4 APPLICATIONS AT LUNAR BASES

Minerals synthesized from lunar basaltic glasses or other lunar starting materials may have a variety of applications at a lunar base. Based on their unique adsorption, cation-exchange, molecular-sieving, and catalytic properties, zeolites may be used as solid support substrates for the growth of plants, as adsorption mediums for the separation of various gases, as catalysts, as molecular sieves, and as cation exchangers in sewage-effluent treatment, in radioactive-waste disposal, and in pollution control. Smectites may be used as an adsorption medium for waste renovation, as adsorption sites for important plant growth cations in solid support plant growth substrates, as cation exchangers, and other important uses. Tobermorites may be used as a cement in building concrete lunar base structures, as catalysts, as mediums for nuclear and hazardous waste disposal, as exchange mediums for waste-water treatment, and other potential uses.

5 REFERENCES

Bohor, B.F. and Hughes, R.E., 1971. Scanning electron microscopy of clays and clay minerals. Clays Clay Miner., 19: 49-54.

Duke, M.B., Mendell, W.W., and Roberts, B.B., 1985. Strategies for a permanent lunar base. In: W.W. Mendell (ed.), Lunar Bases and Space Activities of the 21st Century, pp. 57-68. Lunar and Planetary Institute, Houston.

El-Hemaly, S.A.S., Mitsuda, T., and Taylor, H.F.W., 1977. Synthesis of normal and anomalous tobermorites. Cem. Conc. Res., 7: 429-438.

Höller, H. and Wirsching, U., 1978. Experiments on the formation of zeolites by hydrothermal alteration of volcanic glasses. In: L.B. Sand and F.A. Mumpton (ed.), Natural Zeolites: Occurrence, Properties, Use. Pergamon Press, New York, 329-336.

Höller, H. and Wirsching, U., 1988. Experiments on the formation conditions and morphology of chabazite from volcanic glasses. In: D. Kalló and H.S. Sherry (ed.), Occurrence, Properties, and Utilization of Natural Zeolites. Akadémiai Kiadó, Budapest, 171-191.

Jackson, M.L., 1974. Soil Chemical Analysis-Advanced Course. Dept. of Soil Science, Univ. of Wisconsin, Madison.

Kalousek, G.L., 1955. Tobermorite and related phases in the system $CaO-SiO_2-H_2O$. J. Amer. Conc. Inst., 26: 989-1011.

Komarneni S., Breval W., Miyake M., and Roy R., 1987. Cation-exchange properties of (Al+Na)-substituted synthetic tobermorites. Clays Clay Miner., 35: 385-390.

Ming, D.W., 1989. Applications for special purpose minerals at a lunar base. In: W.W. Mendell (ed.), Lunar Bases and Space Activities of the 21st Century, Lunar and Planetary Institute, Houston, (in press).

Ming, D.W. and Mumpton, F.A., 1989. Zeolites. In: J.B. Dixon and S.B. Weed (eds.), Minerals in Soil Environments, Soil Science Society of America, Madison, Wisconsin, 873-911.

Ridley, W.I., Reid, A.M., Warner, J.L., Brown, R.W., Gooley, R., and Donaldson, C., 1973. Glass compositions in Apollo 16 soils 60501 and 61221. In: R. Brett, W.C. Phinney, and D.W. Strangeway (eds.), Proceedings of the Fourth Lunar Science Conference. Pergamon Press, New York, 1: 309-321.

Wirsching, U., 1981. Experiments on the hydrothermal formation of calcium zeolites. Clays Clay Miner., 29: 171-183.

MORPHOLOGY OF MINERAL WEATHERING AND NEOFORMATION. I. WEATHERING OF MOST COMMON SILICATES*

J. DELVIGNE and G. STOOPS

O.R.S.T.O.M., Laboratoire de Géologie de Surface, Faculté des Sciences de l'Université de St.Jérôme, BP 431, 13397 MARSEILLE, France and Laboratorium voor Mineralogie, Petrografie en Micropedologie, Rijksuniversiteit Gent, Krijgslaan 281, B 9000 GENT, Belgium

ABSTRACT

Observation of pseudomorphs formed by surface alteration of some primary minerals (e.g. olivine, pyroxene, amphibole, mica, feldspar, nepheline, quartz) shows that their microfabric is essentially determined by the original fissuration of the primary mineral (internal porosity, cleavages, intramineral zonations, transmineral fractures). The crystallo-chemical structure of the primary minerals, on the contrary, influences the fabric of the pseudomorph (distribution and orientation of secondary minerals) only in the case of the alteration of the ino- and phyllosilicates, and, less pronounced, in the case of the nesosilicates. Pseudomorphs after tectosilicates never seem to display evidences of microfabrics influenced by crystallo-chemical characteristics.

1 INTRODUCTION

Micropedology is the study of undisturbed soil material with the aid of a magnifying instrument. The technique has frequently also been used to study weathering of rocks and sediments. Thin section studies on mineral newformations, apart from those resulting from weathering, are scarce, except for minerals such as calcite, gypsum, gibbsite and some iron oxyhydrates.

What are the advantages of this micromorphological approach of a mineralogical problem? First of all, the study of undisturbed material allows an unambiguous spatial localization of the weathering and newformation, e.g. with respect to the porosity pattern, to pedofeatures or to other newformations. This information can help in understanding the process at the origin of the weathering or newformation, and in most cases it is useful for the reconstruction of the chronological relations between different weathering stages or newformations and the translocation of material between

* International Training Center for Post-Graduate Soil Scientists-Ghent Publication n° 89/009

the different parts of the profiles and of the toposequences.

In micromorphology, a wide range of magnifying instruments is used, ranging from a simple handlens to the powerful scanning electron microscope (SEM). As in this way quite different levels of organization are reached, the authors preferred to restrict this review to results obtained by thin section studies, using a polarizing microscope.

2 WEATHERING OF SILICATE MINERALS

When studying alteration or weathering of primary minerals in rocks and soils, two different aspects can be considered: (i) type and rate of weathering (i.e. which secondary products are formed, and at which rate), and (ii) the morphology and internal fabric of the secondary products (pseudomorphs). The first aspect depends, apart from the mineral composition, on different external factors such as climate, topography, drainage, mineral association, rock porosity etc., and has been studied already quite in detail, both from a mineralogical and a physico-chemical point of view (e.g. Loughnan 1969). Less attention has been paid up to now to a systematic study of the fabric and morphology of the secondary products, their origin and their diagnostic value.

Although the type of secondary products formed and the rate of crystallization (influencing the texture) also play an important role, the internal fabric mainly seems determined by internal factors, such as the elemental composition, crystal lattice, cleavage directions if any, structural discontinuities (twinning planes, zonations or inclusions) and the presence of intra- or transmineral fractures.

As silicates are the most abundant soil forming minerals (they constitute well over 90% of the earth crust), the authors propose to discuss the foregoing theoretical considerations with the aid of a few examples of common silicate minerals.

2.1 Nesosilicates

Because of the absence of silicate chains or sheets, nesosilicates contain individual isolated SiO_4 tetrahedrons and generally have no distinct cleavage pattern (e.g. garnet, olivine, zircon). The secondary minerals derived from nesosilicates do not inherit any silicate structure.The fabric of the pseudomorph will be determined essentially by the pattern of fractures in the primary mineral (e.g. protoclastic fractures). Some nesosilicates, e.g. kyanite and sillimanite, have cleavages, as a result of Al-chains, and therefore show another weathering pattern.

Olivine. In the absence of cleavage planes, two weathering patterns are possible: a pellicular weathering or an irregular linear, or both (terminology according to Stoops et al. 1979).

Tropical weathering under good drainage conditions results in removal of Si and Mg, whereas the iron precipitates as oxyhydrates along the fractures, leaving a porous pseudomorph with boxwork structure, reflecting the original pattern of fractures (Fig.1). The iron oxyhydrates generally do not have a preferential orientation, and if any, they show a simultaneous extinction parallel to the c-axis of the olivine, because of inheritance of oxygen planes (Delvigne et al. 1979).

In less extreme conditions, only the Mg is evacuated and a yellowish to reddish brown Fe-Si-colloid (isotropic material under crossed polarizers) is filling up a boxwork of iron hydroxides. Two further evolutions are possible: (i) also the silicon is progressively removed and only a ferruginous boxwork remains, which is less regular and less homogeneous than the one formed under more extreme conditions, or, less frequently, (ii) the iron filling the cells of the boxwork is removed slowly, and a less porous pseudomorph is formed, consisting of siliceous zones (opal, chalcedony, quartz) enclosed by a ferruginous boxwork. If the siliceous colloid does not crystallize, it is leached soon or later and a practically empty pseudomorph with only some remains of the ferruginous boxwork results.

Under less strong leaching conditions most of the olivine constituents are recombined to a ferriferous smectite (Fig.2). This gives rise to pseudomorphs composed of bands of smectite, along the original fracture pattern, and wherein the individual crystals are oriented perpendicularly to the fracture walls, forming a boxwork, and unoriented smectite filling up the cells. In a further stage of weathering Mg and Si may be leached, and an irregular, very porous and ferruginous pseudomorph is left.

Similar patterns were observed for the deuteric alteration of olivine, e.g. to iddingsite or serpentine (Delvigne et al. 1979). It is clear that in all these cases the transitional and final fabrics of the pseudomorphs are determined only by the original fracture pattern. Garnet is another nesosilicate studied (Embrechts and Stoops 1982, Parisot et al. 1983) that also shows similar alteration patterns described above. It is noteworth that here the fracture pattern is sometimes influenced by the presence of inclusions.

2.2 Inosilicates

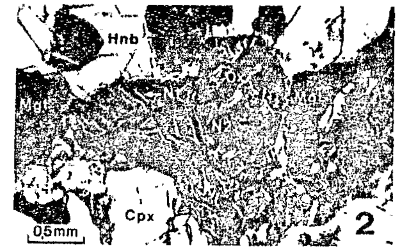
Inosilicates (mainly pyroxenes and amphiboles) are common constituents of both magmatic and metamorphic parent materials. Structurally they are characterized by the presence of single (in the case of pyroxenes such as enstatite, hypersthene, diopsite and augite) or double (in the case of amphiboles such as tremolite, actinolite and hornblende)chains of SiO_4-tetrahedrons parallel to the c-axis of the mineral. This results in an almost perfect cleavage parallel to (110). Weathering will proceed according to these planes of weakness, which will determine thus the fabric of the pseudomorph.

In general, amphiboles are more stable than pyroxenes, calci-magnesian inosilicates are more stable than ferro-magnesian ones, but less stable than the aluminiferous types (augites, hornblendes). Sodic inosilicates have a low stability.

Initially, under slow leaching conditions, smectites are formed in inter- and transmineral fissures (Fig.3 and 4) and in cleavages of e.g. hypersthene, giving rise to a parallel or cross banded pattern enclosing denticulate residues of the primary mineral. In most cases no pores are present between both phases. The smectites are all oriented parallel to the c-axis of the original material, showing a simultaneous extinction, irrespective whether they were formed in cleavage planes or fractures. Finally a pure smectite pseudomorph is formed with a continuous extinction.

Subsequently, under stronger leaching conditions that prevail in the upper horizons, pyroxene and amphibole residues, if any persist, are subject to a congruent dissolution, leaving only a brown staining of iron on the smectites. The smectites previously formed are no longer stable, and can be transformed in two ways: (i) replacement by iron oxyhydrates, giving rise to very porous pseudomorphs with an irregular internal fabric, without traces of former cleavages, or (ii) a slower deterioration to an orange yellowish isotropic material which in turn will alter to a colourless substance with hematite speckles and scattered kaolinite crystals gradually becoming more abundant. The original pattern of weathering is practically lost (Delvigne, 1983).

Tropical weathering and good drainage conditions promote a total loss of Ca, Mg and Si, resulting in a pseudomorph composed mainly of iron oxyhydrates. In the earliest stage, only the outer boundary



Classes of alteration according to Stoops et al. 1979.
Fig. 1 : Alteration (class 2) of olivine (Olv) to iron oxihydrates (Ox) according to a pattern of intramineral protoclastic fissures. No visible pores space is left between the irregular olivine residues and the newformed hydroxides. Associated : clinopyroxene (Cpx) and hornblende (Hnb). PPL 25x.

Fig. 2 : Complete alteration (class 4) of olivine to nontronite. Boxwork pseudomorph consisting of iron hydroxide (Ox) deposited in the irregular intramineral fractures. Well crystallized nontronite (N1) oriented perpendicularly to the fractures (banded structure) and micro-aggregated non oriented nontronite (N2) in the central part of the cells. Associated : clinopyroxene (Cpx) and magnetite (Mgt). XPL 25x.

and the cleavages and fractures are coated by brown iron oxyhydrates; with progressive weathering, dissolution of the silicates is faster than growth of the hydroxide walls, and the silicate residues with a denticulate morphology according to (001) lay loose in their cells, surrounded by a perinuclear pore (Fig.5). The liberated Fe and Al cations contribute to the boxwork. Here, the iron oxyhydrates, especially the goethite, preserve the orientation of the original silicate, and a simultaneous extinction of the different parts of the boxwork and the residues is commonly observed. Finally, only the boxwork is left. Thick walls and relatively small pores point to an iron rich primary silicate. According to the orientation of the section through the pseudomorph, the boxwork consists of parallel walls (parallel to the c-axis), or walls intersecting at right (pyroxenes) or oblique (amphiboles) angles for sections perpendicular to the c-axis.

In the case of fibrous habits (e.g. actinolite), only the outer boundary and some larger open fractures are covered by iron oxyhydrates; cleavages are not maintained in the pseudomorph.

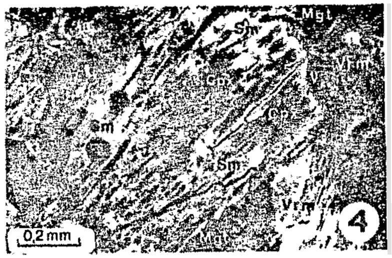


Fig. 3 : Initial alteration (class 1) of hypersthene (Opx) to smectite (Sm) along transmineral fractures. Note the small pore between the mineral fragments and the clay, and the fine denticulation, parallel to the c-axis, of the pyroxene residues. The clay orientation is not visible in PPL. PPL 63x.

Fig. 4 : Alteration (class 3) of diopside (Cpx) to a smectite (Sm). Pyroxene residues in extinction and smectite with maximum interference colours. Clear and regular orientation of the smectite sheets parallel to c-axis of the pyroxene. Well developed intermineral open pores (V) covered by ferri-argilans. Associated : magnetite (Mgt) and vermiculite (Vrm). XPL 63x.

2.3 Phyllosilicates

Phyllosilicates consist of a parallel packing of sheets of SiO_4-tetrahedrons and Al or Mg-Fe hydroxyde octahedrons. According to the type of packing 1/1, 2/1 and 2/1/1 phyllosilicates can be distinguished. A perfect cleavage exists between these layers, which are oriented perpendicularly to the c-axis.

The most common primary phyllosilicates found in soil parent material are the micas (e.g. biotite and muscovite), less common are serpentine and chlorite. Also most secondary clay minerals, such as kaolinite, vermiculite and the smectites belong to this group.

The best example for illustrating the weathering behaviour of the phyllosilicates is biotite (Bisdom et al. 1982) which is less stable than muscovite, and its weathering patterns are clearer than those of the mostly fine grained serpentine and chlorite.

From a morphological point of view, two weathering types can be distinguished: (i) weathering penetrates along the cleavages, layer by layer, and transform the biotite gradually into a vermiculite or smectite pseudomorph of the mesomorphic type (Stoops et al. 1979), i.e. with conservation of the a and b dimensions, but a considerable expansion according to the c-axis, or (ii) weathering attacks the biotite peripherically and penetrates as wedges between the layers; an expansion of the boundaries of the crystal, according to the c-axis results; the wedges are filled with kaolinite, gibbsite or goethite (Fig.6). This increase in volume frequently leads to a destruction of the external morphology of the grain, and even to a disorganization of the surrounding fabric. When smectite or swelling mixed layers are formed, the morphology of the grain is lost already in an early stage.

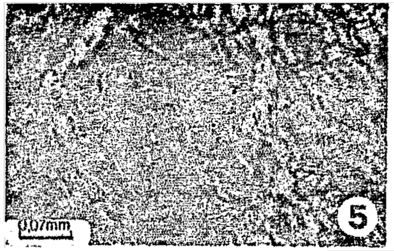


Fig. 5 : Crystal of hornblende (Hnb) altering (class 2) to goethite (black). Fragmentation of the crystal (grey) and formation of important porosity (white) : elongated central pore (V) corresponding to a transmineral fissure, covered by two subparallel goethite coatings separated from the denticulated hornblende residues by a perinuclear pore (P). PPL 160x.

Fig. 6 : Complete alteration (class 4) of biotite to kaolinite (K) oriented according to the original foliation of the mica, and local deposits of iron hydroxide (OxFe) between the kaolinite layers. Local successive degradation of kaolinite to gibbsite (G) as non oriented crystals, distributed in corners or as bands between some kaolinite sheets. XPL 160x.

In the case of transformations of phyllosilicates to chlorite (deuteric alteration) or vermiculite or a mixed layer, the crystallographic orientation of the pseudomorph is the same as that of the original crystal. This is generally also the case for kaolinite, although interlayer crystallizations of kaolinite, perpendicular to the cleavage of the mica have been observed. The first type is considered to be the result of a transformation of the mica with conservation of some lattice elements, whereas the second one is a newformation from soil solutions. Both types can be observed sometimes in the same grain.

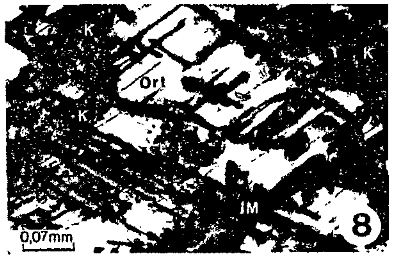


Fig. 7 : Alteration (class 2) of microcline (Mc) to well crystallized gibbsite (G). The alteration follows the irregular pattern of intramineral fractures in which the gibbsite forms a regular banded structure with individual crystals oriented perpendicular to the wall. In the better developed gibbsite zones, a random distribution is seen. Important perinuclear porosity (P) is observed. XPL 63x.

Fig. 8 : Initial alteration (class 1) of orthoclase (Ort) to an isotropic material (IM) according to a cross banded pattern following the feldspar cleavages. In the best developed isotropic zones crystallites of kaolinite (K) appear without specific distribution or orientation. XPL 160x.

When the biotite is rich in iron, goethite can crystallize between the kaolinite layers (Fig.6); if the latter are transformed subsequently to gibbsite, an alternation of white and brownish bands is conserved. This is an excellent example of the use that can be made of the morphology of a pseudomorph to deduce the nature of the original mineral.

2.4 Tectosilicates (framework silicates)

As in the case of the nesosilicates, and in contrast to the ino- and phyllosilicates, no preferential lattice directions exist in the tectosilicates.

The purest example is that of **quartz**, showing practically no cleavage directions, and weathering by congruent pellicular dissolution, starting from the inter- or intramineral fractures. In laterites, the so created pores can get filled by gibbsite or iron oxyhydrates, oriented according to this fracture pattern. It is obvious that these newformed minerals from soil solutions cannot inherit any structural orientation of the quartz. Finally, empty or infilled boxwork pseudomorphs are formed, with the old fracture pattern still clearly visible.

In the case of the **feldspars**, weathering takes place principally along the fractures. Gibbsite can be formed directly, or at the expense of an intermediate unstable isotropic phase (Fig.8), depending upon the leaching conditions (Delvigne 1965). The first formed gibbsite occurs as continuous coatings of microlites oriented perpendicularly to the fracture and cleavage walls, isolating the residual feldspar fragments. Weathering of these residues gives rise to zones of randomly oriented finer gibbsite (Fig.7). In the so formed pseudomorph, the original fractures are thus still recognizable.

Under less severe leaching conditions the isotropic phase can transform into kaolinite, by random crystallization. The pseudomorph has a high microporosity; its micropores can become filled with iron oxyhydrates.

In **orthoclase** and **microcline**, weathering often follows cleavage planes, in plagioclase twinning planes or exsolution directions (perthites). However, no relation exists between the orientation of the secondary products and the lattice of the primary mineral.

Weathering of feldspars, especially of basic rocks, in poorly drained conditions, results in the formation of smectites. Due to vertic movements, the fabric of the weathering products is destroyed soon after their genesis, preventing the formation of pseudomorphs.

In the case of nepheline (a **feldspathoid**) a total transformation into an isotropic phase with polygonal shrinkage cracks was observed, which become coated by fine gibbsite (Delvigne et al. 1987). These linings grow at the expense of the isotropic material, giving rise to a porous boxwork whose fabric is determined by the shrinkage pattern of the intermediate phase, not by the primary mineral.

3 DISCUSSION

From the examples presented above, a few general principles can be deduced. External factors (e.g. climate, drainage, depth) determine the nature of the secondary products formed. This in turn will influence the fabric of the pseudomorph, e.g. formation of a boxwork of sesquioxides versus a global transformation to clay, autodestruction of pseudomorphs of swelling clay.

As internal factor, especially the crystal lattice is important, besides the chemical composition, as it determines (i) the occurrence of planes of weakness (e.g. cleavage, twinning, exsolution), which in turn determine the general weathering pattern (the distribution of the weathering products), and (ii) the crystallographic orientation of weathering products by inheritance of lattice elements (e.g. O-sheets in olivine).

The different silicate types therefore also show a different weathering pattern:

- nesosilicates (e.g. olivine): no regular boxwork is formed, but iron oxyhydrates can inherit the optical orientation of the primary mineral;
- inosilicates: a regular boxwork is often formed, and both secondary clays and iron oxyhydrates frequently have the same orientation as the primary mineral;
- phyllosilicates: cleavage planes determine the weathering pattern, and secondary silicates mostly inherit part of the crystal lattice; in that case they have also the same optical orientation as the primary minerals;
- tectosilicates: as far as no cleavage (or twinning or exsolution) directions are present, an irregular weathering pattern occurs. Inheritance of the lattice by secondary products was never observed.

Weathering patterns discussed above are only observed if the primary mineral is sufficiently large, i.e. not in the case of fibrous habits. Appart from secondary products formed at the expense of the primary mineral, weathering pores can be filled up by newformed minerals from solutions (e.g. gibbsite in quartz). They mostly do not inherit the lattice structure. This is also the case when the compounds of the pseudomorph are formed at the expense of an intermediate amorphous phase (e.g. nepheline), or as a result of the transformation of weathering products. Pseudomorphs are only formed if the secondary product is mechanically stable with respect to its environment: e.g. goethite or gibbsite versus smectite near the surface.

4 REFERENCES

Bisdom, E.B.A., Stoops, G., Delvigne,J., Curmi,P. & Altemüller H.-J., 1982. Micromorphology of weathering biotite and its secondary products. Pedologie, 32, 225-252.

Delvigne, J., 1965. Pédogenèse en zone tropicale. La formation des minéraux secondaires en milieu ferrallitique. Mém. ORSTOM. Ed.Dunod Paris, 13, 177p

Delvigne, J., 1983. Micromorphology of the alteration and weathering of pyroxenes in the Koua Bocca ultramafic intrusion, Ivory Coast, Western Africa. Sci. Geol., Strasbourg, Mem. 72, 57 - 68.

Delvigne, J., Bisdom, E.B.A., Sleeman, J. & Stoops,G., 1979. Olivines, their pseudomorphs and Secondary Products. Pedologie 29,247-309.

Delvigne, J., Soubies, F. & Sardela, I., 1987. Micromorphologie des altérations supergènes de la Lujaurite du massif alcalin de Pocos de Caldas (Minas Gerais, Bresil). In: N. Fedoroff, L.M. Bresson et M.-A. Courty (Ed.), Micromorphologie des Sols - Soil Micromorphology, 97 - 104.

Embrechts, J. & Stoops, G., 1982. Microscopical aspects of garnet weathering in a humid tropical environment. J. Soil Sci., 33, 535 - 545.

Loughnan, F.C., 1969. Chemical Weathering of the Silicate Minerals. Elsevier Publ. Co. Inc., New York, 151p.

Parisot J.C., Delvigne J. & Grake M.C.T., 1983. Petrographical aspects of the supergene weathering of garnet in the Serra dos Carajas (Para, Brasil). Sciences Geologiques 72, 141-148.

Stoops G., Altemuller, H.-J., Bisdom, E.B.A., Delvigne, J., Dobrovolsky, V.V., FitzPatrick, E.A., Paneque, G. & Sleeman, J., 1979. Guidelines for the description of mineral alteration in soil micromorphology. Pedologie 29, 121-135.