FORMATION OF CLAY FROM GRANITE AND ITS DISTRIBUTION IN RELATION TO CLIMATE AND TOPOGRAPHY

Y. TARDY1, G. BOCQUIER2, H. PAQUET1 and G. MILLOT1
1Centre de Sédimentologie et de Géochimie de la Surface, Strasbourg (France)
2S.S.C. - O.R.S.T.O.M., Bondy (France)
(Accepted for publication September 13, 1973)

ABSTRACT


Chemical weathering can be approached from three interpretive points of view: distribution of the secondary minerals in landscapes, weathering of primary minerals and geochemistry of ions in solution. On granitic rocks it is possible to define both climatic and topographic sequences of distribution of clays in association with weathering products: gibbsite – kaolinite – hydrous iron oxides – hydrous manganese oxides – iron-rich montmorillonite – calcium carbonate – calcium sulfate – sodium carbonates and silicates. These stages appear as an absolute accumulation formed by filling of intergranular pores. Another sequence can be found not in intergranular pores but in the cracks and along the cleavages of primary minerals from which they are derived by relative accumulation. The order of appearance of these secondary minerals remains the same regardless of the nature of climates and the topographic position. The conditions of equilibrium are not identical in the interior of grains of different primary minerals nor in the pores outside of them and the secondary minerals found in the different situations are also not identical. This is well demonstrated by the chemistry of waters draining slopes. The equilibrium diagrams and balances between cations and silica sometimes result in disagreement, proving that equilibrium conditions are not satisfied between solutions circulating in the pores and clay minerals found inside the primary minerals.

INTRODUCTION

The nature and distribution of products resulting from the weathering of rocks are influenced by a number of complex factors such as biological phenomena, nature of climate, relief, and parent rock, topographic position, and the age of the profile* or the formation considered (Jenny, 1941; Barshad, 1964).

With time, the influence of each of these factors is modified by climatic changes or tectonic movements. Physical erosion tends to destroy and efface the slow work of chemical weathering, and the speed of the natural reactions (hydrolysis, dissolution, precipitation, authigenesis) is sometimes very slow when compared to the life spans of the land-

*The term "profile" will be always used here in a general meaning in order to designate the full vertical section of the regolith including soil profile and weathering profile.
scapes themselves. Chemical weathering rarely attains its limits, and it is illusory to pretend to define conditions of equilibrium which would be characteristic of a fixed factor. Thus when studying the weathering of granite in regions where the relief is not pronounced, the climatic influence could be characterized by a chain of geochemical phenomena, more or less temporary in character, but differing in extent.

We have chosen to illustrate this from three points of view: (a) distribution of the secondary minerals in landscapes; (b) weathering of the primary minerals; and (c) geochemistry of the ions in solution.

This paper is an interpretive presentation of some studies carried on in France and Africa.

**DISTRIBUTION OF THE SECONDARY MINERALS IN LANDSCAPES**

*Sequences of absolute accumulation*

Ions and clay minerals migrate in weathering profiles and down slopes. The mechanisms of hydrolysis and eluviation which progressively form voids are succeeded by the mechanisms of precipitation, authigenesis and illuviation which lead to the filling of the pores. The fillings are composed of fragments of primary minerals, mechanically transported clay minerals which were formed higher up, clay minerals newly formed in the pores, various hydrous iron and manganese oxides, and salts such as carbonates and sulfates. These movements of materials are closely linked to the movements of water. The nature, intensity and distribution of the accumulations depend upon the topography and climate.

On granite in temperate zones, the amounts of clay minerals produced by pedogenesis are relatively slight (Collier, 1961). Consequently, the mineralogical differentiations are not obvious. The gradations are, above all, centered around the distribution of montmorillonite (Gjems, 1967); accumulation of inter-layer aluminum in such minerals as vermiculite, montmorillonite and chlorite (Jackson, 1964); and amorphous aluminum hydroxides (Souchier, 1971).

In tropical regions, the contrasts are much sharper. In humid tropical climates, Lelong (1967) and A. Novikoff (personal communication, 1973) show that gibbsite and kaolinite are carried along or are formed in the pores and cavities which they progressively fill. Delvigne (1967) gives several examples of absolute accumulations of gibbsite in the highlands and of kaolinite in the lowlands of a region.

In tropical climates with seasonal contrasts, Paquet (1969) shows the relationship which links the distribution of kaolinite and montmorillonite in landscapes. As a general rule, kaolinite is found in the highlands, whilst montmorillonite appears in the lowlands. The ions taking no part in the formation of kaolinite are removed and trapped in the low parts where they give rise to montmorillonite. This montmorillonite is shown to be ferriferous with a high layer charge: the richer in iron the parent rock, the more ferriferous the montmorillonite formed.
In Chad, under a dry tropical climate, Bocquier (1971) has studied these mechanisms in detail as follows. Two domains were identified in the soil catenas: upslope a leached or eluvial domain, and downslope an accumulation or illuvial domain. In the upslope eluvial domain, the migration and accumulation of kaolinite can be seen adjoining some segregations of hydrous iron oxides. In the downslope illuvial domain, ferriferous montmorillonite is formed and fills the pores already containing kaolinite of former leached horizons which had previously supplied material for accumulations still further downslope. Manganese concretions appear upslope of the front of montmorillonitic accumulation, whereas calcareous concretions form further downslope. With time, migration of ions downslope gives way to formation of montmorillonite, which further diminishes the porosity and causes favorable conditions for new accumulations whose front ascends upslope.

When passing from very humid climates to very arid climates, a zonation of the different facies can thus be seen, as described by Glazovskaya (1968), Kovda et al. (1968), Tardy (1970), and Bocquier (1971). Referring to Bocquier's synthesis (1971), and by taking into consideration only sequences of absolute accumulation of secondary minerals

---

**Fig. 1.** Climatic and topographic sequences of appearance of clays and weathering products by absolute accumulation and by filling of pore spaces.
in the voids due to previous weathering phases, the following scheme (Fig.1) applies:

(a) In very humid climates and under excellent drainage conditions, gibbsite can appear. Gibbsite of relative accumulation upslope is followed by an absolute accumulation of gibbsite downslope.

(b) The absolute accumulation of kaolinite succeeds that of gibbsite at the base of the slope under very humid climates or over the whole slope in tropical regions.

(c) Under humid climates with a pronounced dry season, kaolinite can predominate in all soils. Further downslope in these landscapes, conditions for the accumulation of hydrous iron oxides, then of hydrous manganese oxides occur.

(d) At the bottoms of the profiles and downslope in semi-arid regions with a long dry period, accumulations of ferriferous montmorillonite appear followed further downslope by segregation of calcium carbonate.

(e) Finally, in very dry climates, only the very soluble elements migrate. The sodium carbonates and silicates accumulate in the lowlands and calcium carbonate remains separate and distinct on the highlands.

Discussion

The presentation of the sequence of absolute accumulations of secondary minerals is purposely simplified and made schematic here, intended only to illustrate migration of solutions downslopes, progressively concentrating silica and cations and provoking in the intergranular spaces precipitation and illuviation of clay minerals, hydrous oxides, or salts. The renewal and dilution of these solutions, on the one hand, and the evaporation and concentration of the solutions, on the other hand, are directly influenced by the intensity of the rainfall, the temperature and thus, the climate. The concentration also depends on the position in a slope and on the time of contact of the solutions with reacting minerals. These two factors combine to give a sequence of different mineralogical or geochemical stages valid in a majority of cases on granitic rock: gibbsite — kaolinite — hydrous iron oxides — hydrous manganese oxides — montmorillonite — calcium carbonate — calcium sulfate — sodium carbonates and silicates.

In this climatic sequence of absolute accumulation, each stage appears downslope from the preceding one. What is found downslope under one climate foreshadows what is to be found upslope in a more arid climate. Each stage located upslope under one climate foreshadows what is to be found downslope in a more humid climate. Likewise, the absolute accumulations found at the bottom of a given profile indicate what will be found further in the whole profile located downslope and the accumulations in the upper horizons are of the same nature as those found in the whole profiles located upslope.

This sequence corresponds to absolute accumulations formed by the filling of intergranular pores and channels. Near these channels, another system of fine fissures and cleavages is likely to appear where the slow circulation of solutions permits the development of another sequence of authigenic secondary minerals within the primary minerals. The minerals formed by weathering thus correspond to relative accumulations of matter.
WEATHERING SEQUENCES OF PRIMARY MINERALS CORRESPONDING TO RELATIVE ACCUMULATIONS

For a number of years it has been recognized that the primary minerals of crystalline rocks weather at different rates and that secondary minerals appear within these primary minerals in well established sequences (Jackson et al., 1948; Sherman, 1952; Fieldes and Swindale, 1954; Craig and Loughnan, 1964; Loughnan, 1969; Tardy, 1969). Even though the evolution of the micas during weathering of granitic rocks has long been stressed, the formation of clay minerals within the feldspars, especially plagioclases, should not be neglected. In a simplified manner, the three sequences are as follows:

\[ \text{K-feldspar} \rightarrow \text{kaolinite} \rightarrow \text{gibbsite} \]
\[ \text{Biotite} \rightarrow (\text{chlorite}) \rightarrow \text{montmorillonite} \rightarrow \text{vermiculite} \rightarrow \text{Al-vermiculite} \rightarrow \text{kaolinite} \]
\[ \text{Plagioclase} \rightarrow (\text{sericite}) \rightarrow \text{vermiculite} \rightarrow \text{montmorillonite} \rightarrow \text{Al-montmorillonite} \rightarrow \text{kaolinite} \rightarrow \text{gibbsite} \]
\[ \text{progressive weathering} \]

The different secondary minerals form in the cracks and along the cleavages of the primary minerals from which they are derived. They appear progressively and replace one another as the host mineral becomes more weathered and as the interstices are enlarged.

The order of appearance of these secondary minerals remains the same regardless of the nature of the climate. The initial stages, such as vermiculite in biotite or montmorillonite in plagioclase, are found under all types of climates. These are commonly intermediate stages in the weathering of these minerals. The more advanced stages correspond to greater weathering of the supporting mineral and, as a result, are influenced more by the surrounding environment.

(a) Sericite and chlorite do not form under the usual weathering conditions. These two minerals are readily formed in the deeper zones of the “retrodiagenesis” of granites (Lelong and Millot, 1966).

(b) Montmorillonite appears either as a product of the transformation of biotite or as a product of authigenesis in feldspars. Thus, two processes must be differentiated (Tardy et al., 1970). Montmorillonite resulting from biotite is ferriferous. As a rule it does not appear except in semi-arid climates. Montmorillonite resulting from plagioclases contains more aluminum than its precursor. It is found at the bottom of sandy saprolite in humid tropical regions, where, identified by optical methods, it was long confused with sericite. It is also found commonly associated with vermiculite in sandy saprolite of temperate regions. Finally it is found in plagioclases in arid climates (Meilhac and Tardy, 1970; Tsawlassou, 1971).

Converging evolution of clay minerals from biotite and plagioclase takes place only in arid climates. In humid climates, only the plagioclase contains a sufficient reserve of silica to form montmorillonite.
The montmorillonite of biotites is, therefore, characteristic of arid climates which are alone capable of concentrating silica in solution. The montmorillonite of plagioclases is not typical of any climate; it is a transitory stage present in the primary stages of weathering of feldspars (curtailed in humid climates and prolonged in temperate climates).

(c) Vermiculite is also a product of the weathering of plagioclase. More than the typical vermiculite, it often consists of montmorillonite with interlayer aluminum which has acquired behaviour patterns resembling those of vermiculite (Jackson, 1964; Tardy and Meilhac, 1971). The more typical vermiculite which is formed within biotite still has a certain relationship to the climate. The humid climates which remove cations and silica induce the separation of the layers, at the same time precluding the formation of clay minerals more siliceous than biotite itself. Confining to the bottom of sandy saprolite in humid tropical regions (Tsawlassou, 1971; A. Novikoff, personal communication, 1973), vermiculite is the most common product of the transformation of biotite in temperate regions.

(d) Kaolinite is the common weathering product of potassic feldspar, biotite, and plagioclase in humid tropical regions. In temperate regions, kaolinite appears as a secondary mineral linked only to plagioclases. It is rarely linked to biotite.

Thus, in one single sample of sandy saprolite, different secondary minerals may be found, each localized in a different primary mineral. (One of the best examples is given by Kato, 1964.)

In sandy saprolites, the associations most often found are:

for temperate climates:  
biotite $\rightarrow$ vermiculite  
plagioclase $\rightarrow$ montmorillonite and kaolinite

for arid climates:  
biotite $\rightarrow$ montmorillonite  
plagioclase $\rightarrow$ kaolinite

for humid tropical climates:  
biotite $\rightarrow$ kaolinite  
K-feldspar $\rightarrow$ kaolinite  
plagioclase $\rightarrow$ kaolinite

for very humid tropical climates:  
biotite $\rightarrow$ kaolinite  
K-feldspar $\rightarrow$ kaolinite or gibbsite  
plagioclase $\rightarrow$ gibbsite

Discussion

Over a very long period under the influence of constant climatic conditions in an open environment, all weathering can lead to the same end (for example, to gibbsite and then to complete dissolution). However, in most cases, mechanical erosion intervenes before the end is reached. This is particularly true in climates which are neither very humid nor very warm.
The primary minerals, thus conserved in profiles, weather at different rates and each gives rise to a series of secondary minerals which appear successively and which correspond to stages more and more impoverished in cations and silica. The leached stages are more rapidly reached by the more fragile primary minerals (plagioclases). Thus, sequences of weathering remain staggered in certain cases until almost the whole of a primary mineral is altered.

From an interpretation offered by Tardy (1969, 1971) it can be assumed that, when the microfissures enlarge, the secondary minerals which form therein are able to become more and more like those which appear in the spaces between the primary minerals. Up to this stage, the conditions of equilibrium found in the interior of different grains are not identical; neither are they the same as those found in fissures between minerals. In other words, the chemical compositions of solutions differ from one point to another in the same sample.

**GEOCHEMISTRY OF IONS IN SOLUTIONS**

To verify the interpretations given above, it would be desirable to analyse the chemical compositions of the solutions at every point within a given rock. As this unfortunately is impossible, one must be content with the analyses of free waters such as those of springs. Among the results of the analyses of water samples collected on granite and cited by Tardy (1969, 1971) are three characteristic examples for three types of climate:

1. Humid and hot (Korhogo, Ivory Coast) — (humid tropical)
2. Humid and cold (Vosges, France) — (temperate)
3. Dry and hot (Chad and Senegal) — (tropical with long dry season)

The two humid countries are characterized by a rainfall of 1,500 mm, differing from one another in mean annual temperature: approximately 25°C in the first case and 10°C in the other. The dry and hot region receives from 3 to 500 mm of rainfall per year and has a mean annual temperature of approximately 25°C.

Important geochemical differences exist between the waters in the three types of climates.

_Equilibria and the stability diagrams of minerals_

Feth et al. (1964), Garrels and Christ (1965), Bricker and Garrels (1967) have shown the usefulness of stability diagrams that include feldspars, gibbsite, kaolinite and montmorillonite.

The diagram of Fig.2 treats the data published by Helgeson (1969) using the system \([\text{Ca}^2+] / [\text{H}^+]^2 - [\text{SiO}_4\text{H}_4^-]\) as an example. This is a simple illustration, and other diagrams giving the same picture could be used, such as those proposed by Weaver et al. (1971) for the system \([\text{Mg}^{2+}] / [\text{H}^+]^2 - [\text{SiO}_4\text{H}_4^-]\).

Plotted data for the concentrated waters of hot and dry regions are near the field of stability of montmorillonite. At this stage, no distinction can be made among the dilute
Fig. 2. Equilibrium diagram for the system CaO – SiO₂ – Al₂O₃ – H₂O at 25°C, as an example among others showing the positions of the waters: I in Ivory Coast (humid tropical climate), II in Vosges, France (temperate climate) and III in Chad (dry tropical climate).

waters of the humid domain between hot and cold regions: the points both fall in the kaolinite field of stability. A distinction is, however, possible because of the discharge balance of silica and cations.

**Balance of silica and cations**

Garrels (1967) and Garrels and Mackenzie (1967) have shown how it would be possible to take into account the different quantities of SiO₂, Na, K, and Ca removed in water in order to identify the nature of the clay minerals formed in the weathered products. Tardy (1968, 1969, 1971) uses the molecular ratio (when Na₂O, K₂O, CaO represent the equivalent amount of oxides in water):

\[
\frac{6 \text{Na}_2\text{O} + 6 \text{K}_2\text{O} + 2 \text{CaO} - \text{SiO}_2}{\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}} = RE \text{ in water}
\]

which is approximately equal to SiO₂/Al₂O₃ in weathered products of granite. The ratio
RE ("Rapport dans les Eaux") thus permits identification of the minerals formed: gibbsite, kaolinite, montmorillonite, or vermiculite.

In fact, this ratio is calculated using the proportions of different oxides in feldspars and biotite formulas:

- $6\text{ SiO}_2, \text{Al}_2\text{O}_3, \text{Na}_2\text{O}$ for albite
- $6\text{ SiO}_2, \text{Al}_2\text{O}_3, \text{K}_2\text{O}$ for microcline
- $2\text{ SiO}_2, \text{Al}_2\text{O}_3, \text{CaO}$ for anorthite
- $6\text{ SiO}_2, \text{Al}_2\text{O}_3, \text{K}_2\text{O}$ for biotite (ignoring MgO, FeO and Fe$_2$O$_3$ in octahedra). Then, if Na, K, Ca counted in equivalents of oxides are released by hydrolysis and completely removed in solution, the corresponding number of silica moles released is equal to $6\text{ Na}_2\text{O} + 6\text{ K}_2\text{O} + 2\text{ CaO}$. The number of silica moles effectively found in solution is represented as $\text{SiO}_2$. The difference $(6\text{ Na}_2\text{O} + 6\text{ K}_2\text{O} + 2\text{ CaO})-(\text{SiO}_2)$ in waters represents the number of silica moles retained in the profiles as a difference between the total number of moles released and the number of moles effectively found removed. The total corresponding number of moles of $\text{Al}_2\text{O}_3$ released and not removed in such reactions is calculated as the sum $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$. For biotite, only $\text{K}_2\text{O}$ is sufficient to explain the $\text{SiO}_2$ and $\text{Al}_2\text{O}_3$ behaviours which are in the same ratio as they are in potassic feldspar. Then the ratio RE calculated from the equivalents of oxides found in the waters represents the ratio of $\text{SiO}_2/\text{Al}_2\text{O}_3$ in residual weathering products.

RE is greater than 2 in Chad and Senegal; RE is equal to 2.5 in the Vosges in France; RE is less than 2 in Korhogo, Ivory Coast. This indicates the formation of montmorillonite in the first two cases and kaolinite in the third.

Discussion

The two procedures employed show that it is possible to discuss the influence of the climate on the chemical composition of the water which circulates in the watershed of weathered granites. The first uses thermodynamic data and calculations for proximate identification of the new mineral in equilibrium with water of a given composition. The second proceeds by comparison between the quantities of silica and those of the cations which are removed at different rates in the waters. The first process indicates therefore what should be found if the conditions of equilibrium were met, and the second, based on the differential kinetics of removal of the elements, is a measurement of what actually occurs even if equilibrium is not reached.

In the case of the two hot regions, one humid and the other arid, the results of the two methods agree with what is actually found in the field: kaolinite dominant in humid tropical regions, montmorillonite dominant in arid tropical regions (Paquet, 1969; Bocquier, 1971). In the case of temperate regions such as the Vosges, the results of the two methods diverge. The method of balances indicates the formation of clay minerals with two layers of silica and accords better with results in the field, vermiculite and montmorillonite dominating the fraction less than 2 μ and kaolinite present in minor amounts (Tardy and Gac, 1968; Meilhac and Tardy, 1970).
The case of the temperate regions can be interpreted by recalling that sandy saprolites and many soils contain small proportions of clay as compared to a large proportion of partly decomposed primary minerals. These clay minerals, above all vermiculite and montmorillonite, are localized in the fissures within the plagioclases. The very minor amounts of kaolinite are probably distributed throughout the zones of greater porosity. The groundwaters which circulate rapidly in the more permeable zones are assumed to be renewed more often and therefore more dilute than those circulating slowly within the microfissures of the primary minerals undergoing weathering as illustrated in an interpretive picture (Fig. 3).

Within the plagioclase fissures, solutions are probably concentrated and in equilibrium with the montmorillonite which forms there, but it is not these solutions which are collected for analysis. These solutions proceed towards the larger pores where they could be diluted and renewed by the rapidly circulating rainwater supply. This could permit the formation of kaolinite even though the ratio between SiO₂ and cations continues to indicate the formation of montmorillonite in the smaller pores. This may cause a discordance.

![Fig. 3. Schematic and interpretive picture showing development of kaolinite in the highly drained pores and of montmorillonite in the cracks of a primary mineral.](image-url)
between the results of the thermodynamic diagrams which indicate the formation of kaolinite and the balances which indicate the formation of montmorillonite. Consequently, stability diagrams cannot be applied directly. But this discordance can, however, be used to determine the time-lag between the geochemistry of the solutions which circulate in the spaces between minerals and of those which pass through the microfissures of the minerals being weathered.

DISCUSSION – INTERPRETATION

Equilibrium between solutions and secondary minerals

Because the nature of minerals formed is not the same, the chemical compositions of solutions are believed to differ at different points in a rock undergoing weathering. This supposes then that the diffusion of ions and the homogenization of the solutions proceed more slowly than the renewal of the solutions themselves. The diffusion is also dependent upon the permeability of the rock and the renewal of the solutions. The waters sampled have chemical compositions which more strongly reflect the nature of the equilibria found in the zones of greater circulation than those found in the zones of lesser circulation. The volume of water which passes through zones of great permeability is, in effect, more important than that which passes through the fissures in the primary minerals. The first, renewed more rapidly by rainwater, is diluted more than the second. The secondary minerals which form within the primary minerals therefore generally correspond to more siliceous stages richer in cations than those which form in the intergranular joints and the larger pores. The spring waters do not therefore necessarily reflect the conditions of equilibrium within the primary minerals. They could only be in equilibrium with the minerals newly formed and with minerals earlier formed and illuviated in the larger pores and channelways near the foot of a slope.

Evolutionary convergences in the course of time

When mechanical erosion does not intervene too soon, weathering has time to do its work. Within the primary minerals, the fissures enlarge, thus aiding the renewal of solutions and their homogenization. In the cracks of the primary minerals the same secondary minerals are found as in the exterior channelways, and all the channelways converge toward the same outlet. In arid climates, as in Chad, the convergence towards montmorillonite is rapidly reached because within the highly permeable zones, the evaporation concentrates solutions and makes them similar to those which circulate in the zones of minor permeability. In hot and humid climates, the convergence towards kaolinite is reached with equal speed because the primary minerals weather rapidly and the porosity becomes uniform. In cold and humid climates and in temperate climates the primary minerals weather slowly, whereas the intergranular joints are drained by the dilute solutions. The evolutionary convergences are more difficult to reach because the relief is sharp
and the climates are cool. Relief promotes erosion with truncation of profiles before primary minerals have all reached a stage of convergence, and the cool climate slows hydrolysis.

Sequence of past events

The simplicity of the cases described can be disturbed by changes in conditions during the history of the profiles. These changes can be climatic or tectonic in nature or due to the dynamics peculiar to a slope without other intervening changes. Thus Bocquier (1971) shows that the front of montmorillonite accumulation ascends the slope while the ions migrate downslope. As it ascends, the montmorillonite thus fossilizes the facies which, during preceeding epochs, were characteristic of the evolution of the leached regions (kaolinite, hydrous iron oxides). That which is true of upslope — downslope dynamics is also true when different situations of varying permeability are considered.

Within a primary mineral, the secondary minerals are more siliceous and richer in cations than those which form in the spaces of greater permeability in the vicinity (kaolinite in a fissure, montmorillonite in a plagioclase grain). An opposite situation means that the kaolinite of the plagioclase or biotite is inherited from a previous cycle and would have been formed earlier in a site better drained than that which now allows accumulation of montmorillonite in a pore (Bocquier, 1971; Tsawlassou, 1971).

Climatic significance of clay minerals

It is well known that equilibria are only apparent and in any case ephemeral, in nature. Hence, it is difficult to determine which minerals are characteristic of different climatic zones. Only those which occur most frequently can be considered here. In addition, their place of formation must be differentiated: either within primary minerals or as absolute accumulations in pores. Montmorillonite could thus appear within plagioclase under all climates. This primary stage of weathering of highly siliceous minerals can be ephemeral in humid, tropical climates if rejuvenation of the relief is not great. In temperate climates this mineral does not represent a phase of equilibrium; it is only a prolonged transitory event. The vermiculitization of biotite has exactly the same meaning.

The kaolinitization of potassic feldspars and of biotite is characteristic of humid tropical climates. In addition the transformation of potassic feldspar to gibbsite requires a more intense climate of the equatorial type. Finally, the formation of montmorillonite from biotite remains characteristic of semiarid climates only.

When the traces of primary minerals disappear it is necessary to have recourse to sequences of absolute accumulation, at the same time distinguishing upslope from downslope inasmuch as kaolinite can be found upslope in arid regions and montmorillonite is associated with calcium carbonate downslope in humid regions.
CONCLUSIONS

(1) Study of the appearance and distribution of secondary minerals in weathering necessitates a distinction between two kinds of mechanisms: (a) a mechanism of subtraction which affects the primary minerals where the secondary minerals are concentrated relatively in the voids left by the removal of soluble ions; (b) a mechanism of addition which affects the secondary minerals mechanically transported, newly formed, and accumulated in an absolute way in the intergranular spaces created by previous leaching.

(2) In the beginning stages of weathering of primary minerals, the microfissures are small and permeability is low. The solutions are first concentrated and then diluted more and more as the pores gradually open. The sequences of weathering undergone by the primary minerals can be staggered in relation to each other but have the same trend from secondary minerals richest in silica and cations (montmorillonite) to the poorest (gibbsite).

(3) The sequences of absolute accumulation depend first upon the nature of the climate and then upon the topography. This sequence is inverse to the preceding sequence when going from the top to the bottom of profiles, from upslope toward downslope of landscapes, or from humid climates toward arid climates.

(4) The sampled solutions taken from the profiles, downslope or downstream, cannot be in equilibrium except with the minerals accumulated in an absolute way in the vicinity of the sampling points. In the majority of cases these solutions are neither in equilibrium with the minerals of absolute accumulation situated further above nor with the secondary minerals formed within the primary minerals. Only the relative balance of silica and cations removed in solution can give an idea of the general mineralogical evolution of a region.

REFERENCES


