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SCANNING ELECTRON MICROSCOPE MORPHOLOGY OF DEEPLY WEATHERED GRANITE

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Abstract—Laterite profiles developed from granite in southwestern Australia were studied by scanning electron microscopy. The morphology of soil materials reflects the mineralogy of secondary minerals formed from feldspar. In the saprolite, etched feldspar surfaces are coated with kaolinite or radiating, spherical aggregates of tubular halloysite. In the lower pallid zone these minerals have replaced most of the feldspar. In the upper pallid zone a porous framework has developed consisting mainly of quartz and gibbsite with 5-μm euhedral gibbsite crystals in voids. Halloysite crystals in the upper pallid zone are partly unrolled and have splayed ends. Differences in mineralogy and morphology between profiles are thought to be due to variations in the intensity of leaching.

Key Words—Feldspar, Gibbsite, Granite, Halloysite, Kaolinite, Scanning electron microscopy, Weathering.

INTRODUCTION

The widespread availability of scanning electron microscopes (SEM) has resulted in numerous publications dealing with the morphology of minerals in soils and sediments at magnifications in excess of those obtainable with optical microscopes. Most of these publications have concerned specific mineral species or individual mineral deposits (e.g., kaolinite, Keller, 1976, 1977; gibbsite, Eswaran *et al.*, 1977; quartz, Krinsley and Doornkamp, 1973, and Little *et al.*, 1978; bauxite, Bardossy *et al.*, 1978). Relatively little attention has been given to SEM studies of trends in the morphology of soil materials within complete soil profiles.

This publication describes the use of electron microscopy in a study of lateritic weathering of granite. The weathering of single grains of biotite and magnetite in these profiles has been described elsewhere (Gilkes and Suddhiprakarn, 1979a, b).

MATERIALS AND METHODS

Samples were taken from granitic parent material (adamellite), saprolite, and the pallid zone of three bauxitic-laterite profiles (R, L, B) exposed in a railway cut at Jarrahdale, 45 km southeast of Perth, Western Australia. Detailed profile descriptions of the deeply weathered materials have been given by Gilkes *et al.* (1973) and Sadleir and Gilkes (1976). Quartz veins and dolerite dikes are preserved within the weathered materials demonstrating that they formed *in situ*. The R and L profiles exhibit a sequence of horizons typical of laterites occurring in the region [i.e., parent material (~12 m), saprolite (9–12 m), pallid zone (5–9 m), mottled zone (1–5 m), and sandy pisolitic duricrust (0–1 m)]. The upper mottled zone and duricrust which comprise the bauxite were not sampled in this work since they may not be *in situ* weathering products. Grubb (1971) interpreted variations in the abundance and shape of heavy mineral grains in the upper horizons of these soils as evidence for a veneer of sedimentary material. Profiles R and L are 12 m deep and situated 1 m apart. Profile B is 6.5 m deep; here the saprolite grades directly into bauxitic materials. The sample depths and numbers are shown in Figure 1.

The samples were divided into three portions. One portion was finely ground and used for X-ray powder diffraction. The second portion was separated into fractured clods and altered mineral grains for SEM examination. The third portion was impregnated with resin and thin-sectioned for petrographic examination.

Individual mineral grains and fracture surfaces of clods were coated with gold prior to examination in a Philips Scanning Electron Microscope. Clay fractions of dispersed, altered mineral grains and clods were deposited on carbon films and examined by transmission electron microscopy (TEM) using a Hitachi HU11B instrument.

RESULTS AND DISCUSSION

Mineralogy of soil materials

Semiquantitative X-ray powder diffraction (XRD) analyses of specimens of the parent material, saprolite, and pallid zone are presented as depth functions in Figure 1. As expected the mineral distributions with depth for the R and L profiles are quite similar. Feldspar is replaced by halloysite(10Å) in the saprolite and by kaolinite, halloysite(7Å), and gibbsite in the pallid zone. The different basal spacings of halloysite may be due

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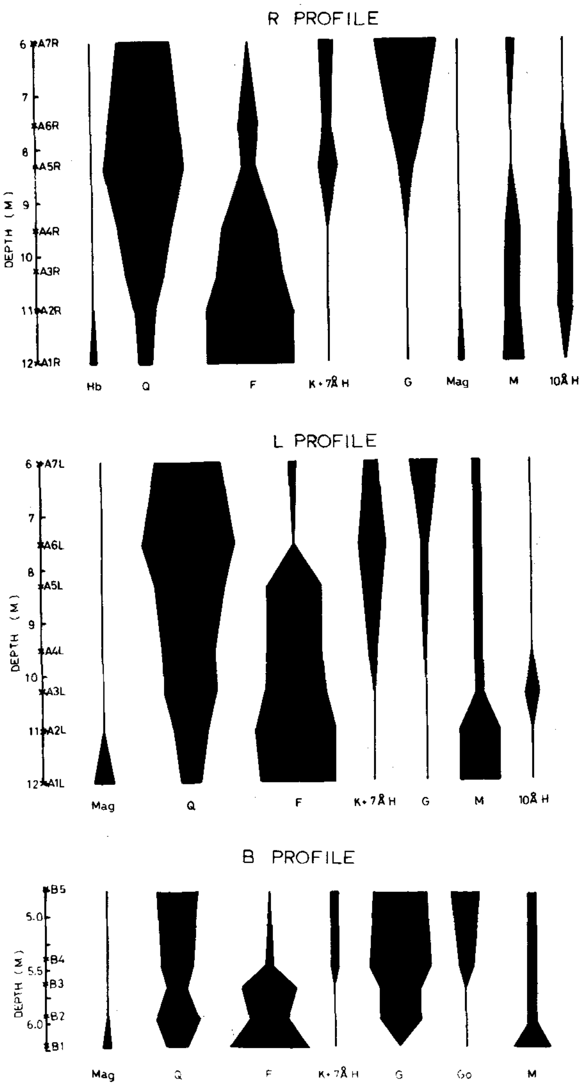

Figure 1. Distribution of minerals with depth in parent rock, saprolite, and pallid zones of three deeply weathered bauxitic laterite profiles from Jarrahdale, southwestern Australia. Hb = hornblende, Q = quartz, F = feldspar, K = kaolinite, H = halloysite with either 7 Å or 10 Å basal spacing, G = gibbsite, Mag = magnetite, M = mica, Go = goethite.

to a loss of interlayer water in the higher soil horizons that experience seasonal drying under the present-day climate and hydrological regime (Herbert *et al.*, 1978). The relative proportion of quartz increases towards the surface as a result of the less resistant minerals (feldspars, biotite, hornblende) having been destroyed by weathering. The absence of thick saprolite and pallid zones in the B profile is reflected in its mineralogy which indicates that most of the feldspar altered directly to gibbsite with no extensive development of halloysite and kaolinite. The difference in mineralogy between the B and the R and L profiles may be due to differences in internal drainage at the two sites (Hsu, 1977). Variations in the mineralogy and abundance of fractured grains may also have affected the nature of the weathering products. Alteration of feldspar generally developed via networks of cracks, twin plane boundaries, cleavages, and exsolution lamellae and resulted in the formation of kaolinite, halloysite, and gibbsite pseudomorphs which commonly contain fragments of unaltered feldspar. Feldspar altered in an identical manner in deeply weathered Malaysian granite (Eswaran and Bin, 1978a). Gilkes and Suddhiprakarn (1979a, b) showed that magnetite altered to hematite and biotite altered to complex mixtures of mixed-layer minerals, kaolinite, gibbsite, and goethite in these profiles. In all three profiles the general extent of alteration of the primary minerals increases towards the surface, but mineral grains exhibiting different degrees of alteration are present in all horizons.

Morphology of soil material

SEM examination of single grains and fractured clods revealed a large variety of morphologies. Single fracture surfaces commonly contain various mixtures of fresh quartz, etched feldspar, altered biotite and magnetite, kaolinite, halloysite, and gibbsite. Broad trends in morphology of soil materials with depth are illustrated in Figures 2–5. These trends mainly reflect the different weathering products of feldspar.

Saprolite

In the lower saprolite of the R and L profiles, feldspar has started to dissolve with associated crystallization of kaolinite and halloysite. Etched feldspar is coated with these secondary minerals (Figures 2 and 3). It is not possible to distinguish between altered plagioclase and alkali feldspar on the basis of morphology. Both kaolinite and halloysite appear to have developed from solution in etchpits on feldspar surfaces. Kaolinite occurs as aggregates of platy crystals about 0.1 μm in size and resembles the kaolinite that replaces feldspar in the deeply weathered Malaysian granite described by Eswaran and Bin (1978b). Halloysite occurs as radiating, spherical aggregates of tubes about 1 μm in length that also resemble those described by Eswaran and Bin (1978b). These aggregates resemble the well-known Bedford, Indiana, halloysite (Diamond and Bloor, 1970). The tubular morphology of the halloysite(10Å) is clearly seen in the TEM photograph in Figure 4A.

Pallid zone

Feldspar in specimen A5R from the pallid zone has altered to halloysite in the form of radiating, spherical and parallel-oriented, felted aggregates (Figure 5A). In marked contrast the equivalent specimen from the closely adjacent L profile (A5L) has altered to kaolinite (Figure 5B). It shows a quite different fabric consisting

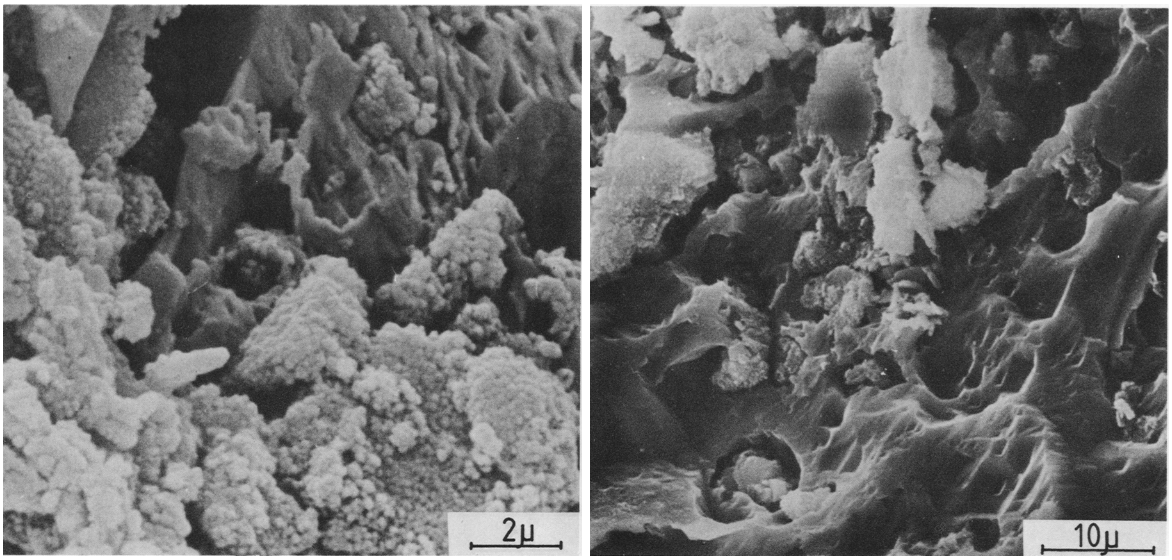

Figure 2. Highly etched feldspar in specimen A3L from the saprolite. Kaolinite (~0.1 μm) forms aggregates on the surface and fills etchpits.

of a porous framework of aggregates of platy kaolinite crystals. In both samples these fabrics represent a greater development of the corresponding early stages of alteration shown in Figures 2 and 3. The alteration products no longer fill etchpits in feldspar but have completely replaced the parent feldspar grains which have mostly altered to halloysite in R profile and to kaolinite in L profile.

Mottled zone

The gibbsite-rich specimens from all three profiles present another quite distinct fabric consisting of large (~5 μm) euhedral to subhedral gibbsite crystals within voids in a finer grained, gibbsite-rich matrix (Figure 6). Eswaran *et al.* (1977) described identical materials from tropical soils. They considered that large, euhedral gibbsite crystals developed in voids, a mechanism

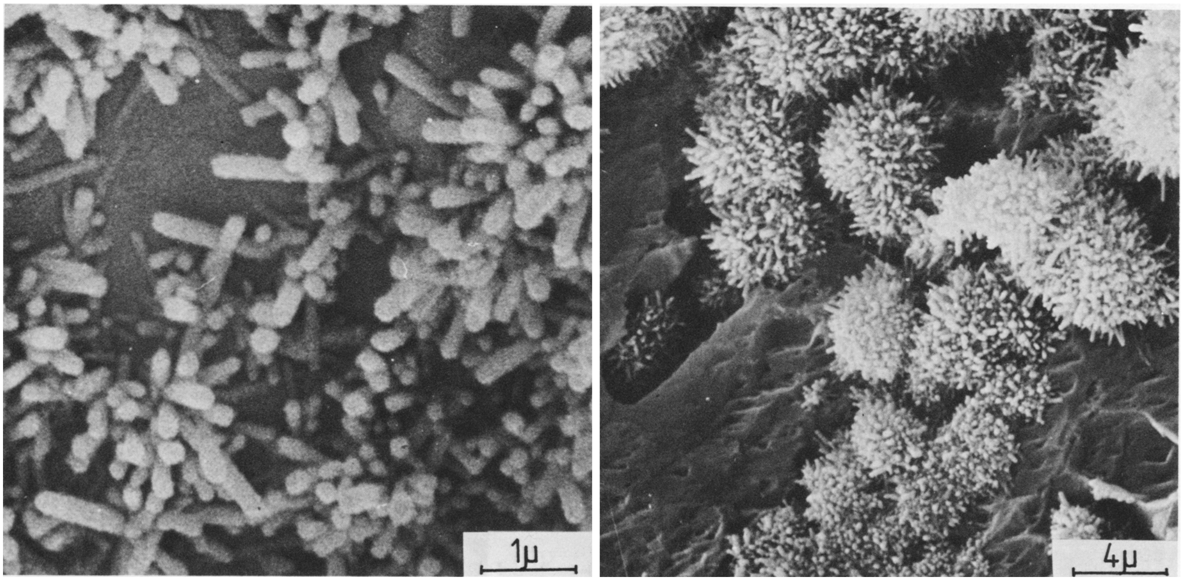

Figure 3. Highly etched feldspar in specimen A3R from the saprolite. Halloysite (~1 μm) forms radiating, spherical aggregates on the surface and fills etchpits.

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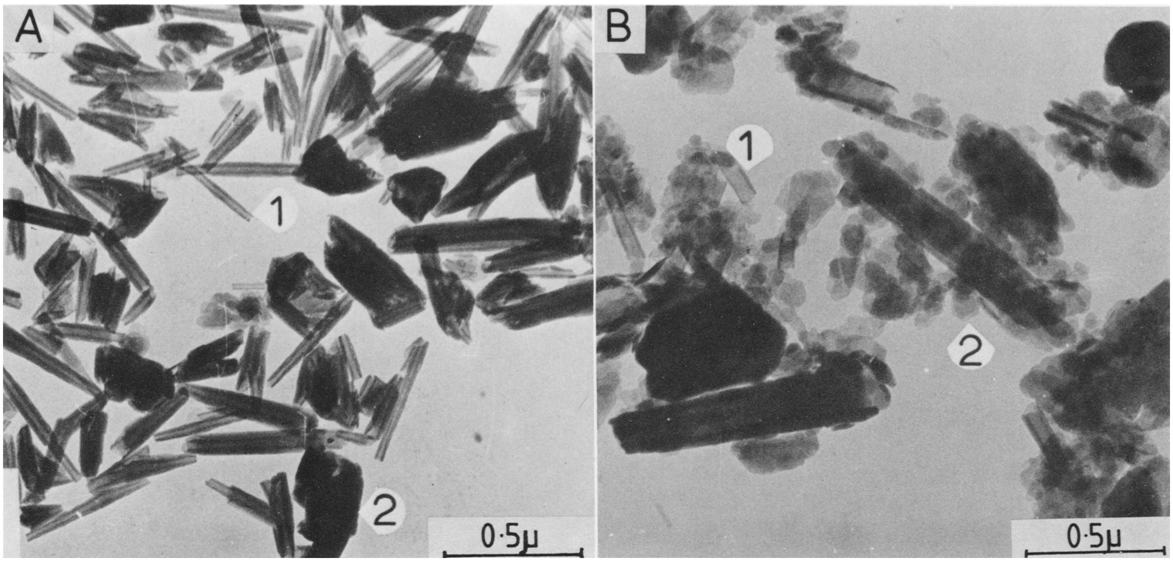

Figure 4. A. Transmission electron micrograph of a halloysite-rich clay fraction of specimen A5R from the lower pallid zone: (1) tubular halloysite commonly aggregated into rafts (2). B. Transmission electron micrograph of a clay fraction of specimen A7R from the upper pallid zone: (1) tubular halloysite that is partially unrolled and commonly exhibits splayed ends; (2) hexagonal crystals of kaolinite or gibbsite.

that is consistent with their abundance in these porous products of isovolumetric weathering. The size and shape of gibbsite crystals depends on the space available for crystal growth.

Halloysite tubes and small, platy crystals of kaolinite or gibbsite adhere to the surfaces of gibbsite crystals. TEM showed that hexagonal crystals are present that resemble the kaolinite occurring deeper in the profiles. These crystals may, however, be gibbsite. Halloysite tubes in the gibbsite-rich specimens show a different morphology than those from deeper horizons. Only large tubes are present, many of which are partly unrolled and have splayed ends (Figure 4B), suggesting that they have been altered. These features may be a

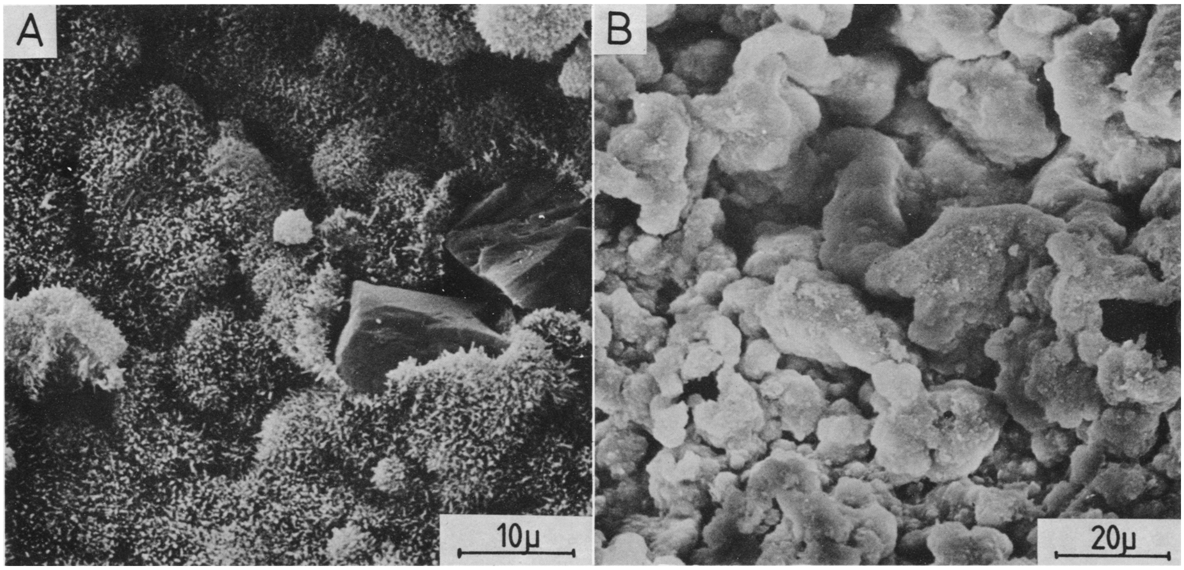

Figure 5. A. Masses of radiating spherical and parallel-oriented, felted halloysite aggregates surrounding unaltered quartz in a fractured clod from specimen A5R from the pallid zone. B. Aggregates of platy kaolinite crystals arranged in a porous fabric in a fractured clod in specimen A5L from the pallid zone.

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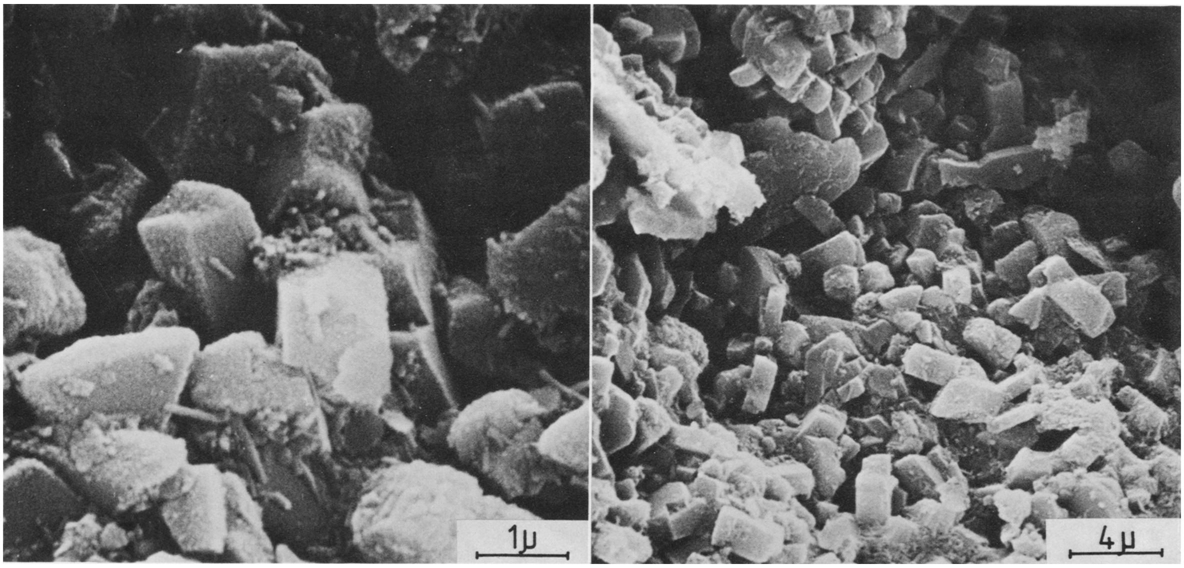

Figure 6. Euhedral gibbsite (~5 μm) in a cavity within the fine-grained, gibbsite-rich matrix of specimen A6R, the pallid zone. At high magnification tubular halloysite crystals are seen on gibbsite surfaces.

consequence of dehydration in the seasonally dry gibbsite-rich zones of the soils. Losses of silicon from halloysite due to leaching had probably occurred in these horizons thus liberating aluminum for gibbsite formation. Hsu (1977) considered that gibbsite formation can be very rapid once Si is separated from Al after breakdown of the Al–O–Si linkage. The B-profile is very well drained so that Si would be readily leached once it had been released from feldspar, kaolinite, or halloysite.

Eswaran and Bin (1978b) urged caution in the interpretation of mineralogical trends in soil profiles as indicators of mineral alteration sequences in deep soils. They pointed out that in thick profiles conditions may have differed at different stages of soil development. Thus, the present-day occurrence of minerals in a soil profile may reflect these changing conditions rather than a mineral-alteration sequence. In the Jarrahdale profiles, the marked morphological similarity between kaolinite and halloysite in etchpits on feldspar surfaces at an early stage of alteration and the fabric of these minerals higher in the profiles, where feldspar has been almost completely replaced, indicates that progressive alteration has occurred under a fairly constant weathering regime. It is not clear why there is so much variability in the extent of weathering and in the nature of weathering products between the closely adjacent R and L profiles. These differences may reflect local variations in the intensity of leaching since water movement in deeply weathered granitic rocks tends to follow cracks, fractured quartz veins, etc. rather than pervading the bulk material. Differences in the original composition of the feldspars may also influence the nature of the weathering products. Eswaran and Bin (1978b) have demonstrated that within a single horizon feldspar grains may alter to different secondary minerals as a result of the presence of voids. Thus, the associations of gibbsite with halloysite and gibbsite with kaolinite may reflect the range of microenvironments occurring within any one horizon.

SUMMARY

The SEM morphology of deeply weathered granite mainly reflects the mineralogy of aluminum-containing secondary minerals. Aggregates of kaolinite and halloysite develop on etched surfaces of feldspar in the saprolite and replace most of the feldspar in the lower pallid zone. Thus, similar weathering environments must exist in the saprolite and lower pallid zone with the extent of alteration increasing towards the surface. The upper pallid zone consists mostly of a porous quartz and gibbsite matrix with ~5-μm euhedral gibbsite in voids.

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Резюме—С помощью электронного сканирующего микроскопа изучались латеритные разрезы, развившиеся в результате выветривания гранита в юго-западной Австралии. Морфология почвенных материалов отражает минералогию вторичных минералов, образованных из полевого шпата. В сапролите, выветрелые поверхности полевого шпата покрыты каолинитом или лучевыми, сферическими агрегатами трубчатого галлуазита. В нижней, паллидной зоне эти минералы почти полностью заместили полевой шпат. В верхней паллидной зоне образовалась пористая структура, состоящая в основном из кварца и гиббсита с 5 μм идиоморфными кристаллами гиббсита в полостях. Галлуазитовые кристаллы в верхних паллидных зонах частично развернуты и имеют скошенные концы. Различия в минералогии и морфологии разрезов объясняется изменением интенсивности выщелачивания. [N. R.]

Resümee—Lateritprofile, die sich im südwestlichen Australien im Granit gebildet haben, wurden mittels Rasterelektronenmikroskopie untersucht. Die Morphologie des Bodenmaterials zeigt die Mineralogie der Sekundärminerale, die sich aus Feldspat gebildet haben. Im Rückstandsgestein sind geätzte Feldspatoberflächen mit Kaolinit oder radial strahligen Aggregaten aus röhrenförmigem Halloysit überzogen. In der tieferen bleichen Zone haben diese Minerale fast den ganzen Feldspat ersetzt. In der oberen bleichen Zone hat sich ein poröses Gerüst gebildet, das hauptsächlich aus Quarz und Gibbsit besteht, mit 5 μm großen idiomorphen Gibbsitkristallen in den Hohlräumen. Die Halloysitkristalle in der oberen bleichen Zone sind teilweise entrollt und haben nach außen gebogene Enden. Die Unterschiede in der Mineralogie und Morphologie der einzelnen Profile werden auf eine verschieden starke Auslaugung zurückgeführt. [U. W.]

Résumé—Des profiles de latérite développés à partir de granite en Australie du sud ouest ont été étudiés par microscopie électronique balayante. La morphologie des matériaux du sol réflète la minéralogie des minéraux secondaires formés à partir de feldspar. Dans la saprolite, des surfaces de feldspar gravées sont recouvertes de kaolinite ou d'aggrégats sphériques et branchants d'halloysite tubulaire. Dans la zone inférieure pâle, ces minéraux ont remplacé la plupart des feldspars. Dans la zone pâle supérieure, une charpente poreuse s'est développée consistant surtout de quartz et de gibbsite avec des cristaux euhédraux de 5 μm de gibbsite dans les vides. Les cristaux d'halloysite dans la zone pâle supérieure sont partiellement déroulés et ont des bouts ébrasés. On croit que les différences de minéralogie et de morphologie entre les profiles sont dues à des variations dans l'intensité du lessivage. [D. J.]