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Qualitative and quantitative analysis of microstructures in Polish glacial tills with respect to their age

A new method has been applied in the course of analysis of glacial tills, in areas glaciated during the North Polish, Middle Polish, and South Polish Glaciations. The method has not yet been commonly employed for assessing engineering-geological characteristics of soils. This study has allowed for determination that matrix microstructure is the most common in glacial tills. Among all tills in Poland the youngest tills have maximum porosity, but contacts and structural ties in these tills are loose. The older the glacial tills, the less porosity and closer contacts and ties they have.

INTRODUCTION

This paper presents the comparative characteristics of microstructures in glacial tills in areas of the North Polish, Middle Polish, and South Polish Glaciations. The study of the subject with relation to age of tills has been conducted for a couple of years; as a result, sufficient data has been collected making it possible to summarize the work and define some general conclusions.

The analysis of microstructures was carried out at the laboratory of the Faculty of Geology, Moscow University. There, a high-resolution scanning electron microscope (SEM) was employed along with an image analyser and a software package applicable to quantitative analysis of microstructure display (STIMAN software, version 2.05). The STIMAN software was entirely developed by Professor W. N. Sokolov's team at the Soil Department of the Faculty of Geology. This software is perfectly suited to the purpose of microstructural studies of all medium- and fine-grained soft and hard granular soils. In particular, it has found application in soil science as one method for studying the microstructures of clay soils.

The scanning microscope method allows a short time of examination, high accuracy, and a complete qualitative and quantitative characterization of samples. Due to such advantages, the method can be considered one of the best in studying soil microstructures.

Sample preparation and a detailed course of examination has been described in detail by V. I. Osipov *et al.* (1989); the same has been presented in brief by J. Trzciński's (1993).

Quantitative analysis of a sample provides information on many parameters tbat characterize morphometry and geometry of pore space; in addition, it provides information on distribution of the said parameters within an arbitrarily chosen range. A set of photographs of sample surfaces enables quantitative characterization of the microstructure with all its mineral elements, their contacts and porosity.

The research study on engineering-geological characteristics of glacial tills originating during different glaciations was conducted in a multi-stage arrangement. Study of physical and mechanical properties was conducted in parallel with microstructural study making use of the scanning electron microscope (SEM). Between 1990 and 1992 a scientific description of materials from glacial tills of the North Polish Glaciation was finalized. In 1993 and 1994, work was under way dealing with glacial tills of the Middle Polish and South Polish Glaciations; the work was financed by the University of Warsaw.

The author wish to express his gratitude to all who offered their help during the research study. In particular, this wish is directed to Dr. J. Dzierżek and Dr. J. Nitychoruk for making it possible to collect samples from areas of their dissertations, and for their kind help in sampling; Prof. R. Kaczyński — who was the scientific adviser for this study; Prof. E. Myślińska — the Head of the Soil Science Division of the Faculty of Geology at Warsaw University, where the entire study was conducted; and Prof. V. N. Sokolov from the Soil Department of Moscow University for making it possible to carry out the microstructural examination in his laboratory and for his kind help in interpreting the result.

LOCATION AND SELECTION OF RESEARCH MATERIAL

Location of sampling points for which the microstructures were qualitatively and quantitatively analysed is shown in Figure 1. For the North Polish Glaciation with its maximum extent along the line A–A', the locations of sampling points are in agreement with Figure 1 of R. Kaczyński and J. Trzciński (1992).

From points Figure 1 that are in marked with more than one number, were samples collected from till horizons of different age or from lithologically different horizons. Samples were collected at different depths, the most common was a depth of 1.5 to 3.0 m below ground level. If possible, samples from deeper horizons were collected only from outcrops. Such are the samples from: Ujście near Piła, Wielka Turza near Działdowo, Poznań, Warszawa, Moszczenica, and Bełchatów. The deeper sampling deals with Bełchatów where samples were collected at a depth of 80 m below ground level. In remaining locations, the sampling depths were in the range of a few to a dozen metres below ground level.

The following criteria were applicable when selecting locations for sampling of glacial tills:

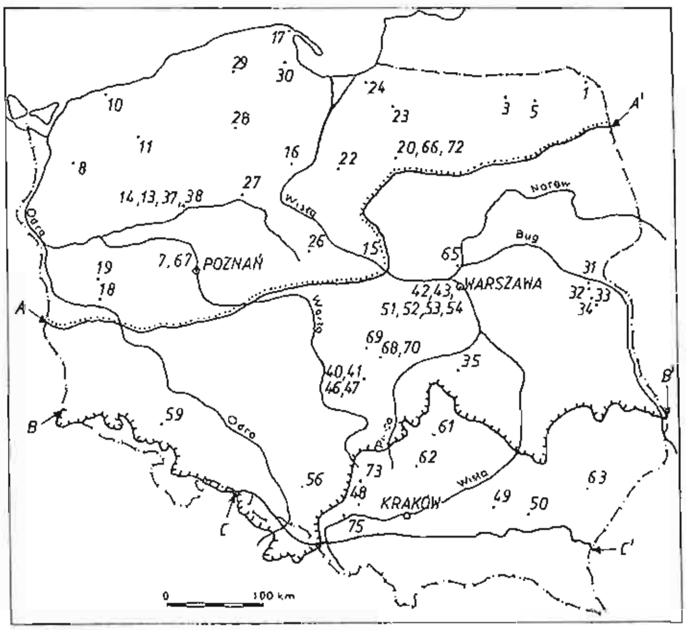

Fig. 1. Location of sampling points; samples collected at these points were subject to microstructural analysis

North Polish Glaciation: *1* — Puńsk, *3* — Giżycko 1, *5* — Ranty, *7* — Poznań, *8* — Stargard Szczeciński, *10* — Włodarka near Trzebiatów, *11* — Jelonki near Połczyn Zdrój, *13* — Ujście 1 near Piła, *14* — Ujście 2 near Piła, *15* — Kobierniki near Płock, *16* — Trzeciewiec near Bydgoszcz, *17* — Władysławowo, *18* — Sulechów–Brzezie, *19* — Świebodzin, *20, 66, 72* — Wielka Turza near Działdowo, *22* — Tiwoli near Brodnica, *23* — Wólka Majdańska near Ostróda, *24* — Elbląg, *26* — Strzelno, *27* — Nakło, *28* — Chojnice, *29* — Bytów, *30* — Przodkowo near Kartuzy, *37* — Ujście 4 near Piła, *67* — Poznań; Middle Polish Glaciation: *31* — Serpelice, *32* — Wólka Nosowska, *33* — Osówka, *34* — Hrud, *35* — Radom, *38* — Ujście 5 near Piła, *42* — Warszawa Metro 1, *43* — Warszawa Metro 2, *46* — Bełchatów 3, *47* — Bełchatów 4, *51* — Warszawa Faculty of Geology, *52* — Warszawa Mokotów 1, *53* — Warszawa Mokotów 2, *54* — Warszawa Mokotów 3, *56* — Gliwice–Ostropa, *59* — Świdnica, *65* — Dębe-on-Narew, *68, 70* — Polichno near Piotrków Trybunalski, *69* — Moszczenica; South Polish Glaciation: *40* — Bełchatów 1, *41* — Bełchatów 2, *48* — Mysłowice, *49* — Brzesko, *50* — Pilzno, *61* — Włoszczowa, *62* — Wodzisław, *63* — Lipiny near Krzeszów, *73* — Woźniki Śląskie, *75* — Pszczyna Stara Wieś; A–A' — maximum extent of the North Polish Glaciation; B–B' — maximum extent of the Middle Polish Glaciation; C–C' — maximum extent of the South Polish Glaciation

Lokalizacja miejsc pobrania próbek, dla których wykonano analizę mikrostrukturalną

Nazwy miejscowości — patrz tekst angielski; A–A' — maksymalny zasięg zlodowacenia północnopolskiego; B–B' — maksymalny zasięg zlodowacenia środkowopolskiego; C–C' — maksymalny zasięg zlodowacenia południowopolskiego

— only such outcrops were selected that ensured freshness of collected samples (clay pits, open mines, sand pits, gravel pits, and foundation excavations),

— till samples were collected from below the freezing and weathering zones,

— an effort was exerted to locate the sampling points so that they would be equally distributed over all three glaciation areas.

However, some difficulties appeared in keeping the sampling points distributed equally; this was due either to lack of new fresh outcrops or lack of glacial till within a given area. Also, Figure 1 does not include all locations from which sample material was collected for laboratory examination since the number of microstructural analysis was sufficient and representative enough to draw more generalized conclusions. From a statistical point of view, 57 samples were selected for qualitative and quantitative microstructural analysis, out of whicb 27 samples were collected from the area of the North Polish Glaciation, 20 samples from the area of the Middle Polish Glaciation, and 10 samples from the area of the South Polish Glaciation.

QUALITATIVE CHARACTERISTICS OF MICROSTRUCTURES

Pictures taken with the use of the scanning electron microscope (SEM) turned out to be helpful in characterizing the microstructures in tills and in classifying their appropriate types. A surface perpendicular to bedding was subject to observation in at least two samples. Magnification was in the range of several hundred to several thousand times.

B. Grabowska-Olszewska's *et al.* (1984) classification was employed for the purpose of determining the characteristics of microstructures.

THE NORTH POLISH GLACIATION

A total lack of orientation of component elements in glacial tills is a particular feature of microstructures in the case of the North Polish Glaciation (Pl. I, Figs. 1–4). Depending on granulometric composition, and particularly on the content of the clay fraction, there are larger elements, aggregates, and silty-sandy grains inserted in a chaotic mass of clayey particles and microaggregates. A skeletal or skeletal-matrix microstructure type prevails in glacial tills with lower elay content and increased quantity of silt and sand fractions. If the amount of the clay fraction increases then the matrix microstructure is more dominant.

The clay microaggregates with their size of a dozen micrometres or so are composed of clay particles, the size of which is a fraction of to several micrometres. Grains belonging to both the silt fraction and fine sand fraction barely appear in aggregates. As to the fine sand grains, they are often surrounded by clay particles; this is the way large aggregates are formed. Their size reaches scores of micrometres or sometimes even more than 100 μm.

Porosity in glacial tills of the North Polish Glaciation is of a complex character. Both the interparticle pores and intermicroaggregate pores are mainly isometric, and their size can be even a dozen micrometres or so.

The interaggregate and intergranular pores are rather anisometric or even fissure-like, and their size can be from several dozen to over 100 μm

The most common contact between particles is of face-to-edge type at large and medium angles. Contacts of face-to-face and edge-to-edge types are very rare or do not occur at all.

Contacts between microstructural elements are of double character. Coagulation contacts, the most common for the microstructures in tills of that age, result from interaction of intermolecular van der Waals forces, electrostatic Coulomb forces, and magnetic forces. Less common are point contacts and phase contacts; both are controlled by ion-electrostatic and chemical forces (B. Grabowska-Olszewska, 1990).

In conclusion it should be noted that the microstructures in the glacial tills belonging to the North Polish Glaciation have very high total porosity and loose structural contacts between component elements, and elements of microstructure are poorly oriented or disoriented.

THE MIDDLE POLISH GLACIATION

In the glacial tills of the Middle Polish Glaciation (Pl. I, Figs. 5, 6; Pl. II, Figs. 7, 8), matrix microstructure is dominant. Another type of microstructure, namely a skeletal-matrix, is less common; this is due to the increase of the clay fraction content in the granulometric composition of tills.

The clay particles form a chaotic and disoriented mass in which large grains and aggregates of silty and sandy fraction have been stuck. In tills of that age it is also possible to observe some orientation of microstructural elements, although this deals with a small number of samples or with some fragments only.

It was noticed that there is almost absolute lack of isometric interparticle and intermicroaggregate pores. Pores of this class are of anisometric or fissure-like shapes only, and their size ranges from a fraction of to several micrometres. The interaggregate and intergranular pores are exclusively of fissure-like type; anisometric pores are rare. There are only a few pores of this class; their size can be scores of micrometres.

Types of contacts in glacial tills of the Middle Polish Glaciation are most often of face-to-edge type, at medium and low angles. Also, face-to-face type contacts appear a more often; however, it is impossible to identify individual clay particles since they have been joined together to such a degree that it is difficult to delineate any boundary between them.

The occurrence of coagulation contacts in the microstructures in tills of this age is of minor importance. The contacts between the structural elements are mostly formed by the contacts of point and phase types. The latter begin to be more important and chemical forces start to be dominant in formation of microstructures.

There is medium or low total porosity in glacial tills that originated during the Middle Polish Glaciation; and contacts between particular elements of microstructure are very close and increasingly stable.

THE SOUTH POLISH GLACIATION

Matrix microstructure is the dominant type in tills of the South Polish Glaciation (Pl. II, Figs. 9–12). The skeletal microstructure cannot be found here, and the skeletal-matrix microstructure can be observed only occasionally.

Depending on the granulometric composition, the glacial tills of the South Polish Glaciation contain a clay fraction as a greater or lesser percentage. The clay fraction makes up a chaotic mass. Embedded in this mass are grains and aggregates of sand and silt fractions. However, the microstructures or their fragments often co-occur with clay particles keeping some previous directional orientation. It is difficult to identify individual clay particles, since these particles and the microaggregates as well, adhere tightly to bigger aggregates and grains.

Interparticle pores are almost entirely missing. Exclusively fissure-like pores are encountered. Both the intermicroaggregate and interaggregate pores are also fissure-like; in addition, they are limited in number. Sometimes thc anisometrie shapes occur among the intergranular pores; but in principle the fissure-like pores are dominant. Their size does not exceed tens of micrometres.

The face-to-face and edge-to-edge types are dominant contacts of elements in microstructures. Contacts of face-to-edge type are almost lacking and are characterized by very low angles.

Phase contacts with dominant chemical forces between microstructural elements occur almost exlusively. Point contacts are very rare; they are held together by ion-electrostatic forces.

It should be noted in conclusion that very poor porosity and strong structural ties are the characteristic features of tills of the South Polish Glaciation.

QUANTITATIVE CHARACTERISTICS OF MICROSTRUCTURES

A representative fragment of the entire sample was selected for quantitative analysis of the sample surface with the use of the scanning electron microscope (SEM). Selected fragments of the sample surface were analysed under eight magnifications in the range of 250 to 32 000 times; a double magnification of consecutive close-ups was the idea involved in magnification procedure. Then, the data set was transmitted to the computer where it was processed using the STIMAN software.

From 10 to 12 parameters were analysed with respect to morphometric and geometric features of porosity. Apart from total porosity and number of pores, the analysis covered the following properties: diameter, perimeter, and total pore area. Direction of orientation and coefficient of microstructure anisotropy were two other parameters used to characterize the geometric arrangement of microstructural elements. These parameters have been discussed by J. Trzciński (1993).

Table 1 offers all results of analysis of microstructures for glacial tills from all three glaciations in Poland. The tabulation contains the most important ten parameters, with their minimum and maximum values and arithmetic averages as well.

From analysis of total porosity a conclusion can be drawn that ranges of variability for glacial tills from consecutive glaciations are partly consistent. In particular, this is clearly visible in the case of tills from the North Polish and Middle Polish Glaciations. A very broad range of variability occurs in the case of glacial till of the Middle Polish Glaciation. There is no correlation between variability ranges for the North Polish and Middle Polish Glaciations. Distinct differences occur in relation to variability of average porosity among the glacial till of all three glaciations. This relationship is exposed not only by the quantitative study with the use of the SEM method but also by laboratory examination. A comparison between these two groups of porosity is shown in Table 2. As can be concluded from this table, there is a very close connection of porosities determined on glacial tills belonging to the North Polish Glaciation. It should be noticed that the maximum number of quantitative analyses and laboratory studies deals only with the tills of this glaciation.

There is also a very good correlation observed in porosity of tills for the Middle Polish Glaciation, despite the fact that the range of analyses and laboratory studies was less in this case. Maximum disproportion appears between laboratory studies and quantitative analyses carried out on glacial tills of South Polish Glaciation. This case refers to the lowest number

Table 1

Quantitative parameters of microstructures in glacial tills

Parameter	Glaciations					
	North Polish		Middle Polish		South Polish	
	R	$\overline{X}$	R	$\overline{X}$	R	$\overline{X}$
Porosity n [%]	30.8–44.1	38.6	22.3–41.5	32.3	19.6–36.2	24.6
Number of pores N [$\cdot 10^3$]	38–842	246	6–274	102	7–293	72
Average pore diameter d_{av} [µm]	0.12–0.40	0.19	0.17–0.88	0.39	0.17–1.35	0.59
Total pore perimeter P [$\cdot 10^3$µm]	70–1011	371	51–391	197	67–440	165
Average pore perimeter P_{av} [µm]	1.08–3.28	1.57	1.22–6.46	2.86	1.50–10.45	4.93
Total pore area S [$\cdot 10^3$µm^2]	9–111	31	24–91	32	23–31	25
Average pore area S_{av} [µm^2]	0.07–0.67	0.18	0.11–2.56	0.61	0.11–3.90	1.30
Average pore form index K_f	0.38–0.60	0.51	0.42–0.61	0.50	0.40–0.49	0.44
Microstructure anisotropy index K_a [%]	0.4–16.5	9.5	5.1–24.0	11.8	4.6–26.3	12.3
Dominant orientation direction of microstructural elements α [°]	23–159	98	3–148	64	12–113	63

R — range of variability; $\overline{X}$ — arithmetic average

of analyses. However, a good agreement in results in both groups of studies confirms the applicability of quantitative analysis of microstructures with the use of the SEM method.

It should be expected that increased porosity is followed by increased number of pores. In particular, abundant pores occur in the tills from the North Polish Glaciation (from 38 to $842 \cdot 10^3$). This is due to the existence of a great number of very fine pores belonging, in particular, to the interparticle and intermicroaggregate types. The total number of pores in glacial tills representing the Middle Polish and South Polish Glaciations decreases in a significant way, and their number is $293 \cdot 10^3$ accordingly. The fine pores in the microstructures of tills from both glaciations are not as abundant as in the case of microstructures in

Table 2

Porosity of glacial tills

Age of glacial tills	Laboratory study		Study with the use of SEM	
	R	$\overline{X}$	R	$\overline{X}$
North Polish Glaciation	31.4–45.8	38.6	30.8–44.1	38.6
Middle Polish Glaciation	25.5–38.2	31.7	22.3–41.5	32.3
South Polish Glaciation	22.5–33.7	28.7	19.6–36.2	24.6

Explanations as in Table 1

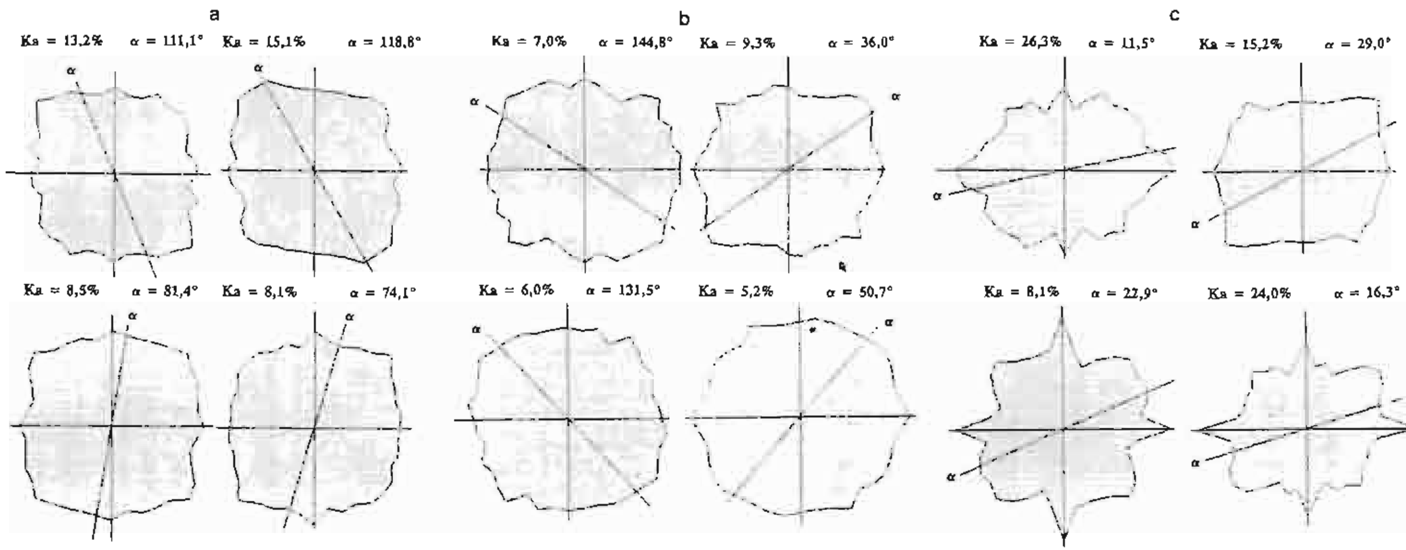

Fig. 2. Rose diagrams for glacial tills: a — of the North Polish Glaciation, b — of the Middle Polish Glaciation, c — of the South Polish Glaciation
K_a — microstructure anisotropy index, α — dominant direction of orientation of microstructural elements

Róże orientacji dla glin zwałowych: a — zlodowacenia północnopolskiego, b — zlodowacenia środkowopolskiego, c — zlodowacenia południowopolskiego
K_a — współczynnik anizotropii mikrostruktury, α — przeważający kierunek orientacji elementów mikrostruktury

tills from the North Polish Glaciation. There is a decreasing trend in a total number of pores, directed toward the tills representing the older glaciations.

Disproportion in distribution of pore sizes in particular tills from different glaciations becomes more distinct when consideration is directed to analysis of average pore diameter. For tills of the North Polish Glaciation this parameter takes a value of 0.12–0.40 μm. For the older glaciations the maximum value of average pore diameter is 0.88 μm for the Middle Polish Glaciation and as much as 1.35 μm for glacial tills of the South Polish Glaciation. The average value shows a very clear increasing trend toward the older glaciations from 0.19 to 0.59 μm. This is evidence for participation in porosity of large pores in older tills as opposed to smaller pores in younger tills.

Consequently, averages for total pore perimeter (P) decrease from as much as $371 \cdot 10^3$ μm for glacial tills of the North Polish Glaciation to $165 \cdot 10^3$ μm for glacial tills of the South Polish Glaciation. An analogous situation refers to the determination of average pore perimeter (P_{av}). The increase in this parameter's value is confirmed for the glacial tills of older and older glaciations. The minimum value of average pore perimeter for glacial tills is equal to 1.08 μm while the maximum is as much as 10.45 μm. Average value of this parameter for glacial tills of the North Polish Glaciation is equal to 1.57 μm, for glacial tills of the Middle Polish Glaciation — 2.83 μm, and for glacial tills of the South Polish Glaciation — as much as 4.93 μm.

Contrary to expectation, average value of total pore area (S) for glacial tills of different ages does not differentiate much. Nevertheless, from analysis of particular ranges of variability there is a big difference emerging in favour of glacial tills of the North Polish Glaciation, in which this parameter reaches a value of $111 \cdot 10^3$ μm^2. The same parameter for the South Polish Glaciation is $31 \cdot 10^3$ μm^2 at most. When analysing the average pore area, an increasing trend is clearly visible in this parameter toward the glacial tills of the older and older glaciations.

The average pore form index (K_f) is a parameter applicable for determining the shape of a pore. The closer the value of this parameter to 1, the more isometric is the shape of the pore. On the other hand, the lower the value of this parameter and closer to 0, the more elongated the pore (meaning: anisometric). The K_f values for glacial tills of the North Polish Glaciation are variable in the range of 0.38–0.60 (with the average equal to 0.51). A similar range for this parameter is also representative for glacial tills of the Middle Polish Glaciation. Sufficiently large range of K_f variability for both the glacial tills provides evidence for different shapes of pores. Significantly lower differentiation deals with the tills of the South Polish Glaciation since the form pore index varies from 0.40 to 0.49 (average equal to 0.44). Therefore, shapes of pores in the till of this age are of lesser variability and their average K_f value indicates the most anisometric pores.

A microstructure anisotropy index (K_a) for the tills representing the North Polish Glaciation is in the range of 0.4 to 16.5%. These values are very low and medium, respectively, and this fact evidences a weak orientation of microstructure in the said tills. The K_a values for the glacial tills of the North Polish and Middle Polish Glaciations are of the same range — from 4.6 to 26.3%. Such facts are a basis for concluding that the microstructures in glacial tills of both glaciations are medium- and high-oriented. Dominant directions of orientation of microstructural elements (α) are consistent with the relationship concluded from analysis of index K_a. The said relationship is clearly shown in Figure 2

Table 3

Quantitative parameters of microstructures in glacial till from selected vertical profiles

Parameters	Ujście near Piła				Bełchatów				Warszawa–Mokotów			
	1		2		2		3		2			
	13	*14*	*37*	*38*	*46*	*47*	*41*	*40*	*52*	*53*	*54*	*43*
Porosity n [%]	34.9	30.8	28.7	24.4	30.2	25.7	22.0	19.6	41.5	36.6	35.6	22.3
Number of pores N [$\cdot 10^3$]	139	77	147	45	53	31	7	13	274	117	247	16
Average pore diameter d_{av} [μm]	0.22	0.23	0.24	0.35	0.40	0.39	1.35	0.89	0.16	0.20	0.17	0.81
Total pore perimeter P [$\cdot 10^3$μm]	244	145	292	144	182	106	67	88	348	232	391	97
Average pore perimeter P_{av} [μm]	1.76	1.88	1.99	3.20	3.47	3.43	10.45	7.00	1.27	1.97	1.58	5.99
Total pore area S [$\cdot 10^3$ μm^2]	28	20	25	23	29	27	25	23	29	31	28	25
Average pore area S_{av} [μm^2]	0.20	0.26	0.17	0.52	0.55	0.87	3.90	1.80	0.11	0.26	0.11	1.54
Average pore form index K_f	0.56	0.54	0.50	0.40	0.45	0.48	0.43	0.43	0.59	0.56	0.52	0.42
Microstructure anisotropy index K_a [%]	8.1	5.8	11.0	15.2	16.9	18.1	26.3	5.5	7.0	5.4	8.2	8.1
Dominant orientation direction of microstructural elements α [°]	74	85	81	29	101	110	12	80	145	148	53	23

1 — glacial tills of the North Polish Glaciations, 2 — glacial tills of the Middle Polish Glaciations, 3 — glacial tills of the South Polish Glaciations; designation of sampling points (by numbers) are given along with the depth of sampling: *13* — 4.5 m, *14* — 7.0 m, *37* — 11.5 m, *38* — 15.0 m, *46* — 3.0 m, *47* — 8.3 m, *41* — 56.0 m, *40* — 77.0 m, *52* — 2.5 m, *53* — 13.0 m, *54* — 19.0 m, *43* — 22.0 m; locations as shown on Figure 1

showing rose diagrams for the structural elements as well as the values of α for the glacial tills.

There is a strong differentiation in minimum and maximum values of quantitative parameters of microstructures for glacial tills from all the sampling points (Tab. 1); this differentiation deals with data from any single glaciation, but also appears among different glaciations. However, the range of average values explicitly indicates essential differentiation occurring between glacial tills of younger and older glaciations.

When consideration is directed to values of parameters for glacial tills in vertical profiles only, then the same differentiation is revealed in a distinct way. Table 3 contains arithmetic averages from quantitative analysis of microstructures in glacial tills from the following three outcrops: Ujście near Piła, Bełchatów, and Warszawa. Consecutive samples were collected from these exposures at increasing depths; they are indicated in the explanation to Table 3.

It should be noticed, when analysing values of parameters for the said exposure, that increasing depth of sampling is followed by a decrease in porosity. Such a situation is representative for each profile. The average pore form index (K_f) also gets lower value with the increase in depth; this is a manifestation of change in pore shape. Pores in till samples collected at shallow depth keep a nearly isometric shape, while pores in glacial tills collected at greater depth are more and more anisometric. This relationship is confirmed by a microstructure with an anisotropy index (K_a), value which increases with depth of sampling. Thus, the glacial tills sampled at shallower depth have weakly oriented microstructure whereas the tills from deeper horizons are highly oriented in this respect. Parameter α, presenting the dominant direction of orientation of microstructural elements, confirms the relationship which was noticed for index K_a.

SUMMARY AND CONCLUSIONS

The qualitative and quantitative analysis of microstructures in glacial tills in Poland has been carried out in order to obtain the complete engineering-geological characteristics of these deposits. This objective has been reached and the characteristics of tills presented with no omission. Completion of the study on microstructures in glacial tills of different age allows presentation of a summary and formulation of general conclusions.

1. The method employed in qualitative and quantitative analysis of microstructures using the scanning electron microscope (SEM) appeared to be very suitable to characterization such as that covered by this paper.

2. High precision and short analysis time are advantages of the method.

3. Samples were collected at depths beneath the zone subject to exogenous conditions.

4. Analysed samples, collected at 57 sampling points, were representative for the North Polish, Middle Polish, and South Polish Glaciations.

When concluding the qualitative analysis of microstructures in glacial tills it should be emphasized that:

1. Matrix microstructure is the main type; skeletal-matrix and skeletal microstructures are of secondary importance.

2. Interparticle and intermicroaggregate pores of isometric type in glacial tills of the North Polish Glaciation change to anisometric and fissure-like types in glacial tills of the Middle Polish and South Polish Glaciations or are entirely missing in those tills.

3. The interaggregate and intergranular pores in the glacial tills of the North Polish Glaciation are primarily of anisotropic type and subordinately of fissure-like type; the fissure-like pores occur almost exclusively in the glacial tills of the Middle Polish and South Polish Glaciations.

4. Contacts between structural elements in the glacial tills of the North Polish Glaciation are mainly of face-to-edge type at large and medium angles, whereas they are of face-to-face and edge-to-edge types in the glacial tills of the South Polish Glaciation.

5. Dominant contacts in the glacial tills of the North Polish Glaciation are coagulation contacts; point contacts are dominant in glacial tills of the Middle Polish Glaciation, and phase contacts dominate in glacial tills of the South Polish Glaciation.

6. The absence of orientation in structural elements is a characteristic feature of glacial tills of the North Polish Glaciation; and the most visible orientation occurs in the tills of the South Polish Glaciation.

Recapitulation of quantitative analysis of microstructures in the glacial tills leads to the following conclusions:

1. Average porosities are lowest in the glacial tills of the South Polish Glaciation whereas maximum values are reached in the tills of the North Polish Glaciation.

2. The total number of pores reaches its maximum in the tills of the North Polish Glaciation whereas it significantly decreases in the tills of both the Middle Polish and South Polish Glaciations.

3. Average pore diameter increases from 0.19 μm in the glacial tills of the North Polish Glaciation to 0.59 μm in the case of tills of the South Polish Glaciation.

4. Minimum average pore perimeter is equal to 1.48 μm in glacial tills of the North Polish Glaciation, and maximum of 10.45 μm is reached in glacial tills of the South Polish Glaciation.

5. Average pore area exhibits an increasing trend toward older glaciations.

6. Pore form index (K_f) for glacial tills of both the North Polish and Middle Polish Glaciations attains greater values than that representative for glacial tills of the South Polish Glaciation.

7. Anisotropy index (K_a) for glacial tills of the Middle Polish Glaciation indicates weakly-oriented microstructures; for glacial tills of the Middle Polish and South Polish Glaciations the index indicates medium- and highly-oriented microstructures.

8. Porosity exhibits a decreasing trend with increasing depth of sampling.

9. Pore form index (K_f) decreases with the increase in depth, and shape of pores becomes more and more anisometric.

10. Microstructure anisotropy index (K_a) for glacial tills increases with depth, and the microstructure itself alters from low- to highly-oriented.

General conclusions to be drawn from the entire qualitative and quantitative analysis of microstructures in the glacial tills in Poland are as follows:

— the older the glacial tills, the more clay particles and microaggregates contained in the tills, thus matrix microstructure becomes more common; on the contrary, skeletal-matrix and skeletal microstructures are more representative in younger tills;

— the younger the glacial tills, the greater the porosities, and ties and contacts between structural elements become more loose;

— total porosity decreases in older glacial tills, and ties and contacts become closer so that strong structural contacts can occur in that tills.

The results of the study presented in this paper deal with one aspect only, namely the differentiation of microstructure parameters in term of a till's age as related to the depth of sampling. There is also another important issue not discussed in this paper, which covers differentiation of microstructural elements in relation to the conditions and the way in which the glacial tills were formed (in other words: in relation to the till's origin). It seems worth stressing that presumably significant differentiation of parameter values within glacial tills of the same age could be controlled by this factor (among other factors). A study aimed at solving the said issue is under way and the results shall be presented in a later publication.

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Jerzy TRZCIŃSKI

JAKOŚCIOWA I ILOŚCIOWA ANALIZA MIKROSTRUKTUR GLIN ZWAŁOWYCH POLSKI NA TLE ICH WIEKU

Streszczenie

Dokonując charakterystyki jakościowej mikrostruktur glin zwałowych, za podstawę przyjęto klasyfikację B. Grabowskiej-Olszewskiej i in. (1984).

Mikrostruktury glin zwałowych zlodowacenia północnopolskiego (tabl. I, fig. 1–4) charakteryzują się całkowitym brakiem orientacji elementów strukturalnych. Mają dużą porowatość całkowitą oraz luźne wiązania strukturalne między elementami, które je budują. Najczęściej występującym kontaktem między cząstkami jest typ płaszczyzna-krawędź (F-E) z dużymi i średnimi kątami. W glinach zwałowych zlodowacenia północnopolskiego dominuje typ mikrostruktury szkieletowej lub szkieletowo-matrycowej. Jeśli zawartość frakcji iłowej jest duża, wówczas gliny zwałowe mają mikrostrukturę matrycową.

W glinach zwałowych zlodowacenia środkowopolskiego najczęściej występuje mikrostruktura matrycowa (tabl. I, fig. 5, 6; tabl. II, fig. 7, 8), rzadko — szkieletowo-matrycowa i szkieletowa. Spowodowane jest to wzrostem zawartości frakcji iłowej w ich składzie granulometrycznym. Obserwuje się wyraźną orientację elementów mikrostruktury. Kontakty między nimi są najczęściej typu płaszczyzna-krawędź (F-E) ze średnimi i małymi kątami. Coraz częściej pojawiają się kontakty typu płaszczyzna-płaszczyzna (F-F) i krawędź-krawędź (E-E). Porowatość całkowita waha się od średniej do małej, a kontakty i wiązania między poszczególnymi elementami mikrostruktury są bardzo bliskie i coraz bardziej stabilne.

W glinach zwałowych zlodowacenia południowopolskiego występuje głównie mikrostruktura matrycowa (tabl. II, fig. 9–12). Nie spotyka się już mikrostruktury szkieletowo-matrycowej i szkieletowej. Dominuje typ kontaktu płaszczyzna-płaszczyzna (F-F) oraz krawędź-krawędź (E-E) między elementami mikrostruktury. Prawie całkowicie brak kontaktów typu płaszczyzna-krawędź (F-E), a jeśli występują, to pod bardzo małymi kątami. W glinach zwałowych tego zlodowacenia porowatość jest bardzo mała, a wiązania strukturalne są silne.

Ilościowa analiza mikrostruktur glin zwałowych (tab. 1–3) charakteryzuje morfometrię i geometrię przestrzeni porowej. Oprócz porowatości (n) i całkowitej liczby porów (N), analizowane były: średnica (d), obwód (p), powierzchnia porów (S) oraz ich kształt, określany przez współczynnik formy porów (K_f). Dla scharakteryzowania geometrycznego układu elementów mikrostruktury, analizowano kierunek orientacji oraz stopień ich orientacji, czyli współczynnik anizotropii mikrostruktury (K_a).

Analizując średnią porowatość w glinach zwałowych (tab. 1), zaobserwowano, że jest ona największa dla glin zlodowacenia północnopolskiego i wynosi 38,6%, natomiast najmniejsza dla glin zlodowacenia południowopolskiego (24,6%). Tendencja wzrostu porowatości w coraz młodszych glinach zwałowych znajduje potwierdzenie w kolejnych parametrach, charakteryzujących morfometrię przestrzeni porowej. Współczynnik formy porów (K_f) dla glin zwałowych zlodowacenia północnopolskiego i środkowopolskiego przyjmuje wartości bardzo zmienne od 0,38 do 0,60 (średnia 0,51). Świadczy to o zróżnicowanych kształtach porów. O wiele mniejsze zróżnicowanie tego parametru występuje w glinach zwałowych zlodowacenia południowopolskiego, gdzie K_f waha się od 0,40 do 0,49 (średnia 0,44). Analiza wartości tego parametru wskazuje na pory najbardziej anizometryczne w glinach zwałowych zlodowacenia południowopolskiego. Współczynnik anizotropii mikrostruktury (K_a) dla glin zwałowych zlodowacenia północnopolskiego przyjmuje wartości bardzo małe i średnie od 0,4 do 16,5% (średnia 9,5 %), co świadczy o jej słabej, a czasami średniej orientacji. Wartości K_a dla glin zlodowacenia środkowopolskiego i południowopolskiego wahają się od 4,6 do 26,3% , a ich mikrostruktury są średnio i wysoko zorientowane.

Analizę ilościową mikrostruktur w profilach pionowych przeprowadzono dla kilku odsłonięć, a prezentowane w tabeli 3 wyniki pochodzą z Ujścia k. Piły, Bełchatowa oraz Warszawy (fig. 1). Porównując porowatości glin w prezentowanych odsłonięciach, wyraźnie widoczna jest tendencja malejącej porowatości wraz ze wzrastającą głębokością. Współczynnik formy porów (K_f), określający kształt porów wraz ze wzrostem głębokości, maleje. Świadczy to o zmieniającym się kształcie porów: od izometrycznych, dla glin zwałowych płytko leżących, do anizometrycznych w glinach leżących głębiej. Kolejne parametry — współczynnik anizotropii mikrostruktury (K_a) oraz kierunek orientacji elementów mikrostruktury (α) — charakteryzują stopień jej orientacji. W glinach zwałowych pobranych z małych głębokości mikrostruktury są słabo zorientowane, a kierunki orientacji elementów strukturalnych bliskie pionowym. W glinach zwałowych pobranych z głębokości większych mikrostruktury są wysoko zorientowane, a kierunki orientacji bliższe poziomym.

Podsumowując jakościową i ilościową analizę mikrostruktur glin zwałowych, należy stwierdzić:

— im gliny zwałowe są starsze, tym więcej zawierają cząstek i mikroagregatów ilastych, a tym samym częściej spotykana jest mikrostruktura matrycowa; w glinach młodszych częściej spotyka się mikrostruktury szkieletowo--matrycowe i szkieletowe;

— im gliny zwałowe są młodsze, tym porowatość jest większa, a kontakty i wiązania między elementami strukturalnymi luźniejsze; pory mają kształty bardziej izometryczne, a mikrostruktury są słabo zorientowane;

— w glinach zwałowych zlodowaceń starszych całkowita porowatość maleje, a kontakty i wiązania są coraz bliższe aż do silnych wiązań strukturalnych; kształty porów są anizometryczne, a mikrostruktury średnio i wysoko zorientowane.

Zaprezentowane wyniki badań przedstawiają zróżnicowanie parametrów mikrostruktur w zależności od wieku i głębokości zalegania glin zwałowych. Ważnym problemem, który nie został poruszony w niniejszym artykule, jest wpływ warunków i sposobu akumulacji glin zwałowych na mikrostrukturę i jej parametry. Należy przypuszczać, że duże zróżnicowanie parametrów w obrębie tych samych wiekowo glin zwałowych jest związane m. in. z tym zagadnieniem.

PLATE I

Figs. 1, 2. Skeletal-matrix microstructure type — North Polish Glaciation

Many silty and sandy grains are suspended in a chaotic mass of clayey particles. Microstruetural elements are disoriented. Microstructure has very high total porosity, loose structural contacts between eomponent elements and very little compaction

Mikrostruktura szkieletowo-matrycowa — zlodowacenie północnopolskie

Duży udział ziarn frakcji piaskowej i pyłowej, które tkwią w bezładnej masie cząstek ilastych. Brak orientacji elementów mikrostruktury, duża porowatość całkowita oraz luźne wiązania strukturalne są przyczyną bardzo małej zwięzłośei mikrostruktury

Figs. 3, 4. Matrix microstructure type — North Polish Glaciation

Clay particles are dominant in granulometric composition. Individual silt and sand grains are suspended in a chaotic mass of clayey particles. The most common contact betwcen particles is of faee-to-edge type at large and medium angles. Elements of microstrueture are totally disoriented

Mikrostruktura matrycowa — zlodowacenie północnopolskie

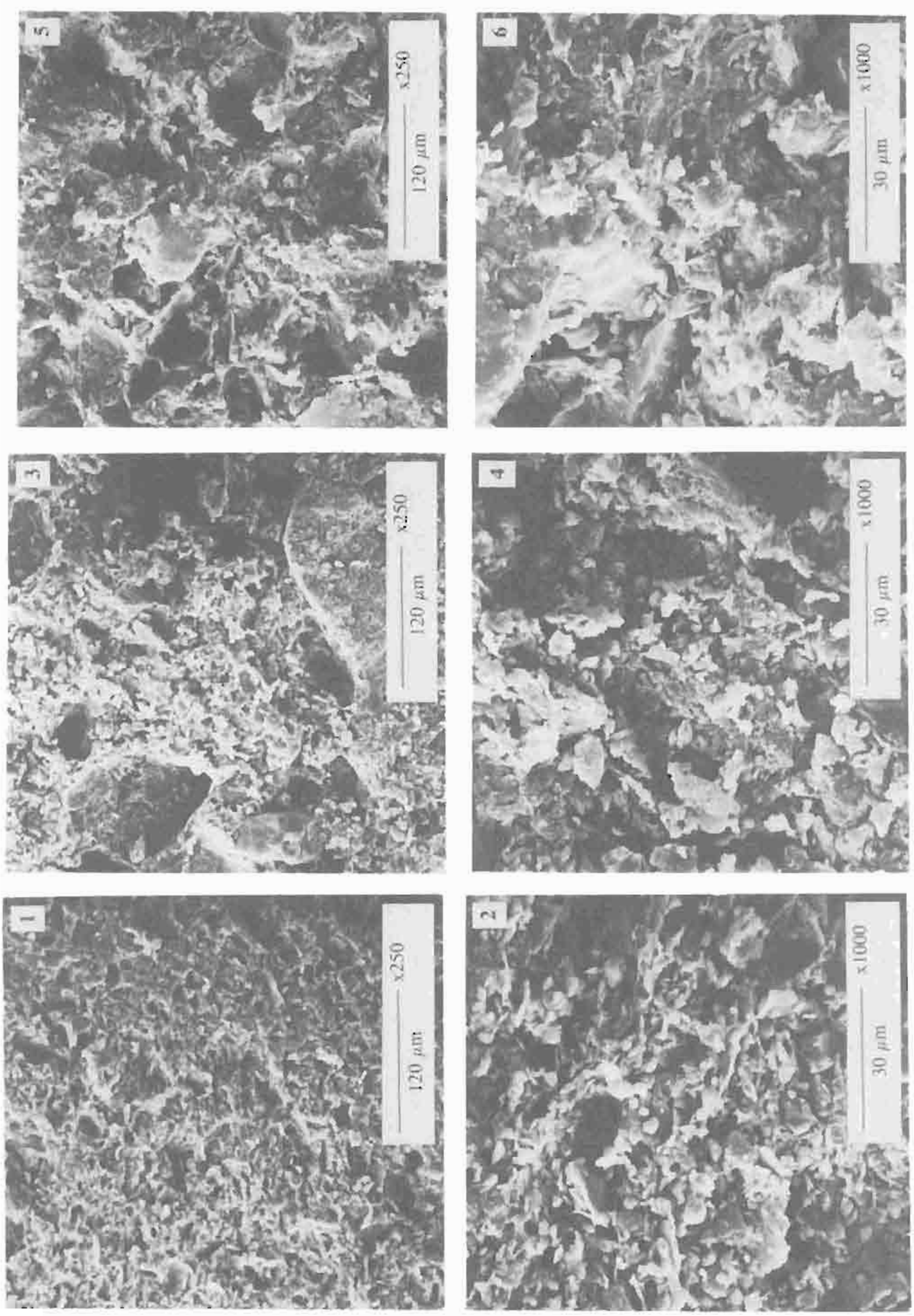
Zdecydowana przewaga zawartości frakeji iłowej, w której tkwią pojedyncze ziarna frakcji pyłowej i piaskowej. Całkowity brak orientacji cząstek ilastyeh powoduje, że najczęściej występuje typ kontaktu płaszczyzna-krawędź pod dużymi i średnimi kątami

Figs. 5, 6. Matrix microstructure type — Middle Polish Glaciation

The clay particles from a ehaotic and disoriented mass in which large grains and aggregates of silty and sandy fraction are suspended. The contacts between the structural elements are mostly formed by contacts of point and phase types. Microstructure in glaeial tills of that age is increasingly stable and has medium eompaction

Mikrostruktura matrycowa — zlodowacenie środkowopolskie

Cząstki ilaste tworzą bezładną, niezorientowaną masę, w której tkwią ziarna frakcji piaskowej i pyłowej. Kontakt między elementami strukturalnymi budują wiązania przejściowe oraz fazowe, które dają bardziej stabilną i średnio zwięzłą mikrostrukturę



Jerzy TRZCIŃSKI — Qualitative and quantitative analysis of microstructures in Polish glacial tills with respect to their age

PLATE II

Figs. 7, 8. Matrix microstructure type — Middle Polish Glaciation

The clay particles are oriented around large grains of the silty and sandy fractions. Face-to-face type contacts appear a more often. Total porosity is medium or low and contacts between particular microstructural elements are very near to each other

Mikrostruktura matrycowa — zlodowacenie środkowopolskie

Cząstki ilaste zorientowane wokół dużych ziarn frakcji piaskowej i pyłowej. Częściej występuje typ kontaktu płaszczyzna-płaszczyzna. Porowatość całkowita średnia lub mała, a kontakty i wiązania między poszczególnymi elementami mikrostruktury bliższe

Figs. 9, 10. Matrix microstructure type — South Polish Glaciation

It is difficult to identify individual clay particles, since these particles, and the microaggregates as well, adhere tightly to bigger aggregates and grains. The face-to-face and edge-to-edge types are dominant contacts of microstructural elements. Characteristic features of microstructure are very poor porosity and strong structural ties

Mikrostruktura matrycowa — zlodowacenie południowopolskie

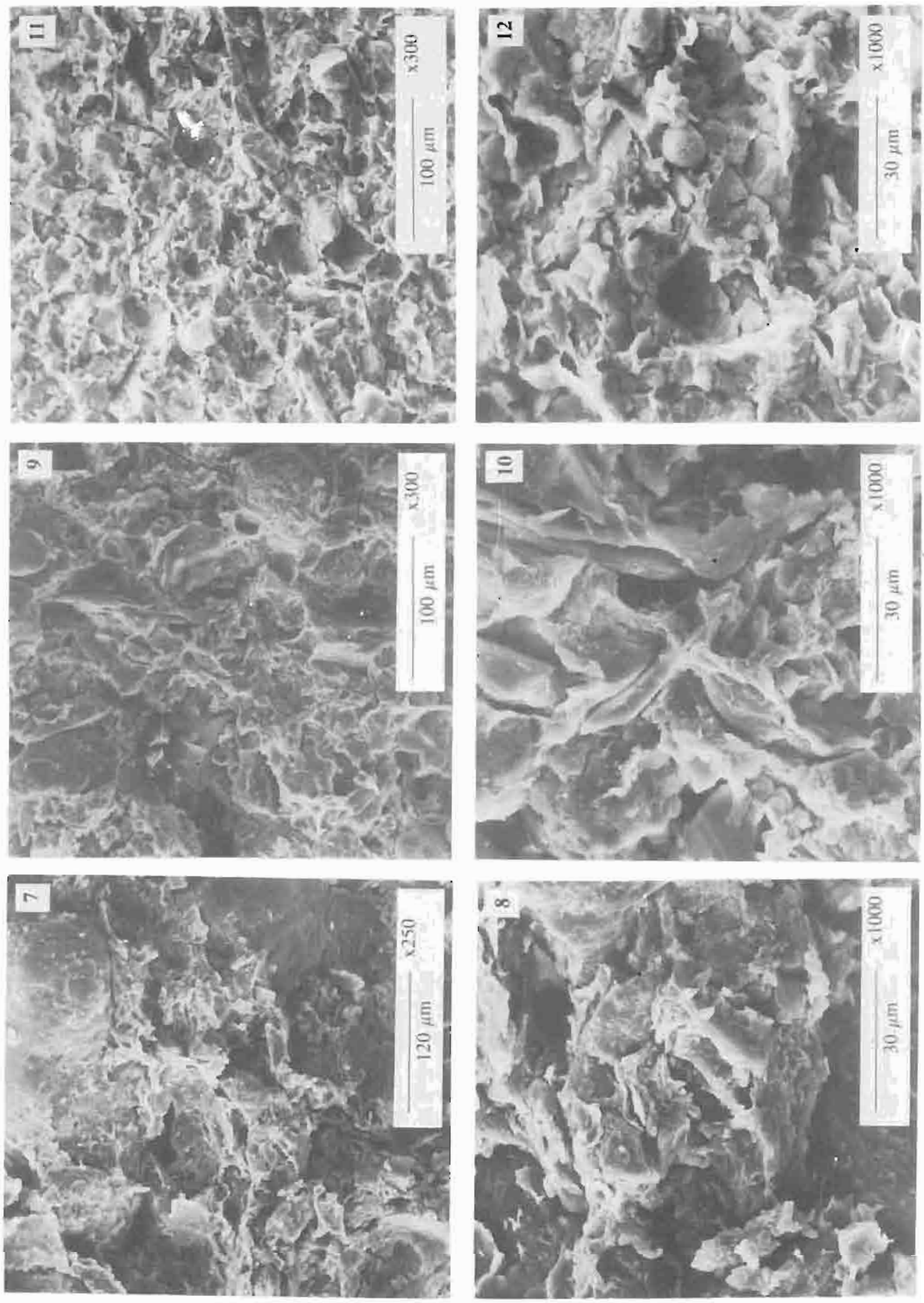
Pojedyncze cząstki ilaste szczelnie przylegają do siebie i do większych ziarn, tworząc uporządkowane kierunki orientacji. Między elementami mikrostruktury dominuje typ kontaktów płaszczyzna-płaszczyzna oraz krawędź-krawędź. Bardzo mała porowatość i silne wiązania strukturalne

Figs. 11, 12. Matrix microstructure type — South Polish Glaciation

The clay fraction makes up a chaotic mass but these particles adhere very tightly to grains of the silty and sandy fractions. Structural ties have phase contacts and their microstructure is very compact

Mikrostruktura matrycowa — zlodowacenie południowopolskie

Cząstki ilaste tworzą bezładną masę, ale bardzo szczelnie przylegają do ziarn frakcji piaskowej i pyłowej. Wiązania wyłącznie o charakterze fazowym, mikrostruktura bardzo zwięzła



Jerzy TRZCIŃSKI — Qualitative and quantitative analysis of microstructures in Polish glacial tills with respect to their age