Andrzej Martini
Wrocław

SUDETIC TORS FORMED UNDER PERIGLACIAL CONDITIONS

Abstract

The flat-topped low ridges (ca 640 m above sea level) of the SW part of the Kaczawa Mts. in the vicinity of Bolków (West Sudetes) built of Cambrian and Sylurian greenstones, were nunataks during the Pleistocene glaciation. They were, therefore, subject — until the Holocene — to an almost uninterrupted influence of the periglacial climate. But the most visible traces have been left here by the periglacial conditions of the last glaciation.

This is confirmed by the specific land-forms and covers. There are frost-riven cliffs, tor-like forms, rubble fields, small altiplanation steps and terraces and characteristic interrelated block-, loam-debris and loam-silty covers. Such facts prove the intensity of frost weathering of the greenschists as well as a vivid congelifluxion and downwash. The strongly schistose greenstones constitute a material susceptible to exogenic processes.

The distribution and the type of land-forms and covers of this area are in close relation with the geologic structure and the initial morphologic situation.

On the basis of numerous references and of the common occurrence of those forms, the periglacial genesis of tor-like forms of metamorphic rocks has been established. Metamorphic rocks have a specific system of fissures particularly favourable to frost weathering; the weathered rock-material easily underwent processes of slope transportation. In less cracked and thus more resistant places the frost cliffs, parallely backwearing, formed series of isolated tors, later modelled by processes of nivation and subaerial weathering.

At present, those relict forms are masked by Holocene accumulation and by low-and-high-growing vegetation. The final morphogenic stamp on this area has been impressed by human activity: fields and pastures have contributed to the fixation or the obliteration of some Pleistocene land-forms.

OUTLINE OF OPINIONS AND PRESENTATION OF THE PROBLEM

The question of the origin of tors has been discussed in geomorphologic literature for a long time. Two main opinions concerning the development of these rock-forms prevail. The first one emphasizes the one-phase morphological evolution, regarding tors as erosional restlings. According to various sites of occurrence of tors, some scientists have emphasized the prevalence of a morphogenetic process in this area. Therefore King (1948, 1958) assigned them to pedyplanation while Eakin (1916), and Boch & Krasnov (1951) — to altiplanation.

The second group is mainly represented by the opinions of Hövermann (1953), Linton (1955, 1964), Wilhelmy (1958) and Jahn (1962). They have connected the origin of tors with a two-phase development where the most important part is ascribed to the processes of differentiated deep weathering, and then of selective denudation, leading to the exhumation of rock-forms. Only the modelling of ready tors was attributed to sub-aerial processes.

It should be noted that, most frequently, these opinions differed, because they concerned forms in various rocks. The famous Linton's theory, for instance, was probably true for the granitoid areas but could not fit in environments of a different geological structure. Besides, it seems right to attribute a more important and frequently an essential part to the kind and structure of the rock itself. An example of this is Jahn's theory of the origin of granite tors (1962) which explains the development of these forms better than the opinions basing mainly or exclusively on climatic assumptions.

As to the well-known polemics of Linton (1955, 1964) with Palmer and Radley (1961), apart from the question whether some arguments on each side are right or wrong, it has undoubtedly stimulated a further development of opinions in both basic theories.

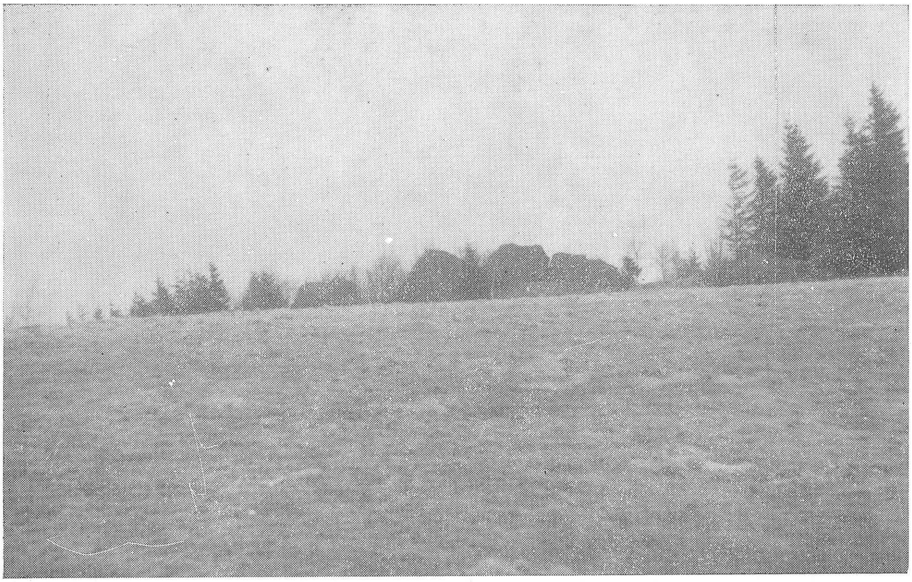
Beginning with Pullan (1959), many scientists have admitted the possibility of existence of several ways in which tors were formed. The kind of rock, the connection with morphologic situation, the type of climate and other factors were taken into account. Czech scientists such as Czudek (1964), Demek (1964a, b, 1965, 1966) and others have proved particularly active in expressing such opinions.

The connection of the tors — erosional restlings — with the backwearing of altiplanation terraces was already mentioned by Boch and Krasnov. The formation and development of this type of rock forms strictly connected with an active periglacial environment, with all its morphogenetic elements, through their isolation from frost-riven cliffs — have been described by Palmer and Radley. Then, there appeared in the literature a more and more marked and stable hypothesis of the origin of some tors as the results of one-phase evolution in a periglacial environment with reference to the specific structural and lithological properties

Photo by A. Jahn

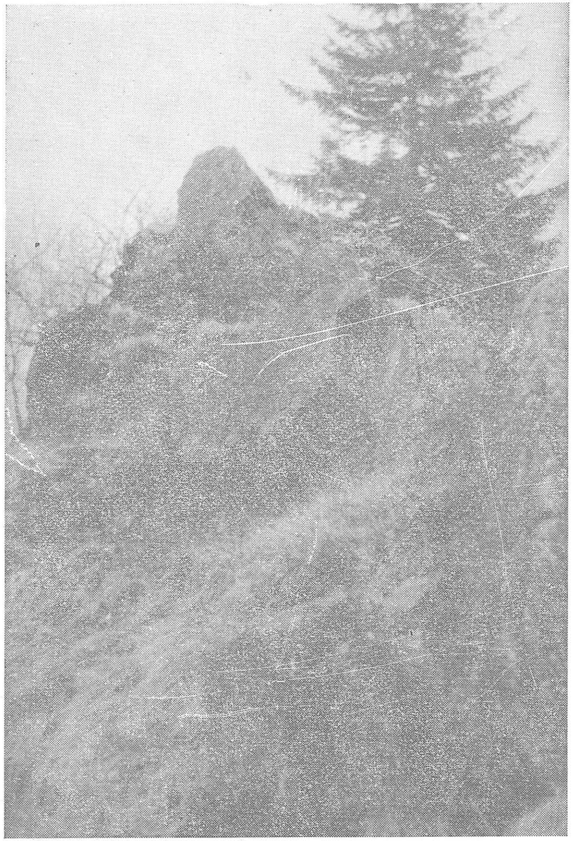
Pl. 1. Example of a tor originated under periglacial conditions. Spitsbergen

Pl. 2. Greenstone tors in the Poręba massif, Kaczawa Mts., West Sudetes

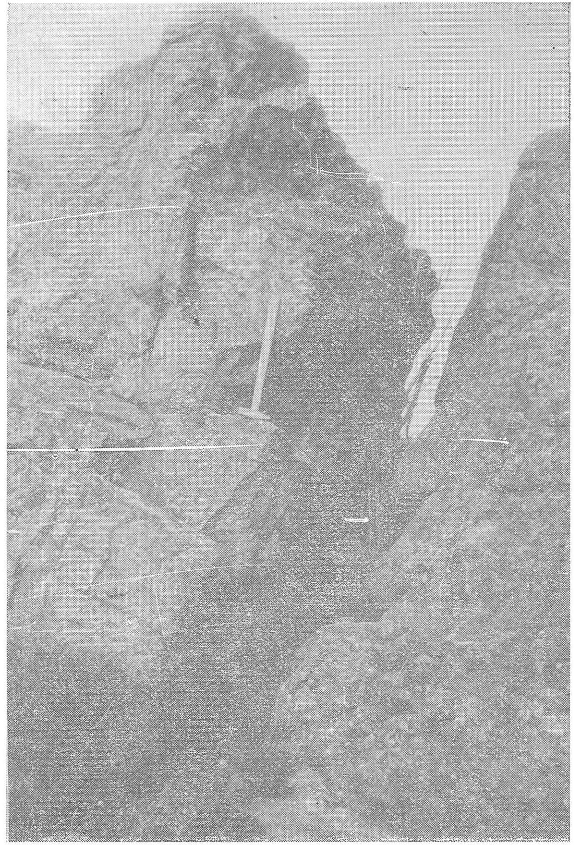


Pl. 3. Tors situated along the edge of a slope and summit surface

Pl. 4. Altiplanation step



Pl. 5. System of joints in a tor due to which the rock disintegrated into blocks



Pl. 6. Vertical fissure promoting the isolation of tors out of the rock-wall

of the bedrock (Waters, 1962; Czudek, 1964; Demek 1964a, b, 1965; Ivan, 1965). The conclusions were mainly based on investigations of European tors which are relicts of the Pleistocene periglacial zone, and on the observations on relations between them and the frost cliffs, the altiplanation terraces and all kinds of interrelated periglacial covers (block-, loam-debris, silt-covers), It was established everywhere that there existed close interrelations between the corresponding types of rock, the lithological and structural properties of which were exceptionally favourable to intense processes of frost weathering and slope transportation. All kinds of metamorphic schists, gneisses and closely joined quartzites were mentioned in the first place.

Waters described tors being now in formation on the specifically joined or bedded rocks in Vest-Spitsbergen. Ohlson (1964) has done the same in northern Scandinavia and recently R. Dahl (1966) has studied the area, describing the rock-forms cautiously, as "tor-like weathering forms". The present writer has obtained oral information and pictures of such forms in Spitsbergen from Professor A. Jahn (Pl. 1).

Several years lasting research and observation of some elements of the Pleistocene periglacial environment of the West Sudetes (Martini, 1963) enabled to emphasize the periglacial one-phase origin of the tors occurring in areas built of metamorphic rock, mainly of greenstones and greenschists. The solid greenstone, characteristically cracked and schistose was particularly favorable to frost weathering, and the material produced by weathering easily underwent slope processes. Owing to this, the processes of the Pleistocene frost environment, in the presence of permafrost, have formed a number of rock land-groups which were in close relation with other land-forms of periglacial morphology.

That is why, not denying the mentioned ways of development of tors formed on other rocks and in different morphoclimatic zones, the periglacial origin of tor-like forms built of certain metamorphic rocks has been proved here.

TOPOGRAPHIC AND GEOLOGIC CHARACTER OF THE AREA

Investigations were carried out on the culminations between the West and the Middle Sudetes at an average altitude of over 600 m. During the Pleistocene (Riss — Odra stage), these culminations formed a group of nunataks within the eastern part of the Kaczawa Mts. and the western part of the Wałbrzych Mts. It is a watershed area between the Nysa Szalona, the Strzegomka and the Lesk and presents the characteristic features of rejuvenated mountain landscape. The rock-forms are mainly grouped on the greenstone ridges with visible summit planations and steep slopes (the massif of Poręba), sometimes with tectonic foundations (Truskolas, Młynarka) situated to the SW of Bolków, (Wrocław voivodship). It should be noted that in the whole greenstone area, the southern part of the Bolków Highlands (which underwent glaciation) included, the occurrence of periglacial forms and covers can be established. But the most outstanding examples were grouped on the nunatak massif of Poręba, which for this reason has become the subject of strict investigations.

The lower stage of the Kaczawa Mts, i.e. the older rock complex is a part of the Caledonian orogeny. The Kaczawa Caledonicum is formed of mostly schistic zones with distinct features of shallow epimetamorphosis; they belong to the Algonkian (the Radzimowice schists) and to the older Paleozoic (Cambrian and Sylurian greenschists). Here especially the greenstone formation is very strongly developed and forms the most powerful rock complex, exceeding 1000 m of thickness. The greenstones represent a shallow facies of the metamorphosis which was brought about by tectonic circumstances in various kinds of older volcanic rock with basalt and diabase chemism. They are grey-green rocks of aphanite (cryptocrystalline) texture and schistose structure. Unlike the thick and massive beds of the greenstones, greenschits are characterized by strong foliation. Their mineral composition is mainly based on albite, epidote, chlorite and, incidentally, quartz (T e i s s e y r e, 1957). The greenstones of the Kaczawa Caledonicum underwent condiserable dynamic deformations which caused the development of a dense network of tectonic cleavage without any changes in their internal texture. That is why the beds of greenschists thus formed are of various thickness and distinctly fissured, which has considerably affected the active morphogenetic processes. Compared to the surrounding rocks of Culm conglomerates or of Rotliegendes the greenstones are relatively resistant to erosional processes. Therefore they form the main mountain ridges in the eastern part of the Kaczawa Mts. Owing to differences in the amount of rock fissures the greenstones display various reactions to exogenic processes. In the investigated area a monoclinal system of greenstones may be observed, with a vertical or almost vertical dip. Those old Caledonian folds have a NW—SE direction and in the eastern part they cross transversal folds running from the SSW to the NNE (R a d w a ń s k i, 1952). It is reflected in the numerous forms of slopes, in the disposition and the isolation of the tors etc. It is easy to distinguish that all the structural and tectonic elements of greenstone rocks have strongly influenced the sculpture of this area.

DESCRIPTION AND DISTRIBUTION OF TOR-LIKE FORMS

The tors have characteristic and — due to greenstone texture — specific shapes of sharp and ragged ridges (Pl. 2), less frequently of single peaks. They differ markedly from the rounded towers and granite needles or tabular sandstone tors. Greenstone tors form steep-walled pyramids, most frequently of small (2—5 m) or medium (up to 10 m) height. They have a narrow base and boldly outlined peaks. The tor chains are in close relation to the strike of the greenschists (NW—SE). Since the whole massif of the Poręba nunatak is elongated in the direction, imposed by the strike of the rock, the tors are grouped in rows in accordance with the whole mountain massif (Pl. 3).

The tors are mainly disposed on the breaks which border the slopes of the massif with a flat top that truncates the vertically dipping greenstones and constitutes the planation surface, sloping at 1°—5°, and corresponding aproximately to the Unisław horizon of the neighbouring Wałbrzych Mts. (S z c z e p a n k i e w i c z, 1954; Pl. 3).

The situation of the tors along the break of slope has often been emphasized in literature (L i n t o n, 1955, 1964; P a l m e r and R a d l e y, 1961; J a h n, 1962; K l a t k a, 1962; C z u d e k, 1964; D e m e k, 1964a, b). The break point of the slope profile, where the convex, slightly inclined upper section changes into a more strongly sloping section is a favourably place for the development of such forms. The location of tors on the breaks — i.e. in zones reflecting primarily the differences in the resistance of the rock, proves their structural connection. The differentiated susceptibility of the bedrock to exogenic processes has been taken advantage of by processes which led to the formation and development of frost riven cliffs and of altiplanation terraces, under periglacial conditions (Pl. 4). These obvious relations between them and the tors, occurring also in the investigated area in the upper parts of the slope, have been described by quite a number of scientists (Palmer and Radley, Waters, Czudek, Demek).

Besides, on the very top surface there occur rock groups, half-buried in blocky and loam-debris material. This can be explained by the difficulty of moving down of the weathering material. The most magnificent rocky land-forms can be found in the upper parts of the massif: on the edge of the summit surface and the slope (Pls. 2, 6, 7), on the top itself near the edge and in the central part. Smaller tors associated with altiplanation terraces and frost cliffs are concentrated in the upper parts of the slope. Such a disposition of those forms (analogous to the granite tors of the Karkonosze Mts. — Jahn, 1962) might suggest that their development was progressing from the bottom. The occurrence of summit tors (in the center and at the edges) might confirm the opinion concerning the simultaneous lateral development of the slope with cooperation of altiplanation (Boch and Krasnov). As the top tors could hardly be isolated from the altiplanation terraces (as it happens in the case of the tors along the slope break) the explanation of these differences of forms and of their disposition should be connected with the bedrock.

Czudek, Demek and others have described the periglacial tors built on the contact-boundary of different rocks as due to obvious disproportions in the susceptibility of the bedrock to destruction. Within the greenstones the formation and distribution of the tors were essentially influenced by the directions, the configuration, the density of joints and beds of this uniform massif. The structural dependence of the tors were emphasized in their papers, by Palmer and Radley (1961), Ohlson (1964), Czudek 1964), Demek (1964a, b), R. Dahl (1966). The most important are the vertical fissures, which cut the rock beds perpendicularly and owing to which the walls crumble easily (Pls. 2, 6, 7). The problem of the effect of the rock structure on the genesis of tors is discussed below.

In the course of field studies on greenstone tors, the above mentioned dependences were confirmed. The flat summit surfaces have an extremely dense network of cracks conformable to the slate planes (ca 20—25 fissures on 10 cm. of rock) and small, irregular, perpendicular fissures. Such a strongly schistose greenstone with distinct foliation created a favourable ground for weathering processes and denudation. Instead, within the tors themselves the rock beds are thicker and the fissures scarce but running distinctly and regularly (Pl. 5). E. g. on 1 m^2 of a rock outcrop there occur four bed fissures and within them ca fifteen smaller cracks connected with schistose structure of the greenstone. The system or vertical fissures in the number of 2—3 per 5—6 m. of rock is disposed perpendicularly (Pl. 2). It is their presence that is of such importance in the formation of tor-like forms.

The differentiation in density and disposition of cracks on flat surfaces and on tors is an absolute rule. All changes are distinctly marked in the morphology of the area. A less dense network of fissures occurs on tors and frost cliffs. A greenstone with a larger number of cracks forms the bases of tors or the surfaces of altiplanation terraces.

It should be distinctly stressed that the rock of which the tors and the summit surfaces are built is relatively fresh and chemically unchanged. There occur only quantitative differences in the fissure system. The digging situated at the base of one of the off-edge tors at the summit side is an example of this fact (Pl. 8, Fig. 1). In that case the summit level with the projecting tors cannot be L i n t o n's basal surface, since better draining conditions would have allowed for a still deeper penetration of weathering. The remarkable height of the tors (up to 10 m) on the flat surfaces, their distinct shape not immediately associated with altiplanation terraces — might suggest a two-phase genesis. The state of the rock itself denies it. This type of rocky land-forms could be developed only owing to the lateral gnawing of frost weathering helped by nivation and with simultaneous removal of the material. The tors are the result of the influence of periglacial environment on the structurally differentiated homogeneous bedrock.

Beside the strike of rocks which determines the directions of tor chains, the dip of the greenstones is also reflected here. As it has been mentioned above, this dip is vertical or has a fanshaped disposition within the limits of 75°—90° N and 75°—90°S. Such a disposition of the dip angles facilitated the upkeeping of bold forms and considerable heights of the tors. The problem of the effect of the parent-rock dip on the shape of the tors has distinctly

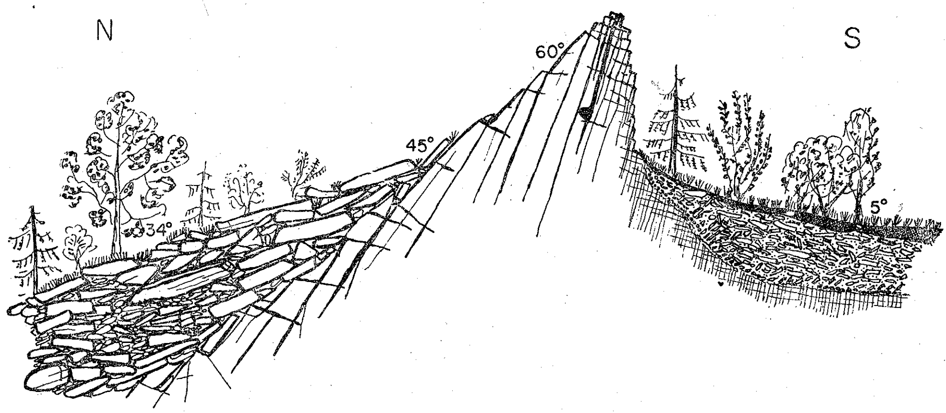


Fig. 1. Scheme of the tor situated between a summit surface and a slope

appeared in D e m e k's (1964) and R. D a h l's (1966) papers. Almost horizontal dips cause the decrease in height of the forms and rather favour the development of structural terraces. The intermediate dips contribute to the development of a whole gamut of transitional forms. The disposition of the tors controlled by the dip reflects also the influence of the bedrock. The characteristic central tors, situated in the axis of the ridge have symmetrical shapes. The edge tors have unevenly disposed walls, according to the prevailing dip of the greenstone. Thus, the tor chains occurring on the northern edge, where the rock dips at 75°—85° N (in accordance with the inclination of the whole slope), form large planes, generally half-covered with consequent block rubbles (Pl. 7). The tor faces on the flat summit side are small and very steep (Pl. 14, Fig. 1). When rock beds are not parallel with the general inclination of the slope, large rock walls are formed, frequently overhanging and more closely fractured, and at their base typical debris material is accumulated (Pl. 9).

The differentiation of forms, sizes and distribution of the tors which reflects the control and the influence of the bedrock has visibly affected the remaining elements of the relief, which was formed under periglacial conditions. Frost riven cliffs, antiplanation steps, rubble fields, a series of various covers, are closely associated with the tors, which naturally speaks in favour of their common origin.

COVERS AND OTHER PERIGLACIAL FORMS ASSOCIATED WITH THE TORS

The solid greenstone rock, adequately fissured and spatially orientated, easily underwent destructive periglacial processes. This considerable susceptibility of the greenstones, derived from specific structural and lithologic properties, contrasts with the results obtained by experiments (Martini, 1967), where a relatively small susceptibility of the rock to frost weathering could be observed. It should be noted, however, that investigations on microgelivation carried out on small rock fragments do not fully reflect the resistance of the rock itself to macrogelivation.

Besides, the microgelivation of the greenstones was considered statically, for a short time during the experiment and without any participation of other processes which would precipitate it (chemical weathering, slope transportation). The greenstone rocks in their natural environment, subject to destructive factors during almost the whole Pleistocene and having specific structural properties, have produced rich weathering material. This exceptional susceptibility of the metamorphic rocks to frost weathering, due to their structure was stressed by a number of scientists: Paterson (1951), Taber (1953), Jäckli (1957), Te Punga (1959), Galloway 1961), Waters (1962), Czudek (1964), Demek (1964a), Ball (1966).

The most typical example of well-developed periglacial covers are rubble fields. According to the situation of the tors which produced them (Martini, 1963) they could be divided into: consequent micro-rubble-fields covering rock walls (parallel to the rock bedding), ruble surrounding the tors which are situated in the axis of the ridge, debris cones and screes. The latter type occurs when the greenstone bedding is discordant with the direction of the slope surface. The extent of accumulation forms depends on the size of the tors. Smaller rubble fields are mostly formed at the base of destroyed frost cliffs. Frequently there can be found larger amounts of debris gathered by people who cultivate the ground on slope planations.

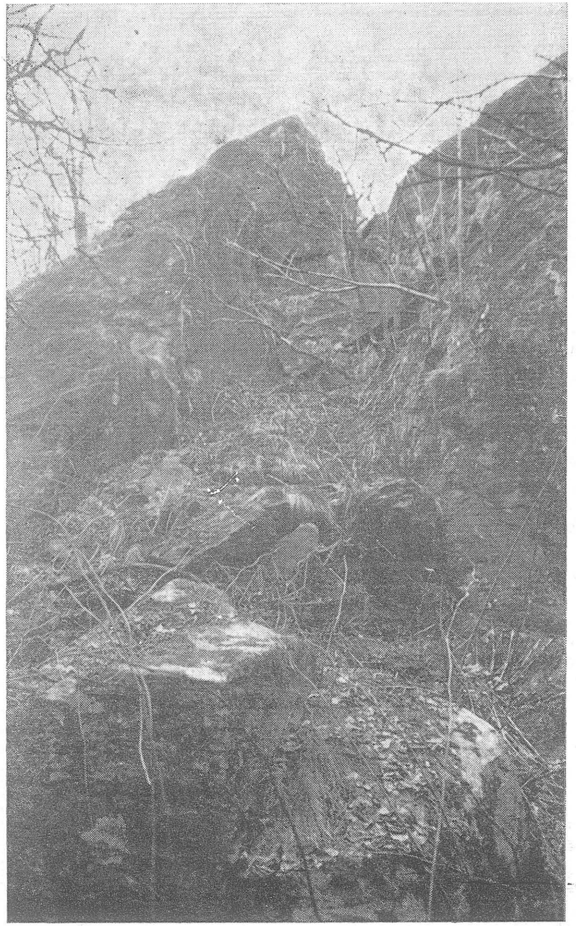
The largest rubble fields, up to 30 m in width, occur near the edge tors. They have been formed owing to intense disintegration of the whole rock wall according to its bedding (Pl. 5). They are built of blocks, frequently of large sizes (reaching 2 m of diameter), which underwent very small transportation, when detached and sliding down (Pl. 10). The transportation may have occurred in the presence of permafrost, snow, melt-waters, with considerable gradients of rock surfaces (ca. 30°—40°). Blocks leaning againts the walls visibly fit into the crack network of the greenstone. The process of block displacement occurred *en masse* with no participation of smaller fractions. B o u t (1953) described such a motion *en masse* of larger phonolite material, whereas K l a t k a (1962) did not admit this possibility of slope transportation of the rubble, arguing that the quartzite block fields of the Świętokrzyskie Mts. are a skeleton facies of congelifluxion covers.

Beside the blocks amassed near the rock wall, there occur large quntities of finer debris with elongated and sharp shapes of "rock tiles" (10—30 cm) characteristic for metamorphic rock. The inner structure of such a rubble field is visible on pl. 11. It has been observed that longer axes of the debris, consistent with the gradient, prevailed — which is a proof of the movement of such weathering material. Excellent examples of such a process are described by B a l l (1966) and R. D a h l (1966).

Block-debris covers which are scree (shown on Pl. 9) differ visibly from the previous group by a smaller gradient (10°—25°), a different type of material and a chaotic disposition of its langer axes. The debris deposited here have much smaller average diameters (5—10 cm). This may be easily explained since the truncated outcrops of rock beds are characterized by a large number of small fissures. There also occur large blocks (ca 2 m) but in much smaller number as compared with rubble, situated consistently with the rock structure.

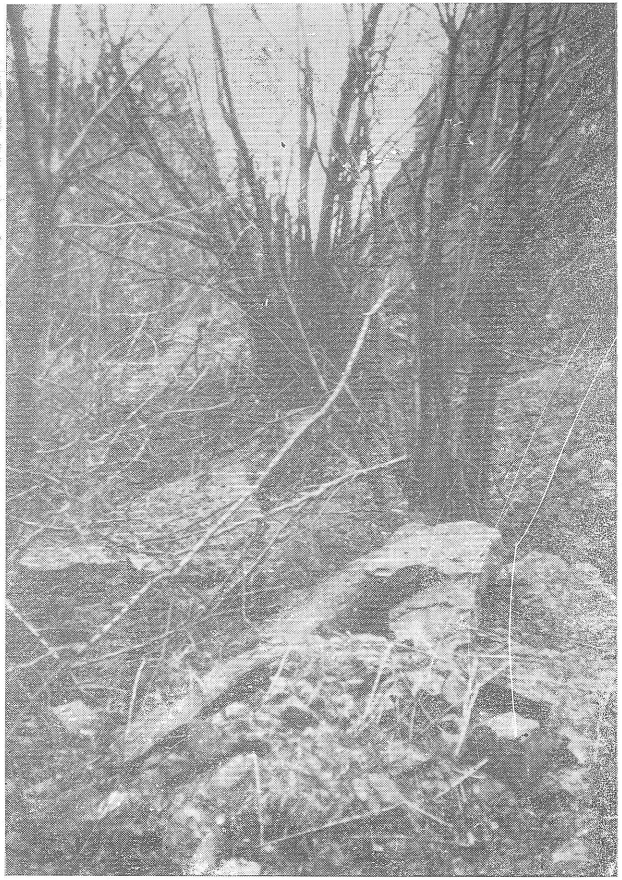
The visible dependence of the size of weathering material upon the size of the crack network is shown in the asymmetrical distribution of the covers. The covers of the northern slope have a great percentage of large blocks whereas the southern slopes are mostly covered with finer scree material. No thermal influence of the slope exposure has been observed here, though in some opinions (Ł o z i ń s k i, 1909; F e z e r, 1953; M y c i e l s k a and N o w a k o w s k a, 1955) this influence has a preference for southern slopes in forming of rubble fields. This structural predominance has already been noted by K l a t k a and O h l s o n.

All the block-debris covers, reaching sometimes a thickness of several metres, are apparently associated with the tors on the one

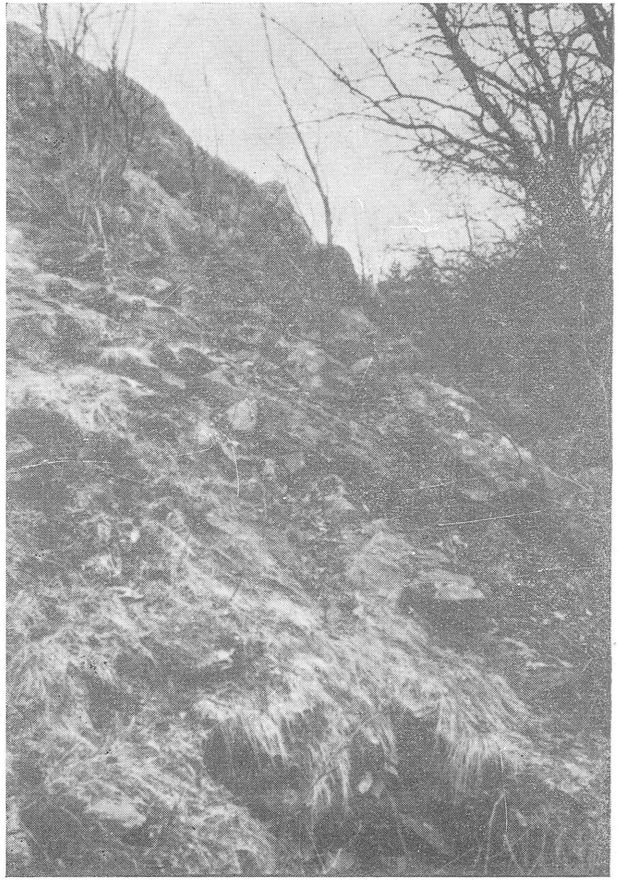


Pl. 8. Differentiated fissure density in a tor and its base

Pl. 7. Isolation of a tor caused by the enlargement of a vertical fissure. In the foreground a cone composed of blocks and debris derived from the disintegrated fissure zone



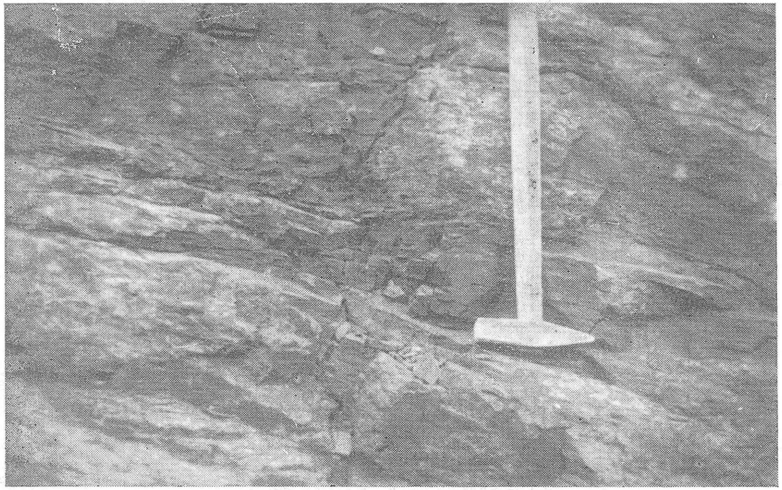
Pl. 9. Example of debris- and block scree at the foot of tors situated along the upper break of a valley slope



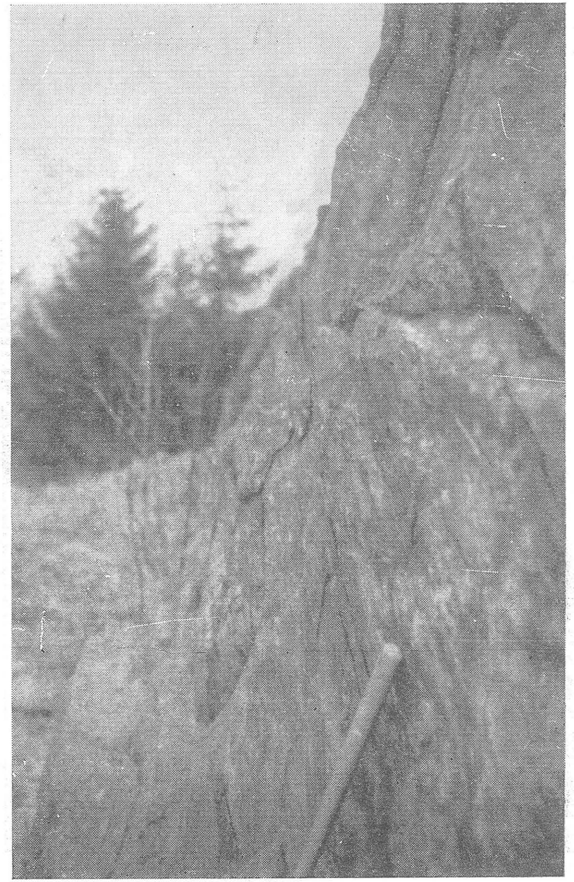
Pl. 10. Consequent block scree

Pl. 11. Structure of consequent debris- and block scree

Pl. 12. Periglacial debris- and silt cover on greenstones, near Dobromierz



Pl. 13. Present-day processes operating on rock faces: selective frost weathering attacks the places of fissure intersecting



Pl. 14. Present-day processes operating on rock faces: exfoliation along the inner foliation planes of greenstones

hand, and on the other they are related to the numerous loam-debris and silty covers which are so characteristic of periglacial colluvium of this area. The tors were producers of blocks and coarser debris. The remaining parts of the greenstone massif, more intensely fissured, have necessarily produced finer debris-, loam- and silty material. Congelifluxion, downwashing, deflation and progressing weathering differentiated still more the fractions of the material of existing covers (Pl. 12). In order to give a clearer picture of the interrelations among the covers and of their association with the greenstone tors and with the rock structure, a synthetic profile of diggings has been set across the main ridge of the Poręba massif along the N—S line.

Digging No 1, on a slightly sloping (2°) surface of an altiplanation terrace, ca 50 m from the edge of the slope and the summit, on a meadow:

A. 0—10 cm: Grey-brown horizon of sod and humus.

B. 10—30 cm: Silty loam with angular debris (25 cm) passing at the bottom into light-yellow silty loam with debris 40 cm in diameter.

C. 30—90 cm: Horizon of blocks exceeding 60 cm. Scale structure of material with outcropping longer axes, with light-yellow silt.

D. 90—120 cm: Silty loam with fine debris of olive-yellow colour, traces of chemical weathering in the bottom part.

E. 120—175 cm: Fine material (0.1—5 cm), chemically weathered, with traces of primary greenstone texture, of green-yellow colour, with continuous transition to upper and lower horizon.

F. 175—200 cm: Loam with angular debris, passing into solid rock at the bottom.

Three genetically separate covers can be distinguished: the uppermost soil cover and the periglacial covers farther connected with the neighbouring tors, separated by a thin formation, chemically modified. This cover might be formed during one of the last interstages. On account of its small thickness and its continuous profile it cannot be a proof of deep chemical weathering of the bedrock. A similar formation within the periglacial debris covers in Wales has been described by Ball (1966). Analyses have revealed, beside rubble, a remarkable content of silt particles (25%) in the horizons B, C, F, whereas the horizon of chemically weathered material E contains ca 35% of sand-size grains and 38% of clay. The content of silt hardly reaches 10%.

Such a disposition of silt particles has been confirmed by the observations of Taber (1953), Galloway (1961), Ragg and Bibby (1966) and a number of other authors who pointed out the favourable conditions of periglacial environment for the formation of silt. The washing away of fines in periglacial waning (cataglacial) phases has formed in the lower slope parts, thick colluvial loam-silty covers (Ball, Ragg and Bibby), which can be found in numerous cross-sections in the Kaczawa Mts. These covers have buried older formations of glacial accumulation and, therefore, within the neighbouring basins, the highest situated erratics are encountered at altitudes of ca 400 m (Martini, 1963).

Cross-section No. 2, placed on consequent rubble field considerably sloping, at the base of an edge tor (Pls. 10, 11) presents an accumulation of blocks and debris connecting the rock walls with lower situated boam-debris covers. There occurs a considerable (0.5%) washing-in of humus: this and the overgrowing of the rubble with vegetation proves its Holocene degradation.

Cross-section No. 3, placed at the foot of the tor, on the summit side (Pl. 8, Fig. 1) displays a small thickness of weathering debris-silty material, slightly displaced.

Cross-section No. 4, in the middle of a flat summit (gradient 0—2°). Thickness of cover 20—30 cm, composed of debris and silt, passing into strongly schistose greenstones.

Cross-section No. 5. Rubble of scree type, gradient 15°—25°. The material is composed of fine angular debris with scarce blocks. The thickness of the cover is considerable — it reaches 3 m. At the depth of 1.5 m the humus content proves the present-day destruction of the rubble cover proceeding from below.

Frost riven cliffs and altiplanation steps are further morphological elements associated with tors and covers and are also a product of periglacial environment. The notion of frost cliff created by Peltier in 1950 was unjustly criticized by Linton (1964). The ocurrence of steep rock walls which express the resistance differences in the rock undergoing processes of intense frost weathering, nivation, congelifluxion and others is strongly signalized in morphological literature dealing with periglacial environment. The periglacial origin of frost cliffs and their association with the development of altiplanation terraces can be found in the papers by Boch and Krasnov (1951), Te Punga (1956), Jahn (1961), Palmer and Radley (1961), Waters (1962), Czudek (1964), Demek (1964a, b, 1965, 1966) and by many others.

Zones which were more strongly fissured and thus more intensely moistened were systematically shattered by frost. The movement of the weathering material caused by gravitational sliding down on snow or by congelifluxion initiated the formation of steep and frequently overhanging rock walls. When the original shape of the slope conformed to the strike and dip of distinctly bedded rocks, elongated edges were formed which at the same time were the thresholds of altiplanation terraces and steps (Waters, 1962).

On the greenstone nunatak of Poręba there also occur cliffs and altiplanation terraces (Pl. 4). Their sizes are small: 1.5—2 m of height, and from over ten metres to below one hundred metres of width. The terrace slope reaches 1° to 4°. They do not differ in size from the examples given by Te Punga, Waters or Czudek. They are at various stages of development, from some of them tors have already been isolated. Some others, buried in debris and overgrown with vegetation, are almost obliterated. The uneven development of those forms resulted from the local structural, climatic and hydrologic conditions which affected the local denudation. The close pattern of fissures, zones of greater humidity, springs — which favour frost weathering and nivation — have caused lateral undercutting of the edge. Those steps were then cut along vertical fissures jointly with the interaction of slope-transportation processes. In consequence of intense destruction only the hard tors were saved. There occur single tors which show what must have been the size and range of the old frost cliff which was liquidated together with the altiplanation terrace, on a sector frequently exceeding 100 m. It is a fact that, besides the local denudation balance which has created a number of forms at various stages of development and destruction, the activity of Man has exerted an essential influence. Ploughing and removing the debris, he nivellated the vanishing terraces thus integrating the neighbouring terraces into a broader area with a slightly more sloping surface (3°—8°).

The importance of local denudation conditions and their connection with the degree of development of such forms has been particularly emphasized in the papers by Czudek and Demek. As the climate grew warmer at the beginning of the Holocene the morphogenetic processes of periglacial environment stopped and the denudation balance acquired a different structure — all this exerted its influence on the present picture of partly developed or destroyed tors, frost riven cliffs and rock rubbles. The present-day period has lasted for too short a time to blur the traces of the Pleistocene relicts under the conditions of a new denudation balance. This correct statement of Palmer and Radley taken up by Waters, Czudek and Demek may find its confirmation also in the Sudetic area.

Summarizing the question of frost riven cliffs, the connection of which with periglacial environment is obvious, their importance should be emphasized in the development of other elements of the relief formed on metamorphic rock. The conditions of the forms of frost riven cliffs and altiplanation terraces are: initial ridges with a levelled surface (old planations — Te Punga, or altitudes smoothed by the glacier — Waters), a rock with various resistance (but, owing to a proper fissure system, susceptible of frost weathering — Te Punga, Waters, Jahn, Czudek), and a whole complex of processes controlled by frost environment and causing secondary development of tor-like forms.

ORIGIN AND AGE OF THE TORS

The formation of tors developed on metamorphic greenstone rocks as a result of a continuous one-phase action of processes of the Pleistocene or present-day periglacial environment on the bedrock, which is differentiated as to resistance. The genetic association of the tors with the development of frost cliffs and altiplanation terraces is not to be denied in the light of facts proved by numerous investigators and obtained in the field. The evolution and development of tor-like forms might be presented as follows: the long greenstone ridges with flat summits, which are the fragments of older, Tertiary planation surfaees, were nunataks during the Pleistocene. Owing to this fact, almost uninter-ruptedly up to the Holocene they were subject to the action of periglacial environment. A complete lack of traces of deep wathering excludes the possibility of a two-phase genesis of the tors. The horizon of the chemically weathered greenstone of small, 0.5 m thickness, found between two covers of periglacial debris in a continuous and undestroyed profile might only be a proof of the change of climatic conditions during one of the last interstages or in the last interglacial period, with no essential morphologic changes.

However, the complex of periglacial processes has exerted a visible morphogenetic influence. Frost weathering, nivation, congelifluxion in the presence of permafrost have an effect on the greenstone rock, differentiated in resistance. In the transitional zones, differing in quantity, density and disposition of fissures, frost cliffs and altiplanation terraces were formed. As a results of these structural differences (Pl. 8) there appeared, on the summit, series of rock walls. A further action of those processes taking advantage of the local weakness of the bedrock adapted the direction of its action to the structure. The lateral shattering of the rock walls by weathering and nivation had a particular influence (R. Dahl, 1966).

The vertical dip of the greenstone beds favoured a better thermal conductance in vertical directions. This is reflected in the top of the permafrost which, in the outcrops of bedrock lies nearer to the surface than places covered with weathering material or with snow (Paterson, 1951; Ohlson, 1964). The resulting more advantageous cooling of the rock, together with a favourable moistening of the fissures caused disintegration of whole rock walls within the crack network controlled by structure (Pl. 5). It is then that numerous consequent rubble fields or screes were formed.

In the next stage the same complex of processes caused the widening of the vertical fissures in the greenstone and this led gradually to a complete isolation of single tors (Pl. 7). The stage of full development of the tors consisted in a further widening of the initially narrow fissures in rock walls and frost cliffs, and then of the large notches, with cones of block and debris material at their outlet.

If the denudation processes which removed the material weakened, a burrying of the rock forms occured. In other cases the balance of local denudation permitted the preservation of distinct tor forms up to now. The whole process, divided here into stages in order to get a clear picture of the origin of tors under Pleistocene periglacial conditions, occurred simultaneously. It only acted in various places with various strength and intensity — depending on local conditions. That is why, after the change of environment in the Holocene and the disappearance of the whole periglacial denudation system, there remained a rich set of tor forms at various stages of evolution — from distinctly isolated rock walls (Pl. 3), through single tors to forms buried in rubble.

Considering the immediate relation of tor forms to the youngest covers, the age of the tors might be connected with the last periglacial period. However, because of their large sizes they may be considered as the cummulative effect of several periglacial periods. The warmer climate of the last interstadial or interglacial stage did not achieve the destruction of the forms which were created in the cold environment, but caused only slight chemical changes of the greenstones.

It is a common fact in this part of the Sudetes that periglacial covers overlay glacial formations (of the Riss glaciation — Szczepankiewicz, 1954). It is difficult to establish the presence of older formations among the nunataks. But in the neighbouring basins (e.g. south of Bolków), under the ground moraine, the occurrence of sands and gravels coming from older slope covers has been established (Zimmermann, 1938).

CONCLUSIONS

The last question is the decline of the forms discussed above, which is caused by washed-in humus and growth of low and high vegetation. The present climatic period has interrupted the cycle of periglacial morphogenesis. A soil cover is formed, and the development of forests has stopped the processes of slope transportation. This is the way in which the dissimulation of the periglacial relief occurred, but because of the very short time of action, this relict relief is frequently strongly underlined in the landscape and particularly in the landscape of the European old mountains.

The last morphologic feature was impressed by Man's action who exploited the natural flattenings of the altiplanation terraces and summits to lay out fields. The liquidation of some edges followed while others were reinforced with stones, brought from the fields, and they were distinctly marked in morphology. Inexpert cultivation frequently causes a relatively strong soil erosion.

The relict character of periglacial forms was emphasized by Te Punga, Waters, Klatka, Czudek, Demek, Ball and others. In Europe those forms undergo only slight modelling by frost weathering under present-day conditions. At present it is expressed by the crumbling of the tor along intercrossing fissures (Pl. 13) or by the exfoliation of plates from the tor walls parallelly with the cleavage surface of the greenschist (Pl. 14). Only this insignificant modelling effect of frost weathering was admitted by Linton (1964) who criticized the periglacial conceptions of Palmer and Radley.

However, the one-phase periglacial origin of the tors, proved and documented by numerous scientists may be primarily referred to metamorphic rocks, i. e. such rocks that have well oriented fissures and thus are particularly subject to frost weathering and congelifluxion. In this regard it can be established that the type of relief-forming processes is determined by the kind of rock under appropriate climatic conditions. The European tors of metamorphic schists were formed in the course of one-phase selective denudation in the Pleistocene periglacial environment, as they are forming in the same way in sub-polar zones up to this day.

Translation by T. Potulicka

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