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UPFREEZING OF STONES IN BOULDER CLAY OF CENTRAL AND NORTH POLAND

Résumé de l'auteur

L'inclinaison et l'orientation des droites passant par la longueur des cailloux ont été étudiées dans les horizons de sols lessivés formés à partir de l'argile morainique. Cette étude a été effectuée d'une part sur le territoire de la Pologne Centrale (stade de la Warta) et d'autre part, la Pologne septentrionale (trois stades de la dernière glaciation).

Les résultats des mesures montrent que la disposition des cailloux n'est pas la même dans les parties supérieures et dans les parties inférieures des profils. En profondeur, la disposition des éléments est due aux processus glaciaires. Dans les parties supérieures, la disposition se caractérise par une plus grande valeur moyenne de l'inclinaison des cailloux ainsi qu'une plus grande dispersion de direction des grands axes, caractères dus à l'action de la multigélation. Cette disposition s'accompagne d'une diminution du nombre des cailloux dans la partie centrale de la zone soumise à l'action de gel et par un accroissement des cailloux dans la partie superficielle.

Les conditions thermiques responsables des mouvements des cailloux ont été variables. Le nombre de cycles gel--dégel, au cours de la période de climat périglaciaire, ne dépassait pas 50 par an dans la couche superficielle du sol; au-dessous de la profondeur de 10—50 cm, elle était limitée à un cycle par an. L'épaisseur de la zone active, au cours du périglaciaire, était comprise entre 1,5 et 2,0 m. Dans les phases du début et de la fin de la dernière période froide, la couche gelant et dégelant chaque année pouvait être plus épaisse. Au cours de l'Holocène, la quantité maximale de cycles gel-dégel dans la partie supérieure du sol moins de 50 cm d'épaisseur a été de l'ordre de 20 par an et la pénétration du gel annuel dans les sols argileux ne dépassait pas 1 m.

Les zones à déformations de la disposition des cailloux très avancées — épaisseur atteignant 1,5 m, valeur moyenne d'inclinaison supérieure à 45°, quantité de cailloux inclinés de plus de 30° supérieure à 70% — correspondent au territoire couvert de glace au stade de la Warta. La position des cailloux a été acquise lors de la dernière période froide et a été seulement un peu plus accentuée au cours de l'Holocène. Les zones de la Pologne septentrionale qui ont été glaciées lors des phases de la dernière glaciation plus anciennes montrent des modifications moins intenses de la position des cailloux jusque la profondeur de 90—70 cm. Les modifications sont survenues ici au cours de la fin du Pléistocène et à l'Holocène. Dans les régions les plus septentrionales de la Pologne, des modifications ont été observées à la profondeur moins de 35 cm. Elles sont sans doute apparues au cours de l'Holocène.

Quant aux mouvements responsables des changements de la disposition des cailloux, ils ont été répartis en trois composants: le mouvement vertical vers le haut qui est responsable des changements de la quantité de cailloux dans le profil, la rotation autour de l'axe moyen qui influence les changements de l'inclinaison et la rotation autour de l'axe court qui cause un accroissement de la dispersion des orientations des cailloux.

Les études effectuées montrent que la vitesse des modifications de la disposition des cailloux et celle de leur migration vers le haut dans l'argile morainique ne sont pas importantes. Les changements dans la zone d'action des cycles gel-dégel annuels ne deviennent perceptibles par la méthode employée qu'après 17 à 19.000 ans d'activité.

INTRODUCTION

The upfreezing of coarse-grained particles in superficial deposits in periglacial regions is well known. It is visible as an accumulation of stones on the tundra or polar desert surface. Although upfreezing occurs wherever ground temperatures oscillate around 0°C, it is considered to be especially important in periglacial climates.

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The relation between upward stone migration and freeze—thaw and ground-ice development has been observed both in the field and in laboratory.

WASHBURN (1969, 1973) distinguishes between upfreezing by either pulling-up or pushing-up. According to the frost-pull hypothesis, first formulated by HAMBERG (1915) and completed by BESKOV (1930), the upfreezing mechanism consists of an upward movement of a stone during the period of frost penetration from above. The upper part of the stone freezes sooner than the lower part, and detaches from the subsoil. The stone does not return to its original position because of thawing progresses from the surface downward.

The frost-push hypothesis, based on HÖGBOM's (1914) and NANSEN's (1922) ideas, explains upward movement as the result of the greater thermal conduction of a stone. During soil freezing water freezes at its base earlier than in the surrounding material and causes upward pushing. The shift of fine material during thawing prevents backward movement. These two upfreezing processes can occur either together or interchangeably, according to conditions.

The tilting of upfreezing stones has also attracted attention. CAILLEUX and TAYLOR (1954) suggest that during the thawing of water saturated ground particles became arranged on edge according to the laws of liquid mechanics.

Laboratory experiments do not confirm this concept. According to PISSART (1973), the rotation of stones occurs during freezing. The upfreezing force meets resistance acting in the opposite direction. This resistance is a function not only of the plasticity of the surrounding material but also of stone dimension and shape. At the time of freezing these two forces form a system which causes rotation. WASHBURN (1973) accepts this explanation and illustrates it graphically.

Fossil traces of stone upfreezing in Central Poland were first described by DYLIK (1961, 1967), who identified them as a distinct frost-structure type. The presence of fossil stone pavements is also partially attributed to the upfreezing process (DYLIK, 1967; KLATKOWA, 1965; WIECZORKOWSKA, 1975). The stone mantle from the climax phase of the last cold period in the Łódź region is of special note [1]. GOŹDZIK (1973) describes a structure in which upfreezing occurred towards the end of the waning phase of this period. A general phenomenon in Central Poland is the accumulation of stones on the boulder clay lying beneath a cover of younger deposits. Stones also occur at the surface, often on quite flat or convex areas. One might suggest that upfreezing was of great importance in their origin.

Lithologically, the boulder clay is especially susceptible to this process.

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[1] According to DYLIK (1967) the last cold period in Central Poland is divided into three phases: waxing, climax and waning. Included is a period of the advance of the North-Polish glacier. This corresponds with the Tubantian period in the Netherlands (VAN der HAMMEN, 1971).

The definition „Late Pleistocene" concerns the latter part of the waning phase and includes the Oldest Dryas immediately preceeding the Bølling interstadial, Middle Dryas, Allerød interstadial and Younger Dryas. The North-Polish glaciation corresponds to the Würm and the Middle-Polish glaciation corresponds to the Riss.

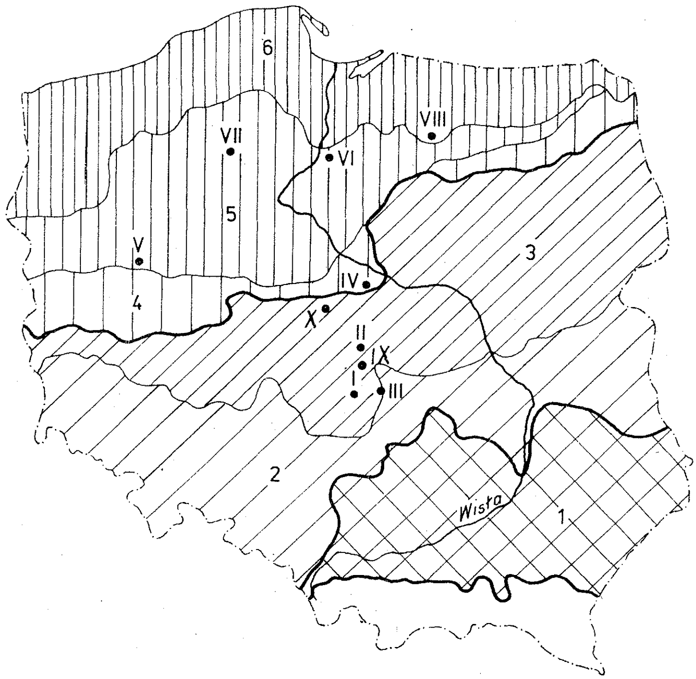


Fig. 1. Location of the study areas

Profile location: I — Zelów; II — Aleksandria; III — Gościmowice; IV — Gostynin; V — Daleszynek; VI — Budy VII — Kamień Krajeński; VIII — Olsztyn; IX — Rzgów; X — Kanibród
1. South Polish glaciation; Middle Polish glaciation: 2. Radomka stage, 3. Warta stage; North Polish glaciation: 4. Leszno stage, 5. Poznań stage, 6. Pomeranian stage

The presence of fine grained impermeable material subject to repeated ice segregation and frost heave would favour the vertical and rotary displacement of stones.

The present study examines the arrangement of thick-clastic components in boulder clays of the Warta Stage of the Middle-Polish glaciation. The influence of movements caused by freeze—thaw processes is investigated. In order to compare, areas covered by various stages of the North-Polish glaciation were also studied.

METHODOLOGY

Measurements were made of the orientation (0) and inclination (I) of stones having dimensions $>$ 2 cm in the upper parts of boulder clay deposits. Measurements concerning stone long axis were undertaken on stone possessing a long mean axis ratio of not less than 1,25. The orientation was fixed by measuring the azimuth of the long axis always according to its inclination and the inclination by measuring the angle of the long axis in relation to the horizontal surface.

The measurements were made in the field by removing clay, layer by layer, from an area 0.5 $\times$ 0.5 m in dimensions to a depth of 1.0 to 2.5 m. The results for each 10 cm of depth were noted separately.

Table I

Measurements of stones inclination and orientation in soil profiles developed on boulder clay

locality	horizon	depth cm	number of stones	$\tilde{I}$ degrees	I > 30° %	$\tilde{\theta}$ degrees	L %	M ± 40° %	D
I — Zelów	1. A_3—A_3B	15—45	30	37	63	356	17	43	
	2. B—C	45—150	31	45	74	338	28	48	1,3
	3. C—C_{Ca}	150—250	33	16	9	322	53	61	
II — Aleksandria (a)	1. A_3—A_3B	20—45	40	42	62	162	23	29	
	2. B—BC——C	45—140	100	45	79	157	49	55	1,7
	3. C—C_{Ca}	140—195	64	26	33	132	45	70	
II — Aleksandria (b)	1. A_3—A_3B	20—45	40	42	62	162	23	29	
	2. B	45 —75	33	49	79	133	52	52	
	3. B—C	75—110	35	53	83	173	41	54	1,7
	4. C	110—140	32	48	75	177	59	77	
	5. C—C_{Ca}	140—170	34	27	38	130	34	67	
	6. C_{Ca}	170—195	30	24	27	135	28	73	
III — Gościmowice	1. P	105—120	40	51	85	311	23	45	
	2. B—C	120—230	39	39	62	295	37	54	1,4
	3. C—C_{Ca}	>230	35	13	6	309	53	69	
IV — Gostynin	1. A_3—A_3B	20—40	51	40	69	165	36	36	
	2. B—C	40—95	60	32	45	122	19	43	1,7
	3. C_{Ca}	95—160	42	13	20	38	40	69	

V — Daleszynek	1. A_3—A_3B	15—30	42	32	48	112	13	34	
	2. B	30—70	51	31	39	346	10	39	1,7
	3. C_{Ca}	70—110	50	16	14	123	57	61	
VI — Budy	1. (B)	20—70	32	38	56	137	27	57	
	2. C—C_{Ca}	70—140	33	16	15	120	29	51	0,9
VII — Kamień Krajeński	1. A_3—A_3B	15—30	50	18	18	290	44	68	
	2. B—C	30—105	54	16	23	285	43	70	1,0
VIII — Olsztyn	1. A_3—A_3B	12—33	46	28	41	140	26	44	
	2. B—C	33—95	44	20	31	126	38	55	1,2

$\tilde{I}$ mean value of inclination
$I > 30°$ number of stones of inclination greater than 30°
$\tilde{\theta}$ resultant angle of orientation
L resultant vector of orientation
$M \pm 40°$ number of observations of stone orientation in the sector of the modal value class $\pm$ 40°
D dispersion coefficient of orientation
Symbols of soil horizons explained in fig. 2.
P horizon of stones in the bottom part of sand cover

The quantity of stones at different depths was also measured. The clay was placed in buckets of 10 litres capacity. Then, a sieve diameter of 5 mm was used to separate stones from fines.

The investigations were made in ten areas. Five were on terrain of the Warta stage of the Middle-Polish glaciation and five others were on terrain of different stages of the North-Polish glaciation. Figure 1 presents the location of these areas. 814 stones were measured; their quantity in any location was not less than 65 (tab. I).

The profiles chosen had features of Grey Brown Podzolic soils (sols lessivés) except for profile VI which represented Brown soils and profile III where the clay was covered by a sandy layer of over 1 m in thickness with a Podzol in the upper part. Symbols employed in Polish soil science were used to designate the soil horizons (Fig. 2).

An A_3 horizon was present in Gray Brown Podzolic soils under a humus horizon A_1. This was a sandy or sandy-dusty horizon of a thickness of 10—20 cm, containing numerous stones. The illuvial B horizon was not always distinguished by a clear colour; it was sometimes the same colour as the brown clay beneath. Lumps of clay of variable size surrounded with sand and dust from the A_3 horizon occurred in the A_3B horizon. Often, numerous fine fissures filled with sandy material were present together with frost fissures of considerable dimensions.

Assuming that stones show a long axes orientation parallel to or (seldom) vertical to the direction of glacial movement, and that the inclination of these axes is, for the greater part, small (Andrews, Smith, 1970; Cailleux, Tricart, 1959; Holmes, 1941; Johansson, 1965; Karczewski, 1963; Lundqvist, 1949), one can evaluate the degree transformation of the stone fabrics by frost processes. This can be accomplished by comparing the lower parts of the profiles, where the arrangement corresponds to glacial conditions, with the upper parts in which changes were observed. The limit between these two parts of the profiles was marked by an increase in the quantity of strongly inclined stones. The results of measurements for the sandy A_3 horizons, considering their origin may be different from clay, were examined separately. In the A_1 horizons, often modified by ploughing, measurements were not made. Thus, the profiles were divided into three parts: frost-unchanged clay (Cca, C), frost-changed clay (C, B), and frost-changed sand (A_3B, A_3). Only profile II, having a sufficiently large quantity of measurements, was further subdivided into six layers of a 15—35 cm thickness.

The measurements were analysed statistically and graphically (Tab. I; Figs. 3—7).

The distribution of the orientation and inclination values for the various parts of the profiles was presented on nets. Radial lines were used to plot orientation azimuths while concentric circles were used to plot the inclination values. The resultant angle (θ) and the resultant vector (L) of orientation were also marked on these nets by means of an arrow, both calculated according to Curray (1956). The resultant angle marks the preferential direction. The resultant

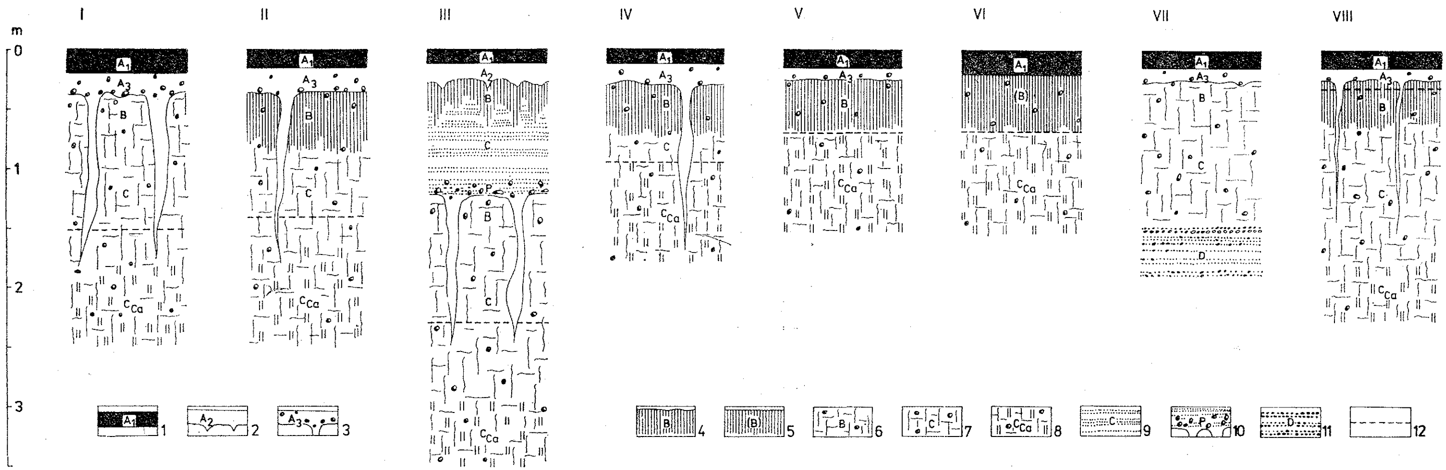


Fig. 2. Soil profile descriptions for study localities

I — Zelów; II — Aleksandria; III — Gościmowice; IV — Gostynin; V — Daleszynek; VI — Budy; VII — Kamień Krajeński; VIII — Olsztyn
1. humus horizon; 2. bleached horizon of Podzol, sand; 3. bleached horizon of Gray Brown Podzolic soil, sand or sand and dust with stones. Beginning of frost wedge filled with sand; 4. illuvial horizon, boulder clay or eolian sand; 5. browned horizon, boulder clay; 6. illuvial horizon not marked in morphology of soil, decalcified boulder clay; 7. noncalcareous parent rock, decalcified boulder clay; 8. calcareous parent rock, boulder clay with $CaCO_3$; 9. parent rock, eolian sand; 10, pavement, stones in eolian sand; 11. underlying sediments, glaciofluvial sand and gravel; 12. limit of deformations in the stone frabic

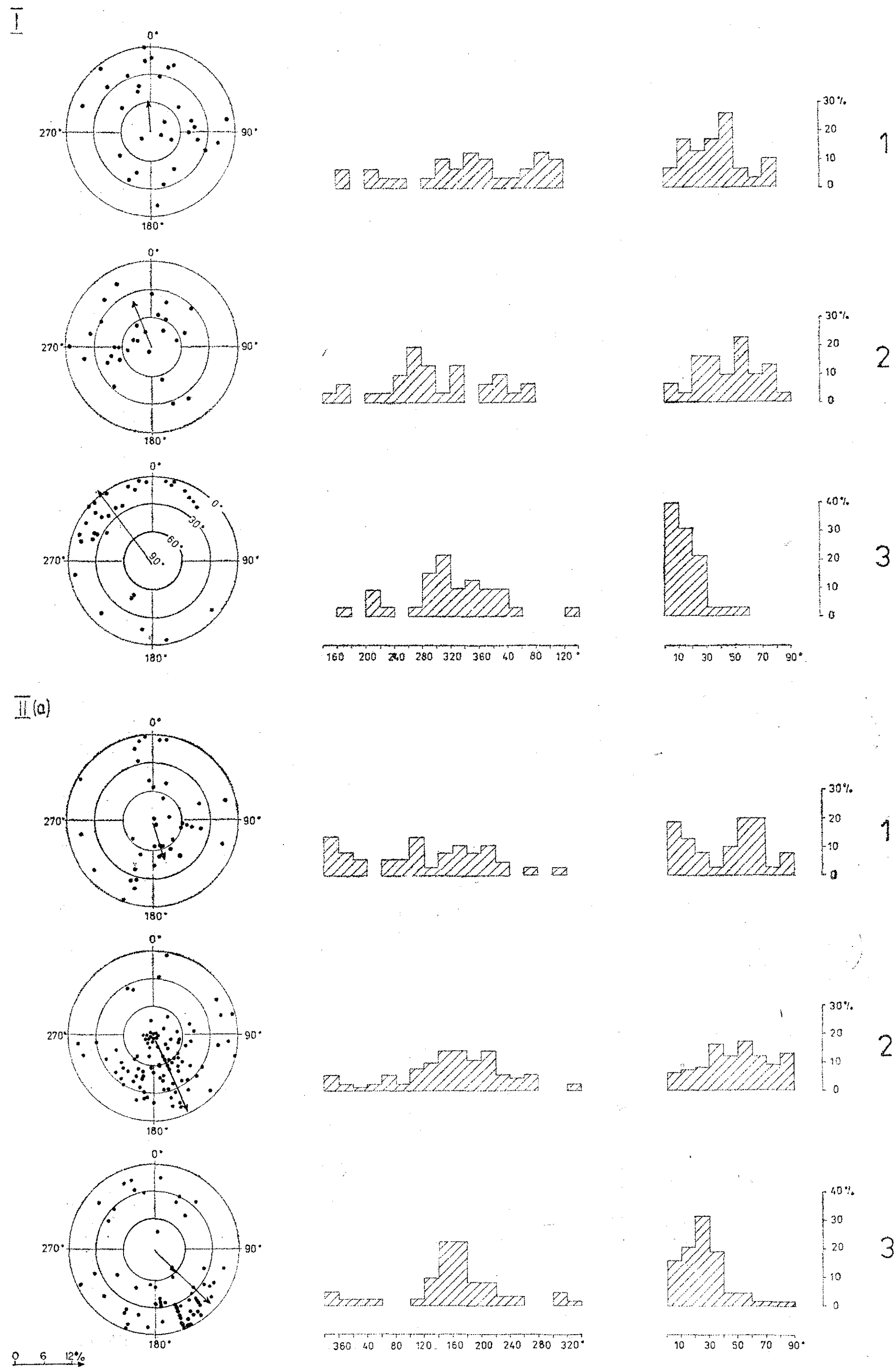


Fig. 3. Results of measurements of stones in the profile I at Zelów and II at Aleksandria (a)

1, 2, 3. numbers of horizons according to table I; diagrams (from right to left): histogram of inclination values, histogram of orientation values, rose diagram of distribution of orientation and inclination values; arrows indicate directions and percentage values of resultant vector

vector is a measure of central tendency and characterizes the degree of scatter about the prefered direction. Its dimension is directly proportional to the degree of dispersion.

Frequency histograms of orientation and inclination values were made. The mean angle of inclination ($\tilde{I}$) and the percentage of the value of inclination above 30° ($I>30°$) was calculated. The value of 30° was agreed upon as the limit between the original inclination and that obtained from frost processes, since in all the lower parts of the profiles the majority of stones had inclinations of less than 30° while above the number in 30—40° class suddenly increased.

To observe the degree of preferred orientation a percentage of all observations in the sector between +40° and −40° from value of the modal class (M ±40°) was used for each part of the profile. The dispersion coefficient of orientation (D), expressing the ratio between the mean percentage of observations in the sector of the modal value ± 40° in the parts of profiles changed and unchanged by frost processes, was used for particular profiles.

The intensity of changes in the arrangement of stones, according to age of the area, is shown by means of curves on Fig. 8, drawn from data in table I.

Measurements of stone quantities in the profiles from the Warta stage area are represented on Fig. 9, where the columns indicate the percentage in relation to the least quantity of stones in the given profile.

STONE INCLINATION

Profiles I and II, situated in area of the Warta stage, show changes of stone inclination, up to a depth of 140—150 cm from the surface. In the lower parts of the profiles, where the stones are in their original position, the mean angles of inclination are 16° and 26° and the frequency of stones at inclination above 30° is only 9% and 33%. Higher parts of the profiles show mean values of inclination rise to 45° and the quantity of strongly inclined stones to 74% and 79%. However, both these parameters decrease to 37°, 42° and to 63%, 62% respectively, in sandy parts of the profiles (horizons A_3 and A_3B).

In profile III, the clay is covered by eolian sand forming a cover 120 cm thick. In the lower part of the cover is a layer of stones approx. 15 cm thick. The depth at which changes of stone inclination appear in profile III, by comparison with profiles I and II, can be estimated as 140 cm. The mean value of stone inclination in this profile increases from 13° to 39° in the clay, and to 51° in the overlying sand. The frequency of stones at inclinations greater than 30° changes from 6% to 62% and then to 85% respectively.

The intensity of inclination changes resulting from frost processes in profiles I, II and III is similar. The depth as well as the intensity of changes are clearly different in areas of the last glaciation, as shown in profiles IV, V, VI, VII and VIII.

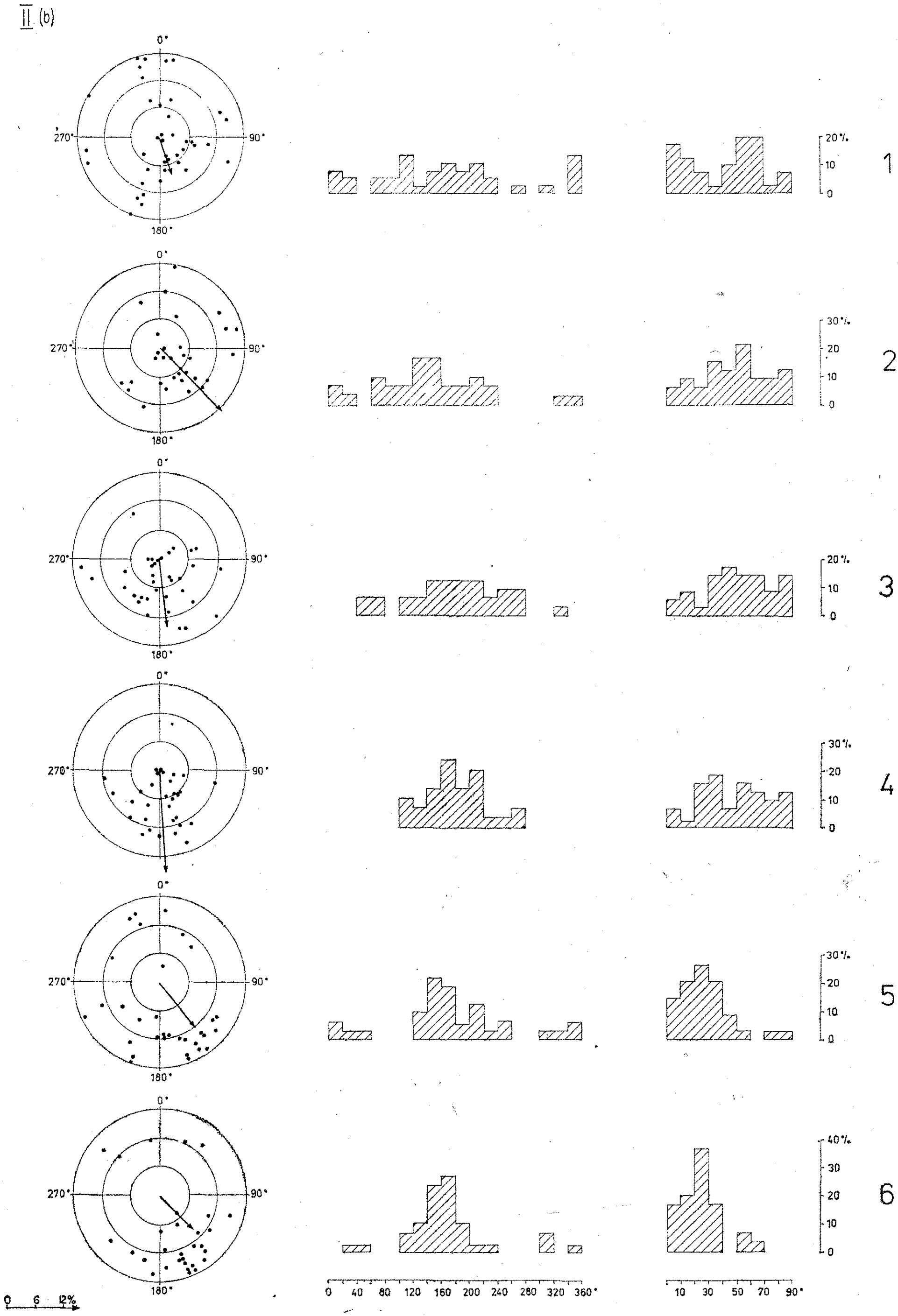
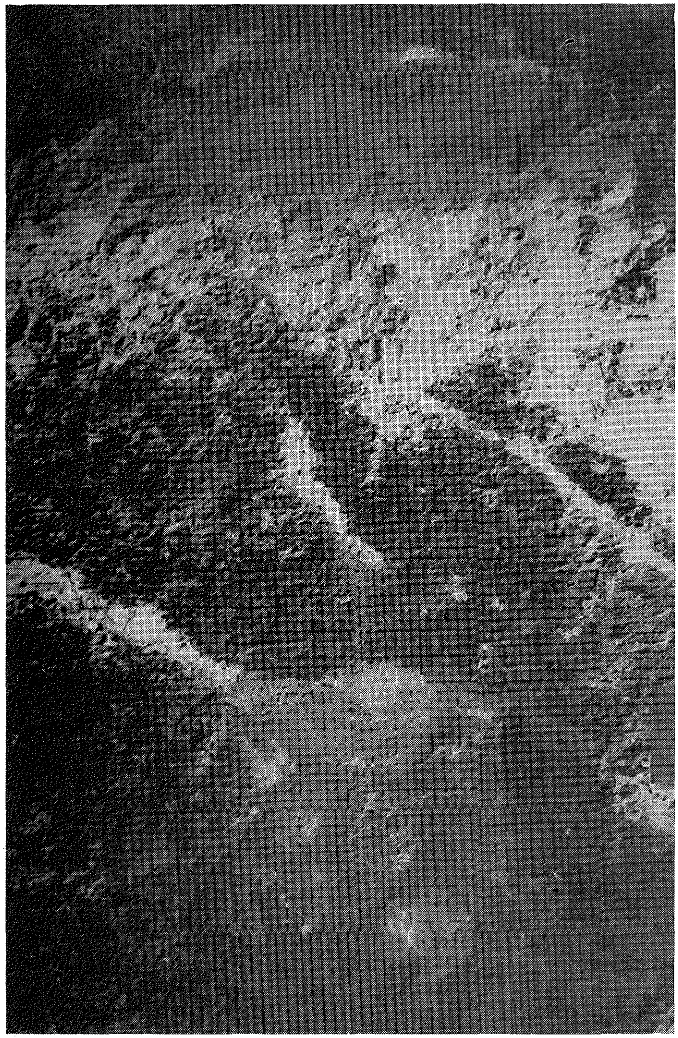


Fig. 4. Detailed results of stone measurements in profile II at Aleksandria (b)

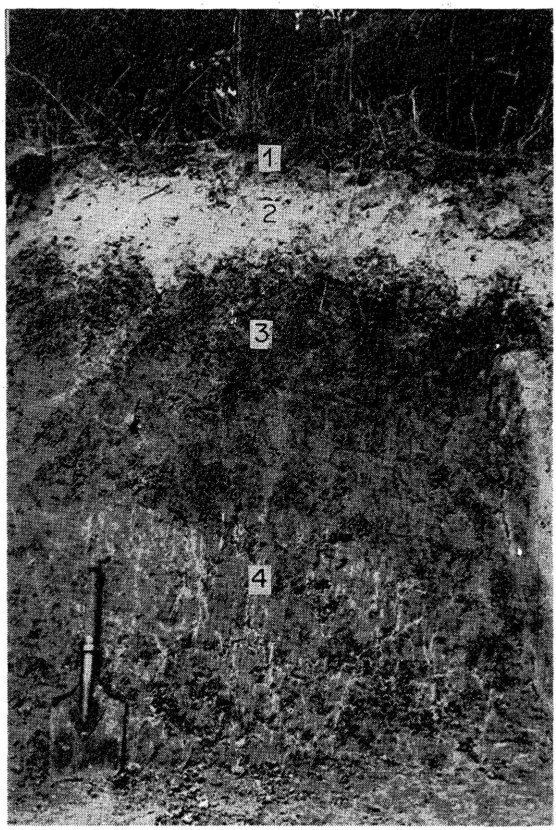
Explanations, see fig. 3



Pl. 1. Zelów. Upper part of profile I with frost wedge (cut with the sloping wall)

Pl. 2. Aleksandria. Upper part of profile II, up to 1,2 m depth

Pl. 3. Zelów. Upfrozen stones in the lower part of the sand cover overlying the boulder clay (compare with profile III)



Pl. 4. Gostynin, Proflie IV. On the right side the part of a frost wedge is visible (see pl. 5)

1. horizon A_1; 2. horizon A_3; 3. horizon B; 4. horizon C_{Ca}

Pl. 5. Gostynin. Frost wedge in profile IV

Pl. 6. Olsztyn. Profile VIII. Small fissures filled with sand

In profile IV, the oldest, from the area of the last glaciation (Leszno stage), the depth of deformations reaches to 95 cm. The mean inclination value increases upwards through the profile from 13° to 40°, and the frequency of angles above 30° increases upwards from 20% to 69%.

Profiles V and VI, situated in the area of the Poznań stage, have similar mean inclination values for lower horizons — 16°, and mean inclination values for the clayey middle horizons (B and (B)) — 31° and 38°. The mean inclination value for the upper horizons (A_3 and A_3B) was 32° in profile V. The frequency of stones inclined at angles above 30° increased upwards from 14% through 39% to 48% in profile VI and from 15% to 56% in profile V. The depth of the stone deformations is the same for both profiles — 70 cm.

Profile VII, also from the area of the Poznań stage, did not show changes in the arrangement of stones. In both upper and lower parts of the profile, to a depth of 105 cm, the mean inclinations were almost the same — 18° and 16°; the percentages of stones of inclinations above 30° were 18% and 23%, approximately similar to values obtained in other profiles for undisturbed horizons. It seems probable that freezing and thawing processes were restricted in this profile to the uppermost A_1 horizon which was not examined.

In profile VIII, located in the area of the Pomeranian stage, inclination changes appear only in the upper A_3 and A_3B horizons to a depth of only 33 cm; the original arrangement remained lower down. Mean inclinations in the two parts of profile are 28° and 20°, and the quantity of stones with inclinations greater than 30° were 41% and 31%.

In the undisturbed parts of all the profiles the quantity of stones with long axis inclinations greater than 30° was not large, fluctuating between 6% and 33%. Mean inclination values range here between 13° and 26°. In portions subject to frost processes the frequency of stones at inclinations above 30° reaches to a maximum of 85% and mean inclination increases to 50°. These changes are most intensive in profiles of the Warta stage and decrease progressively in the area of the last glaciation. The curves represent this clearly on Fig. 8.

The frequency histograms (Figs. 3—7) reflect changes in the inclination of stone long axes and allow one to separate stages of transformation.

In the lower parts of the profiles the histograms are positively skewed. This reflects a majority of small inclinations and a greater scatter of values above the mode.

In profiles VII and VIII no deifference was found between the lower and middle parts. This is why frost processes were not thought to have altered the arrangement of stones.

In the middle parts of the remaining profiles there is a differentation of histograms reflecting the advancement of changes resulting from frost processes. The bimodality of histograms is clearly marked in profiles III, IV, V and VI. Profiles IV, V and VI, submitted to frost processes during a relatively short period, have the first peak higher than the second. Profile III was subjected to

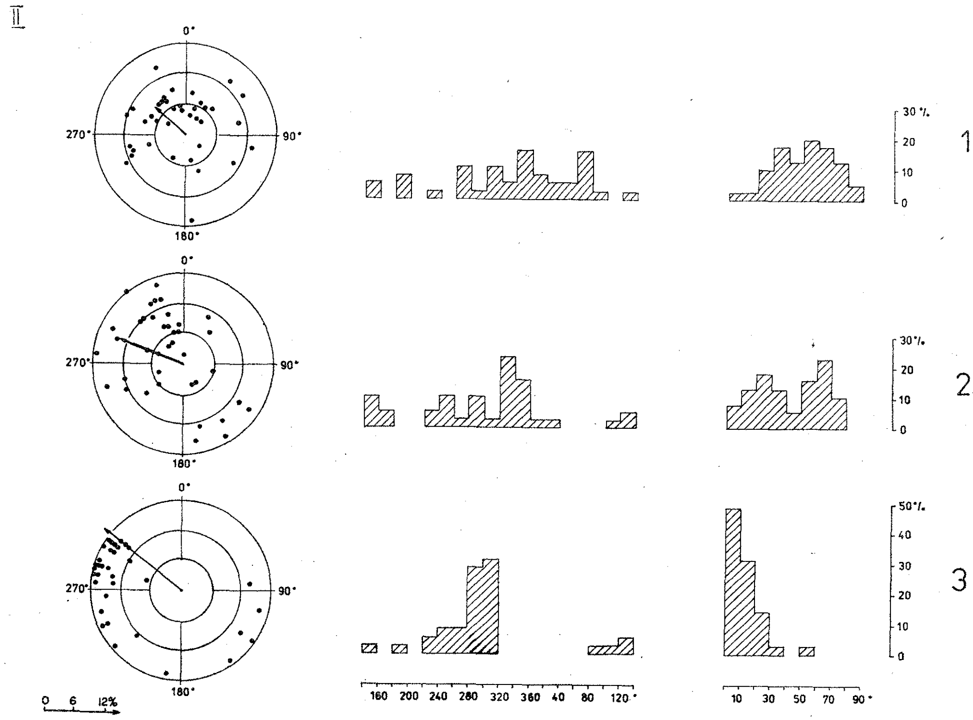


Fig. 5. Results of stone measurements in profile III at Gościmowice

Explanations, see fig. 3

alteration during a longer period and therefore its second peak is higher than the first.

The bimodality in the profiles may reflect differential stone behaviour during upfreezing depending on their original arrangement, shape and dimension. Some stones may be more rapidly influenced by rotation associated with freezing than others.

The bimodality of middle parts disappears in profiles I and II which were influenced by frost processes for the longest time. The histograms show here a modal value higher than the mean value together with a slight negative skewness.

The upper parts of profiles (A_3 and A_3B) are characterized by inclination values which reflect the differentiated duration of frost processes and the bicyclic development of some. The younger profiles, IV, V and VIII have for these parts a one-modal histogram with positive skewness. The modal values of the histograms of the older profiles, I, II and III, are to the right (i.e. towards classes of higher values) and show the negative skewness.

Profile II shows in the upper part a bimodality which seems related to the two-cyclic development of this profile.

It is well known (Manikowska, 1966, 1973) that horizon, A_3 is extraneous to profiles called Grey Brown Podzolic soils developed on boulder clays of the

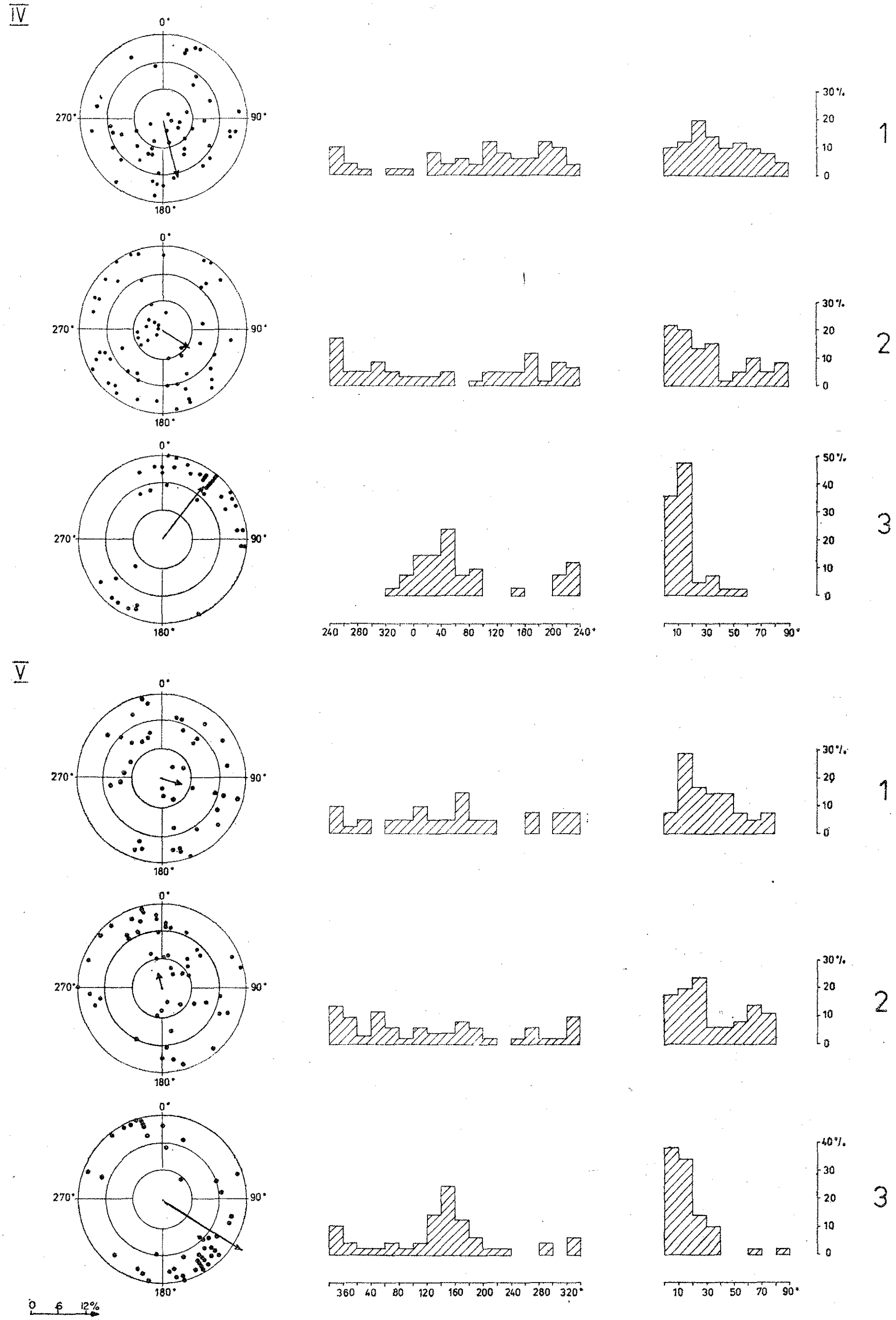


Fig. 6. Results of stone measurements in profile IV at Gostynin and in profile V at Daleszynek
Explanations, see fig. 3

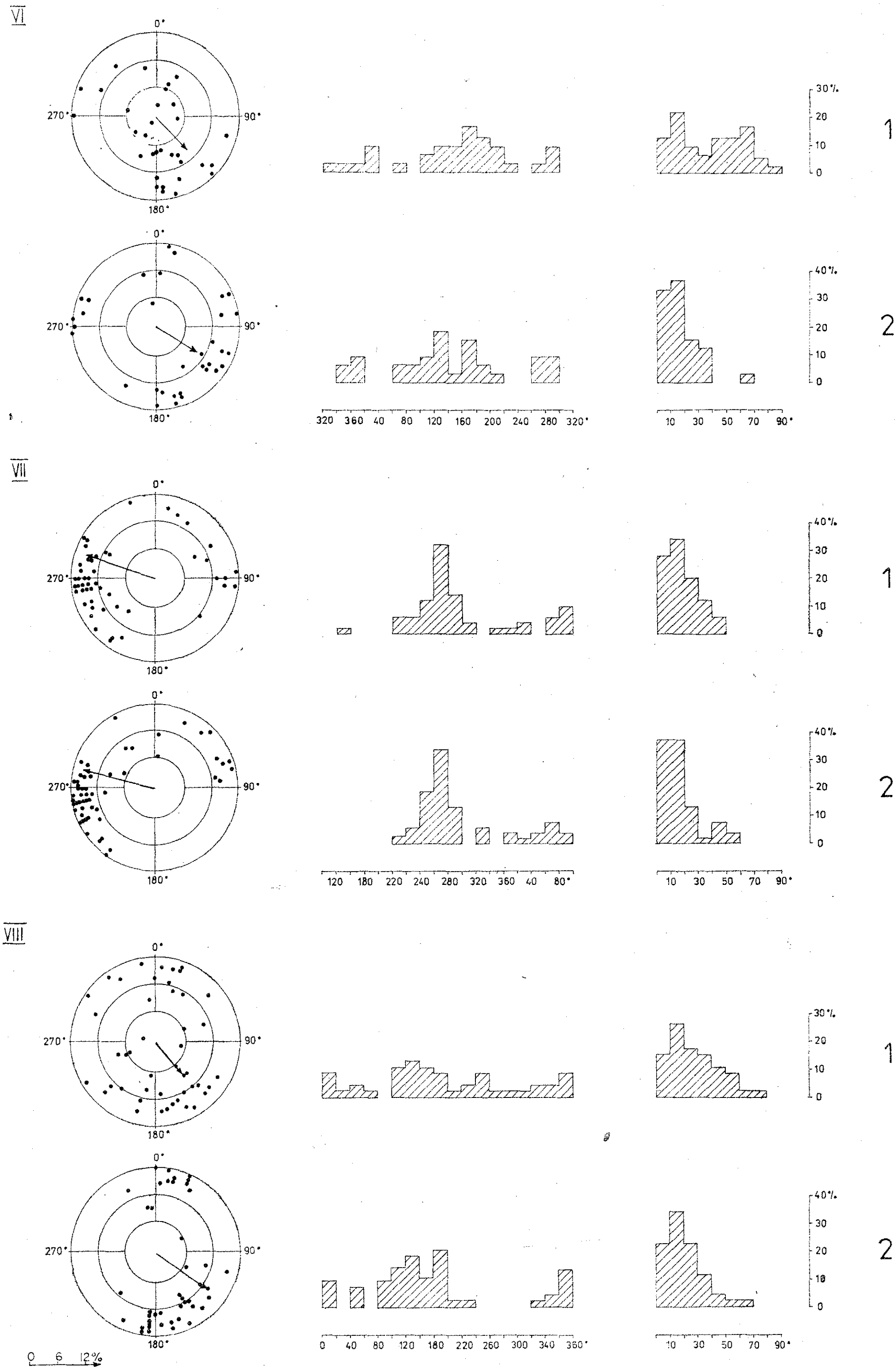


Fig. 7. Results of stone measurements in profiles VI at Budy, VII at Kamień Krajeński, and VIII at Olsztyn

Explanations, see fig. 3

Warta stage in Central Poland. It formed by the accumulation of a thin eolian cover on the clay during the Late Pleistocene. In an earlier period of frost action, changes in the arrangement of stones in the clay resulted from upfreezing and a stone pavement was formed on the clay surface. In a second stage, after accumulation of sand, the stone pavement itself was subject to upfreezing giving a new cycle of rotation and upward migration. The initial phase of the new cycle is marked by a bimodality in the histogram of the upper part of profile II. Probably, such a sequence of events is also recorded in the relative decrease of the mean inclination value in the upper horizons of both profiles, II and I from the Warta stage.

In the upper parts of the remaining profiles there is no bimodality and the mean inclination value is always greater than for the lower parts. This suggests either considerable upfreezing during the second cycle, after the deposition of the sand cover or a monocyclic process of upfreezing.

The rate of inclination change for particular stones is not regular. It is expressed by the statistic data for stone populations at different depths in particular profiles as well as at different profiles subjected to frost processes for different periods of time.

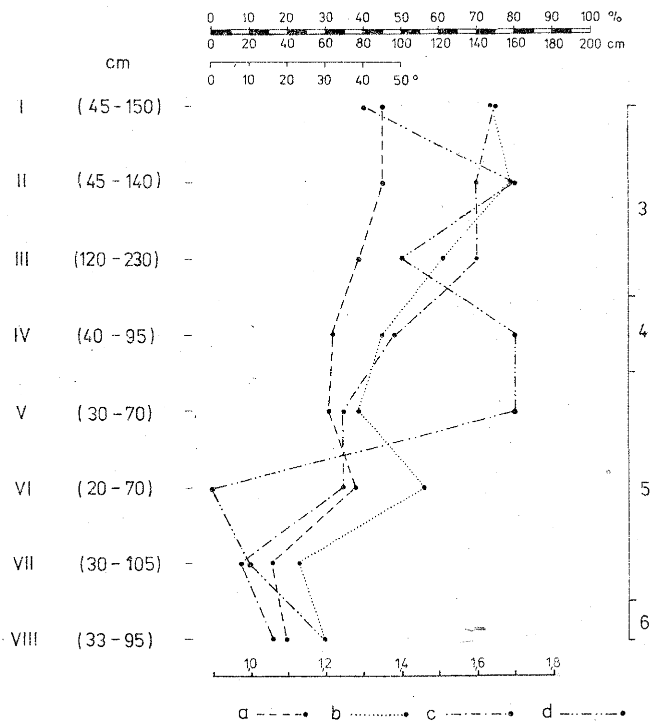


Fig. 8. Intensity of changes in the stone fabrics conditioned by the age of the area

I — VIII — number of profiles; 3—6 — areas of glaciation as in fig. 1; a — mean inclination values (Ī) in the horizons at the depth indicated; b — percentage frequency of stones at inclinations above 30° (I > 30°); c — depth to which changes in the stone arrangement occur; d — value of the dispersion coefficient of orientation (D) in particular profiles

One can summarize the sequence of stone inclination changes in boulder clay under the influence of freezing and thawing processes.

First, there will be a small increase in the inclination of a few stones, but the majority, with low inclinations, will be preserved (e. g. IIb-5, IV-1, V-1, VII-1, VIII-1).

Second, there will be a rapid increase of the inclination of some stones and a slow increase of the remaining majority (e. g. IIb-4, IV-2, V-2, VI-1).

Third, there will be a rapid increase in the inclination of the majority of stones and a slow increase of the remainder (e.g. IIa-1, IIb-3, III-2).

Finally, there will be a rapid increase in the inclination of the majority of stones (e.g. I-2, IIa-2, IIb-2, III-1).

STONE ORIENTATION

The scatter of points in the rose diagrams, the histograms of stone orientation values, and the resultant orientation vectors (Figs. 3—7; Tab. I) show a greater range in the parts of the profiles which were subject to frost processes than in unchanged clay. There is a correlation between the inclination and orientation changes which suggests causal similarity of the processes involved.

The histograms for unchanged by frost processes parts of profiles show a clear dominance of one direction together with a secondary orientation, opposite to the principal direction. This is probably the result of the transport and accumulation of boulder clay during which stones are arranged with their long axes oriented parallel to the direction of ice movement.

Histograms for horizons subject to frost processes show a higher dispersion of directions; the bimodality becomes less clear or disapears and the modal class decreases in value. Traces of the previous distribution still remain since the value of the resultant angle is approximately the same for all horizons.

Profiles IV and V are exceptions. The resultant angle of the middle part of profile V has a value which is 180° different from that of the lower horizon. It suggests that, originally, in the middle part of this profile, there was a predominance of stones having an orientation similar to the axis direction in the lower horizon, but inverse to their inclination. The difference of about 90° between the resultant angles of the lower and higher parts of profile IV is, probably, the result of upfreezing. Alternatively, one may be dealing with two different stone orientations, the boundary between which was the limit of frost deformations.

The number of observations in the modal value $\pm 40°$ sector for lower parts of the profiles amounts to about 50—70%. It decreases in profiles from the Warta stage area (I, II, III), the Leszno stage, and the southern part of the Poznań stage (IV, V), to about 40—50% in the middle parts of the profiles and to about 30—40% in their upper parts.

Resultant vectors of all these profiles show similar changes indicating an increase in dispersion of stone directions in the upper parts of the profiles. Their values decrease from about 40—50% in the lower parts to about 20—30% in the upper ones.

Two of the most northerly located profiles (VI, VII) do not show the changes in orientation parameters, while in one of them (VI) there are clear changes of the inclination of stones. Orientation changes occur only in the thin upper part (A_3—A_3B) of the last profile, in the Pomeranian stage area (VIII). The quantity of observations in the sector M $\pm$ 40° decreases here by over 10% in relation to the lower horizon and the resultant vector changes from 38% to 26%.

The curve of the dispersion coefficient of orientation (D), presented in fig. 8, ilustrates the relationship between the degree of dispersion and the duration of upfreezing. It shows a similar general tendency like remaining curves.

The depth of orientation changes is generally approached to this of inclination changes. However, it seems that the orientation changes appear with some delay. For example, changes in inclination occur without changes in orientation in profile VI and the orientation changes are marked to a depth of about 110 cm while inclination changes are still visible at a depth of 140 cm in profile II.

The increase of dispersion of the orientation directions in profile II is well marked only by some parametres. It is visible in the shape of the histograms and in the value M $\pm$40°; however, a distinct bimodality of the orientation distribution in the lower horizons causes a decrease of the resultant angle value.

The dispersion of orientations shows a tendency to increase in all the profiles, including those in which upfreezing of stones took place during two cycles (i. e. before and after the accumulation of the sandy cover). The data do not indicate that long axis orientations are restricted to a narrow range of directions following upfreezing near the surface of clay. It may be that stones were here subject to frost segregation which would not have led to a preferred orientation.

STONE FREQUENCIES

Measurements of the frequencies of stones were made for four profiles from the Warta stage area marked by I, II, IX and X (Fig. 1). Most stones occur in the sandy-dusty A_3 horizons. They sometimes form accumulations in the lower part of this horizon and reflect, probably, remnants of a pevement previously formed at the surface. The frequency of stones decreases in the A_3B horizons in relation to the A_3 horizon. However, it is always greater in the A_3B horizon than lower down. For example, in profile I there is a minimum of stones at a depth of 60—120 cm which comprises the B horizon and the upper part of the C horizon.

A renewed increase in the number of stone commences in the lower part of the zone where changes occur in the arrangement of stones. A further increase occurs in the noncalcified zone. This increase is recognizable in the sum of all stones, but it is insignificant if noncalcareous stones only are considered.

Upfreezing is probably the principal cause of stone frequency variation in particular parts of the profiles. However, one must take into account also weathering processes. No doubt, a disappearance of calcareous stones in the upper parts is an effect of chemical weathering. It is possible that slight decrease in the frequency of noncalcareous stones above the decalcified zone may be the result of weathering. However, it is not yet possible to determine the importance of this process in relation to the upfreezing process.

Generally, a considerable reduction in stone frequency in the middle parts of profiles and an increase in the upper ones seems consistent with the mechanism of upfreezing of stones.

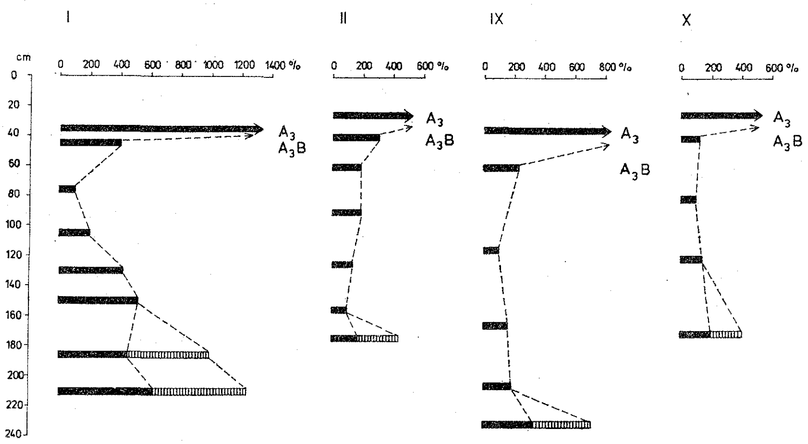


Fig. 9. Quantitative proportions of stones in profiles in the area of the Warta stage

Columns indicate a percentage content of stones in the particular horizons in relation to the horizon of the least quantity of stones in the given profile; calcareous stones marked by lines

As mentioned above, the A_3 horizon was formed through the deposition of a thin eolian cover upon the clay. Originally, this covered a pavement formed during the first cycle of upfreezing. The stones moved to the cover from the pavement or from clay lying lower down during the second cycle of upfreezing.

It appears that pavements occurring on flat or slightly inclined clay surfaces result from upfreezing. However, mass wasting and/or eolian processes may mean that these features are partially allochthonous or erosional in origin. Therefore, accumulations of stones on clay surfaces and in the A_3 horizons cannot be attributed solely to upfreezing.

The increase in stone frequency in the A_3B horizons requires explanation. It does not correspond to either the upfreezing or weathering hypotheses, because both processes increase in intensity towards the surface. Some downward movement of stones is implied, probably before the accumulation of the sandy covers.

THERMAL CONDITIONS OF UPFREEZING PROCESSES

Upfreezing occurs wherever ground temperatures approach or exceed 0°C, i.e. wherever freezing and thawing of ground takes place, either during annual or diurnal cycles.

The number of freeze—thaw cycles cannot be estimated using air temperatures, since there is a great divergence between air and ground temperatures. The latter are more credible although not every fluctuation across 0°C is tantamount to freezing or thawing of soil.

Soil water is a solution of salts which may freeze at temperatures lower than 0°C, dependent on concentration. According to RADOMSKI (1973) the temperature at which soil freezes can decrease to —2°C because of this.

The kind of soil water as well as the cryostatic pressures forming in freezing ground are also significant. It is known that water bounded with particles of solid phase by means of molecular forces freezes in temperature lower than 0°C. Freezing from the surface causes an increase of cryostatic pressure which decreases the freezing point of wet ground.

A traditional opinion is that freeze—thaw cycles are frequent in periglacial areas and are of great importance to weathering and sorting of weathered material. However, opinions have changed considerably during last years.

For example, WASHBURN (1969, 1973) recorded the maximum number of cycles at a depth of 5 cm as 30 (data for two years) in the maritime region of Greenland. At a depth of 10 cm the cycles were less frequent. In general, he states that the number of cycles and their importance for the polar environments has been overemphasized.

FRENCH (1976) expresses a similar opinion stating that the number of freeze——thaw cycles near the surface does not exceed 50 during one year and that the annual cycle is the only one recorded at a depth of 5—10 cm.

According to CZEPPE (1960, 1961, 1966) the extinction of temperature fluctuations about 0°C occurs at a depth of about 50 cm. During the 1957/58 year in SW Spitsbergen the number of complete cycles recorded was 44 at a depth of 5 cm and 29 at a depth of 20 cm.

Changes caused by the annual freeze—thaw cycle reach deeper. The zone of changes corresponds with the active layer, or the zone of seasonal thaw. The depth of the active layer depends not only on general climatic conditions but also on many local factors. Seasonal thawing greater than 3 m is not usually observed.

An active layer of a maximum depth of 1.5 m was found on the west coast of Greenland (WASHBURN, 1969) and of about 2 m on the south-west coast of Spitsbergen (CZEPPE, 1959; DUTKIEWICZ, 1967). Mean maximum thickness of an active layer in Central Yakutia amounted to 2.12—2.65 m (GAVRILOVA, 1973) while in Banger's Oasis, on the east coast of Antarctica it ranged from 40 cm to over 1 m (AVSIUK, MARKOV, ŠUMSKIJ, 1956). Summer thawing in the Canadian Arctic ranges from about 45 cm in latitude 74°N to about 3 m in latitude 61° N where permafrost is discontinuous (BROWN, 1970).

During the last cold period of the Pleistocene permafrost occurred widely in the periglacial zone, including Poland, as indicated by the presence of ice-wedge casts (DYLIK, 1963). Degradation of this permafrost took place in Central Poland before the Oldest Dryas and Bølling interstadial. Afterwards, disconttinuous permafrost occurred (GOŹDZIK, 1973).

The climate of this period in Poland was a continental modification of a periglacial climate with an increase of oceanic influences in the terminal phase. Mean annual air temperature was not higher than —5 °C in the coldest phase of the last cold period (Goździk, 1973). It is estimated as being —3 °C at least for the pleniglacial period in the loess area of Poland (Jahn, 1975). Under these conditions ground temperatures may have dropped below —20 °C, favouring the development of thermal contraction cracks. The climate turned milder in the Late Pleistocene — the mean temperature of July amounted to about 10—12 °C in the Older Dryas and 12 °C in the Younger Dryas (Wasylikowa, 1964).

The frequency and depth of daily freezing and thawing would have been greater in Central Poland during the Pleistocene than in contemporary areas of continental periglacial climate situated in higher latitudes. The daily ground temperature increase is greater in temperate latitudes than in high latitudes where daily temperature oscillations are relatively small.

The depth of thaw amounted to 1—2 m, sometimes more, in southeast Poland during loess deposition (Jahn, 1975). In Central Poland it is estimated as about 1.0—1.5 m for the coldest phase of the pleniglacial (Goździk, 1971). The active layer would have been deeper during periods of less severe cold such as the beginning and end of the last cold period.

The seasonal zone of freezing which Poland experiences in the Holocene is shallower than in present periglacial areas. The number of freeze—thaw cycles is also smaller.

The depth of winter freezing for France and Belgium amounst to about 30 cm at present (Cailleux, Taylor, 1954; Pecrot 1956). A similar depth of seasonal thaw can probably be attributed to Poland during the Atlantic phase of the Holocene. The climate during the remaining phases of the Holocene in Poland were similar, probably, to the contemporary climate.

Information regarding contemporary ground thermal conditions in Poland can be found in publications of the National Institute for Hydrology and Meteorology, Warsaw.

Figure 10 presents data concerning the maximum depth of freezing in different soil types in Poland. Measurements show thas soils freeze to shallow depths during most winters. During 108 measuring years (58%), out of 186, temperatures were $\leqslant$ 0 °C at a depth less than 50 cm; in this number 80 (43%) were at a depth extending from 20 to 50 cm and 28 (15%) were at a depth not below 20 cm.

There is considerable variation of freezing depths depending on meteorological conditions and other factors in particular years. Figure 10 indicates that the depths vary from between 5 and 10 cm to between 50 and 100 cm. Radomski (1973) concludes that the greatest depth of freezing on flat terrain in Poland is approximately 1.2 m. This is rare and occurs only during exceptionally cold and snowless winters.

In order to analyse the influence of soil type on freezing depths all data from Poland for the period 1954—1960 were examined. A distinction was made between

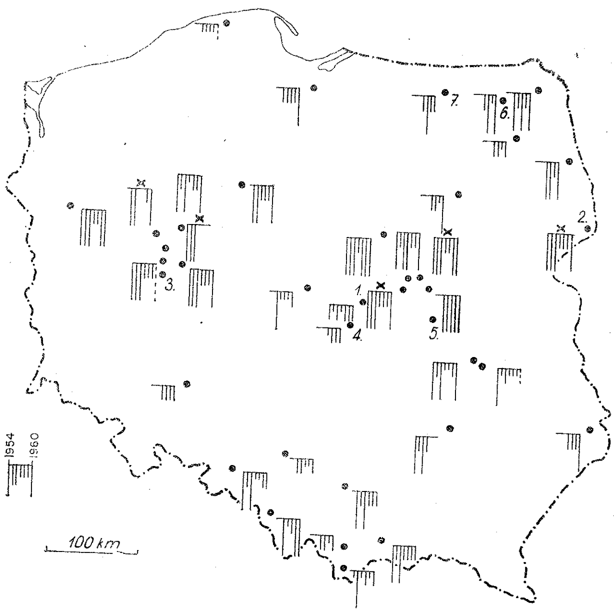


Fig. 10. Depth of the range of ground temperatures ≤0°C in Poland for 1954—1960 period (Source: Results of soil temperature measurements, PIHM, Warsaw)

Temperature ≤ 0°C: at the depth of 50 cm — the longest vertical line, at the depth of 20 cm — line of medium lenght, at the depth of 10 cm — the shortest line; point — location of the station; crooss — station recording data to the depth of 1 m or 1,5 m; 1—7 — stations which are presented in table II

soils developed on sands and gravels (40 stations, 153 measuring years) and on clays, loesses and loams (30 stations, 102 measuring years). The following percentages were obtained for particular depths:

Depth of freezing	0—20 cm	20—50 cm	≥ 50 cm
Sands and gravels	11	39	50
Clays, loesses and loams	23	52	25

The results show that the depth of ≥ 50 cm appears most often in sandy and gravelly soils while that of 20—50 cm in clayey, loess and loamy soils. The depth of 0—20 cm is twice as frequent in second group than in the first one. This is consistent with prevailing opinions that soils consisting of fines are frozen to shallower depths than coarse-grained soils.

In summary the depths of contemporary freezing of soils in Poland does not exceede 1 m. The depth is less than 50 cm in sandy and gravelly soils in 50% of all cases. The likelihood of shallow freezing for clayey soils is greater and amounts to 75%. Probably, such a situation existed in Poland during the phases of the Holocene which experienced a climate similar to the present. Some phases of even milder climate had probably still shallower freezing.

Data illustrating the ground temperature changes in the annual and five year cycles for several clayey profiles (Fig. 10) are outlined in table II. The first part concerns two soils from Central Poland (1. Skierniewice) and East Poland (2. Białowieża) and comprises data for five consecutive winters. The second part presents data from five different areas in Central Poland (3. Borowo, 4. Strzelna, 5. Warka) and North-east Poland (6. Siejnik, 7. Kętrzyn) from one winter only.

These data show that contemporary minimum ground temperatures do not drop below —7°C in clay soils. During many winters they drop below 0° C by only a fraction of one degree.

The number of times when temperatures rise through 0°C during one autumn--winter-spring period amounts to 20; however, there is only one cycle during some years. The number of cycles decreases with depth, although the changes do not always follow a regular path. Usually the greatest number occurs at the depth of 5 or 10 cm.

The frequency of ground temperature fluctuations about 0°C in one profile varies in particular years (for example: Skierniewice — 6 to 18 cycles, Białowieża — 1 to 8 cycles) as well as in particular profiles in the same year (for ex.: 1956/57 — 1 to 20 cycles). The reasons for this variability are complex. Neither weather, thickness of snow-cover nor variability in the mechanical composition of the clay soils are decisive. The period of negative temperatures in soils is much shorter than that of ground frost and fluctuations of temperature at the ground surface are not sufficient to judge the number of freeze—thaw cycles in the ground.

Often oscillations of ground temperature are insignificant and drop below 0°C by only a fraction of a degree. The displacement of the freezing point of 1°C below zero, which can occur in natural conditions, causes a considerable decrease in the number of freeze—thaw cycles from a maximum of 20 to a minimum of 2, as well as making soil freezing impossible during some years.

If freezing exceeds 50 cm in clay profiles, which happens relatively seldom, amplitudes of short-term oscillations of temperature around 0°C, if any, are so small that they do not cause freezing and thawing. Therefore, there is usually only the annual cycle of freezing and thawing. It follows that short—term processes of freezing and thawing disappear in clayey profiles on the terrain of Central and North Poland at the depth of 20—50 cm or even shallower.

Molga (1970) states that the amplitude of diurnal soil temperature under Poland's present climatic conditions is equal to zero at the depth of 70—80 cm and that insignificant differences of diurnal temperature occur at a depth of 50 cm. This agrees into the opinions expressed above.

CHRONOLOGY OF FROST-DEFORMED ZONES

The stone deformations described in this paper occur in the area of the Warta stage, of the Central Polish glaciation, and of particular stages of the North Polish glaciation. A correlation exists between the age of the soil concerned the depth and intensity of the deformation. The earlier the area was ice-free the thicker are the deformed zones and the more striking are the changes in the arrangement of the stones.

However, the depth and intensity of stone deformation are a function not only of time, but also of soil thermal conditions. The depth of annual thaw in clay terrain experiencing a moderate, continental climate amounts to less than 1 m. Also, short—term freezing and thawing does not exceed 50 cm. In periglacial climates the maximum thaw of permafrost is about 3 m, while diurnal, short--term, freezing and thawing does not penetrate more than 30—50 cm below the surface. Thus, the annual thaw is about three times deeper, while the short--term thaw resembles that resulting from the contemporary climate of Poland. The frequency of freeze-thaw cycles occurring in the seasonally thawed zone is considerably greater than in Poland at present.

It follows, therefore, that stone upfreezing at depths of less than 1 m in the area of the last glaciation in Poland may have been formed in the Holocene. However, variability in depth of upfreezing is connected to areas situated progressively more northward.

The 30 cm depth of deformation observed in the most northerly profile (VIII) is attributed to a relatively short period of upfreezing. Although small fissures, filled with sand and resembling frost fissures, occur, it cannot be proved that the shallow upfreezing zone developed in the periglacial climate of the Late Pleistocene. Profile VII shows no deformations which probably existed in the A_1 horizon to a 15 cm depth but they have been destroyed by cultivation.

The deeper depths of deformations in the profiles VI (70 cm), V (70 cm) and IV (95 cm) in areas of Poznań and Leszno stages, is related probably to annual freeze—thaw cycles. The upfreezing process must have occurred here longer than in profile VIII. Upfreezing began in these profiles during the end phase of the North Polish glaciation, immediately after retreat of ice, and profile IV was affected a little sooner than profiles V and VI. A greater intensity of deformations in profile IV is probably an expression of this difference.

Profiles I and II from the area of the Warta stage posses a depth of deformation of 1.5 m and 1.4 m respectively. These depths exclude the possibility of their origin only in the Holocene because they exceed the depth of freeze—thaw during this period. On the other hand, these depths correspond to the average depth of the active layer in the periglacial climate of the last cold period.

The upper A_1 and A_3 horizons of these profiles developed upon thin covers of eolian sands deposited on boulder clay. Earlier upfreezing zones had a depth of about 1.1 m or even greater if they had been subject to denudation processes and a lowering of the land surface.

Long-continued upfreezing in the active layer before the accumulation of the eolian cover caused substantial deformations in stone fabrics at depths exceeding the zone of present seasonal thaw. Upheaving of stones, generally from the pavement lying upon the boulder clay, and their migration upwards through the sand cover occurred first under periglacial conditions and then during the Holocene. The two-stage upfreezing in profiles I and II is observed in some of the statistic parameters presented earlier. As a result of the superimposition of Holocene upfreezing processes upon longer-lasting Pleistocene upfreezing processes more intense and deeply-deformed zones developed than those zones formed only during the waning phase of the Pleistocene and in the Holocene.

Well developed upfreezing zones beneath Late Pleistocene deposits of considerable thickness are important proof that the deformations of the stone arrangements in the profiles of the Warta stage area are relict features. It is evident in profile III where the deformation zone 1.1 m thick, is covered by 1.2 m of eolian sands. The age of the upfreezing zone in boulder clay is Pleistocene since the thickness of the overlying sands excludes an influence of Holocene processes. The intensity of deformations in the boulder clay is less than in the corresponding horizons of profiles I and II which experienced frost processes during the deposition of the sand cover and during the Holocene.

The deposition of the eolian cover in profile III was simultaneous with formation of dunes in Central Poland; they were formed in the Late Pleistocene (Chmielewska, Chmielewski, 1960; Dylikowa, 1964; Manikowska, 1977; Rotnicki, 1970; Wasylikowa, 1964). Most likely, thin sandy covers forming the upper horizons in profiles I and II occurred also in this time. In Poland cool periglacial conditions dominated with permafrost, probably discontinuous, and tundra vegetation, with only a short interruption in the Allerød interstadial.

The accumulation of dune sands and eolian covers was preceeded by a long cold period of the last glaciation. Undoubtedly, at that time important transformations occurred in the upper layers of Warta stage boulder clay. At the same time generally due to upfreezing processes, a stone pavement formed which is accompanied by the large frost wedges.

In the Late Pleistocene the depth of the active zone must have been considerable. Therefore, the stone arrangement due to upfreezing in the bottom 15 cm part of the sand in profile III is capable of interpretation. The stones were upheaved from the pavement and from the top of boulder clay. Their movement upwards stopped completely in the Holocene when annual freezing failed to penetrate deeper than 1 m.

It appears that the deeper zones with stone fabric deformations resulting from annual freeze—thaw occur in the area of the Poznań stage. They are absent from within the area of the Pomeranian stage. Thus, one may conclude that stone fabrics may reflect annual cycles only after 17 000 — 19 000 years, at which time the ice sheet retreated from the area of the Poznań stage (Rożycki, 1972). However, this should be confirmed by other observations.

DISCUSSION

The possibility of non-upfreezing processes being capable of deforming stone arrangements in the upper boulder clay horizons must be considered. Slope processes, especially creep, is one possibility. Such movement is recognized in the deformation of frost wedges in Central Poland. GOŹDZIK (1967), for example, describes inclined frost fissures on gentle slopes built of glacio-fluvial sediments. He interprets this phenomenon as resulting from congelifluction in the waning phase of the last cold period. This mass movement had a laminar character and its rate decreases from the surface downwards, to a maximum depth of ca. 1.5 m. The observed walues of frost fissure declivity range from a few degrees to 45°.

Such movement also occurred on slopes built of boulder clay where inclined frost fissures are also observed. However, mass movement could have been a decisive influence on the arrangement of stones observed only in a few situations. For example, only in those places where the stones were oryginally arranged with their long axes parallel and inclined to the direction of mass movement down the slope would the long axis inclination be significantly greater. If the original inclination of the stone axis was opposite to the direction of movement, the axis would take a horizonatal or slighty inclined position. If the long axis was more or less perpendicular to the direction of movement and horizontal, the stone would turn round and the axis would not change in inclination. Finally, if the stone were perpendicular and inclined, the stone would tend to assume the position of its long axis parallel to the direction of movemant without any significant change of inclination.

Thus, slope processes could cause the vertical arrangement of stones only in some cases. Moreover, the extent of slope movement on boulder clay surfaces is not known sufficiently. Probably, it was limited to more sloping terrain. Regarding the profiles studied there are many arguments against an important role of mass movement:

— all the profiles, except for profile VII, are situated on flat or slightly sloping surfaces ($\leqslant 1°$);

— deformed horizons on sloping surfaces do not display any accordance of stone orientation direction with surface inclination;

— increase of dispersion of stone orientation, which accompany increase of inclination, cannot be the result of mass movement;

— the sudden increase of inclination observed at the bottom of the deformed zone seems more consistent with the mechanism of upfreezing that with mass movement.

Plant roots and soil meso- and macrofauna may cause ground displacement. However, these cannot be regarded as main agents in the development of stone fabrics within deformed zones. If these factors were responsible for deformations, the changes would be, more or less, uniform in all profiles, as the Holocene would be the principal period of their activity. Furthermore, the deformation zone overlaid by cover sand would not have been subject to biogenetic factors, since these were too weak in the cold period when this zone was near the surface.

These considerations support the thesis that the stone fabrics in the upper horizons of boulder clay soils are the result of upfreezing.

Furthermore, the effects of frost processes upon elongated stones suggest some comments on the mechanism of upfreezing. The most important is the statement of three components of movement: vertical upward movement, rotation round the middle axis by which the stone long axis is oriented vertically, and a rotation movement round the minor axis, which causes a change in the orientation of the long axis. In boulder clay, stone fabrics are characterized by a concentration of stone orientations and by small inclination values of the long axes. These three kinds of stone movement cause an increase in dispersion of orientation, an increase in mean value of inclination, a reduction of stones in the freezing—thawing zone, and an increase of their number near the surface.

The vertical dimension of the object frozen in the surrounding material decides the rate of upheaving during freezing (Hamberg, 1915, *cf.* Washburn, 1973). Maximum heave during one freeze—thaw cycle is proportional to the effective height of the object. During successive phases of freezing the inclination of the stone long axis changes slowly but continuously due to rotation. Thus, its effective height increases, which causes increasing heave values during successive freezing and, in sum, an increase of the speed of stone migration upwards, as wellas of its rotation movement. Thus all these movements occur at an accelerated rate.

In the upper layers of the boulder clay of the Warta stage area a phenomenon occurs that seemingly denies accelerated upfreezing of stones. This is an increasing number of stones in A_3B horizon. It may be explained by a downward movement of stones frozen out onto the surface. The stones would sink into the clay during periods of shallow thawing which occur at intervals during the year in the surficial layer.

Vilborg (1955) noticed accumulation of coarse sand and gravel under stones raised by freezing. He explained this by subsidence of grains from the walls around a void under the stone during thawing. This is not confirmed by the present investigations. Changes in grain-size distribution of matarial under stones were not observed; neither were the „sandy chimneys" mentioned by Dylik (1961, 1967). According to present observations the voids under the stones during upfreezing were filled without a visible sorting of material. This supports the frost-pull hypothesis (see p. 88). The voids under the stones were probably so small that there was no place for coarser grains. Thus, the formation of ice lenses under the stones which the frost-push hypothesis demands, is not likely.

CONCLUSIONS

1. Measurements of the inclination, orientation and quantity of stones in the soil profiles formed on boulder clay in the area of Central and North Poland showed visible changes in relation to lower horizons where stones had retained

Table II

Frost phenomena in soils of Poland developed in boulder clay

(according to „Results of soil temperature measurements", PIHM, Warsaw)

	1. SKIERNIEWICE — medium clay																			
winter:	1952/1953				1953/1954				1954/1955				1955/1956				1956/1957			
depth in cm:	5	10	20	50	5	10	20	50	5	10	20	50	5	10	20	50	5	10	20	50
I. Number of days with the ground temperature ⩽ 0°C	36	15	0	0	86	92	57	0	34	35	0	0	65	68	59	0	16	3	0	—
II. Number of cycles in which ground temperatures cross 0°C	12	8	0	0	18	10	10	0	11	14	0	0	8	5	6	0	6	1	0	—
0°C and −1°C	0	0	0	0	1	1	1	0	0	0	0	0	1	1	1	0	0	0	0	—
III. Minimum ground temperature in °C	−0.3	−0.2	0.3	2.0	−4.8	−4.6	−3.2	0.1	−0.6	−0.3	0.2	2.0	−2.4	−2.2	−1.3	1.2	−0.5	−0.2	0.2	—
IV. Minimum air temperature near the ground	−24.9°				−34.1°				−26.7°				—				−21.9°			
V. Interval of depth in which the greatest depth of temperature ⩽ 0°C is comprised	10—20 cm				20—50 cm				10—20 cm				20—50 cm				10—20 cm			

	2. BIAŁOWIEŻA — heavy clay																								
winter:	1955/1956					1956/1957					1957/1958					1958/1959					1959/1960				
depth in cm:	5	10	20	50	100	5	10	20	50	100	5	10	20	50	100	5	10	20	50	100	5	10	20	50	100
I. Number of days with the ground temperature ⩽ 0°C	64	70	72	64	0	21	22	19	0	0	89	110	117	0	0	6	7	7	0	0	81	94	95	67	0
II. Number of cycles in which ground temperatures cross 0°C	7	6	2	1	0	4	4	3	0	0		8	6	6	0	0	1	1	0	0	4	2	4	2	0
0°C and −1°C	2	1	1	0	0	1	1	0	0	0	7	5	2	0	0	0	0	0	0	0	3	2	1	1	0
III. Minimum ground temperature in °C	−4.6	−4.5	−4.2	−0.9	0.4	−1.8	−1.3	−0.4	1.5	1.8	−3.2	−2.8	−1.7	0.1	1.8	−0.8	−0.7	0.0	0.8	2.0	−6.9	−6.6	−5.7	−1.7	0.8
IV. Minimum air temperature near the ground	−34.4°					−21.5°					−29.2°					−19.6°					−27.9				
V. Interval of depth in which the greatest depth of temperature ⩽ 0°C is comprised	50—100 cm					20—50 cm					20—50 cm					20—50 cm					50—100 cm				

	3. BOROWO — medium clay				4. STRZELNA — light clay				5. WARKA — medium and light clay				6. SIEJNIK — heavy clay				7. KĘTRZYN — light clay			
winter:	1956/1957				1956/1957				1956/1957				1956/1957				1956/1957			
depth in cm:	5	10	20	50	5	10	20	50	5	10	20	50	5	10	20	50	5	10	20	50
I. Number of days with the ground temperature ⩽ 0°C	22	10	3	0	71	18	0	0	66	24	0	0	90	42	16	0	72	46	11	0
II. Number of cycles in which ground temperatures cross 0°C	7	5	2	0	19	7	0	0	18	10	0	0	16	9	8	0	20	15	3	0
0°C and −1°C	3	1	0	0	3	1	0	0	2	1	0	0	5	2	1	0	2	2	1	0
III. Minimum ground temperature in °C	−3.7	−2.8	−0.2	1.0	−0.9	−0.6	0.2	1.2	−3.0	−1.7	0.2	0.9	−5.4	−3.0	−1.3	0.7	−4.2	−3.3	−1.8	0.3
IV. Minimum air temperature near the ground	−19.6				−18.2°				—				−26.8°				−26.4°			
V. Interval of depth in which the greatest depth of temperature ⩽ 0°C is comprised	20—50 cm				10—20 cm				10—20 cm				20—50 cm				20—50 cm			

Location of stations marked by numbers in Fig. 10.

their original fabric created during the transport and accumulation of the till. In the deformed zones stone long axis directions show increasing inclination and dispersion as well as a diminution of stone frequencies in lower horizons and an abundance of stones in upper horizons.

2. Repeated freezing and thawing of the ground is the reason for the changes. Mass movements and soil (biological) processes cannot be responsible for the complex deformations under discussion.

3. The quantitative measurement of stones enables one to establish the nature of the upfreezing process. It is possible to observe a differentiation of zone with deformations in areas of different ages, as well as to infer the mechanism of stone movements and the origin of stone fabrics within the frost-deformed zones.

4. Depth and intensity of changes in stone fabrics decrease from the older to younger terrain more recently abandoned by ice retreat. Zones of strongly deformed stone fabrics, to 1,5 m depth, occur in the area of the Warta stage, where they developed in the active layer during the last cold period and continued during the Holocene. Such deep zones of deformations underwent a two-stage development before and after accumulation of a thin sand cover. In these zones the mean stone inclination value is above 45° and the frequency of stones of inclination abowe 30° is greater than 70%.

The zones of deformation at a depth of 90—70 cm could originate during the Holocene, because this depth does not exceed the range of freeze—thaw in this period. These zones occur in the area of the older stages of the last glaciation, i.e. of Leszno and Poznań stages. Therefore, they probably developed also during the waning phase of the last cold period.

In the youngest areas (i.e. the northern part of the Poznań stage and Pomeranian stage) the deformed zone, 35 cm deep or less, originated in the horizon of short-term freezing-thawing. The period of transformations was too short here to produce visible changes in the horizon of annual freezing.

5. It is concluded that the movement of stones caused by freeze-thaw process has three components: (a) upward vertical movement creating changes of stone frequencies in a profile, (b) rotation around the middle axis causing changes of inclination, (c) rotation around the minor axis increasing dispersion of orientation.

6. Changes of stone fabric in the horizons which are subject only to annual freeze—thaw, i.e. at a depth below 10—50 cm independently of the climatic zone, are very slow. The deformations are distinctly developed only after ten to twenty thousend years. If the freeze-thaw processes occur in short-term cycles deformations appear sooner; however, stone heaving is probably opposed by back movements.

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