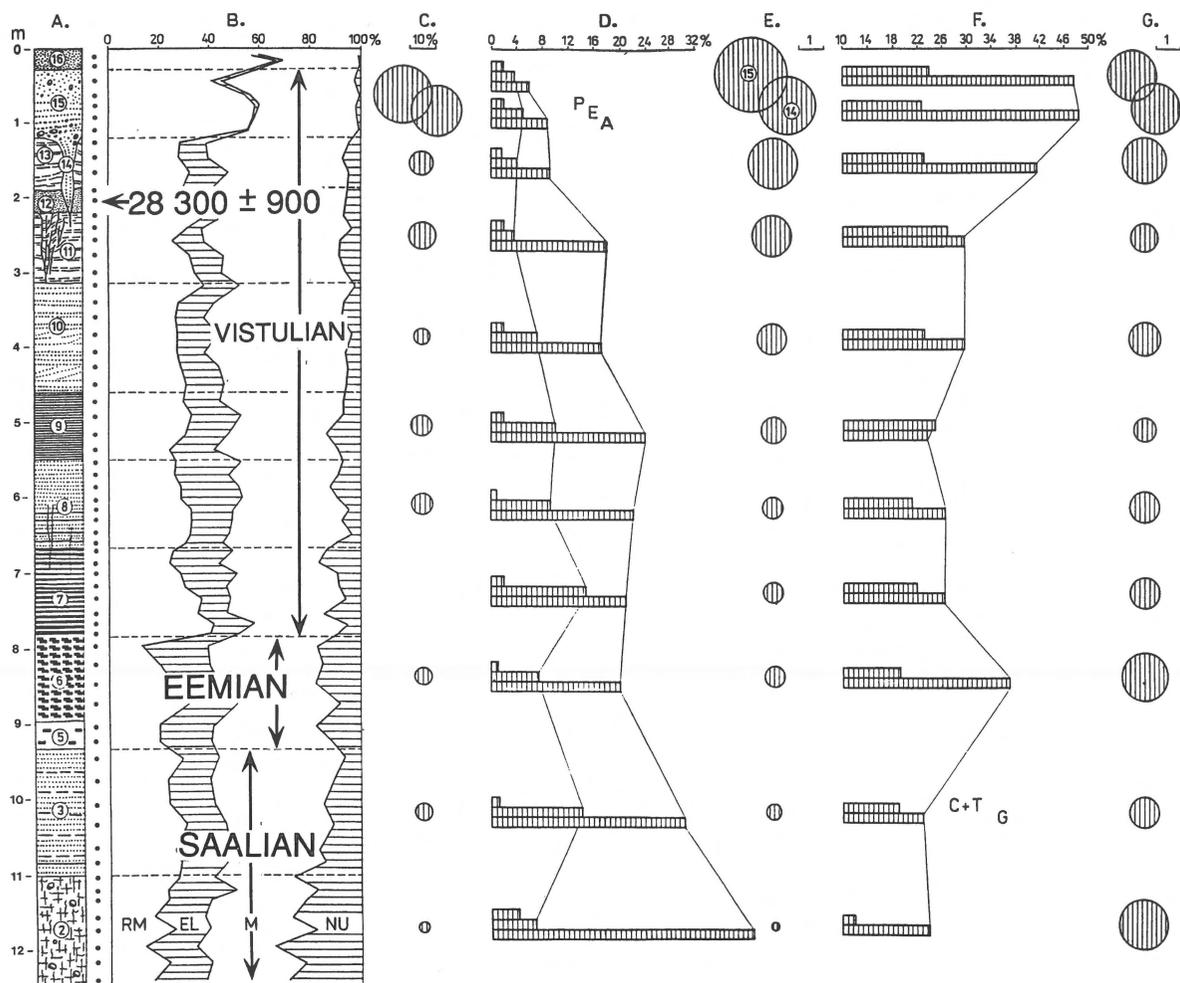


Fig. 3. Stratigraphy, abrasion features and mineralogy of closed depression deposits and their substratum at Kalinko. A. Stratigraphy: see Table 1; B. Morphoscopy of quartz grains: RM – round mat, wind-abraded grains, EL – rounded shiny, water-abraded grains, M – intermediate grains, NU – angular, unabraded grains; C. Percentages of γ -type quartz grains; D. percentages of relatively unstable heavy minerals – pyroxenes, epidotes, amphibolus; E. Ratio $T + C/A + P$; F. Percentages of stable heavy minerals – zircons + tourmalins, garnets; G. Ratio $G/T + C$. Circle diameter changes proportionally to the number of grains or value of ratio. Abbreviations of mineral names as in Table 1.

which cover all older deposits by a thin widespread mantle, passing into a pavement outside the depression.

Three stratigraphic horizons with wedge casts were found. Thin frost fissures formed synchronously with the deposition of unit 8, the oldest slope sediment. Large ice wedges developed in the top part of unit 11. They melted during the bog-soil formation. A polygonal net of large sand wedges was formed immediately before and during the deposition of the sand-gravel unit 15. The sand filling the

wedges (unit 14) is distinctly different from that surrounding the wedges.

Pollen analysis indicates that peat 6 was formed during the optimum and final parts of the Eemian interglacial. The topmost part of this peat shows some climatic oscillations which probably represent the beginning of the Vistulian. Gytja 7 was certainly formed in cold conditions, as were all younger deposits which could be studied palynologically, viz. units 8, 9, 11 and 13. Well-preserved, open-tundra pollen assemblages were found in unit 13. The pa-

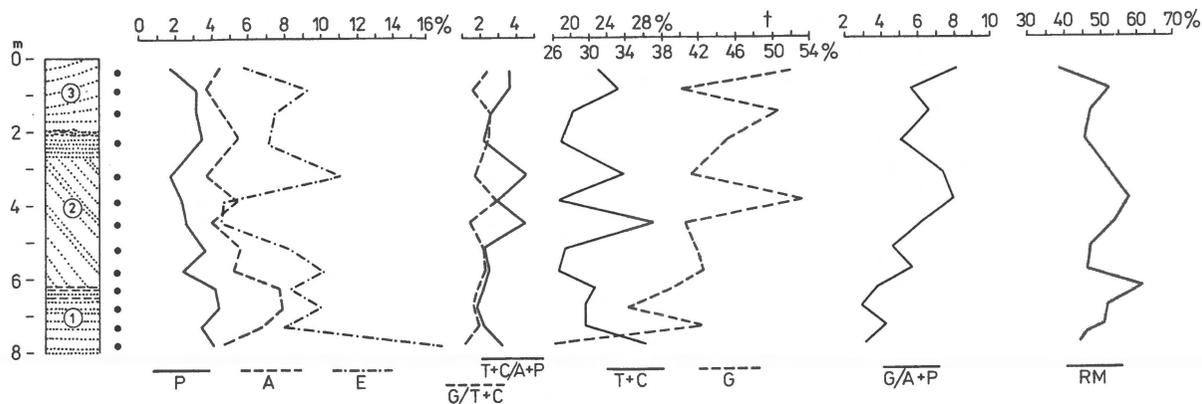


Fig. 4. Stratigraphy, mineralogy and RM-grain content of the Late Vistulian dune at Zamęty. Stratigraphy: 1. Oldest Dryas sands and silts, 2. Older Dryas sands with Allerød soil in the top part, 3. Younger Dryas sands. Abbreviations of minerals as in Table 1; †: upper scale for T + C.

lynological study by Z. Balwierz will be the subject of a special publication.

The humus of the bog soil (unit 12) was radiocar-

bon-dated at $28\,300 \pm 900$ BP (Lod 86), an age which is comparable with that of the Denekamp peat layer in the Netherlands (Ran & Van Huisste-

Table 1. Results of mineralogical analysis of closed depression deposits and their substratum at Kalinko.

Deposit	number of samples	mineral %										weathering ratio					F* %
		C	T	R	C+T+R	G	A	H	P	E	A+P	$\frac{C+T}{A+P}$	$\frac{C+T+R}{H}$	$\frac{C+T}{E}$	$\frac{G}{A+P}$	$\frac{G}{C+T}$	
1	4	5.4	7.9	4.1	17.4	34.9	25.8	23.3	4.6	7.8	30.4	0.4	0.7	1.7	1.1	2.6	13.4
2	10	4.0	7.8	4.7	16.5	24.0	41.0	36.9	4.2	7.1	45.2	0.3	0.5	1.7	0.5	2.0	21.0
3	3	5.4	13.7	3.3	22.4	23.0	29.6	26.5	1.0	14.2	30.6	0.6	0.8	1.3	0.8	1.2	11.7
4	6	6.0	13.9	5.6	25.5	34.0	18.8	15.7	2.7	10.2	21.5	0.9	1.6	1.9	1.6	1.7	10.2
1+2+3+4	23	5.2	10.8	4.4	20.4	29.0	28.8	25.6	3.1	9.8	31.9	0.6	0.8	1.7	1.0	1.8	14.1
5+6	2	4.7	15.6	1.1	21.4	37.0	20.0	17.5	1.1	7.4	21.1	1.0	1.2	2.7	1.8	1.8	13.7
7	3	4.2	19.4	1.6	25.2	26.2	21.1	18.4	2.2	14.8	23.3	1.0	1.4	1.6	1.1	1.1	7.6
8	4	5.9	18.4	3.2	27.5	26.4	22.2	18.7	0.9	9.2	23.1	1.1	1.5	2.6	1.5	1.1	9.5
9	5	6.6	20.3	1.8	28.7	23.6	23.5	20.2	2.0	10.1	25.5	1.1	1.4	2.7	0.9	0.9	8.2
10	4	4.0	22.5	3.5	30.0	29.7	17.4	13.7	1.9	7.2	19.3	1.4	2.2	3.7	1.5	1.1	7.1
11+12	5	9.4	20.7	3.2	33.5	29.7	18.1	11.6	2.1	3.6	20.2	1.5	2.8	8.4	1.5	1.0	6.6
13	3	6.8	21.7	5.6	33.1	41.4	9.3	6.6	1.8	4.1	11.1	2.6	5.2	7.0	3.7	1.5	6.4
14	5	4.0	21.7	1.7	27.4	47.7	8.7	7.4	1.9	5.3	10.6	2.4	3.7	4.8	4.3	1.9	6.3
15	4	7.8	17.3	2.4	27.5	48.5	6.1	4.9	1.8	3.7	7.9	3.2	5.6	6.8	6.2	1.9	5.6

1–4. *Saalian* (substratum): 1. glaciofluvial sand, 2. older glacial till, 3. intermorainic sand and silt, 4. younger glacial till; 5–6. *Eemian*: 5. sand with plant detritus and humus streaks, 6. peat; 7–15. *Vistulian*: 7. clayey-sandy gyttja, 8. sand interlaminated with redeposited organic material, syngenetic frost fissures, 9. silt with humus admixture, 10. stratified sand, 11. silt and sand beds, ice-wedge casts at the top, 12. bog soil-humic silty bed (radiocarbon age $28\,300 \pm 900$ BP – Lod 86), 13. silt and sand beds, 14. vertically laminated sand filling frost wedges, 15. sand and gravel with cobbles; 16. *Recent* soil humus horizon. Symbols of minerals: C – zircon, T – tourmaline, R – rutile, G – garnet, A – amphibole (hornblende + lamprobolite + actinolite + cummingtonite + anthophyllite), H – hornblende, P – pyroxene, E – epidote, F – feldspar. Heavy minerals as percentage of total of transparent minerals in fraction 0.10–0.25 mm; feldspar as percentage of total quartz and feldspar grains in fraction 0.5–0.8 mm. *) Number of samples as in Table 3.

den 1990, Vandenberghe 1981, Van der Hammen et al. 1967).

The age of other deposits can be inferred only on the basis of stratigraphic correlation. The sedimentary sequence of units 9–13 can be correlated with the Plenivistulian silty-sandy deposits filling small lateral valleys in the Bełchatów open-cast mine area. These sediments were well-dated radiometrically (Krzyszowski 1990, Manikowska 1992a). Their deposition began between 43 000 and 33 000 years BP and ended between 25 000 and 20 000 years BP, depending on the distance to the main valley. These silty-sandy deposits with organic intercalations commonly accumulated during this period in central Poland, both in valleys and, like at Kalinko, in closed basins. The contemporaneous periglacial climate was cold and rather wet, and a continuous tundra vegetation prevailed.

About 22 000–20 000 years ago, deposition of sandy braided river sediments began in the valleys of central Poland (Turkowska 1990). In small, periodically active valleys and closed depressions, sand and gravel accumulated as the result of high-energy surface meltwater runoff (Klatkova 1985, Manikowska 1992b). The sandy-gravelly unit 15 at Kalinko is the corresponding deposit. This type of sedimentation was common up to 14 000 BP. The climate was then extremely continental, with very cold winters, but without much snow. A cold desert landscape dominated. Continuous permafrost was present and many frost wedges with primary sand infillings were formed, for example at Kalinko, where large sand wedges forming regular polygons of about 15–20 m in diameter occur.

These data allow to attribute the units 9, 10 and 11 at Kalinko to the Middle Plenivistulian and the units 13, 14 and 15 to the Late Plenivistulian: unit 13 to the period ca. 28 000–20 000 BP and the units 14 and 15 to the period ca. 20 000–14 000 BP. The units 7 and 8 belong probably to the Early Plenivistulian.

The widespread sedimentation of aeolian coversands and dune sands began ca. 14 000 BP in central Poland (Manikowska 1985, 1991). Extensive coversand fields and some small dunes were formed in the Oldest Dryas. Deposition of sand and silt laminae is typical for the weakening of aeolian activity during the Bølling phase. Locally, even an initial soil

was formed on aeolian sediments. Such a soil is represented by one or two 1–2 cm-thick humus streaks, the age of which is about 12 500–12 000 BP (Konecka-Betley 1991, Manikowska 1985, 1991). During the Older Dryas, large parabolic dunes were formed and coversand accumulation continued. Stabilization of the surface took place in the Allerød, when a weakly developed but continuous podzolic soil was formed. The radiocarbon dates obtained for this soil range from 11 800 to 10 400 BP (Manikowska 1985). Only small modifications of existing dunes and the deposition of thin sediments on their slopes occurred during the Younger Dryas. These processes ceased at the beginning of the Holocene due to the formation of a well-developed Preboreal rusty soil of which the radiocarbon age is ca. 9700–9400 years BP (Manikowska 1977, 1986, 1990).

The dune at Zamęty is of a form typical for central Poland. It is composed of: (1) sandy deposits of the Older Dryas, with a topmost silty layer probably of Bølling age, (2) sand of the Older Dryas forming the main body of the dune, with the Allerød soil at the top and (3) a thin cover of Younger Dryas sand lying on the dune slope (Fig. 4). Generally, the dune deposits in the region are slightly younger than the sandy-gravelly deposits represented by unit 15 at Kalinko.

Sand grain mineralogy

The results of the heavy-mineral analysis of the Kalinko section are shown in Table 1 and Fig. 3. Mean values for the lithologically different deposits were calculated.

Within the group of very resistant minerals, a tendency for upward increase is observable. The percentages of zircon grains increase slightly in younger Vistulian deposits (excluding sands filling the frost wedges), while the percentages of tourmalines show a distinct increase from on the average 11% in the substratum to 23% in the depression fill. The rutile content varies per deposit, but is generally a little smaller in the filling sediments than in the substratum (mean values 2.7 and 4.4%, respectively). The upward increase of the total number of very

resistant minerals (C + T + R) in the Vistulian units is fairly large and regular. The sand filling the frost wedges (14) and the sandy-gravelly deposits (15), however, show a slight decrease.

Garnet is considered as resistant but its Ca variety weathers faster than the Fe-Mn species (Ollier 1975). Thus, it behaves generally as a medium-resistant mineral. The garnet content in the Kalinko section changes distinctly from ca. 23–35% (mean 29%) in the substratum, via 37% in the Eemian, to 23–30% in the older Vistulian and up to 41–49% in the younger Vistulian units.

Within the unstable minerals, the amphiboles (also hornblende separately) and epidotes decrease upward within the Vistulian deposits from ca. 23 to 6% and from ca. 15 to 4%, respectively. The largest decrease starts from unit 13 or even from the units 11 and 12. In the substratum, both minerals show a large quantitative variation as do the epidotes in older filling sediments. There are slightly more pyroxenes in the substratum than in the depression sediments, in both of which pyroxenes occur in generally small and constant amounts (mean values 3.1 and 1.7%, respectively).

The above relations are illustrated by the weathering ratios in Table 1 and Fig. 3. In general, the ratios C + T/A + P, C + T + R/H and C + T/E increase upward in the depression fill, thus showing a gradual relative decrease of unstable minerals. The G/A + P ratio reflects a diminution of amphiboles (and pyroxenes) and an increase of garnets, but the G/C + T ratio, contrary to expectation, did not show an upward increase of garnets.

Among the light minerals, the feldspars show a more or less gradual decrease from a mean value of 14.1% in the substratum to 5.6% in the youngest Vistulian deposits.

It may be concluded that the progressive weathering, indicated by the decrease of the unstable minerals in the Kalinko section, has been accelerated in the youngest fill deposits, i.e. in the units 13, 14 and 15 (possibly also in 11 and 12), where the increase of the garnet content is also particularly great.

The oldest dune deposits at Zamęty (Table 2, Fig. 4: unit 1) are similar to the youngest sediment (unit 15) at Kalinko as regards the total content of very resistant minerals (25.1 and 27.5%, respectively) and amphiboles (6.5 and 6.1%), but they contain less garnets (35.6 against 48.5%) and more pyroxenes (4.0 against 1.8%) and epidotes (11.1 against 3.7%). The C + T + R/H ratio is comparable (5.9 and 5.6) but other ratios are smaller.

The younger parts of the dune (units 2 and 3) show a decrease of amphiboles, pyroxenes and epidotes to 3.3, 2.6 and 7.5%, respectively. The proportion of garnet increases in these parts to 44.0 and 47.2%, which is comparable with the percentages of this mineral in the youngest Kalinko deposits. The weathering ratios for the younger dune parts are similar to or larger than those for the youngest sediment at Kalinko. The C + T/E ratio is an exception, which probably results from the locally greater content of epidote at Zamęty.

The mean feldspar content in the dune is smaller than in the youngest deposit at Kalinko (4.2 against 5.6%).

The conclusion may be drawn that the oldest dune deposits at Zamęty are somewhat less altered than the youngest sediments filling the Kalinko depression, but within the younger parts of the dune the degree of mineralogical transformation is the same or higher. The upward decrease of unstable

Table 2. Results of mineralogical analysis of Late Vistulian dune deposits at Zamęty. Stratigraphy as in Fig. 4, abbreviations as in Table 1.

Deposit	number of samples	mineral %										weathering ratio					F %
		C	T	R	C+T+R	G	A	H	P	E	A+P	$\frac{C+T}{A+P}$	$\frac{C+T+R}{H}$	$\frac{C+T}{E}$	$\frac{G}{A+P}$	$\frac{G}{C+T}$	
1	4	5.1	18.4	1.6	25.1	35.6	6.5	4.7	4.0	11.1	10.5	2.3	5.9	2.3	3.4	1.6	3.9
2	6	5.9	15.8	2.1	23.8	44.0	4.9	3.9	2.7	7.6	7.6	4.4	6.4	3.3	6.1	2.1	5.2
3	3	5.1	17.5	1.8	24.4	47.2	3.3	2.9	2.6	7.5	5.9	3.3	8.6	3.1	6.8	2.1	3.5
1+2+3+4	13	5.4	17.2	1.8	24.4	42.3	4.9	3.8	3.1	8.7	8.0	3.3	6.4	2.6	5.3	1.9	4.2

heavy minerals and the increase of garnets are distinct in the dune sediments.

Abrasion of sand grains

The proportion of grain-abrasion categories in the sediments of the Kalinko depression is shown in Fig. 3 (diagram B) and Table 3, which illustrate the upwards decreasing number of EL and NU-grains and the corresponding increase of M and RM-grains. The percentages of unabraded grains (NU) and of those abraded by water (EL) decrease from 16.0 and 24.8% in the substratum (mean for units 1, 2, 3 and 4) to about 2 and 3% in the sandy-gravelly deposit (unit 15) and in the sand filling the frost wedges (unit 14). The frequency of aeolian, round mat grains (RM) increases from 24.2% in the substratum to 58.2 and 57.1% in the youngest sediments. The proportion of grains partly abraded by the wind (M) shows first an increase from 35.0 (substratum) to 50.5% (units 11 and 12) and then a decrease to 37.5 and 37.9% (units 14 and 15).

The intensity of the changes is not uniform. The decrease of EL and NU-grains starts from the oldest Vistulian deposits, but its intensity changes considerably in the two youngest units. The increase of RM-grains, rather small in the older Vistulian deposits, is very large for the youngest units. The content of M-grains gradually increases, along with a decrease of EL and NU-grains, but it finally decreases within the units 14 and 15, where EL and NU-grains almost disappear. The M-grains became here the only source for new RM-grains produced by continued wind action.

The proportion of γ , i.e. most spherical, grains increases from 7.4% in the substratum to 22.9% in the youngest unit (Fig. 3, column C, Table 3). The increase is gradual and only between the units 13 and 14 a large change occurs.

All these results indicate an upward increase of aeolian transformation within the Kalinko depression fill (excluding the Eemian sediments). This increase is slow in older Vistulian deposits and fast in the youngest Plenivistulian units 14 and 15.

The dune sediments at Zamęty possess a mean content of 50.4% of aeolian (RM) grains (Fig. 4).

The values for the lower, middle and upper parts of the dune deposits are almost identical: 50.4, 50.2 and 51.2%, respectively.

The Zamęty dune contains slightly less RM-grains than the youngest Kalinko deposits, but approximately the same amount as is found generally in central Polish dune deposits, viz. 52% (Manikowska 1985). There are no essential differences in aeolian grain content between the fluvial, sandy-gravelly sediment (unit 15) and the sands filling frost wedges (unit 14) from Kalinko, and the typical aeolian deposits from Zamęty and other dunes of the region. The Zamęty sequence does not show any progress of wind abrasion in its successive aeolian sediment series.

Interpretation

The main processes which caused the above described changes in the sediments filling the Kalinko depression took place on the surrounding slopes, before transport and accumulation within the basin (except for wave action on the lake shore). The processes were probably: 1) chemical weathering, 2) aeolian abrasion and breakage and 3) density sorting.

If chemical weathering during the Eemian should have been long and intensive, then the amount of unresistant minerals in the Eemian deposits and es-

Table 3. Results of grain abrasion analysis of the Saalian, Eemian and Vistulian deposits at Kalinko. Stratigraphy and abbreviations as in Table 1 and Fig. 3.

Deposit	number of samples	%				$\gamma\%$
		RM	EL	M	NU	
1	12	21.2	31.0	32.8	14.9	11.4
2	14	22.6	19.9	35.8	21.7	4.1
3	15	23.0	21.1	42.4	13.5	6.8
4	10	29.8	27.2	29.0	14.0	7.3
1+2+3+4	51	24.2	24.8	35.0	16.0	7.4
5+6	18	23.6	24.7	36.5	15.2	7.3
7	14	31.3	17.4	39.5	11.8	-
8	13	32.1	15.9	45.2	6.8	7.4
9	14	33.3	15.9	43.5	7.3	8.2
10	16	31.2	13.2	50.3	5.2	6.6
11+12	12	33.1	11.6	50.5	4.8	10.5
13	6	33.4	12.5	47.3	6.8	9.6
14	24	58.2	2.6	37.5	1.7	21.7
15	26	57.1	3.0	37.9	2.0	22.9

pecially in the adjacent post-Eemian slope deposits should be relatively small. It would then also be expected that the quantities of these minerals increase within the Vistulian sequence. In reality, however, we observed a decrease of such minerals, not only near the base (where it is gradual), but especially higher up (more pronounced). Possibly, an intensive degradation of interglacial soils occurred during the Late Plenivistulian. However, the changes in mineralogy parallel the changes due to wind-abrasion. This suggests a genetic relation between these phenomena. A slight decrease of amphiboles, pyroxenes and epidotes in older Vistulian deposits goes together with a gentle increase of wind-abraded grains, while a larger decrease of these unstable minerals in the youngest sediments co-occurs with a sudden increase in aeolian grains. Moreover, the youngest sediments contain also large amounts of garnet which is generally typical for aeolian deposits (Goździk 1980, Kamińska et al. 1986, Manikowska 1985, Urbaniak-Biernacka 1976, Vandenberghe & Krook 1981).

Thus, it seems that the decrease of unstable minerals in the Vistulian sediments at Kalinko was caused mainly by selective mechanical abrasion and breakage during aeolian transport. The decrease is also influenced by the relative increase in garnets. The large garnet content can be explained by the relatively high density of this mineral (3.3–4.4 g/cm³) which causes selection during aeolian transport. Density sorting is often indicated as the cause of a high garnet frequency in aeolian sediments (Van Huissteden 1990).

Density sorting probably also caused the high proportion (40%) of garnets in the Eemian lake shore deposit (unit 5). This amount is large in relation to the low garnet content (23%) in the intermorainic Saalian source deposit (unit 3). Such an increased garnet frequency could have developed due to intensive reworking by waves.

The analytical data suggest that the input of aeolian elements to the Kalinko depression started in the Early Vistulian. It was small in the beginning but intensified with time to a maximum during the Late Plenivistulian. Some data suggest an intensification just before or after ca. 28 000 BP, but the highest increase is observed in sand-wedge infill-

ings and sandy-gravelly deposits dated 20 000–14 000 BP. Thus, the period of most intensive wind abrasion occurred from 30 000 to 14 000 BP. Similar conclusions have been drawn by Goździk (1981) and Manikowska (1990) on the basis of studies in the Bełchatów open-cast brown-coal mine.

Typical aeolian sediments of Plenivistulian age have not been identified in central Poland. The wind activity during the Late Plenivistulian consisted of repeated transport of surface material over an unvegetated surface and of the formation of only thin sand covers and ephemeral convex dune forms. These wind-transformed deposits next became the source of the material filling the frost cracks or were redeposited by rivers and slope waters. Dutch scientists found many beds with typical aeolian features in Plenivistulian deposits filling valleys in the Netherlands. They call them fluvio-aeolian sediments (Schwan 1987, Vandenberghe & Van Huissteden 1988, Van Huissteden 1990).

At the beginning of the Late Vistulian aeolian accumulation phase, about 14 000 BP, many deposits rich in wind-abraded grains occurred in central Poland. Probably, they were the main source of the material which formed aeolian covers and dunes during the Late Vistulian. This is suggested by the similarity in abrasion characteristics between the Zamęty dune and other dunes in central Poland, and the youngest sediments filling the Kalinko depression and other deposits of comparable age. Also, the minor occurrence or absence of wind-abrasion features in sands forming the dunes of comparable scale and age situated more to the north, in the area of the last glaciation (Seppälä 1971, and others), must be considered as an important argument. The source of older wind-reworked deposits was absent in that area.

It is possible that, during the first stage of Late Vistulian aeolian activity in central Poland, the deflation locally reached unaltered or only slightly wind-transformed older deposits. This seems to be the case at Zamęty. The admixture of such material was rather small and new aeolian sediments quickly attained the transformation degree of Late Plenivistulian deposits. Subsequently, the progress became extremely slow.

Conclusions

1. The Vistulian periglacial sediments in central Poland, as represented by the deposits filling the closed depression at Kalinko, show a distinct difference in mineralogical composition and mechanical abrasion when compared to their Saalian substratum.
2. The influence of Eemian weathering is rather small and difficult to interpret precisely.
3. The upward decrease of unstable minerals (mainly amphiboles) and the concomitant increase of more resistant kinds (especially garnets) are significant. Simultaneously, the number of wind-abraded grains increases whilst that of unabraded and water-abraded grains decreases. All these features may be explained as a result of aeolian transport.
4. Initially, the changes were gradual; they intensified strongly from about 30 000 BP onward. The maximum of aeolian abrasion is dated between 20 000 and 14 000 BP, when cold desert conditions existed in central Poland.
5. Typical aeolian sediments older than 14 000 BP have not been identified in the Vistulian of central Poland. Changes due to aeolian transport before the Late Vistulian are recorded in non-aeolian sediments, i.e. in slope, lake and fluvial sediments, as well as in sands filling the frost wedges.
6. Aeolian coversands and dunes were formed during the Late Vistulian, from about 14 000 BP onward. Their mineralogical composition and content of wind-abraded grains are similar to those of the non-aeolian Late Plenivistulian deposits.
7. The main source for Late Vistulian coversands and dune sands were the Late Plenivistulian, non-aeolian deposits with their aeolian abrasion features. The relatively short, Late Vistulian aeolian accumulation phase did not cause important changes. Its sediments did not essentially increase their aeolian transformation in relation to Late Plenivistulian deposits.
8. In sediments which already have a high degree of aeolian reworking, a further influence of aeolian transport is more visible in mineralogical changes than in an increase in wind-abraded grains.

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