

FORMATION OF HALLOYSITE FROM FELDSPAR: LOW TEMPERATURE, ARTIFICIAL WEATHERING VERSUS NATURAL WEATHERING

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Abstract—Weathering products formed on surfaces of both potassium and plagioclase feldspar (An_{70}), which were continuously leached in a Soxhlet extraction apparatus for 140 days with 7:2:1 of distilled water per day at a temperature of approximately 78°C, are morphologically identical to natural products developed on potassium feldspars weathered under conditions of good drainage in the humid tropics. The new products, which first appear as tiny bumps on the feldspar surface, start to develop mainly at exposed edges but also at apparently random sites on flat cleavage surfaces. As weathering continues, the bumps grow outward from the feldspar surface to form tapered projections, which then develop into wide-based thin films or sheets. The thin sheets of many projections merge laterally to form one continuous flame-shaped sheet. The sheets formed on potassium feldspars may then roll to form tubes that are inclined at a high angle to the feldspar surface. Etch pits of triangular outline on the artificially weathered potassium feldspars serve as sites for development of continuous, non-rolled, hollow tubes. It is inferred from its morphology that this weathering product is halloysite or its primitive form. The product of naturally weathered potassium feldspars is halloysite $\cdot 4H_2O$.

The flame-shaped films or sheets formed on artificially weathered plagioclase feldspar do not develop into hollow tubes, but instead give rise to a platy mineral that is most probably boehmite. These plates form within the flame-shaped films, and with continued weathering are released as the film deteriorates. There is no indication from this experiment that platy pseudo-hexagonal kaolinite forms from any of these minerals under the initial stage of weathering.

INTRODUCTION

SOME form of the general statement . . . “Kaolinite is the clay mineral formed from the chemical weathering of potassium feldspar” . . . is commonly found in introductory textbooks of geology and frequently in more advanced ones. Examples in the geological record of chemically weathered rocks often show that kaolinite is in fact abundant as an apparent alteration product. However, studies of clay mineral products developed or developing at present from chemical weathering of various rock types suggest instead that halloysite is more commonly the alteration product. Over the past 10 yr, published studies on various clay minerals formed as weathering products have increased substantially in number. In addition, techniques of clay mineral identification have steadily improved and now allow more ease and certainty in identifying and distinguishing platy kaolinite from tubular halloysite. Whereas the petrographic microscope, D.T.A., or chemical analyses were used formerly as the sole method of identification of these minerals, more often today identification is made with a variety of tools and techniques, which include X-ray diffraction and electron microscopy. Emphasis in this study of weathering products has been placed on the use of the electron microscope.

In a summary of the literature on successful laboratory synthesis of kaolinite, Grim (1968) points out that because most of these mineral identifications were made by X-ray diffraction alone and were not made in conjunction with the electron microscope, there is no certainty that halloysite was not formed also. Other attempts to synthesize only halloysite have been unsuccessful based on X-ray diffraction analysis (Polzer, 1967; Roy and Brindley, 1956; Roy and Osborn, 1952; and Roy and Osborn, 1954), however De Kimpe *et al.* (1964) have synthesized a kaolin mineral that morphologically is much like halloysite. This present study shows that artificially weathered feldspars develop the same type of alteration products as are found on naturally weathered feldspars taken from humid tropical environments and, moreover, that the artificially produced weathering product may in fact be halloysite.

A survey of the literature on kaolin clay minerals formed during recent chemical weathering shows that halloysite is commonly the alteration product formed from parent rocks of widely differing compositions under varying climatic conditions. Other similar studies often are not specific as to whether halloysite or kaolinite has formed, and merely list the presence of kandite or kaolinite minerals.

Localities where halloysite has been identified as a modern weathering product are shown in Fig. 1, and the authors, geographic areas, and rock types studied are listed in Table 1. Table 2 is a tabulation of the various analytical techniques used to identify the clay minerals in each study. Only about 25

et al. (1963) partially agree, but believe that halloysite may form at times without allophane as the intermediate material.

It seems that there is considerable uncertainty in our understanding of the transition of mineral phases that take place when aluminosilicate

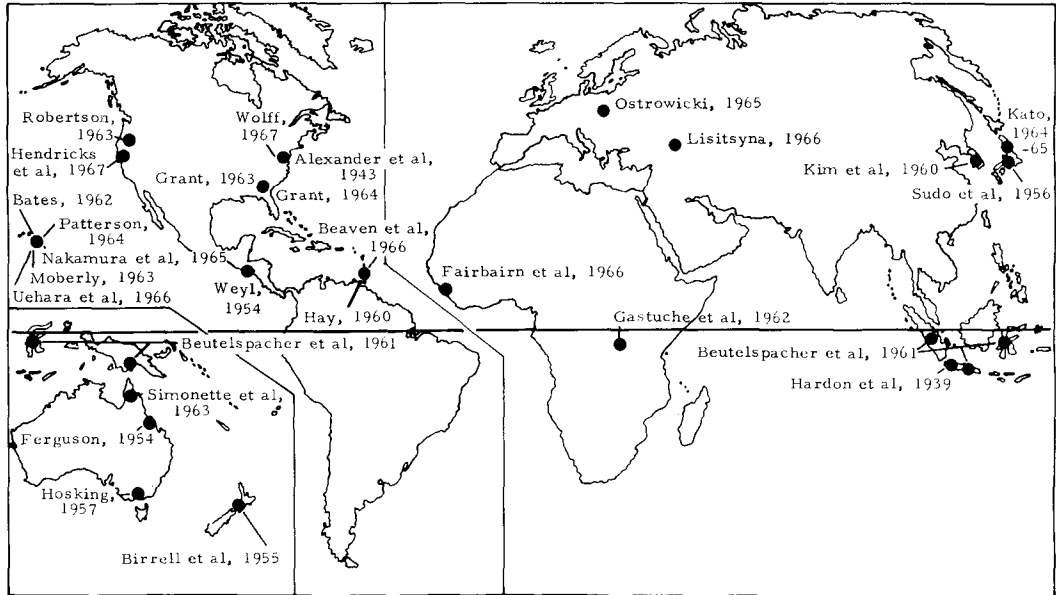


Fig. 1. Localities of studies of recent weathering in which halloysite has been identified.

per cent of these studies listed kaolinite as being present in the weathering products. Grim (1968) has commented that "Although the presence of halloysite in weathering products is well established, it is a rare component of such materials, and peculiar conditions must be required for its formation."

His view was understandable, as 50 per cent of those studies listed in Table 1 are not more than 4 yr old. Keller (1964) noted that "...aluminous silicates react with water to give rise... to... a clay mineral..." "Field occurrences show that the clay mineral formed is commonly either allophane or halloysite..." He further noted that "In our present stage of knowledge, it may be stated that K-feldspar alters to kaolinite via intermediary mica under certain conditions, but directly to kaolinite under others, and that it alters to halloysite (endellite) via a gel phase, possibly including transitory allophane." Sudo and Takahashi (1956) suggested, and Jackson (1959) seems to agree, that there may be a gradual transition in the products of chemical rock weathering from allophane to halloysite $\cdot 4\text{H}_2\text{O}$ to halloysite $\cdot 2\text{H}_2\text{O}$. Chukrov,

minerals decompose during chemical weathering to form new products, particularly tubular halloysite and platy kaolinite, and that the electron microscope may be a valuable tool when used to study the beginnings of decomposition of one mineral, i.e. feldspar, and the formation of its alteration products. Therefore, a study was begun to determine what surface alteration products form during natural weathering of feldspar in the humid tropics as well as what products form on feldspar surfaces under similar conditions in artificial weathering.

PROCEDURE

The products forming on feldspars in igneous rocks from Hong Kong were selected for the study of natural weathering (Table 4). Hong Kong, which adjoins the southernmost point of Kwantung Province, China, lies just within the northern limits of the tropics, has hot humid summers and somewhat cooler and drier winters, and an average annual rainfall of 85 in. Altitudes ranging from sea level to about 3000 ft within the Colony afford conditions of good drainage over much of the area.

Table 1. Studies on recent rock weathering in which halloysite has been identified

Study number	Authors	Date	Geographic area	Parent rock
1	Alexander, <i>et al.</i>	1943	Maryland, U.S.A.	gabbro, amphibolite
2	Birrell, <i>et al.</i>	1955	New Plymouth, New Zealand	volcanic ash
3	Sudo and Takahashi	1956	Japan	glassy tuff
4	Hay	1960	St. Vincent, B. W. I.	andesitic ash
5	Beutelspacher and van der Marel	1961	Java, Sumatra, Celebes, Papoealand	rhyolite, granite, basalt, serpentine
6	Bates	1962	Hawaii, U.S.A.	basalt
7	Gastuche, <i>et al.</i>	1962	Kivu, Republic of the Congo	basalt, volcanic ash
8	Robertson	1963	Oregon, U.S.A.	tuff or pumice
9	Simonette and Bauleke	1963	North Queensland, Australia	basalt
10	Patterson	1964	Hawaii, U.S.A.	basalt
11	Kato	1964-65	Shinshiro City, Japan	granodiorite
12	Nakamura and Sherman	1965	Hawaii, U.S.A.	basalt
13	Fairbairn and Robertson	1966	Sierra Leone	kimberlite
14	Hendricks, <i>et al.</i>	1967	Northeast California, U.S.A.	andesite
15	Wolff	1967	Maryland, U.S.A.	quartz monzonite
16	Ferguson	1954	Queensland, Australia	basalt
17	Weyl	1954	El Salvador	dacitic ash
18	Hosking	1957	Australia	granite, basalt, sediments
19	Moberly	1963	Hawaii, U.S.A.	basalt
20	Grant	1964	Georgia, U.S.A.	biotite-plagioclase gneiss
21	Ostrowicki	1965	Poland	serpentinite
22	Beaven, and Dumbleton	1966	Trinidad, Jamaica, Grenada, Barbados, B.W.I.	volcanics, meta-sediments
23	Uehara, <i>et al.</i>	1966	Hawaii, U.S.A.	pahoehoe lava
24	Grant	1963	Georgia, U.S.A.	granite
25	Lisitsyna	1966	Batumi, U.S.S.R.	labradorite-augite porphyry
26	Hardon and Faveje	1939	Java	andesitic tuff
27	Kim and Kim	1964	Kyongsang Namdo, Korea	anorthosite

The effect of climate coupled with conditions of good drainage have resulted in deep chemical weathering of a considerable part of the predominantly igneous bedrock. Halloysite · 4H₂O seems to be the most common clay mineral formed in the weathering products of a variety of rock types in Hong Kong. Clay mineral data on weathering products of this region will be published in another study.

Soxhlet extraction units (Fig. 2) were used in the artificial weathering of a potassium feldspar (microcline) and a plagioclase (An₇₀) feldspar (Table 3). The technique is that first used by Pedro (1961) in similar leaching studies. Distilled water in the distilling flask was maintained at its boiling point by a heating mantle. Condensation was achieved by the water-cooled condenser at the top of the apparatus from where the water fell onto the feldspar below. The water level in the chamber containing the feldspar would rise to the level of the top of the siphoning tube and then would drain back into the distilling flask and the cycle would be repeated. The temperature of the water leaching

the feldspars was approximately 77–78°C, and the pH was about 6.5. Approximately 7 l of water flowed over each sample per day, and leaching of both feldspars was continued for 140 days. The feldspars were broken into pieces of approximately $\frac{1}{2}$ – $\frac{3}{4}$ in diameter so that alteration products that might form could be related to specific cleavage surfaces.

The artificial weathering conditions used in the laboratory parallel the natural weathering conditions in Hong Kong, i.e. a hot, humid environment with high rainfall and good drainage; however, for a given period of time the amount of artificial rainfall far exceeds the amount of natural rainfall. Pedro (1961) has pointed out that the absolute humidity maintained in the Soxhlet apparatus is so high that the amounts of dissolved gases, i.e. oxygen, and carbon dioxide, are much lower in the extractor than in normal rainfall. In addition, the temperature of the artificial rainfall is considerably above natural rainfall. Nevertheless, it should be noted that temperatures that have been recorded in the top few centimeters of soils in the humid tropics approach

Table 2. Analytical techniques used in the identification of halloysite for studies listed in Table 1

Study number	Electron microscope	X-ray	D.T.A.	Petrographic microscope	Chemical techniques
1*	X	X		X	X
2	X	X			X
3	X	X	X		
4	X	X	X		
5	X	X			
6	X	X	X	X	
7*	X	X		X	X
8	X	X	X	X	X
9*	X	X	X		X
10	X	X	X	X	
11*	X	X	X	X(i.r.)	X
12	X	X	X	X	X
13*	X	X	X		X
14	X	X	X		X
15	X	X			X
16*		X	X		
17		X		X	X
18*		X	X		X
19		X			
20*		X	X	X	
21		X	X	X	X
22		X			
23		X	X	X	X
24			X	X	
25				?	X
26	(Identification techniques not known)				
27	(Identification techniques not known)				

*= Kaolinite present.

i.r. = Infrared.

those used in this artificial weathering study. Surface and very near surface soil temperatures at Poona, India have reached 75°C and similarly, temperatures in the range of 84–86°C have been recorded in soils of the Congo and East Africa (Mohr, and van Baren, 1954), and 80°C in the Republic of the Sudan (Carlisle, 1968). Although these soil temperatures represent extremes, they do place the artificial temperature conditions within the limits of naturally existing ones.

Surface replicas of the various cleavage surfaces of the K-feldspar and plagioclase feldspar were prepared with replica tape, shadowed with platinum-palladium and back with a carbon film for examination with the Phillips 100-B electron microscope at the end of the leaching period. The replica tape was dissolved with acetone and the replica was treated with hydrofluoric acid for about 15 min to remove any adhering mineral matter.

ARTIFICIAL AND NATURAL WEATHERING EFFECTS ON FELDSPAR

A comparison of the morphology of artificially

produced weathering products developed on K-feldspar surfaces with those formed naturally shows both products to be essentially the same. Moreover, the evolution in the formation of the weathering products in both instances is remarkably similar. The morphology of the end product produced artificially from the weathering of K-feldspar appears to be the clay mineral halloysite, whereas the mineral formed from plagioclase (An₇₀) feldspar is most probably boehmite.

Continual percolation of hot, distilled water through each Soxhlet extractor chamber containing the feldspar fragments quickly produced visible changes in the color of the water within the distilling flask as well as altering the color of some surfaces of the feldspar fragments themselves. Dissolved material carried downward into the distilling flask from the plagioclase feldspar gave the water a slightly milky color after 4 days, and with increased leaching time the milky color became more pronounced. Water from the K-feldspar, on the other hand, developed a slight cloudiness after 14 days and maintained the same cloudiness to the end of

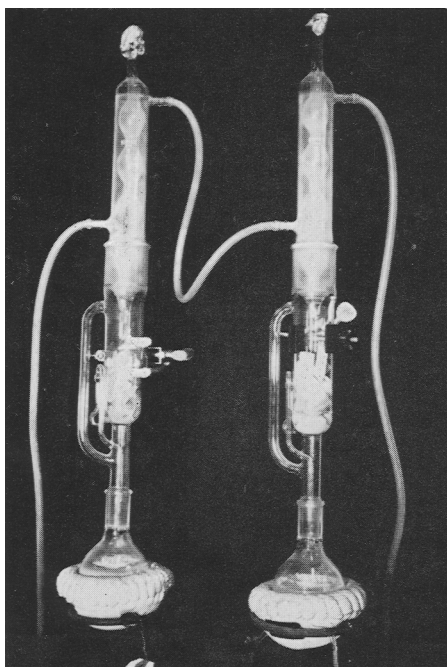


Fig. 2. Soxhlet extraction apparatus for leaching feldspars with distilled water.

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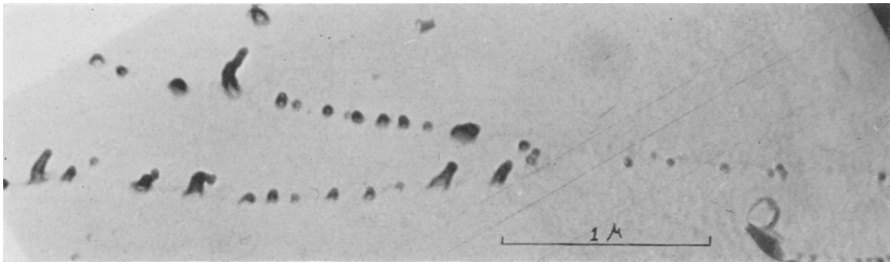


Fig. 3A. Replica of naturally weathered K-feldspar surface showing initial weathering products in form of small bumps and tapered projections. Joining of the lines of alteration products suggest influence of crystal dislocation at site of formation. Sample DWB-3.

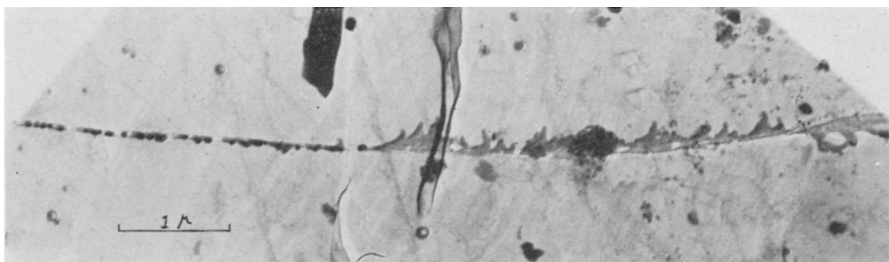


Fig. 3B. Replica of artificially weathered K-feldspar showing alteration product as line of small bumps grading laterally into flame-shaped sheet.

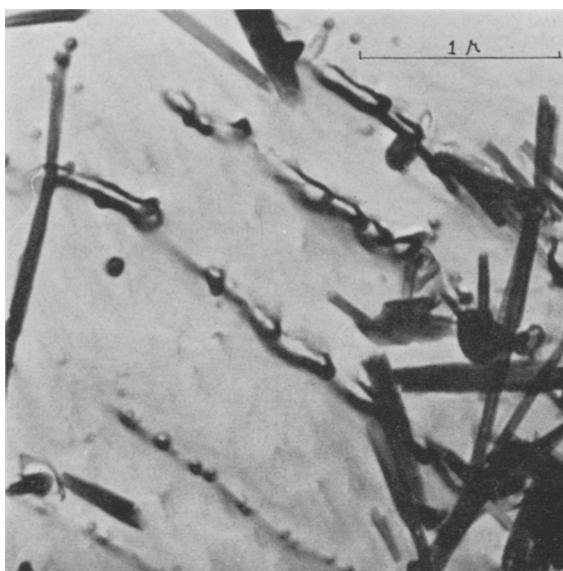


Fig. 4A. Replica of a naturally weathered K-feldspar surface showing an alteration product developing as rows of overlapping tapered projections. Sample DWB-3.

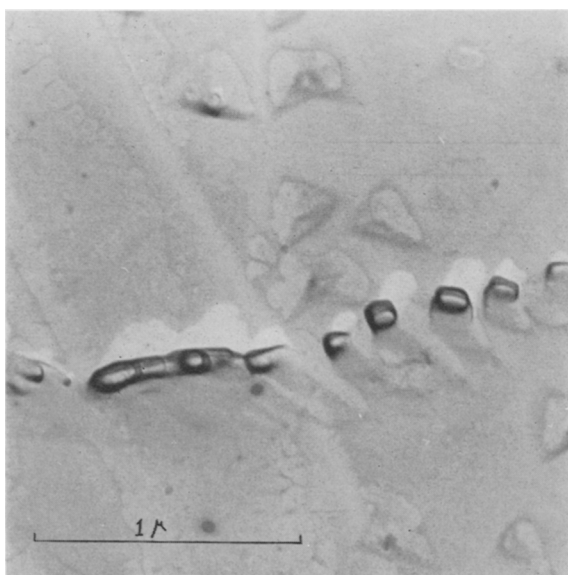


Fig. 4B. Replica of an artificially weathered K-feldspar surface showing development of non-rolled tubes. Line of tubes in right half appears to be based on etch pits like those in upper half of photograph and those in lower right quarter. Tubes are tilted and overlap one another in left half of photograph.

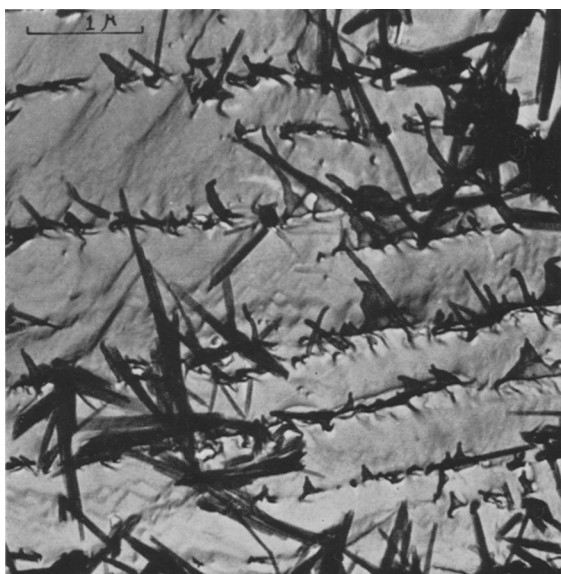


Fig. 5A. Replica of a naturally weathered K-feldspar surface showing rows of tapered projections, many with wide, sheet-like bases. Sample DWB-3.

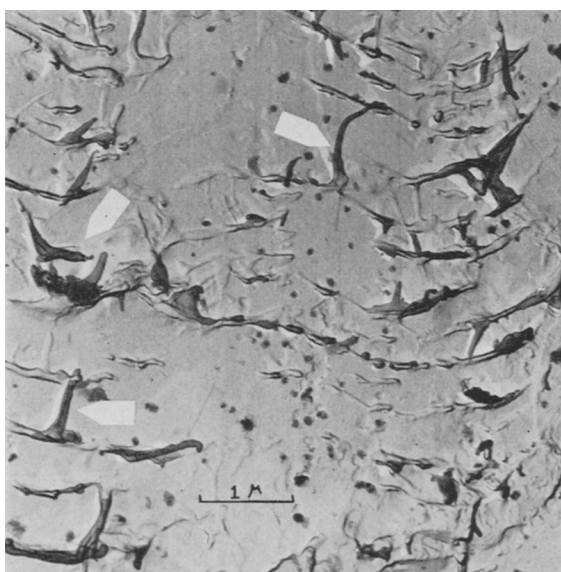


Fig. 5B. Replica of an artificially weathered K-feldspar surface showing tapered projections, some with wide sheet-like bases. Arrows show tubes formed by rolling of the thin sheets.

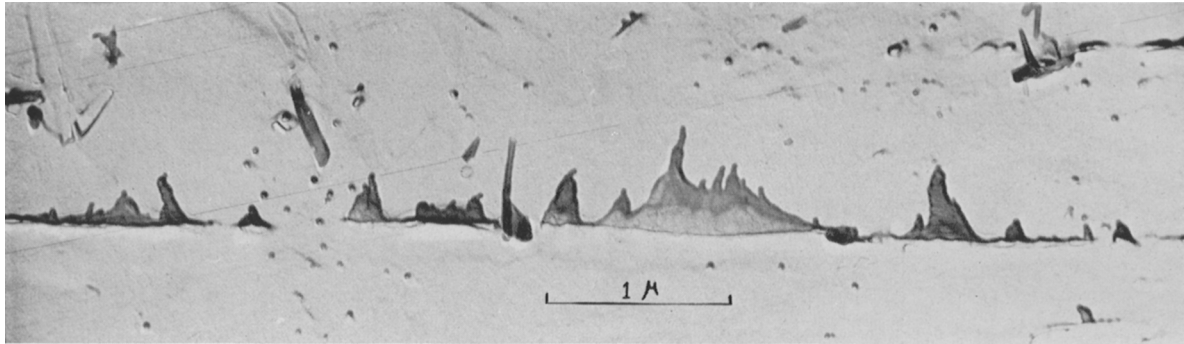


Fig. 6A. Replica of coalescing, wide-based tapered projections on a naturally weathered K-feldspar surface. Sample DWB-3.

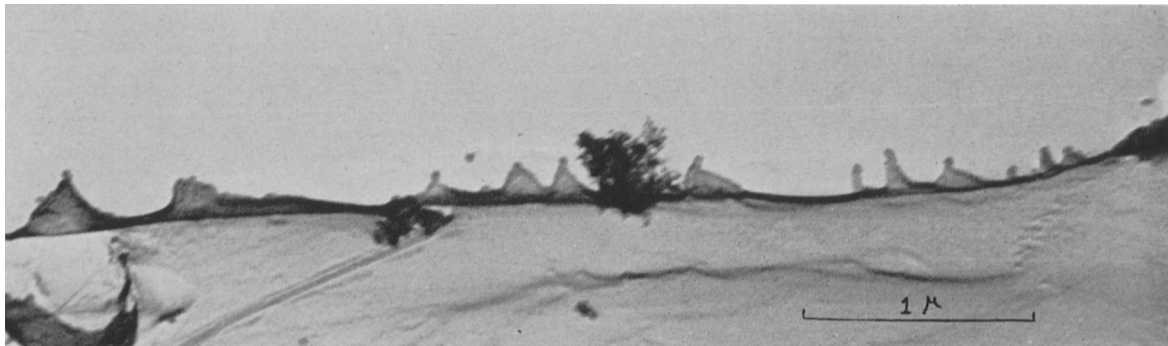


Fig. 6B. Replica of coalescing, wide-based tapered projections on an artificially weathered K-feldspar surface.

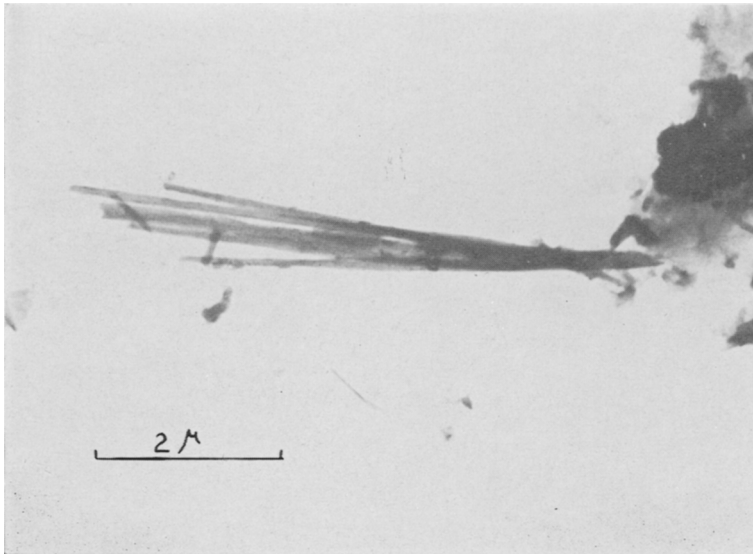


Fig. 7A. Transmission electron micrograph of a bundle of halloysite tubes from naturally weathered Hong Kong granite.

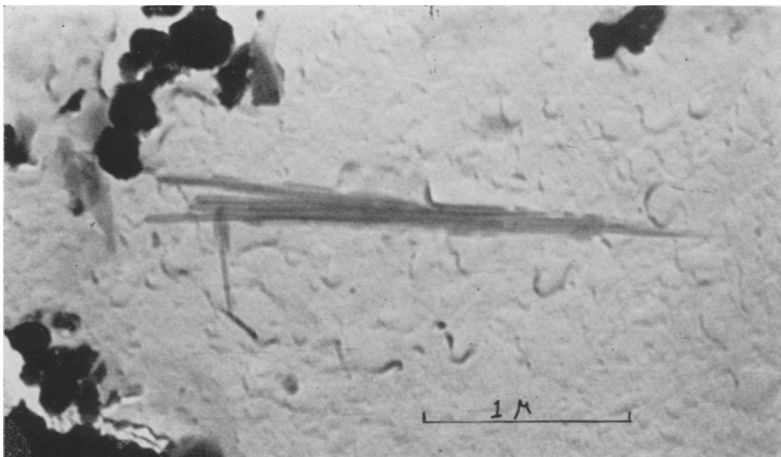


Fig. 7B. Replica of an artificially weathered K-feldspar surface showing a bundle of tube-like, alteration products, perhaps halloysite.

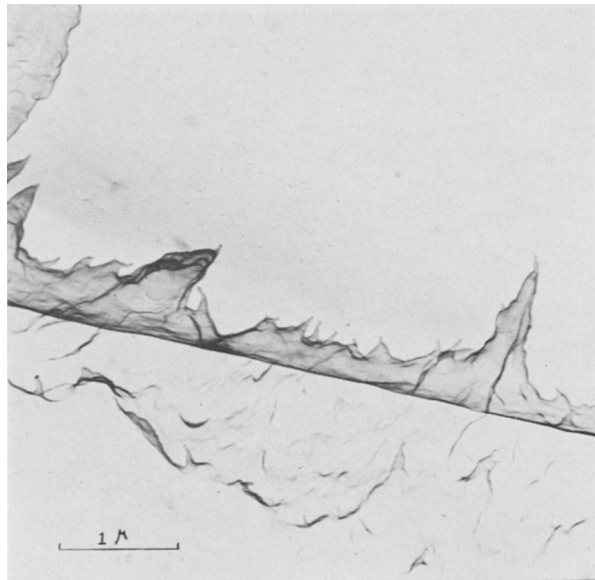


Fig. 8. Replica of an artificially weathered plagioclase (An₇₀) feldspar surface showing a well-developed, flame-shaped sheet with tapered projections as terminations.

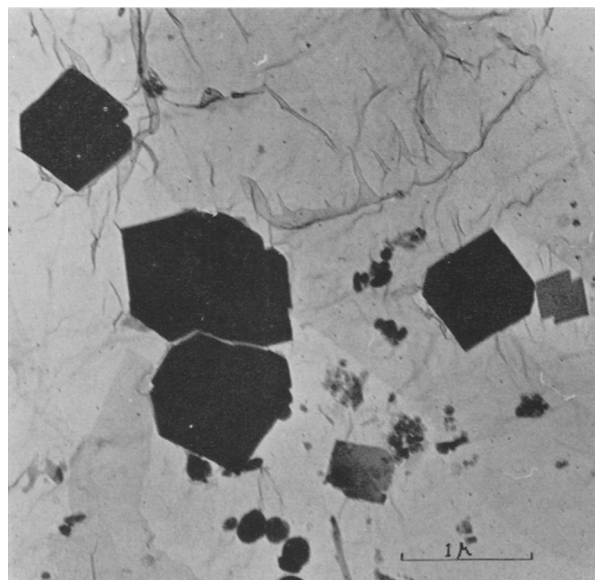


Fig. 9. Replica of an artificially weathered plagioclase (An₇₀) feldspar surface showing regularly formed, geometric plates, most probably boehmite.

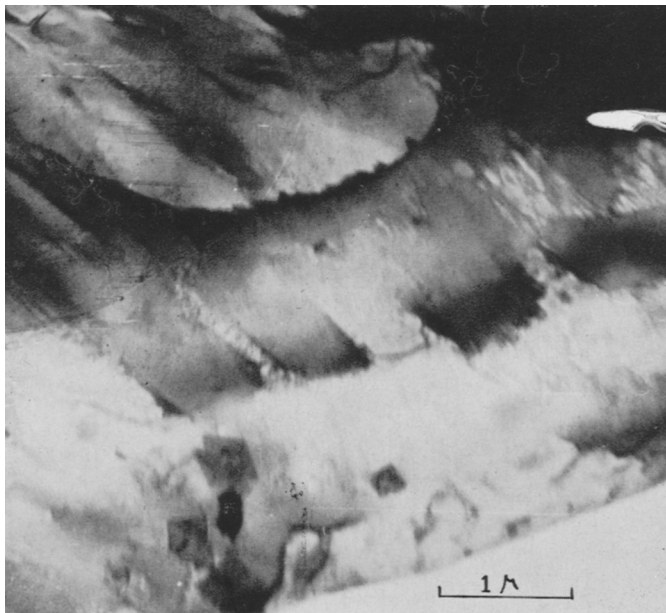


Fig. 10. Replica of saddle portion of a flame-shaped sheet formed from artificial weathering of plagioclase (An_{70}) feldspar. Note initial development of plates of regularly formed, geometric outline within sheet material and well-formed, smaller plates below similar to those of Fig. 9. Plates forming are most probably boehmite.

Table 3. Typical chemical analyses for feldspars used for this artificial weathering study

K-feldspar (microcline) from mine at Casper Mt., Casper, Wyoming. Chemical analysis obtained from F. F. Miller of International Minerals and Chemical Corporation, Custer, South Dakota.	
SiO ₂	64.4%
Al ₂ O ₃	19.6
Fe ₂ O ₃	0.04
CaO	0.1
Na ₂ O	3.0
K ₂ O	12.6
Ign.	0.2
	99.94%
Plagioclase feldspar (An ₇₀) from anorthosite outcrop along shore at Silver Bay, Minnesota, SE1/4 NE1/4 sec. 6, T. 55 N., R. 7 W. Sample number M-3190.	
SiO ₂	47.25%
Al ₂ O ₃	31.56
FeO	2.29
CaO	15.39
Na ₂ O	2.52
K ₂ O	0.37
MgO	0.27
H ₂ O ₊	0.40
H ₂ O ₋	
	100.05%

Table 4. Localities of naturally weathered K-feldspar samples

DWB-1	Orthoclase from syenite; surface of crystals weathered to depth of 1–2 mm; Mesozoic in age; roadcut in fresh syenite 1/4 mile SW of Wong Nai Chung Gap along Deep Water Bay Road, Hong Kong Island, Hong Kong, B.C.C., 114° 10' 20" E., 22° 15' 30" N.
DWB-3	Orthoclase from Hong Kong granite, partially weathered, slightly bleached, dull pale pink color; Upper Jurassic in age. Same locality as DWB-1.

the leaching experiment. A small portion of the milky liquid was removed from the plagioclase feldspar distilling flask after 119 days, dried and X-rayed. The material was amorphous to X-ray.

A rust-red discoloration appeared after 29 days on the (100) cleavage surface of the K-feldspar fragments in the uppermost zone of the chamber, i.e. the most well drained and aerated part of the leaching column. Electron microprobe analysis showed that the discoloration was caused by a very

small amount of iron on those surfaces. It seems that during the artificial weathering sufficient iron was able to migrate to the (100) cleavage surface of this K-feldspar to produce visible iron oxide stain, and that the staining of only one surface resulted from a differential rate of weathering with respect to the major cleavage surfaces. A white alteration product formed on the (001) and (010) cleavage surfaces but no iron oxide stain appeared here.

Surface alteration on the plagioclase feldspar was observed as a pale pink discoloration after 112 days of leaching. The pink alteration product was not restricted to a specific cleavage surface, as was the case for the K-feldspar, but instead seemed to form as coatings at random sites on all surfaces.

Electron micrographs in Figs. 3 through 7B display the most commonly observed forms of surface alteration products formed on naturally and artificially weathered K-feldspars. Figures 3A and 3B show the first stage in the natural and artificial weathering of K-feldspar. The first alteration product to form on the mineral's surface appears as lines of tiny bumps, as small as 0.01 μ in diameter. This initial product and all those described subsequently form at a variety of sites on feldspar surfaces. Formation of these products may take place along apparent crystal dislocations (Fig. 3A), at the intersection of cleavage planes, along etch pits, on any irregularity on the mineral's surface, and at apparently random sites on flat surfaces. The morphology of the alteration products is the same on all feldspar surfaces examined. The tiny bumps grow outward from the feldspar surface to form tapered projections (Fig. 3A) which may attain a micron in length. It is not evident in most instances whether the tapered projections are hollow or solid, though it seems that many are hollow. Figure 4B shows hollow tubes rising upward from the artificially weathered K-feldspar from bases that outline etch pits. Lengthening of the tubes is often accompanied by a tendency for them to tilt and overlap one another (Figs. 4A and 4B).

As the tapered projections continue to grow, they develop wide bases that are more sheet-like than tube-like in form (Figs. 5A and 5B). As the bases widen they coalesce to form a continuous flame-shaped film or sheet (Figs. 6A and 6B). Segments of the flame-shaped sheet may roll to form tubes that are inclined at a high angle to the feldspar surface (Fig. 5B, arrows). Thus it appears that the form of the alteration product may be either as rolled tubes (Fig. 5B, arrows) or as non-rolled hollow tubes (Fig. 4B).

Figure 7A shows a bundle of halloysite tubes

formed under natural weathering conditions from the Hong Kong granite, taken from a suspension of the clay fraction and mounted on a Formvar-covered electron microscope grid. This mineral was identified as halloysite $\cdot 4\text{H}_2\text{O}$ by X-ray diffraction. Figure 7B similarly shows a bundle of tubes formed during the artificial weathering of K-feldspar. This alteration product has not been identified by X-ray because of the small amount present. Nevertheless, from the general form of the bundle of tubes the alteration product is inferred to be halloysite or its primitive form.

The outer weathered surfaces of orthoclase crystals in syenite (sample DWB-1), exposed in a near vertical face along a road cut through fresh rock, show the same form of alteration products as the other K-feldspars. The syenite rock surface was bare of soil and plant material where the feldspars were sampled. The south-facing cut was exposed to the sun and subject to rainfall and surface rainwash. The obvious depth of weathering penetrated only 1–2 mm into the exposed feldspars. Although the roadcut is slightly less than 5 yr old, the various forms of weathering products described thus far are already well developed here. It would be interesting to know the minimum time needed for formation of similar surface alteration products in the tropics and in temperate areas as well.

Artificial weathering products formed on the

plagioclase feldspar developed into much the same forms as those on K-feldspar. Long flame-shaped sheets formed on the plagioclase feldspar (Fig. 8), but no hollow tubes nor well defined rolled tubes were seen. Although this sample of plagioclase feldspar has an unweathered appearance in hand specimen, it was noted in replicas of cleavage surfaces prior to leaching that trace amounts of flame-shaped sheets were already present and that scattered tiny bumps could be seen in small areas. After the leaching period, there was a pronounced increase in the amount of flame-shaped sheet material covering the feldspar's surface. Moreover, there was now one additional product not present at the start. Scattered over the plagioclase feldspar surfaces were areas containing prominent flakes of regular geometric form (Fig. 9), the diameters of which range from 0.25 to 1.25 μ . X-ray diffraction data shows the mineral to be most probably boehmite (Table 5). An artificial weathering study on kaolinite by Pedro and Berrier (1966) using a Soxhlet apparatus, showed by X-ray diffraction that kaolinite was partially converted to boehmite and not gibbsite after prolonged leaching. Based on conditions of minimal temperature and pressure under which boehmite could form (Kennedy, 1959) and on the X-ray reflections from the artificially weathered feldspar it would seem likely that the regularly shaped platy weathering

Table 5. X-ray reflections for plagioclase feldspar (An_{70}) before and after 107 days of artificial weathering, and newly developed reflections of boehmite

Fresh feldspar			Weathered feldspar		Weathering product-boehmite	
\AA	hkl and I est.	I est.	\AA	hkl and I est.		
6.56	$\bar{1}\bar{1}0$ <i>m</i>	<i>w</i>	6.11	020 <i>m</i>		
4.69	021 <i>w</i>	<i>w</i>	2.35	041, 130 <i>w</i>		
4.04	$20\bar{1}$ <i>m</i>	<i>m</i>				
3.92	$\bar{1}\bar{1}1$ <i>w</i>	<i>w</i>				
3.77	$\bar{1}\bar{3}0$ <i>m</i>	<i>m</i>				
3.65	$1\bar{3}\bar{1}$ <i>m</i>	<i>w</i>				
3.47	$11\bar{2}$ <i>w</i>	<i>w</i>				
3.38	$\bar{1}\bar{1}2$ <i>m</i>	<i>m</i>				
3.26	(?) <i>m</i>	<i>w</i>				
3.20	040 <i>s</i>	<i>s</i>				
3.17	002 <i>s</i>	<i>s</i>				
3.14	220 <i>s</i>	<i>w</i> (?)				
3.05	$\bar{1}\bar{3}\bar{1}$ <i>w</i>	<i>w</i>				
2.94	041 <i>m</i>	<i>w</i>				
2.84	131 <i>m</i>	<i>w</i>				
2.52	$\bar{2}41, \bar{1}\bar{1}2$ <i>m</i>	<i>w</i>				
2.39	310, 150 <i>m</i>	—				
2.23	$\bar{2}44$ <i>m</i>	<i>w</i>				

Estimated intensity (I est.) of X-ray reflections. s = strong, m = medium, w = weak.

product formed on the plagioclase feldspar surface is boehmite.

The boehmite crystals form within the flame-shaped sheets (Fig. 10), from which they are ultimately released. Considering the somewhat ragged outline of flakes within the sheet in Fig. 10, it might seem that they undergo some further growth after their release. No naturally weathered plagioclase (An_{70}) feldspars have yet been studied for comparison purposes.

DISCUSSION

Comparison in this study of artificially and naturally produced surface weathering products on feldspars suggests that the products, whether formed in an artificial or natural weathering environment, evolve in a similar way. Further, halloysite and boehmite seem to be the new mineral phases produced under these artificial weathering conditions and that their formation is in part related to the chemical composition of the parent feldspars. What the detailed nature of the transition phases that exist between unaltered feldspar and either halloysite or boehmite are, is not known at present. Speculation based on their morphological aspects and from the literature suggest that these intermediate forms might be classed as allophane.

The composition of the flame-shaped sheets shown in Figs. 6A, 6B, 8, and 10 is not known. Published electron micrographs of allophane (Beutelspacher and van der Marel, 1968), (Grim, 1968) are dissimilar to the flame-shaped sheets and other weathering products formed on either feldspar type. On the other hand, Yoshinaga *et al.* (1968) have shown electron micrographs of soil allophane exhibiting a certain degree of structural order that corresponds in form to the tapered projections formed on both artificially weathered feldspars. Perhaps, as suggested by Sudo and Takahashi (1956), Jackson (1959), and Keller (1964), during rock weathering minerals such as feldspar alter first to allophane and then to halloysite- $4H_2O$. The results of leaching experiments similar to this one (Pedro, and Berrier, 1966; Pickering, 1962) suggest that the flame-shaped sheets formed on the K-feldspar would have a chemical composition approximating allophane or halloysite.

Low temperature studies on the alteration of K-feldspar in solutions of varied pH (Wollast, 1967) indicate that kaolinite will form only if the leaching solutions contain silica in excess of about 5 ppm. It is assumed that this concentration of silica would be necessary also for the formation of halloysite. When the silica content falls below this level (about 5 ppm), formation of various hydrous aluminum

oxides should take place instead. Pickering (1962) speculated that "In well-drained soils in areas of high rainfall the groundwater is probably undersaturated with many of the chemical products of weathering." This artificial weathering study simulated conditions of good drainage in combination with high rainfall. It is likely that the solutions leaching the plagioclase feldspar may be undersaturated with respect to silica, thus inhibiting formation of halloysite but instead favoring formation of boehmite. The SiO_2/Al_2O_3 ratio for the original plagioclase (An_{70}) feldspar was 1.5/1, whereas the ratio in the K-feldspar was 3.3/1. The variation in silica content of the two feldspars coupled with their different end products of weathering also suggests that the K-feldspar silica content is sufficiently high to maintain a silica concentration in the leaching solution above Wollast's (1967) figure of about 5 ppm, and thus allow halloysite to form as the stable alteration product whereas at the same time halloysite would not form from the plagioclase (An_{70}) feldspar.

Pickering's (1962) experiments further indicated that within the normal natural weathering temperature range of 0–35°C, dissolution reactions in silicate rocks are essentially the same, indicating to him that chemical weathering processes are no different in the tropics than in cooler climates. The warmer temperatures of the tropics would have the effect merely of speeding up the dissolution process. Replicas of surface alteration products formed from feldspars weathered under varied climatic conditions have as yet not been examined with the electron microscope. Such information is needed for correlation with the results of Pickering (1962) and Wollast (1967).

Occurrences of halloysite in weathered materials within the geologic column seem to be less common with increasing age. The common occurrence of halloysite in modern weathering products suggests that the element of time is related to the presence of halloysite and that halloysite may change slowly with time to kaolinite. However, well preserved tubular halloysite is found with platy kaolinite in a weathered residuum of Jurassic or Cretaceous age developed from Precambrian granite-gneisses in Minnesota. In this case, at least, halloysite has been stable for a considerable period of geologic time. Moreover, kaolinite has often been reported in modern weathering products as well, further complicating understanding of the geologic relationship between the two minerals.

It seems however that certain of these problem areas can be eliminated with similar artificial weathering studies and with further examination of the weathering products with the electron microscope. The apparent latitude that exists in

establishing an artificial weathering environment that will produce like alteration forms to those formed naturally, coupled with a highly accelerated weathering rate offers a tool for removing the factor of geologic time from the study of certain aspects of rock weathering.

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Résumé—Les produits d'altération par les intempéries formés sur les surfaces du feldspath de potassium et de plagioclase (An_{70}), qui ont été lixiviés de manière continue dans un appareil d'extraction Soxhlet pendant 140 jours avec 7,21. d'eau distillée par jour à une température d'environ 78°C, sont morphologiquement identiques aux produits naturels développés sur des feldspaths de potassium altérés par les intempéries dans des conditions de bon drainage dans une région tropicale et humide. Les nouveaux produits qui apparaissent d'abord comme des protubérances de dimensions réduites à la surface du feldspath commencent à se développer surtout aux bords exposés mais également de manière apparemment aléatoire aux surfaces plates de fente. A mesure que l'altération continue, les protubérances se propagent vers l'extérieur à partir de la surface du feldspath afin de former des projections effilées, qui se développent ensuite en pellicules ou feuilles minces et à base large. Les feuilles minces d'un nombre élevé de projections se fondent alors dans le sens latéral afin de former une seule feuille continue en forme de flamme. Les feuilles formées sur les feldspaths de potassium peuvent alors s'enrouler pour former des tubes inclinés en angle élevé par rapport à la surface du feldspath. Des cavités de forme triangulaire sur le feldspath de potassium à altération artificielle servent en tant que centres pour le développement de tubes continus, non-roulés et creux. On suppose sur la base de sa morphologie que ce produit d'altération est le halloysite ou une forme primitive de celui-ci. Le produit du feldspath de potassium à altération naturelle est le halloysite $\cdot 4 H_2O$.

Les pellicules ou feuilles en forme de flamme formées sur le feldspath de plagioclase à altération artificielle ne se développent pas en tubes creux mais donnent lieu à un minéral sous forme de plaques, probablement le boehmite. Ces plaques se forment à l'intérieur des pellicules sous forme de flamme, et à mesure que l'altération continue, sont libérées quand la pellicule se dégrade. Cette expérience ne tend pas à démontrer la formation des formes de kaolinite pseudo-hexagonal sous forme de plaques à partir de ces minéraux lors du commencement de l'altération.

Kurzreferat—An den Oberflächen von Kalium- sowie von Plagioklasfeldspaten (An_{70}) gebildete Verwitterungsprodukte, die in einem Soxhlet Extraktionsapparat 140 Tage lang ununterbrochen mit 7,21. destilliertem Wasser pro Tag bei einer Temperatur von ca. 78°C ausgelaugt wurden, sind morphologisch identisch mit den Naturprodukten, die sich an Kaliumfeldspaten bilden, die in den feuchten Tropen unter guten Ablaufbedingungen, der Verwitterung ausgesetzt waren. Die neuen Produkte, die zunächst als winzige Höcker an der Oberfläche des Feldspates auftreten, entwickeln sich zuerst hauptsächlich an den exponierten Kanten aber auch in scheinbar regelloser Anordnung an flachen Spaltoberflächen. Bei fortschreitender Verwitterung wachsen die Höcker auswärts von der Feldspatoberfläche und bilden konische Ansätze, die sich später in dünne Filme oder Blättchen auf breiter Grundlage entwickeln. Die dünnen Blättchen zahlreicher Ansätze vereinigen sich seitlich und bilden ein kontinuierliches, flammenförmiges Blättchen. Die auf Kaliumfeldspaten gebildeten Blättchen können sich dann zusammenrollen und formen ein in einem steilen Winkel zur Feldspatoberfläche geneigtes Röhrchen. Ätzgrübchen mit dreieckigen Kontouren auf den künstlich verwitterten Kaliumfeldspaten dienen als Ansatzorte für die Entwicklung kontinuierlicher, nicht gerollter Hohlröhrchen. Aus der Morphologie wird geschlossen, dass es sich bei diesem Verwitterungsprodukt um Halloysit oder um die Primitiveform desselben handelt. Das Produkt des natürlich verwitterten Kaliumfeldspates ist Halloysit $\cdot 4H_2O$.

Die flammenförmigen Filme oder Blättchen auf künstlich verwittertem Plagioklasfeldspat bilden keine Hohlröhrchen, sondern ergeben anstatt dessen ein Plättchen, das höchstwahrscheinlich Boehmit ist. Diese Plättchen bilden sich innerhalb der flammenförmigen Filme und werden bei fortgesetzter

Verwitterung in dem Masse, in dem sich der Film zersetzt, freigegeben. Nach diesem Versuch bestehen keine Anzeichen für eine Bildung von pseudohexagonalem Kaolinit aus irgend einem dieser Minerale im Anfangsstadium der Verwitterung.

Резюме—Продукты, образовавшиеся на калиевом полевым шпате и плагиоклазе (Ap_{70}), которые подвергались выщелачиванию в экстракционном аппарате Сокслета в течение 140 дней (7,2 л. дистиллированной воды в день при температуре приблизительно $78^{\circ}C$), морфологически тождественны с природными продуктами, образующимися за счет калиевых полевых шпатов в условиях влажных тропиков. Новообразования преимущественно развиваются на обнаженных краях, а также на плоских поверхностях спайности. При продолжении выветривания бугорки растут, образуя конусообразные выступы, которые затем образуют тонкие пленки или листы. Тонкие листы с многочисленными выступами сливаются, переходя в один непрерывный лист. Листы, образовавшиеся на калиевых полевых шпатах, сворачиваются, возникают трубки. Судя по морфологическим особенностям продуктом изменения является галлуазит, возможно, в самой ранней стадии его существования. Продукт естественного выветривания полевых шпатов—галлуазит с $4H_2O$. Пленки или листы на искусственно измененных плагиоклазах не дают полых трубок; в этом случае, по-видимому, возникают пластинки бёмита. Проведенное исследование не дает оснований думать, что пластинчатый псевдогексагональный каолинит образуется из полевых шпатов в начальную стадию выветривания.