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MICROMORPHOLOGY OF A WEATHERED GRANITE NEAR THE RIA DE AROSA (NW SPAIN)

BY

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ABSTRACT

A detailed study has been made of several weathering profiles on the late-Hercynian Caldas de Reyes granite, NW-Spain. The field examination has been complemented by laboratory studies of large thin sections of hardened weathered material in conjunction with X-ray diffraction analyses.

Three groups of features have been investigated by these methods.

(a) *General structure of regoliths.* — They consist of a saprolite, mostly covered by colluvium. The latter can be distinguished from the saprolite by field methods, heavy mineral content and fabric analyses.

The saprolites generally display spheroidal weathering. Microfabric analyses showed that spheroidal weathering is conditioned by micro-crack systems. Weathering starts in the joints; it was found that water transport occurred along joint planes, even those of sizes which could not be detected with the naked eye. Reducing conditions could be deduced from the colour and mineral content along these fine channelways, but in later stages oxidizing conditions prevail. Oscillating groundwater has affected the formation of the secondary minerals along the joints, but not in the surrounding saprolite.

The soils formed on the regoliths are entic- and orthic haplumbrepts. The umbric epipedon may reach a thickness of 1 40 metres above an altitude of 250 metres.

(b) *Mineral transformations.* — Kaolinite and metahalloysite are the most common secondary minerals in weathered granites, metamorphic rocks and in an estuarine terrace. In one locality large red pleochroic secondary muscovite has been observed to form.

Gibbsite may also form in a highly alkaline environment and where water movement is very restricted in micro-cracks of weathered feldspars.

Secondary minerals (gibbsite and microcrystalline material) may form from plagioclase upon weathering, whereas the weathering products of microcline contain no secondary minerals.

Interlamellar crystallized kaolinite or metahalloysite between exfoliated biotite-vermiculite lamellae can be observed during the weathering of biotite. The interlamellar crystallization of kaolinite or metahalloysite is not apparent between exfoliated muscovite lamellae.

Minute droplets containing titanium, derived from the weathering of biotite crystals and their sagenite inclusions, are commonly found along the original cleavages of exfoliated biotite. Sometimes anatase has been observed to form out of these droplets.

(c) *Fabric analyses.* — Fabric analyses have been performed to the regoliths according to Brewer's (1964) method, but because it was applied to deeper saprolites his terminology had to be supplemented with various new terms. Certain fabrics (skelsepic plasmic fabrics) are common in colluvium but not in saprolites and neither in soils.

SAMENVATTING

Aan verschillende verweringsprofielen van de laat-Hercynische Caldas de Reyes graniet, NW-Spanje, werd een gedetailleerde studie verricht van de verweringsverschijnselen. Het veldonderzoek werd aangevuld met laboratorium-onderzoek van grote slijpplaten gemaakt van door plastic verhard verweerd materiaal, waarbij tevens diffractogrammen werden gebruikt. Drie groepen van verschijnselen werden met deze methoden onderzocht.

(a) *Algemene structuur van regolithen.* Zij bestaan uit een saproliet welke meestal bedekt wordt door colluvium. Dit colluvium kan van de saproliet onderscheiden worden door veldmethoden, zware mineralen inhoud en maaksel analyses.

Het verschijnsel van de sferoidale verwering komt vaak in de saprolieten voor. Micro-maaksel analyses toonden aan dat het verschijnsel van de sferoidale verwering gebonden is aan micro-barst systemen. De verwering begint in diaklazen. Vastgesteld werd dat watertransport reeds plaats kan vinden in diaklazen welke met het blote oog niet zichtbaar zijn. Reducerende omstandigheden in deze uiterst fijne kanaaltjes blijken uit de kleur en de mineraalsamenstelling van het verweerde materiaal in de kanaaltjes. In latere stadia van de verwering zijn de diaklazen meer open en prevaleren oxiderende omstandigheden. Het oscillerende grondwater heeft wel invloed op de vorming van secundaire mineralen in de diaklazen, maar niet op die van het omringende verweerde materiaal.

De bodems welke in de regolithen ontstaan zijn "entic"- en "orthic haplumbrepts". De "umbric epipedon" van deze bodems kan 1,40 m dik worden boven een hoogte van 250 m boven zeeniveau.

(b) *Mineraal-omzettingen.* Kaoliniet en metahalloysiet zijn de meest voorkomende secundaire mineralen in verweerde granieten, metamorfe gesteenten en in een estuarien terras. Op één plaats werd de vorming van grote rood-pleochroitische muscovieten geconstateerd.

Gibbsiet kan ook in een sterk alkalisch milieu gevormd worden en tevens daar waar bijna geen waterbeweging optreedt, nl. in micro-barsten van verweerde veldspaten.

Secundaire mineralen (gibbsiet en microkristallijn materiaal) kunnen bij de verwering ontstaan uit plagioklaas, terwijl bij de verwering van microklien geen secundaire mineralen geconstateerd werden.

Interlamellair gekristalliseerde kaoliniet of metahalloysiet tussen geëxfolieerde biotiet-vermiculiet-lamellen kan waargenomen worden bij de verwering van biotiet. Deze interlamellaire kristallisatie van kaoliniet of metahalloysiet is niet duidelijk tussen geëxfolieerde muscoviet-lamellen.

Kleine druppeltjes welke titanium bevatten, voortkomende uit de verwering van biotiet-kristallen met de daarin voorkomende sageniet-insluitsels, worden vaak gevonden langs de oorspronkelijke splijtrichtingen van geëxfolieerde biotiet. De vorming van anataas uit de druppeltjes kan soms geconstateerd worden.

(c) *Maakselanalyses.* Maakselanalyses zijn, gebruik makend van het systeem van Brewer (1964), toegepast op regolithen. Daar het systeem van Brewer uitsluitend betrekking heeft op bodems en niet op de dieper gelegen saprolieten, was het noodzakelijk om verschillende nieuwe termen toe te voegen aan zijn systeem. Bepaalde maaksels ("skelsepic plasmic fabrics") zijn veelvuldig aanwezig in het colluvium maar niet in saprolieten en bodems.

CONTENTS

1. INTRODUCTION

1.1. PURPOSE AND METHODS

The purpose of this study has been to obtain an insight in weathering phenomena occurring at a microscopical scale. For this purpose samples have been hardened with plastic (Vestopal) in the field and large thin sections have been prepared. The weathering profiles of the late-Hercynian Caldas de Reyes granite, situated east of the Ría de Arosa (see Fig. 1.1) in the humid temperate climate of northwestern Spain, have been selected for this investigation.

Initially the study of weathering profiles consisted of conventional grain analyses, chemical, heavy mineral and X-ray analyses of loose material. In order to obtain more detailed information about weathering phenomena it was decided to harden the loose material in the field with plastic (Fig. 1.3 and 1.4) and to prepare large thin sections (method Jongerius & Heintzberger, 1963) of the undisturbed material.

Minerals occurring in the fractions smaller than 2 μ and 2—50 μ have been determined by means of X-ray diffraction. In most cases a diffractometer was used, sometimes a Guinier-de Wolff quadruple camera. Identification was done mainly according to the procedures given by Brown (1961). The results are given in table 3.1.

Metahalloysite was thought to be present whenever a broad peak at 7.2 or 7.3 Å disappeared after heating at 550 °C. For one sample its presence was proved by treatment with potassium acetate and ethylene glycol after the method of Miller & Keller (1963) and by electron microscopic observations, which showed tubes as well as plates.

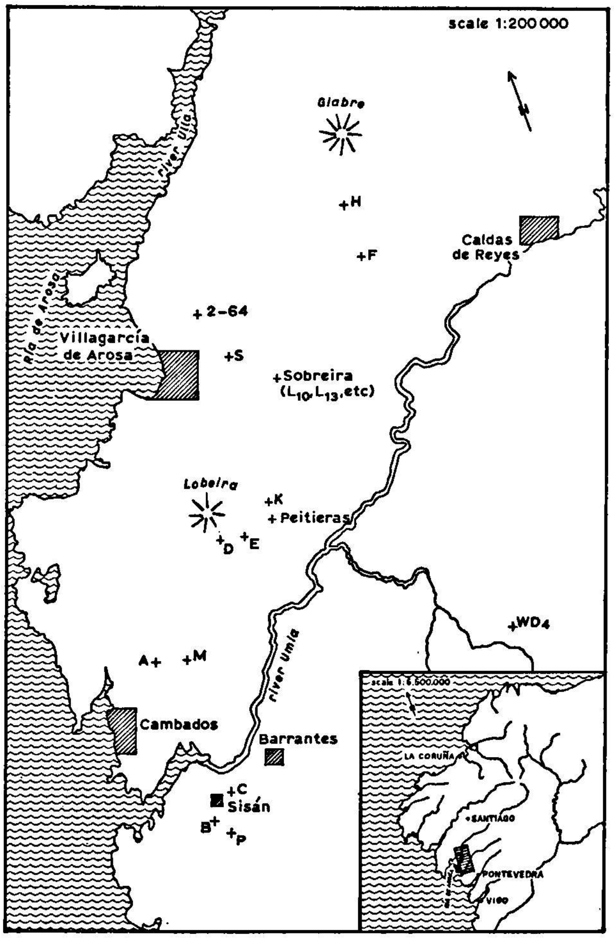

Fig. 1.1. Map and location of the studied area. The studied profiles are indicated by +.

Fig. 1.3. Sampling equipment and storage drums for plastics.

Fig. 1.4. Some of the hardened samples (granite, clay, amphibolite, schists, augengneiss, scales of spheroidal weathering etc.).

When no distinction could be made between muscovite or biotite the mineral has been inserted in table 3.1 as mica.

Vermiculite was identified from its 14.4 Å reflexion as well as from the 13.8 and 11.8 Å basal reflexions of partially dehydrated material.

Mixed layers were thought to be present when reflexions from interplanar spacings larger than 20 Å occurred, or when a broad peak was observed between 11 and 10 Å. After heating, the latter peak shifted towards the 10 Å side, indicating a mica-like component.

The name feldspar has been used when no distinction could be made between alkalifeldspar and plagioclase.

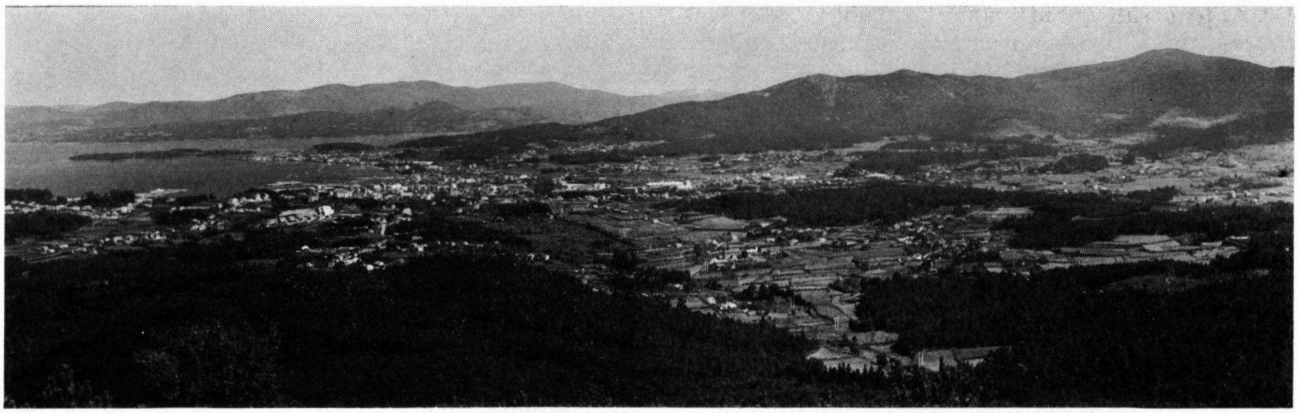

Fig. 1.2. The town of Villagarcía de Arosa along the Ría de Arosa (seen from Lobeira hill) and the Giabre mountain range.

1.2. LOCATION

The part of the Caldas de Reyes granite which has been studied is situated on the east side of the Ría de Arosa (Fig. 1.1). A low area can be found near the coast (Fig. 1.2) and in the valley of the river Umia. Circular residual hills surrounded by low-angle slopes are present in this area (Pannekoek, 1966).

In the higher areas of the Caldas de Reyes granite steeper rounded hills (Lobeira, greatest elevation 260 m) or groups of hills characterize the topography. Most of them are situated in the coarse-grained biotite-hornblende granite and have tors or boulders at their tops. Detailed information on the geomorphology of the Ría de Arosa is given by Pannekoek (1966); Nonn (1966) made a geomorphological study of the whole coastal area of Galicia.

1.3. GEOLOGY

The Caldas de Reyes granite is a late-Hercynian, post-tectonic granite, which shows several varieties. The main types are: medium-grained biotite- and biotite-muscovite granite, and coarse-grained biotite-hornblende granite. Several xenoliths are present especially in the latter granite type. They consist of: megacrystal granites, diorites, gneisses, amphibolites, schists, and hornfelses. A geological map of Galicia has been published by Parga Pondal (1963); the petrology of the area has been summarized by den Tex (1961) and Floor (1966).

1.4. CLIMATE

The climate is Köppen's Cf climate (warm-temperate rainy climates, Trewartha, 1954). Lautensach (1964) defines it as a full Atlantic permanently humid climate. According to the elaboration of Köppen's system, applied to Spanish climates by López Gómez (1959), the climate of the area under consideration is defined by the formula Cfsb$_2$, indicating that it is a humid-temperate climate with a cool summer, a winter temperature between 6° and 10°C, and that the amount of rainfall in the coolest month is more than three times that of the warmest.

A table is given below for two cities (Santiago de Compostela, altitude 228 m, and Pontevedra, at sea level) which are situated north and south of the studied area (Fig. 1.1).

Mean temperatures (°C)

	J	F	M	A	M	J	J	A	S	O	N	D	Ann.	Max.	Min.
Sant.	8.1	8.7	9.9	11.2	14.4	17.1	18.9	19.7	18.3	14.3	10.4	8.9	13.3	40.3	4.6
Pont.	8.5	9.4	10.6	12.3	14.0	17.6	19.2	19.3	18.1	14.5	11.0	9.3	13.7	40.3	7.0

Mean precipitation (mm)

	J	F	M	A	M	J	J	A	S	O	N	D	Ann.
Sant.	140	157	153	105	94	63	55	49	85	157	172	212	1442
Pont.	160	165	152	104	93	59	39	41	90	141	183	228	1455

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2. WEATHERING PROFILES

Two terms which are commonly used in the description of weathering profiles are defined in the Glossary of Geology (1957) as follows.

Regolith is the entire mantle of unconsolidated material, whatever its nature or origin.

Saprolite is a general name for thoroughly decomposed, earthy, but untransported rock.

A third term, saprock, was introduced by Grant (1966). It denotes in this study weathered but still cohesive rock.

2.1. SAPROCK

2.1.1 *Joints*

In quarries it can be seen that the initial stages of granite weathering proceed mainly along joints. They divide the rock into smaller parts and permit water to penetrate well below the rock surface. The base of granite weathering is therefore situated below the bedrock- or basal surface (Ruxton & Berry, 1959—60). This may explain the thick weathering mantle found in granite areas, as well as the inhomogeneous character of weathering profiles.

Exfoliation- or sheet joints (Ruxton & Berry, 1959—60), which are roughly parallel to the topography, also conduct the groundwater in the bedrock at different levels. The depth to which this water movement is possible is not known. It is difficult to study the phenomenon since it occurs already in "closed" joints which are difficult to detect with the naked eye. This is evident in a quarry north of the city of Villagarcía de Arosa (2—64 in Fig. 1.1). After dynamite blasting "closed" joints appeared, lined with bluish green material in which siderite (Table 3.1, sample 2—64) and pyrite were found. These colours and minerals do not occur in the open joints. Therefore a reducing environment exists in the "closed" joints. Moreover these joints have films of clay saturated with water. In open joints the environment is, of course, oxidizing.

Subhorizontal and vertical joints enclose separate granite blocks in the bedrock. The weathering of such a block is most intense at the corners where two vertical joint planes and one subhorizontal intersect. Therefore the corners of the block become rounded and the resulting gap is filled with weathering debris. In this stage, the subhorizontal joints are commonly hardly opened.

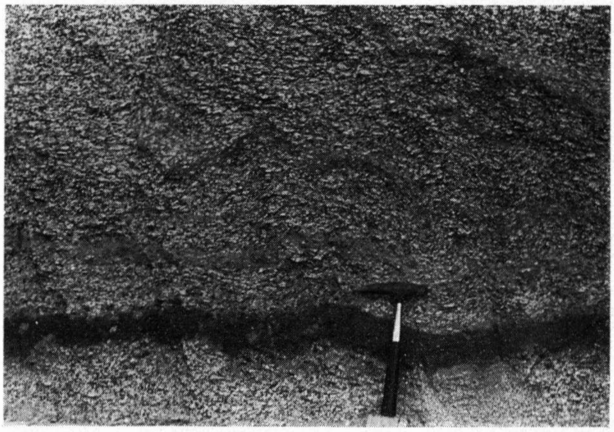


Fig. 2.1. Fine sandy material (dark band) accumulated along a former joint in the coarser saprolite.

Fig. 2.2. Spheroidal weathering and concentric banding. The base of the hammer rests on a remnant of a bounding joint.

It is interesting to note that the weathered material along the joints is finer-grained than in the surrounding zone, even in saprolites (Fig. 2.1). This means that weathering conditions remain different along joints in all stages of granite weathering.

2.1.2 *Spheroidal weathering*

This phenomenon is well exposed in the coarse-grained biotite-hornblende granite (Fig. 2.2). Examination of large thin sections (method Jongerius & Heintzberger, 1963) made it possible not only to trace mineralogical changes through different zones in a single thin section, but also to observe mechanical changes, especially the system of micro-cracks (Bisdom, 1967).

Spheroidal weathering is related to the development of micro-crack systems. In a boulder several zones can be distinguished: an "unweathered" inside zone, and two outside zones which constitute a limonite-rich band.

The "unweathered" granite has been called zone 1, and it is distinguished by mainly "structural" micro-cracks, which are not induced by weathering. Examples are joints, cleavages etc. Their width normally does not exceed 10 μ.

The boundary between the "unweathered" granite of zone 1 and the limonite band is indented. This means that at some places the iron hydroxides invade the "unweathered" granite more than at others, mainly along micro-cracks directed towards the core of the boulder. Although it would appear from field observations that the weathering front is situated at the indented boundary of the limonite band, microscopic observations show that this front is actually situated somewhat deeper, because the iron hydroxides indicate a certain stage in the weathering process but not the initial stage.

Apart from the micro-cracks directed towards the core of the boulder, there are many others. In zone 2 (inner part of the limonite band), which is a transition zone between zone 1 and zone 3, these other micro-cracks are frequently smaller than in zone 3. In the latter zone (part of the limonite band adjacent to the boulder surface) some of them, which are roughly parallel to the surface of the boulder, become even larger than those directed towards the core. This transition is realized by a dense system of micro-cracks built up in zone 3, including those of the structural type and those formed by weathering.

The following criteria serve to distinguish between structural micro-cracks and those of the weathering type. The structural ones (Fig. 3.4) are rather straight, as can be seen in unweathered granite; intersections are rather angular. Micro-cracks formed by weathering agents are sinuous (Fig. 3.5). A dendritical pattern of sinuous micro-cracks passing through a plagioclase crystal results from a combination of both types (Fig. 3.5). Chemical and physical processes widen existing micro-cracks, penetrate into zones of weakness such as dislocations, cleavages, twin planes, grain- and subgrain boundaries and develop new cracks. It is evident that the micro-crack patterns built up in this manner can be expected to vary with the rock types and weathering conditions. Even the coarse-grained Caldas granite itself shows these variations. The width, number and pattern of the micro-cracks in the various zones determine whether scales can form. In zone 3, for instance, with its very dense dendritic micro-crack system, flakes are hardly produced, and they are weathered instead directly to "grus" (granules).

The discussion so far concerned weathering phenomena in the saprock (weathered but still cohesive rock) of a boulder. The same decomposition pattern is present in the initial stages of rock weathering in the saprock of a bedrock bounded by joints.

Examination of the released scales shows enlarged cracks, lying around and within the scales, and situated roughly parallel to the boulder surface. This indicates that along one crack, out of the entire system of zone 3, a scale has been released. In the released scale itself there are other cracks, roughly parallel to the boulder surface, which however did not reach the critical point of traversing the entire scale. Therefore, the process of releasing a scale is thought to be dependent not only on the processes taking place in the bounding macro-cracks, but also to a certain extent on those in the scale itself. It is supposed therefore, that the entire system swells and contracts on a micro-scale until a crack is formed along which the scale can be released.

The arrangement of the scales and flakes resembles overlapping roof-tiles; after reaching a certain length, they develop a certain curvature. The explanation of the curvature is to be found in the concentric structure of zone 3, in which the crack bounding the released scale has been formed. The structure of zone 3 is concentric, because this zone is situated in the limonite band parallel to the boulder surface.

It must be noted that the formation of the crack pattern of zone 3 is not related to the development of a limonite band. This band merely represents a stage of granite weathering induced by the development of micro-cracks along which weathering agents could invade the rock. Granites which have no limonite band parallel to the boulder surface, can also show the effects of spheroidal weathering.

2.1.2. a *Concentric banding.* — Macro-cracks bordering the scales or situated inside the scales produce (in section) concentric bands around the boulder (Fig. 2.2). Even in "ghost structures" (see 2.1.2. b) this phenomenon can still be observed. The impression of complete circles or bands is due to the arrangement of rounded scales and the rounded part of the macro-cracks which bound the scales. The latter can not give the impression of continuous bands, because the scales are arranged like overlapping roof-tiles.

2.1.2 b *Ghost structures.* — As the boulder becomes smaller due to the progression of the weathering front, the micro-cracks of zone 1, which enter the boulder core from all directions, will become connected. The entire core is then veined with micro-cracks, and weathering processes can develop more rapidly a dendritic pattern of micro-cracks in the core of the boulder. The process of scaling ceases, and the core crumbles. In the undisturbed regolith, the former core

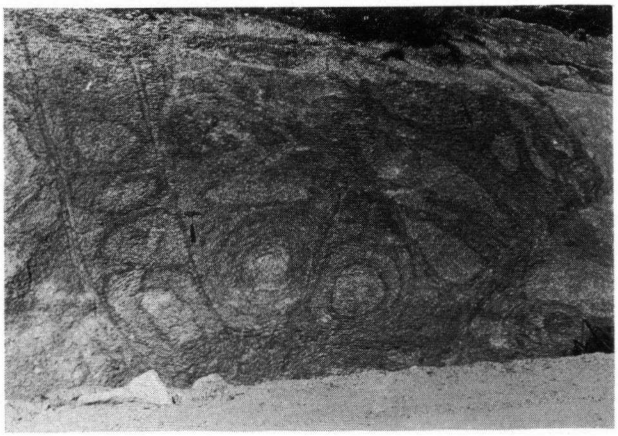


Fig. 2.3. Ghost structures and concentric banding. Note bounding joints in which the weathering of the former block started, and the absence of concentric banding in the cores of the ghost structure.

of the boulder has been transformed into angular weathered debris, surrounded by an encircling zone of scales, flakes, or rock fragments and minerals, showing concentric banding. This banding gradually disappears towards the original bounding joints in which the weathering started. The weathered core of the boulder together with the concentric banding, which gradually disappears, constitutes the ghost structure (Fig. 2.3).

The gradual disappearance of the concentric banding is due to continual increase in thickness of the cracks in the scales. Weathering debris, including clay minerals, is washed out of the macro-cracks, thus providing space for other rock fragments. The micro-cracks within the scales are still occupied by weathering debris which expands and shrinks, producing slight movements of the surrounding minerals and rock fragments. This movement of the fragments may affect the crack attitudes or close the cracks to a certain extent. The final weathering debris is angular, and mineral fragments as well as many rock fragments are present, all showing the effects of the original crack system.

2.2. SAPROLITE

Most granite weathering profiles in the studied area have an in situ weathered lower part (saprolite and saprock) upon which colluviated material has been deposited (Fig. 2.4).

Fig. 2.4. Granite saprolite with overlying colluvium (hammer-head near boundary). Quartz and schist fragments are derived from veins and xenoliths situated uphill.

A saprolite is a thoroughly decomposed, earthy, but untransported rock (Glossary of Geology, 1957). However, it is not clear in this definition which textural classes are represented by the term earthy, and when a rock is thoroughly decomposed.

In a saprolite boulders, gravel, and finer textured material may be present. Therefore a saprolite is not necessarely thoroughly decomposed and earthy. Important is that the rock has been weathered in situ, and that it has lost a direct connection with the cohesive weathered rock (saprock).

The writer therefore proposes the following definition: *a saprolite is an in situ weathered rock, which has lost direct connection with the cohesive decomposed rock (saprock), and in which all textural classes may be represented.*

Several saprolite types are present in the studied granite area. Examples will be discussed in sequence of increasing decomposition.

(a) The most common is the "granite arénisé" (Collier, 1961), which consists of gravelly loamy coarse sand and gravelly sandy loam (7th Approximation, U.S. Dept. of Agriculture). The feldspars are not thoroughly decomposed and have to be broken by hammer.

(b) A saprolite of a biotite-muscovite granite north of Cambados (A in Fig. 1.1) contains weathered plagioclases of which some can be pulverized by hand. Microcline is divided into smaller parts by cracks transecting it, but it is hardly weathered (Fig. 2.5).

Fig. 2.5. Medium-grained granite saprolite, with stone layer at the base of the colluvium.

(c) A coarse-grained granite saprolite east of Villagarcía de Arosa (L 10 in Fig. 1.1) contains completely weathered plagioclases and microcline with solution cavities.

(d) The most advanced weathering stage is reached in a profile west of Barrantes (C in Fig. 1.1) in which even microcline is only found sporadically in its most decomposed stage. Plagioclase crystals are completely decomposed and only remnants of former sericite inclusions are sometimes found at their original sites. This stage of granite weathering is represented by spotted clay (argile tachetée, described by Collier, 1961), which mainly consists of kaolinite, locally in large vermiforms (Fig. 4.5).

The thickness of a saprolite can not be established in regoliths which do not show the underlying bedrock. They are often more than 6 to 8 metres thick. This is in accordance with observations of Schermerhorn (1959) in granites of northern Portugal. The thickness of saprolites may probably reach at least 30 metres, because in the coarse-grained granite, hills of this altitude are frequently composed of boulders while their surroundings consist of weathering debris. Sometimes the boulders have a length of 20 metres and a height of 8 metres. In the finer-grained granites they normally reach only sizes of about one metre.

In fine- and medium-grained granite outcrops exceeding a few metres in size, bedrock is mostly exposed, since the maximum size of boulders in these rocks is much smaller (Fig. 2.6). In coarse-grained granites however, boulders may reach a size up to 20 metres in length and since natural exposures are usually much smaller, only in quarries is it possible to determine whether or not they represent bedrock.

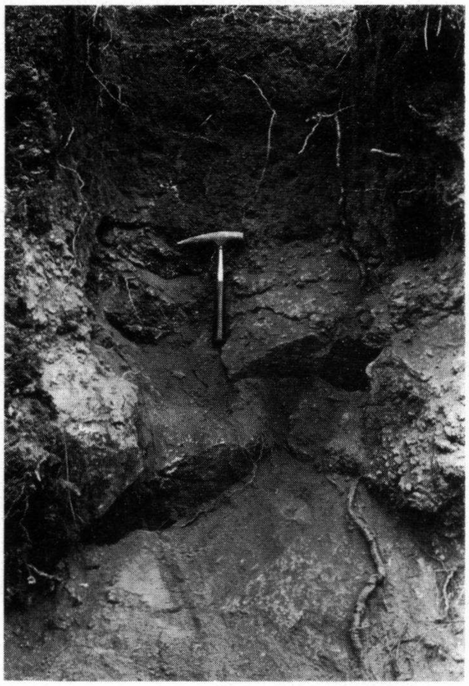


Fig. 2.6. Orthic haplumbrept on top of medium-grained granite bedrock.

Influence of the groundwater table. — The depth of the groundwater table has been measured in wells during the summer of 1965. The groundwater table is arc-shaped and the depth below the surface decreases from the hilltops towards the valleys. A depth of 10 metres has been measured in a hill-top with a height of 30 metres and it decreases to 2 metres near the valley bottom. This level has been found in the saprolite or in the underlying bedrock. The water transport in the bedrock occurs mainly along joints, as could be seen during the construction of a well. The adjacent saprock has pores of varying diameters, which indicates that it serves as reservoir-rock.

During the month of September the lowest level is reached. Therefore it is the favourite month of well construction. The September level appears to be several metres below the midwinter level, according to information supplied by local farmers.

Traces of some limonite-goethite staining are found as mottling or bands in parts of the profile affected by oscillating groundwater levels. Concretions are seldom present in the granite saprolites. The effects of the oscillating groundwater level upon the formation of secondary minerals will now be considered. The results of X-ray diffraction analyses are given in table 3.1.

Samples A1, A2, C16, C18, 2—64 and possibly L10 have been affected during part of the year by the oscillating groundwater level. The secondary mineral content of saprolites and colluvia which have been affected directly by the groundwater table, differs in some respects from unaffected parts of the profiles: montmorillonite occurs abundantly in A1, palygorskite (possibly) in L10 and 2—64, sepiolite (possibly) in L10, siderite in 2—64, and finally it is possible that differences are present in mixed-layer minerals.

Montmorillonite (sample A1) is found in the clayey material along a small joint in the Cambados saprolite. Sample 2—64 represents the clayey material found in "closed joints" (see saprock) in a quarry north of Villagarcía de Arosa, which could be sampled after blasting of the granite. Therfore, with the exception of sample L10 (granite saprolite), these unusual secondary minerals occur along joints.

The formation of kaolinite and metahalloysite is not affected by groundwater and they constitute the main secondary minerals of the area. Sample A2, for instance, has been collected in the granite adjacent to the joint of sample A1. The saprolite contains no montmorillonite, but it is also affected, during part of the year, by the groundwater.

According to the X-ray diffraction data of these few samples it must be decided that the oscillating groundwater table chiefly affects the secondary mineral composition along joints, while it appears to have little or no effect on the weathered granite adjacent to the joints.

Age of saprolites. — In granites the bedrock weathers not only at its surface but also at the same time along joint systems. Therefore similar stages of weathering occur simultaneously at different heights of the in situ weathered profile. It is therefore very difficult to establish the ages of saprolites. Because of the occurrence of saprolite material below raised beaches and below slope-deposits probably dating from the early Quaternary, Nonn (1964, 1966) and Pannekoek (1966) presumed that the older saprolites have been formed in the older interglacials and earlier. This is in accordance with the conclusions of Fitzpatrick (1963), who made a study of deeply weathered rocks in Europe, Asia and North America.

2.3. COLLUVIUM

Colluvium is, according to the Glossary of Geology (1957), a general term applied to loose and incoherent deposits, usually at the foot of a slope or cliff and brought there chiefly by gravity. Talus and cliff debris are included in such deposits.

The division of a regolith in saprolite and colluvium was one of the purposes of this study. Field observations in conjunction with heavy mineral analyses (see regolith) and the examination of large thin sections were used for this study.

The division is evident in the field in granites which contain rather coarse continuous quartz veins in the saprolite (Fig. 2.7). In the overlying colluvium, quartz from these veins is present as separate stones, or as a stone line at the base of a colluvium sheet. Granite stones are only rarely present in colluvia, but schist-fragments derived from xenoliths in the granite are common (Fig. 2.8).

Continuous joints, lined with finer-textured material than its surroundings, are often of great assistance in the identification of a saprolite. These clay coats are locally very thin and hardly detectable.

The boundary between colluvium and saprolite may be a sharp line, but in the coarse-grained granites it is commonly obscure, due to the coarse texture of both the saprolite and the base of the colluvium (Fig. 2.9 and 2.10).


Fig. 2.7. Aplites and quartz veins cut across the saprolite up to the base of the colluvium indicated by a stone line of quartz fragments.


Fig. 2.8. Colluvium with mainly schist fragments on top of granite saprolite (boundary near hammer-head).

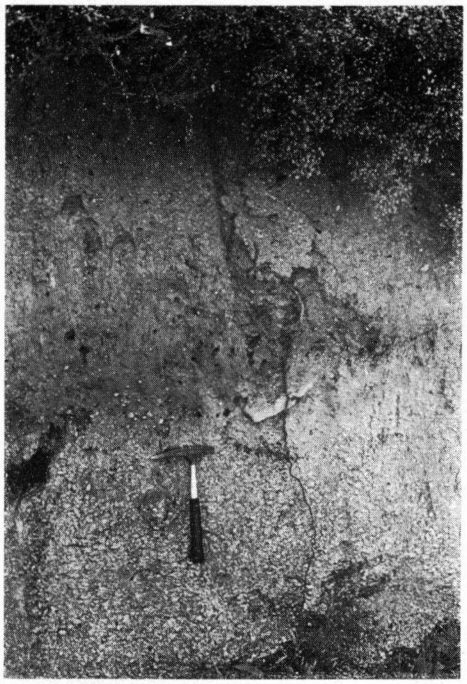


Fig. 2.9. Orthic haplumbrept in coarse-grained granite. Base of colluvium indicated by one stone.

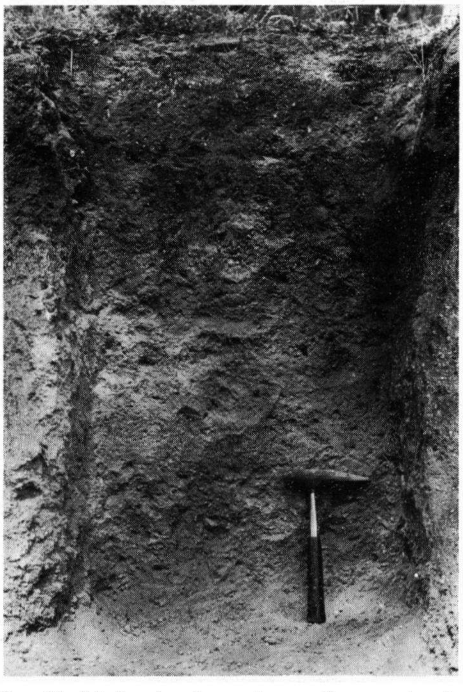


Fig. 2.10. Orthic haplumbrept in medium-grained granite. Division between colluvium and saprolite can only be made by heavy mineral analyses and/or large thin sections.

Several layers are sometimes present in the colluvium. They may be indicated by stone lines or texture differences, but they are frequently not recognized in the field. In those cases they can often be established by heavy mineral analyses (see 2.5), thin section studies, and other techniques.

Thin sections reveal differences in fabrics (chapter 4) but are also of great help to establish mineralogical changes, as for instance the weathering stages of the coarser minerals. Microcline can be taken as an example in the Barrantes profile (C in Fig. 1.1). Only near the base of the regolith, weathered and partly dissolved microcline has been found. However, on top of the regolith fresh microcline and even some plagioclases can be found. Therefore the latter layer can not belong to the Barrantes saprolite and must have been derived from another source containing less-decomposed granite. This material has its origin in less-weathered profiles or rock outcrops situated higher along the hill-slope.

Mass movement could not be related to a certain stage of rock weathering. It occurred in relatively fresh weathered material as well as in the most decomposed granites. The large feldspars in the coarse-grained granite saprolites are often arranged into such a network that even on steep slopes thick saprolites are maintained, although a weak disturbance is sufficient to produce slides.

According to Baker (1959) mass movements occur at the rock-soil interface. Culling (1965) states that soil creep is confined to the upper layers of the surface cover. Leith and Gupton (1963) found that 90 percent of the failures investigated occurred in thick saprolites and that the fresh bedrock is rarely exposed. From these data the same conclusion is reached as in the Caldas de Reyes granite, which indicates that mass movements may occur at any level between the bedrock and the surface.

Pannekoek (1966) suggests that rain wash (transport of finer material) and sheet floods or muddy flows (capable of transporting pebbles or even boulders) are the mechanisms of the mass movement.

2.4. SOILS

Most soils in the area belong to the great group of the Haplumbrepts, according to the classification scheme of the U.S. Department of Agriculture (7th Approximation, 1960). A typical example will be described first.

Orthic Haplumbrept

Area: Peitieras, Prov. of Pontevedra, Spain.
Vegetation: pine, heath, ulex, fern.
Parent material: biotite-hornblende granite; colluvium and saprolite.
Topography: slope 10 degrees, elevation 160 m.

A11 0-12 cm, very dark gray (10YR 3/1) when dry, black (10YR 2/1) when moist; sandy loam; fine crumbs, not compact; loose; no mottles; roots; no concretions; weathered minerals; gradual boundary.

A12 12—35 cm, dark brown-brown (10YR 4/3) when dry, very dark brown (10YR 2/2) when moist; sandy loam; fine crumbs, not compact; loose; no mottles; few roots; no concretions; weathered minerals; gradual boundary.

B 35—65 cm, strong brown (7.5YR 5/6) when dry, dark yellowish brown (7.5YR 4/4) when moist; gravelly sandy loam; crumbs, not compact; loose; no mottles, limonite-goethite colouring; no concretions; weathered minerals and rock fragments; gradual boundary.

C below 65 cm, very pale brown (10YR 8/4) when dry, light yellowish brown (10YR 6/4) when moist; gravelly sandy loam; no structure other than coarse angular weathering debris; loose; no mottles; no concretions.

Depth	Horizon	Particle size distribution in microns (%)				
cm		2000—200	200—50	50—20	20—2	< 2
0—12	A11	54.0	16.6	7.4	11.4	10.6
12—35	A12	51.7	12.5	8.1	11.9	15.8
35—65	B	46.2	15.5	8.7	15.3	14.3
65—..	C	48.7	19.1	10.6	15.9	5.7

Organic	matter	Humus %	pH(H_2O)	pH(KCl)
% C	C/N			
6.034	15.6	3.3	5.3	4.1
1.747	12.8	0.9	5.4	4.4
0.786	12.5	—	5.6	4.2
0.230	19.2	—	5.3	4.0

Cation exch. cap.	Extractable cations, meq./100 g				Base sat. %
	Ca	Mg	Na	K	
54.88	0.00	0.48	0.00	0.13	1.11
10.88	0.00	0.47	0.00	0.08	5.05
24.02	0.00	0.53	0.00	0.05	2.41
22.89	0.00	0.37	0.00	0.05	1.83

Light minerals (1000—500 μ)

	Feldspars	Quartz	Micas	Rock-fragments
A11	48	51	1	14
A12	65	35	+	14
B	47	51	2	18
C	47	42	11	5

Light minerals (<500 μ)

	Feldspars	Quartz	Micas
A11	85	11	4
A12	70	27	3
B	86	13	1
C	38	9	53

+ (present in minor amounts)

Heavy minerals

Horizon:	A11	A12	B	C
Zircon	27	38	52	84
Tourmaline	+	+		
Garnet	+		+	
Rutile	+	+	+	
Anatase	+	1	+	
Staurolite	+	+	+	+
Andalusite	+	1	+	+
Sillimanite-grain	+	1	+	
Sillimanite-fibrolite		+		
Epidote	33	20	18	6
Hornblende	39	38	30	10
Titanite	1	1	+	
Turbid	10	2	+	+
Opaque	15	5	5	14

The orthic haplumbrept has a cambic horizon mainly due to iron staining. B-horizons with accumulation of clay or humus have not been found in the area. Therefore the B-horizon is only poorly developed, but it can be classified as a cambic horizon (Fig. 2.6, 2.9 and 2.10). This cambic horizon is, however, absent in most profiles, which are therefore A—C profiles. They have similar characteristics as those of the A- and C horizon of the orthic haplumbrept. If the umbric epipedon is more than 25 cm thick they may be classified therefore as entic haplumbrepts (Fig. 2.7).

Difficulties arise, however, if the umbric epipedon is less than 25 cm thick, because these soils are not given in the classification scheme. The epipedon is too thin to be defined as an umbric epipedon and has to be called by definition an ochric epipedon. The types of soils which resemble those found in the area most closely are the dystrochrepts of the ochrept-suborder. They have however by definition a cambic horizon which is not present in this A—C profile. Therefore the soils with an umbric epipedon of less than 25 cm had to be called entic haplumbrepts with an umbric epipedon of less than 25 cm in thickness.

The A-horizon in the area reaches a thickness of 1.40 m along the flanks of the Giabre mountain (location in Fig. 1.1). These soils are situated above an altitude of 250 m, and have been called Atlantic Ranker by Albareda Herrera (1964). They have a cambic horizon at the base and therefore they are orthic haplumbrepts. They can not be related directly with peat formation, although Jongerius (personal communication) thinks that water logging is possible during part of the year. These and the other humus forms present in the area will be discussed in a forthcoming publication by Jongerius & Bisdom.

Jongerius noted that the thick umbric epipedon has the most favourable humus form at its base. A gradual change from mull-like moder at the bottom to fine moder and eventually to grob moder at the top of the umbric epipedon has been observed.

Below an altitude of 250 m the humus forms are fine moder, mull-like moder and mull.

Most soils are developed in colluvium, which makes it rather difficult to establish the rate of weathering because the material has already been weathered at other sites. This rate must be considerable because a decrease in coarseness of the weathered minerals and rock fragments is always observed in the A-horizon.

The secondary and primary minerals present in the fractions < 2 μ and 2—50 μ of the three orthic haplumbrepts at the locations D, E and H (see Fig. 1.1) are included in table 3.1.

Profiles D and E are situated at the southern flank of the Lobeira hill at altitudes of 170 m and 160 m, respectively. Profile H (altitude 270 m) is the orthic haplumbrept on Mt. Giabre with an umbric epipedon of 1.40 m. The samples are listed below according to depth and part of the profile to which they belong.

sample	depth cm	umbric epipedon	cambic horizon	C-horizon	D-horizon
D1	10—25	+			
D2	45—58		+		
E1	0—9	+			
E2	25—32		+		
E3	51—59			+	
E4	90—100				+
H2	105—120	+			
H3	155—165		+		
H4	170—175			+	

Table 3.1 indicates that no large differences exist in primary and secondary mineral species in the profiles themselves, nor between the various profiles. Kaolinite, metahalloysite, gibbsite, vermiculite, biotite, muscovite, illite, mixed layer minerals, plagioclase, microcline and quartz are common minerals in these profiles.

Some unusual large d-spacings (21Å, 23Å, 29Å, 34Å, 37Å and 45Å) have been measured in the mixed layer minerals of both a paleosol and recent soils. These mixed layer minerals are all present in parts of profiles which contain organic matter. This possibly indicates an association of the clay minerals with organic compounds.

In the Cambados profile (A in Fig. 1.1), paleosols are present. Only the upper one, situated directly below the recent soil, is complete, whereas the underlying paleosols have been more or less truncated. The humus forms are not very different because both the recent and the paleosol have a mull.

Samples A3 and A4 have been taken in the umbric epipedon and cambic horizon of a paleosol.

2.5. HEAVY MINERALS IN REGOLITHS

Heavy mineral analyses (fraction $< 500\ \mu$) are often of great assistance to establish the boundary between saprolite and overlying colluvium in a regolith, especially in the coarse-grained profiles where the boundary is difficult to establish by field observations. However, several hundreds of analyses are required in order to obtain reasonably reliable regional interpretations.

The colluvium is distinguished from the underlying saprolite by the presence of metamorphic minerals derived mainly from high grade metamorphic xenoliths. The continual presence of metamorphic heavy minerals, from a certain level in a granite regolith to the surface, indicates colluvium, providing the granite below the level is free of xenoliths. However, it is possible that heavy minerals migrate from the colluvium into the saprolite. This applies for instance to the orthic haplumbrept of location Peitieras (see 2.4). Horizon C has a very high zircon content (84 %), and a low epidote (6 %) and hornblende (10 %) content, which distinguishes this horizon from the B, A11, and A12 soil horizons. However, staurolite and andalusite are present in this saprolite horizon. Interpretations from a single profile are difficult, but comparison with others developed in this granite, indicate that the C-horizon belongs indeed to the saprolite notwithstanding the presence of staurolite and andalusite.

In the colluvium itself, different layers can be distinguished by heavy mineral analyses. An example is given in table 2.1.

Table 2.1. Heavy mineral content in Cambados regolith (A in Fig. 1.1)

depth in m:	0.20	0.50	1.10	1.40	2.60
Zircon	24	33	25	16	82
Tourmaline	15	13	23	1	2
Garnet	7	5	4	2	2
Rutile	+	1	1	1	
Anatase	1	2		+	
Brookite		+			
Staurolite	10	7	12	6	2
Kyanite	1	+		+	1
Andalusite	2	5	11	1	5
Sillimanite grain	+	+			
Sillimanite fibrolite		+	+	+	
Chloritoid	+				
Epidote	19	12	10	3	4
Hornblende	5	2	3		1
Titanite	16	20	11	70	1
Turbid	2				+
Opaque	34	44	43	27	82

The sample at 2.60 m depth is situated below the top of the saprolite, which is indicated by a stone line above the saprolite (Fig. 2.5) and quartz veins which cross the saprolite. The very high zircon content (82 %) distinguishes the saprolite from the overlying colluvium. Sinking of the metamorphic minerals staurolite, kyanite and andalusite, must have occurred in this zone.

The other samples are situated in the colluvium. Most spectacular is the anomalous titanite concentration at 1.40 m depth. The three other samples (at depths 0.20 m, 0.50 m and 1.10 m) are more difficult to distinguish, because no large differences in heavy mineral content exist. Field observations indicate however that a recent soil as well as a paleosol are present. This means that there are two separate layers between the surface and 1.10 m depth.

The biotite-muscovite granite contains no xenoliths composed of high grade metamorphic rocks and therefore the metamorphic minerals in the colluvium have not been derived from the granite itself. In order to determine the source of these heavy minerals, samples were collected from the beach, one kilometre west of this area. Transportation of sand from the beaches landinwards has frequently been observed. Table 2.2 shows that the metamorphic heavy mineral contents of both the beach and the colluvia in the studied area are indeed comparable.

Table 2.2. Metamorphic heavy minerals from beach to 1 km landinwards.

	beach	marine terrace	500 m landinwards	1000 m landinwards (see 0.20 m Cambados profile, table 2.1)
Staurolite	44	18	11	10
Kyanite	+	4	+	1
Andalusite	21	11	5	2
Sillimanite-grain	+	+	+	+
Sillimanite-fibrolite	23	5	1	

2.6. MINERALS IN RIVER SEDIMENTS

The river Umia, which is the main stream of the area, and its tributaries have been examined for their mineral content. A kilometre east of Caldas de Reyes the hornblende percentages are below 20, and downstream they increase to about 40. This high percentage remains constant in these parts, where the river does cross hornblende-bearing granites. Staurolite, andalusite, sillimanite, garnet, zircon, tourmaline, and epidote are common constituents, while rutile, anatase, brookite, kyanite, augite, titaniferous augite, and titanite are present in small amounts.

Numerous angular feldspar fragments are found in the river sediments, while quartz pebbles are present in small amounts.

In a terrace, south of the city of Cambados, various types of sediments are found between altitudes of 5 and 30 metres, which differ greatly from those in the nearby Umia river. Pebble layers, sands with cross-bedding, silty clays, iron banks with quartz pebbles, and biotite-muscovite granite pebbles are present. However, this does not necessarily mean that the terrace is marine, because the nature of the quaternary sediments transported by the Umia river is not known. The terrace is situated only a kilometre inland along the margin of the present estuary. There is a possibility that a similar situation existed during the time of sedimentation of the terrace, which is in accordance with Nonn's opinion (1964, p. 152).

3. WEATHERING OF PRIMARY AND FORMATION OF SECONDARY MINERALS

3.1. INTRODUCTION

For studying mineral decay and development of new minerals in the granite weathering profiles, microscopical examination of thin sections was used in conjunction with X-ray diffraction analyses of two size classes ($< 2\ \mu$ and 2—50 μ).

The secondary minerals gibbsite and kaolinite are considered first, thereafter the weathering of primary minerals (plagioclase, microcline, biotite, muscovite etc.) is discussed together with the formation of secondary minerals.

3.2. GIBBSITE AND KAOLINITE

X-ray diffraction analyses of the fractions smaller than 2 μ and 2—50 μ revealed that gibbsite is most common in the finest fraction, whereas kaolinite is not only present in both size classes but may even reach sizes of more than a millimetre.

The optical identification of these minerals in thin sections is difficult, especially when they belong to the finest fractions and are associated with minerals from which they are difficult to distinguish.

An example is the gibbsite — muscovite (coarser than 2 μ) — illite (smaller than 2 μ) association found in and outside plagioclases. With the exception of one profile in which muscovite and illite form, all others show weathering of muscovite. This is accompanied by exfoliation and decreasing birefringence colours of muscovite. The moving apart of the muscovite lamellae, with respect to each other, gives the impression that the muscovite-illite field enlarges, the volume of the minerals increases, and that mineral aggregates form. This gives great difficulty in distinguishing optically gibbsite from muscovite and illite in weathered plagioclases.

Newly formed illite has been reported to have occurred during plagioclase weathering (Kato, 1965a), but the observations of the writer indicate that optical observations, without X-ray analyses, may give misleading interpretations.

Two processes may be involved in the formation of gibbsite: direct crystallization from solutions or formation through an intermediate gel phase. Most frequently the gibbsite formation is seen to have occurred during the weathering of plagioclases. Together with illite, muscovite and other secondary minerals it may remain after the plagioclases are completely weathered.

Kaolinite and metahalloysite, in contrast to gibbsite, have no characteristic optical properties and their occurrence in the finest fraction is therefore only indicated by X-ray diffraction. However, because they are also present in coarser sizes, more data could be obtained than in the case of gibbsite. Vermicular kaolinite forms during the weathering of biotite by interlamellar crystallization. The role of allophane (sample H2 of table 3.1) in relation to the formation of kaolinite is not known.

Grey, undefined microcrystalline masses of unknown composition have been noted in the thin sections of the Sobreira profile (L10 in table 3.1; location in Fig. 1.1). It can be seen that a gel is superimposed upon these masses (Fig. 3.1). Illite-muscovite and kaolinite or metahalloysite have been formed from the microcrystalline mass and the gel (Fig. 3.2 and 3.3). The crystals in the early stages of development are fibrous. Well-formed red pleochroic muscovite (ana-

Fig. 3.1. Secondary illite-muscovite formation in a gel (white), superimposed upon microcrystalline material (crossed nicols, 200 ×).

Fig. 3.2. Secondary muscovite (I, coarse, white, fibrous minerals); and kaolinite (II, small vermiforms) (crossed nicols, 200 ×).

Fig. 3.3. Small kaolinite vermiforms (crossed nicols, 200 ×).

lysed with the electron microprobe: moderate Si, Al, K, Mg and traces of Ti and Fe) and grey kaolinite — or metahalloysite vermiforms have subsequently been formed from these fibrous minerals. Kaolinite (metahalloysite) — illite (muscovite) conversion has not been observed.

3.3. WEATHERING OF FELDSPARS

3.3.1 *Micro-cracks*

The weathering of a feldspar does not only proceed on the feldspar surface, but also along micro-cracks in the mineral (see 2.1.2). These micro-cracks are a combination of structural- and weathering types (Fig. 3.4 and 3.5). During weathering the micro-crack pattern becomes progressively more complicated and many of them enlarge to macro-cracks. At a certain stage of feldspar weathering the cracks will transect the feldspar crystals in such a way that the crystals break into numerous parts (Fig. 3.6). These parts in turn are subject to the same process untill eventually the entire mineral has vanished (Fig. 3.7).

The importance of micro-cracks in the weathering of feldspars has also been noted by Cady, 1950; Chapman & Greenfield, 1949; Collier, 1961; Delvigne, 1965; Grant, 1963; Harriss & Adams, 1966; Kato, 1964b; Leneuf, 1959; Meyer & Kalk, 1964; Pedro, 1964a; Romashkevich, 1964; and Sivarajasingham, Alexander, Cady & Cline, 1962.

The formation of gibbsite in tropical areas is often associated with good drainage conditions. There are, however, examples which show that this is not necessary, as for instance during the gibbsite formation

Fig. 3.4. Structural micro-crack through plagioclase and quartz. The large crack is a transition towards a weathering micro-crack (crossed nicols, 30 ×).

Fig. 3.6. Broken plagioclase, some gibbsite-illite-muscovite clusters (including micro-crystalline material of possibly kaolinite or metahalloysite) (crossed nicols, 160 ×).

Fig. 3.5. Dendritic pattern of micro-cracks, which is a combination of structural- and weathering micro-cracks (crossed nicols, 30 ×).

Fig. 3.7. Weathered zoned plagioclase; secondary minerals are more abundant in calcic core. Illite-muscovite, as in Fig. 3.6, is of primary origin (crossed nicols, 160 ×).

in micro-cracks of weathered feldspars. They certainly show very restricted water movement in this capillary environment. In these micro-cracks "abrasion pH" values of 8—10 may be reached and therefore gibbsite forms in a highly alkaline environment (Delvigne, 1965). According to Heydemann (1966) the formation of bauxite (gibbsite) during the weathering of limestone takes also place in highly alkaline environments (pH 8 to 9). However, these alkaline environments must be regarded as special cases while most bauxites form in weakly alkaline environments (Delvigne, 1965; Heydemann, 1966).

3.3.2 *Secondary minerals*

Correns & von Engelhardt (1938) suggest that feldspars upon weathering go into an ionic solution, from which secondary minerals are formed. These processes may occur in cavities along cleavage planes or other fractures in the feldspars.

Delvigne (1965) gives a well-documented review on feldspar weathering, including many laboratory experiments. Also Lerz & Borchert (1962) have done much work on this subject. According to Delvigne the depth to which the feldspar is affected during weathering at its surface or along micro-cracks does not exceed a few unit cells. It seems that the Si-O-Al bonds are broken more rapidly by weathering agents than Ca-O or (Na, K)-O bonds. Therefore minerals with numerous bonds of this type weather readily. For instance anorthite weathers more rapidly than albite. The immediate products of feldspar weathering are not known. Pedro (1964c) expects that a complex alumino-silica ionic form may precede the simple ionic form.

Many secondary minerals have been reported to form during the weathering of feldspars. Gibbsite and minerals belonging to the kaolinite group (halloysite and kaolinite) are thought to form at the expense of feldspars (Abbott, 1958; Craig & Loughnan, 1964; Delvigne, 1965; Grant, 1963—64—66; Kato, 1964b; Keller, 1964; Mitchell, 1963; Schermerhorn, 1959; Stephen, 1963; and Young & Stephen, 1965).

An intermediate gel stage is also possible (Delvigne, 1965). Meyer & Kalk (1964) found that the secondary products of weathered feldspars were not gibbsite or kaolinite but allophane and opal. Some authors think that illite or montmorillonite are the secondary minerals (Craig & Loughnan, 1964; Delvigne, 1965; Kato, 1964b; and Mitchell, 1963).

It is difficult to relate the secondary minerals directly with the weathering of feldspars. If the minerals occur in a micro-crack it are probably weathering products of the mineral itself, but if large holes have been formed in advanced stages of feldspar weathering this effect will become smaller. In these advanced stages, elements in the percolating solutions are thought to have more effect on the nature of the formed secondary minerals than those of the feldspar itself.

Fig. 3.4 to 3.11 show some stages of the weathering of plagioclases and microcline. Microcline seems to dissolve without giving rise to secondary minerals, with the possible exception of gibbsite in micro-cracks. However, limonite and goethite are present, but the iron necessary for their formation must have been transported by solutions from outside the mineral. Gibbsite, mostly formed as a result of plagioclase

Fig. 3.8. Microcline weathered mainly along twin planes (crossed nicols, 30 ×).

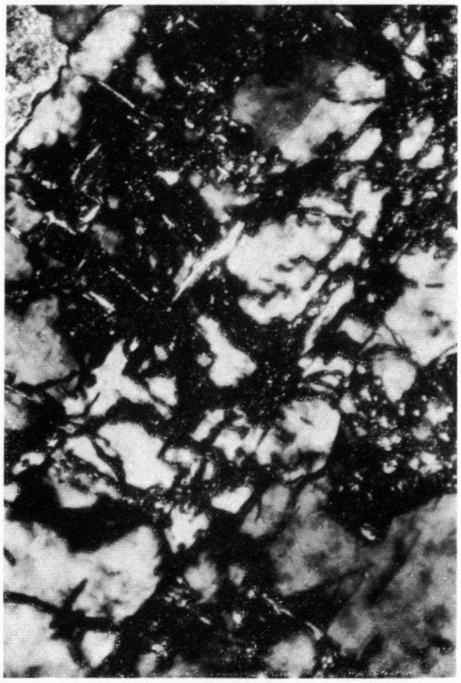


Fig. 3.9. Pitted microcline fragments; original twinning still evident (crossed nicols, 160 ×).

Fig. 3.10. Advanced weathering stage of microcline. Original twinning still evident. No secondary minerals (crossed nicols, 160 ×).

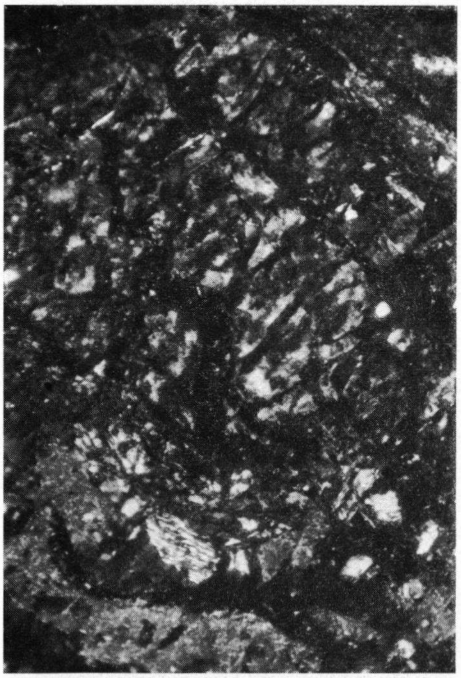


Fig. 3.11. Remnants of microcline (white) in clay-limonite matrix (dark gray cloudy material) (crossed nicols, 160 ×).

weathering, seems to be unstable in the weathering environment. It may, perhaps, be converted to the more stable kaolinite. This conversion may take place as a result of uptake of SiO_2, but it is not known whether the mineral remains in its crystallized form or is dissolved beforehand. According to Bonifas (1959) it is doubtful that gibbsite remains in crystal form during the conversion to kaolinite.

The same problem is involved in the conversion of kaolinite to gibbsite, which occurs in the formation of bauxite. If the kaolinite of latosols, with as secondary minerals kaolinite and gibbsite (Bennema, 1965), is desilicified and alumina remains, bauxite may form.

Heydemann (1966) showed in his experiments that destruction of kaolinite is possible, although it is a very slow process, and that this mineral was even destroyed completely. Therefore the formation of gibbsite from kaolinite is probably preceded by a solution phase.

More information on the formation of kaolinite and gibbsite can be obtained from the papers of Barshad, 1966; Cady, 1960; Crompton, 1960; Delvigne, 1965; Gastuche, Bruggenwert & Mortland, 1964; Grant, 1966; Hess, 1966; Heydemann, 1966; Keller, 1964; Maignien, 1966; van der Merwe & Weber, 1965; Patterson, 1964; Pedro, 1964; Schnitzer & Skinner, 1964; de Villiers, 1965; Wolfenden, 1965; and Yaalon, 1960.

With respect to the effect of organic compounds on the behaviour of ions and the genesis of clay minerals the reader is referred to Antipov-Karataev & Kellerman, 1962; Bastisse, 1964; Breburda, 1965; Juste, 1966; Parfenova, Mochalova & Titova, 1964; Reijnders, 1964; Romashkevich, 1964; and Webley, Henderson & Taylor, 1963.

3.4. WEATHERING OF BIOTITE

In Fig. 3.12 to 3.19 weathering sequences of biotite are given. In the early stages of weathering the mineral exfoliates along cleavage planes. It may break (Fig. 3.12) and curl (Fig. 3.19) during this process. Raman & Jackson (1964) have described the latter feature in vermiculite. The biotite in Fig. 3.17 shows buckling, but it has certainly not disintegrated completely to vermiculite (discoloured biotite), as parts of the mineral have not yet been weathered. Therefore it is thought that layer buckling may already occur before the entire mineral has been converted to vermiculite. The occurrence of various stages of decay in one biotite crystal is rather characteristic. Fig. 3.19 shows that discolouring of biotite may start at the outer, sheaf-like, exfoliated and buckled portion of the biotite crystals. The central parts may have the original colour indicating that the ferrous iron has not yet been oxidized and liberated, after which it is normally transported away.

Kaolinite is commonly found between the exfoliated biotite lamellae before the biotite has been completely weathered to vermiculite (Fig. 3.15). Kaolinite, where it is protected by the biotite and vermiculite layers, forms commonly roughly parallel to these lamellae. Wilson (1966) studied this phenomenon and concluded that "the crystallographic axes of biotite and included kaolinite are commonly parallel" (epitactic crystallization). However, this does not appear to apply in all

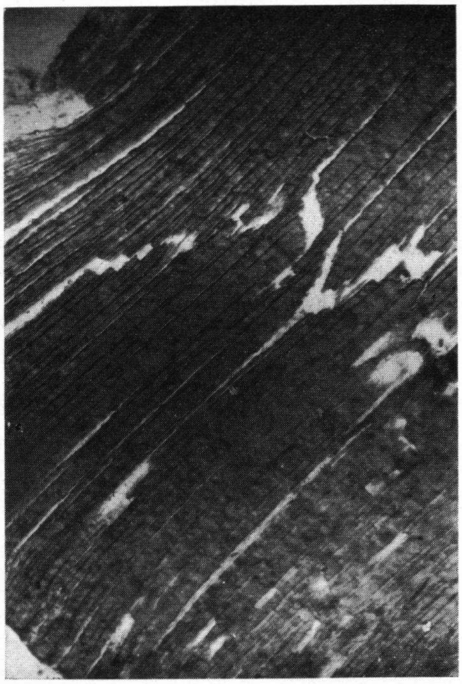


Fig. 3.12. Beginning exfoliation of biotite along cleavage planes. Note also breaking of the mineral (160 ×).

Fig. 3.14. Exfoliated vermiculite-biotite. Many fragments nearly completely dissolved (crossed nicols, 200 ×).

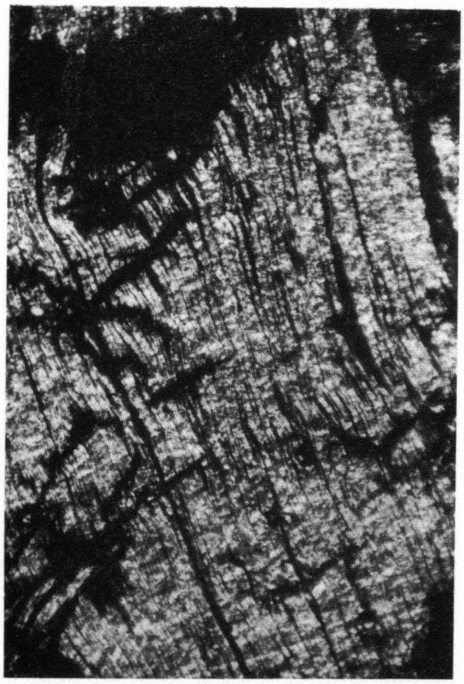


Fig. 3.13. Exfoliated biotite-vermiculite (crossed nicols, 160 ×).

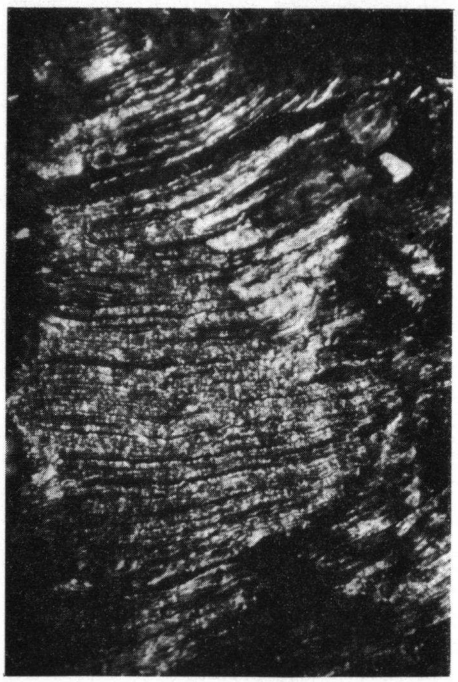


Fig. 3.15. Interlamellar crystallized kaolinite or meta-halloysite (white) between exfoliated vermiculite-biotite lamellae (dark) (crossed nicols, 160 ×).

Fig. 3.16. Giant vermiforms of kaolinite or metahalloysite formed by interlamellar crystallization between exfoliated vermiculite-biotite lamellae (crossed nicols, 160 ×).

Fig. 3.18. Interlamellar crystallized kaolinite or metahalloysite (white) in curled biotite-vermiculite lamellae (dark) (crossed nicols, 200 ×).

Fig. 3.17. Buckling of biotite-vermiculite (160 ×).

Fig. 3.19. Interlamellar crystallization of kaolinite or metahalloysite (light) in curled vermiculite-biotite (dark). Minute droplets containing titanium, derived from the weathering of the biotite crystals and their sagenite inclusions, along the original cleavages (160 ×).

cases. If the biotite does not curl upon weathering (Fig. 3.16) epitactic crystallization is most possible, but if buckling occurs, the kaolinite crystal arrangement may have a rather irregular pattern (Fig. 3.19). Optical observations on coarse interlamellar crystallized kaolinite indicate that the general crystallization direction of kaolinite is parallel to the biotite lamellae. However, minor deviations are numerous, which also seem to depend on the crystallization stages of the kaolinite.

Interlamellar crystallized kaolinite in exfoliated biotite-vermiculite may result in coarse kaolinite vermiforms (Fig. 3.16), which have a completely different micromorphology compared with those formed out of a microcrystalline mass (Fig. 3.3).

The oriented growth of kaolinite within biotite, vermiculite or muscovite has also been noted by Delvigne, 1965; Jonas, 1964; Kato, 1965a; Lodding, 1961; Mackenzie, 1963; and Rex, 1966.

It can not be concluded from X-ray diffraction analyses (table 3.1) whether or not vermiculite is the final product of biotite weathering. It is equally possible that the process continues further and mixed layer minerals are formed.

3.4.1 *Secondary anatase*

Secondary anatase forms from droplets in the zone of oscillating groundwater level of the Barrantes profile (Fig. 3.20; location in Fig. 1.1). Similar droplets have been observed to form during the weathering of biotite. Titanium may be present in the biotite lattice or in the form of rutile (sagenite) inclusions in the mineral. Upon weathering the titanium is released and forms minute droplets, which are in part turbid and in part translucent (Fig. 3.19). It can be found in original cleavages of the biotite or in the mineral itself. Often, however, no droplets form upon weathering although titanium is present in the biotite. In those cases the element must have been removed; it can be transported over varying distances depending mostly on the pH of the medium (Craig & Loughnan, 1964).

According to Raman & Jackson (1965) low anatase concentrations are commonly not noted in diffraction patterns obtained with a diffractometer, because the X-ray peaks fall very close to various silicates in soils. In these cases thin sections or X-ray diffraction in a Guinier-de Wolff camera (Hartman, personal communication) are very helpful to identify the mineral. Huddle & Patterson, 1961, and Reijnders, 1964, also discuss the behaviour of titanium in soil profiles and sediments.

3.5. WEATHERING OF MUSCOVITE

The disintegration of muscovite appears to be quite similar to that of biotite in thin sections, because it exfoliates also upon weathering. However, the lamellae are not curved (Fig. 3.21) in the initial stages, while in the final stages of weathering it may show some curvature. The exfoliation of the lamellae themselves starts at the outer portions with very fine splinters (Fig. 3.23). This is accompanied by a white translucent material which is frequently birefringent (Fig. 3.22). It may be found also along cleavages in small pockets or in continuous bands. Its nature is not known and no data about it could be found in the literature.

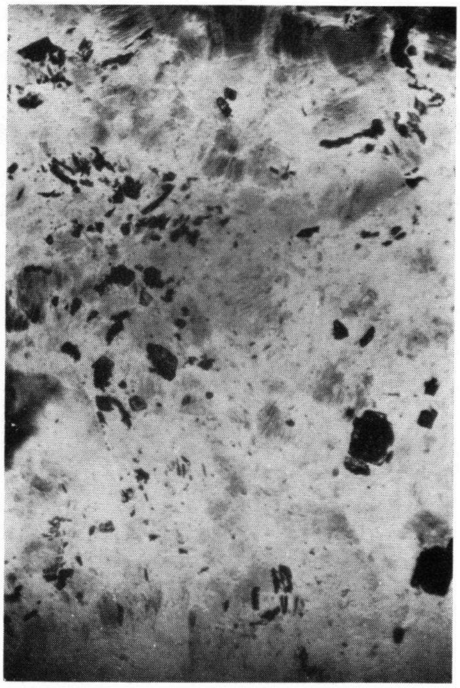


Fig. 3.20. Secondary anatase (dark) in kaolinite matrix (light) (160 ×).

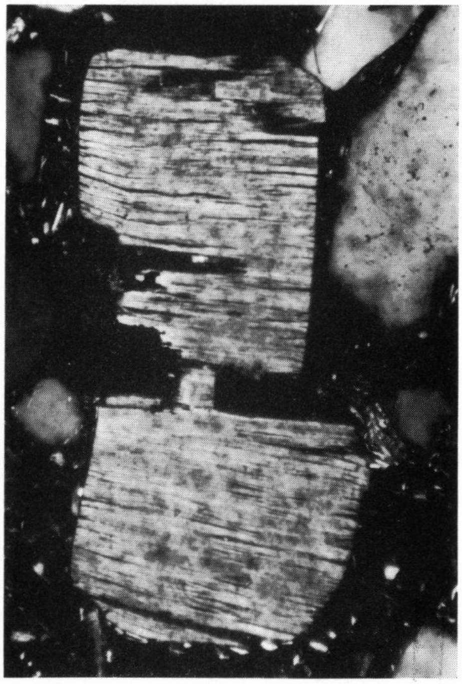


Fig. 3.21. Exfoliation of muscovite along cleavages (crossed nicols, 160 ×).

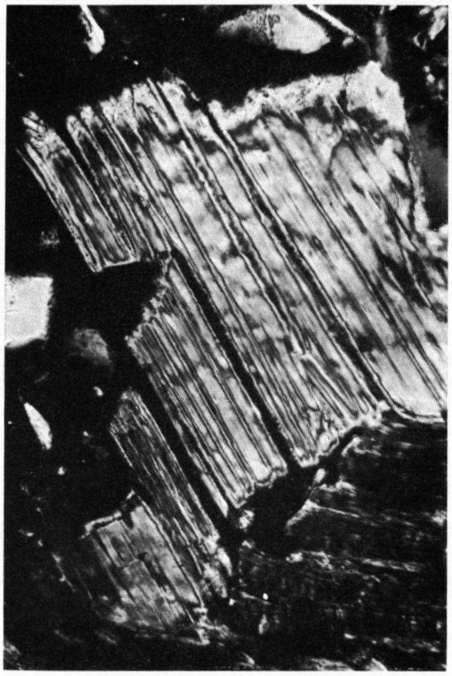


Fig. 3.22. Birefringent translucent material (white) along cleavages and near the ends of muscovite lamellae (crossed nicols, 160 ×).

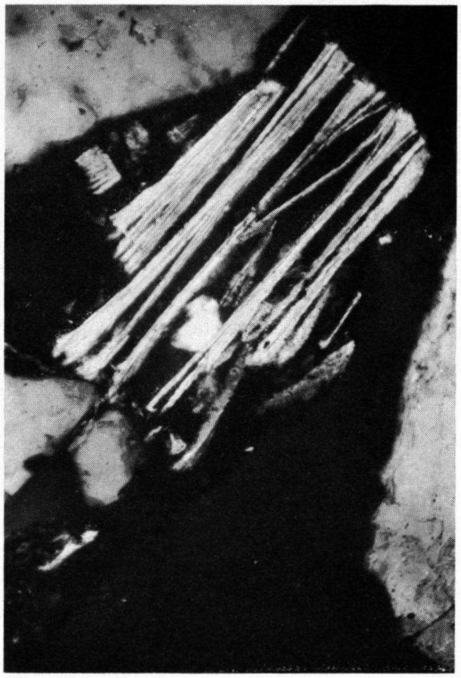


Fig. 3.23. Splintering of exfoliated muscovite lamellae along cleavages (crossed nicols, 160 ×).

During weathering, muscovite shows decreasing birefringence colours and finally, before it is completely dissolved, it turns gray. The decrease of birefringence is unevenly distributed over the mineral and makes optical determinations rather difficult.

According to Brindley (1966) it is not known whether illite constitutes a valid group separate from the micas. As a simplification in table 3.1, the mineral is called illite if it is smaller than 2 μ, and muscovite if it is coarser. This is only an arbitrary division since mineral compositions are not dependent on size classes. Finally it must be noted that the rate and intensity of weathering are different from place to place in a profile. Muscovite may be unweathered at one site in the profile, while it has been weathered to illite at a nearby site.

The principles of mica disintegration are only partly understood. However, changes in interlayer ions, and octahedral layer changes which disintegrate faster than the tetrahedral layers are known to occur (Arvieu & Chaussidon, 1964; Brindley & Sandalaki, 1963; Millot, Lucas & Paquet, 1966; Seed, 1965).

The question whether there is a continuous sequence of reactions in the weathering of micas, montmorillonite, chlorite etc. to kaolinite, forms one of the main problems of modern mineral weathering research. Jackson (1963) summarized some of the work done on this problem and proposed the following sequence:

$$\begin{tikzcd}
 & & \text{montmorillonite} \arrow[dr] & & & \\
\text{mica} \arrow[r] & \text{vermiculite} \arrow[ur] \arrow[rr] & & \begin{array}{l}2:1 - 2:2\\ 14\,\text{Å}\\ \text{intergrade}\end{array} \arrow[r] & \text{Al chlorite} \arrow[r] & \begin{array}{l}\text{kaolinite}\\ \text{and}\\ \text{halloysite}\end{array}
\end{tikzcd}$$

A similar sequence is given by Glenn and Nash (1964):

$$\begin{tikzcd}
\text{mica} \arrow[r] & \begin{array}{l}\text{expanded K}\\ \text{depleted}\\ \text{mica}\end{array} \arrow[r] & \begin{array}{l}\text{chloritized}\\ \text{expansible } 2:1\\ \text{silicates}\end{array} \arrow[r] & \text{kaolinite}
\end{tikzcd}$$

According to Jackson (1963) the 2 : 1 — 2 : 2 intergrade clays appear to accumulate Al in acid soils nearly to the 2 : 2 level during weathering; then a subsequent weathering step 2 : 2 → 1 : 1, involving silica tetrahedra inversion, could give kaolinite (Glenn, Jackson, Hole & Lee, 1960). The sequence given by Jackson implies that change to each succeeding phase is complete (Wilson, 1966). In the case of biotite weathering, which may contain several different phases, Jackson's sequence of reactions is therefore inapplicable according to Wilson. This author also envisages the direct transformation of biotite to kaolinite as drastic because it would involve a conversion of the octahedral layer from tri-to dioctahedral with the expulsion of iron and magnesium and the introduction of aluminium; introduction of Si^{4+} ions in the tetrahedral layer; tetrahedral inversion; and formation of a complete gibbsite sheet in the interlayer spaces.

Wilson concludes that epitactic crystallization affords a more acceptable explanation. Thus, initial weathering opens out the biotite flakes along the cleavage planes. The expanded surfaces then act as templates that control the orientation of the kaolinite during subsequent growth presumably from an alumina-silica gel. However, the precise chemical and physical conditions that could induce such a crystallization are unknown, according to Wilson.

Altschuler, Dwornik & Kramer (1964) described the transformation of montmorillonite to kaolinite. According to these authors, intracrystalline leaching of tetrahedral silica layers results in approximately regular interposition of resultant stripped pockets within montmorillonite and creates a regular 1 : 1 mixed-layered montmorillonite-kaolinite. The stripped kaolinite-like pockets develop hexagonal outgrowths of true kaolinite by lateral epitaxy. In this mechanism the tetrahedral layers are thought to be less resistant to weathering than the octahedral layer, which is in contradiction to what has been said above.

Concludingly it may be said that it remains a question whether a sequence of reactions between the 2 : 1 — 2 : 2 minerals and kaolinite exists, or whether the relation is perhaps an epitactic crystallization and thus not a direct conversion of micas to kaolinite.

As in the case of biotite, it can not be determined from X-ray diffraction analyses (table 3.1) whether or not the mixed-layer minerals can be related to muscovite weathering: it is very probable that, at least in part, they are derived from primary biotite and muscovite.

3.6. WEATHERING OF OTHER PRIMARY MINERALS

3.6.1 *Hornblende*

Weathering of hornblende results in the liberation of iron, upon which the colour changes from green-yellow to gray, until finally the mineral disintegrates completely. No secondary minerals could be detected.

3.6.2 *Quartz*

Silica gels have sometimes been observed along microcracks in the mineral, while pitting of quartz occurs sometimes in the Barrantes and Cambados profiles. Where the quartz contains inclusions of other primary minerals, the latter are often completely weathered, which may produce cavities in the quartz.

3.7. WEATHERING OF METAMORPHIC ROCKS

Samples of weathered amphibolite (K in table 3.1; location in Fig. 1.1) and schists (L13 and S3) have been examined for their secondary mineral content. It follows from table 3.1 that kaolinite and metahalloysite are the most common secondary minerals, similar to those of the granites.

3.8. QUATERNARY ESTUARINE TERRACE

Sample P4 (table 3.1) has been taken in a silty clay, whereas sample B4 represents the composition of a clay ball armoured with quartz pebbles. Kaolinite is the main secondary mineral in both samples.

Summarizing, it may be stated that kaolinite and metahalloysite are the most common clay minerals in granites, metamorphic rocks and terrace sediments of the area, independent of the age or depth of weathering.

4. FABRIC ANALYSES OF WEATHERING PROFILES

An attempt has been made to apply Brewer's (1964) method of fabric analyses of soils to the entire regolith. This involved the introduction of a number of new terms into Brewer's system. At this stage this application is still mainly descriptive, and much more work has to be done to relate the observed fabrics to the processes involved in weathering.

The most characteristic fabrics occurring in various profiles of the area are given in table 4.1. A summary of the definitions introduced by Brewer is given first. This is followed in every section by a number of terms proposed and used by the writer.

4.1. PLASMA

> Plasma of a soil material is that part which is capable of being or has been moved, reorganized, and/or concentrated by the processes of soil formation. It includes all the material, mineral or organic, of colloidal size and relatively soluble material which is not bound up in skeleton grains.

The plasma definition of Brewer thus includes all the material of colloidal size which is not bound up in skeleton grains. This means that colloidal material present in skeleton grains may not be termed plasma, so that all the terms of Brewer which are based on plasma, as for instance plasmic fabrics, can not be used, and new names must be introduced. In the writers opinion this is not necessary if the plasma definition is modified in such a way that plasma may also occur in skeleton grains. The definition must, however, also include the possibility to describe the plasma present in those parts of a weathering profile which are lying below the soil horizons. It is proposed to call the plasma in the new definition m-plasma, in order to avoid confusion with the plasma definition of Brewer. The proposed definition of m-plasma is (*referring to terms introduced by the writer):

> *m-plasma includes all the material (minerals, gels, organic matter) of mainly colloidal sizes, present in weathering profiles (soils, colluvia, saprolites and saprocks).

The definition refers to "mainly colloidal sizes" because locally even coarser sizes than silt are included in the m-plasma. This possibility is indicated by Brewer in his silasepic fabric which consists of clay, silt and sometimes even coarser material.

4.2. PLASMIC FABRICS

A. Asepic plasmic fabrics: domains in the plasma are mainly unoriented with regard to each other. They are divided into two subgroups (domains are clusters of anisotropic plasma grains in which some degree of orientation exists):
   a. Argillasepic fabric: the plasma consists dominantly of clay minerals.
   b. Silasepic fabric: the plasma consists of clay, silt and sometimes even coarser material (Fig. 4.4).

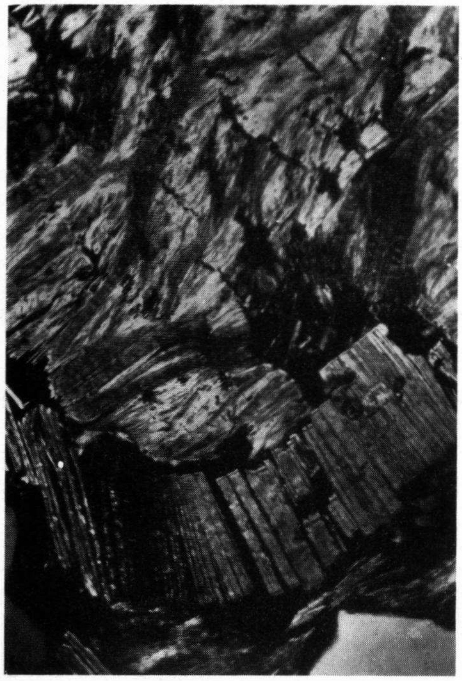
B. Sepic plasmic fabrics: domains in the plasma are mainly oriented with regard to each other (striation).
   a. Insepic fabric: isolated patches, or islands, in the plasma have a striated orientation. (Fig. 4.1, 4.3, 4.5, 4.9).
   b. Mosepic fabric: this is an extreme development of insepic fabric, the patches with striated orientation are numerous and may even adjoin each other.
   c. Vosepic fabric: the plasma is oriented dominantly parallel to the walls of voids.
   d. Skelsepic fabric: the plasma is oriented dominantly parallel to the surface of skeleton grains (Fig. 4.6, 4.8).
   e. Masepic fabric: elongated oriented zones in the plasma; they may have several directions (Fig. 4.9).
   f. Lattisepic fabric: two sets of very short, discontinuous plasma separations (features characterized by a significant change in the arrangement of the constituents rather than a change in concentration of some fraction of the plasma), usually oriented approximately at right angles to each other.
   g. Omnisepic fabric: all the plasma exhibits a complex striated orientation pattern (Fig. 4.7).

The plasmic fabrics of Brewer are based on plasma separations and not on concentrations of the plasma. It is questionable, however, if all oriented patches occurring in the plasma are really due to separations. This is indicated by Fig. 4.1, 4.5, 4.8 and 4.9, in which the elongated oriented zones and isolated patches are all composed of secondary minerals in various stages of growth. The plasmic fabric types in these figures are therefore certainly due to concentration. Nevertheless Brewer's terms based on separations are applied in this work.

An extreme case of plasma concentration is given in Fig. 4.5. Coarse kaolinite vermiforms are present beside smaller ones in a matrix of kaolinite, as is indicated by X-ray diffraction analyses. Most kaolinite vermiforms have grown to sizes which are larger than silt and therefore do not belong anymore to the plasma.

Most of the plasmic fabric types of Brewer occur also in weathered primary minerals. They may be indicated by the prefix "min" (for instance* minasepic fabric, *minsilasepic fabric etc., see table 4.1) in order to avoid confusion. It must be noted however that the entire plasmic fabric or part of it is the result of the formation and growth of secondary minerals and has therefore formed as a result of concentration rather than separation of the plasma.

Fig. 4.1. Insepic plasmic fabric in crack plane between two mineral grains of Cambados saprolite. Oriented patches in plasma are possibly metahalloysite (crossed nicols, 160 ×).



Fog. 4.2. Interlamellar crystallized kaolinite or metahalloysite (white) in curled biotite-vermiculite lamellae (minphyllsepic and minphyllasepic fabric) of Cambados saprolite. Straight lamellae of exfoliated muscovite (crossed nicols, 160 ×).

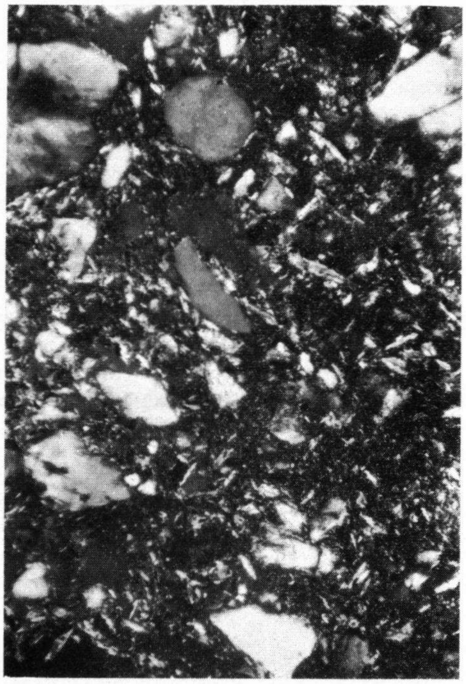


Fig. 4.4. Silasepic plasmic fabric in A-horizon of recent soil in colluvium of the Cambados profile. The humus form is a mull, which is intimately mixed with primary and secondary minerals (crossed nicols, 160 ×).

Fig. 4.3. Insepic plasmic fabric, with exfoliated muscovite skeleton grain, of Cambados saprolite (crossed nicols, 160 ×).

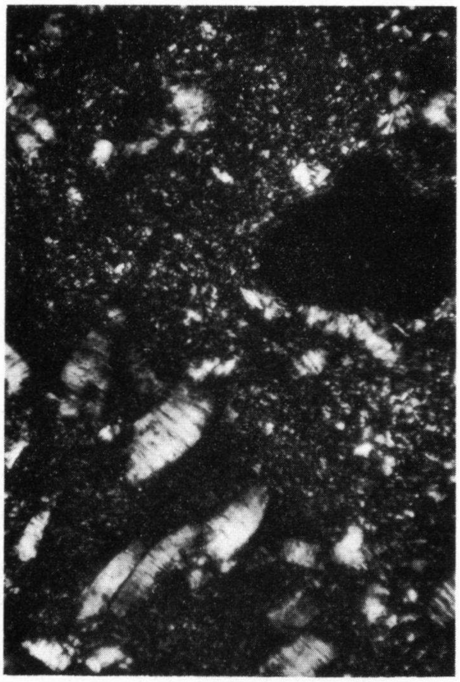


Fig. 4.5. Insepic plasmic fabric of Barrantes saprolite. All oriented patches are kaolinite, of which some have grown to large vermiforms (crossed nicols, 160 ×).

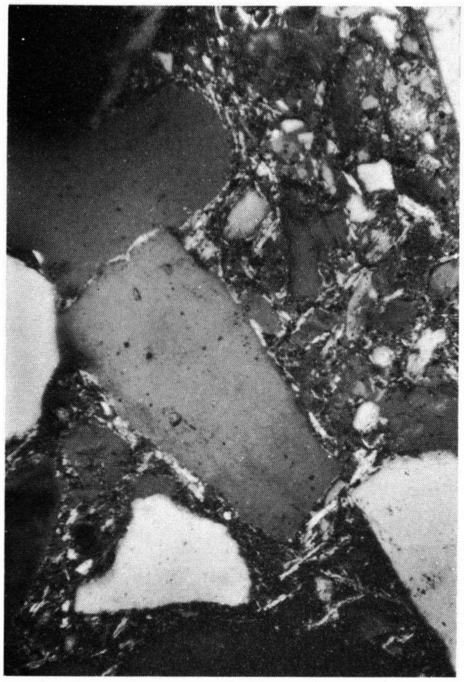


Fig. 4.6. Skelsepic fabric in colluvium of Cambados profile. Oriented silt-clay around skeleton grains (crossed nicols, 160 ×).

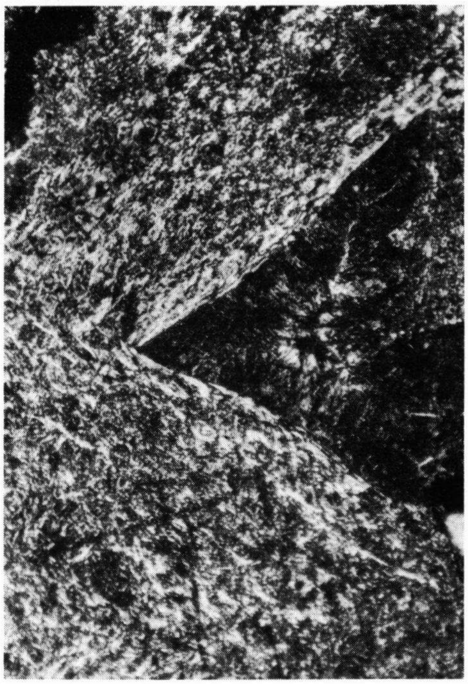


Fig. 4.8. Skelsepic fabric around completely weathered primary mineral (minphantosepic fabric) in Cambados saprolite. Highest degree of plasma orientation near the surface of the skeleton grain. The skeleton grain has a mininsepic plasmic fabric (crossed nicols, 160 ×).

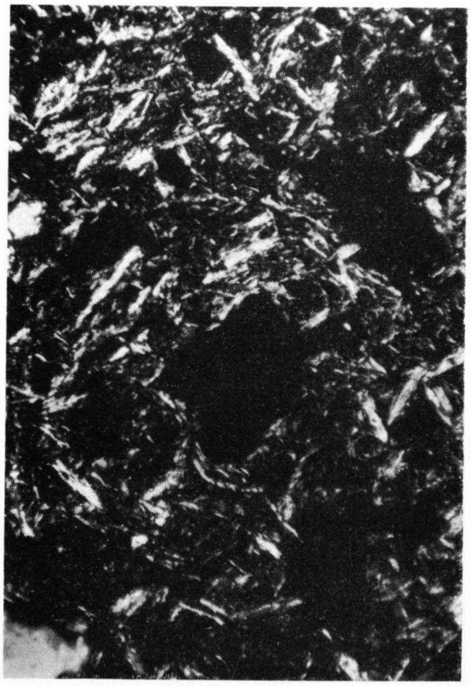


Fig. 4.7. Omnisepic fabric of silt-sized and coarser biotite in the Sisán estuarine terrace (crossed nicols, 160 ×).

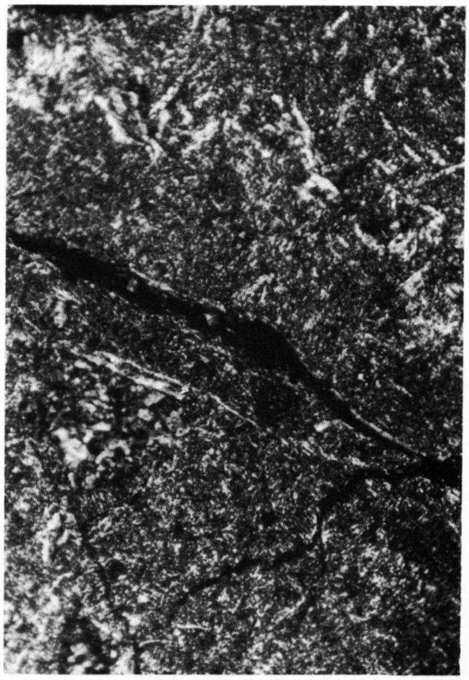


Fig. 4.9. Elongated and patchy zones of oriented plasma (masepic and insepic fabrics) of possibly metahalloysite in Cambados saprolite (crossed nicols, 160 ×).

Additional terms are proposed in connection with crystallization of secondary minerals between exfoliated mica layers, which themselves may show various stages of decomposition:

- *Minphyllasepic fabric: no orientation of secondary minerals is visible under the microscope between the exfoliated mica layers (phyll from phyllosilicates) (Fig. 4.2).
- *Minphyllsepic fabric: some orientation of secondary minerals is visible under the microscope between the exfoliated mica layers (Fig. 4.2).

Finally primary minerals which have been completely weathered but can still be indicated in the plasma as a distinct entity (Fig. 4.8) must be defined.

- *Minphantosepic fabric: a completely weathered primary mineral which is present in the plasma as a distinct entity (phanto from phantom) (Fig. 4.8).

Sometimes remnants of primary mineral inclusions can be distinguished as separate entities in the plasma with or without secondary minerals accompanying them. These are for instance illite-muscovite or illite-muscovite-gibbsite fields indicating former plagioclases.

4.3. RELATED DISTRIBUTION OF PLASMA AND SKELETON GRAINS

a. Porphyroskelic: the plasma occurs as a dense groundmass in which skeleton grains are set after the manner of phenocrysts in a porphyritic rock.
b. Agglomeroplasmic: the plasma occurs as loose or incomplete fillings in the intergranular spaces between skeleton grains.
c. Intertextic: the skeleton grains are linked by intergranular braces or are embedded in a porous groundmass (matrix in the sedimentary petrological sense).
d. Granular: there is no plasma, or all the plasma occurs as pedological features (recognizable units within a soil material which are distinguishable from the enclosing material for any reason).

Mineroplasmic is a term proposed to describe the distribution of plasma in relation to skeleton grains, when the plasma occurs in a primary mineral, rock fragment or saprock. The prefix "minero" is used here instead of "min".

- *Mineroplasmic: the plasma occurs in weathered primary minerals, rock fragments or saprock.

4.4. VOIDS

4.4.1 *Arrangement of voids*

a. Intrapedal: voids occurring within the s-matrix of peds or apedal soil materials (s-matrix is the matrix including skeleton grains; a ped is an individual natural soil aggregate).
b. Interpedal: voids occurring between peds.
c. Transpedal: voids traversing the soil material without any specific relationship to the occurrence of peds; they usually extend beyond the limits of a single ped.

Five new terms are proposed:

- *Intramineral: voids occurring in weathered primary minerals.
- *Intermineral: voids occurring between primary minerals.
- *Transmineral: voids traversing one or more primary minerals.
- *Interplasmamineral: voids bounded partly by a primary mineral surface and partly by plasma.
- *Interplasmal: voids occurring in the plasma.

4.4.2 *Morphological classification of voids*

a. Simple packing voids: they are due to random packing of single grains.
b Compound packing voids: they result from packing of compound individuals, such as peds.
c. Vughs [1]: these are relatively large irregular voids. They have never a planar shape.
d. Vesicles: they differ from vughs principally in that their walls consist of smooth, simple curves; that is, they are smoothed and regular.
e. Channels: these are voids that are significantly larger than those which would result from normal packing of single grains.
f. Planes: these are simply voids that are planar according to the ratios of their principal axes. Three types are distinguished:
f1. Joint planes: planar voids that traverse the soil material in some fairly regular pattern, such as parallel or subparallel sets.
f2. Skew planes: planar voids that traverse the soil material in an irregular manner.
f3. Craze planes: these are essentially planar voids with a highly complex conformation of the walls due to the interconnection of numerous short flat and/or curved planes.

One new term is proposed:

- *Crack planes: these are planar voids which traverse the weathered but still cohesive rock (saprock) or minerals and rock fragments in the regolith over minor distances.

It must be noted that the crack planes have frequently very irregular patterns similar to skew planes or even craze planes.

4.4.3 *Size classification of voids*

a. Microvoids 5—30 μ
b. Mesovoids 30—75 μ
c. Macrovoids > 75 μ

4.4.4 *Conformation of the void-walls*

a. Curved: this term is applied particularly to acicular and planar voids (see below) that deviate significantly from a straight line or flat plane in the direction of their long axes.

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[1] In geological literature this term is written without h.

b. Regular: there are virtually no reentrant or acute angles between faces or segments of the walls.
c. Irregular: this term is applied particularly to equant and prolate voids whose walls have a significantly irregular conformation.
d. Mammillated: the walls consist of rounded, interfering, spheroidal surfaces.

4.4.5 *Smoothness of the void-walls*

a. Orthovoids: the walls appear morphologically to be due to the unaltered, normal random packing of plasma and skeleton grains.
b. Metavoids: the walls appear morphologically to be significantly smoother than would result from the normal random packing of plasma and skeleton grains.

The smoothness of a void wall is not necessarily the result of the random packing of plasma and skeleton grains. The walls of crack planes have frequently no plasma cutans, which makes the surfaces of the minerals adjacent to the crack plane the void wall. For this case the term paravoid is introduced.

* Paravoids: the walls appear morphologically not to be due to a random packing of plasma and skeleton grains.

4.4.6 *Shape (ratios of axes) of voids*

The shapes are: equant, prolate, arcuate, planar, and acicular.

4.5. CUTANS

Cutan: a modification of the texture, structure, or fabric at natural surfaces in soil materials due to concentration of particular soil constituents or in situ modification of the plasma; cutans can be composed of any of the component substances of the soil material.

4.5.1 *Characteristics of the surfaces affected*

a. Grain cutans.
b. Void cutans.
c. Ped cutans.

4.5.2 *Mineralogical nature of the cutanic material*

a. Argillans: mainly composed of clay minerals.
b. Ferri-argillans: consist of a mixture of clay minerals and iron oxides.
c. Organo-argillans: consist of clay minerals stained by organic compounds.
d. Sesquans: consist of sesquioxides or hydroxides.

4.6. FABRICS IN CRACK PLANES

The important role of joints and cracks in the weathering of granites has been explained in sections 2.1.1 and 2.1.2. In the initial stages of weathering the decomposition of the rock takes place along micro-cracks, which are normally not wider than 10 μ (Bisdom, 1967). In more advanced stages of saprock weathering the micro-cracks are widened and new ones are formed. At a certain stage the pattern of micro- and macro-cracks in the saprock is developed in such a way that mineral and rock fragments may be released because they are bounded on all sides by cracks. Therefore these fragments form part of the saprolite because they have become part of the loose, in situ weathered granite. The plasmic fabrics which occur in the cracks which bound the mineral and rock fragments in the saprolite, are no longer named with the prefix "min". Cracks in the fragments themselves, however, have to be given the prefix "min" as is the case with fabrics occurring in the plasma of cracks present in the saprock.

The micro-cracks are occupied by limonite, gels, microcrystalline material and secondary minerals. Sometimes the growth of secondary minerals normal to the void walls is observed. Examples of minargillasepic, mininsepic and minlattisepic fabrics occur in samples WD4a, A13k, and A17 in table 4.1, which indicates that both oriented and unoriented plasma occur in the micro-cracks (microvoids),

Where the micro-cracks have become macro-cracks (microvoids larger than 10 μ, meso- and macrovoids), the clayey material may remain in the cracks but it can also be removed.

The removal of clayey material is frequently observed in the saprolites above the level affected by oscillating groundwater. These saprolites consist of angular weathering debris with minor amounts of clay (4.4 — 6.9 %). In thin sections (WD4b and F8a) it can also be observed that in the macro-cracks, between the mineral and rock fragments, silt sized (2—20 μ) material and coarser grains are common. It is also noted that many macro-cracks are devoid of any weathering debris. The plasmic fabric type is always silasepic if minerals are present in the macro-cracks.

In profiles which are at least during part of the year affected by an oscillating groundwater level the weathering profiles consist of more clayey material. The macro-cracks are occupied by clay which may locally fill the entire crack (Fig. 4.1). With the exception of skelsepic- and minskelsepic fabrics, all other plasmic fabrics could be observed in the macro-cracks (A13d, A13i, A14a, A16a, M8b, M8c, and L9a).

4.7. FABRICS IN SAPROLITES

Other morphological void types than crack planes occur also in saprolites (A25a to L9b). It follows from table 4.1 that vughs and channels are not only present in the plasma surrounding primary minerals or rock fragments, but also in the m-plasma inside weathered primary minerals. Joint, skew, and craze-planes are only common in the plasma situated around the primary minerals.

The plasma can be oriented (sepic) or unoriented (asepic). No cutans are present, although sometimes higher iron concentrations occur in the void walls than in the plasma adjacent to the walls. Skelsepic fabrics are rare (Fig. 4.8), but all other fabric types including minphyllsepic and minphantosepic fabrics are common.

4.8. FABRICS IN COLLUVIA AND SOILS

The most characteristic property of colluvia is the occurrence of skelsepic fabrics (Fig. 4.6), which are only rarely found in saprolites. They also have a rather dense packing although many voids occur. The fabric analyses of thin sections A8, A9 and A10 indicate that omnisepic fabric types are present. This means that virtually the entire plasma is oriented. In those parts of the colluvia which are affected by soil formation, this orientation can be disturbed (A1 to A5b), and the fabric becomes eventually silasepic (Fig. 4.4). These silasepic fabrics are therefore common in the umbric epipedons in the area(E1, F2, H1, and H7). Cutans are uncommon, although sometimes, as in the case of saprolites, iron can be concentrated in the pore walls.

4.9. FABRICS IN AN ESTUARINE TERRACE

From the heterogeneous terrace deposits mentioned in 2.6, two profiles have been sampled: profile B, which consists of quartz pebbles and a matrix of clay and silt; and profile P, consisting almost entirely of silt-sized micas.

Sample B1 and B2 have been sampled below the groundwater level. There is no oriented plasma around the pebbles of quartz and rock fragments. Some orientation can be observed only around voids. Mud balls have been studied micromorphologically (B3 and B8a); they are very densely packed, while voids are relatively small. A lattisepic fabric was found in sample B3, but most of the plasma is unoriented.

Some of the mud balls have an armour of fine and coarse gravel (B8b). The boundary between a mud ball and its armour is quite sharp and irregular, while plasma is usually oriented in this zone (skelsepic fabric). However, this orientation occurs only where the pebble has been imprinted in the mud ball and not on the other side of the pebble. The matrix of the armour is unoriented near the mud ball surface (silasepic fabric), but is vosepic at the outside of the armour, which means that the plasma is oriented around voids. Channel argillans are frequently present.

The fabric of a gravel which has been cemented to a hard horizon by ferri-argillans is given by sample B33. The horizon is not massive because meso- and macrovoids are numerous.

Sample B39 is part of the umbric epipedon of a recent soil, which has a silasepic fabric. No orientation around skeleton grains is present in this umbric epipedon.

With regard to profile P, it follows from table 4.1 that omnisepic fabrics are present at the base of the profile (sample P5), while interlamellar crystallization of kaolinite (Fig. 4.2) in biotite occurs here on a large scale.

In sample P3 the plasma is still oriented in several directions (Fig. 4.7), but interlamellar crystallization of kaolinite in biotite has only locally been observed. The omnisepic fabric of sample P3, which forms part of a prisma, has probably resulted from shrinking and swelling combined with rotational movements of skeleton grains (Lafeber, 1964). Joint-siltans, with a lamination across the joints, are thought to be deposited in former desiccation cracks in the same manner as channel argillans.

5. SUMMARY AND CONCLUSIONS

Joints, micro-cracks, and spheroidal weathering

1. Granite weathering proceeds from joints. This means that the same stages of in situ weathering occur simultaneously at all levels.
2. Water transport in the bedrock occurs already along joints which are difficult to detect with the naked eye. In these joints reducing environments exist, which can be inferred from the colour of the weathered material (bluish green) and the mineral content (pyrite and siderite).
3. The material present along joints in saprolites is always finer grained than in the surroundings, irrespective of the stage of weathering of the saprolite.
4. Crack systems are important in the weathering of rocks. The phenomenon of spheroidal weathering is directly relatable to micro-crack systems in the weathered but still cohesive rock (saprock) of a boulder. Where a very dense micro-crack system exists in the saprock, no scales can form and the rock crumbles immediately. Where scales have been formed, they are in turn crumbled by a further development of cracks.
5. Micro-cracks can be divided into two categories: structural- and weathering micro-cracks. Structural micro-cracks have been developed in zones of weakness which existed already in the rock before weathering started (joints, dislocations, cleavages, twin planes, grain- and subgrain boundaries). Weathering micro-cracks are only to be found on the outside of boulders, in rock fragments and minerals which are intensively weathered. Frequently they are sinuous, whereas structural micro-cracks are straight. Combinations of both types of micro-cracks are common.
6. Spheroidal weathering is not related to zones of iron concentration. The limonite band, which occurs frequently near the surface of boulders,

has resulted from the development of cracks. Weathering agents proceeding along the cracks liberate iron from biotite and hornblende, which is subsequently concentrated in bands by a process of diffusion through the micro-cracks.

7. The largest thickness of saprolites (presumably 30 metres) is found in the coarse-grained biotite-hornblende granite.
8. Mass movements initiate along any level between the bedrock and the surface.

Influence of groundwater

9. The groundwater level may oscillate over several metres. The lowest level is reached in the month of September.
10. The oscillating groundwater level chiefly affects the secondary mineral composition along joints, while it appears to have little or no effect on the weathered granite adjacent to the joints. In the joints montmorillonite, siderite, and possibly palygorskite and sepiolite, are present, as well as kaolinite, metahalloysite, gibbsite, vermiculite, muscovite, illite, biotite, mixed-layer minerals, feldspars and quartz, which can also be found in the surrounding granite.

Fabrics in saprolite and deposits

11. A number of additional terms are proposed by the writer in order to make it possible to apply the fabric system of Brewer not only to soils but to the entire weathering profile, including the plasmic fabrics which occur in weathered primary minerals.
12. Skelsepic plasmic fabrics (oriented clay-silt around minerals) are common in colluvium, but are only rarely found in saprolites. In soils they are also rarely present, although most soils have been developed in the colluvium. This indicates that soil forming processes have destroyed the skelsepic fabric.

Soils

13. Most uncultivated soils in the area are entic- and orthic haplumbrepts. Soils with an umbric epipedon of less than 25 cm, which have no cambic horizon have been termed: entic haplumbrepts with an umbric epipedon of less than 25 cm in thickness.
14. Above an altitude of 250 metre, an umbric epipedon of 1.40 metres in thickness has been found. The epipedon cannot be related directly with peat formation. It has a mull-like moder at the base, which gradually changes to fine moder, which in turn changes to grob moder at the top of the umbric epipedon. Mull-like moder and fine moder are frequently present below the 250 metre altitude, whereas mull has only been found below 50 metres.
15. Some unusual large d-spacings (21Å, 23Å, 29Å, 34Å, 37Å and 45Å) have only been measured in the mixed-layer minerals of both a paleosol and recent soils. These large d-spacings are all present in parts of the profile which contain organic matter. This possibly indicates an association of the clay minerals with organic compounds.

Heavy minerals

16. Heavy mineral analyses are often of great assistance to establish the boundary between the saprolite and the overlying colluvium, because the colluvium contains normally metamorphic heavy minerals which are not found in saprolites devoid of xenoliths. Staurolite, andalusite and sillimanite are the commonest metamorphic heavy minerals.
17. Staurolite, andalusite, sillimanite, garnet, zircon, tourmaline, and epidote are common heavy minerals in the river Umia. Rutile, anatase, brookite, kyanite, augite, titaniferous augite, and titanite are present in small amounts. Numerous feldspar fragments are found in the river Umia and its tributaries.

Mineral transformations

18. Kaolinite and metahalloysite are the most common secondary minerals in both weathered granites and metamorphic rocks. They occur in all fractions smaller than 50 μ, but kaolinite may be even larger.
19. Gibbsite may form in a highly alkaline environment and where water movement is very restricted, e.g. in micro-cracks of weathered feldspars.
20. Illite (muscovite smaller than 2 μ)- and muscovite inclusions in plagioclases are more resistant to weathering than plagioclases. Together with gibbsite and microcrystalline material (possibly kaolinite and metahalloysite) they are present in weathered plagioclases.
21. Microcline is most frequently devoid of secondary minerals. Solution seems to be most intense along twin planes. Therefore microcline weathering debris is rather angular, whereas plagioclases are weathered very irregularly along micro-cracks which cross the mineral in a dendritical pattern.
22. Biotite exfoliates upon weathering along cleavages, and lamellae are formed, which in turn follow the same process. The exfoliation process is accompanied by solution and discolouring (brown-white-gray) of the mineral. Interlamellar crystallization of kaolinite or metahalloysite may take place between the biotite-vermiculite lamellae, and very coarse kaolinite minerals may form in this manner.
23. Muscovite is also exfoliated upon weathering. The lamellae are frequently accompanied by a white translucent and birefringent material. It also discolours upon weathering, but the lamellae remain straight until the final stages of weathering in which curling may occur. Biotite may show already buckling and curling during the biotite-vermiculite conversion.

24. No relation has been found between the mixed-layer minerals and the primary micas, because the nature of the former has not as yet been elucidated.
25. Large red pleochroic secondary muscovite as well as kaolinite has been observed to form and was determined by X-ray diffraction and the electron microprobe.
26. No secondary minerals have been found related to the weathering of hornblende.
27. Minute droplets containing titanium, derived from the weathering of the biotite crystals and their sagenite inclusions, are commonly found along the original cleavages of biotite. Sometimes anatase has been observed to form out of these droplets.

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