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A Study of the Ferrallitic Weathering of an Amphibole Schist in Peninsular Malaysia

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ABSTRAK

Pertukaran mikromorfologi dan mineralogi yang disebabkan oleh luluhawa di dalam satu profil skis amfibol di Semenanjung Malaysia telah dikaji. Sungguhpun batuan hamparan yang keras tidak dijumpai, banyak batu-teras batuan asal didapati terdedah. Pemerhatian dengan mikroskop elektron pengimbas dan keratan nipis menunjukkan bahawa aktinolit mengalami luluhawa lebih cepat daripada epidot. Kedua-dua mineral ini mengalami perlarutan kongruen dan diganti oleh kaolinit baru yang berbentuk vermi dan haloisit pada bahagian bawah saprolit. Data ini disokong dengan kajian difraktometer sinar-X. Analisis kimia bagi lingkungan luluhawa menunjuk bahawa dalam peringkat pertama luluhawa feralitik, mengikut cara isovolumetrik, unsur-unsur alkali dan bumi beralkali terhilang bersamaan dengan sebahagian besar silikon, tetapi aluminium didapati malar. Ferum didapati berkumpul semasa peringkat pertama luluhawa. Permukaan luluhawa bagi profil skis amfibol ini didapati tajam dan proses pedoplasma berlaku mengikut struktur-struktur geologi dengan menghasil bahan tanah yang kaya lempung.

ABSTRACT

Micromorphological and mineralogical changes resulting from the weathering of an amphibole schist in Peninsular Malaysia have been studied. Although the hard bedrock mass is not reached, many large corestones of unweathered rock material are exposed. Thin sections and SEM observations show that the actinolite weathers faster than epidote. Both undergo congruent dissolution and are replaced by new formed vermiform kaolinite and halloysite in the lower saprolite, but by kaolinite and gibbsite in the upper saprolite. This data is corroborated by XRD studies. Chemical analyses of the weathering rims, expressed according to the isovolumetric method, show that they are already in the first stage of ferrallitic weathering with the alkaline and alkaline earth elements lost, as is a large part of the silicon, though aluminium remains practically constant. Iron accumulates during the first stage of weathering. The weathering front is abrupt, and pedoplasmation follows geological structures, forming a clay-rich soil material.

INTRODUCTION

In Peninsular Malaysia, observations of weathering profiles were first cited in the Malayan Geological Survey Memoirs (Roe 1951). Later, soil scientists made several detailed studies on the chemical, mineralogical and micromorphological changes related to the transformation of hard rock material to soil (Yeow 1975; Eswaran and Wong, 1977). Most of these studies dealt with relatively coarse grained, rather homogeneous rock material (e.g. granites, gneisses), and little attention was given to the heterogeneous metamorphic rocks, although they form quite an important soil parent material.

In this study, the micromorphological and mineralogical changes due to weathering of an amphibole schist profile under humid tropical, well drained conditions were investigated.

MATERIALS AND METHODS

Location and Geological Setting

An amphibol schist profile exposed along the Karak-Kuantan Highway at 54 km was sampled in detail (Zauyah 1986).

The amphibole schist outcrops as a lenticular-shaped body (1 km long) and forms one of many similar bodies occurring commonly within a sequence of low-grade regionally metamorphosed schists of the Bentong Group (Lower Palaeozoic). These schists outcrop on the eastern slopes of the Main Range of Peninsular Malaysia near the town of Bentong and have given rise to a dissected, hilly to undulating terrain. The amphibole schists occurring in this area have been postulated by Richardson (1947) to have developed through the metamorphism of calcareous sediments.

The climate of this region is equatorial with a mean annual rainfall of 234 cm distributed throughout the year with a maxima between October and January and between March and May. The mean annual temperature is 26°C.

The profile sampled is located on a gently sloping part of a hill, 130 m above sea level, in a dissected hilly terrain.

A schematic sketch of the weathering profile is shown in *Fig. 1* and the profile description in Table 1. The weathering sequence of this rock was studied starting from the alteration zone surrounding a corestone as the bedrock mass is not exposed. Fresh rock samples (R) were collected from most of the corestones occurring in the lower, as well as the upper saprolite. The other samples were collected from the weathering rims and in between the corestones (Cr). In addition, soil material was sampled along joint planes (R(s) as well as in the overlying soil, a clayey, kaolinitic, isohyperthermic Typic Hapludox.

Laboratory Analyses

Thin sections in all rock samples were prepared. For the weathered or soft saprolite, the samples had to be impregnated with polyester resin (Eterset 2660P) prior to the preparation of thin sections of 12 cm x 9 cm and 9 cm x 6 cm size. Weathering features were described according to Stoops *et at.* (1979) and Bullock *et al.* (1985). Fresh fracture surfaces of all the samples were examined with a Jeol 35C scanning electron microscope.

Total analysis of the major elements was carried out by X-ray fluorescence according to Hutchison (1974). Active and free iron were determined according to Schwertmann (1964), and Mehra and Jackson (1960), respectively. Free iron was removed from uncovered thin sections as proposed by Bullock *et al.* (1975).

The bulk mineralogy of all the fresh rock and weathered samples and the sand, silt and clay fractions of the soil samples were analysed by X-ray diffraction. The crystallinity of kaolinite was determined on non-oriented powder mounts of

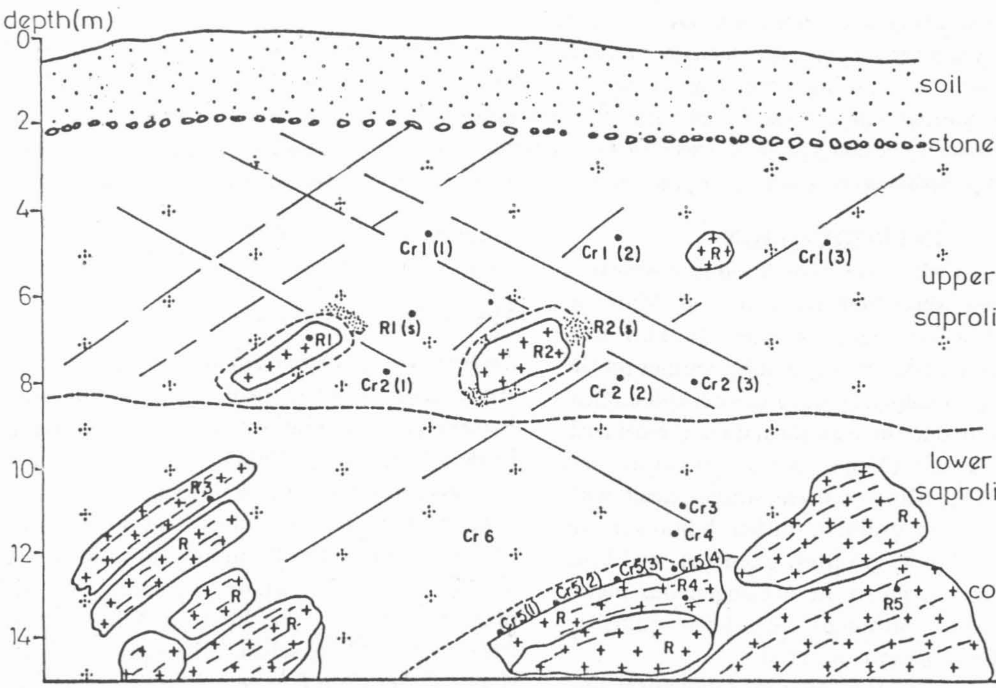

Fig. 1. Schematic sketch of weathering profile over the amphibole schist showing the sampling points.

dithionite-citrate-bicarbonate-treated clay samples, after Hinckley (1963).

RESULTS AND DISCUSSION

Macroscopic Description

The fresh rock material from the corestones is fine grained, very hard and shows a compositional banding (10 to 15 mm) of dark gray (7.5YR 3/10) to gray (7.5YR 6/0) and olive gray (5Y 6/2).

The first 10 cm of the weathering rim shows many shades of colours. The predominant colours are pale yellow (2.5YR 8/4) to yellow (10YR 7/8) with black streaks (10YR 2/1). The weathered rock material is quite coherent closest to the core but becomes friable towards the outside. At about 20 to 30 cm from the hard rock, the colours become more uniformly reddish yellow (7.5YR 6/8). The weathered material also becomes soft and breaks easily between the fingers, though the rock fabric is still preserved.

The samples collected between the corestones belong to the lower and upper saprolite. Generally, the samples in the lower saprolite are reddish yellow (10YR 6/8), while the samples from the upper saprolite are yellowish red (5YR 4/6). These samples may break easily between the fingers but the rock fabric is still evident.

The soil samples along joints in the upper saprolite are yellow red (5YR 4/6) to red (2.5YR 4/6) and have yellow mottles (10YR 8/8). They generally have an angular, blocky to crumb structure and silty clay texture.

The soil is yellowish red (5YR 5/8 and has a weak, medium to fine subangular blocky structure and a clayey texture. In the upper A1 horizon, the structure tends to be granular.

Microscopic Observation

Petrology of the Fresh Rock Material

The amphibole schist is composed of alternating bands of pale coloured minerals (epidote, clinozoisite, quartz) and green coloured actinolite.

The actinolite crystals occur as slender prisms or needles oriented with their lengths parallel to schistosity.

Clinozoisite crystals are present as colourless granules elongated in the direction of the schistosity. This mineral also occurs as veins parallel to, as well as cutting across, the schistosity. Epidote occurs as pale green grains which are also elongated in the direction of the schistosity.

TABLE 1
Description of the weathering profile developed over Amphibole Schist.

Location	:	Road-cut along Kuala Lumpur-Karak Highway, at 54 km stone.
Elevation	:	130 m above sea level.
Landform	:	Dissected hilly terrain. Profile is located on a gently sloping part of a hill.
Vegetation	:	Old rubber
Drainage	:	Well drained
Classification of soil	:	FAO/UNESCO Legend: Acric Ferralsol Soil Taxonomy: Clayey, kaolinitic, isohyperthermic Typic Hapludox

Profile Description

A1 0-0.20 m

Yellowish red (5YR 5/8); clay; weak, granular; very friable; few fine vein quartz fragments; few fine roots; few fine pores; gradual smooth boundary.

Bo1 0.20-0.90 m

Yellowish red (5YR 5/6); clay; weak, fine subangular blocky breaking into granules; very friable; few fine roots; few fine pores; gradual smooth boundary.

Bo2 0.90-2.0 m

Yellowish red (5YR 5/6); clay; weak, fine subangular blocky; friable; few fine roots; few fine pores; abrupt smooth boundary.

Cr 2.0-5.0 m (Upper saprolite)

Yellowish red (5YR 5/6 and 5YR 4/6); soft altered rock with distinct schistosity and joint planes; breaks easily between the fingers; evidence of faunal activity; diffuse boundary.

Cr + R 5.0-8.4 m (Upper saprolite)

Strong brown (7.5YR 5/8) and yellow (10YR 8/8); soft altered rock with few corestones which are coherent; distinct schistosity and joint planes; evidence of faunal activity; gradual smooth boundary.

Cr + R 8.4-15 m (Lower saprolite)

Yellowish red (5YR 5/6) and reddish yellow (10YR 6/8); soft altered rock with many large (1 to 2 m) corestones which are very coherent; weathering rims occur on these corestones; schistosity and joint planes are very distinct.

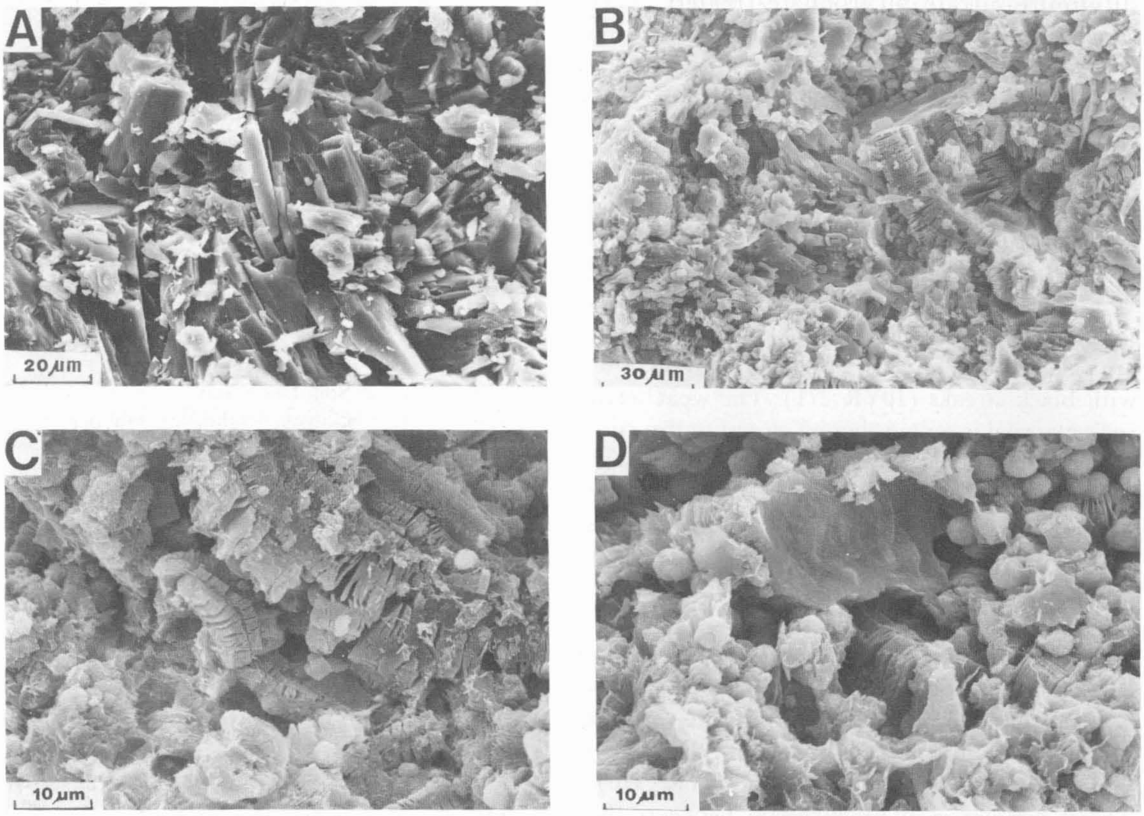

Fig. 2. Microfabric of the fresh amphibole schist and its weathering rim in the lower saprolite.
A : Tightly packed prismatic crystals of actinolite surrounded by granular ones which are probably the epidote minerals.
B : Porous microfabric of the weathering rim consisting of booklets of kaolinite.
C : Booklets of kaolinite are closely associated with tubular halloysite and some globules.
D : Locally the globules, most probably hematitic, form an important component of the fabric.

Polycrystalline quartz is present as veins running parallel to schistosity. A few grains of microcline are associated with it.

Micromorphology of the Weathering Stages

It was not possible to follow closely the alteration of each individual mineral in this profile. Actinolite seems to be the first mineral to weather, mainly by dissolution, leaving a crust which is yellow to dark brown. There is a sharp boundary between the fresh rock material and the alteration product. At this boundary, the iron released is seen to coat the epidote. The alteration products are described below as observed in the different rock samples collected.

(a) *Weathering rim around the corestones in the lower saprolite.*

In thin sections, the pale yellow weathered material shows broad bands composed of vermiform kaolinite in a micromass of finer kaolinite. Streaks of opaque brown iron oxyhydrates are oriented parallel to the original schistosity. In other parts, the groundmass is masked by brown opaque amorphous substances. The iron is only slightly extracted when the thin sections are treated with dithionite-citrate-bicarbonate solution (Bullock *et al.*, 1975).

The changes occurring in the amphibole schist due to weathering can also be clearly observed under SEM. *Fig. 2* shows the microfabric of the fresh amphibole schist and its weathering rim. The fresh rock material *(Fig. 2A)* has a compact microfabric composed of tightly packed prismatic crystals of actinolite surrounded by granular epidote. In the weathering rim *(Fig. 2B)*, these prismatic grains have completely disappeared. The microfabric is porous and consists mainly of kaolinite booklets 30 to 50 µm long. At

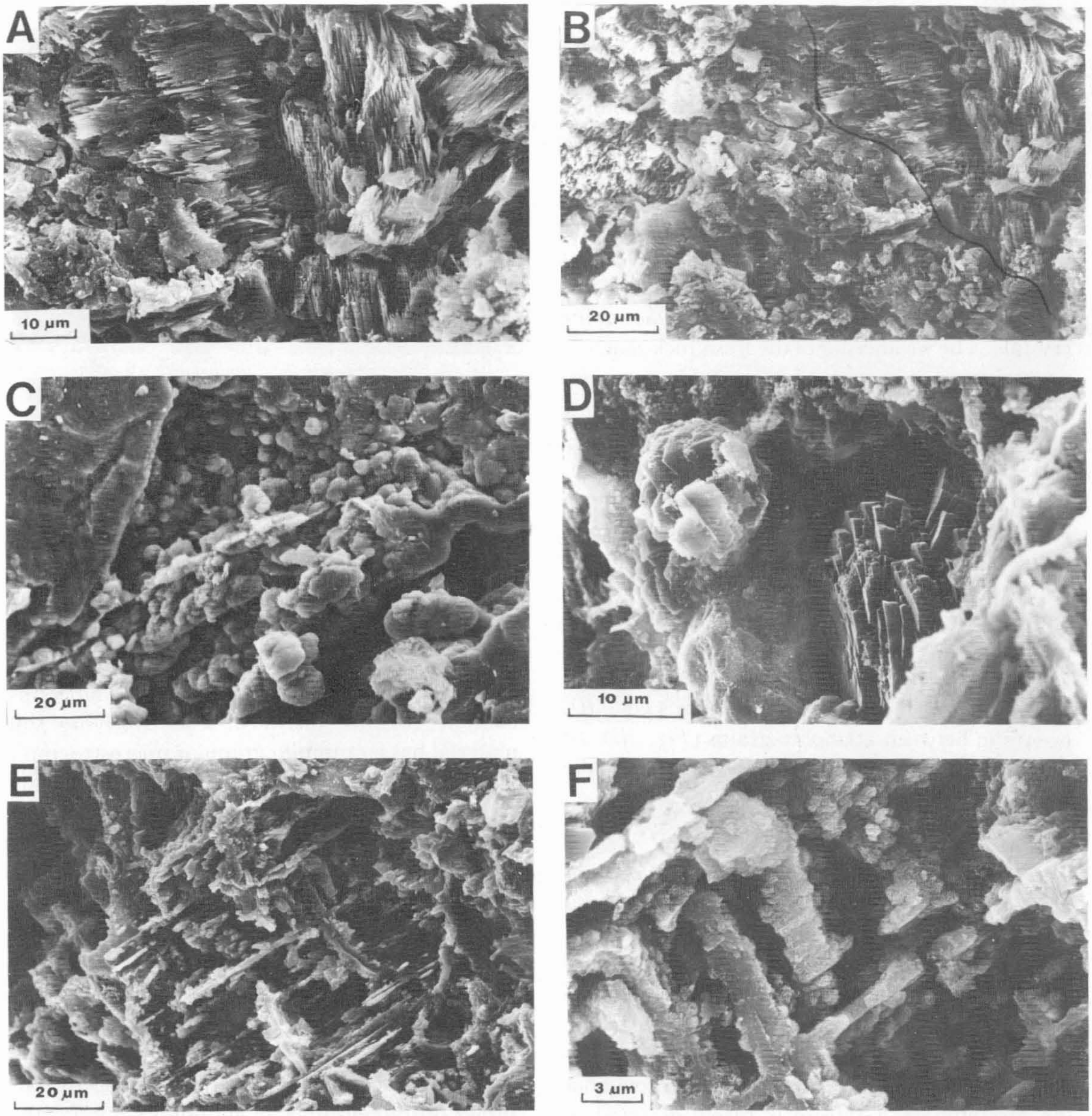

Fig. 3. Microfabric of the amphibole schist and its weathering rim in the upper saprolite.

A : The fresh rock is composed of fibrous actinolite showing a preferred orientation.

B : The microfabric at the boundary of the weathering rim shows an abrupt change from fresh rock (right) to the altered part (left). The fibrous mineral has disappeared in the groundmass

C : The porous microfabric consists of globules of hematite disseminated in the groundmass.

D and E : Well crystallized gibbsite occurs in between a framework which follows the orientation of the original actionolite grains.

F : Detail of the framework, composed of goethite.

higher magnifications, *(Fig. 2C)* tubular halloysite and globules of about 3 µm in diameter are observed closely associated with these booklets. These globules *(Fig. 2D),* which are probably of hematitic material, correspond to the reddish iron oxyhydrate droplets in the thin sections.

(b) Weathering rim around the corestones in the upper saprolite.

The weathering rim surrounding the fresh rock of a corestone sampled from the upper saprolite is dark brown in colour and shows a network of yellowish brown crystalline iron oxyhydrates oriented parallel to the original schistosity. Fine granular gibbsite occurs in between this network of iron oxhydrates (probably goethite). In some parts, a mixture of iron oxyhydrates and kaolinite occurs as lineaments following the schistosity, with gibbsite filling the spaces in between. The gibbsite is believed to be the alteration product of epidote and clinozoisite as both these minerals are rich in aluminium, and because it occurs in places where these two minerals were observed in the fresh rock material i.e. in between the actinolite crystals. The weathering of the fresh rock material occurring in this part of the profile was also observed under SEM. *Fig. 3* shows the microfabric of the fresh amphibole schist and its weathering rim. The fresh rock material *(Fig. 3A)* is composed of fibrous grains of actinolite showing a preferred orientation. There is an abrupt change in the microfabric at the boundary of the weathering rim *(Fig. 3B).* The altered part is more porous and the fibrous mineral is altered. The following minerals are identified: globules of hematite *(Fig. 3C)* are found disseminated in the groundmass while well crystallized gibbsite *(Fig. 3D)* occurs in between actinolite grains *(Fig. 3E).* At high magnification, this framework is actually composed of goethite *(Fig. 3F).*

(c) Material in between the corestones

The samples are homogeneously stained brown or dark-brown. Much of the groundmass shows distinct relict schistosity due to the parallel alignment of the iron oxyhydrate crystalline framework. The main clay mineral identified is kaolinite which occurs as vermiforms or booklets in the paler coloured parts. Occasionally, iron oxides occur as reddish droplets disseminated throughout the groundmass. Gibbsite is rarely detected in such large masses as seen in the rim samples.

Excremental infillings with crescent-like internal fabric commonly occur in between the schistosity planes or along planar voids cutting across the schistosity *(Fig. 4).* In other samples, faunal activity causes breakup of the rock fabric leaving fragments of rock in the voids together with excrements. It is clear that faunal activity is the most important agent of pedoplasmation in these materials.

The soil material in the joint planes has a light red, dotted micromass with a mosaic to stipple-speckled b-fabric. Only a few quartz grains and some iron impregnated rock fragments are present, giving rise to an open porphyric c/f-related distribution. Many fine (10-30 μm) rounded reddish opaque nodules are also present. SEM-observations of the rock fragments show the presence of tubular halloysite on the edges and between the lamellae; the soil material consists of booklets of kaolinite and globules. Thin veins contain goethite discoids. The overlying soil material has a crumb to granular microstructure, with a dotted, reddish brown micromass showing dominantly stipple speckled b-fabric. Few grains of quartz and runiquartz are embedded in the clay.

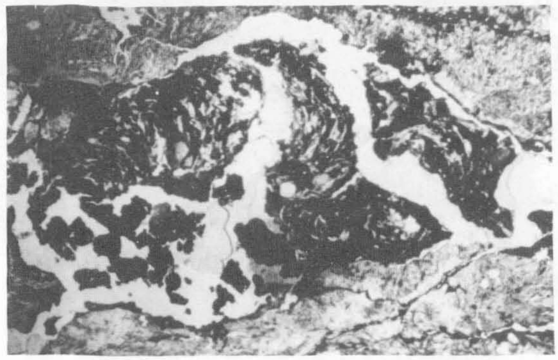

Fig. 4. A planar void excremental infilling with cresent-like internal fabric which occurs in the saprolite sample (PPL. x 14)

Mineralogical Changes

The alteration of the amphibole schist in the lower saprolite is studied by examining the X-ray diffractograms of the fresh rock material (R4), its weathering rim (Cr5(4) and the saprolite material above it (Cr4) *(Fig. 5).* The fresh rock shows diffraction lines of actinolite, epidote and some trioctahedral chlorite (the 0.29 nm reflection of epidote is very weak on the diffractogram presented in *Fig. 5,* but was much stronger on a less oriented preparation where, however, the 1.42 nm reflection of chlorite is missing). In the weathering rim, actinolite, apidote and chlorite disappear immediately and completely, leaving only high defect kaolinite (no distinct 11 T peak). goethite (0.418 nm) and traces of gibbsite (0.485 nm). Kaolinite becomes the dominant mineral in the saprolite with smaller amounts of goethite. X-ray diffraction thus confirms the micromorphological observation.

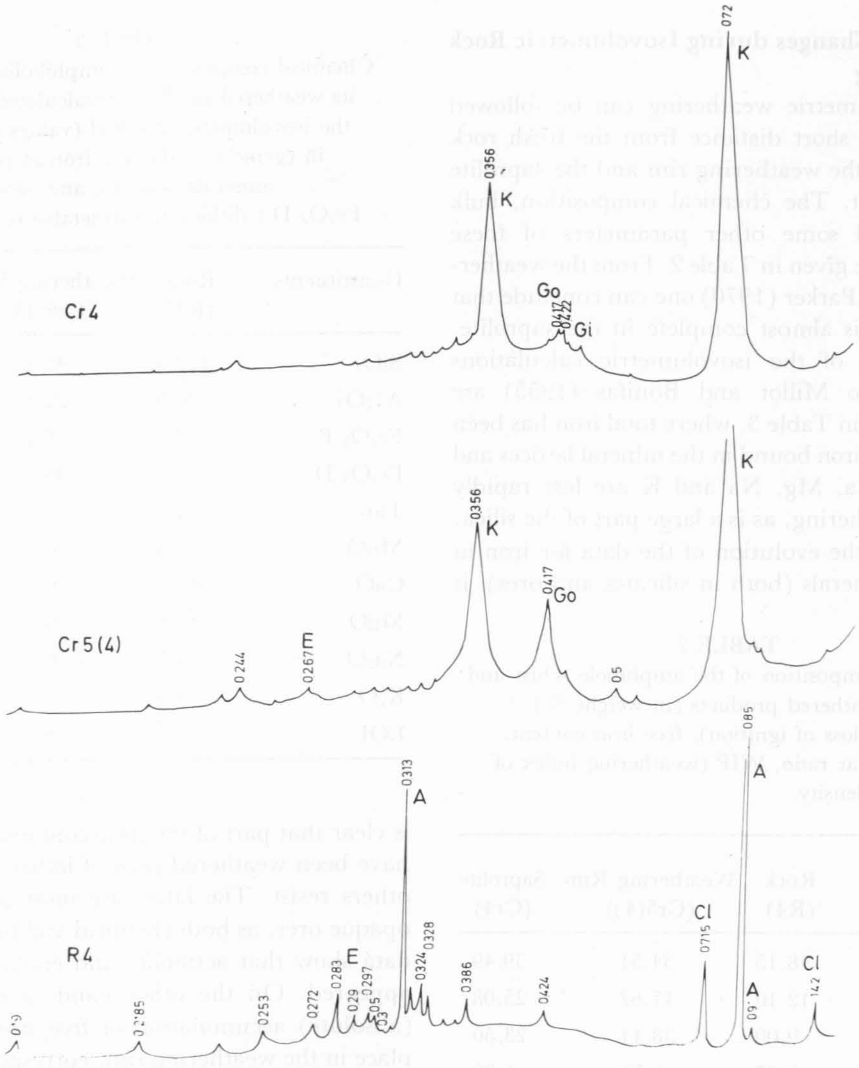

Fig. 5. X-ray diffraction pattern of the fresh amphibolite schist (R4), its weathering rim (Cr5(4)) and the saprolite material above it (Cr4). (A = actionolite, E = epidote, Cl = chlorite, K = kaolinite, Gi = gibbsite, Go = goethite).

The weathering rim of the corestone in the upper saprolite (R1, R2) shows that gibbsite is the dominant mineral, followed by goethite. A sharp peak at 0.445 nm, indicates the presence of halloysite. Kaolinite occurs only as traces.

X-ray diffractograms of saprolite samples in between the corestone (Cr6, Cr2(2) and Cr2(3) also show the dominance of kaolinite as well as the abundance of goethite and gibbsite. In Cr6 no distinct 11 T peak of kaolinite is present, indicating a high-defect kaolinite, whereas a somewhat better organized kaolinite is found in Cr2(2), with a Hinckley Index of 0.32.

The clay fraction of the soil material in the relict joints of the upper saprolite consists mainly of kaolinite and goethite, with some traces of halloysite. The silt fraction has, in addition, a considerable amount of gibbsite. The overlying soil material has a similar composition except for the absence of halloysite and the presence of a small amount of irregular mixed layers in the BO_1 and BO_2. The crystallinity of the kaolinite is much better than in the saprolite, with values of 0.44 for the Hinckely Index, pointing to a mixture of a low defect (about 6%) and a moderate to high defect kaolinite.

Chemical Changes during Isovolumetric Rock Weathering

The isovolumetric weathering can be followed only over a short distance from the fresh rock material to the weathering rim and the saprolite nearest to it. The chemical composition, bulk density and some other parameters of these materials are given in Table 2. From the weathering index of Parker (1970) one can conclude that weathering is almost complete in the saprolite. The results of the isovolumetric calculations according to Millot and Bonifas (1955) are represented in Table 3, where total iron has been split up into iron bound in the mineral lattices and free iron. Ca, Mg, Na and K are lost rapidly during weathering, as is a large part of the silica. Looking to the evolution of the data for iron in primary minerals (both in silicates and ores), it is clear that part of the iron-containing minerals have been weathered (loss of lattice iron), while others resist. The latter are most probably the opaque ores, as both chemical and mineralogical data show that actinolite and epidote have disappeared. On the other hand, a considerable (absolute) accumulation of free iron has taken place in the weathering rim, corresponding to its darker colour. This conclusion is corroborated by the presence of crystalline goethite and hematite nodules, as shown by XRD and micromorphology. In the saprolite the iron accumulation is far less pronounced.

TABLE 2

Chemical composition of the amphibole schist and its weathered products (in weight %) (LOI = loss of ignition), free iron content, Si/A1 molar ratio, WIP (weathering index of Parker) and density.

Constituents	Rock (R4)	Weathering Rim (Cr5(4))	Saprolite (Cr4)
SiO_2	48.15	34.51	39.49
Al_2O_3	12.10	17.62	25.08
Fe_2O_3	9.00	38.11	23.50
TiO_2	0.67	1.69	1.88
MnO	0.21	0.25	1.37
CaO	15.80	0.19	0.04
MgO	12.00	0	0
Na_2O	1.45	0.59	0.45
K_2O	0.35	0	0
LOI	1.50	8.05	10.01
Total	101.23	101.01	101.82
FREE IRON %	0.29	32.66	14.08
SiO_2/Al_2O_3 mole ratio	6.8	3.3	2.7
WIP	89.0	6.0	4.2
DENSITY g/cc	2.55	1.22	1.16

TABLE 3

Chemical composition of amphibolite schist and its weathered products recalculated by using the isovolumetric method (values expressed in $cgcm^{-1}$). Fe_2O_3 P : iron in primary minerals (silicates and ores), Fe_2O_3 D : dithionite extractable or free iron.

Constituents	Rock (R4)	Weathering Rim (Cr5(4))	Saprolite (Cr4)
SiO_2	122.8	42.1	45.8
Al_2O_3	30.9	21.5	29.1
Fe_2O_3 P	22.3	6.7	10.9
Fe_2O_3 D	0.7	39.8	16.4
TiO_2	1.7	2.1	2.2
MnO	0.5	0.3	1.6
CaO	40.3	0.2	0.05
MgO	30.6	0	0
Na_2O	3.7	0.7	0.5
K_2O	0.9	0	0
LOI	3.8	9.8	11.6

The free iron content of the saprolite further decreases towards the soil, but values of 17% are reached in the BO horizon. The amount of oxalate extractable iron is very low (0.26% in the BO_1 and 0.14% in the BO_2), indicating that all is practically present in a crystalline form.

CONCLUSIONS

Due to the fine texture of the rock material, it was not possible to follow the weathering scheme of each mineral individually. It is evident, however, that actinolite is the first mineral to disappear, followed by the epidote minerals. Similar conclusions can be drawn from the data presented by De Coninck *et at.* (1987). As far as could be seen by SEM, congruent dissolution had taken place.

The alkaline and alkaline-earth elements are removed immediately and practically completely, as is a part of the silica. The other part recombines with the aluminium set free during weathering of the epidote minerals to form kandite minerals. Initially, halloysite and kaolinite are formed in the lower saprolite, and kaolinite and gibbsite in the upper saprolite. This difference in the secondary products formed can be explained by stronger leaching in the upper part (gibbsite formation), and a more moist environment in the lower part (halloysite). At all stages, a typical ferrallitic weathering is observed.

The weathering front is abrupt and weathering is immediately almost complete. The rock structure is preserved, however, over large distances and pedoplasmation proceeds along geological structural planes. The soil material found in joint planes has the same properties as the overlying soil material, except for the presence of small rock fragments and a denser microstructure. The soil itself is very clayey with a relatively high free iron content, in accordance with the composition of the parent rock.

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