Andrzej Martini *

Wrocław

PRELIMINARY EXPERIMENTAL STUDIES ON FROST WEATHERING OF CERTAIN ROCK TYPES FROM THE WEST SUDETES

Abstract

The studies embraced the fundamental rock types occurring in the West Sudetes, such as granites, gneisses, metamorphic schists, crystalline limestones, sandstones, greenstones, basalts, etc. These underwent cyclic freezing and thawing in laboratory, under conditions of the so-called Iceland cycle (according to J. Tricart) characterized by a determined amplitude (up to 15°C) and considerable humidity.

In general, a great susceptibility to frost weathering was observed in sandstones, several types of granite and metamorphic schists. Crystalline limestones, gneisses and volcanites also revealed great resistance to the weathering. Rocks characterized by well developed grains tended to a uniform many-fractional disintegration, whereas cryptocrystalline and massive rocks having fine grains gave relatively more coarse material (in the form of chips) and silt material in grain-size below 0.5 mm. Differences in weathering of the individual rocks were, among others, a result of various amount of water used in the experiment. These were caused also by a different initial state of the rock samples.

An analysis of the data obtained under laboratory conditions and in the field allows, in connection with the literature data, to draw some conclusions as to a series of dependences and connections that condition and determine the effects and type of frost weathering. The dependences were subdivided into groups reflecting the active part of the process (temperature and water), and its passive part (dependences being a result of lithological features of rocks such as mineral composition, texture, structure, kind of cementing material, quantity and distribution of fractures, etc.). Considerably important fact of influence of other types of weathering upon frost activity has also been taken into consideration.

After discussing the above dependences and the connection with the differentiated material obtained during experiment, the author refers to the problem of macro- and microgelivation. Resistance, or susceptibility of a given rock to frost weathering can, at present, be estimated only generally. A detailed estimate of effectiveness of the process calls for a precise determination of conditions of the process and of the rock.

The problem of quantitative presentation of some processes solved by means of laboratory experiments is thought at present to be more and more important in the today's geomorphology.

Therefore, experiments concerning reaction of various rock types taken from the West Sudetes have been made to seize, from quantitative point of view, the value of today's frost weathering, its intensity, scale of physical disintegration, and to determine the character of the material obtained. The experiments have been made in the Laboratory of the Department of Physical Geography at Wrocław University in the years 1964—1965 under the scientific leadership of Prof. Dr. Alfred Jahn.

* Institute of Geography, The University, Wrocław, Poland.

EXPERIMENTAL METHODS

The experiments discussed in the present paper have been modelled after the previous works by Tricart (1956), Sukhodrovski (1962) and Wiman (1963), and therefore the method applied does not deviate in its character from that used in the works mentioned above, under conditions of the so-called Iceland cycle. This cycle, characterized by approximately 40-day oscillations of temperature near 0°C, by an amplitude ranging from −7° to +6°C, and a constant relative humidity amounting to about 70 per cent., does not differ from natural conditions, as it may be observed in the case of Siberian cycle. Particularly unnatural in the Sibirian cycle appears to be its great velocity of freezing (about 2 hours to pass from +10 to −30°C), a fact being also stressed by Tricart (1956). Taking this into account one restricted the studies here considered to the Iceland cycle only. The fact that Tricart and Wiman did not obtain weathered material under dry conditions also contributed to the decision of conducting experiment only under conditions of humid and water environments, being of profit to the most specimens of the rock types examined.

The samples were put into the frost-proof vinidure containers and placed in a freezer of „Frigera" type, characterized by a great possibility of obtaining various temperatures and their amplitudes by means of special, semi-automatic control. Changes of temperature in freezer were controlled using telethermograph, and humidity by means of August's psychrometer. Inner stratification of temperature was prevented by an installed fan. Samples under water conditions were half-immersed in distilled water, and humid conditions were created by putting humid lignin on the specimens examined; humidity value was not greater than that of relative humidity in the freezer.

The experiment embraced approximately 40 types of rocks under water conditions and the same quantity under conditions of humid environments. Except for certain samples (rock samples No. No. 16a and 1a), most of the rocks were represented by three identical fragments, under similar conditions. Comparisons of weighted and percentage means are presented in Tables I and II. Some differences as compared with the experiments by Tricart and Wiman, consisted in the presence of the same rocks characterized, however, by various degree of primary weathering, and in observations of the samples and of the material obtained under the microscope, before and after the experiment. During microscopic observations (enl. × 10 to 25) a standard with millimetre scale, amounting to 1 cm^2, was used to trace both quantity and density of the cracks under examination.

In contrast with Tricart, who conducted his experiments mainly on fragments of various limestone types, and with Wiman, who in turn applied freezing and thawing cycles to examine partly weathered granitoid and metamorphic rocks, the present author used in his experiment certain rocks typical of the West Sudetes area, from fresh to completely weathered. For the most part, the specimens were taken in the Karkonosze Mts. region and in the areas of the Jelenia Góra basin (granites and Cretaceous sandstones), as well as from the Izera Mts. (gneisses, mica schists) and Kaczawa Mts. (crystalline limestones, greenstones, Permian sandstones and basalts).

DESCRIPTION OF MATERIAL

GRANITES

The examinations embraced various types of granites of the Young Variscian intrusion, which came from the Karkonosze block, basin of Jelenia Góra, and from the main ridge of the Karkonosze Mts. The material sampled was from porphyraceous equigranular aplitic granites charatectristic of the region under consideration. If possible, fresh, or completely weathered rocks were collected either immediately at the quarry walls, or from waste covers, or even spherical hollows (small kettles) occurring on the tors. Porphyraceous granite (sample No. 3, Pl. 1) taken in a small quarry in the vicinity of Jelenia Góra, near the road to Staniszów, may serve here as typical example. The author was also successful in collecting some completely fresh rock specimens (without visible chemical changes of minerals) at the quarry face and, simultaneously, the same strongly weathered granite taken from the overlying cover. In addition to the chemical changes, the granite was also characterized by a strongly loosened structure, so that it easily crumbled when taken in hand. Samples of transition character were also taken from this rock. This was an easy procedure mainly due to the fact that an undisturbed weathering profile was found in an over ten metres thick series resting on fresh rock, immediately under the surface. In their grey granite mass composed of orthoclase, oligoclase, quartz and biotite characterized by fine to medium grains, the samples of fresh rock (No. 3c) also contain feldspar crystals in the shape of phenocrysts, up to 2 cm in diameter. The individual minerals are well developed (mainly feldspars) and reveal grains of various size. Texture of the rocks is chaotic and compact. Such a type of rocks represents certain lithological conditions that make possible frost weathering mainly due to a differentiated thermal conductivity of the individual minerals and to a great possibility of water imbibition. The specimen of the same mean-weathered rock (3b) differs from the previous in chemically partly weathered feldspars (plagioclases), and in small amount of minute fissures between phenocrysts and the remainder of the rock body. The strongly weathered rock (3a), easily crumbling in the hand, is characterized by a highly developed net of cracks between feldspars (approximately 15/1 cm^2). Smaller amount of the cracks occurs on the phenocrysts, particularly along planes of cleavage twinnigs, and perpendicularly to the long axis of the given individual. A part of cracks divides also biotite flakes and even quartz. In this rock the net of cracks stresses its chaotic texture and ignores structure. Generation of larger fissures (2,5 cm long and 1 mm wide) is connected with seperation of the individual grains. Smaller cracks (up to 1 cm long, 0,2 mm wide) cut across various mineral grains thus excluding their structural or textural origin proving, however, mechanical genesis. Strong chemical alterations in most minerals can also be observed (feldspars and biotites). This constitutes favourable conditions for further frost weathering mainly due to a great difference of physical properties between them and unaltered quartz.

From fresh granite (3c) only small amount of weathered material was obtained (Pl. 1), amounting to 0,02% (water conditions) and 0,03% (humid conditions). The material was grouped within grain-size intervals, 0,05—2 mm (Fig. 2). For the most part these were small grains of biotite, and quartz, as well as mineral chips of quartz and feldspars, characterized by sharp edges and cymbiform shapes. In this case we have to do with a rare phenomenon of weight predominance of the weathered material obtained under humid conditions over those obtained under water ones within the group of granites (Fig. 11, Tables I and II). There occurs here also a small amount of minute fissures and cracks on the edges of the samples, tending to separate the individual minerals. Insignificant quantity of weathered material was obtained also in the case of sample No. 3b (approximately 0,1 g) characterized by a minimum predominance in weight under water conditions. The material obtained in this case is represented by not numerous mineral aggregates composed of rock body, up to 2 mm in size, constituted by quartz, feldspars and biotite. In smaller fractions chips and lumps of sharp-edged milk quartz and transparent quartz, some quantity of slightly altered feldspars and fresh biotites belong to the main constituents. It can be observed that in the rock here considered a certain loosening of minerals has taken place particularly at the edges of the specimens. In addition, also minute fissures may be seen characterized by their irregular course, 1 cm long and 0,05 mm wide, and by a completely straight course on less chemically weathered feldspars (mainly pink orthoclases), perpendicularly to their long axis. The strongest reaction to frost weathering was observed on samples 3a. Here, the granite has disintegrated almost completely, giving rich material under both humid and water conditions, with a slight predominance of these latter (Fig. 11, Tables I and II, Pl. 1). Scattering of material between fractions of weathered material was marked by a weight predominance within intervals characterized by smaller grain size under water conditions, and by a greater amount of coarser material under humid conditions (Fig. 2). In the latter case a part of non-crushed sample might have been observed, however, the sample was so strongly loosened that it fell to pieces immediately after the photographs were taken. Loose aggregates that were formed after the experiment originated at the place of lower strength of crackings in sample; within other intervals of grain size the material is grouped fairly characteristically: in a fraction 0,05—2,0 mm there occur beside minute aggregates also individual grains of less weathered feldspars, biotite and quartz. The smallest fractions are occupied mainly by fine-grained quartz and by its chips and sharp-edged splinters, cymbiform in their shapes, together with rare accessory minerals. In grain-size below 0,06 mm there occurs also quartz, very fine-grained, with a large amount of amorphous substance occurring as „floccules". Such a kind of material occurs only in rocks previously chemically altered.

In addition, a marked increase can be noted of various types of fissures no doubt caused by mechanical factors, which separate the individual mineral grains and cut across the feldspars, quartzes, and biotites without any difference, always in relation to the character of the minerals (perpendicular position to the long axis on feldspars, splitting of biotite flakes and of individual quartzes undeveloped as crystals). An uplifting of edges of biotite and muscovite flakes, a proof of frost weathering effect, is here very characteristic. Distinct fissures cutting the individual minerals occur on the less chemically weathered crystals, however, in the case of strongly altered feldspars such fissures disappear. Cracks that separate minerals of various degree of weathering are here more visible. Beside greater fissure, the quantity of which increased in comparison with those from the sample before the experiment, a series of characteristic, minute fragments occurs such as splinters (quartz), scales (biotite) and angular lumps (quartz, feldspar), that divide the individual grains into smaller elements, and are grouped in the fractions below 0,5 mm.

This type of granite, common in the basin of Jelenia Góra in the Karkonosze Mts., proved to be highly resistant to mechanical weathering, however, in fresh state only. When subject to chemical factors this resistance decreases almost to 0 value, particularly in the case of strong chemical changes. Feldspars, susceptible to chemical changes, alter their consistency, thus causing numerous differences in physical properties in relation to the adjacent, slightly altered biotites mainly, however, quartzes (the problem consists mainly in thermal conductivity and inner cohesion — resistance to the activity of external mechanical forces). These differences in turn cause a rapid loosening of the whole rock due to the activity of frost weathering. Quartz occurs in rock body and rarely is developed as crystals, giving only small fragments conformable with shell-like fracture. On the other hand, feldspars in weathered material are developed in holocrystalline or fragmental form, and biotite falls into characteristic flakes according to its cleavage. Disintegration of minerals according to their cleavage is a characteristic feature of those, which are well developed as crystals.

The next type of porphyraceous granite (No. 7a) does not differ from the previous one. The sample was taken from weathering cover near the Wielki Szyszak (main ridge of the Karkonosze Mts.). This also represents porphyraceous granite revealing slightly larger feldspar grains (orthoclase grains) amounting to 3,5 cm in length, at places. This rock, somewhat chemically weathered, represents a transition type, mainly as concerns its preservation state, thus also its resistance, and may be placed between granite 3b and 3c. This can also explain the presence of weathered material in 4% under water conditions, and in 1,8% under humid conditions. The material itself and its distribution within the intervals of the individual fractions, the quantities of fissures, and their character do not deviate from similar features of previous rock, particularly of type 3b.

Porphyraceous granite (type of granodiorite revealing a visible predominance of plagioclases) gathered in the vicinities of the Szklarka waterfall, near Szklarska Poręba, represents another type of granite, the behaviour of which during examination did not deviate from previous ones. The sample (No. 16a) taken from the tor face, also revealed some chemical changes of feldspars and a loosening of minerals, especially on the side exposed to the aeral factors. Considerable quantitative differences between the weathered material produced under water conditions (5,8%) and that formed under humid conditions (0,5%) may be explained by a fact that biotite schlier (Pl. 2b), approximately 19,76 g in weight, was formed between them during the existence of water conditions. Both kind of fissures and character of the material are similar to those described in the previously given example. Exceptions are represented by distinct, irregular cracks and split edges (effects of frost activity) that separate smaller aggregations of the remaining schliers from the rock body.

almost uniform size of the individual mineral grains any strong contrasts as to thermal conductivity and linear expansion of crystals, so characteristic of porphyraceous granites, are lacking here. This reflected both in the character of the material (fine scales) and in scarce cracks that probably coincide with the cleavage of the rock itself. In the fresh porphyraceous granites there occurs also a distinctly marked joint that, however, did not appear in the form of cracks after the experiment. Previously weathered granite revealed a dense net of fissures that was responsible for the disintegration of rock, but conditioned only by its structure and texture.

When comparing the collected granite material with the data obtained by Wiman (1963) we may state a considerable similarity — naturally in the Iceland cycle. This author examined, among others, two types of granite collected from debris cones. In spite of their origin the granites were not changed chemically on a large scale (porphyraceous granite Gorberg from Dälärne and red granites from Järne). The material obtained ranges in its quantity from 0,15 to 0,21%. Distribution of the material within the fraction is also similar. Most of the granular (mineral) weathered material is between 0,5 mm and 2 mm. Wiman's data coincide then with the results obtained from the examination of not very disturbed granites No. 3b, 4a, 6a, 0—3a. Interesting results were obtained also by D. W. Kessler, H. Insley and W. H. Slight (1940), who conducted a series of technolo-

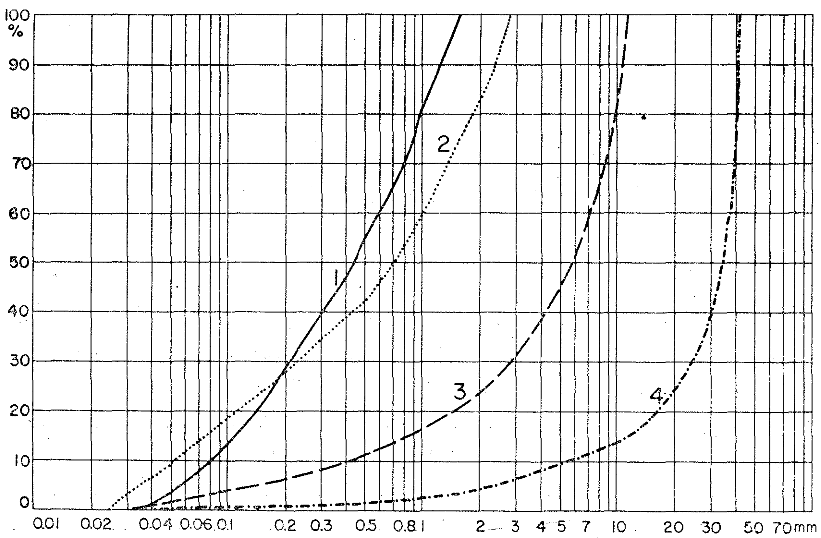


Fig. 3. Grain-size distribution curves of weathered material

Equigranular and fine-grained granite from the waste cover (Jelenia Góra) No. 4a: 1 — humid environment, 2 — water environment

Porphyraceous granite (granodiorite type) from a tor wall, No. 16a: 3 — humid environment, 4 — water environment and the joint of the rock. Some of them directly cut the minerals, irrespective of their resistance, and widen on the surface of the sample.

Fresh, equigranular, fine-grained granite (4b) proved to be highly resistant to mechanical weathering. The experiment allowed to obtain some traces of material (0,007%) under water conditions and 0,002% under humid conditions. There were observed only scarce, regularly distributed, long and very narrow cracks tending to split the sample into regular perpendicular parallelepipeds. The behaviour of aplite granite was quite similar. The sample taken from the main ridge of the Karkonosze

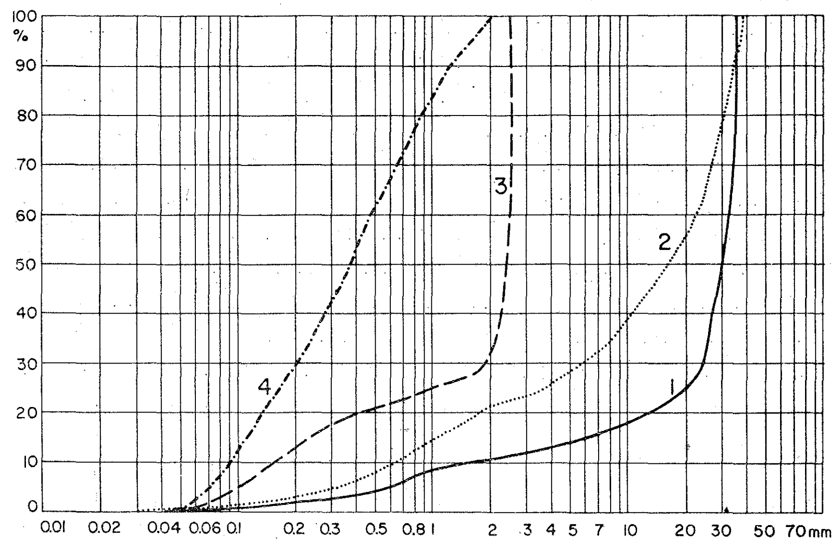


Fig. 2. Grain-size distribution curves of weathered material

Porphyraceous granite from the waste cover surface (Jelenia Góra), No. 3a: 1 — humid environment; 2 — water environment

Porphyraceous (fresh) granite, Jelenia Góra, No. 3c: 3 — humid environment, 4 — water environment

Mts, (No. 6a) represents an equigranular rock, cream-pink in colour, poor in biotite, its body consisting of quartz and feldspars. The quantity of material obtained under water conditions amounted to approximately 0,14%; under humid conditions no weathered material was obtained there. The character of the material discussed did not differ from that of the material obtained from granite No. 4 (fine scales of rock body taken on the surface of specimens). Here were found also similar long and narrow cracks, regularly distributed.

Generalizing this we may state that the resistance and behaviour of the equigranular granites under conditions of frost weathering depend mainly upon the structure (grain sizes of the rock). On account of an water in small kettle), we cannot wonder at its low resistance to experimentally produced frost weathering. This sample might also have been crushed in the hand.

Porphyraceous granite No. 0—3a taken from debris cover in the main ridge area, relatively slightly altered from the chemical point of view, behaved similarly as fresh granite No. 3. It gave about 0,09% material under humid conditions, and 0,06% material under water conditions. Effect of frost weathering brought about the formation of fine and very fine weathered material and slightly weakened the structure of rock at the edges of samples.

Completely different reaction was that of fine equigranular granite No. 4 from quarries situated in the vicinity of Jelenia Góra. Here some specimens of fresh rock and those of partly chemically weathered rock have been obtained. The granite differs in its petrologic character from the porphyraceous one in having no large feldspar crystals, in smaller amount of biotite, and in greater quantity of quartz, frequently of highly complicated intergrowths. This is a grey-pink rock characterized by fine-grained structure, and by compact and chaotic texture. In the first sample No. 4a taken from the waste cover, distinct changes are seen that took place due to chemical weathering, and now occur as a transition of feldspar colour into brown one. In addition, there are observed both selective destruction of biotite (visible on the surface of samples in the shape of microcaverns) and greater loosening of mineral grains, fairly distinctly marked, as compared with massive and compact texture of fresh rock (4b). Rock No. 4a is characterized by a series of up to 3 cm long and 0,05 mm wide cracks parallel to the surface that was most exposed to the activity of external factors, with a tendency to exfoliate. Fissures that might separate the individual minerals are lacking. Sample 4a yielded during the experiment 0,1% of weathered material under water conditions, and minimum quantity (0,03%) of this material under humid conditions. The character of thic detritus differs slightly from the analogous character of porphyraceous granites. Larger mineral aggregates are lacking here (Fig. 3); there occur, however, some small scales below 2 mm in size, very thin and friable, just from the surface chemically most altered. Within intervals of fine fractions there are found grains of quartz, biotite and even of tabular feldspars. This material does not resemble the corresponding fraction of weathered material from porphyraceous granites there. Differences of environment influence the quantity of the material obtained, a fact being due to the detriment of humid conditions. The quantity of cracks decreases; these are, however, fairly distinct and regularly distributed. It may be thought on this basis that they are concordant with the cleavage

Great similarity to the strongly chemically weathered granite (3a) is seen in porphyraceous granite (No. 0—2a). Granite from the small kettle (*kociołek*) on the Orla Skała tor at Szklarska Poręba, contains equigranular minerals, however, without larger crystals of feldspars. Here occurs a considerable quantity of cracks of various types from dendritic bundles, occurring in the rock body, up to large ones crossing the individual crystals. After the experiment, their quantity increased to 10/cm². The amount of the weathered material obtained is also considerable (36,4% under water conditions and almost 20% under humid conditions). This material resembles granite No. 3a, i.e. in the interval above 2 mm are grouped less cracked mineral aggregates and larger feldspars. Most of the material obtained occurs, within a fraction 0,5—2,0 mm, in the shape of characteristic quartz fragments, biotite fragments, characterized by uplifted edges, and fairly weathered feldspars. Grain-size beneath 0,06 mm is represented by quartz dust together with amorphous clay substance that occurs only in rocks previously affected by chemical weathering. Differences in reactions

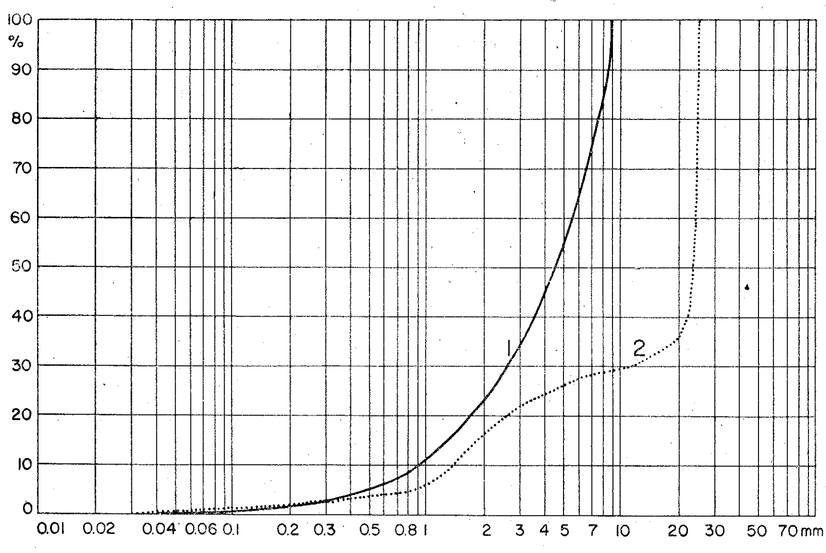


Fig. 1. Grain-size distribution curves of experimentally obtained weathered material of porphyraceous granite from a kettle (*kociołek*), Szklarska Poręba, No. 0—2a

1 — experiment under conditions of humid environment; 2 — experiment under conditions of water environment

of rocks between various environments, in which the experiment has been made, are quantitative only, both in material and in quantity of fissures (Fig. 1; Pl. 3). Taking into consideration the specific conditions, under which the rock has existed in the nature (great amount of chemically active gical examinations of granites in the United States of America. Among others, they treated the samples with about 5 thousands cycles of freezing and thawing under minimum temperature of $-12°C$. However, the samples did not reveal any changes, except for a slightly increased porosity (similarly as in Wiman's experiments). On the other hand, a strong reaction was noted after treatment with phosphoric acid caused scarring of samples on their surface. The granite used in the experiment was fresh since the study was conducted with a view of applying the granite as building material.

On the basis of these scarce literature data and on own observations we may state that porphyraceous granite is relatively highly resistant to frost weathering when fresh; however, its resistance is considerably low, when it is chemically weathered. The second fact is that fine-grained, equigranular and aplite granites are, for the most part, more resistant to weathering. In the case of granites, the most important feature, beside the initial state of the rock, is also a textural and structural moment that is revealed in a specific character of the material obtained (mainly granular material — mineral aggregates of crystals and of their small splinters), and in a stable system of fissures. This system is connected with the structure of the granite, separates the individual grains and mineral aggregates, and partly cuts the crystals, particularly in the case of a strong loosening of rock due to the activity of chemical factors and due to the further intense action of low temperatures.

VOLCANITES

When examined, the rocks of this group disclosed a considerable resistance. Keratophyre samples No. 17a, used during the experiment, gave only 0,06% weathered material under water conditions and 0,009% under humid conditions (Fig. 11, Tables I and II). The keratophyres represent a fairly important formation in the Kaczawa Mts. This was the area where this sample was gathered from a scree at the tor, near the main road Jelenia Góra—Jawor. These are Old Palaeozoic alkali-trachytes that beside quartz contain also albite, anorthoclase and numerous iron oxides. This represents a very fine-grained massive and hard rock characterized by trachytic structure. Felsitic rock body, grey in colour with violet tint is sometimes coloured in the shape of brown spots caused by iron oxide pigment. It reveals scarce long and narrow fissures probably controlled by the system of structural cracks of the rock. On the surface are found small hollows left after removing of chemically weathered iron oxides. Scarce material obtained under water conditions is developed as very fine scales composed mainly of rock body or of not numerous fragments of quartz below 0,5 mm in size. After the experiment, the number of cracks on the surface of samples slightly increased (one crack in 4 cm^2). Under conditions of humid environment the quantity of weathered material was sixtime lesser.

Still greater resistance has been revealed by basalts (No. 18a), the samples of which, covered with lichens, were taken also from the tor scree, at the same way in the Kaczawa Mts. This is an effusive rock, black in colour, corresponding to the gabbro with great amount of olivine. Its structure is of microcrystalline character, resembling glass, and the texture is compact. The age of the basalts is thought to be Tertiary (Neogene, Miocene).

Weathering processes, mainly, however, chemical weathering, are responsible for the formation of thin, rusty-brown crust on blocks, under which the material is untouched. After a certain span of time such a crust bleaches. No cracks can be found on the samples, although the rock reveals a highly visible columnar jointing that probably influences block disintegration. For in the case of fine-grained disintegration, the basalts did not lose any material, except for organic parts (lichens). Thus under conditions of water environment a material has been obtained amounting to approximately 0,1% (95% of this material were lichens), and under humid conditions only 0,006%, also with a marked advantage of organic remains. Rock material was restricted to micro-scales of rock body, coming from the edges of samples. No changes have been ascertained on the rock surface, except for these parts, which were covered with lichens. The uncovered sufrace was rough and rugged, brown-coloured in contrast with the black and ideally smooth surface of the remaining parts of the rock. This throws some light on the rôle of so far underestimated organic elements. The influence of biochemical weathering may equally be important as that of chemical weathering, mainly upon further process of frost weathering.

Interesting data as to the action of frost weathering against basalt are given by Sukhodrovski (1962a, b). He treated some fragments of basalt, taken from deluvial cover of Francis Joseph's Land, also under water and humid conditions, and under dry conditions in regelation cycles. He carried out approximately 100 cycles within a temperature interval from $-15°$ to $+25°C$. Number of oscillations near the temperature $0°C$ was approximate to natural ones occurring on the archipelago mentioned above; however, the amplitudes of temperature oscillations exceeded actual day values. The experiment yielded mainly a fine-grained material from fine-sand and silt fractions. The material got detached from the rock surface. Within an interval from 0,25 mm to 1 mm Sukhodrovski obtained 17,7% of weathered material, and below 0,25 mm — the remainder of material, the finest fractions below 0,06 mm amounting to approximately 18,5%. Sukhodrovski has also stated that the main portion of the detritus came from the near-surface weathered parts of the fragments (particularly of their edges), which were subject to physical, chemical and biological processes. He computed the weight of weathered material obtained from 1 cm^2 of sample surface, which under water and humid conditions amounted to 5,9 mg. On this basis, and knowing the specific gravity of basalt (about 3,0 g/cm^3), as well as the volume of the given specimen, he determined a linear decrease of the sample surface, amounting to 0,019 mm a year, caused by frost weathering. Similar computation made for basalts under dry conditions gave a result amounting to 0,03 mg/cm^2; linear decrease was approximately 0,001 mm a year. Hence, a conclusion can be drawn that the process here considered goes on 160 times slower than in the environment under water conditions. Under these conditions the total amount of weathered material from basalts was approximately 0,005%, a fact showing that the basalts from the area of Francis Joseph's Archipelago reveal similar resistance as those from the Sudetes.

Basing on the experiments mentioned above and on those made by Tricart (1956) and Wiman (1963) we may state only an insignificant effectiveness of frost weathering under conditions of dry environment. Effusive rocks reveal a considerable resistance to frost activity (effect of fine granular disintegration here considered). The scarce material obtained during the experiment is grouped mainly in the fine and very fine fractions. This fact is fairly important, particularly in the presence of rather numerous silty covers occurring within basalt cones so abundant in the area of the West Sudetes. A high resistance of effusive rocks, as compared with other rock types, has also been stated by Tricart during his experiments conducted, among others, on Moorish porphyry from Frejus.

SANDSTONES

Group of these rocks revealed the relatively lowest resistance to frost weathering performed under conditions of experimental environment. Samples were taken from the Stromiec Mt., north of Jelenia Góra, and in the vicinity of Biegaszów, near Złotoryja, on the northern slope of the Kaczawa Mts.

The sandstones from the Stromiec (samples No. 5) are shallow-water marine deposits laid down in the Lwówek bay of the Cretaceous sea (Cenomanian-Turonian). They consist mainly of quartz (more than 95%), feldspars, quartzite, rarely of porphyry. These are medium-grained and fine-grained rocks (approximately 40% of grains are found in an interval from 0,5 to 2,0 mm), revealing a siliceous cementing material, and in the top portions a calcareous cement that is responsible for the formation of pseudokarst phenomena. These sandstones, yellow-grey-green in colour, are characterized by a compact and porous and chaotic texture. Quartz pebbles, up to 1 cm in size, are rarely found here. The amount of CO_2 in calcareous cement may attain, at places, to 5%. The sample No. 5a was taken from the summit waste cover of the Stromiec. The rock was fairly strongly weathered by physical-chemical processes that led to a complete loosening of the sample (porous texture). On its surface there are seen, in weathered clay matrix, distinct small hollows after previously here existing quartz grains, and a distinct change of tint into brown. A marked net of cracks and fissures is lacking here. It is, however, visible in the samples 5b taken at the bottom of the cover, where samples were not subject to so an intense influence of external processes. The next samples (5c), taken from the so-called I. pseudokarst horizon, are also characterized by a strongly loosened texture, mainly due to the leaching away of considerable part of calcite cement. Sandstone of this horizon is markedly cracked showing also some tendencies to scale off and to split quartz aggregates. Sandstone No. 5d, almost fresh, revealing siliceous cement, and taken from a wall of a small abandoned quarry, belongs to the last type of rock in the section considered. It is characterized by a compact texture and by scarce fissures. Quartz grains differ in their size and roundness and this fact, irrespective of their considerable compactness, as compared with the previous types, has decided upon their insignificant susceptibility to frost weathering.

Each of these sandstones reacted in its specific way to the experiment performed by the author. Samples 5a, relatively strongly chemically altered, have lost only 1,6% of weathered material under water conditions, and 0,7% under humid conditions (fig. 11); most of the material was grouped in the intervals below 0,5 mm (Fig. 4, Tables III and IV). This fact can be explained probably by a good deal of clay-like matrix. Lack of greater amount of fissures contributed to formation of not very numerous aggregates, their size being more than 2 mm. In its character the material does not differ from other sandstones. The fragments obtained during the experiment are not angular as those from magmatic rocks. Medium-grained fractions are composed mainly of the individual quartz grains, and only small amount of material (in a fraction below 0,06 mm) shows features of fragments of the rounded quartz grains. The remainder of fine material is represented by amorphous clayey mass always occurring beside the chemically weathered specimens.

Analogous observations were made by Tricart during his experiments on variegated sandstones from Lutzelburg. The comminution of sand grains was here interpreted by him as caused by their weakness due to the penetration of iron oxide into certain original cracks. On this basis Tricart supposed a possibility of formation of loesses, partly at least, from comminution of grains on old covers and alluvial deposits due to frost activity.

It might have been observed after the experiment that the rock was somewhat loosened and revealed an increased amount of cracks occurring in cement and separating the individual sand grains, as well as a series of hollows after removing of aggregates.

A considerable greater deal of material was obtained from the samples 5b. Under water conditions it was 55,5%, under humid conditions only 8,9%. Scatter of the weathered material and its character do not deviate from that in other sandstones. The type here considered contained, however, more than 50% of sand weathered material (Tables III and IV, Fig. 4). This can be explained by an increased amount of cracks up to 4 on each 1 cm^2. On the surface of the specimens the quantity of hollows is also greater.

Similar disproportion of weight, in favour of water conditions, is shown by the sandstone No. 5c. This is expressed by a value amounting to 75%

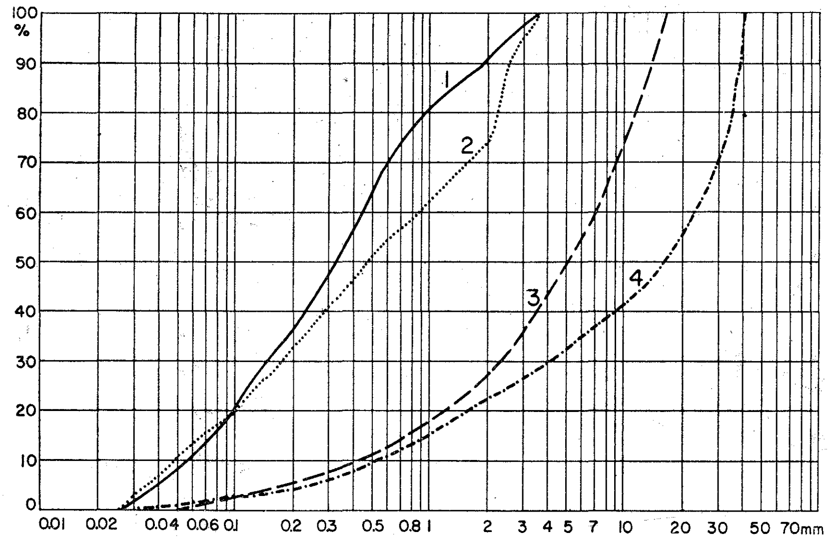


Fig. 4. Grain-size distribution curves of weathered material

Cretaceous sandstone from the waste cover surface (Stromiec), No. 5a: 1 — humid environment, 2 — water environment

Cretaceous sandstone from the waste cover bottom (Stromiec), No. 5b: 3 — humid environment, 4 — water environment in relation to 10,3% (Fig. 5, Pl. 5). Removing of calcite cement considerably weakened the internal compactness of the rock and caused a decrease of resistance to frost weathering. This has been expressed in a complete lack of aggregates and in the presence of sand fraction amounting to 70%.

The fact of low resistance of the sandstones from the Stromiec (pseudokarst beds) to frost weathering was already observed in 1963 by Jodłowski [1]. His study on this type of sandstone has shown a loss of weathered material in samples, amounting to 18%, scarcely during 8 cycles, having amplitude from −25 °C to +10 °C.

In relation to the previous kinds the fresh sandstone having siliceous cementing material (No. 5d) is characterized by a greater resistance. This is proved by a loss in material amounting only 3,5% under water conditions and 0,18% under humid conditions. The material consists of the individual grains occurring within sand interval 0,06—2.0 mm and amounting to 85,0%. The finest fraction contained a lot of angular fragments of mat and transparent quartzes, originated after disintegration of larger grains and of siliceous cementing material. This was a considerable difference as compared with other sandstones (Fig. 5, Pl. 6).

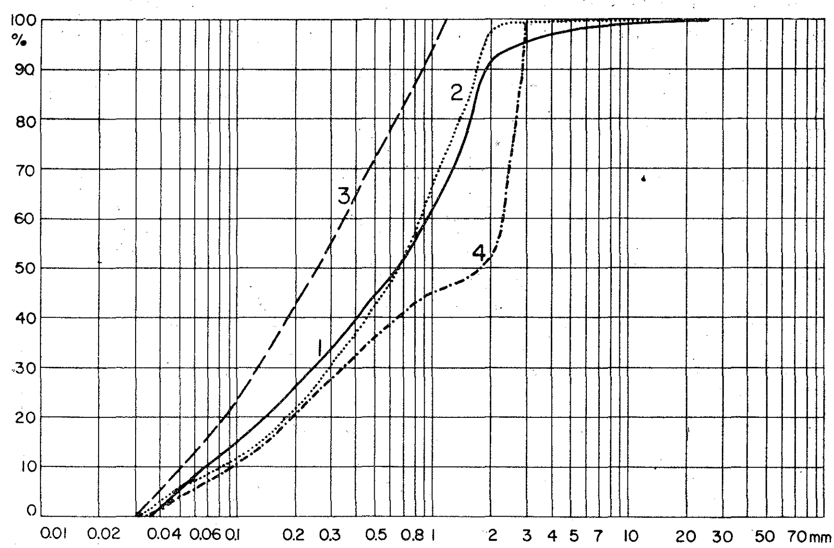


Fig. 5. Grain-size distribution curves of weathered material

Cretaceous sandstone from the pseudokarst bed (Stromiec), No. 5c: 1 — humid environment, 2 — water environment
Fresh Cretaceous sandstone (Stromiec), No. 5d: 3 — humid environment, 4 — water environment

[1] St. Jodłowski — Pseudokarst phenomena in Cretaceous sandstones in the Kaczawa Mountains; Wrocław, 1963 (manuscript).

The Permian conglomeratic sandstones (No. 19a) of Rotliegendes age (the uppermost part of the so-called Świerzawa beds), cherry in colour, taken from the vicinity of Złotoryja, contain numerous fragments and pebbles of quartz, phyllite schists, gneissose granites from the Izera Mt., and greenstone slates. These are deposits of alluvial cones in inland basins, that prove violent and turbulent sedimentation. In spite of diagenesis, this rock is porous and highly susceptible to frost weathering mainly due to the differentiated, almost porphyraceous structure and varied petrologic and mineral compositions. Certain quartz pebbles attain about 1 cm in diameter, and some angular fragments of feldspars even 1,5 cm. They stick in quartz mass, the cementing material of which is of ferruginous--calcareous character. The specimens taken from the cover (No. 19a) gave more material than those from fresh rock (19b); the environment conditions were naturally differentiated in favour of water conditions (Pl. 7).

The material, amounting to 40,4%, obtained under water conditions (under humid conditions only 6,6%), allows to refer this rock to the first group of rocks, very feebly resistant to frost weathering (I group of rocks — more than 10% of weathered material, according to Tricart and Wiman). Distribution of the material within the individual fractions is also highly interesting (Fig. 6). A lot of material occurs within the intervals of sand grain-sizes (approximately 60%) and within the intervals having greater dimension of grains than 2 mm (more than 30%). This is connected with the conglomerate character of rock structure. Coarser material is represented mainly by greater fragments of feldspars, quartz (Pl. 7b) and by aggregates of strongly agglutinated quartz grains of various size. Polymineral composition can be observed in all fractions except for the finest ones that, as a rule, consist of angular fragments of quartz (in other fractions quartz occurs only as round grains). In the conglomeratic sandstone here considered a highly loosened structure of rock might have been observed after the experiment, mainly as numerous traces of hollows left after the removed grains and rock fragments. In addition, a series of irregular cracks might have been traced showing a tendency to split in the form of thick scales, particularly at the edges of the samples. In this case some fissures cut greater crystals (for the most part across the chemically medium-weathered feldspars, or the fragments of gneissose granites, or greenstone slates) and disappeared in the rock body. This may be a proof of their frost origin. This type, beside the fissures loosening the structure of the sandstone, on a large scale contributed to the disintegration of the rock. Differences between the samples taken from the waste cover and the relatively fresh rock were quantitative only, in favour of weathered samples and of water conditions.

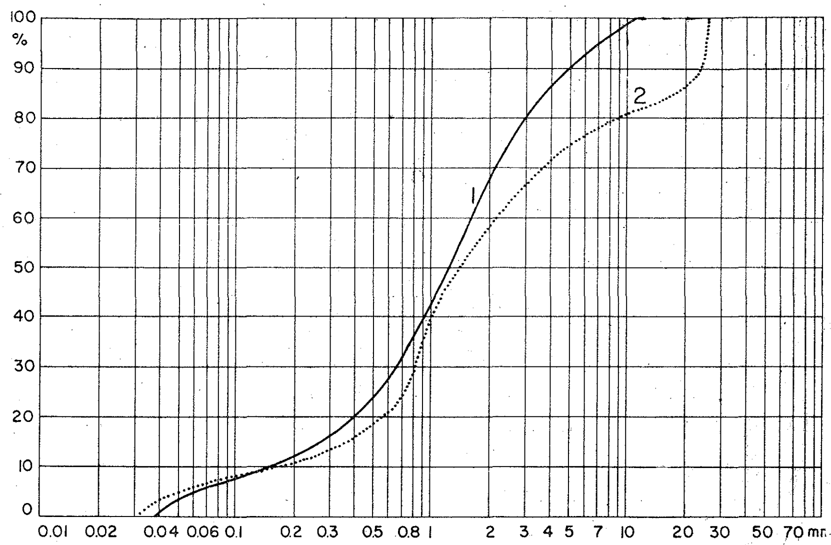


Fig. 6. Grain-size distribution curves of weathered material. Conglomerate sandstone (Permian) from the waste cover (vicinity of Złotoryja), No. 19a

1 — humid environment, 2 — water environment

To the last kind of sandstones taken for examination belongs Zechstein sandstone, pink in colour, from Biegaszów, vicinity of Złotoryja. This is coarse-bedded, fine-grained rock characterized by psammitic structure and by calcite matrix. The texture is porous and chaotic. The weathered material obtained during the experiment allows to refer the rock in study to the group of rocks that are moderately resistant to physical weathering (1—10% of material, according to Tricart and Wiman). The experiment yielded here approximately 3% of material under water conditions and 0,6% of material under humid conditions. Distribution of this weathered material within the individual fractions markedly depends upon the structure of rock, as it may be seen in the predominance of fine grains from 0,06 to 0,5 mm in diameter (about 55%). Larger rock fragments are lacking here. In the material there predominate mainly well and medium-rounded quartz grains, this being characteristic feature of the whole class of sandstones. Similarly as in most sandstones distinct fissures are also lacking here, and only general loosening of the rock may be observed.

Summing up all the results obtained during the analyses of sandstones we can draw a conclusion as to a low resistance of these rocks to the activity of physical factors. A dominant part is played here by the structure of the rock. This is markedly seen in the quantity of the material obtained mainly from sand-grain sizes, and in its character (removing of the individual mineral grains without damaging them). Thus, the quantitative differences are conditioned by the kind of cementing material, by the sort of rock-forming substance, and by the resulting differences in porosity. The sandstones characterized by an easily leachable calcite matrix (5c) give more weathered material than those characterized by siliceous matrix (5d). Sandstones of differentiated structure and mineral composition (19) undergo quicker disintegration than those, which are characterized by a well sorted material revealing a uniform mineral system (5d, 20). Greater loosening can be observed also in sandstones of chaotic texture, as compared with those having well arranged mineral grains. Thus, physical weathering influences sandstones in connection with their lithological features. On account of a low compactness (as compared with other rock groups) of specific, sandstone-forming minerals (rounded quartz grains), the activity of frost weathering does loosen such a rock, but cannot crush the grains. In this connection Tricart's rule stressing „common indifference of frost towards the original texture" [2] must be regarded as disputable. Maybe, it is right for lithologically differentiated limestones, however, it may hardly be applied in the case of sandstones and of rocks having similar development, as i.e. oolitic limestone from Reville, described by Tricart (this last type of rock is thought by him to be an exception). A considerable difference in the weathered material obtained under conditions of water environment and of humid environment, so characteristic of sandstones, may be explained by an increase in water content, thus by a better growth of ice crystals in the presence of considerable porosity of the sandstone rock.

METAMORPHIC SCHISTS

In this class of rocks are included greenstone schists of Cambrian-Silurian age, which constitute a huge formation in the Kaczawa Mts. These are basic rocks of shallow metamorphosis (greenstone facies) originated from subvolcanic diabase lavas. Albite, epidote, chlorite, subordinately also quartz, biotite, magnetite and others are main mineral constituents here. The rock is of green colour that during weathering process passes into brown. Schistose texture revealing a distinct foliation of layers plays an important part in the resistance of the greenstone schists. Due to the cryptocrystalline development of mineral grains, the microstructure of the schists here con-

[2] It results from Tricart's consideration that under the notion „texture of rocks" he also understand their structure (J. Tricart 1960, p. 216). The present author applies the notions texture and structure according to Polish petrologists.

sidered is thought to be porphyroblastic (larger grains of fimbriated albites occur against a background of rock mass).

Samples No. 1 were taken at the sections of these rocks in the vicinity of Bolków and Dobromierz, according to the existing advancement of the rocks in weathering process. The specimens taken from the waste cover (1a) have thin clay coating, brown in colour, and are characterized by a considerable brittleness particularly concordant with bedding system. The rock distinctly splits into fragments, according to its foliation. This is connected, too, with a dense system of cracks that is particularly seen at the edges of the specimens. Cracks perpendicular to the surface of layers are very rare (1/5 cm^2), slight and irregularly distributed. Samples that are chemically less weathered reveal greater consistency, almost complete lack of fissures, and only feeble tendency to imbricated foliation of rock (1b). Fresh greenstone schists (1c) almost does not contain any cracks, and the surface of the specimens does not reveal changes of its green-olive colour. Under the microscope there are distinctly seen crystalline aggregates of albite porphyroblasts.

A great differentiation in effectiveness of weathering processes against greenstone schists has been observed in the results of the experiment. Of considerable importance is here relatively large amount of weathered material obtained during the experiment from the sample No. 1a, i.e. 11,6% under water conditions. It should be stressed here that this increase took place after splitting off large plate, approximately 6 cm (Pl. 8b) in size, and about 32 g in weight; this amounting to 10% of the whole sample. The remainder of the weathered material amounts to little more than 1%. More conclusive and comparative material has been obtained under humid conditions (approximately 0,3%). It may, therefore, be supposed that the resistance of greenstone to fine-granular physical weathering is rather great. The effect of splitting off so large part of the specimen is highly characteristic of greenstone schists. This can be seen in numerous greenstone waste covers on many hills and in debris cones at the foot of tors, in the vicinity of Bolków. The covers *in situ*, revealing a considerable thickness up to 0,5 m, consist mainly of such sharp-edged, plate-like fragments, 5 to 10 cm in diameter [3]. Distribution of the weathered material here obtained is characterized by a relatively great amount of the finest fractions, as compared with those above 0,06 mm. In proportion to the remainder, the sand-size material is scarcely represented. Such a fractional distribution of weathered material approximately coincides with that occurring in the area of Bolków. According to Tricart, its great number

[3] A. Martini — Block fields of Bolków and Wałbrzych Mountains and Hills. Wrocław 1963 (manuscript).

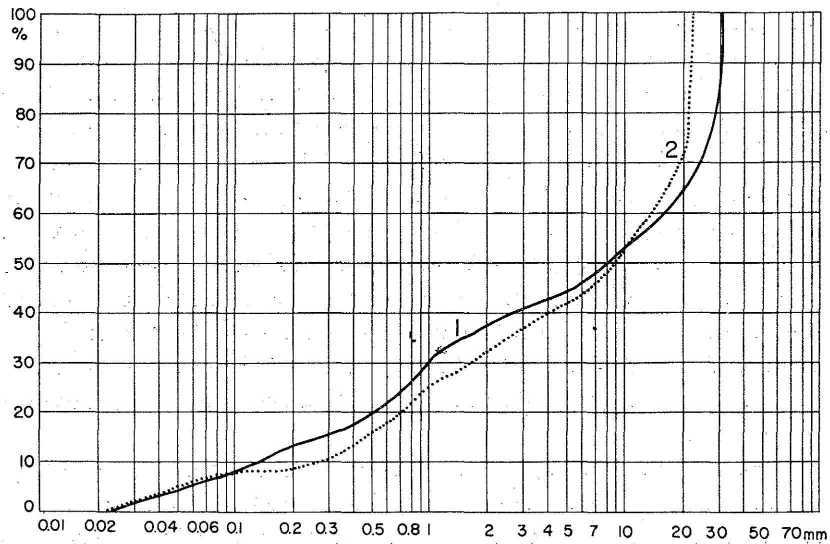


Fig. 7. Grain-size distribution curves of weathered material. Mica schist taken at the contact with quartz vein (Rozdroże Izerskie). Sample from the waste cover, No. 15a
1 — humid environment, 2 — water environment

facilitates solifluction, hence this region is characterized by a strongly developed covers occurring even on slightly inclined slopes.

The character of experimentally produced weathered material (fine-granular) is closely connected with the lithological features of greenstone schists. In all intervals of grain sizes there are found fragments of rock body occurring as sharp-edged plates, lamellae and scales. In fractions below 0,5 mm are found fine crystals of albite and quartz, and the finest fraction is made of amorphous material bearing a character of „floccules" similarly as in all rocks that relatively strongly underwent chemical weathering. After the experiments the specimens of greenstone schists (1a) reveal strongly developed system of fissures (6 cracks in 1 cm^2), that cut the rock according to its foliation. They are seen particularly at the edges of samples, where frost weathering caused their greatest widening. Hence derives a feature very characteristic of the rocks revealing well developed bedding (not only among greenstone schists), i.e. highly differentiated susceptibility of rock to external factors, according to the situation of the rock under examination. Weathering process most intensely attacks rock edges at the places where the walls cut with bedding system. Here, the rock is the weakest and here the best conditions exist for water infiltration. Samples of medium-weathered and fresh greenstone rock (1b, 1c) have shown a slight loss of the material from 0,01 to 0,04% under water conditions, and no loss under humid conditions. This fact stresses a considerable dependence of frost weathering on the initial state of rock.

Mica-chlorite-quartz schist from the quarry at Krobica, near Świeradów (samples No. 8), also proved to be resistant to weathering. This is a rock from supracrustal series of Sudetes complex, formed under conditions of a strong thermal and directional metamorphosis from pelitic-sandy deposits in Pre-Cambrian time. The schist being of metallic lustre and olive in colour has a distinct foliation and lamination expressed in alternate distribution of micaceous minerals (muscovite, biotite, chlorite), seperated by the laminae of fine-grained quartz. The samples collected at the place mentioned above also are differentiated as to their previous weathering degree and show a great resistance to frost activity under conditions of the experiment.

The sample 8a, bearing distinct traces of chemical alterations of muscovite and biotite, reveals a series of minute cracks within micaceous laminae, along which the minerals exfoliate in the shape of fine leaves. This ability to split off (after all on a small scale only) the scales from the rock is, beside the important chemical changes (transition of biotite into chlorite etc.), also a feature, distinguishing the sample 8a from the fresher specimens 8b and 8c. This could have been observed after the experiment. Quantitative differences between the individual samples were very insignificant. Recovery of material was 0,4% under water environment conditions, and 0,35% under humid environment conditions (sample 8a). Similarly it was in samples 8b, where under humid conditions approximately 0,32% material was formed [4], and in samples 8c about 0,2% (Fig. 11). Interesting is here the kind of the material obtained, conditioned by the texture and structure of these schists. A good deal of the material occurs within the fine-grained fractions below 0,5 mm (approximately 40%; Tables III and IV, Fig. 8), and consists of quartz and of fine scales of micaceous minerals. Fractions of greater sizes consist of biotite and muscovite flakes, rarely of quartz fragments, and in the case of coarse-grained material — exceptionally only — of large rock fragments in the shape of plates. Such plates are found in the most chemically weathered samples 8a, characterized by a relatively loosened structure (Fig. 8, Pl. 9). Interesting in these schists is the distribution of cracks, concordant with the system of primary foliation and lamination of rock, which was still better visible after the experiment. Here, a splitting of mineral flakes has been observed, so characteristic of frost weathering. The priority of removing micaceous

[4] Material from the samples 8b under water conditions has not been determined due to its destruction. Visually, the quantity of the material did not deviate from the data mentioned above.

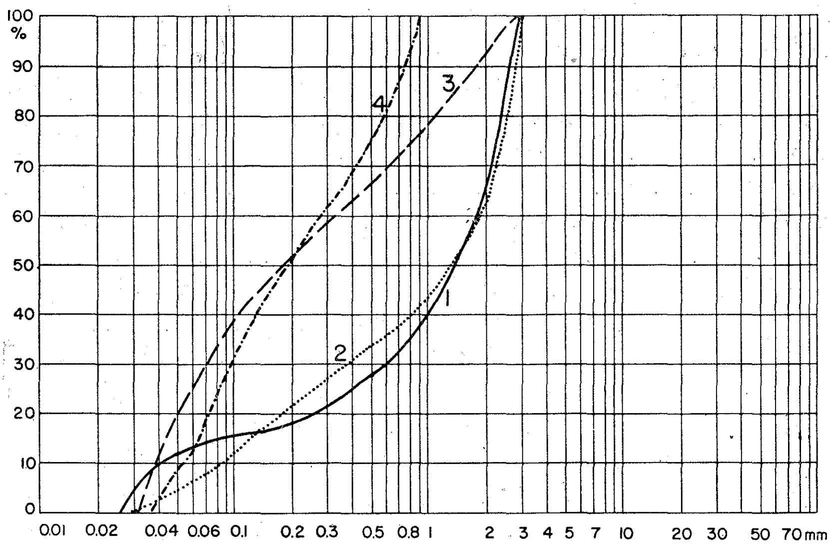


Fig. 8. Grain-size distribution curves of weathered material

Mica-chlorite-quartz schist from the waste cover (Świeradów), No. 8a: 1 — humid environment, 2 — water environment

Mica-chlorite-quartz schist, fresh (Świeradów), No. 8c: 3 — humid environment, 4 — water environment

minerals, before the layers of compacter fine-grained quartz are removed, is also an important fact there. In this case there are formed typical „microribs" of quartz on rock edges. This type of fine-granular weathering, as we see, also depends upon the lithological features of rock. Cracks perpendicular to the surface are scarce; some of them only were responsible for splitting larger slate lamellae from parent rock. On account of an, imbricated distribution of laminae they take then a characteristic stair-like form.

Summing this up we can be convinced that metamorphic schists are highly resistant to the activity of mechanical weathering, particularly in the case of its directional action, perpendicular to the surface of beds. This dependence was already stressed by Paterson (1951) who observed it when examining metamorphic biotite schists in the northwestern area of Greenland. Particularly resistant are rocks chemically unweathered. Similar results are those obtained by Wiman during examination of phyllite schists taken from a cover on the Storslaagafjället Mt. in Norway. Their loss of weathered material in Iceland cycle amounted to approximately 1%.

An interesting case of a high susceptibility to frost weathering may be observed in micaceous schists taken also from Old-Palaeozoic cover of the Karkonosze Mts. at the contact with hydrothermal quartz vein, (No. 15a). They show a strong and secondary alterations of two kinds. The first kind of alterations is of textural-structural type and appears as two diagonally oriented systems of joints: original system, concordant to the bedding of schists and, probably, secondary system formed under conditions of contact processes. The second kind of alterations is represented by mineral changes occurring as numerous, well developed quartz and feldspar crystals, also as other minerals. Here took place a strong decomposition of micaceous minerals (biotite and muscovite). The problem of these changes that may be a result of the contact with hydrothermal solutions, or due to the posterior chemical weathering, can be of interest for petrographers. In this case the influence of these changes on the decrease of rock resistance is highly important.

The samples were taken from weathering cover in a stone quarry, at Izerskie Rozdroże. During the experiment, a rich material has been obtained that allows to refer this rock to the first group distinguished by Tricart (almost complete disintegration, more than 10% of weathered material). It amounted 43% under water conditions and 17,5% under humid ones. The weathered material consists of finest fractions revealing also a transition to a fraction of larger fragments up to 5 cm in diameter and to 30 g in weight (Pl. 10). Elongated „rock splinters" (up to 3 cm), chipped off according to the double system of joints in rock, are highly characteristic. Rock aggregates occur also in grain-sizes up to 2 mm. Finer fractions contain fragments of feldspars, quartz and other minerals, characterized by cymbiform and sharp shapes proving intense frost disintegration. Fraction below 0,06 mm contains, beside distinct quartz fragments, also amorphous fine substance occurring in the form of „floccules" mentiones above. The substance appears in the case of previous chemical activity on the rock. A detailed distribution of the individual fractions is shown in Fig. 7.

CRYSTALLINE LIMESTONES

This group is represented by a variety of crystalline limestones gathered in a quarry at the Miłek, Wojcieszów. This is a metamorphic rock, mainly of amphibolite and hornfels facies, probably of Cambrian age. As far as their mineral composition is concerned crystalline limestones contain mainly quartz and calcite, also diopside, basic plagioclases, scapolite and others. In their chemical composition they are approximate to that of limestones and marls. Their microstructure is granuloblastic and the texture massive and compact, rarely directional. On account of differentiation of rocks that underwent metamorphosis, a series of types is distinguished, characterized by different appearence and various colour, from black and grey-yellow to cream. Calcite grains are here best developed and this gives to the rock a fine-granular character. Crystalline limestone relatively easily undergoes processes of chemical erosion. The samples taken from the waste cover are already characterized by a certain degree of chemical activity (2b), and differ from relatively fresh samples taken at the face of the quarry (2a). Sample 2b represents a rock revealing numerous, yellow, clay-like streaks, which occur here at several cm long and very narrow (0,05 mm) cracks. In the remaining part of the rock surface there exists a tendency to split off numerous scales of fine shapes. Fresh rock (2a) is characterized by a lack of these clayey substances and by a lesser amount of exfoliated surface parts.

After the experiment the amount of the material from a sample chemically weathered was approximately 0,2% under water conditions and approximately 2,6% under humid ones (Pl. 11). On the other hand, fresh rock did not react completely to frost weathering in the environment under humid conditions. Small amounts of the material have been obtained only under water conditions (0,06%). Weathered material was represented mainly by fine-grained particles (approximately 60%) revealing grain sizes up to 0,5 mm (Fig. 9). This is a feature characteristic of this type of rocks, expressed in the form of numerous silty and still finer fractions, mainly composed of rhombohedral fragments of quartz, sharp-edged quartz chips and amorphous substance in the case of sample 2b (previously under the influence of chemical factors). Weathered material of greater sizes is made by very thin scales of calcite body, splitting off the faces of the sample. Microscope picture of these scales resembles butterfly's wing strongly enlarged. These places can be seen as white rims and also in the shape of scales of greater sizes (Pl. 11). Their edges are deviated and form semicircular fissures wedged into the superficial part of the rock. The scales forming weathered material are, as a rule, built up of rock body, in which any crystalline grains are hardly distinguishable. Calcite and quartz grains are rarely individually removed, and only at the edges of samples. Superficial splitting of rocks (microdesquamation ?) observed on the individuals characterized by fine grains and compact texture, is a common phenomenon, differentiated only according to the given kind of rock. Similar desquamation of limestones has been observed to occur on various Tatra limestones. Particularly distinct is this phenomenon on rock walls of black limestone in the area of Hala Pisana, Kościeliska Valley. Elements bearing character of distinct cymbiform shape that, according to Tricart are characteristic of frost weathering, as proved by him on common limestones, have not been observed.

The second type of rock of this group was represented by calcareous (crystalline) schist also taken from the waste cover (2c) and from the quarry face (2c′). Its different appearance, as compared with crystalline limestone, consists in a more regular parallel texture. This property was responsible for a greater amount of coarse-grained material in the waste that occurs here as thin chips and splinters of rock, mainly at the edges of bedding planes (see Pl. 12). The amount of fine-grained material was relatively great (Fig. 9), and that of weathering material from sample 2c was in accordance with crystalline limestones (about 1,3%), under minimum predominance of water environment. Fresh rock did not show any material losses under humid conditions. The schists here considered contain some fragments characteristic of frost weathering and reveal a series of fine cracks arranged discordantly to the feebly marked texture of rock.

In general, the crystalline limestone is a rock resistant to physical weathering and not to chemical weathering. Some differences in obtaining or non-obtaining the weathered material under conditions of experimental milieu should be explained by the internal features of the limestones. Tricart's (1956) studies have shown an extremely different behaviour of limestones to freezing. There existed a transition here from the highly susceptible Cretaceous limestones to the resistant Hauterivian limestones

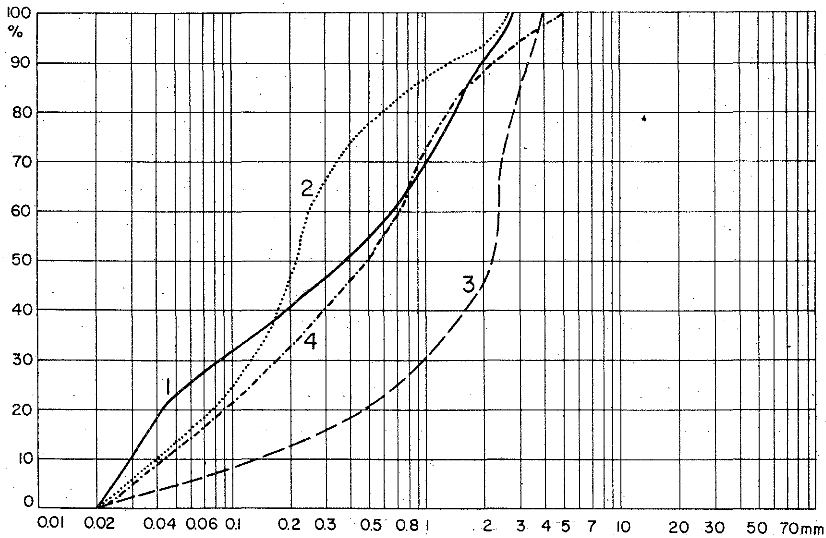


Fig. 9. Grain-size distribution curves of weathered material

Crystalline limestone from the waste cover (Wojcieszów), No. 2b: 1 — humid environment, 2 — water environment
Calcareous (crystalline) schist from the waste cover (Wojcieszów), No. 2c: 3 — humid environment, 4 — water environment

at Barbettanne. This latter, taken from a fold bend bearing traces of certain recrystallization, lost during the Iceland cycle only 3% of material. Tricart supposes that rocks that have undergone long tectonic processes are resistant to frost weathering. This fact is explained by a considerable pressure, to which they were subject, and which was responsible for a compactness greater than previously. The recrystallization caused that they become less porous. His observations concerning the character of the weathered material obtained from limestones generally coincide with those mentioned above, particularly as concerns a considerable amount of fines. The quantity of weathered material mainly depends upon cementing material and upon the degree of consistency of a given limestone. For instance, very susceptible is chalky cementing material there. Coarse-grained particles bear characteristic features occurring mainly in cymbiform shapes. As a rule, they are discordant with the rock texture. According to Tricart this demonstrates an indifference of frost to the texture of rock. These features are rather characteristic of limestones. As far as other rock types are concerned, the frost weathering acted mainly against lithological features. As a result of considerable destruction of textural-structural system of a rock, caused by chemical weathering, the frost attacks it and destroys in different way, but always is controlled by the existing minerals.

Evidently, these conclusions are a result of observations of granular disintegration; however, this rule cannot be applied as universal in the case of block disintegration (strictly speaking a disintegration of rocks into fragments amounting to more than 10 cm in size). Certain rocks revealing distinctly marked structure particularly, however, directional texture, as in schists and gneisses, disintegrate due to frost weathering into fragments with sharp edges, but in the forms concordant with the texture of parent rock. Due to almost non-textural appearence the limestones can yield waste fragments characterized by irregular shapes there.

GNEISSES

The group of gneisses is represented by several varieties of these rocks collected, for the most part, in the area of the so-called „Death's bend" in the Izera Mts., in a waste cover and at the walls of numerous tors. The gneisses are one of the constituents of the Karkonosze cover, being, however, slightly younger than crystalline schists, thus corresponding to the Late Pre-Cambrian. The samples collected for examination are mainly lamellar biotite gneisses, revealing lepidoblastic to granoblastic structure and gneissose texture, with a fairly distinct mineral lineation. On account of the fact that, as a rule, they are orthogneisses, they contain beside quartz also biotite, feldspars (acid oligoclase) and numerous minerals characteristic of metamorphic rocks such as andalusite, disthen, sillimanite, staurolite, graphite and others. Banded gneisses prove a high degree of kinetic metamorphosis due to which the lighter quartz-feldspar portions are alternately arranged with dark plasters of pressed biotite.

Apart from the fact that the specimens collected were previously subject to external processes, the group of gneisses demonstrated a greater resistance, as compared with other rock taken for examination The material obtained was from 0,02 to 1,0%. Some differences between them depended upon the structure of gneisses and upon the degree of previous weathering.

The greatest amount of weathered material was obtained from the samples of brown banded gneiss (No. 13a) — about 1,2% under water conditions and approximately 0,95% under the conditions of humid environment. To this also contributed the texture of rock, which is markedly seen as compared with the remaining part of gneisses, its slight weakness being caused by weathering (a sample deriving from the waste cover). Within micaceous minerals there are visible considerable chemical changes and loosening of these minerals. Scarce cracks run according to the lineation of the minerals and occur mainly within micaceous laminae and equigranular and fine-grained quartzes and feldspars, thus stressing their concordance with the texture and structure of the rock. Strongest loosening of the samples occurs at the edges and surfaces which are perpendicular to the rock texture. Loss of the larger particles greater than 0,5 mm in size, was probably facilitated by short (up to 2 mm) cracks, discordant with the texture, occurring at the edges of the samples. The weathered material consists of quartz-feldspar aggregates and of greater micaceous flakes. In their character they are strongly connected with the lithological development of gneissose rock, i.e. they occur in the form of fine and elongated laminae. Such a kind of material makes approximately 50% of the weathered mass (Fig. 10). Finer fractions are made up by isometric blocks of quartz and feldspars, biotite plates, as well as by numerous, very resistant minerals belonging to the metamorphic group, without any traces of frost activity.

Somewhat lesser amount of the material (0,45% under water conditions) was obtained from biotite gneiss revealing strongly altered biotites, taken from a tor talus in the vicinity of the „Death's bend" (11a). The same type of rocks taken from the tor walls (11b) gave insignificant amount of weathered material only (up to 0,05%). In their character and distribution of material (Fig. 10) the samples No. 11 do not deviate from other gneisses. It should, however, be stressed here that one of the samples

No. 11, apart from yielding fine-grained material, shattered into more or less equal, sharp-edged fragments (Pl. 13). Such a kind of debris is characteristic of rocks revealing parallel texture. Flat, sharp-edged fragments resembling perpendicular parallelepipeds are formed due to the joints perpendicular to the surface of beds. Thickness of plates depends on numerous cracks running concordantly to the linear texture. On this account gneisses give fragments somewhat larger than that of mica schists, which reveal a more developed schistose texture. Rocks bearing chaotic texture produce, as a rule, sharp-edged fragments of irregular shapes. Other types of biotite and lens-like gneisses (14a and 12a) were sampled in the vicinity of the „Death's bend". They are lesser weathered and are characterized by a more gneissose texture than the types mentioned previously. Therefore, they lost only insignificant amount of the material, from 0,01 to 0,08%. Grain-size gradation and character of this material do not deviate from those of the varieties discussed above.

A considerable resistance of gneisses to frost weathering was also stressed by Wiman (1963), who in his experiments concerning a.o. gneisses from Scania, taken from a debris cone obtained scarcely 0,06% of weathered material in the Iceland cycle, apart from the fact that distinct cracks and crevices are present running in accordance with the structure of a rock.

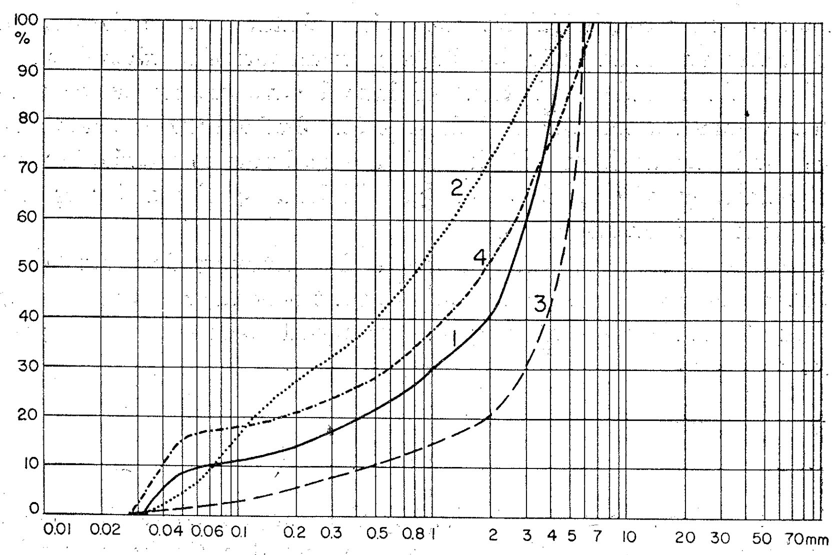


Fig. 10. Grain-size distribution curves of weathered material

Banded (biotite) gneiss from the cover, Izera Mts., No. 11a: 1 — humid environment, 2 — water environment
Banded gneiss from the waste cover (Izera Mts. — „Death's bend"), sample No. 13a: 3 — humid environment, 4 — water environment

VEIN QUARTZES

This last group of rocks has been taken into consideration rather for comparative purposes. The specimens taken from quartz quarry in the Izera Mts. (Rozdroże Izerskie) proved to have maximum resistance to frost weathering. The rock here considered represents a pure milk quartz revealing various colouring, from greenish to pink and white; the quartz is a result of a hydrothermal intrusion that took place in this area and intruded into old crystalline schists of the Karkonosze cover. Although certain crevices and microcracks are found on the surface of the fragments, which appear at the boundaries of the individual incompletely developed quartz crystals, no physic-chemical changes have been observed after the experiment, and no weathered material has been obtained (sample No. 15d″). An exception constitute here quartz samples taken near the contact zone with crystalline schists. Rock samples are characterized by a parallel system of cracks that resembles those occurring in calcareous slates (crystalline slates No. 2c). Traces of paralelly elongated, fine quartz scales might have been observed, as well. These latter and sharp edges of samples were places where weathered material was crushed out.

On account of variously developed quartz the weathered material consisted of fragments belonging to different fractions (Table III). Most of the fragments revealed sharp edges, cymbiform shape and a surface characterized by conchoidal fracture. These features prove the existence of frost activity. An anomaly showing a great amount of weathered material (1%) obtained under conditions of humid environment, as compared with the immeasurable traces of the material obtained under conditions of water environment from a rock, which is resistant to weathering, may be explained by mechanical loosening of the hand specimen during sampling (strokes of hammer).

As to the rocks sampled in contact zone, i.e. metamorphic schist No. 15a, or quartz No. 15b, we may observe a distinct dependence of the decrease in rock resistance to weathering on its internal weakness resulting from contact processes.

GENERAL DISCUSSION

Strokes of hammer during shaping the samples no doubt loosened their internal cohesion and, therefore, we should critically approach to the results available for us (naturally in the case of quantitative problem). Here, an artificial increase of results took place. This type of material was observed in great quantity in the case of quartz and crystalline limestones. These rocks, revealing a similar high resistance to frost weathering, are characterized by a monomineral composition and by a compact and massive structure. Fragments of other rocks were hand-worked on a smaller scale. A further difficulty in comparison of the material arises due to the fact of subjective estimation as to the initial weathering of a given sample. Frequently, the state of one sample from a determined waste cover must not correspond to that of other type of rock taken also from waste cover. Small size of rock samples used for experiments are also an important factor during estimation of results. On account of a greater size of the specimen having the same mass and taken from a rock face, the amount of the weathered material obtained will always be greater. In this connection the experimental data should, at present, be regarded as approximate only.

Taking into consideration the system of rock division according to the resistance to frost weathering we can, according to Tricart (1956), generally ascertain a great susceptibility to this process in such rocks as sandstones, certain porphyraceous granites and metamorphic schists. The amount of the weathered material obtained is here more than 10%, reaching sometimes a state of complete disintegration of the rock examined. The group of rocks more resistant to weathering (from 1,0 to 10,0% of weathered material) embraces further types of granites, sandstones and, to a low degree, of metamorphic rocks. The least loss (below 1% of weathered material) has been observed in fine-grained granites, most of metamorphic schists, crystalline limestones, gneisses and volcanites. In this group extreme resistance to weathering is particularly characteristic of eruptive rocks and of most of gneisses, in which the content of weathered material rarely exceeds 0,1%. Considerable part of rocks did not demonstrate any changes, in particular as concerns experimental conditions without greater amount of water. These are mainly metamorphic schists, crystalline limestones, aplite granite, first of all, however, vein quartz.

Much of the results coincide with those obtained also on an experimental way by Wiman, Sukhodrovski and Tricart. This was several time stressed during description of the rocks used in the present experiment.

TWO TYPES OF FROST WEATHERING

Great extent of intervals of the quantity of the weathered material obtained during the experiment, and a series of disproportions occurring within one class of rocks allow to draw a conclusion as to different reactions of these rocks to the activity of frost, depending on many lithological fea-

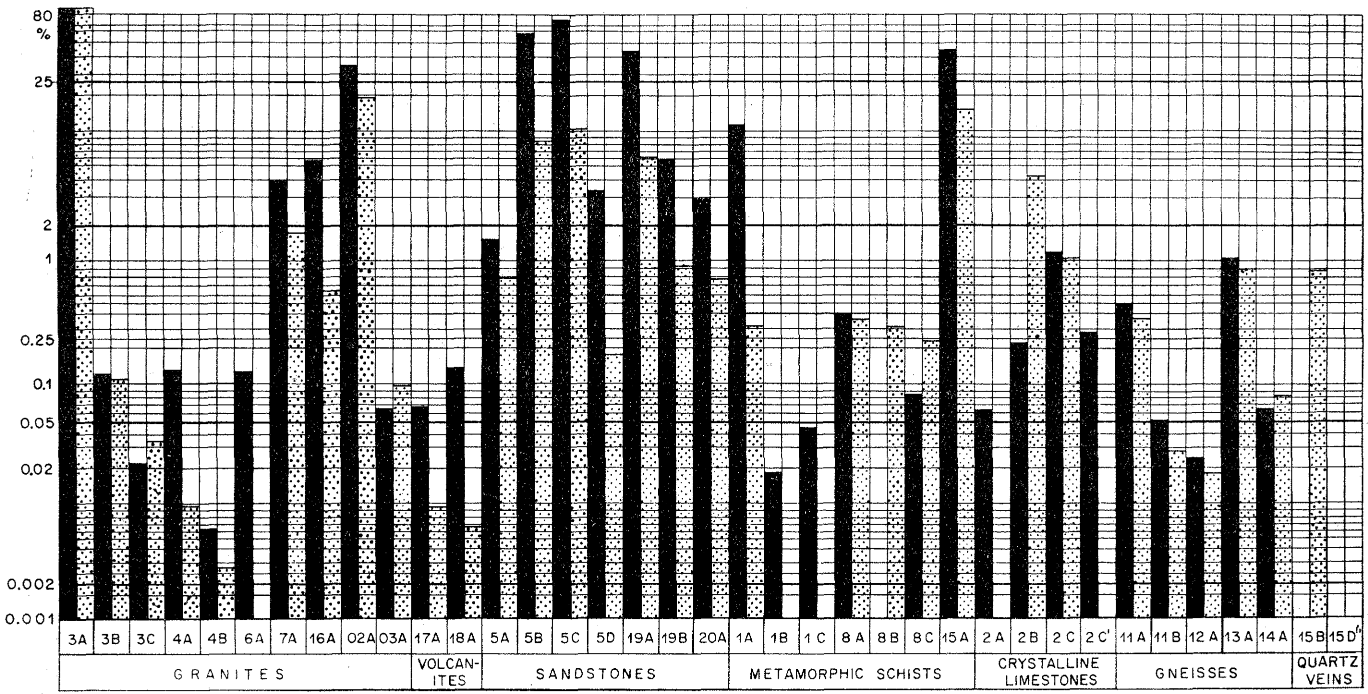


Fig. 11. Weathered material obtained experimentally, in %% of original weight

Diagram made on the basis of Tables I and II. Note: black columns — water environment, dotted columns — humid environment tures. However, before an analysis, the problem of frost weathering process should be taken into consideration from the point of view of thermal stimult (amplitudes within the intervals of low temperatures, oscillations near 0 °C), and of ice activity that in common influence the differentiated rock mass, which is passive part of this process. The active part of the frost weathering process is, as a whole, represented by external factors mentioned above, i.e. by temperature and water. On this account, we may speak about a certain dualism of frost weathering (considered from the view point of factors and not of effects of the activity). This dualism manifests in the activity of low temperatures (particularly of their great amplitudes; therefore, they may be called low-temperature ones), and in the bursting activity of ice crystals. Thus, this in general corresponds to the historically substantiated term — frost weathering.

The action of low-temperature weathering does not differ from the activity of insolation, except for the range of minus temperatures. Minerals undergo not only expansion, but also they contract according to the temperature used and to the specific physic-chemical features characterized by various degree of linear and volumetric expansions, i. e. by the degree of contractility. Diversity of minerals in rock and of their different reactions is responsible for numerous differentiated internal stresses that lead to a decrease in the cohesion of rock. This is reflected in numerous and different cracks and crevices increasing in their number on minerals after the experiments. This is particularly well visible among rocks characterized by large grains of different sizes (granites, conglomeratic sandstones). Rocks revealing microcrystalline and monomineral structure (basalts, grennstones, crystalline limestones) react as a whole due to the sum of internal stresses of the individual microcrystals occurring in the rock body. Such an effect cannot be excluded in coarse-crystalline and polimineral rocks. Structural loosening of these rocks will then be a resultant of the individual crystalline stresses cancelling out each other, thus it will be weaker. The effect of such a complete reaction of the low--temperature weathering is greater in the case of rock elements having a certain defined form that restricts them to a greater degree. This particularly takes place among pebbles in connection with anisometric fragments taken out of the rock wall. Pebbles, particularly elongated ones and composed of fine-grained rocks, no doubt reveal a greater linear contractility (along their long axis) than other rock fragments. As a result of this we can observe a disintegration of such a pebble into equal fragments at the planes perpendicular to their long axis. Examples of such a type have been encountered amidst quartzite pebbles, and those built up of effusive rocks amounting to 15 cm in size, in the vicinity of Torzym (Zielona Góra region), within sand and gravel series of fluvioglacial origin, at a depth of 2 m. The fragments that have originated from disintegration of pebbles are characterized by sharp edges, surfaces not affected by chemical activity, and almost isometric crystals that still more speaks for the thesis mentioned above. Choosing of a shape that would, on a minimum scale, undergo further transformations seems to be normal phenomenon in the nature. Other examples of the same character have been found also among crystalline pebbles (fine-grained granitoids) in the Tatra Mts. Evidently, disintegration of pebbles also depends upon the original discontinuity surfaces in rock (bedding, ability of jointing), as proved by calcareous pebbles by Taber (1950). The rôle of water in this process cannot be neglected at all (this will be discussed below); however, a generally lower value of porosity and of water permeability in pebbles should be stressed here, particularly as compared with other rough fragments, even of the same rock. A decreased porosity is a result strictly of used surface of the pebbles, where most of the pores on the surface undergo destruction. After all, the problems concerning the reaction of pebbles to frost weathering will be an object for additional studies.

Returning to the problem of effect of low temperatures we should not forget, first of all, to take into account the results of this effect upon the texture and structure of rocks, on the one hand, and upon the minerals, on the other. Such an activity is markedly seen mainly amidst better developed feldspar crystals, as compared with other minerals that are elements precisely defined in space. During microscopic observations of granites (3a, 7a, 16a) a series of cracks might have been ascertained, perpendicularly directed to the longer axis of the individuals. The cracks coming at the surface disappeared in the fine rock body, thus proving greater tensions in feldspars. Influence of textural and structural features of rocks on the effectiveness of frost weathering will be discussed below. For the while, we can state a general use of the structure of minerals through the tensions caused by the activity of low temperatures, a phenomenon that can easily be observed under the microscope. Of course, a tension first of all uses all kinds of discontinuity zones such as crystal faces, cleavage planes, sites of recrystallization, and various initial cracks and crevices that originate during the formation of rocks.

Theoretical principles of the mechanics of thermal contraction cracks were presented by Lachenbruch (1962). According to this author the distribution of cracks depends upon the concentrations of tensions and upon the place of mechanical weakness of the given medium (geometrical sites of its low strength). As a rule, the cracks are produced exactly perpendicularly to the direction of greatest tensions. These tensions, the result of which are cracks, are caused not only by low temperatures, but also by a rapid cooling of material. As a matter of fact, this latter dependence is also a result of the kind of the given medium, for Taber (1929) experimentally demonstrated greater effectiveness of the activity of ice crystals during a rapid drop of temperature in loose sediments.

Dylik (1963), discussing numerous new problems concerning Pleistocene permafrost, among other demonstrated also Dostovalov's opinion[5] as to the development of ice-fissure systems within the permafrost. Analogously, we might refer these theoretical considerations also to the outcrops of fresh rocks. According to Dostovalov we can state that in a uniform mass there occur systems of orthogonal cracks, since the vector of thermal gradient is perpendicular to isothermal surfaces, and the isothermal surfaces are parallel to the independant and free vertical and horizontal surfaces. In other words, summing up the considerations by Dostovalov, we must accept that the distribution and value of tensions producing fissures depend upon the thermal gradient and the kind of the material. The thermal gradient depends, in turn, on the given type of climate. Upon the kind of material depend also the coefficient of linear change in volume and the modules of displacement, which is constant for the given type of rock.

Consequently, the whole activity of low-temperature weathering is used now by water, intruding all irregularities of the rock surface. This water, when passing into solid phase disintegrates the rocks still more. It should be stressed here that such a loosening of rocks, caused by ice crystals, consists not in the increase of their volume by about 9% as it was previously accepted, but mainly in the strenght of their crystallization. This is stressed to-day by soil mechanics (Wiłun 1962), and was experimentally ascertained by Taber in the years 1929—1930. The moment of immediate action of ice crystal growth after the contraction of rock, against low temperatures, gives just an effect of a process defined as frost weathering. Extent of action and degree of intensity of these processes can be different, but they cannot exclude each other. Although water can penetrate the original fissures, we may hardly suppose that after freezing no changes take place just in these fissures before the action of ice

[5] Dostovalov B. M. — O fizicheskikh usloviyakh obrazovaniya morozobojnykh trieshchin i razvitiya trieshchinnykh ldov v rykhlykh porodakh. *S. d. Issled. Viech. Mierzl. v Yakuck. Rep., Akad. Nauk. SSSR,* 1952.

Dostovalov B. N. — Zakonomiernost i razvitiya tietragonalnykh sistiem ledіannykh i gruntovykh jyl v dispiersnykh porodakh. *Periglacjalnye yavleniya na territorii SSSR,* Moscow 1960.

crystal growth, due to the contraction (their difference) of minerals during decrease of temperature. Double character and simultaneity of action (with a minimum advance in time and space of low-temperature weathering) during succeeding regelation are responsible for a high effectiveness of frost weathering (in general sense). Repeated action of these processes is here worth taking into consideration. Ice crystals, like wedges bursting asunder the rock, are characterized by a better thermal conductivity than that of water, thus nothing exists that could stop further over-cooling of rock. This was already stressed by Dobrowolski (1923), and a series of examples on disintegration of rocks containing fissures filled up with sublimation ice during its minimum melting was described from the high-mountain area of Pamir by Sekyra (1964)

Action of frost weathering restricted by three conditions: (1) initial fissures, (2) moisture occurring in them, and (3) regelation, was already formulated by Dobrowolski in 1923. The problem discussed at present is an enlargement of that conception, as well as of the conception by Sukhodrovski (1962a, b), who was the first to define, from the view-point of the process, the twofold character of frost weathering. On the basis of his laboratory works, and on the field surveys conducted on the Francis Joseph's Archipelago, he has distinguished also temperature weathering and proper frost weathering. The term low-temperature weathering used in the present paper does better define its character. According to Sukhodrovski both these processes took place separately. At the abrupt walls of cliffs and of denudation resistant hills, where water was in small quantities, he says, mainly temperature weathering 'acted, in contrast with flat surfaces containing more atmospheric water, where frost weathering prevailed. The distribution, particularly that of fine-granular disintegration, seems to be somewhat exaggerated. In the case of block disintegration this problem is not so simple, and has not, as yet, been explained. Also Sukhodrovski did not ascertained in the Francis Joseph's Archipelago area, where severe climate prevailed, any intense activity of frost weathering, the traces of which are found in the form of numerous block fields within the area of the European old mountains. Interesting hypothesis was pushed forward, as to their genesis, by P. Kessler (1925). He stated an opinion as to the existence of a more intense frost weathering in the Pleistocene and at the beginning of the Holocene than nowadays, mainly due to a lesser amount of carbon dioxide in the then atmosphere. Thus, an attempt could be made to demonstrate a restraining influence of carbon dioxide upon the frost weathering processes. Kessler's hypothesis seems to be right, at least if we take into account a fact that an increase in carbon dioxide quantity causes greater activity of chemical weathering, that is connected with frost weathering (this will be discussed below), and consequently leads to further disintegration of rocks. Maybe, this quantity decrease thermal conductivity of the air, a fact being of considerable importance during low-temperature weathering.

Field data obtained by Sekyra (1964) are also certain proof of low-temperature weathering. In Pamir, he described numerous examples of fine-granular and medium-granular frost disintegration among sandstones, limestones, dolomites and Palaeozoic-Mesozoic schists. The frost disintegration here considered was controlled by the structure of rocks. In this rigorous and severe climate characterized by mean annual temperature ca. $-1\,°C$, and amplitudes about $70\,°C$ ($+28\,°C$ to $-46\,°C$), and minimum annual precipitations up to 73 mm, herein three rainy days, the frost disintegration is very effective.

Freezing front is also very important for weathering processes, as proved by Taber (1929), particularly when it coincides with thermal conductivity of the individual minerals. Of considerable importance is also the number of oscillations of temperature near $0\,°C$. This appears to be understood mainly due to the fact that frequently repeating, even slight tensions, are responsible for greater destructions. This effect has long ago been known in mechanics.

A greater efficiency of the process under conditions of oscillations near $0\,°C$ was stated by Wiman (1963) on the basis of the Iceland cycle experiments. Wiman's stand is polemical in relation to that of Tricart, who judging from the quantity of weathered material, suggests the effectiveness of the process in favour of continental climates. Tricait thinks that thickness of the layers that undergo weathering is in this case greater, and debris fragments are larger, in contrast with these climatic zones in which this process is short-lived and rather of little intensity. He stresses here more favourable conditions for frost weathering in marine climates, mainly due to a slower freezing of rocks, but his opinion as to the predominance of the Siberian cycle is supported by a greater amount of material obtained in the experiments here considered. In addition, he pays attention also to the effect of a rapid loss of heat, under low-temperature conditions, causing too quick isolation of non-frozen water by ice in rock pores. According to Tricart this produces a greater amount of coarse-detritus in continental climates.

The data obtained by Tricart and Wiman cannot be completely conclusive, first of all, due to fairly artificial conditions deviating from natural ones in the so-called Siberian cycle. The fact of isolating water in pores and fissures of rocks also does not commend itself, particularly in the light of greater thermal conductivity of ice than that of water (Dobrowolski 1923), and of ice crystal growth just at the cost of water taken in this case away (Taber 1930).

The problem of influence of oceanity and continentality upon frost weathering is elucidated by field data obtained in the areas stretching within marine climate zone (coasts of Spitsbergen, Kärkevagge region in Northeast Sweden) and more continental climate zone (Francis Joseph's Archipelago, mountainous areas of Spitsbergen and Lapland).

Quantitative predominance of frost weathering under conditions of marine climate was demonstrated by Jahn (1961) on the basis of observations and measurements made in the years 1957—1959 in Spitsbergen. A precise determination of the quantity of debris found at the base of a steep 10 m cliff built up of cracked and friable limestones allowed to state that the cliff retreats, about from 2,5 to 5,0 cm a year. A considerable intensification of frost weathering process in the region of Kärkevagge was reported by Rapp in 1962. Among others, he presented the process of frost bursting that, together with abundant melting water, causes strong downfalls of parts of steep rock walls. On the other hand, a minimum effect of frost activity was presented by him in his previous paper (1957) concerning the areas of Sweden Lapland and inland part of Spitsbergen. In his studies on talus slopes Rapp has determined the annual retreat of slopes, due to frost shattering and to slope processes, to be approximately from 0,01 to 0,1 mm a year. An analogically low estimate of weathering effectiveness was presented by Sukhodrovski (1962) after his examinations in the Francis Joseph's Archipelago. The phenomenon of climatic differences influencing frost activity would be more distinct, if the same types of rocks were examined. Nevertheless, a considerably greater amount of water and more frequent oscillations near 0°C contribute to a more effective action of frost weathering, as compared with the continental climatic conditions.

Basing on his own researches made in Spitsbergen, and on those carried on by Rapp (1957), Jahn refers the process of frost weathering to the coastal zone and determines it as periglacial littoral weathering that acts stronger on cliff than abrasion. Jahn (1961) cites also the old opinion by Nansen, who already in 1924 paid attention to this phenomenon and thought that it could lead to the formation of „strandflats".

To the end of the discussion on all the relationships existing between frost weathering and rock, we should also present the problem of better disintegration of block and debris edges, ascertained during microscope and field observations. This was also described by Sukhodrovski (1962). Such a preference is a result of stronger, at that place, thermal influences due to a lesser rock mass and to two, at least, limiting planes of action.

Table I

Weathered material obtained during experiment under the Iceland cycle humid conditions

No.	Sample number	Kind of rock used in experiment	Initial weight of samples in grammes	Weight of weathered material obtained in grammes	Obtained weathered material in %% of initial weight	Grain-size gradation of weathered material										Notes
						<0,06 mm		0,5—0,06 mm		2,0—0,5 mm		20,0—2,0 mm		>20,0 mm		
						in grammes	in %%*	in grammes	in %%*	in grammes	in %%*	in grammes	in %%*	in grammes	in %%*	
		GRANITES														
		Porphyraceous granite (Basin of Jelenia Góra)														
1	3a	Strongly weathered granite — from surface of the cover	269,4	268,83	99,8	1,395	0,51	9,325	3,45	17,34	6,44	39,92	14,8	200,35	74,59	Total disintegration of the sample
2	3b	Medium-weathered granite — bottom of the cover	167,1	0,188	0,1126	0,024	0,0144	0,067	0,04	0,023	0,0138	0,074	0,0444	—	—	
3	3c	Fresh granite	268,7	0,101	0,0375	0,002	0,00074	0,02	0,00745	0,009	0,003340	0,07	0,026	—	—	
		Equigranular granite (Basin of Jelenia Góra)														
4	4a	Granite from the cover	245,5	0,237	0,0967	0,016	0,0065	0,117	0,0477	0,104	0,0425	—	—	—	—	
5	4b	Fresch granite	142,2	0,004	0,00281	0,004	0,00281	—	—	—	—	—	—	—	—	Traces of weathered material
		Aplite granite (Karkonosze Mts. — Main Ridge)														
6	6a	Granite from the cover	82,7	—	—	—	—	—	—	—	—	—	—	—	—	No changes
		Porphyraceous granite (Karkonosze Mts. — Main Ridge)														
7	7a	Granite from the cover	66,5	1,206	1,8135	0,005	0,0075	0,059	0, 089	0,167	0,251	0,975	1,466	—	—	
		Porphyraceous granite, granodiorite type (waterfall „Szklarka")														
8	16a	Granite from a tor wall	339,85	2,225	0,5556	0,067	0,0168	0,175	0,0438	0,301	0,075	1,682	0,42	—	—	
		Porphyraceous granite (Szklarska Poręba)														
9	0—2a	Granite from a small kettle (*kociołek*)	76,8	15,229	19,9675	0,084	0,1095	0,81	1,058	2,605	3,4	11,8	15,4	—	—	
		Porphyraceous granite (Karkonosze Mts. — Main Ridge)														
10	0—3a	Granite from the waste cover	98,6	0,097	0,0987	0,008	0,0081	0,043	0,0435	0,046	0,0468	—	—	—	—	
		VOLCANITES														
		Keratophyre (Kaczawa Mts.)														
11	17a	Keratophyre from a tor scree	64,4	0,006	0,0093	0,002	0,0031	0,004	0,062	—	—	—	—	—	—	
		Basalt (Kaczawa Mts.)														
12	18a	Basalt from a tor scree	76,2	0,005	0,00656	0,005	0,00656	—	—	—	—	—	—	—	—	
		SANDSTONES														
		Cretaceous sandstone (Stromiec, near Jelenia Góra)														
13	5a	Sandstone from the top of waste cover	160,2	1,118	0,6955	0,117	0,073	0,599	0,374	0,298	0,186	0,104	0,0625	—	—	
14	5b	Sandstone from the bottom of waste cover	175,85	15,881	8,9882	0,083	0,0472	1.618	0,92	2,67	1,461	11,51	6,56	—	—	
15	5c	Sandstone from the pseudokarst bed	65,5	6,811	10,35	0,395	0,6	2,695	4,1	3,197	4,86	0,524	0,79	—	—	
16	5d	Fresh sandstone	109,35	0,197	0,1809	0,026	0,0239	0,118	0,1084	0,053	0,0486	—	—	—	—	
		Conglomerate-like sandstone from Rotliegendes (vicinity of Złotoryja)														
17	19a	Sandstone from waste cover	121,0	8,066	6,663	0,343	0,283	1,898	1,565	3,315	2,74	2,51	2,705	—	—	
18	19b	Fresh sandstone	482,7	4,2	0,863	0,602	0,125	1,618	0,332	0,995	0,206	0,985	0,2	—	—	
		Zechstein sandstone (Biegaszów, near Złotoryja)														
19	20a	Sandstone from waste cover	226,4	1,491	0,6586	0,286	0,1266	0,997	0,440	0,153	0,0677	0,055	0,0243	—	—	
		METAMORPHIC SCHISTS														
		Green schist (Dobromierz)														
20	1a	Green schist from waste cover	272,76	0,226	0,3176	0,058	0,0212	0,062	0,0227	0,038	0,0139	0,067	0,0245	—	—	
21	1b	Green schist from the bottom of waste cover	119,48	—	—	—	—	—	—	—	—	—	—	—	—	No changes
22	1c	Green schist, fresh	177,5	—	—	—	—	—	—	—	—	—	—	—	—	No changes
		Mica-chlorite-quartz schists (vicinity of Świeradów)														
23	8a	Mica schist from waste cover	88,95	0,313	0,3512	0,02	0,0225	0,087	0,0977	0,091	0,1020	0,115	0,129	—	—	
24	8b	Mica schist from the bottom of waste cover	179,0	0,597	0,3202	0,074	0,041	0,196	0,1	0,25	0,14	0,077	0,0392	—	—	
25	8c	Fresh mica schist	54,4	0,128	0,2353	0,032	0,0588	0,057	0,1048	0,029	0,0533	0,01	0,0184	—	—	
		Mica schist taken at the contact with quartz vein (Rozdroże Izerskie)														
26	15a	Mica schist from waste cover	146,6	25,64	17,4884	1,383	0,943	3,777	2,575	4,78	3,26	6,775	4,61	8,925	6,1004	4 „needles" — 3 cm in lenght. Also a split of sample and the smaller part — 5 cm, weight — 30,485
		CRYSTALLINE LIMESTONES														
		Crystalline limestone from the Miłek, Wojcieszów														
27	2a	Black limestone with white veinlet, fresh	186,49	—	—	—	—	—	—	—	—	—	—	—	—	No changes
28	2b	Yellow-grey limestone from waste cover	281,2	0,816	2,63	0,212	0,755	0,251	0,89	0,279	0,96	0,074	0,025	—	—	
29	2c	Calcareous schist from waste cover	102,7	1,244	1,2133	0,067	0,0653	0,201	0,196	0,3	0,292	0,676	0,66	—	—	
30	2c′	Fresh calcareous schist	70,7	—	—	—	—	—	—	—	—	—	—	—	—	
		GNEISSES														
		Banded biotite gneisses (Izera Mts. — Death's bend)														
31	11a	Banded gneiss from waste cover	151,7	0,578	0,379	0,054	0,036	0,068	0,045	0,11	0,073	0,346	0,225	—	—	
32	11b	Banded gneiss, fresh taken from a tor	152,35	0,046	0,02975	0,012	0,00775	0,026	0,0168	0,008	0,0052	—	—	—	—	
		Lenticular gneisses (Izera Mts. — Death's bend)														
33	12a	Lenticular gneiss from waste cover	298,85	0,057	0,0191	0,013	0,00435	0,015	0,00503	0,029	0,00972	—	—	—	—	
		Bańded gneiss (Izera Mts. — Death's bend)														
34	13a	Banded gneiss from waste cover	152,85	1,325	0,95446	0,025	0,0164	0,118	0,0770	0,122	0,0802	1,06	0,697	—	—	
		Augen-gneiss (Izera Mts. — Death's bend)														
35	14a	Augen-gneiss from waste cover	217,5	0,181	0,08376	0,02	0,0092	0,081	0,0372	0,069	0,0318	0,011	0.00506	—	—	
		VEIN QUARTZ														
		Vein quartz (Izera Mts. — Rozdroże Izerskie)														
36	15d	Fresh vein quartz	40,2	—	—	—	—	—	—	—	—	—	—	—	—	No changes
		Vein quartz from the contact zone														
37	15b	Vein quartz, slightly schistose, fresh	306,55	3,315	1,094	0,897	0,29	0,951	0,31	0,514	0,184	0,953	0,31	—	—	

* in %% of initial weight of the whole rock sample.

Weathered material obtained during experiment under the Iceland cycle water conditions **Table II**

No.	Sample number	Kind of rock used in experiment	Initial weight of samples in grammes	Weight of weathered material obtained in grammes	Obtained weathered material in %% of initial weight	Grain-size gradation of weathered material: <0,06 mm, in grammes	<0,06 mm, in %*	0,5—0,06 mm, in grammes	0,5—0,06 mm, in %*	2,0—0,5 mm, in grammes	2,0—0,5 mm, in %*	20,0—2,0 mm, in grammes	20,0—2,0 mm, in %*	20,0 mm loose aggregates, in grammes	20,0 mm loose aggregates, in %*	Notes
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		GRANITES														
		Porphyraceous granites (Basin of Jelenia Góra)														
1	3a	Strongly weathered granite — from surface of waste cover	231,3	231,046	99,99	3,015	1,3	17,316	7,5	31,11	13,4	78,695	34,1	100,91	43,6	Total disintegration of the sample
2	3b	Medium-weathered granite — bottom of waste cover	122,0	0,151	0,1238	0,01	0,0082	0,05	0,041	0,07	0,0574	0,021	0,0172	—	—	
3	3c	Fresh granite	160,75	0,041	0,02245	0,001	0,0006	0,025	0,0156	0,015	0,00625	—	—	—	—	
		Equigranular granite (Basin of Jelenia Góra)														
4	4a	Granite from waste cover	159,0	0,207	0,1303	0,026	0,0164	0,063	0,0396	0,085	0,0535	0,033	0,0208	—	—	
5	4b	Fresh granite	145,5	0,145	0,0717	0,028	0,00193	0,1	0,0686	0,017	0,00117	—	—	—	—	
		Aplite granite (Karkonosze Mts. — Main Ridge)														
6	6a	Granite from waste cover	52,95	0,075	0,1405	0,009	0,0177	0,046	0,085	0,02	0,0378	—	—	—	—	
		Porphyraceous granite (Karkonosze Mts. — Main Ridge)														
7	7a	Granite from waste cover	60,7	2,405	3,946	0,052	0,086	0,2	0,33	0,405	0,66	1,748	2,87	—	—	
		Porphyraceous granite, granodiorite type (waterfall „Szklarka")														
8	16a	Granite from a tor wall	455,15	26,79	5,8599	0,073	0,0154	0,384	0,0835	0,879	0,191	5,692	1,25	19,762	4,32	
		Porphyraceous granite (Szklarska Poręba)														
9	0—2a	Granite from a small kettle (*kociołek*)	61,25	21,239	36,485	0,15	0,245	0,947	1,54	3,925	6,4	8,202	13,4	9,015	14,9	Two loose aggregates, 2,5 cm, weight 9,015 g.
		Porphyraceous granite (Karkonosze Mts. — Main Ridge)														
10	0—3a	Granite form waste cover	60,1	0,04	0,06642	0,002	0,00332	0,028	0,0465	0,01	0,0166	—	—	—	—	
		VOLCANITES														
		Keratophyre (Kaczawa Mts).														
11	17a	Keratophyre from a tor scree	102,8	0,071	0,0696	0,015	0,0147	0,024	0,0235	0,032	0,0314	—	—	—	—	
		Basalt (Kaczawa Mts.)														
12	18a	Basalt from a tor scree	51,8	0,075	0,145	traces	—	0,075	traces	—	—	—	—	—	—	Traces of organic material — lichens?
		SANDSTONES														
		Cretaceous sandstone (Stromiec, near Jelenia Góra)														
13	5a	Sandstone from the top of waste cover	262,1	4,411	1,65	0,55	0,21	1,336	0,5	1,402	0,53	1,123	0,41	—	—	5 aggregates, 2—4 cm, weight 43,51 g.
14	5b	Sandstone from the bottom of waste cover	137,5	76,503	55,55	1,313	0,95	6,3	4,6	10,48	7,5	14,9	10,8	43,51	31,7	
15	5c	Sandstone from the pseudokarst bed	58,3	45,994	74,48	2,5	4,3	16,388	28,2	23,656	40,7	0,75	1,28	—	—	
16	5d	Fresh sandstone	92,5	3,231	3,49	0,186	0,195	1,04	1,125	1,7	1,84	0,305	0,33	—	—	
		Conglomerate-like sandstone from Rotliegendes (vicinity of Złotoryja)														
17	19a	Sandstone from waste cover	63,2	25,539	40,39	1,295	2,04	4,019	6,95	9,489	15,0	6,935	11,0	3,805	6,0	One aggregate, 2,5 cm, weight 3,805 g.
18	19b	Fresh sandstone	466,1	28,909	6,3025	1,935	0,412	1,001	2,16	5,565	1,19	11,399	2,4	—	—	
		Zechstein sandstone (Biegaszów, near Złotoryja)														
19	20a	Sandstone from waste cover	182,4	5,287	2,916	0,415	0,226	2,695	1,48	0,984	0,54	1,193	0,67	—	—	
		METAMORPHIC SCHISTS														
		Green schists (Dobromierz)														
20	1a	Green schist from waste cover	310,0	36,229	11,669	0,205	0,066	0,345	0,111	0,508	0,162	2,886	0,93	32,285	10,4	One aggregate lamina, 6,0 cm, weight 12,598 g.
21	1b	Green schist from the bottom of waste cover	80,0	0,015	0,01875	0,001	0,00125	0,004	0,005	0,01	0,0125	—	—	—	—	
22	1c	Green schist, fresh	126,75	0,061	0,04717	0,003	0,00237	0,026	0,02	0,02	0,0158	0,012	0,009	—	—	
		Mica-chlorite-quartz schists (vicinity of Świeradów)														
23	8a	Mica schist from waste cover	67,9	0,28	0,4075	0,041	0,06	0,04	0,0585	0,098	0,143	0,101	0,146	—	—	Lack of data
24	8b	Mica schist from the bottom of waste cover	126,7	—	—	—	—	—	—	—	—	—	—	—	—	Lack of data
25	8c	Fresh mica schist	68,45	0,055	0,081	0,007	0,0103	0,038	0,056	0,01	0,0147	—	—	—	—	
		Mica schist taken at the contact with quartz vein (Rozdroże Izerskie)														
26	15a	Mica schist from waste cover	96,5	41,852	43,36	2,634	2,73	4,036	4,18	6,997	7,25	15,857	16,2	12,598	13,0	Two aggregates, 2,0 cm, total weight 12,598 g.
		CRYSTALLINE LIMESTONES														
		Crystalline limestone form the Miłek (Wojcieszów)														
27	2a	Black limestone with white veins, fresh	128,49	0,081	0,0616	0,011	0,0086	0,028	0,0218	0,042	0,0312	—	—	—	—	
28	2b	Yellow-grey limestone from waste cover	66,2	0,155	0,2346	0,026	0,0393	0,095	0,144	0,024	0,0363	0,01	0,015	—	—	
29	2c	Calcareous schist from waste cover	165,5	2,306	1,387	0,344	0,204	0,845	0,51	0,848	0,51	0,269	0,163	—	—	
30	2c'	Fresh calcareous schist	42,6	0,254	0,2872	0,006	0,014	0,05	0,117	0,052	0,122	0,146	0,342	—	—	
		GNEISSES														
		Banded biotite gneisses (Izera Mts. — Death's bend)														
31	11a	Banded gneiss from waste cover	190,2	0,801	0,4513	0,052	0,0263	0,297	0,156	0,267	0,14	0,245	0,129	—	—	Disintegration of both specimens into two parts
32	11b	Banded gneiss, fresh taken from a tor	81,75	0,042	0,0513	0,009	0,011	0,021	0,0256	0,012	0,0147	—	—	—	—	
		Lenticular gneiss (Izera Mts. — Death's bend)														
33	12a	Lenticular gneiss from waste cover	229,5	0,06	0,02616	0,01	0,00436	0,028	0,0122	0,022	0,0096	—	—	—	—	
		Banded gneiss (Izera Mts. — Death's bend)														
34	13a	Banded gneiss from waste cover	198,7	2,109	1,244	0,376	0,376	0,226	0,111	0,471	0,237	1,036	0,52	—	—	
		Augen-gneiss (Izera Mts. — Death's bend)														
35	14a	Augen-gneiss from waste cover	183,1	0,136	0,0687	0,027	0,0136	0,064	0,0323	0,045	0,0228	—	—	—	—	
		VEIN QUARTZ														
		Vein quartz (Izera Mts. — Rozdroże Izerskie)														
36	15d	Fresh vein quartz	73,7	—	—	—	—	—	—	—	—	—	—	—	—	No changes
		Vein quartz from the contact zone														
37	15b	Vein quartz, slightly schistose, fresh	306,1	—	—	traces	—	—	—	—	—	—	—	—	—	Traces of weathered material

* in %% of initial weight of the whole rock sample.

Summing up all these considerations one should once more stress the coexistence of both types of frost weathering in favour of low-temperature frost weathering, that prepares the rock to the process of ice crystal growth. The situation is almost identical as that observed in the relationship between weathering and denudation. A different extent of these frost weathering processes should also be taken into consideration. There are cases in which the rôle of ice crystals is lesser due to the feeble precipitations (under conditions of rigorous continental climates), or greater (marine climates), where water predominates and its effects are stressed by still more intense regelation. Therefore, a discussion on the results obtained under dry conditions (Tricart, Wiman), i.e. under conditions causing no macroscopic changes, and drawing conclusions as to the effectiveness of frost weathering process without water, appear to be inappropriate.

The experiments made by Kessler, Insley and Sligh (1940) on granites that also revealed no macroscopic changes, might suggest some similar conclusions as to the ineffectiveness of frost weathering, or to a considerable resistance of the granites examined. This would be explained by the lack of broken material. It should, however, be kept in mind here that examinations were made on granite samples used for building purposes, thus on a fresh rock, „untainted" by any external activity.

COMBINED ACTION OF VARIOUS TYPES OF WEATHERING UPON THE ROCKS

We can at present pass to a discussion on an important dependence of frost weathering upon the initial state of rock that, at a given moment, is under the influence of frost weathering. This term used below defines generally the whole process, irrespective of its forms. It is also deep-seated in the literature and cannot be differentiated.

Literature data, field observations and experimental results allow to state the presence of strong interrelations between physical weathering and chemical weathering (chemical *sensu lato* — together with organic weathering). Rocks that already underwent chemical weathering, show only slight resistance to frost activity. This was easily seen in granites and metamorphic rocks. The same type of fresh rock is absolutely more resistant (e.g. granite No. 3c). Curve of dependence of frost weathering effect upon the present state of rock would be almost a power curve. This means that an action of even intense frost weathering upon fresh rock does not afford any effects (prescinding from rock type). Rock that already underwent chemical weathering will, having disturbed internal structure, also undergo further disintegration under frost conditions. A total disintegration of the rocks that are strongly destructed by external processes, may take place even during a feeble action of frost weathering.

All the processes help each other and aim at destructing the rock. At present, we cannot exclude the existence of chemical weathering in the areas characterized by relatively low temperatures and scarce precipitations, which have so far been reckoned as the only domain of physical weathering. Sukhodrovski cites Polynov[6], who was of the opinion that a certain type of weathered material from Francis Joseph's Archipelago represented a product of cooperation of chemical, biological and physical weatherings. Some traces of chemical and organic weathering have been ascertained in Antarctica by Kelly and Zumberge (1960). Of course, it does not attain such an expansion as that in the tropical zones, but sufficiently helps in loosening texture and structure of rocks, and contributes to frost weathering, thus causing the process to develop on a greater scale.

Cailleux (1962) describes forms of disintegration of gneisses and granites from the region of McMurdo Sound, Antarctica, the genesis of which he explains by a cooperation of frost weathering with chemical processes (precipitation and recrystallization of minerals). Czeppe (1964) demonstrates, on the basis of exfoliation of Carboniferous sandstones from West Spitsbergen that chemical weathering does occur also inside of the fresh rocks under conditions of periglacial climate. Changes of cementing material, migration of iron oxides, formation of concentric zones of various chemical and mineral compositions, thus revealing also various mechanical properties, lead, according to him, to exfoliation of rock (plates approximately 4 mm in thickness). Removing of Fe, Mg and Al oxides and simultaneous enrichment in silica cause that external zones are harder than the unweathered rock.

In this case frost weathering is a process that only accelerates such an exfoliation of rock. A cooperation of chemical weathering and frost activity was also stated by Ohlson (1964) during his examination of limestones from Lapland in Finland.

A considerable part is played by organic factors. Resistance of a rock covered by turf cover is weakened by the activity of humic acides and the rock easily undergoes cracking. Observations of this type were made, among others, at the rock faces within the Lejowa Valley mouth in the West Tatra Mts. A part of dark-grey Eocene limestone was covered with

[6] Polynov V. B. — First stages of soil development on massive-cristalline rocks (in Russian). *Pochvoviedeniye*, 1954, no. 7.

a thin turf layer, about 3—6 cm in thickness. Under the layer was a white rugged rock revealing numerous fine fissures that disappeared at the boundary lines and were lacking in the free smooth areas deprived of turf cover (Pl. 14). This net of fissures was closely connected with the stratification of the whole series. It appears that this process would not be so distinct in the case of greater thickness of turf cover that would isolate rock surface from immediate activity of temperature and water. Some examples of isolating rôle of lichens covering rocks are given by Paterson (1951) from the northwestern areas of Greenland. According to him the lichens influence the porosity of rocks and can change their thermal conductivity, thus protect them against frost weathering.

These observations, although right, forced, however, Paterson to draw extreme conclusions as to the low effects of chemical weathering under polar conditions. According to him, this weathering does not play so an important rôle as it really plays in the weakening of external surfaces and of internal structure of fresh rocks. This has already been stressed in various later papers of the individual research workers discussed above. Paterson agrees only in a certain development of porosity of superficial part of rocks due to the chemical removing of some minerals (biotites).

When discussing the problems of cooperation and interaction of weathering processes we cannot disregard other connections and relationships resulting from lithological features of rock material and from water conditions. These connections are, however, highly many-sided. For instance, the structure of rock influences the porosity, which allows the rock to take a determined quantity of water that, in turn, is necessary for the process of frost weathering. At the time of thawing chemical action may take place and, destroying the individual minerals, can produce favourable conditions for low-temperature weathering. Loosening of the internal structure of rock, connected with this process, leads to an increase of porosity and consequently to a possibility of greater imbibition of water that provides for more effective work of the growing ice crystals.

Now and then, the processes can be less intense (according to the temperature, direction of its application, or to the kind of rock), but their coexistence during certain period of time can lead, in consequence, to a complete destruction of rock material.

The problem of complex destruction was already discussed by Kelly and Zumberge (1961), who had ascertained, during their study in Antarctica, a coexistence of frost weathering with crystallization of potassium and sodium salts, which caused a loosening of diorite rock surfaces. Thus, a complex might here occur consisting in an almost complete physical weathering (without insolation).

On account of so a great amount of various external factors influencing differentiated substratum, thereby also affecting the kind and character of its weathered material, we cannot precisely determine the value of frost weathering. One can only give a series of certain dependences controlling its activity, and an approximate effect.

LITHOLOGICAL DEPENDENCES OF FROST WEATHERING

The group of the most important dependences is represented by those resulting from the structure of the given rock. Within these dependences would be included: structure of rocks (development of mineral grains and their interrelation), texture of rocks (kind of mineral arrangement), system of cracks connected with them, or kind of cementing material important in the case of sedimentary rocks. These dependences were strongly stressed in the description of rocks. Such features as kind and form od surface (pebbles), connected with packing, influence the porosity of rocks. Due to its monotony, or its variety, the mineral composition also plays an important and decisive rôle, all the more, in connection with the texture and structure of rocks. E. g. Paterson (1951), bassing on the observation of behaviour of biotite schists, informs that a large number of dark ferromagnetic minerals considerably facilitates disintegration of parent rock into fine fragments. On the other hand, the rocks poor in these minerals (biotite, hornblende and others), such as quartzes and gneisses, disintegrate into thick plates. Paterson does not interpret these phenomena, although chemical weathering plays here actually an important part. Important for the effect of frost disintegration is also resistance to chemical weathering of the individual rock-forming minerals. This problem has been, however, ignored in the papers by Paterson. Differences in the resistance to frost weathering can also exist in fine-grained rocks that reveal a great number of heavy, dark minerals (basalts), as compared with those characterized by a uniform fine graines composed of lighter minerals (calcite in crystalline limestone). In addition, there should be mentioned also thermal anisotropy of minerals in relation to their main axis, e.g. that of calcite; and then we obtain a new series of interrelated complexes determining the differentiated rock mass. This problem was already explained by Tricart (1956).

The increase of frost weathering intensity that depends upon the original state of a rock, thereby upon water conditions and external changes of temperature, can ignore the altered texture and structure of the rock which underwent weathering processes. In any case, however, the activity of frost processes is in accordance with the mineral character of rocks. The individual minerals with their cleavage planes, crystallographical development and mutual position (e.g. proper arrangement of biotite on the surface of rock favours its loosening), as well as with the centres of their weakness (mylonitization) or their reinforcement (recrystallization) produce a series of centres differing in their physical and chemical properties, and a series of various discontinuity planes that, first of all, are attacked by frost weathering. This was stressed in 1930 by P. Eskola, who supposed that the microgelivation activity of frost weathering is in accordance with microtexture and structure of rocks.

Wiman (1963) underestimated a possibility of increase of initial, or of posterior internal weakness in mineral grains and in rock, mainly on account of the results obtained during his experiments showing slight changes in porosity due to frost activity, although in his paper he presented opinions by Von Moos and Quervain (1948). On the other hand, an old hypothesis of Birket-Smith (1928) concerning facilitation of frost weathering acting against fresh rock, previously covered with ice cap, has frequently been cited by Paterson (1951). A thick ice sheet produced a strong compression, thus it could bring about certain irreversible microscopic alterations of minerals.

Penultimate dependence of effectiveness of frost weathering, i.e. the quantity of water, has been expressed in various opinions and documented by experiments and field observations (comp. Paterson 1940, 1951). The significance of this fact needs not explain, particularly in connection with a diversified action of external factors (a complex of frost, chemical and organic weathering) and with differentiated lithological features of rocks. Irrespective of certain environmental disproportions in the material obtained during experiments we no doubt may state that an increase in water quantity also increases the effectiveness of frost weathering.

The influence of microrelief of rock surfaces upon the intensity of frost processes represents the last dependence. Since the quantity of water is of considerable importance for the kind of these processes, the rock surfaces, on which greater amount of water exists, are, naturally, more predisposed to disintegration. In connection with this the horizontal surfaces are, as a rule, also more predisposed, since water flows down from all inclined surfaces.

Considering this problem in detail we meet with certain complications connected with the lithological properties of rocks that are responsible for differentiated porosity, system of joints, various types of stratification, etc. These features controll a better penetration of water into the rock, or its quicker migration at the surface. Thus, inclined surfaces of more porous rocks (e.g. sandstones) may be more susceptible to frost weathering than horizontal surfaces of less porous ones.

However, the problem of greater porosity, or susceptibility of rocks becomes more complicated if we take into consideration the distribution of fissure systems and their relation to rock surfaces. Fissures are highly important, particularly on account of the fact that they retain snow better than smooth rock surfaces. At the time of snow melting the places richer in fissures are better supplied with water. This problem was already touched by Paterson (1940, 1951), Rapp (1960) and Czeppe (1964). Of great importance is also the fact of fissure systems and their relation to rock surfaces. Rock surfaces cutting fissure systems under the acute angle are best convenient for water retention and for its penetration into the rock mass, thus cause better conditions for frost weathering (Paterson 1951). This concerns all surfaces — horizontal, medium-inclined, and vertical. In the case of these latter worse conditions are only if the stratification of rock is of „imbricated" type (i.e. layers dip outside of a rock wall). The worst conditions are found in the case of concordance of rock surfaces with stratification (intersection angle =0°). The cases of increased susceptibility of rock to frost weathering under conditions of favourable stratification and advantageous relation to rock surfaces, discussed above, can be observed mainly on distinctly bedded rocks such as slates, sandstones and metamorphic schists.

Quantity of cracks on rock surfaces is also very important (their concentration, or scattering). A low resistance to frost activity has been observed on strongly cracked greenstones (vicinity of Bolków) and on granites (Karkonosze Mts., Tatra Mts.), where the quantity of cracks amounts to over a dozen on each 10 cm.

Concentrated cracks running on the horizontal rock surfaces make a sort of fine hollows. Water held up in these latter causes that the rock are stronger attacked by frost. Paterson (1951) gives some examples of rhomboidal hollows made due to diagonal cracks in biotite schists occurring in West Greenland. Numerous hollows of „stellar" type can be observed on granites in the Tatra Mts., and the Karkonosze Mts. (Pl. 16).

Convergent systems of joints, particularly in granites, play an important part, too. This can easily be observed on numerous tors in the Karkonosze Mts. (Pl. 15). Frequently, among the individual types of joints of Karkonosze granite (Q, S, L), a series of fractures can be found differing only in mininum angular values. This leads to a concentration of fissures, thereby also decreases the resistance of rock.

Even strongly resistant aplite granite undergoes considerable disintegration due to frost activity, in the places of intersections of convergent vertical joints of Q and S types. Such examples are reported from quarry faces, near Sobieszów (Ostrosz Mt.).

If convergent vertical cracks reveal certain dips ranging from 75° to 80° then on faces are formed characteristic furrows and ribs resembling letter X. Beside frost weathering also gravitation plays an important part in shaping the relief of vertical walls. Due to gravity the loosened material falls easily away, or is removed by melt waters. The effect of dynamically acting water that brings down the rock material from the walls previously subject to frost weathering, was already considered by Paterson (1940, 1951) and Rapp (1960).

The above mentioned section near Sobieszów yields rich observation material that stresses the problem here considered. Rock faces on which only one system of fissures predominates represent smooth plates. If, however, at least two convergent systems of fissures appear furrows and ribs are formed. At the base of these forms much fine-grained and medium--grained, angular aplite debris accumulates. Within the ribs on walls the quantity of minute cracks increases fivefold (up to about 15 on each 100 cm^2). Between the furrows a distinct loosening of rock can be observed. The individual rock elements, 1 to 5 cm in size, are squeezed out by frost activity to the half of their size.

Similar observations might have been made in the neighbouring section of porphyraceous granite. Here, however, some distinct zones of chemical weathering activity have been observed in furrows. At the top parts of the section, where rocks were covered with a turf and moss layer, a strong organic weathering could be seen.

Ending the discussion on this problem one should touch still another question concerning the protective rôle of the weathered material, that rests in the minute drainless hollows and is not brought out. This was discussed by Paterson (1951), who, among others, observed the activity of frost on limiting edges of the hollows amounting to several metres in diameter, 0,5 m deep, and filled up with debris of biotite schists.

THE PROBLEM OF MACRO- AND MICROGELIVATION

After comparison of various factors connected to each other, we should not be surprised at the quantitative differentiation of the material obtained during experiments. Basing on rich field observations and on experimental data Tricart made a comparison of frost weathering processes and, taking the material into consideration, he ascertained block macrogelivation that divides the rock blocks along joints, grooves and bedding planes, and granular macrogelivation that influences grains and mineral crystals and depends upon the type of cementation of the individual rock grains. In addition, he distinguished also microgelivation that disintegrates the rock into fragments, irrespective of its lithological features. Similar classification was accepted by Wiman (1963), and Sukhodrovski distinguished, in turn, block and granular macrogelivation, restricting the activity of this latter to a narrow surficial zone of rocks.

The problem of block disintegration was not an object of the present study, but the genesis of this phenomenon has not been explained sufficiently in geomorphology. Granular macrogelivation does not present today any greater controversy, whereas microgelivation, the effects of which were accurately examined under the microscope, does not run chaotically, but is strongly controlled by mineral features of the given rock, or by their changes.

On account of the fact that both quantitative effect and character of the weathered material are a resultant of numerous parameters conditioned by external factors or by the rock itself, it is difficult to refer the given kind of gelivation to the individual types. Therefore, a considerable resistance of granites to microgelivation, however, under closely defined conditions and state of rock, may be cited here as an example only.

Tricart set up a thesis on the independence of macrogelivation and microgelivation processes, basing his opinion on disintegration of granites into coarse fragments that produced a slight amount of fine weathered material. This can hardly be accepted since, apart from other aspects, one type facilitates the activity of other type. Moreover, it cannot be excluded that microgelivation weakness appearing at the places of greater fractures and grooves in rocks may lead, under favourable thermal conditions, to block disintegration. We can only generally state a dependence of differentiated destruction of rocks upon the factors mentioned above. In connection with this another kind of gelivation needs not to be a result of intensity of frost weathering (very low temperatures, or their frequent oscillations).

On the basis of complex connections we may only determine the general resistance of rocks to frost weathering. Rocks revealing variously grained structure (granites), previously weathered, yield a large amount of various granular waste. In massive, fine-crystalline rocks, where chemical weathering is considerably feeble, and the rock more compact, the tensions can produce debris macrogelivation concordant to the joint system of rock (equigranular and aplite granites). In the rocks, in which decisive is the structure of a rock revealing feebly cemented grains (mainly sandstones), monofractional material predominates. This moment based on equal

Table III

Grain-size distribution of the weathered material obtained experimentally in humid environment (obtained weathered material — 100%)

No.	Number of sample	<0,06 mm in %	0,06—0,5 mm in %	0,5—2,0 mm in %	2,0—20,0 mm in %	>20,0 mm in %
			GRANITES			
1	3a	0,5	3,5	6,5	15,0	74,5
2	3b	12,8	35,6	12,2	39,4	—
3	3c	2,0	19,8	8,9	69,3	—
4	4a	6,8	49,3	43,9	—	—
5	4b	100,0	traces	—	—	—
6	6a	—	—	—	—	—
7	7a	0,4	4,9	13,9	80,8	—
8	16a	3,0	7,8	13,6	75,6	—
9	0—2a	0,5	5,3	17,1	77,1	—
10	0—3a	8,2	44,3	47,5	—	—
			VOLCANITES			
11	17a	33,3	66,7	—	—	—
12	18a	traces	100,0	—	—	—
			SANDSTONES			
13	5a	10,5	53,6	26,6	9,3	—
14	5b	0,5	10,2	16,8	72,5	—
15	5c	5,8	39,6	46,9	7,7	—
16	5d	13,1	60,0	26,9	—	—
17	19a	4,2	23.5	41,1	31,2	—
18	19b	14,4	38,5	23,6	23,5	—
19	20a	19,2	66,8	10,3	3,7	—
			METAMORPHIC SCHISTS			
20	1a	25,8	27,6	16,8	29,8	—
21	1b	—	—	—	—	—
22	1c	—	—	—	—	—
23	8a	6,4	27,8	29,1	36,7	—
24	8b	12,2	33,0	42,0	12,8	—
25	8c	25,0	44,5	22,7	7,8	—
26	15a	5,4	14,8	18,6	26,4	34,8
			CRYSTALLINE LIMESTONES			
27	2a	—	—	—	—	—
28	2b	26,0	30,7	34,2	9,1	—
29	2c	5,4	16,1	24,1	54,4	—
30	2c'	—	—	—	—	—
			GNEISSES			
31	11a	9,3	11,7	19,0	60,0	—
32	11b	26,1	55,6	17,3	—	—
33	12a	22,8	26,2	51,0	—	—
34	13a	1,9	8,9	9,2	80,0	—
35	14a	11,0	44,8	38,1	6,1	—
			VEIN QUARTZ			
36	15d	—	—	—	—	—
37	15b	27,0	26,7	15,5	28,8	—

Note: sequence and kind of rocks according to tabl. I and II.

Table IV

Grain-size distribution of the weathered material obtained experimentally in water environment (obtained weathered material — 100%)

No.	Number of samples	<0,06 mm in %	0,06—0,5 mm in %	0,5—2,0 mm in %	2,0—20,0 mm in %	>20,0 mm in %
			GRANITES			
1	3a	1,3	7,5	13,6	34,3	43,3
2	3b	6,7	33,1	46,3	13,9	—
3	3c	2,4	61,0	36,6	—	—
4	4a	12,6	30,4	41,0	16,0	—
5	4b	19,3	69,0	11,7	—	—
6	6a	1,2	61,9	26,9	—	—
7	7a	2,2	8,3	16,8	72,7	—
8	16a	0,3	1,4	3,3	21,2	73,8
9	0—2a	0,7	4,2	17,6	36,9	40,6
10	0—3a	5,0	70,0	25,0	—	—
			VOLCANITES			
11	17a	21,2	33,8	45,0	—	—
12	18a	traces	100,0	traces	—	—
			SANDSTONES			
13	5a	12,5	30,2	31,8	25,5	—
14	5b	1,7	8,2	13,7	19,5	56,9
15	5c	6,5	37,8	53,8	1,9	—
16	5d	5,7	32,2	52,7	9,4	—
17	19a	5,1	15,8	37,1	27,1	14,9
18	19b	6,7	34,7	19,2	39,4	—
19	20a	7,8	51,1	18,6	22,5	—
			METAMORPHIC SCHISTS			
20	1a	0,7	1,0	1,4	7,9	89,0
21	1b	6,7	26,6	66,7	—	—
22	1c	4,9	42,6	32,8	19,7	—
23	8a	14,6	14,3	35,0	36,1	—
24	8b	—	—	—	—	—
25	8c	12,7	69,1	18,2	—	—
26	15a	6,3	9,7	16,7	37,2	30,1
			CRYSTALLINE LIMESTONES			
27	2a	13,5	34,6	51,9	—	—
28	2b	16,8	61,3	15,5	6,4	—
29	2c	15,0	36,6	36,7	11,7	—
30	2c'	2,4	19,7	20,4	57,5	—
			GNEISSES			
31	11a	6,0	34,5	31,0	28,5	—
32	11b	21,4	50,0	28,6	—	—
33	12a	16,6	46,7	36,7	—	—
34	13a	17,8	10,7	22,3	49,2	—
35	14a	19,9	47,0	33,1	—	—
			VEIN QUARTZ			
36	15d	—	—	—	—	—
37	15b	traces	—	—	—	—

Note: sequence and kind of rocks according to tabl. I and II.

distribution of a great number of fine pores in sandstones was cited also by Paterson (1951). Cryptocrystalline, compact, massive and very resistant rocks can, however, give more silt material, as compared with the remaining part, or coarse-debris material depending on favourable external and internal conditions (favourable slaty texture). Weathered material of this type is characteristic of debris-silt greenstone and basalt waste covers in the West Sudetes. On account of repeated recrystallization, gneisses and crystalline limestones are highly resistant to frost activity. In the case of crystalline limestones only chemical weathering can help in production of more weathered material due to frost activity. On account of their maximum resistance to the action of all weathering processes, quartzes do not show any changes. It may be that the so-called „granite grit" occurring in the Karkonosze Mts. is here weathered material deriving from disintegration of rocks due to the complex weathering processes.

Thus, quantity and quality of disintegration of a rock subject to frost weathering depend upon texture, structure, chemical weathering, water amount and mutual relationship of these factors.

Further experimental studies of identical rock types as to other temperature cycles, and more precise measurement methods will permit to estimate the problem of behaviour of these rocks under various climatic conditions, in low-temperature weathering, or in complex weathering.

Additional research works carried on in connection with field observations may determine more in detail the character and effectiveness of frost weathering, so important for further morphogenetic processes.

Translated by Romuald Żyłka

References

Birket-Smith, K. 1928 — Physiography — Greenland. vol. 1.

Cailleux, A. 1962 — Etudes de géologie au détroit de McMurdo (Antarctique). Territoire des Terres Australes et Antarctiques Françaises. CNFRA, 1.

Czeppe, Z. 1964 — Exfoliation in a periglacial climate. *Geographica Polonica*, vol. 2.

Dobrowolski, A. B. 1923 — Historia naturalna lodu (Natural history of ice). Warsaw.

Dylik, J. 1963 — Nowe problemy wiecznej zmarzliny plejstoceńskiej (résumé: Nouveaux problèmes du pergélisol pléistocène). *Acta Geogr. Lodziensia*, no. 17.

Escola, P. 1930 — On the disintegration of rapakivi. *C. r. de la Soc. Géol. de Finlande*, No. 3.

Jahn, A. 1961 — Quantitative analysis of some periglacial processes in Spitsbergen. *Zeszyty Naukowe Uniwersytetu Wrocławskiego, Nauki Przyrodn.*, Ser. B. no. 5.

Kelly, W. C. & Zumberge, J. H. 1960 — Rock weathering in the Antarctica. *Bull. Geol. Soc. America*, vol. 171.

Kelly, W. C. & Zumberge, J. H. 1961 — Weathering of quartz diorite at Marble Point, McMurdo Sound, Antarctica. *Jour. Geol.*, vol. 69.

Kessler, P. 1925 — Das eiszeitliche Klima. Stuttgart.

Kessler, D. W., Insley, H. & Slight, W. H. 1940 — Physical, mineralogical and durability studies on the building and monumental of the United States. *Jour. Research National Bureau of Standroads*, vol. 25.

Lachenbruch, A. H. 1962 — Mechanics of thermal contraction cracks and ice-wedge polygons in permafrost. *Geol. Soc. America, Special Papers*, 70.

Moss, A. von & Quervain, F. de 1948 — Technische Gesteinskunde. Basel.

Nansen, F. 1924 — The strandflat and isostasy. Kristiania.

Ohlson, B. 1964 — Frostaktivität, Verwitterung und Bodenbildung in den Fjeldgegenden von Enontekiö, Finnisch Lappland. *Fennia*, no. 89 (3).

Paterson, T. T. 1940 — The effects of frost action and solifluction around Baffin Bay and in the Cambridge District. *Quart. Jour. Geol. Soc. London*, vol. 96.

Paterson, T. T. 1951 — Physiography studies in NW Greenland. *Meddelelser om Grønland*, Bd. 151, no. 4.

Rapp, A. 1957 — Studien über Schutthalden in Lappland und auf Spitzbergen. *Ztschr. f. Geomorphologie*, Bd. 1.

Rapp, A. 1960 — Recent development of mountain slopes in Kärkevagge and surroundings, Northern Scandinavia. *Geog. Annaler*, vol. 42.

Sekyra, J. 1964 — Cryological phenomena in the North Pamir (Central Trans-Altai). *Biuletyn Peryglacjalny*, no. 14.

Sukhodrovski, V. L. 1962 a — Sklonovyie processy v periglacyalnoj zonie Zyemli Franca-Josifa (Slope processes in periglacial zone, Francis Joseph Land). *Izvestya Akad. Nauk SSSR*, ser. geog.

Sukhodrovski, V. L. 1962 b — Fizicheskoye vyvyetrivaniye gornykh porod v prilednikovoj zonie Zyemli Franca-Josifa (Physical weathering of rocks in near glacial zone, Francis Joseph Land). *Isledov. lednikov i lednikovykh rajonov*, vyp. 2; Akad. Nauk SSSR.

Taber, S. 1929 — Frost heaving. *Jour. Geol.*, vol. 37.

Taber, S. 1930 — The mechanics of frost heaving. *Jour. Geol.*, vol. 38.

Taber, S. 1950 — Intensive frost action along lake shores. *Amer. Jour.* Sci., vol. 248.

Tricart, J. 1956 — Etude experimentale du problème de la gélivation. *Biuletyn Peryglacjalny*, no. 4.

Wiłun, Z. 1962 — Wpływ mrozu na grunty i środki zapobiegawcze (Frost action upon the grounds and preventive means). Mechanika gruntów i gruntoznawstwo drogowe, part XI. Warsaw.

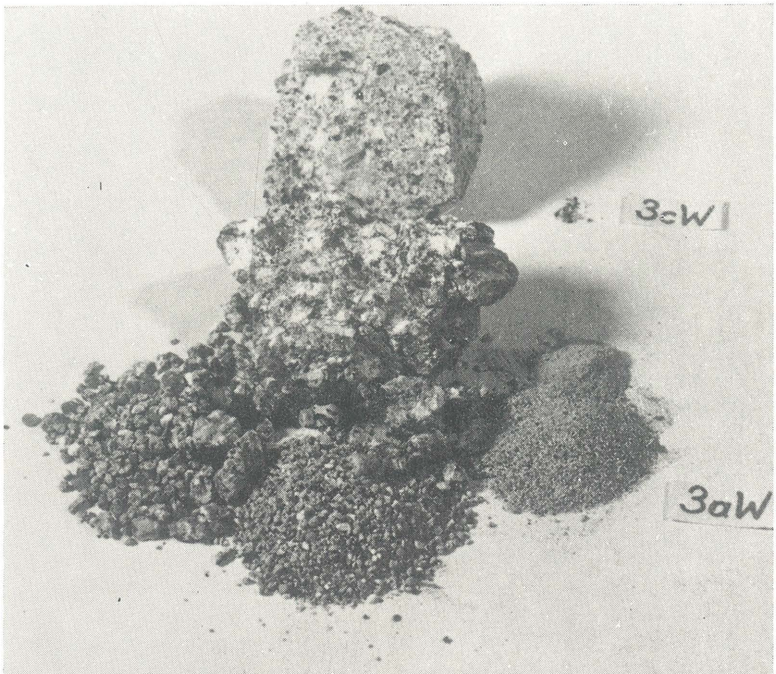
Wiman, S. 1963 — A preliminary study of experimental frost weathering. *Geog. Annaler*, vol. 45.

Determination and characteristic of rocks were made on the basis of:

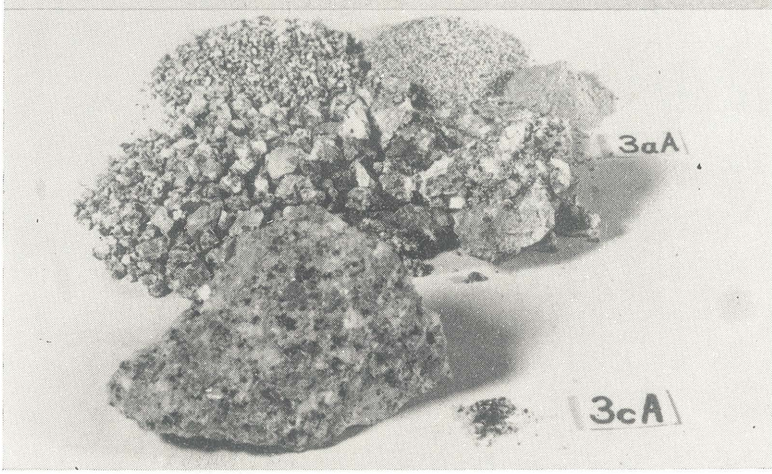
Bolewski, A. & Turnau-Morawska, M. 1963 — Petrografia. Warsaw.

Teisseyre, H., Smulikowski, K. & Oberc, J. 1957 — Regionalna geologia Polski, t. 3 — Sudety. Warsaw.

a



b

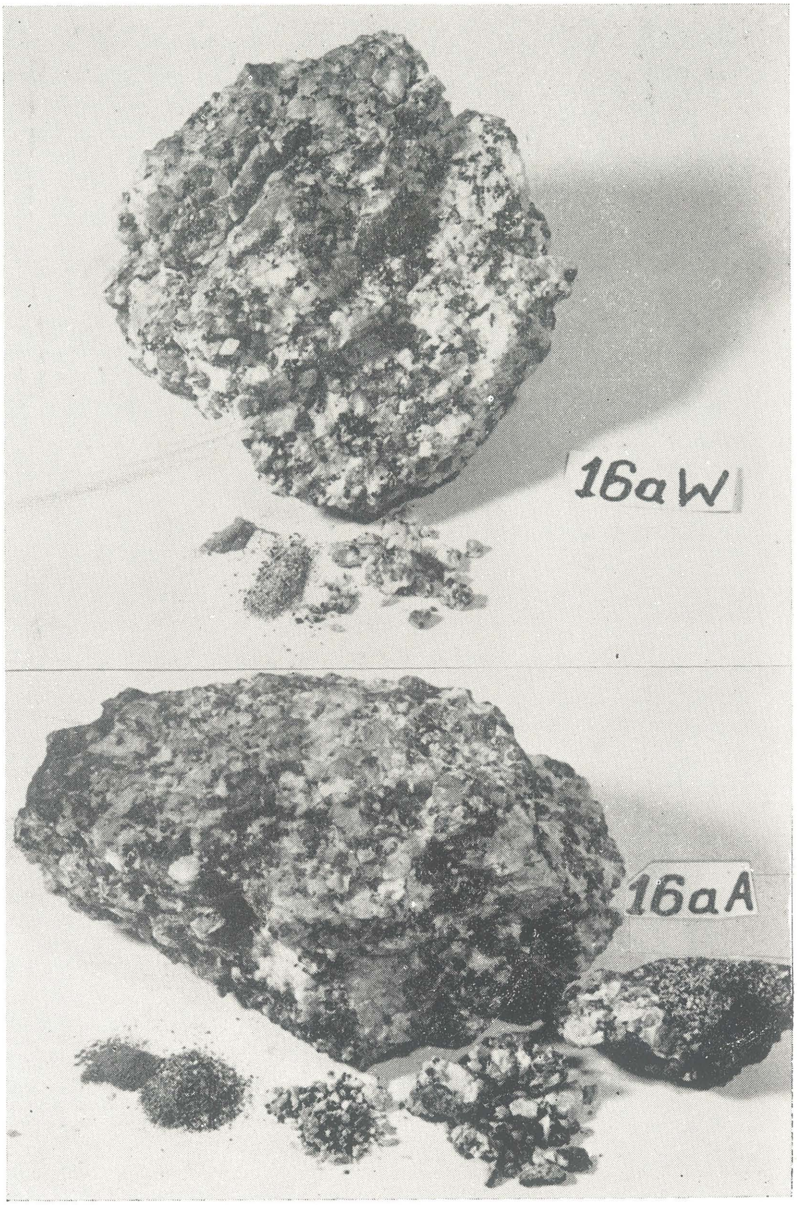


Pl. 1. Porphyraceous granite (Jelenia Góra) strongly weathered from the waste cover surface (3a) and fresh from a quarry wall (3c)

a — sample in humid environment; b — sample in water environment

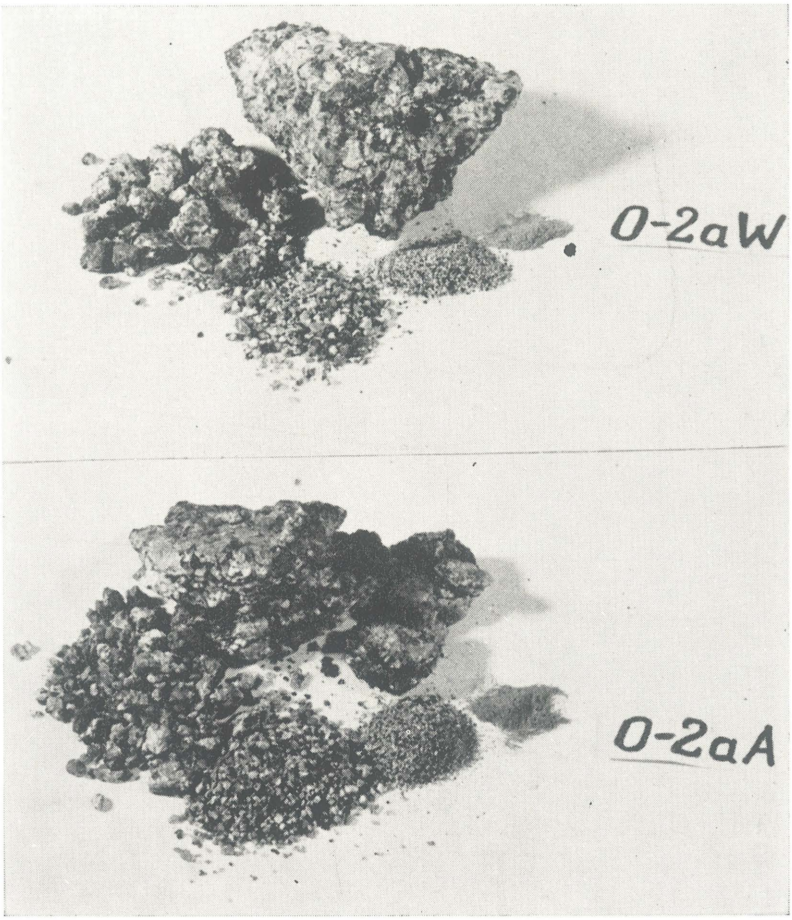
a

b



Pl. 2. Porphyraceous granite (granodiorite type) from a tor near the waterfall „Szklarka" in the vicinity of Szklarska Poręba

a — sample in humid environment; b — sample in water environment



a

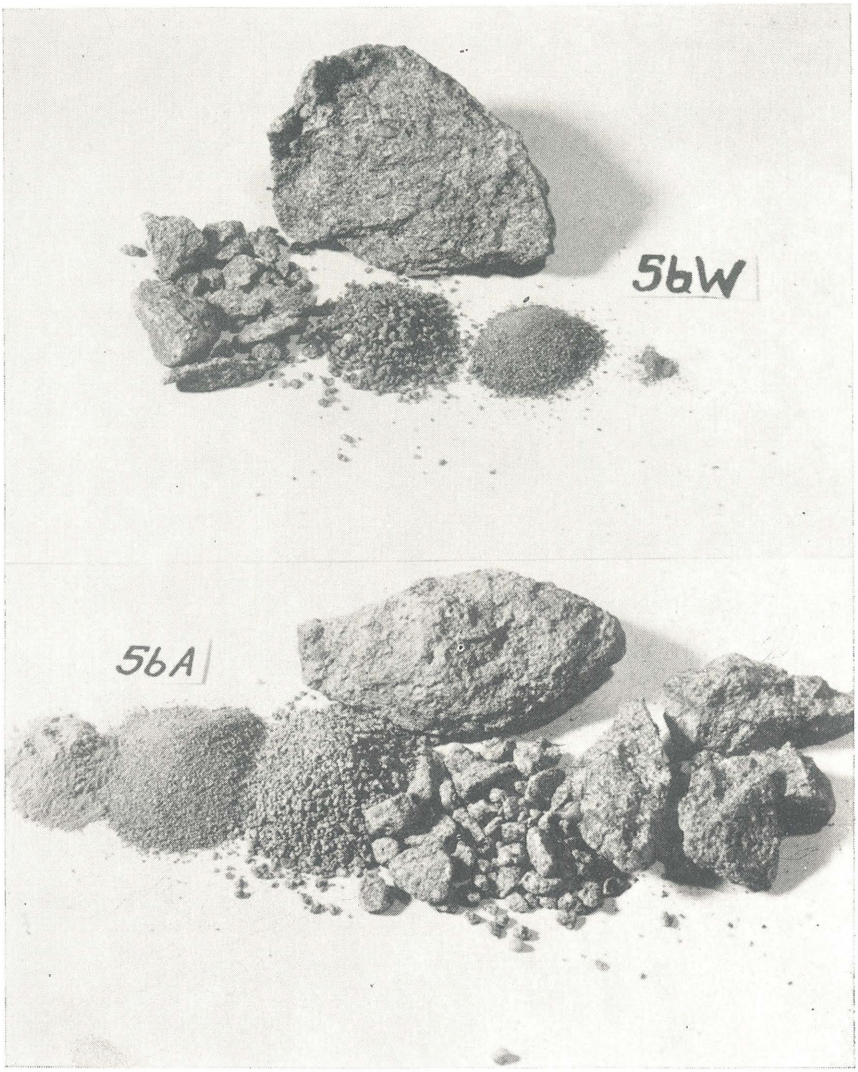
b

Pl. 3. Porphyraceous granite from a kettle (*kociołek*), Szklarska Poręba

a — sample in humid environment; b — sample in water environment

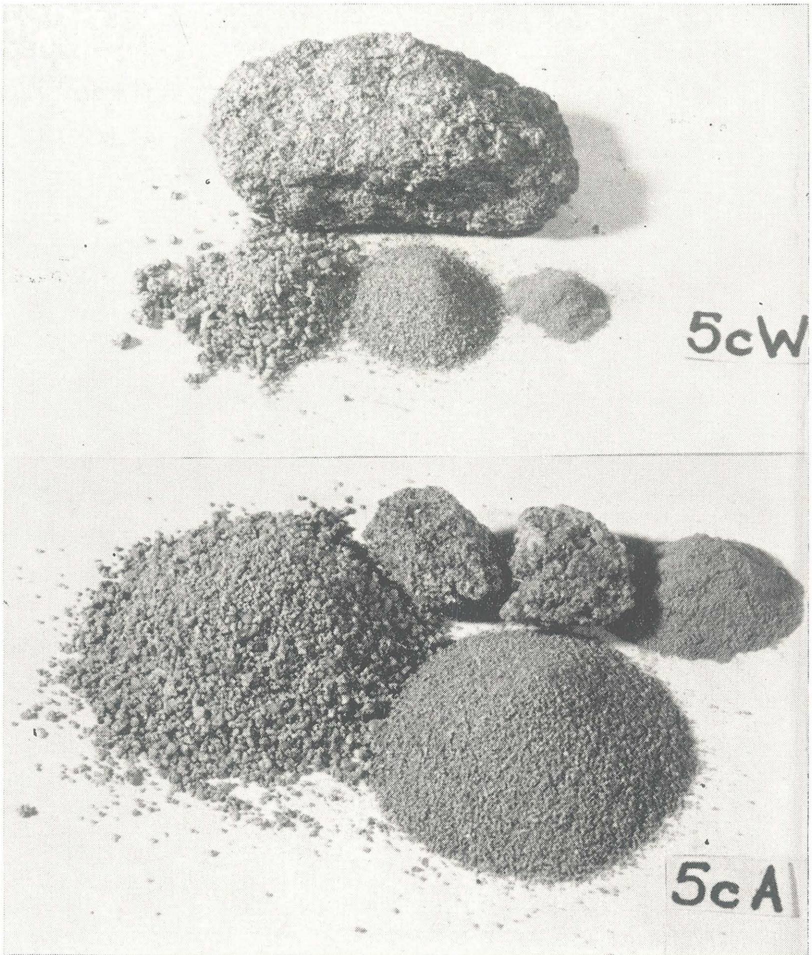
a

b



Pl. 4. Cretaceous sandstone from the waste cover bottom, Stromiec, near Jelenia Góra

a — sample in humid environment; b — sample in water environment

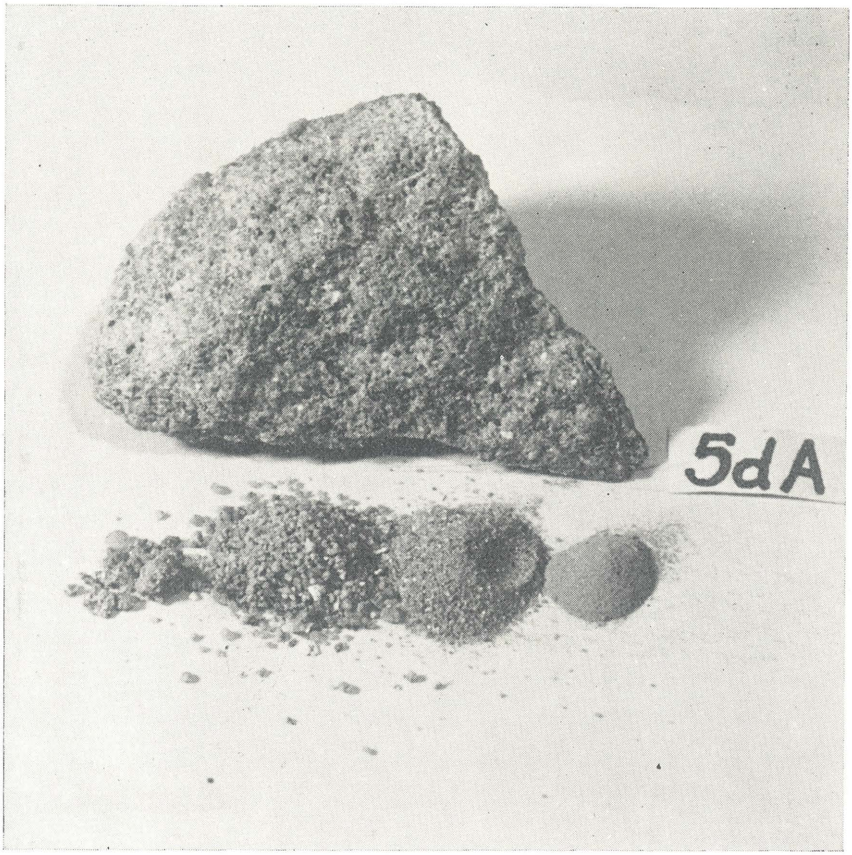


a

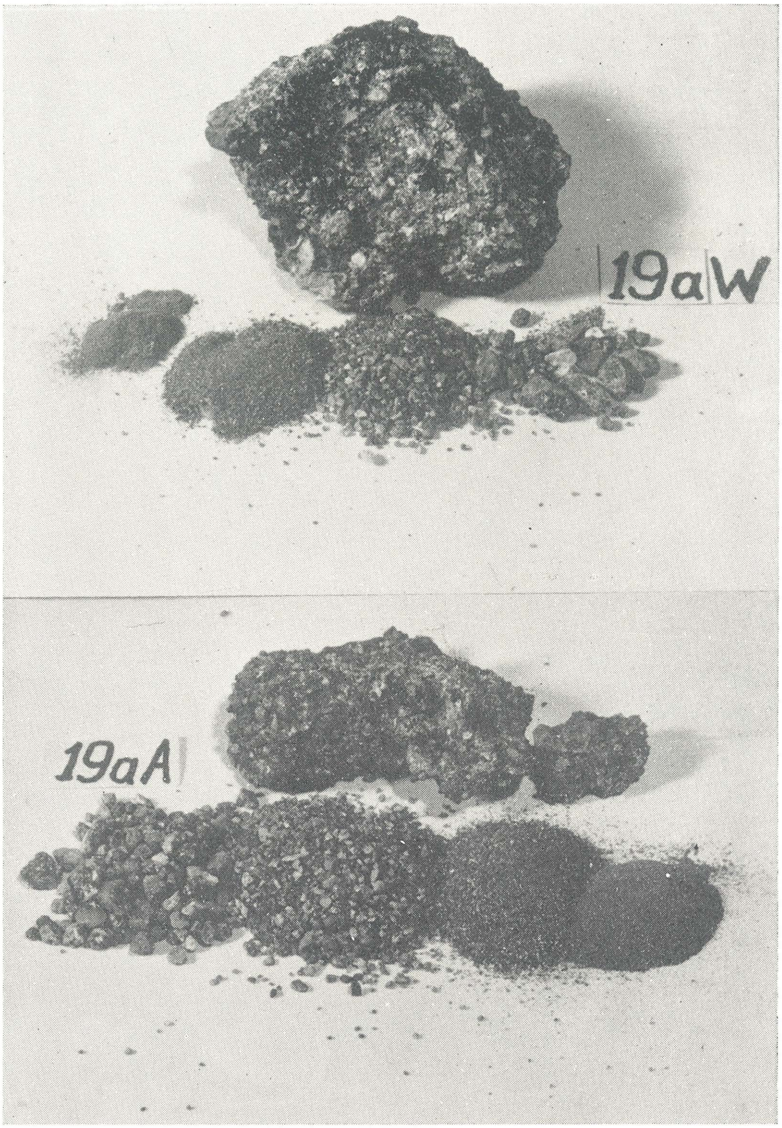
b

Pl. 5. Cretaceous sandstone from the pseudokarst bed, Stromiec, near Jelenia Góra

a — sample in humid environment; b — sample in water environment



Pl. 6. Fresh Cretaceous sandstone from a quarry, Stromiec, near Jelenia Góra. Sample in water environment

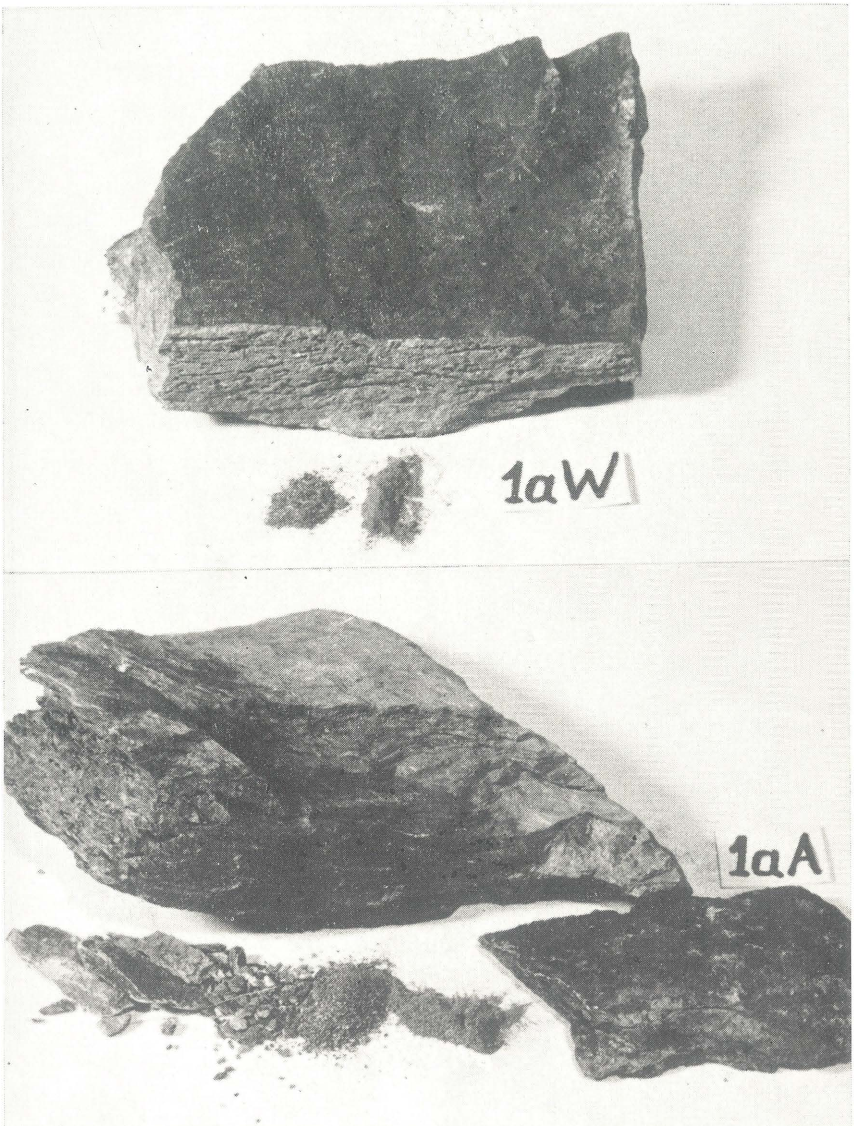


a

b

Pl. 7. Conglomerate-like sandstone (Permian) from the waste cover. Vicinity of Złotoryja

a — sample in humid environment; b — sample in water environment

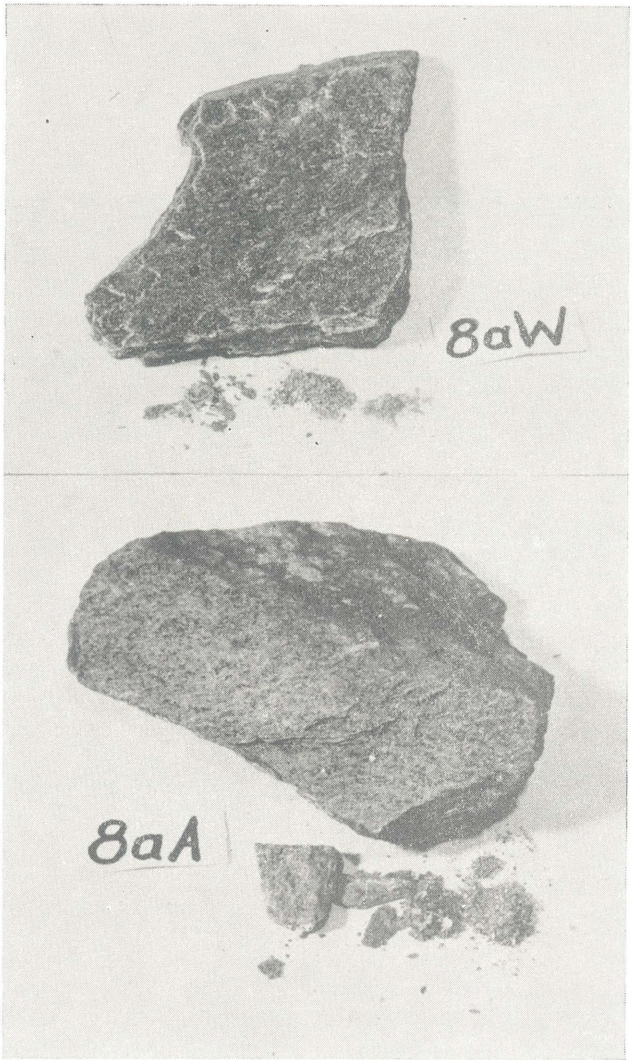


a

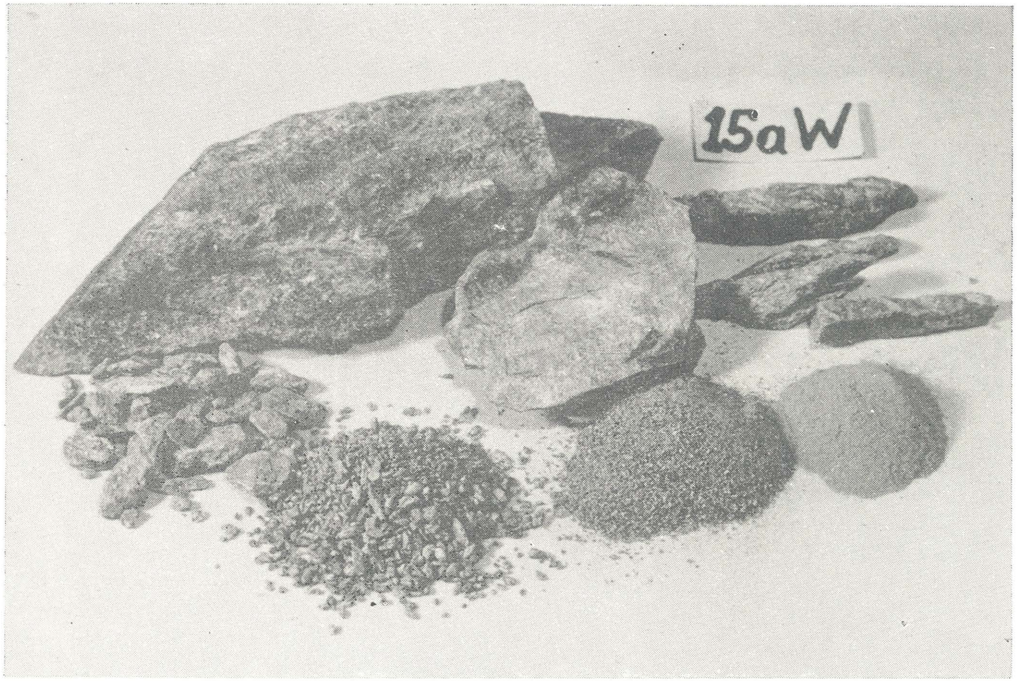
b

Pl. 8. Green schist from the waste cover. Vicinity of Dobromierz and Bolków

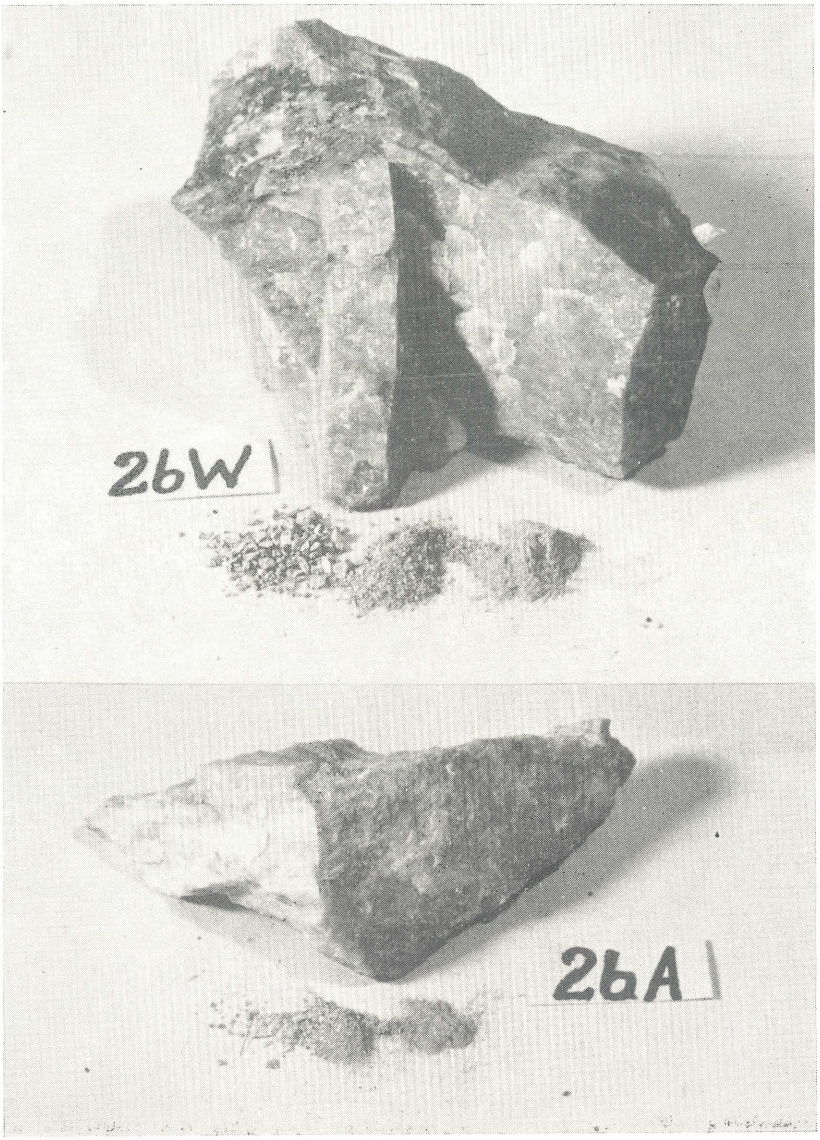
a — sample in humid environment; b — sample in water environment



Pl. 9. Mica-chlorite-quartz schist, sample from the waste cover. Stone quarry at Krobica, vicinity of Świeradów



Pl. 10. Mica schist taken at the contact with the vein of hydrothermal quartz; sample from the waste cover. Stone quarry at Rozdroże Izerskie. Sample in water environment

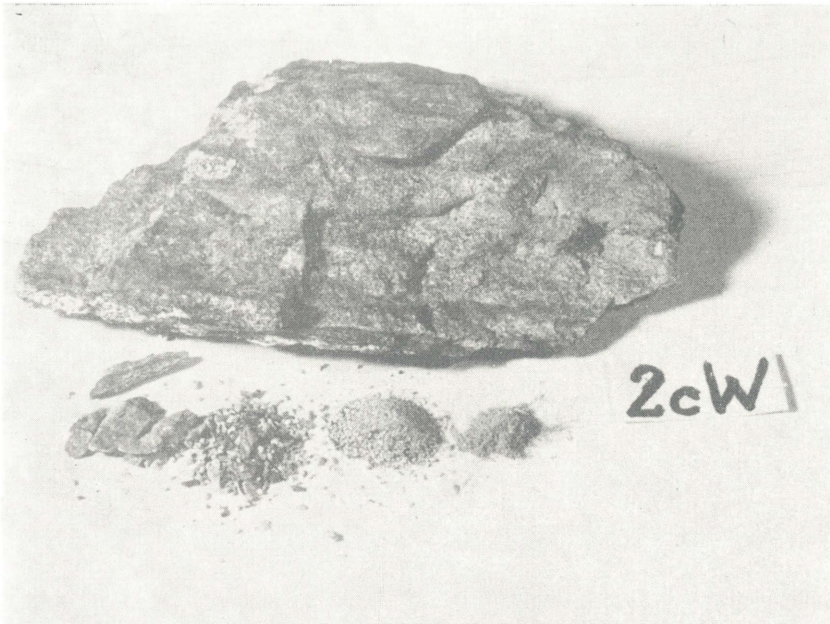


a

b

Pl. 11. Crystalline limestone, sample from the waste cover. Stone quarry at the Miłek, Wojcieszów

a — sample in humid environment; b — sample in water environment

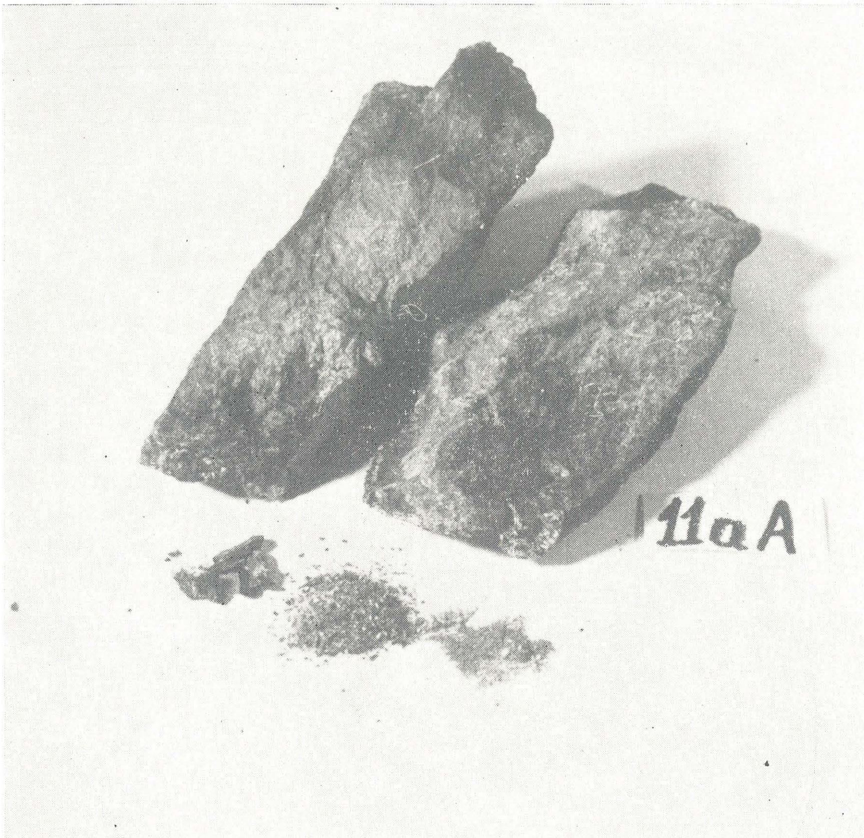


a

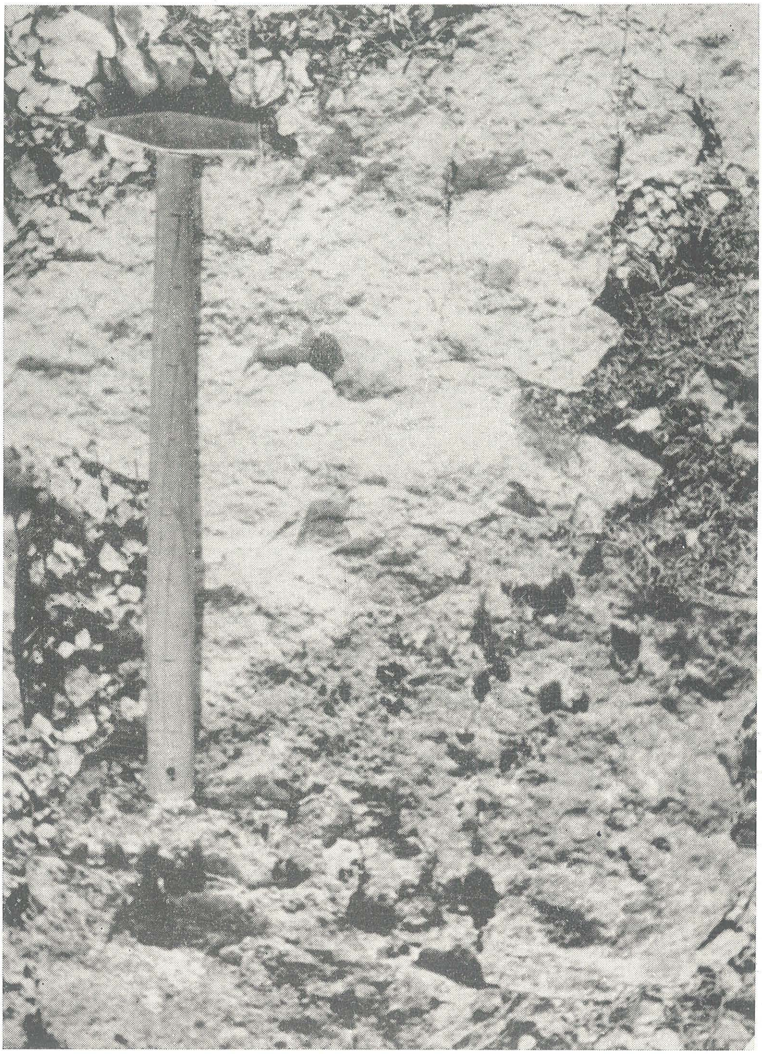
b

Pl. 12. Calcareous (crystalline) schists, sample from the waste cover. Stone quarry at Miłek, Wojcieszów

a — sample in humid environment; b — sample in water environment



Pl. 13. Banded (biotite) gneiss, sample from the waste cover. Izera Mts., near the „Death's bend". Sample in water environment



Pl. 14. Example of influence of chemical weathering upon the development of frost cracks — Eocene limestone from the Lejowa Valley, Western Tatra Mts.

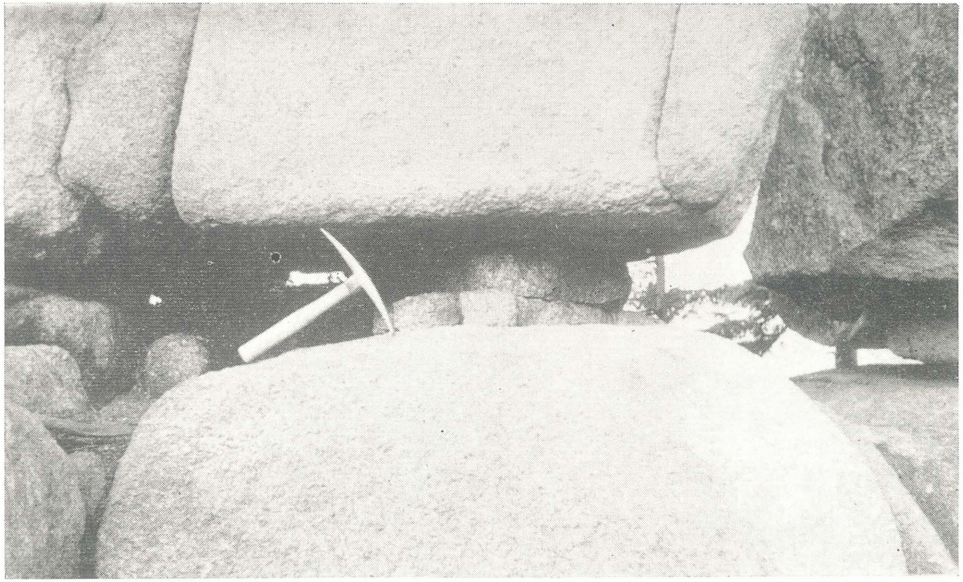


Photo. by B. Dumanowski

Pl. 15. Example of an intense frost weathering at the place of convergent system of horizontal joints L on porphyraceous granite. Skałka Wiaterna on the Sucha Mt. in the Karkonosze Mts.

Pl. 16. Granular microgelivation in a hollow of „star type" at the place of crossing of several cracks. Variously grained granite. Zadni Staw Kettle in the Pięć Stawów Polskich Valley, High Tatras

Pl. 17. Block macrogelivation along the joints of granite. Pięć Stawów Polskich Valley, High Tatras