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DEGREE OF LEACHING AS DISTINCT FROM DEGREE OF WEATHERING AND ITS IMPLICATIONS IN SOIL CLASSIFICATION AND FERTILITY

J. PAPADAKIS,

Institute of Soils and Agriculture, Buenos Aires, Argentina

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The concept of weathering sequence is very useful in pedology; however, in this concept two different processes are involved: weathering and leaching. It would be useful to separate weathering sequence from leaching sequence and give separately the degree of weathering and leaching of each horizon; the first is based chiefly on the mineralogical composition of the non-clay fraction, the second on the composition of the clay fraction and the presence of certain soluble substances such as calcium carbonate, etc.

Leaching Sequence

Taking as a basis the work of Polynov (1937) and some other authors (Papadakis, 1959; Crompton, 1960), we may propose the following sequence; for each phase we give the substances that are leached and the diagnostic features.

PHASE 1 (CALCIC): leaching of $CaSO_4$, $CaCO_3$, $MgCO_3$; effervescence with HCl takes place and/or more than 1 per cent of $CaSO_4$ is present.

PHASE 2 (ACIDIFICATION): leaching of exchangeable Ca, Na, Mg, K; pH is higher than 5.5 and/or increases with depth.

PHASE 3 (INCIPIENT LATERISATION): leaching of SiO_2; pH is lower than 5.5 and decreases with depth; the horizon is not yet "oxic".

PHASE 4 (ADVANCED LATERISATION): leaching of SiO_2; the horizon is "oxic" (CEC is less than 10 me.; the clay fraction contains more than 90 per cent of 1:1 lattice clays and free sesquioxides and the ratio free R_2O_3/clay is 0.12 or more); but the charge of mineral colloids is still negative.

PHASE 5 (EXTREME LATERISATION): leaching of SiO_2; pH in water is equal to or lower than that in N KCl.

PHASE 6 (PODZOLISATION): leaching of sesquioxides and/or humus; an "albic" (bleached) and a "spodic" (podzolic B) horizon, as defined by 7th Approximation (Soil Survey Staff, 1960), have been formed; the "albic" should have hue 10YR or yellower, chroma 2 or less, and value 4 or more; one only of these horizons is sufficient if there are

proofs of Al_2O_3 leaching; sometimes the "spodic" horizon overlies an "argillic" (textural B) horizon and may be confused with it.

Naturally chlorides and sulphates are the first substances leached; but given their mobility it is not convenient to consider desalinisation as phase 1 of the sequence.

The diagnostic criteria given are, in general, satisfactory; however, it is useful to check them and establish minor differences on the basis of base saturation, clay mineralogy, SiO_2/R_2O_3 ratio, etc. Naturally a horizon in phase 2 cannot have the diagnostic criteria of phases 1, 4, 5, or 6. Each horizon is characterised separately; but the variation of pH in the solum is considered; given that CEC and charge are affected by organic matter, when a horizon in phases 4 or 5 is encountered, the characterisation is extended to the overlying horizons, except in cases of lithologic discontinuity, etc.

Leaching naturally affects all soil constituents at the same time and the difference between phases is more quantitative than qualitative, each phase marking the peak of the leaching of a certain group of substances. Podzolisation may follow directly after phase 2.

Leaching itself is less important than the leaching-weathering balance (Crompton, 1960); when the amount of a substance liberated by weathering exceeds that taken away by leaching the substance accumulates; if the opposite occurs, its content decreases. That is why the duration of a phase of leaching depends greatly on the composition of parent material and its rapidity of weathering. Many parent materials do not contain $CaCO_3$, $MgCO_3$, or $CaSO_4$, and leaching begins with phase 2; others are more or less laterised and leaching begins with phase 3, 4, or 5.

Besides the above substances, clay is also leached. It seems that there is a close association between leaching of clay and leaching of silica (Papadakis, 1960). It may be said that illuvial clay horizons are formed when the silica that moves down from the A-horizon cannot be leached out from the B; that is why textural B horizons are frequent in desert soils but are seldom encountered in well drained soils of very humid climates (red soils, latosols, sols bruns acides, etc.). Clay illuviation is often accelerated by organic chelates or by sodium ions.

Clay illuviation takes place chiefly in phase 2. The degree of leaching of illuvial horizons is consequently that shown by the diagnostic features mentioned above; and the suffix IL is added to show that carbonates, gypsum, clay, humus, or sesquioxides have been leached into the horizon.

Naturally the degree of leaching decreases with depth and the vertical sequence of soil horizons follows a leaching sequence. If A_1 is in phase 1 (calcic), all the underlying horizons are in the same phase. If A_1 is in phase 2 (acidification), it may overlie a horizon in 2-il

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(textural B), which may overlie another in 1 (calcic). When A_1 is in phase 3, 4, or 5, we often encounter at some depth an accumulation of silica that might be considered as a horizon in phase 2-il. In some grey wooded soils we often encounter a bleached horizon (phase 6), overlying a podzolic B (phase 6-il), which overlies a textural B (phase 2-il), which may overlie a horizon containing carbonates (phase 1-il). Usually we encounter only a part of the sequence; an intermediate horizon may be lacking; but the sequence is never reversed, except in cases of lithologic discontinuity, etc.

The rapidity with which the degree of leaching decreases with depth depends on leaching rainfall and drainage. In "red desert" soils (Papadakis, 1962) the entire sequence terminates usually at a depth of 10 in. (25 cm) where $CaCO_3$ accumulates; in "grassland" soils (Papadakis, *loc. cit.*) the same sequence terminates at 40 in. (100 cm) or more; in lateritic soils silica accumulation is often encountered at a depth of 30 ft (10 metres) or more. Naturally, in cases of impeded drainage the less leached horizon is encountered above the water table or the impermeable layer that impedes drainage.

A useful convention is to consider the grade of leaching of a soil to be that of its A horizon. Sometimes a thin surface layer, enriched in bases and silica by above-ground plant residues, is less leached than the rest; this thin layer should not be taken as a criterion.

Relation to Leaching Rainfall

There is, of course, a close correlation between degree of leaching and leaching rainfall (rainfall minus potential evapotranspiration). We have computed it for 2,400 stations (Papadakis, 1961), and we prepared maps showing its distribution in the six continents; but for reasons of brevity this part is omitted.

Implications in Soil Classification

Granted that leaching is one of the more important processes of soil formation, it helps our understanding of soils and classification considerably. For instance, an invasion of the leaching sequence in a soil profile suggests lithologic discontinuity, flooding, etc. In a young soil, all horizons are equally leached. Grey desert soils (Papadakis, 1962) and young rendzinas have phase 1. "Chernozems" and "nonchernozem pedocals" (Papadakis, *loc. cit.*) have phase 2 or less, and they usually have a horizon in phase 1 at some depth. All "grassland soils" (Papadakis, *loc. cit.*) have phase 2 or less. "Sols bruns" (Papadakis, *loc. cit.*) have phase 2, but some dispersion of iron by organic matter is observed (Kubiena, 1952) and causes them to tend towards phase 6. "Rouges méditerrannéens" (korichnevie, non-calcic brown, dry forest soils) have phase 2, but in this case iron is dispersed by silica and flocculates in concretions of greater size (Kubiena, *loc. cit.*); a horizon in phase 1 is often encountered at some depth. "Krasnozems"

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("ulrisols", red acid soils) have phase 3. Lateritic soils (oxisols, kaolisols) have phase 4 or 5. "Acrox" (Soil Survey Staff, 1960) have phase 5. Podzols have phase 6. Grumusols (black tropical, regur) have phase 2; a horizon in phase 1 is often encountered at some depth. Hydromorphic soils have phase 2 or less; they often have a horizon in phase 1 at some depth. But "hydromorphic krasnozems" (Papadakis, 1952) have phase 3, ground water laterites phase 4 or more, and ground water podzols (aquods) phase 6. Ando soils have phase 2, but are rich in sesquioxides (allophane) and their apparent density is low.

The difference between "prairie" and other "grassland" soils of drier climate, and that between "eutrophic braunerde" and "sol brun acide" is in degree of leaching. In all categories of soil classification a difference in degree of leaching results in different soils. When parent material in an advanced phase of leaching receives Ca, Na, SiO_2, etc., by flooding, or from the atmosphere, the soil formed is difficult to classify within the usual schemes of soil classification, and the establishment of new groups may be necessary.

Implications in Soil Fertility

Soil fertility is greatly affected by leaching (Wells and Taylor, 1960). Available K, Ca, Mg, and S decrease as degree of leaching increases; however, the reduction of CEC in phases 4 and 5 makes the small amounts of bases that remain more available. The concentration of sesquioxides in phases 3, 4, and 5 impairs availability of P and possibly of Mo. Leaching of Mn, Co, Cu, and P takes place chiefly in phase 6.

We should not confuse the fluctuations in time of the "potential" and "actual" fertility (Papadakis, 1938, 1952) of a given soil—which depend on the crops grown, etc—with its "inherent" fertility, which is the resultant of soil-forming processes and parent material. Organic matter is a reserve of mineral nutrients; as a consequence, mineral deficiencies are more serious at low levels of "actual" or "potential" fertility. The minerals liberated by decay of organic matter may be lost by leaching or immobilised by sesquioxides; consequently the recuperation of "potential" fertility is more difficult in soils in phases 4 or 5.

Were it not for leaching, availability of minerals would increase with degree of weathering; consequently weathering and leaching should be considered separately.

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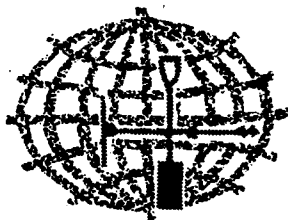
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WEATHERING AND SOIL SCIENCE

By

G. DONALD SHERMAN,

Senior Professor of Soil Science,
University of Hawaii, Honolulu

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Senior Professor of Soil Science, University of Hawaii, Honolulu

Weathering is the process by which rocks are either disintegrated into a more or less unconsolidated mixture of smaller fragments or decomposed into new and different chemical compounds and minerals. Soils are a product of rock weathering, but only of that portion at and near the surface where the processes of disintegration and decomposition occur under the influence of climate and vegetation. Because decomposition occurs at the surface of the earth, its products, both chemical and mineral, are developed from the low-energy processes of normal pressures and temperatures. The first products of weathering are subject to further physical and chemical weathering, producing one or more series of mineral constituents until the system attains a steady dynamic equilibrium where further changes are unobservable in our generation.

Merrill (1897) in his classical thesis on rock weathering made a distinction between weathering and alteration. He has defined weathering as the superficial changes in a rock mass brought about by atmospheric agencies which produce more or less complete destruction of the rock as a geological body. One of the most interesting concepts of weathering was presented by Polynov (1937). He defined weathering as the complex process, cyclic in nature, which causes the breaking down of the monolith of rock or solid body, thereby producing an increase in surface or interface between it and the surrounding media. Interfaces exist as boundaries, whether in solid and liquid state, or in liquid and gaseous state; they possess specific physico-dynamic properties which become more important quantitatively and qualitatively as the ratio of the interface to surrounding mass (the specific surface) increases. Polynov's concept applies to the products of both disintegration and decomposition. However, the latter process provides a series of products varying in chemical activity ranging from ionic through amorphous or gel state to cryptocrystalline, a state of disorderly formation of crystal lattice, to the final state of well ordered, relatively inert, true crystalline mineral.

Many other workers have contributed to our knowledge of weathering. Van Hise (1904) proposed the term "katamorphism" to cover all processes which produced simpler products out of complex compounds. Harrison (1934), following out this idea, applied it

in situ to a study of rock weathering under tropical climatic conditions. Still others (Goldich (1938) and Reiche (1950)) attempted to set up weathering sequences, based on susceptibility of minerals to decomposition by chemical processes, which in essence follow the sequence of temperature of crystallisation proposed by Bowen (1922).

Relationship of Weathering to Soil Science

It is essential to make a distinction between weathering, soil formation, and pedogenesis. WEATHERING, past and present, has broken down rocks to form unconsolidated sands, silts, loams, and clays. SOIL FORMATION is the result of weathering at the thin surface of the earth's weathered crust and differs from other aspects of weathering in that influences of climate and vegetation have been the determinative factors in the final product. PEDOGENESIS comprises the processes which produce the horizons that make up a soil profile, and often referred to as the soil-forming processes.

A soil profile consists of a combination of these horizons which are horizontally differentiated soil zones, and it may comprise various arrangements of the A, B, and C horizons. Although horizons are products of weathering, they reflect the many modifications in the normal processes of weathering brought about by the influences of vegetation and other biotic factors, as well as by higher and lower temperatures of the prevailing climate. Jackson and Sherman (1953) and Sherman (1949, 1952) have emphasised the interplay between climate and biotic factors and the weathering responsible for the materials that make up soil. For example, a soil formed under a sparse vegetation and moderate climate having a small range between maximum and minimum temperature would have poorly developed horizons in its profile, as it would be chiefly the product of chemical weathering. Such a soil, representative of a normal weathering product for its environment, is typified by the Molokai profiles with their very weak A horizons. On the other hand, where vegetation is moderate or heavy and temperature varies to a considerable degree, shallow soil profiles may still develop owing to lack of root penetration, as in the extraordinary example of highly weathered, deep bauxitic saprolite in a hot, humid, tropical region.

Once a soil is formed, the processes of weathering continue to operate and are therefore a basic part of the process of soil formation. It is the degree of modification of the weathering process, brought about by the influence of vegetation and surface climatic environment, that produces the variations in profiles which provide the basis for soil classification. More specifically, while the translocation of clay may be considered a physical change, there would be no true clay without chemical weathering at some time in the past weathering history of the soil-forming materials.

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The modified weathering processes of soil formation produce chemical changes altering the mineral composition of the soil, which in turn determines the physico-chemical properties of the soil. Soil scientists, agronomists, and engineers are beginning to appreciate the importance of the role that these properties derived from minerals play in the management and utilisation of soils.

Basic Concepts of Weathering

Weathering can be divided into two provinces: namely, physical or disintegration, and chemical or decomposition. Since this paper deals with the relationship of weathering to soil science, physical weathering will be reviewed here only briefly, while mineral decomposition at normal atmospheric conditions will be considered in detail.

PHYSICAL WEATHERING, OR DISINTEGRATION, concerns the breaking down of rocks into smaller units by mechanical means. The broken particles, no matter how small they may be subdivided, will retain their original composition as they occurred in the rock. The physical processes act on the rock in place, or the rock may be moved about and eroded and abraded into smaller particles or fragments; in any event, these physical actions in place are very limited and not as important as they once were considered to be. They are due to cracking and subsequent erosion due to uplift or any other actions of an unstable surface of the earth; or to the prising action of crystal growth and the action of ice crystals formed in confined openings in rock.

The most important agency of breakdown of rocks is physical weathering by movement, and of these agencies glaciation has been by far the most effective. Glaciers have been responsible for the grinding up of huge mountain ranges or rocks into gravels, sands, silts, and clays, and for the deposition of these materials over wide areas in the temperate regions. Glaciers have deposited finely divided soil-forming material in regions where intensity of chemical weathering is extremely low and have thus furthered and enhanced the action of chemical weathering by increasing the specific surface of the rock fragments and particles on which reactions must take place. Large areas in the temperate zones of Europe and the Americas would be desolate countries today if glaciation had not occurred, for it has provided a parent material on which decomposition and soil formation have been made possible.

Other movement agencies in physical weathering are abrasive action of moving water and sand-blasting by wind-driven materials. Erosion has filled valleys, depressions, and lake beds with materials on which soil development can and will occur on these deposited erosion materials. Rivers have built up from eroded materials deltas which became important because centres of civilisation were able to support themselves through profitable agricultural production made possible by the kind of material deposited on them for soil development.

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CHEMICAL WEATHERING, OR DECOMPOSITION, is a prime requirement of soil formation, for, with few exceptions, soil development would be impossible without the formation of products of mineral decomposition. The chemical weathering of rocks is governed by various capacity and intensity factors, each of which has an important role to play; thus, the final effects of decomposition will be determined by the integrated influence of all factors affecting chemical weathering.

The capacity factors involve, among others, the susceptibility of the rock to undergo chemical changes, which is a property inherent in the rock material and related directly to the nature of its constituent minerals. Because minerals vary in their resistance to weathering, sequences of susceptibility of minerals to weathering have been established. Certain minerals such as ilmenite, magnetite, and zircon are considered resistant to weathering, whereas olivine is one of the minerals considered very susceptible to weathering. The size of the minerals is also a capacity factor in that the finer the material the greater is the surface exposed to the processes of weathering. One other inherent factor is the nature of the surface of the mineral. If the surface is dense and highly polished, it can make a susceptible mineral quite resistant to weathering. For example, rocks of an olivine basalt on the island of Hawaii contain olivine of this characteristic; pyroxenes in this particular basalt have begun to decompose, but the olivine crystals in the same rock mass show no evidence of weathering, owing to their highly polished and dense surfaces.

The intensity factors of weathering are the influences of climate, drainage, vegetation, and time; and of these, climate is the most important in determining the direction of weathering. Temperature not only controls the rates of reaction, but, by the effect of the different seasonal environments, it is also responsible for the duration of the weathering process. Rainfall and drainage (or the moisture regime), a second factor, are reflected in the rapidity of decomposition. Drainage conditions determine to a large extent the nature of the secondary minerals formed. Under a warm, humid climate in tropical regions, good drainage, which ensures the rapid removal of silica and bases, causes a direct weathering of rocks to oxide minerals, but a restriction in drainage favours the synthesis of alumino-silicate clay minerals.

Vegetation plays an auxiliary role in weathering in that it produces the microclimates which first modify the weathering processes, and secondly may enhance or retard weathering, depending on whether the vegetation produces a base-poor or base-rich organic matter addition to the soil. Vegetation can and does effectively retard weathering by the cyclic return of bases and silica to the surface. The forest protects the soil from dehydration due to exposure to radiant heat; and in the tropics the forest cover can protect soil from induration which develops the laterite crust.

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Lastly, the time of exposure determines the extent of weathering. Soil formation will become quite uniform in its pedogenesis if exposure to weathering remains under a uniform type of climatic environment and drainage conditions for a long time, even though there may have been much variation in the soils of the area in the early stages of exposure to the environment.

Capacity and intensity factors are expressed through the well known agencies of chemical weathering such as oxidation and reduction, hydration and dehydration, hydroxylation, hydrolysis, carbonation, acidification, and solution. Bases are released in the early stages of weathering, with calcium and sodium being removed rapidly, while potassium and magnesium, which can be retained ·in crystal-lattice positions, also become subject to removal as decomposition proceeds. With the depletion of bases, the 2:1 clay minerals lose stability and desilication occurs, beginning with removal of silica and progressing to the initiation of kaolinisation. Finally, kaolin itself becomes unstable and decomposes, and thus desilication is completed. The residuum is an oxide system with the level of bases determined by the cyclic efforts of vegetation and rainfall, and a silica content dependent on·the cyclic sources of vegetation and additions by wind-borne dust particles.

Importance of Weathering to Soil Science

Soil scientists are of necessity concerned with weathering, as it is the mechanism that determines many important properties of the soil. Thus, (1) Weathering determines the nature of the materials on which soils are formed. It not only produces the textural separates, but the processes of weathering determine the nature and type of secondary minerals on which soil formation and pedogenesis occur and the secondary minerals which are concentrated by removal or by being the residuum in the different horizons of the soil profile. Further, it determines the nature of the soluble materials available to the processes of soil formation and pedogenesis; (2) The products of weathering, both chemical and mineral, determine the physico-chemical properties of the soil, and the latter determine to a large extent the cultural management of the soil. The properties of a soil containing montmorillonite clay and a soil containing kaolin clay vary greatly, and it is well known that their management is quite different also; (3) Lastly, soil scientists are interested in the present weathering process in that it controls the release of elements which are essential to plant growth. Inadequate release of elements means that supplements of fertiliser materials are required before maximum crop production can be attained. In fact, the fertiliser industry can be considered an adjunct to weathering, as an attempt to make up for deficiencies of the weathering process. The products of weathering may also have an important effect on the efficiency of added fertiliser materials through their capacity to render elements relatively insoluble.

Soil formation and classification have a common relationship to weathering. Jackson *et al.* (1948, 1952) have proposed a sequence of weathering of clay-size minerals in soils. Their sequence consists of thirteen stages, namely: (1) gypsum (also halite, sodium nitrate, etc.); (2) calcite (also dolomite, aragonite, apatite, etc.); (3) olivine-hornblende-pyroxenes; (4) biotite; (5) albite-microcline-orthoclase; (6) quartz; (7) muscovite-illite; (8) inter-stratified 2:1-layered silicates and vermiculite; (9) montmorillonite group; (10) kaolin group; (11) gibbsite-boehmite-allophane; (12) hematite-goethite; and (13) anatase (also zircon, rutile, ilmenite, corundum, etc.). This writer would not assign allophane to stage 11, but rather to stage 10. Furthermore, he would assign nontronite to the montmorillonite group. This sequence of weathering has promoted in soil scientists a greater appreciation of both mineral composition and state of weathering of the soils when classifying them.

Sherman (1949, 1952) has proposed a sequence of tropical soil formation based on degree of weathering and mineral composition, which is based in turn on the influences of climatic, drainage, vegetation, and time factors. In the matter of the assignments of the effect of the soil factors, he is in close agreement with the prior work of Mohr (1944). How far can the products of weathering be used as a tool in soil classification? This work of Mohr and Sherman points out the completeness of decomposition of the primary minerals and the obvious instability of the clay minerals. These authors emphasise that the ultimate product of tropical soil formation in a warm, humid region with free drainage would be a soil rich in any one or a combination of the oxides of aluminium, iron, silica, and titanium. When the original minerals of the rocks are subject to weathering their influence nevertheless may be confined to only a slight determinative effect on the early first mineral products, for as weathering progresses there will be loss to a common mineralisation of all materials, and finally to a common suite of minerals.

Another feature of weathering in the humid tropics is the concentration of hydrated, amorphous colloidal-oxide minerals which exist in disorderly atomic arrangements as long as they are protected from dehydration. The ultimate soils of the humid tropics are characterised by profiles which have horizons with differentiated types of crystalline and amorphous oxides of aluminium, iron, silica, and titanium.

Weathering in cool, humid regions is much slower owing to the shortness of the period of the year favourable to decomposition and to the effects of freezing and low temperatures during the winter. Therefore, the primary mineral produced by slow alteration strongly influences the secondary mineral first formed. Stephen (1952a, b) has shown that a definite relationship exists between the primary weathering mineral and the secondary mineral which is formed. The stability of this secondary mineral is probably increased first by dehydration

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due to dry summers, and secondly by dehydration due to freezing during winter. In either case dehydration has the resultant effect of increasing the crystallinity of the material and thus reducing the development of an amorphous system. The well oriented clayskins on soil peds are found primarily in soils in cool temperature zones.

There is an obvious difference in stability of mineral systems between the slow chemical weathering of soils of temperate regions and the accelerated weathering of soils of warm, humid, tropical regions. In the former, silicate clays predominate in the secondary minerals, while the formation of oxides is very limited, as desilication and resilication can operate in the slowly weathering system. In the latter, soil formation and free drainage conditions favour both leaching and desilication. Continuous desilication will ultimately produce the end product—the oxide soil—and only restricted or impeded drainage will produce conditions for resilication and clay-mineral formation in the tropics.

Physical and chemical properties of the soil depend to a large extent on the nature and character of the secondary minerals. The differences in the general properties of soils having 2:1- and 1:1-layered aluminosilicate clays are well known; however, when the clay minerals become associated with appreciable amounts of free oxides, considerable modification of both physical and chemical properties will occur. Structural stability, moisture movement, composition characteristics, and cation-exchange capacity can be altered considerably. The hydrated colloidal amorphous fraction of a soil exhibits a wide range of degree of hydration, cation-exchange capacity, and other properties. Thus, Kanehiro and Sherman (1956) have shown that soils having a high content of hydrated amorphous minerals lose a large portion of their cation-exchange capacity on air drying, while Sherman (1957) has shown that in this dehydration a change of state produced the differential crystallisation of gibbsite and iron oxides.

The above is only one of the important properties of the amorphous fraction. Fieldes and Swindale (1954) have shown that the amorphous system precedes the development of crystalline minerals. Likewise, Bates (1959) has suggested that in the decomposition of one crystalline system (halloysite) and development of a subsequent second crystalline mineral (gibbsite) there is developed an amorphous system. In humid environments where dry seasons are not intense there is persistence, or a degree of stability, of the amorphous system, so that soils develop almost complete amorphous colloidal systems, such as occur in the soils of the Hydrol Humic Latosols and in the B horizon of the soils of the Ferruginous Latosols of Hawaii. In these soils the mineral system is as follows: (Al, Fe, Si, Ti) ⟶ hydrated colloidal hydroxides and oxides (gels) ⟶ hydrous oxides ⟶ crystalline oxides, as proposed by Tamura and Jackson (1953). This system

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