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SLOPE DEVELOPMENT UNDER PERIGLACIAL CONDITIONS IN THE ŁÓDŹ REGION

The writer discusses the problem of slope development, choosing as examples three localities: Góra Św. Małgorzaty, Łódź—Teofilów and Walewice which were inspected during the part of the Symposium held in Łódź. The scope of theoretical considerations is also limited to those topics prepared for the Symposium, which have determined the composition of the present work.

(1) GENETIC CLASSIFICATION OF PERIGLACIAL SLOPE DEPOSITS BASED ON LITHOLOGIC FEATURES

Identification of deposits due to congelifluxion, earth slides, slumping of permafrost blocks due to gravity, downwash and deposits of mixed origin formed primarily by downwash and subsequently modified by congelifluxion or periglacial creep.

CONGELIFLUXION DEPOSITS

Congelifluxion deposits invariably show peculiar textural features and sometimes also some specific structural properties. Their material is remarkably heterogeneuos and the component particles show a large variety in size; the disorderly distribution of the particles forming the deposits is thus visible at first sight. The congelifluxion deposits overlying the older fossil slope in Walewice include all the elements of the substratum in which the slope was cut. Their heterogeneous mass consists therefore of tiny colloidal particles of morainal boulder clay and river silts mixed with sands of various origin and containing lumps of morainal clay and boulders over 20 cm in diameter. Likewise, the deposits in Góra Św. Małgorzaty exhibit generally all the components of the initial glaciofluvial material such as dusty particles, sand, gravel, variously sized pebbles (Pl. 1). Naturally, the primary features, both textural and structural have been notably modified by congelifluxion. In Góra Św. Małgorzaty the heterogeneity of congelifluxion deposits is still increased by the fact that apart from substratum material it also includes fossil soil, developed on the surface of the previous slope. Organic matter displaced along slope, though also increasing the heterogeneous texture of the congelifluxion deposits particullarly emphasizes their structural characteristics.

In the localities in question, congelifluxion structures fall into two main types, one of which shows pseudo-bedding while the other exhibits a peculiar tongue or lobe-like structure. An example of one of the varieties of pseudo-bedded structure is found in the proximal part of the rhythmically stratified slope deposits of Walewice. It shows feebly marked thin bands, very reduced in extension and dipping according to the line of the fossil slope (Pl. 2). This set of lense-like bands consists of very small heterogeneous particles including boulder clay, sand and river silt — in other words all the elements of the "bedrock" material of the congelifluxion movement. Another variety of that type occurs on a younger fossil slope, whose abrupt face is covered with markedly bedded deposits. The bands parallel to the nearly vertical slope thus dip almost vertically (Pl. 3). The origin of this deposit is accounted for by the downflow of melted mud along a frozen slope.

The second type which is abundantly exemplified in Walewice and especially in Góra Św. Małgorzaty represents the best-known namely a lobe-like congelifluxion structure. In Walewice these lobes consist mainly of boulder clay (Pl. 2) while Góra Św. Małgorzaty exhibits huge tongues of heterogeneous material including large stones, though their lobe-like structure is chiefly emphasized by the displaced fossil soil. Moreover, the top part of the congelifluxion series exhibits lobes composed of sand but including scattered particles of fossil soil (Pl. 5). A peculiar sight is that of fragments of truncated lobes, whose frontal parts show almost vertical bands of stones.

EARTH SLIDE DEPOSITS

Characteristic slide structures were found for the first time in Walewice (Pl. 4). They occur in the deposits covering the younger fossil slope. Abundant evidence of the existence of permafrost during the formation of that slope obviously reveals the connection of these deposits with processes operating in a frost-controlled environment. Rapid mass movement, as recorded by the slide structure, resulted undoubtedly from a depression of the permafrost table and the formation of a deep active zone. The melted mineral mass sliding over the top-surface of permafrost flew abruptly down the steep slope, in the form of a small earth slide.

DOWNWASH DEPOSITS

A most common type of such deposits in Walewice, Teofilów and Góra Św. Małgorzaty, like in many other places of the region in question, is that of rhythmically bedded slope deposits. Best investigated is the distal part of the sediments occurring in Walewice (Pl. 6). In texture, they are defined by the presence of sands, from fine to coarse-grained ones and that of fines in the form of mud. Characteristic is here also the predominance of opaque grains which testify to eolian erosion and a reduced lenght of transportation.

As concerns structure, the deposit is defined by its bedding. The layers are well-merked and more readily discernible than the laminae in the proximal part of the rhythmically bedded slope deposits where transportation was generally effectuated by congelifluxion. The layers dipping according to the line of slope are much more continuous than in the proximal part. Best-developed are the sandy layers in contrast to the less conspicuous and thin bands of fines. Stratification and trourough sorting point to transportation by water while the parallel arrangement of the laminae, the general absence of any signs of turbulence, and the high percentage of wind-worn grains as well as the considerable slope gradient indicate that these deposits were laid by downwash operating on the slope. Furthermore, their structure shows that the process took the form of sheetwash. Only here and there some buried fossil furrows reveal an ephemeral concentration of flow. This shows that in some rare and rather exceptional areas, rillwash was also present.

Likewise, concentrated downflow was achieved in particular areas alone as a result of the sudden availability of large quantities of water, though in the first place it was controlled by the local topographic conditions. Examples known from Walewice and Góra Św. Małgorzaty point to the significance of the gradient and of depressions between congelifluxion lobes or at their front.

Most important however was the presence of frost fissures, especially such as contained fissure-ice and were oriented according to the line of slope.

DEPOSITS OF MIXED ORIGIN

Numerous slope deposits due to combined action of congelifluxion and downwash belong to that category. Even under the periglacial conditions which seasonally prevail to-day in Poland during the early spring, an alternation of both these processes is frequently observed. Usually late in the afternoon, congelifluxion ceases and is replaced by downwash (Dylik, 1954). In the rhythmically bedded sediments overlying the older fossil slope at Walewice, deposits laid solely by congelifluxion may be distinguished from those accumulated solely by downwash, in extreme situations only either proximal or distal.

The yellow sands on top of the congelifluxion series of Góra Św. Małgorzaty provide an excellent instance of combined origin. The basal part of these sands shows a typical rhythmically bedded structure of slope sediments (Pl. 7). Those parallel layers in which fine-grained alternate with coarse-grained ones — including small stones — and dip according to the line of the former surface, are undoubtedly an effect of sheetwash, while the top part of the deposit shows a strikingly deformed structure. The primary stratigraphic pattern is disturbed and exhibits superimposed lobal structures.

The formation of downwash sediments was associated with aggradation of permafrost. From the moment however when ground ice began to melt more intensively lowering thereby the top of permafrost, new conditions were created which induced deformation of the primary sediment. A comparatively deep active zone of permafrost was in a condition of saturation. The water-soaked mineral mass was flowing downslope in a manner owing to which the initial sorting and bedding were partly preserved. Particularly strong was the extension and deformation of the layers in the frontal parts of the lobes and in their close vicinity (Pl. 8).

(2) CLASSIFICATION OF PERIGLACIAL SLOPE PROCESSES

Slope deposits provide the soundest, and almost unique basis for conjectures concerning the processes which modelled slopes in the

Pleistocene past, under periglacial conditions. By analysing the texture and structure of these deposits it has been possible to distinguish the following major types of slope processes: rapid movement due to gravity, slow displacement by congelifluxion, imperceptible downcreep movement, downwash over the slope surface (Dylik, 1967a).

RAPID MASS MOVEMENT

A study of the form of the younger fossil slope in Walewice and of the overlying sediments suggest the conclusion that the processes operating here were of vigorous nature. The presence of a permafrost block at the foot of the buried slope over a lenght of some 10 m (Pl. 9) proves that the block was detached from the upper edge of the nearly vertical wall and displaced downwards by gravity (Dylik, 1967a).

The structure of the sediments overlying the buried slope in the vicinity of the aforesaid block point to sliding processes, probably earth-slides under specific periglacial conditions. The relatively large earth mass involved at the time in the active zone slided abruptly along the grading surface of permafrost and on falling down at the slope base buried, fossilized its former steepness.

CONGELIFLUXION

From the study of the deposits described above it appears that congelifluxion falls into several varieties of slow downslope movement of plastic water-saturated masses.

Most original of all is the form of that process whose record is found in the covering deposits of the younger fossil slope in Walewice (Pl. 3). The process consisted basically in the downflow of thin mud patches, derived from thawing permafrost. That shallow thawing was probably an effect of intensive insolation of the steep, west-facing slope. These successively downflowing mud patches bacame successively frozen one of top of the other. The participants of the Alaska Symposium during the VIIth INQUA Congress in the U.S.A. were given the opportunity to examine a similar phenomenon in Ready Bullion Creek. Walewice provides instances of that process which even though extinct, is still recorded by characteristic Pleistocene sediments. To the present writer's knowledge they represent the very first traces of that phenomenon in the Pleistocene. The proximal part of the rhythmically bedded sediments

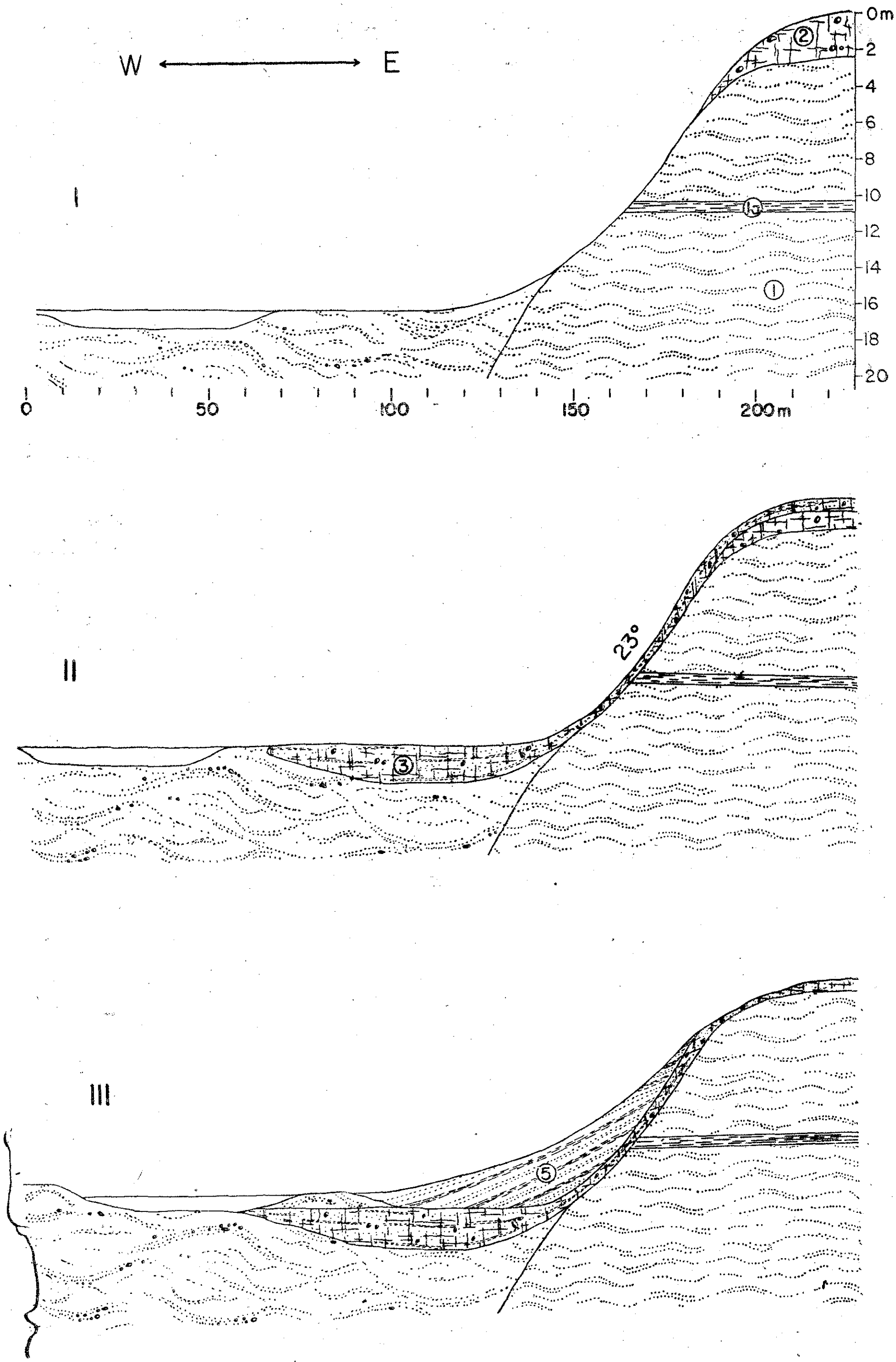
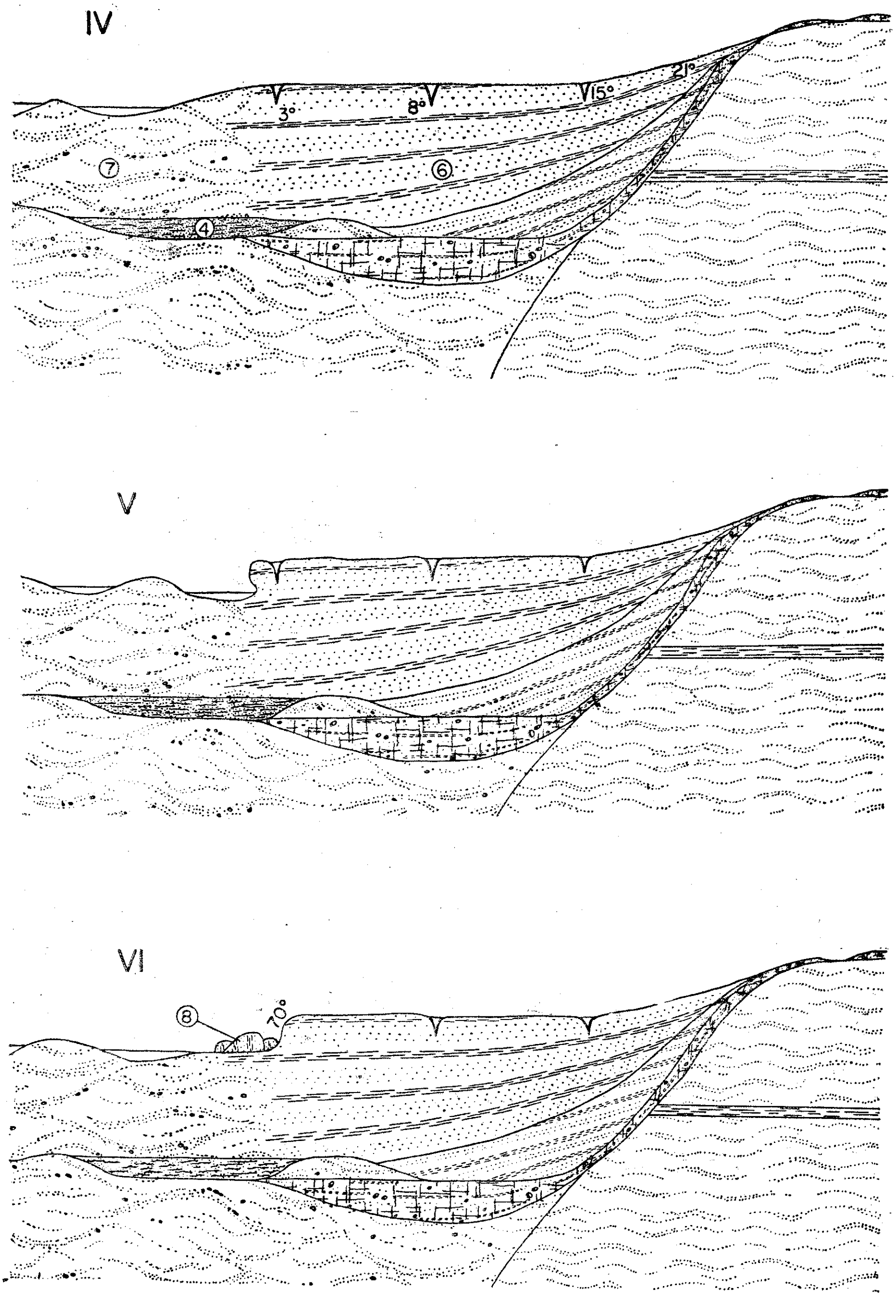


Fig. 1.



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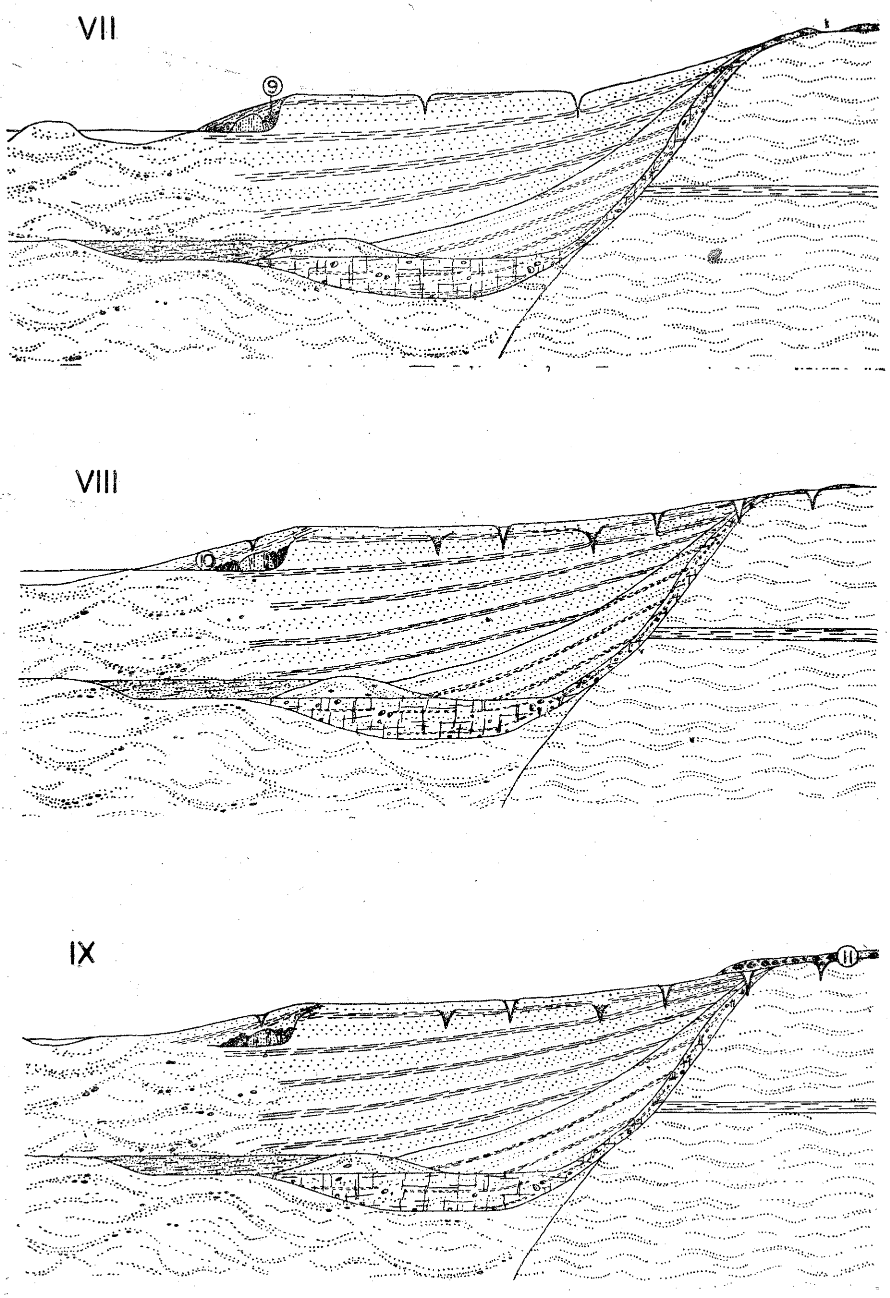

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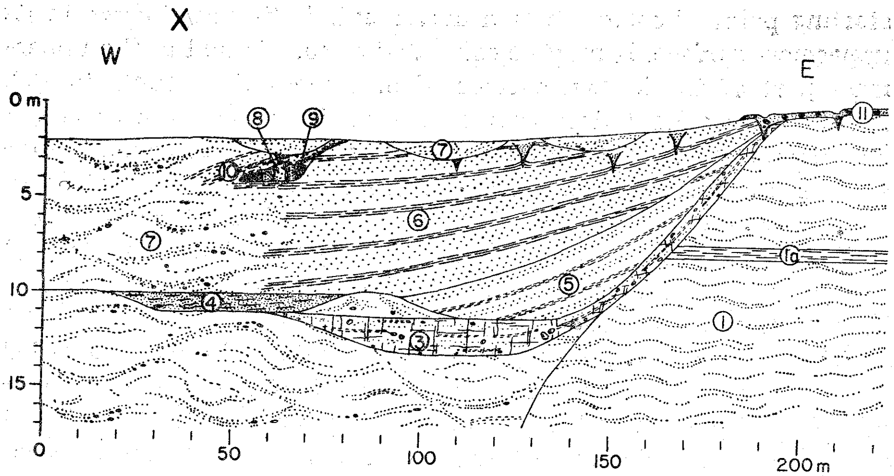

Fig. 1. Succesive stages (I—X) of slope development in Walewice

1. stratified fine sand with ripple-marks, well sorted; 1a. silts; 2. boulder clay; 3. conglelifluxion deposits — mainly composed of displaced boulder clay; 4. clayey silts with admixture of organic matter; 5. rhythmically stratified slope deposits (proximal part): fine sands alternated by silts; 6. rhythmically stratified slope deposits (distal part): coarse- and medium-sized sands; 7. stratified river sands; 8. block of permafrost; 9. congelifluxion and earth-slide deposits; 10. rhythmically stratified slope deposits covering the younger fossil slope; 11. stone pavement

mantling the older fossil slope in Walewice are in all likelihood attributable to some phenomenon of a similar type.

Lobe-like congelifluxion constitutes a very common form of that process (T r i c a r t, 1967). Even though it may not be in fact its most widespread variety it certainly is the one that is best identified. For, that type of congelifluxion is undoubtedly best recorded in the Pleistocene sediments by the most characteristic and readily legible structures. Both Walewice and Góra Św. Małgorzaty — the latter in particular — illustrate the fact in a most striking and instructive manner.

Lobe-like congelifluxion largely depends for its development on two basic, may be indispensable conditions which are: a relatively high slope gradient and an abundance of thouroughly water-saturated fines. On the older fossil slope in Walewice, lobal congelifluxion started on a rather steep slope grading 23° (Fig. 1: I). In the downslope part, the movement continued under the impulse given in the uppermost part of the steepest slope and went on further over a lesser or even negligible inclination (P i s s a r t, 1967). Thus developed the congelifluxion whose numerous traces are found in the basal part of the Góra Św. Małgorzaty slope deposits. The starting point of congelifluxion movements is there unknown in its uppermost surface. It may be estimated at ca. 30° and in the uppermost part of the known surface of movement it amounts to 25°. Below, the gradient decreases to 4° and in its lowermost part it rises again but in a direction opposed to that of the general slope surface gradient. This is undoubtedly a result of the extinction of movement and of the rolling down of the surficial parts of the flowing mass. The top parts of the congelifluxion mass formed abrupt fronts and as a result of their further advance rolled down beneath to form the basal lobe parts.

That development of movement is particularly well recorded in Góra Św. Małgorzaty because the fronts of the former tongues as well as the underrolled parts consist predominantly of fossil soil which is clearly discernible in all the exposures. Pedologic processes must have provided a large quantity of fines, including colloidal particles which facilitated downslope transportation of the material. An abrupt break of the slope at the base of the hill top provided the abundant waters required for the onset of congelifluxion.

Likewise, on the older fossil slope in Walewice the predominant mass of morainal boulder clay of which the congelifluxion tongues are chiefly built, included a good deal of fines. In Walewice the congelifluxion lobes exhibit the greatest thickness at the slope base, a fact that may be accounted for by a large quantity of water in this slope portion. On the steep slope grading more than 20°, the continuity of the lobes was often disrupted.

Still rather problematic is the nature of the movement that deformed the yellow sands discordantly overlying the series of congelifluxion lobes containing fossil soil in Góra Św. Małgorzaty. The lobe-like forms built of that material and superimposed upon one another in various directions have not yet been satisfactorily investigated. The structure of the lobes which moved so slowly as to allow of the development upon them of frost-fissure polygons (Pl. 8), seem to provide evidence of congelifluxion processes. Some doubts are however aroused by the coarse grain size of the sands, which might suggest mass movement due to oversaturation with water. The movement may have been therefore one of the mud-flow instead of the congelifluxion type, the latter being determined by saturation of the material. For the time being, however the present writer refrains from expressing any premature opinion, until further studies facilitate a satisfactory explanation.

Numerous traces of another variety of congelifluxion, namely its sheet type are found in Góra Św. Małgorzaty. This is probably the most common form of the process (T r i c a r t, 1967), but despite the number of its deposits in Góra Św. Małgorzaty it has not yet been sufficiently investigated. The characteristics of sheet-congelifluxion cannot, therefore, be exhaustively discussed.

The studies to date of the correlate deposits of that type of slope processes make it possible to present the most typical features of sheet-congelifluxion even though such a description will be far from complete. The absence of lobes indicates that the movement was not an organized, concentrated one and therefore not localized. Congelifluxion operated along a wide front, over vast slope segments. Sheet congelifluxion occurred on slopes with lesser gradients than those showing lobal congelifluxion. Some observational data collected in Góra Św. Małgorzaty suggest that it operated on surfaces with negligible gradients, often no more than 2°. Owing to discernible structural features in the correlate deposits their genetic identification is chiefly based upon textural properties, such as heterogeneity of the material and in particular the wide grain size gradation of the particles involved. Moreover, the presence of large stones amidst fines shows that the congelifluxion mass sliding over permafrost must have been thoroughly saturated.

PERIGLACIAL CREEP

Many exposures throughout Poland exhibit deposits of a disorderly, chaotic structure, often accumulated on slopes by creep. Rather poorly known, these deposits are not readily recongnizable and for many various reasons. Creep being a very slow and imperceptible process, it usually fails to produce any typical textural characteristics. Besides, in face of the fact that creep is no one-time process but rather involves a whole number of processes with different mechanics it is clearly impossible to expect any well-marked peculiarities. The only trait they have in common is the rate of displacement of particles downslope which rate is so slow as to make transportation imperceptible and render its direct observation quite impossible (B i r o t, 1960; D y l i k, 1967a; P a r i z e k and W o o d r u f f, 1957; S h a r p e, 1938; W i l l i a m s, 1957). Displacement due to upheaving of fine particles by needle-ice constitutes one of the very few examples of a more rapid and noticeable creep. Transportation of particles under the impact of rain drops and the overthrow of material around uprooted trees may also be regarded as belonging to that category. No less difficult is the dating of creep phenomena, strickly speaking — a determination whether they are Pleistocene, Holocene or recent in age.

The above considerations permit to appreciate at its full value the contribution of G o ź d z i k who discovered the traces of periglacial creep and presented an excellent description of the evidence collected in Łódź—Teofilów, one of the localities examined by the participants of our Symposium.

G o ź d z i k (1967) found some traces of that type of periglacial creep in rissian outwash sands and würmian slope deposits though he failed to detect any features, whether textural or structural, in the deposits themselves, which show merely some primary sedimentary properties. Nor do those sediments exhibit any epigenetic features and synchronous structures, developed during creep. One shining exception is that of the deformation of frost fissures showing a polygonal pattern (Pl. 11). These deformations are not accidental for they are widespread, in many instances over all the sloping surfaces; all the points of curvature of the bent fissures occur at an equal depth from the surface on which the frost fissures developed; finally a significant fact is that the value of inclination of the bent fissure segments above the point of curvature represents a function of the primary fossil slope gradient. The inclination of those fossil slope surfaces is — it must be remembered — so insignificant as to be measurable in minutes, rather than in degrees.

Nowhere disrupted, the frost-fissures do not also show any signs of vigorous displacement. Likewise, the macroscopic sedimentary pattern of the deposits fails to show any deformations even in the immediate vicinity of the fissures. This plainly suggests two conclusions, which are that: the movements responsible for the deformation of the fissures were far from vehement and that deformation was a result of repeated displacements of individual soil particles. The aforesaid essential characteristics of the slope movements in question, namely the displacement of individual particles as well as the slow rate and imperceptibility of the process constitute the typical features of creep. Many reasons suggest that this was rather a peculiar type of periglacial creep. In particular, it may be inferred from the fact that in several instances the movement took place inside the series of periglacial formations and that the fossil slope surface involved in creep processes is covered with periglacial sediments.

G o ź d z i k has suggested the following explanation of the substance of that process. As long as the sediments within which frost-fissure polygons were subsequently developed each of their individual grains was protected by a segregation-ice coating. Owing to the formation of such coatings the entire mass grew in volume and the individual particles shifted upward, vertically to the slope surface. In seasons of thawing and growth of the active layer of permafrost, those ice coatings melted away and the released mineral particles collapsed though, this time, not vertically to the slope surface but vertically according to the pull of gravity (Fig. 2).

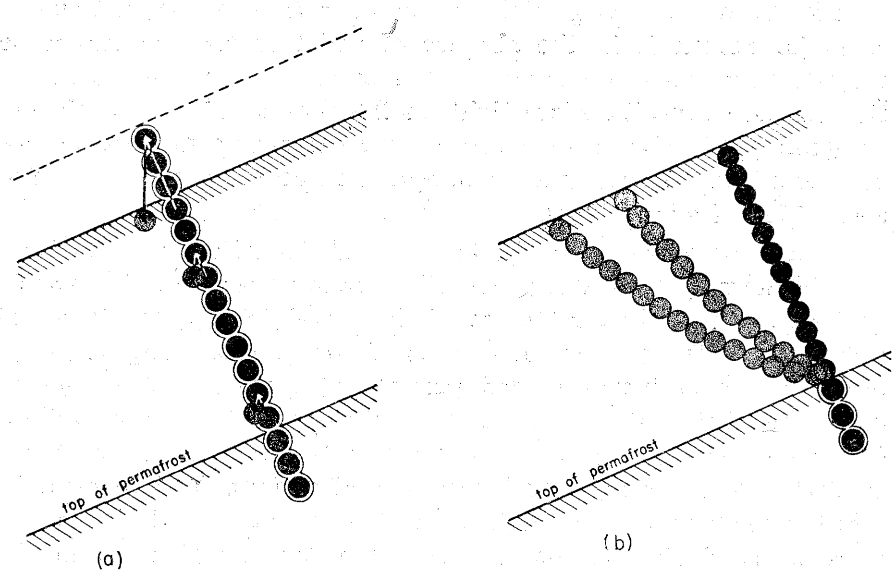

Fig. 2. Schematic diagram showing the mechanism of periglacial creeping (according to J. S. G o ź d z i k)
(a) arrows pointing upwards indicate vectors of particle shifting caused by freezing of bonded water; arrows pointing downwards — vectors of particle shifting caused by melting
(b) scheme of displacement of soil particles due to operating of the process presented in (a)

During a whole, probably very long series of such recurrent regelation cycles, a huge mineral mass was displaced downslope as a result of periglacial creep.

The constant spacing between the points of curvature of the deformed frost fissures and the fossil slope surface is accounted for by the generally constant depth of the active layer of permafrost at the time when creep took place. The importance of that explanation gains in strength if we realize that it furthermore provides the means to determine the depth of the active layer at any given time and place. This is by far the soundest, if not the only reliable manner of solving this intriguing problem that has been so widely discussed.

DOWNWASH

In periglacial morphogeny, especially as concerns the modelling of slopes, this is a most vital process. For various reasons, however, its significance in periglacial environment is still underestimated. A major reason is in the absence of relief forms that might be unhesitantly ascribed to downwash and also a poor knowledge of its correlate deposits. More light on the process of downwash and its geomorphic significance has been shed owing to observations of present-day events and by adequate measurements (M o r t e n s e n, 1930; J a h n, 1961).

Numerous exposures in Middle Poland, including those in Góra Św. Małgorzaty and Walewice, show many traces of downwash. These consist in the first place of the correlate deposits described above. In Walewice a series of cuts of considerable lengths provides evidence of intensive and persistant sheetwash. That variety of downwash is mainly responsible for the production of the rhythmically bedded slope deposits that cover — the older fossil slope, in particular — over several hundreds of meters. As already indicated elsewhere, the deposited patches of downwash sediments were successively incorporated into the permafrost mass in the course of its progressive aggradation (D y l i k, 1963, 1967b).

It seems moreover as if the fact that downwash operated on the surface of permafrost is likely to clarify the mechanism of that process. It may be inferred to have operated under very severe climatic conditions, while the thickness of the active layer was at its maximum. The possibilities of organised downflow being thus reduced the water escaped along a wide front over the slope surface. Such conditions were therefore — on account of the proportion between the thawed moving mass and that of permafrost — reminiscent of those discussed above as a sloughing process, recorded in the form of pseudo-bedded congelifluxion deposits.

The already mentioned buried fossil furrows in Walewice, though rather insignificant provide evidence of organized and concentrated downflow. Also the differences in the size and frequency of the traces left by the two varieties in question testify differences in the climatic conditions of sheetwash on the one hand and rillwash on the other. Fairly large furrows — naturally buried with the time — which are clearly visible in the proximal top portions of the rhythmically bedded sediments were cut in fissures of melted fissure ice oriented according to the line of slope (Pl. 12). This period was probably one of intensive ice-melting, accompanied by a lowering of the permafrost top; the best evidence of these facts is provided by the aforesaid small earth-slide movements, occurring synchronously with the erosion of furrows by concentrated downwash. Such a relationship between the conditions of sheet- and rillwash is fully consistent with the results of Cailleux (1948). In the upper or distal part of the rhythmically bedded slope deposits, long lense-like layers predominate, testifying thereby to a prevalence of sheetwash. The fossil furrows encountered here and there within these deposits are few and poorly developed. The second, younger generation of fissure polygons developed within these deposits failed to induce any lively erosion. No erosional furrows were formed even along the fissures oriented according to the line of slope. Instead of furrows produced by erosion due to the melting of fissure-ice, "moulages de fentes" or sand-wedges were formed retaining the nearly unaltered shape of the previous ice-wedges.

Góra Św. Małgorzaty exhibits a number of facts revealing the significance of the local situations and events including the organization of downflow and the action of rillwash. One of the sections shows a congelifluxion lobe in the horizontal plane; this lobe is clearly cut away or may be cut through, while downwash deposits appear in direct contact with congelifluxion sediments. The rectilinear and well marked boundary suggests that downwash, its direction in particular, was controlled by a frost fissure (Pl. 13). From this observation another relevant conclusion may be derived concerning the inter-action and close relationship between congelifluxion and downwash. A series of other cuts in Góra Św. Małgorzaty permitted to establish a number of other close connections between congelifluxion terraces and downwash. Amongst others it was ascertained that in the superimposed pattern of the congelifluxion terrace, downwash deposits separate the single congelifluxion lobes. Elsewhere there were traces of downwash operating along the fronts of congelifluxion terraces.

(3) MODELLING OF PERIGLACIAL SLOPES UNDER VARIOUS CONDITIONS

FORMER RELIEF

The former relief upon which the periglacial slopes were developed and modified, differed from one another in each of the exposures presented during the Symposium.

In Łódź—Teofilów the initial form was that of an outwash plain of the dead ice hollows left on its surface. The scarcity of materials obtained by cuts and borings does not permit to reconstruct the primary slopes and their subsequent modifications by würmian periglacial processes.

In Walewice, the modifications of the former slope are, on the contrary, very well-marked and perfectly identifiable at each of its evolutional stages (Fig. 1). The primary slope, prior to all the subsequent würmian periglacial processes was abrupt, grading 23° and cut by a river. Later, as a result of congelifluxion and downwash, chiefly sheetwash, there was a prevalence of accumulation processes which induced the development of a gentle slope in the form of an accumulational glacis, grading scarcely 2—4°. The subsequent operations of the river stream largely destroyed the peripheral glacis portions, thus producing a new abrupt slope that was almost vertical and even overhanging. The following and very intensive phase of slope processes in the form of slumps, earth-slides and sheetwash, again buried the steep slope thus forming a successive gentle form of accumulational glacis (Fig. 1).

Likewise, in Góra Św. Małgorzaty periglacial slope processes ultimately produced a more even and more gentle surface than that of the previous slope, though this result was not rapidly achieved and not each phase of slope-modelling smoothed the previous unequalities. The primary form was that of a kame hill. The uphill portions, either wholly devoid of a slope cover or only thinly veneered are very abrupt, grading some 35° while the downhill portion overlain with rather thick periglacial slope deposits has a much lesser gradient of ca. 10—15°. Smoothing of the slope and its modelling under periglacial conditions was here much more complex a process than in Walewice, especially as concerns the modifications of the slope profile. This question will be more amply discussed in section (7) of the present paper.

NATURE OF THE ROCK MATERIAL

The component rock material of the previous forms has largely influenced the course of the subsequent slope processes and has found its ultimate expression in the form of correlate deposits.

The kame origin of the Góra Św. Małgorzaty hill accounts for the predominance of large stones, pebbles and gravels within this previous form. At the same time, however, it explains the presence of sands, even fine ones and of silts. Nearly from the base to the top of the slope deposits, stony material predominates, especially and most characteristically within the congelifluxion lobes. The primary fines occurring already in the kame sediments along with the derived waste material created suitable conditions for the onset of congelifluxion. A most vital role in the formation of congelifluxion lobes was that of pedologic processes whose effects are so perfectly recorded in the lobes in question.

In Walewice, also the substratum material largely influenced the course of slope processes. The congelifluxion lobes covering the older fossil slope include predominantly morainal boulder clay, which primarily rested on the surface of the valley terraces in which the slope was cut. Undoubtedly, the abundance of colloidal particles included in that material largely facilitated the development of congelifluxion. Boulder clay patches are also often found in the rhythmically bedded sediments of the proximal series. The large proportion of river silt which is also one of the principle components of the substratum sediments, contributed likewise to the prevalence of congelifluxion in this sedimentary series. This material is also present in the sheetwash deposits, though its quantity is here rather reduced by the action of downwash which carried the finest particles far away towards the valley axis and down its bottom as well as into numerous braided river beds.

SLOPE MODELLING DURING THE SEPARATE PHASES OF THE LAST COLD STAGE

The waxing phase was cold and humid. It was further characterized by rather frequent thermal oscillations, according to the interesting remarks of W o l d s t e d t (1958) who compared the sequence of climatic changes in the cold Pleistocene stages with those of the weather from autumn to summer.

The climate of the waxing phase is likely to have promoted intensive river erosion, whose effect was the formation of the abrupt, older Walewice slope, now buried under slope sediments. The origin of the fossil valleys, seen in the Góra Św. Małgorzaty profile (Fig. 3) may also be attributed to that phase. The rather unexpectable climatic changes of that phase found their expression in alternating downwash and congelifluxion. Evidence of these changes is provided by the thick slope deposits (several meters) where a repeated alternation of downwash and congelifluxion is readily recognizable. A similar alternation of these processes was also observed in the older slope deposits covering the older fossil slope in Walewice.

The climax phase of the last cold stage was characterized by very severe climatic conditions. The climate was continental, cold and dry. Its most typical manifestations were: the development of permafrost which aggraded under those suitable conditions, a thin snow cover and intensive wind-action. In Walewice, the rhythmically bedded sediments, the younger ones in particular, which were deposited by sheetwash constitute the geomorphic record of the climax phase. The thin accumulation covers thus produced were incorporated into the aggrading permafrost body. These sediments include a high percentage of opaque grains which testify to the intensity of eolian processes. Frost-fissure polygons constitute one of the most typical manifestations and the soundest proof of the existence of permafrost. In Walewice they fall into two generations. Evidence of the intensive melting of fissure ice within the polygons of the older generation indicates a fairly well-defined, though short-lived interval in the climatic severity of the climax phase. This warmer interval gave rise to a number of slope processes which took place below the younger fossil slope.

In Góra Św. Małgorzaty, the events of the waxing phase are not so readily distinguished from those of the climax phase. The slope processes whose effects are represented by the yellow sands which the present writer interpretes as rhythmically bedded sediments, may be safely ascribed to the climax phase. Evidence to that effect is provided by the nature of sheetwash and the association of its deposits with aggradation of permafrost. A like testimony is that of the frost-fissure polygons, developed at the surface of these sediments, still during the deformation of their structure by conge-

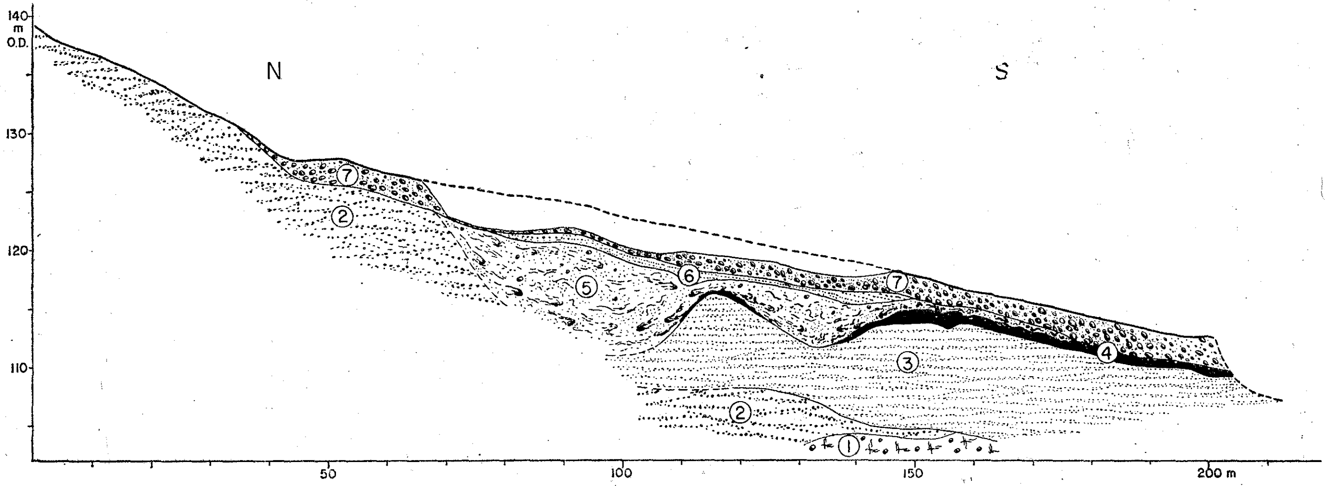

Fig. 3. Cross-section of the deposits in Góra Św. Małgorzaty

1. morainal boulder clay; 2. glaciofluvial sediments; 3. river sand; 4. organic matter; 5. congelifluxion deposits; 6. yellow sand, rhythmically bedded; 7. stone series

lifluxion (Pl. 8). Evidence of the climatic properties of the climax phase is further afforded by numerous traces of intensive wind--action.

Whether or not the boundary of the climax phase ought to be shifted downwards so as to include to foregoing time in which congelifluxion, lobal in particular, was the prevalent slope process — remains an open question. Such an extension of the climax phase is strongly suggested by the wind-worn stones found in these congelifluxion deposits.

Relatively little can be said concerning the slope processes of the waning phase of the last cold stage. In Góra Św. Małgorzaty the beginning of this phase coincides with the discordant surface, separating the lobe series of yellow sands from the one that is conventionally referred to as "stone-series" on account of the stone beds occurring in several layers of its sediments. This stone series whose top-portion is still imperfectly known, is interpreted by the present writer as a combined deposit. Predominant among its components are downwash deposits; their well-washed and well-sorted material testifies to the intensity of the process. The stony layers containing numerous wind-worn stones are likely to represent the residues of congelifluxion deposits. If this reasoning be correct, there is a possibility to discover — in the formation of the stone series — the climatic fluctuations whose frequency and nature suggest an analogy with those of the waxing phase. Secondary climatic oscillations were associated with processes of downwash and congelifluxion.

In Walewice, the waning phase is marked by an increase in the activity of the river whose major records are: its accumulation effects and the formation of a stone mantle which represents a residuum of the congelifluxion (Pl. 14) that was still operating on the permafrost surface prior to the melting of fissure-ice in the upper generation of polygonal patterns.

(5) GLACIS

In Middle Poland accumulational glacis are very common forms, and the exposures presented during the Symposium provided excellent oportunities for getting acquainted with that element of the relief which is so characteristic of periglacial morphogeny.

The gentle slope surface of the 10-mts terrace of the Mroga in

Walewice is built of rhythmically bedded sediments and represents one of the most peculiar varieties of accumulational glacis (Pl. 15a).

The stone series deposits in Góra Św. Małgorzaty constitue a similar form of glacis due chiefly to sheetwash whose operations

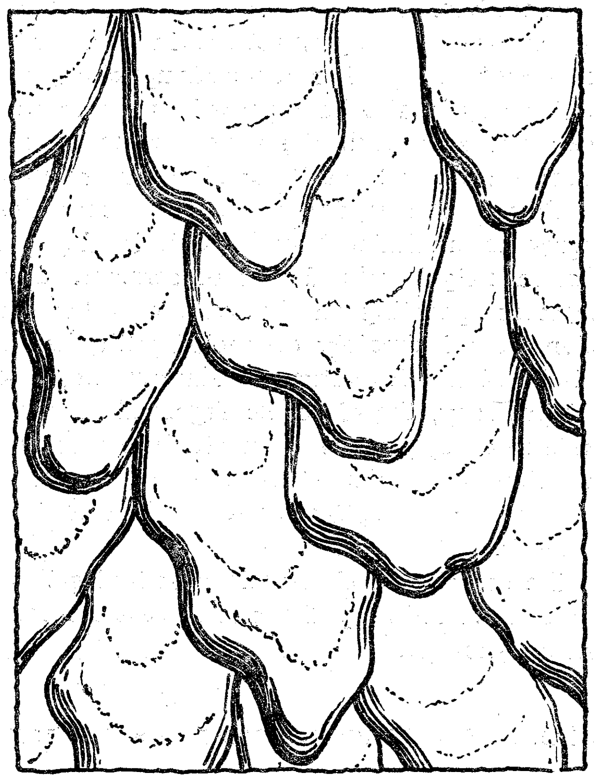

Fig. 4. Schematic diagram of glacis composed of congelifluxion terraces

were interrupted at times by mass movement induced by congelifluxion (Pl. 15b).

Below the stone series, there is a range of fossil forms due to coalescing congelifluxion lobes (Fig. 4). Those are certainly most peculiar forms of accumulational glacis produced by congelifluxion. Worthy of note is that this type of form is very common in present-day periglacial regions, anyway in Spitsbergen (Pl. 15c). Similar forms are also occurring in Swedish Lapland.

Above the accumulational glacis in Walewice extends a flat surface situated below mid-terrace height. This is probably a planation of the glacis d'érosion type. That interpretation is suggested by numerous traces of vigorous denudation revealed by the fact that the boulder clay which elsewhere forms a continuous cover appears here only in patches, with intervening deposits of the underlying stratigraphic horizons such as river-sands and silts emerging at the surface.

A flat and only faintly sloping surface in Góra Św. Małgorzaty above the accumulational glacis and the abrupt slopes of the uppermost hill portion should also be regarded as a glacis d'érosion.

From observations in both the exposures mentioned above it may be inferred that both these types of glacis are closely bordering on each other. It can be, furthermore, assumed that the relationship between accumulational and denudational glacis is not solely one of close neighbourhood but of common dynamics. The erosional processes operating on the surface of the contemporary glacis d'érosion were intimately connected with the accumulative ones which induced the formation of accumulational glacis. Both these glacis types may, therefore, be regarded as correlate forms whose dynamic interdependence is an absolute rule. A similar relationship in origin and neighbourhood was presented in a place called Rome during the Belgium Symposium in 1966 (Seret, de Béthune, 1967).

Owing to the scarcity of observations and of satisfactory data, the present writer is not in a position to discuss the other problems implied in the question (5).

(6) THE ROLE OF PERIGLACIAL RIVERS IN SLOPE MODELLING

The rivers of the contemporary periglacial regions show certain peculiarities and largely contribute to the development of the relief pattern. A voluminous literature chiefly contributed to by Soviet, American and Canadian workers (Bird, 1967; Lavrushin, 1963; Leopold, Wolman, Miller, 1964) has been dedicated to this problem. In contrast, little attention has been hitherto devoted to periglacial valleys, especially to the morphology of valley floors and to the correlate processes operating in the Pleistocene past of the old periglacial regions. Some of the few exceptions in that respect are the works by Zonneveld (1956) and the unpublished paper by Kuydowiczówna (1965).

A most striking and typical feature of periglacial rivers is the intricate braided pattern of their beds which frequently changed their course because of the difficulty of breaking their way through the huge masses of accumulated material. The profile of Góra Św. Małgorzaty seems to suggest the existence of subsequently buried periglacial braided stream beds. In Walewice it was even possible to discover some traces of old and likewise buried river beds of the Würmian anastomosis system.

These braided streams of the unstabilized periglacial rivers determined their vital role in the development of slopes. The best defined mechanism of the action of braided periglacial river beds was reconstructed in Walewice on the basis of numerous cuts and detailed studies of the fossil forms and the structure of the sediments.

It appears, that one of the braided river beds advancing towards an accumulational glacis has largely reduced this form. Destruction became more effective according to whether the undercut glacis bordering on the river bed merged into it, where the slope was abrupt. In such cases the slope was undercut with increasing vigour and finally from abrupt, almost vertical, it was converted into an overhanging slope.

The phenomenon in question was not merely confined to the common and well-known process of mechanical lateral erosion but became an active, uncommonly effective and very imperfectly known process namely that of thermal erosion. Its operations were determined by running water bordering directly on a slope cut in permafrost. In substance, thermal erosion was due to the fact that water has a higher thermal capacity than the nearby mineral mass consolidated by ground-ice. Accordingly, at the contact of water and permafrost segregation ice melted with greater or lesser intensity away from the frozen slope body. As a result niches, called thermoerosional, were formed in the basal slope segments. These niches, assisted by the process responsible for their formation, were the direct causes and instruments of the undercutting of slopes.

In Walewice, the presence of thermoerosional niches was ascertained as well in the profile of the downward portion of the fossil slope which shows a niche-like shape as from the peculiar textural properties of its infilling deposits. This texture differs widely from that outside the niche. It consists of a disorderly assemblage of variously sized mineral lumps due to the collapse of mineral agregates as a result of the melting away of the connecting accumulated segregation ice (Pl. 16). The presence close by an abrupt slope of a frost-fissure filled with ground-ice largely increased the effectiveness of thermal erosion. Whenever a developing thermoerosional niche drew nearer to a sufficiently deep fissure it caused the detachment and slumping of permafrost blocks. Evidence of such blocks was found in several parts of Walewice; one of them was excavated by removing the cover of subsequent slope deposits (Pl. 9).

The mechanism in question which plays a vital and interesting part in the development of slopes was for the first time recognized in Walewice with reference to extinct Pleistocene events. Present-day phenomena of thermal erosion, of the formation of thermoerosional niches and of frozen blocks are, however, fairly well-known from Alaska (Pls. 10, 17) and Siberia.

(4) ESSENTIAL FEATURES OF PERIGLACIAL SLOPES

(7) THE ROLE OF PERIGLACIAL MODELLING IN THE DEVELOPMENT OF POLYGENETIC SLOPES, BOTH PLEISTOCENE AND PRE-PLEISTOCENE

It appears justified and even necessary to treat both those problems jointly. Chiefly because periglacial slope modelling was not a one-time process. Nor was its development homogeneous, for in a periglacial environment various slope processes were at work whose effects often differed widely from each other. In other words, during the existence of a periglacial environment, slope processes followed successively upon one another, and as a result each of them created various slope properties, such as shape and gradient. Such examples as Góra Św. Małgorzaty and Walewice tend to confirm the correctness of that opinion.

In the earliest evolutional phase of slope processes in Góra Św. Małgorzaty, downwash, followed by congelifluxion, obliterated the unequalities produced by the old system of braided river beds. It accounts for the paradoxical fact that the underlying deposits and congelifluxion are in some places dipping northward, i. e. in a direction opposite to that of the slope surface gradient. Later, lobe-like congelifluxion prevails; its tongues are clearly oriented southward i.e. according to the line of slope. In some places the lobe fronts are upturned; it means that in these segments their basal parts are inclined in a direction opposite to that of the main gradient. At the same time the lobes are visibly merging into the covering congelifluxion mass. The statement refers to congelifluxion masses flowing down the south-facing sides of buried river valleys.

As a result of congelifluxion conveying increasingly large masses downslope, the general slope gradient decreases. The slope becomes longer and more gentle. It does not mean, however, that the slope surface gets smoothed. The congelifluxion tongues terminate with abrupt fronts and — on the whole — each of the consecutive lobes is shorter. Finally, the slope which due to the operations of sheetwash and congelifluxion was becoming increasingly smoother, acquires a step-like profile consisting of a series of superimposed congelifluxion terraces (Fig. 5). Subsynchroneously,

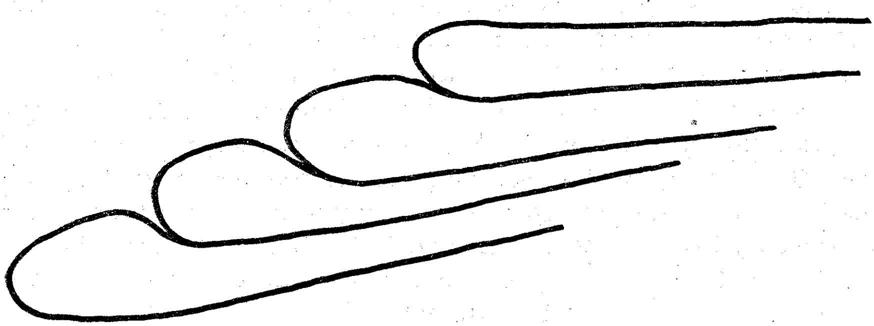

Fig. 5. Schematic diagram of congelifluxion terraces

frost fissures and downwash contribute to a further diversification of the slope surface. Downwash operated between the piling successive congelifluxion lobes, sharpens the outline of the congelifluxion terrace fronts if it operates —as it sometimes does — at the terrace front. A question that should be here most emphasically stressed is that of the relationship between rillwash and frost-fissure polygons. The fissures perpendicular to the direction of congelifluxion mevements were rather underdeveloped owing to the pressure exercised upon them by the masses transported downslope, while the cracks parallel to the direction of movement often provided the routes which determined and promoted the organization of rillwash.

It must be stressed again, that in the period of predominant lobal congelifluxion the general slope profile even though it bacame elongated and gentler was at the same time undergoing various deformations, and finally acquiring a broken, step-like profile. Worthy of note is further the fact that the individual elements of this step-like profile were slightly concave owing to the protruding nearby front, upon which coarser material accumulated so that the congelifluxion mass became even upturned.

The main bulk of the yellow sands overlying the buried congelifluxion terraces, came into existence as a rhythmically bedded slope deposit, laid mainly by downwash. Thus the buried congelifluxion terrace sediments were truncated and the slope surface became smoother. As a result of comparatively deep thawing, however, the sands became saturated, perhaps even oversaturated with water thus initiating a new phase of congelifluxion downflow, may be one of the mud-flow type. The process led to further deformations of the surface and to the production of a terraced, i.e. broken and step-like profile. With the gradual extinction of the process the profile grew smoother, thus marking the beginning of the future smooth and gentle general surface of the hillside (Fig. 6).

This smoothness, however, and the diminished slope gradient were ultimately achieved by downwash, with short intervals of congelifluxion during the waning phase of the Würm. In fact, the general smoothness and gentler inclination were most certainly achieved during that period, though it is difficult to say whether and to what an extent the subsequent Holocene processes did further contribute to their formation.

In Walewice, the periglacial modification of the slope started from a very abrupt river-cut hillside. Congelifluxion was the primary modelling factor. From the two congelifluxion lobes seen in the section but unfortunately identified in the uppermost slope portion alone, it may be inferred that the slope sediments deposited on river-laid ones built congelifluxion terraces like that in Góra Św. Małgorzaty.

Later, the prevalence of sheetwash evened and smoothed the slope surface which became altered and slightly concave. Owing to some warmer interval during the climax phase, fissure-ice began to melt away and erosion along the furrows running parallel to the slope line was rather vigorous. Naturally, the slope surface became diversified, even though these changes are but feebly marked in the shape of the long and somewhat concave slope.

At more or less the same time, however, the prevailing slope processes were inhibited and river-erosion began its operations. One of the furrows of the braided system of the Mroga river of

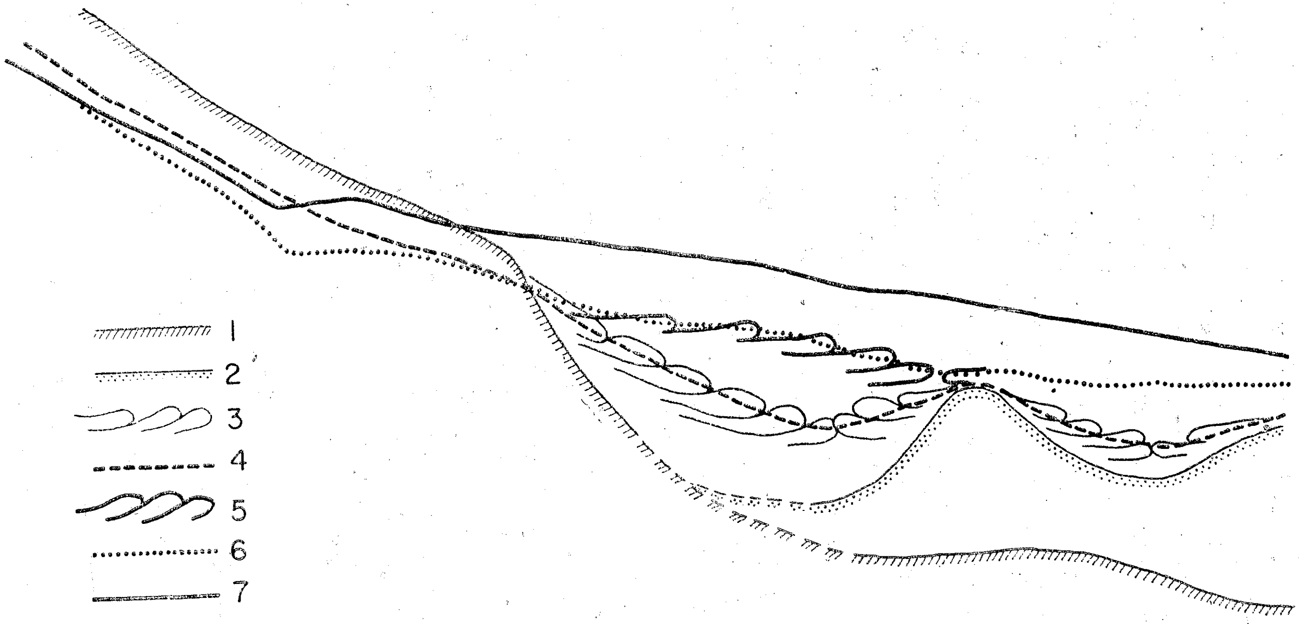

Fig. 6. Schematic diagram showing the periglacial slope development in Góra Św. Małgorzaty

1. glacigenic slope surface (Rissian boulder clay and glaciofluvial gravels); 2. slope surface of Eemian and early Würmian river sediments; 3. first generation of congelifluxion lobes; 4. erosional surface cutting the first generation of congelifluxion lobes; 5. second generation of congelifluxion lobes developed in the top part of rythmically stratified slope deposits; 6. erosional surface cutting the second generation of congelifluxion lobes; 7. present-day slope surface

that time shifted towards the accumulation glacis, thus initiating severe erosion of the rhythmically bedded deposits.

In this river bed, lateral erosion — thermal erosion in particular — taking advantage of the presence of frost-fissures, gave rise to slumping, thus producing a new abrupt, even overhanging slope. Soon afterwards, however, this steep fossil slope was buried by effective slope processes. Their operations began still during the aforesaid warm interval, which promoted the development of earth-slides. Later, however, possibly together with the return of severer climatic conditions, sheetwash set in again and its deposits ultimately buried the younger fossil slope and rebuilt the continuity of the accumulational glacis. The spreading of a congelifluxion mantle, still upon the surface of permafrost, was the last slope process in Walewice. Vestiges of this mantle are only preserved in the form of a residual stone pavement.

The examples of slope development discussed above suggest a number of general conclusions. For, it appears that even within a relatively short period like that of the last cold stage, the development of slopes was polygenetic. Periglacial slope modelling tended to obliterate the previous forms and to produce elongated gently grading slopes.

This statement does not mean, however, that each of the processes and each of the stages in the modelling of slopes led to smoothing and gentler inclinations. It must be added that slope formation depends not only on lateral, slope processes but also on the action of rivers, especially under the specific conditions created by permafrost and by such associated phenomena as ice--fissure polygons and the peculiar process of thermal erosion.

Congelifluxion, whose result was the formation of congelifluxion terraces, diversified the slope surface with a tendency to produce concave surfaces and broken, step-like profiles.

Rillwash, often connected with frost-fissures diversified the slope-surface, chiefly by the production of a profile perpendicular to the general line of slope. Sheetwash, in its turn, led to the formation of more or less extensive accumulational glacis. With growing accumulation the slope profile represented by accumulational glacis though primarly concave, acquired a rectilinear shape. Accumulational glacis is often associated with glacis d'érosion, and both these forms may be reasonably regarded as correlate and genetically related ones.

Such a sequence of slope processes seems to justify the view that the relatively youthful, feebly developed slopes consist of a range of concave segments separating the more or less steep steps of congelifluxion terrace fronts. A further — and maybe ultimate — stage of slope development finds its expression in a very elongate, gently grading, rectilinear profile.

Translation by T. Dmochowska

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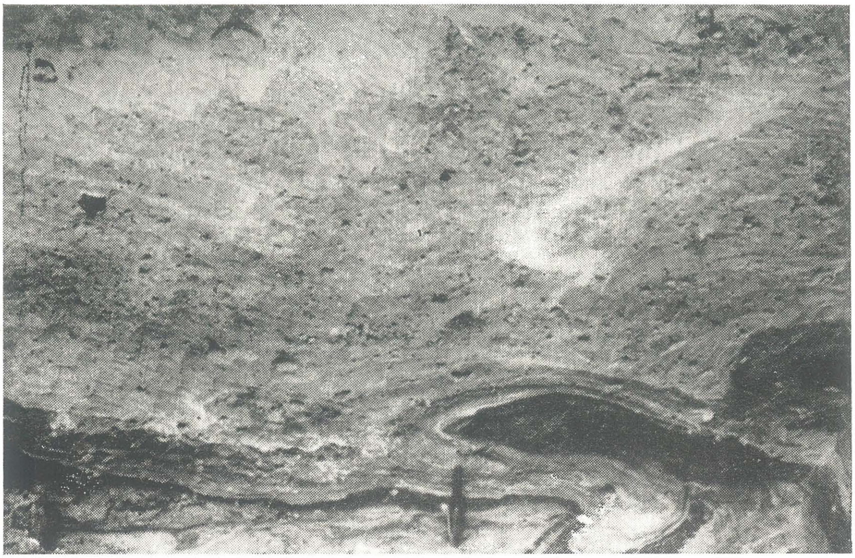

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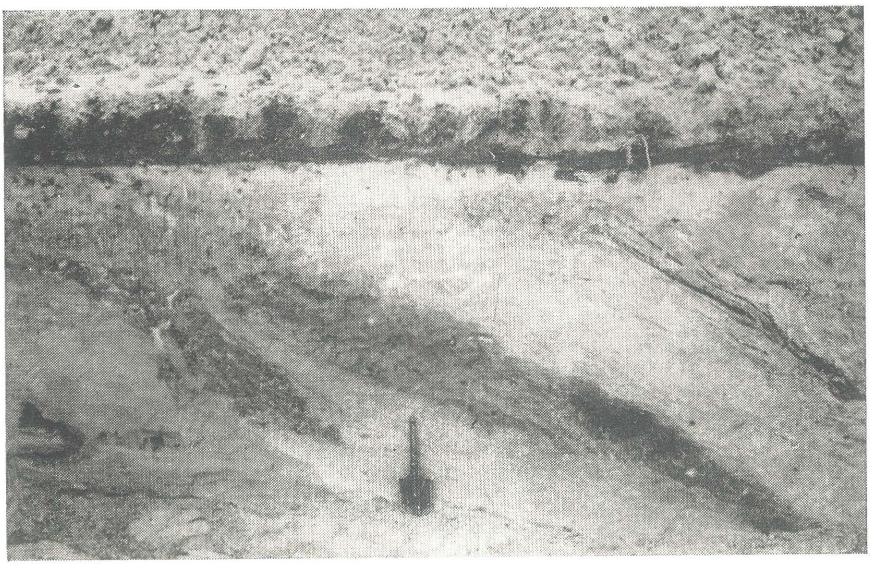
Pl. 1. Góra Św. Małgorzaty. Texture of congelifluxion deposits



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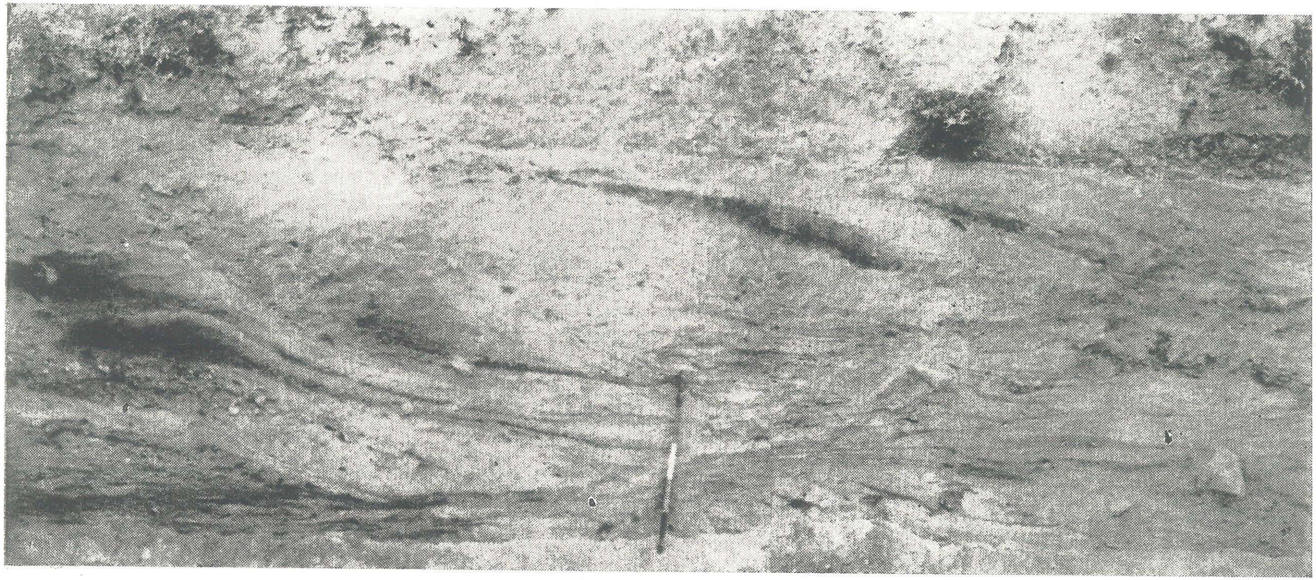
Pl. 2. Lobe-like structure of congelifluxion (on the left) and pseudo-bedding structure (on the right)

Photo by J. Dylik

Pl. 3. Walewice. Nearly vertical pseudo-bedding of congelifluxion deposits covering the younger fossil slope

Photo by J. Dylik

Pl. 4. Walewice. Earth-slide structure



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Pl. 5. Góra Św. Małgorzaty. Structure of congelifluxion lobes containing fossil soil

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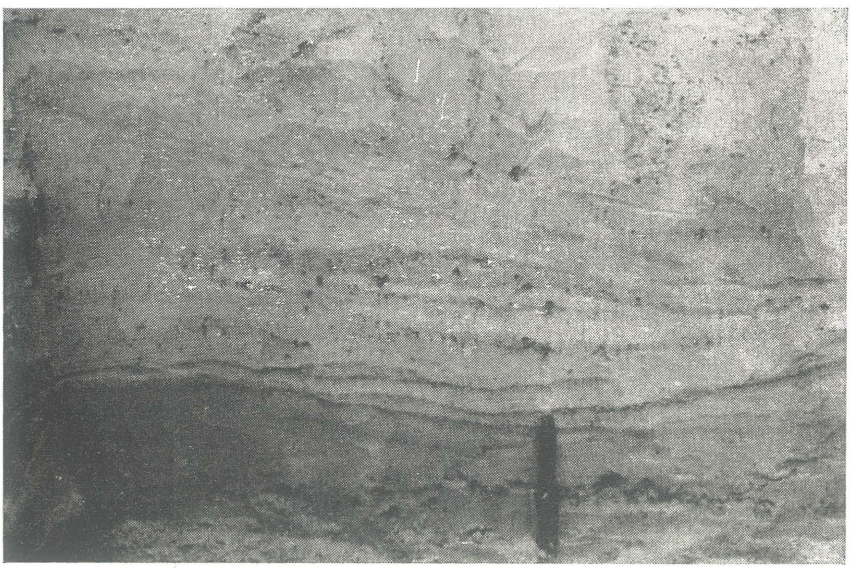
Pl. 6. Walewice. Structure of downwash deposits; distal part of rhythmically bedded slope deposits



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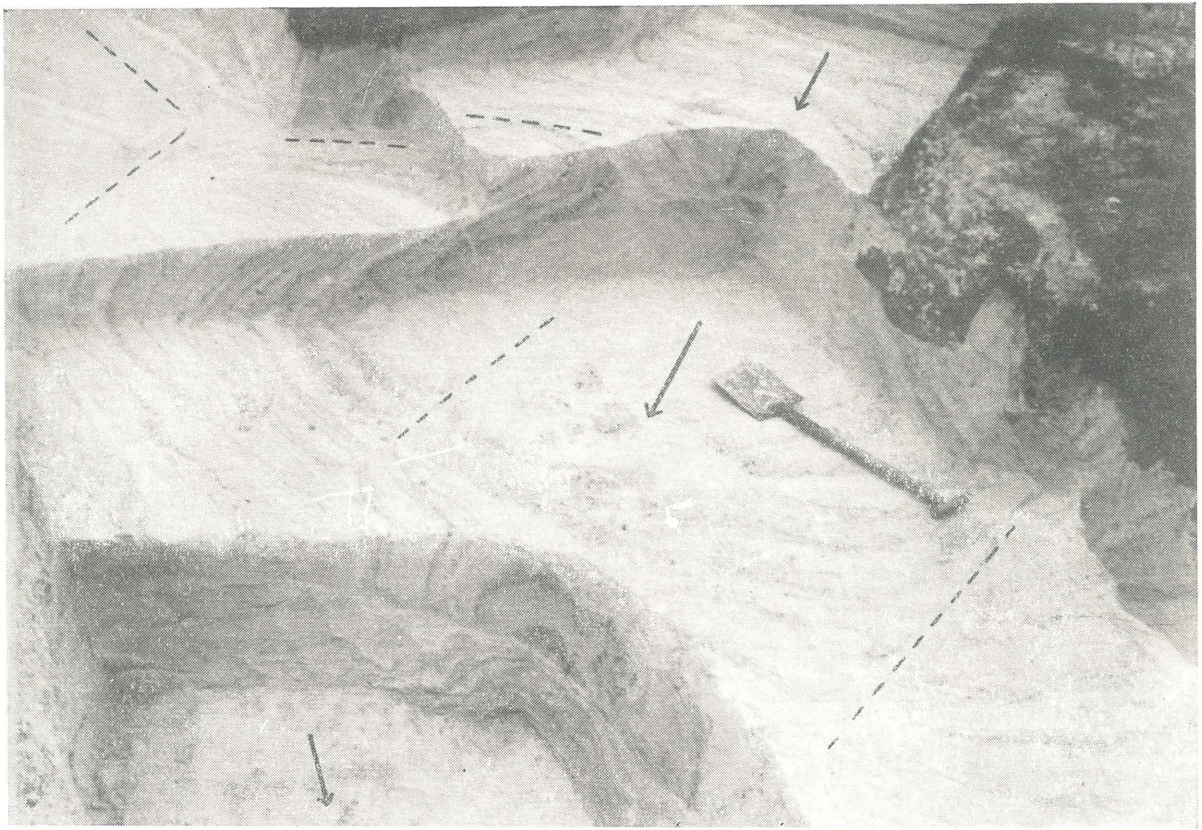
Pl. 7. Góra Św. Małgorzaty. Typical structure of rhythmically bedded yellow sands



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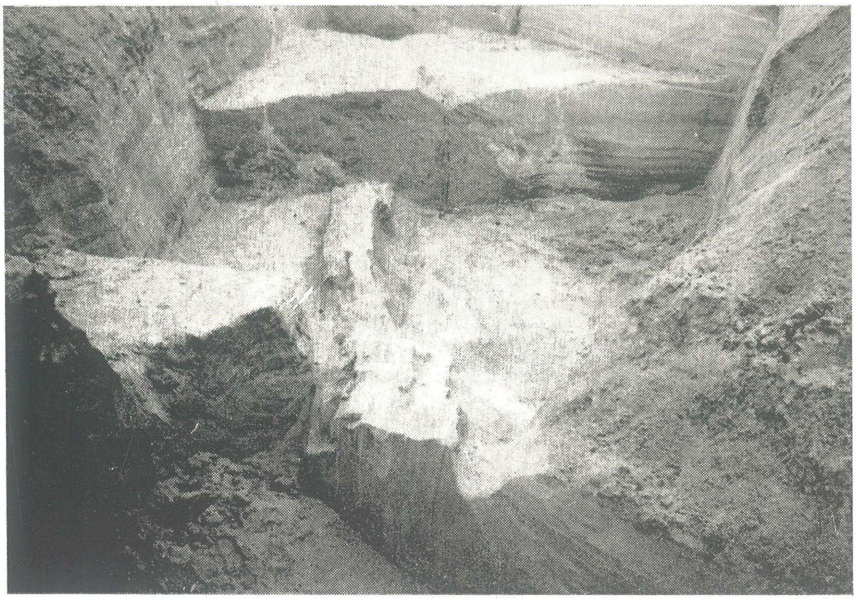
Pl. 8. Góra Św. Małgorzaty. Structure of congeliflurion lobes, deformation of primary structure of rhythmically bedded slope deposits, and fragment of frost-fissure polygons (vertical and horizontal sections) — yellow sands

Arrows indicate direction of downmovement; brocken lines — frost fissures



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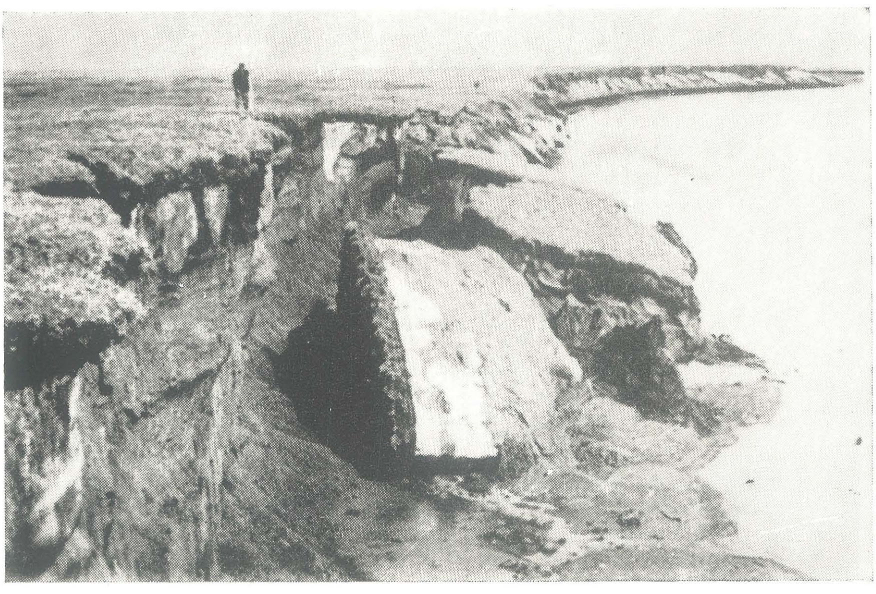
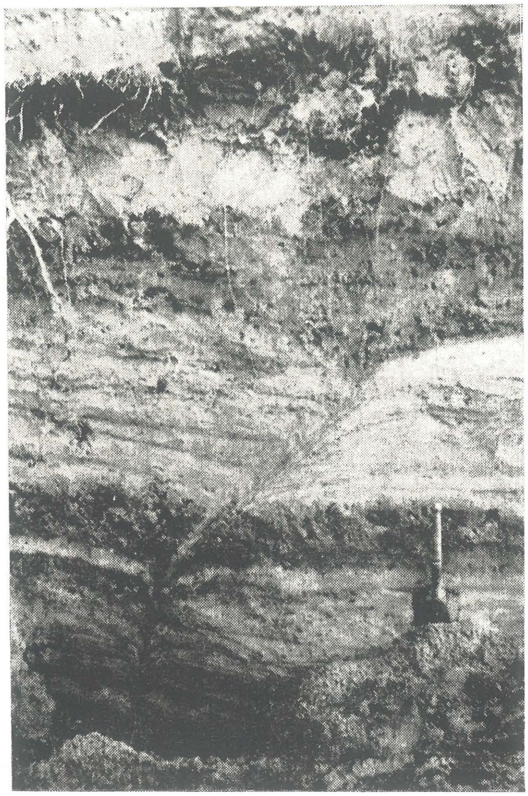
Pl. 9. Walewice. Fossil block of permafrost



After H. J. Walker and H. M. Morgan, 1964

Pl. 10. Blocks of permafrost in the Colville River valley, Alaska



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Pl. 11. Łódź-Teofilów. Deformation of frost fissure, caused by periglacial creeping

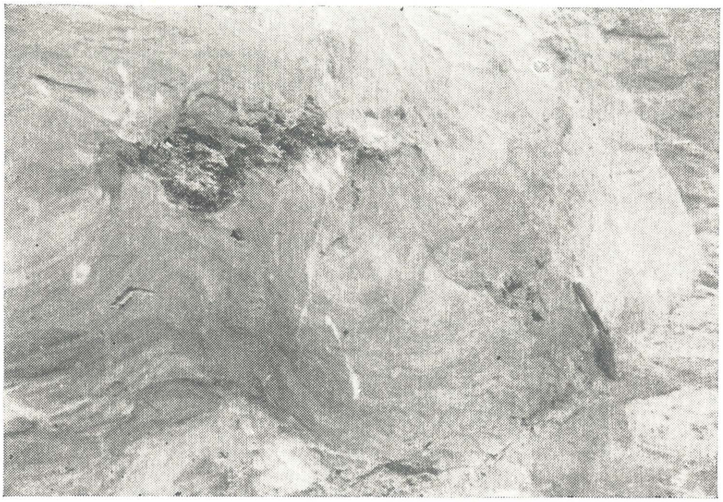


Photo by L. Jędrasik

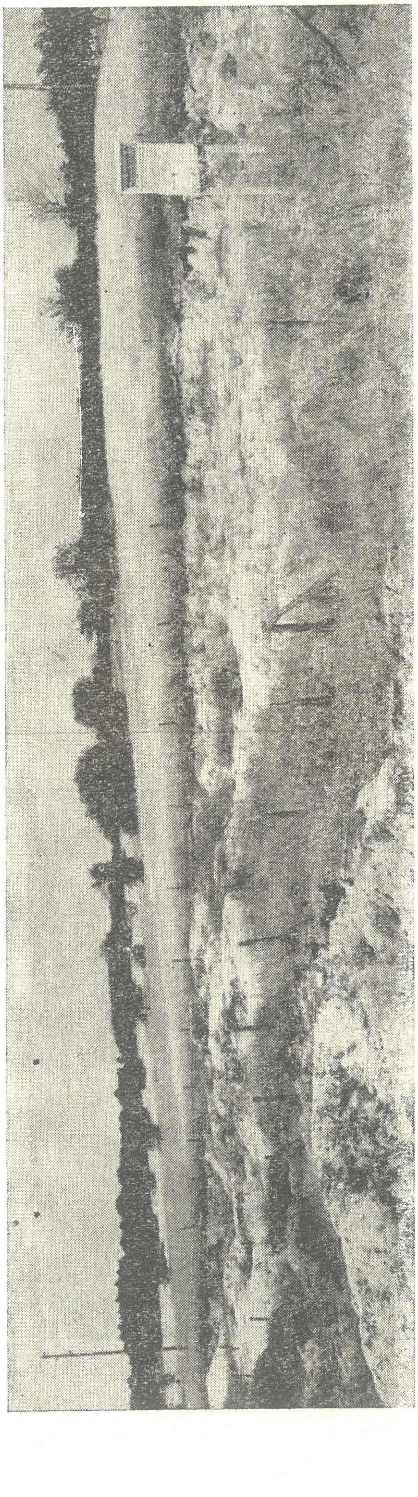
Pl. 12. Walewice. Fossil furrows originated due to infilling of eroded frost fissures primarily containing fissure ice

Photo by J. Dylik

Pl. 13. Góra Św. Małgorzaty. Congelifluxion lobe in horizontal section. Lobe is dissected due to downwash processes operated probably along the frost fissure

Photo by J. Dylik

Pl. 14. Walewice. Cross-section of stone mantle. Visible traces of flowing mud



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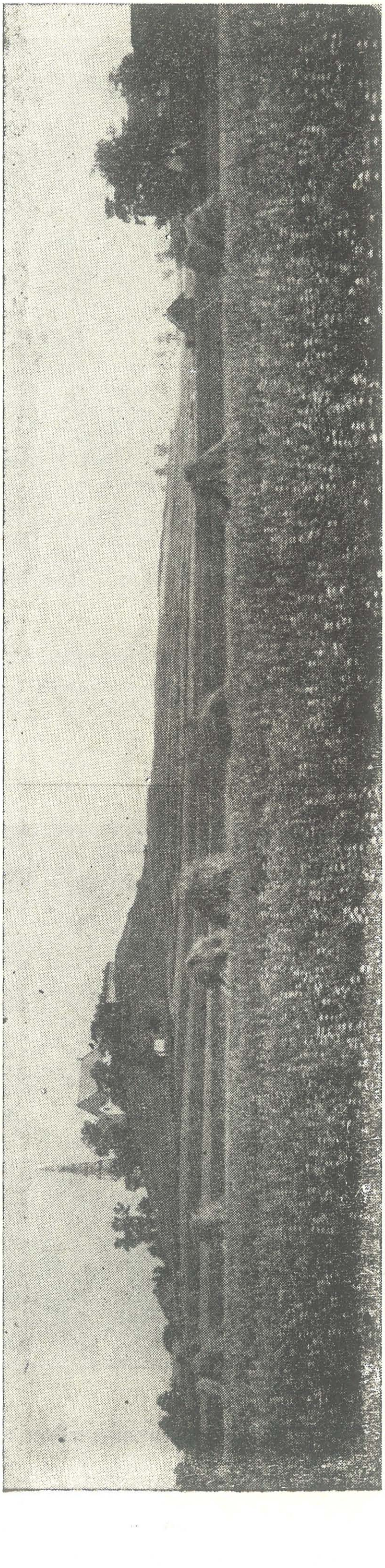

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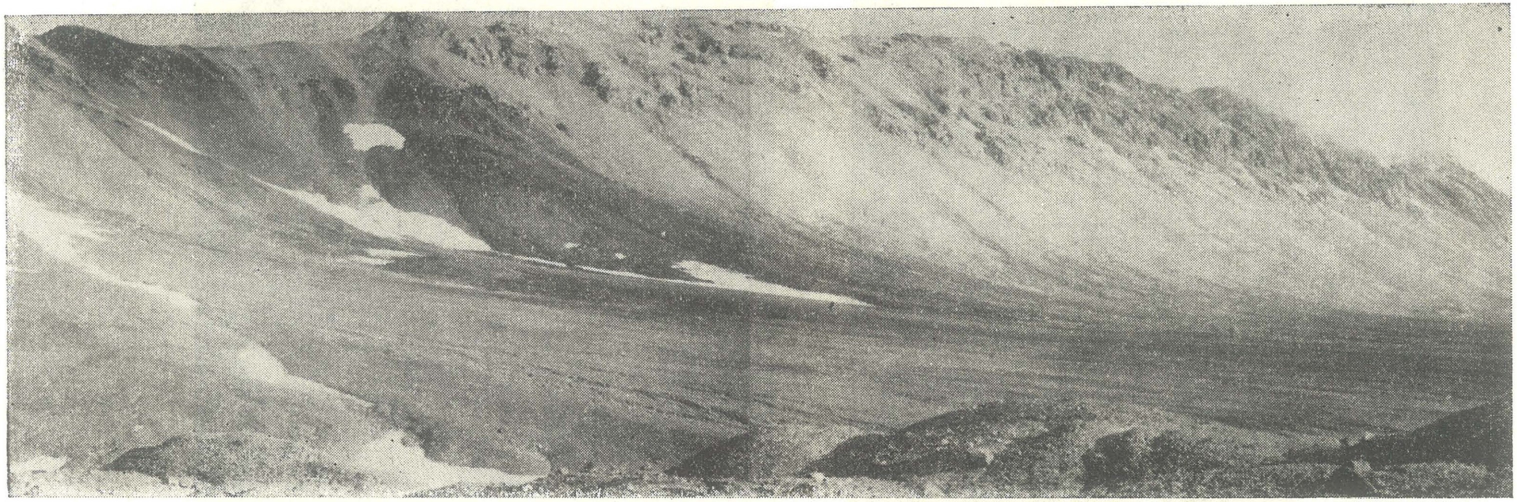

c

Photo by J. Dylik

Pl. 15. Accumulational glacis in: Walewice (a), Góra Sw. Małgorzaty (b), and congelifluxion glacis in Wurmbrandegga, South Vestspitsbergen (c)

Photo by J. Dylik

Pl. 16. Walewice. Fossil thermoerosional niche (on the right)

After T. L. Péwé

Pl. 17. Thermoerosional niche. Youkon valley