

FREQUENCY DISTRIBUTION OF CLAY MINERALS IN MAJOR GREAT SOIL GROUPS AS RELATED TO THE FACTORS OF SOIL FORMATION

by

M. L. JACKSON

Department of Soils, University of Wisconsin,
Madison, Wisconsin

ABSTRACT

The frequency distribution or relative abundance of minerals in soils varies with the five principal classes of factors that govern soil formation. The characteristics of the minerals of the parent material, the time factor, climatic factors, relief factors and biotic factors each can be shown to have important independent effects on clay mineralogy of soils under proper circumstances. The soil parent material exerts a control over the frequency distribution of minerals in soils by introduction of the clay minerals into the soil directly, by controlling the course of chemical weathering in the soil through the relative susceptibility of its minerals to weathering, by furnishing abundant divalent metallic cations, by impediment of drainage, or by acceleration of leaching when highly permeable. The time factor is conspicuous as long times give an advanced degree of weathering even in temperate climates. Climate is important, since highly weathered materials inevitably occur as a result of intense leaching in warm tropical and equatorial climates. Relief is important in concentrating leaching water and metallic cations, in affecting oxidation or reduction. The biotic factor affects minerals conspicuously where an A_0 horizon develops and resulting cheluviation moves R_2O_3 out of the A_2 horizon.

Inherited minerals such as illite, quartz, feldspars, ferro-magnesian minerals, carbonates and gypsum are most abundant in clays of little-weathered parent materials and soils of the zonal Desert, Brown, Chestnut and Tundra soils as well as intrazonal Mountain groups and azonal Regosols and Lithosols. Secondary layer silicate minerals such as vermiculite, secondary chlorite, montmorillonite, kaolinite and halloysite are most abundant in clays of moderately weathered parent materials and soils of the zonal Chernozem, Prairie, Gray-Brown Podzolic, Podzol, Red-Yellow Podzolic, and Low Humic Latosol groups as well as intrazonal Planosol, Rendzina, Dark Magnesium soil, and Wiesenboden groups. Secondary sesquioxide minerals such as hematite, goethite, allophane, gibbsite and anatase and residual resistant primary minerals such as ilmenite and magnetite predominate in the more highly weathered parent materials and soils of the zonal Ferruginous Humic Latosols, Hydrol Humic Latosols, Latosolic Brown, and Ando soils and Laterites, as well as the intrazonal Tropical Savannah and Ground Water Podzol ortstein soils.

INTRODUCTION

An extremely wide variety of minerals occurs in the clay fraction in the major great soil groups of the world. It is the purpose of the present article to examine the frequency distribution or relative amounts or percentages of minerals that occur in the clay fractions of different great soil groups as related to the major factors of soil formation. Occasional reference is made to

the minerals of the silt fraction where they are related to the minerals in the clays. The term "layer silicates" is employed for the layer structured group of silicates, which makes up the largest portion of the clay fraction of many soils of intermediate degree of weathering, but also makes up important constituents of silts, sands, and consolidated rocks and thus cannot as accurately be termed "clay minerals." "Great soil groups" is used in the sense employed in the soil classification field (Thorp and Smith, 1949), falling in the categorical listing: soil phase, soil type, soil series, soil family, great soil group, soil suborder and soil order. "Factors of soil formation" refers specifically to the five principal *classes* of soil genetic factors: parent material, time, climate, relief and living organisms (Muckenhirn and others, 1949). Since many analytical data on this subject have been published in various journals, the main objective centers on clarification of the way the soil genetic factors control clay distribution.

The criteria used in soil classification encompass many characteristics other than soil mineralogy, such as the number and thickness of various horizons, and the organic content, structure, color, texture (*amount* of clay, silt and sand, as distinct from its mineralogy), acidity, and mottling of each horizon. These characteristics are important to soil classification as to use-suitability and to interpretations of soil genesis. Many of these factors are controlled by the soil-forming factors more or less independently of the mineral species of the soils, and thus significant soil groupings often do not follow soil mineralogy in close detail.

Broad differences in soil mineralogy do, on the other hand, cause differences in important soil characteristics, and this gives rise to a rough, broad correlation between soil groupings and soil mineralogy. The fact that geochemical weathering of rocks reflects wide differences in climatic factors leads to "a broad general . . . association of chemical weathering processes and products with soil formations distributed over the earth" (Jackson and Sherman, 1953, p. 242).

SOIL CLAY MINERALOGY AS INFLUENCED BY PARENT MATERIAL FACTORS

The soil parent material (both mantle rock and hard rock) influences soil clay mineralogy directly and profoundly in three principal ways: (1) it provides the lithological minerals which young alluvial and little-weathered soils (Lithosols and Regosols) inherit in bulk from the mantle rock, and from which older soils inherit the more resistant minerals accumulated as a residue as the less stable minerals are removed by the chemical weathering (Jackson and others, 1948); (2) the chemical nature of the mineral suite present in the rock determines the supply of micas which weather to vermiculite, chlorite and beidellite, and of divalent and other cations which influence the direction and extent of chemical weathering of clay minerals; and (3) the permeability of the parent material, as controlled by its texture, porosity, and state of subdivision, greatly influences the *rate of leaching* and concurrent accumula-

tion of specific mineral products of weathering. The importance of parent-material factors is brought out by the divergence in soil mineralogy in soils on different parent rocks when the other factors are held constant. Geographically, the frequency distribution of minerals and soils in county after county in state after state largely follows the parent rock distribution pattern, yet it must be recognized that with enough time, significant functional relationships with climate, vegetation and relief are developed.

Inherited Lithological Minerals in Soil Clays

Primary illite, quartz and feldspars inherited directly from the mantle rock parent material occur in the clays of little-weathered soils on late Pleistocene till in Ontario (Jackson and others, 1948) and China loess deposits (Hseung and Jackson, 1952). When weathering and leaching are very limited, ferromagnesian minerals, carbonate, and gypsum of lithological origin occur in Desert, Brown, and Chestnut zonal soil groups (Hseung and Jackson, 1952). Sierozems, Brown soils, and Chestnut soils of Colorado surface soil horizons (Schmehl and Jackson, 1957) had 20 to 36 percent illite in the -2μ clay fractions, while quartz and feldspars made up 30–35 percent of the coarse clay and fine silt. Other minerals included 4–11 percent kaolinite (probably lithological). Alpine Turf soils (Retzer, 1956) of the Colorado Rocky Mountains developed from basalt, micaceous granite, quartzite and shale tended to contain over 50 percent of the lithological minerals quartz, feldspars and illite in the various size fractions of the clay. Chlorite, kaolinite, vermiculite and montmorillonite made up the remainder. Illite has been noted in liberal amounts in Tundra and other cold-region soils. Illite inherited from shale occurs abundantly in some till-derived soils of the central United States including some soils of the Prairie, Chernozem, and Gray–Brown Podzolic zonal groups (Alexander, Hendricks and Nelson, 1939; Bidwell and Page, 1951). Kaolinite inherited from rock (Peterson, 1946) dominates the clay of Gosport soils of Iowa (Gray–Brown Podzolic).

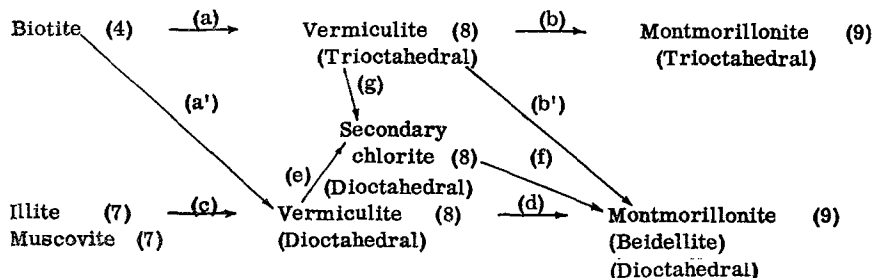
Chemical Nature of Parent Material as a Control on Soil Clay Minerals

Soil clay minerals, besides being inherited outright from the parent material (above), may include secondary minerals which have been influenced greatly by the chemical nature of the parent material as to primary minerals and cationic content.

Distribution of vermiculite.—It appears that vermiculite of soils characteristically forms directly from micas, including illite, through cleavage across the Z-axis concurrent with layer charge reduction (Jackson and others, 1952) as evidenced by the occurrence of large crystals of vermiculite pseudomorphic after mica commonly found in clay, silt, sand and gravel sizes, associated with a decrease in the mica content compared to the parent material. A soil developed on weathered granite (Mountain soil) of Colorado has vermiculite (with 15 percent mica still interstratified) in crystals the size

of the parent black mica grains still found in the interior of unweathered granite fragments, and no appreciable chloritization has occurred (unpublished studies in this laboratory).^{*} In Ando soils of Japan, vermiculite is formed only if mica is present in the ash (Aomine and Jackson, unpublished) while glassy ash forms allophane (below).

The weathering sequence is represented by equation (1) :



in which the reactions are indicated by arrows (and letters) while numbers in parenthesis represent weathering sequence index numbers (Jackson and others, 1948, 1952 ; Jackson and Sherman, 1953). Formation of trioctahedral montmorillonite was observed by MacEwan (1948). Formation of the vermiculite 14Å spacing as a result of Mg treatment of biotite [reaction (a)] was observed by Barshad (1948). Reaction (a) was described by Walker (1949, 1950) and (a) and (c) by Jackson and others (1952) and Rolfe and Jeffries (1952). Reactions (a) through (d) agree with the Fieldes and Swindale (1954) data on mica weathering in soils. Vermiculite occurs in Latosols (Aguilera and Jackson, 1953 ; Whittig and Jackson, unpublished).

Dioctahedral vermiculite seems to be much more common in soil clays than the trioctahedral type. Thus the 060 spacings of the clays of Hiawatha (Podzol), Iron River (Podzol) and Omega (Brown Podzolic) and other sandy soils of northern Wisconsin (Brown and Jackson, 1958 ; Whittig and Jackson, 1956) are 1.50Å, characteristic of the dioctahedral type. Similar results have been observed with the Ireland soils Kilcolgan (Regosolic Brown Forest soil from limestone) and Moate (Gray-Brown Podzolic, from limestone till) with 80 percent vermiculite in the clay (Sawhney and Jackson, unpublished data).

Distribution of secondary chlorite.—Secondary chlorite (equation 1) refers to chlorite formed from mica during weathering by interlaying with positively charged aluminum, ferric iron and (or) magnesium hydroxides. The aluminum hydroxide interlayer is thought to be most common in secondary chlorite in acid soil clays.

Secondary chlorite has the stability advantage of the large stable 2:1 layers formed by cleavage of mica crystals. It was spoken of as "aluminous chlorite" by Jackson and Sherman (1953, pp. 235-236) and found to follow mica-vermiculite (hydrous mica) in weathering stability sequence (Jeffries, Rolfe and Kunze, 1953). Because secondary (aluminous) chlorite forms from

mica immediately following (or even concurrent with) vermiculite under proper circumstances, it may be assigned the weathering stability (Jackson and others, 1948, 1952) index number 8, the same as vermiculite (equation 1).

Secondary chlorite is distinct from ferromagnesian chlorite occurring in serpentine rocks, which (perhaps owing to its ferrous iron content) appears to weather much more readily and has been given weathering stability index 4 (Jackson and others, 1948). If there is a fairly abundant source of aluminum (and possibly iron) from soil acidity, intergradational vermiculite-chlorite having a temperature stability much lower than the 550°C characteristic of ferromagnesian chlorite may form by mica weathering (equation 1). For example, slightly chloritized vermiculites have been derived from muscovite schist (Red-Yellow Podzolic) soil of Virginia (Rich and Obenshain, 1955). And chlorite-vermiculite intergradational material occurred in Crosby coarse clay (Gray-Brown Podzolic soil) of Indiana (Klages and White, 1957). Secondary chlorite is associated with abundant montmorillonite in the basalt-derived Dark Magnesium Clay soils of Hawaii and Ladybrook (Grumosol or Black Clay) of Queensland, Australia. These are situations in which magnesium (derived from basaltic rock) seepage, or slow drainage, is abundant for supplying the interlayer cation.

Distribution of montmorillonite series.—The occurrence of abundant montmorillonite in certain soils (reviewed extensively, Jackson and Sherman, 1953) is commonly controlled by the soil parent material. Alluvial deposits from stagnant or slow-moving water often have montmorillonite concentrated by sedimentation processes. Marl-derived Houston clay (Kunze and Templin, 1956) (Rendzina) and basalt-derived Black Cotton, Ladybrook, Aina Haina soils (Dark Magnesium clay) and Waipiata soils are rich in montmorillonite (Sawhney and Jackson, 1958) because of abundance of divalent cations supplied by the parent material. The high cation exchange capacity and water-holding properties of highly montmorillonitic soils makes them to some extent self-perpetuating, but functional weathering gives rise to mineral sequences of kaolinite, gibbsite, and free iron oxides (Jackson and others, 1948; Ferguson, 1954; Hosking, Neilson and Carthew, 1957).

The moderately weathered Prairie, Gray-Brown Podzolic, and Podzol soils of central United States, commonly developed on loess or loess-capped parent material, characteristically have a high content of montmorillonite-series minerals in the clay (Ross and Hendricks, 1945). To a lesser extent, montmorillonite also occurs in till-derived soils in this region. Some of this montmorillonite may be directly lithological, or unrelated to weathering (as suggested by Beavers, 1957), but considerable weathering change (equation 1) of the mica component (mica is abundant in the loess silt) to the expanded types of mineral is likely (Bray, 1937; Jackson and others, 1952; Murray and Leininger, 1956). The greater abundance of montmorillonite in the loess than till is still influenced by parent material (greater amounts of finer mica particles in loess than present in till). With progressive leaching, the interlayers of chlorite are lost and montmorillonite results (reaction f, equation 1), as shown in the permeability and time functions (below). In the absence of

sufficient interlayering cations, chlorite is by-passed as beidellite (montmorillonite series) forms (reaction d) directly. This has also been demonstrated in the laboratory (White, 1951, 1956).

Distribution of phosphate.—A majority of soil parent materials have their phosphate as calcium phosphate. As the free CaCO_3 is leached out, that phosphate becomes fairly soluble and weathers chemically, reacting with aluminum ions from aluminosilicates and iron ions from iron minerals (reviewed by Chang and Jackson, 1958). A weathering index or sequence is found for phosphate of various great groups of soils, measured by the percentage of the total inorganic phosphate that is chemically bonded with calcium, with aluminum, with iron, and (as a further step in the sequence) with iron and occluded in iron oxides (Chang and Jackson, 1958).

Soil Parent Material Permeability Factor

High permeability of the soil parent material to water has a profound influence on the frequency distribution of the soil clay minerals formed by chemical weathering. High permeability leads to rapid leaching of the metallic cations and other substances dissolved by weathering reactions, leaving the product formed with lowered contents of monovalent and divalent cations and even of silica. Four analogous situations will be considered, leading, respectively, to beidellite, kaolinite, allophane and gibbsite.

Highly sandy soils of northern Wisconsin.—The Hiawatha (Podzol) and Ahmeek (Brown Forest group) sandy soils of northern Wisconsin show greatly different clay minerals in different horizons as a function of soil depth. The high permeability of the coarse sandy parent material allows the mica of A horizons to be leached of potassium and rapidly transformed through vermiculite and chlorite to beidellite (equation 1). Some of the fine fractions of these soils are more extensively leached and are (Whittig and Jackson, 1955) nearly amorphous relics of 2:1 layer silicates, and possibly could be characterized as allophane-like. The clay of Plainfield sand of central Wisconsin (Gray-Brown Podzolic group), a somewhat less sandy soil, is high in chlorite presumably derived by chloritization of the glauconitic mica characteristic of the Cambrian sandstone parent rock. These soils illustrate exceptionally fast weathering in consequence of coarseness of parent material, giving high permeability and leaching rate, low water-holding capacity, and little clay to be weathered, all contributing to accelerated weathering.

Kaolinite in red earths.—High permeability of the granite parent material of soils of the Piedmont Plateau of southeastern United States has been interpreted (Ross and Hendricks, 1945) as the cause of kaolinite occurring in abundance in the Cecil and related soils (Kelley and others, 1939; Coleman, Jackson and Mehlich, 1950). Less permeable rocks gave montmorillonite and chlorite. Porous rocks of Hawaii form deeper soils (more rapid weathering) than hard rocks (Dr G. D. Sherman, private communication). Kaolinite and associated iron oxides maintain permeability, and quartz maintains the silica supply, and thus the system has a kind of self-perpetuation. But an increase

of rainfall decomposes the kaolinite in Hawaii to give allophane and free oxides (Tanada, 1951 ; Tamura, Jackson and Sherman, 1953).

Allophane in Ando soils.—Volcanic ash of Japan, when finely divided and open and porous in drainage character, quickly forms allophane. Ashes of only a few decades age have considerable allophane, pseudomorphic after the original ash particles, and also as thread-like precipitates (Aomine and Jackson, in manuscript). Silica leaches rapidly from freshly deposited ash (S. Aomine, private communication). Older buried layers, the age of which is established as several thousand years by several means of dating, contain halloysite formed by resilication of the allophane, by silica leached from fresh ash overburden. In older layers that received insufficient silica (no overburden), the allophane forms crystalline gibbsite and halloysite.

Gibbsite in old Appalachian mountain soils and tropics.—High gibbsite concentrations in soil clays have been found in the old mountain soils of the Appalachian and Piedmont areas (Alexander, Hendricks and Faust, 1942 ; Coleman, Jackson and Mehlich, 1950). These soils have an abundance of other minerals, including lithological illite, vermiculite, etc. (Coleman, Jackson and Mehlich, 1950). Rotten (porous) trachite of Hawaii consists of nearly pure crystalline gibbsite (Tamura and Jackson, unpublished). Gibbsite commonly is abundant under tropical weathering (as reviewed, Jackson and Sherman, 1953, p. 284). Precipitation of gibbsite (like that of allophane in the previous section) is favored by high rock permeability which allows the dissolution and rapid removal of ions released by weathering. Gibbsite (also like allophane) takes on silica in the presence of silica in solution (Alexander, Hendricks and Faust, 1942 ; Goldman and Tracey, 1946). When silica is abundant relative to leaching rate, kaolinite and halloysite are abundant relative to gibbsite. Conversely, the greater the rate of leaching, the greater the thickness of the gibbsite deposit. Hence, gibbsite occurrence in soils reflects a higher weathering (leaching) index number (11) than kaolinite index number (10) (Jackson and others, 1948).

TIME FACTORS

Time is a necessary component of all of the other soil-forming factors affecting soil clay mineralogy. But time is not unique in this overlapping ; for example, climatic factors require parent material to operate on. Thus to assess the time factor, one must observe its effect with the other factors held more or less constant. The present day trend in soil genesis interpretation has been to recognize changes in soils and soil mineralogy as a function of time, with de-emphasis on the earlier steady state (" equilibrium ") concept, because older landscapes inevitably have minerals of greater stability index than younger landscapes (as reviewed by Jackson and Sherman, 1953, pp. 257 and 281-290). For example, older limestone-derived soils of central Pennsylvania are rich in kaolinite (Alexander, Hendricks and Nelson, 1939) ; nearby the younger Hagerstown soils are rich in illite and beidellite (Jackson and others, 1954). The great soil group may be Gray-Brown Podzolic in both

cases. As another example, clays weathered a million years from limestone were montmorillonite throughout the profile, and less weathering (equation 1) was noted in Illinois till (140,000 years old) and still less in Wisconsin till (18,000 years old) (Murray and Leininger, 1956). The clay mineral differences in both examples clearly reflect the effect of different weathering time.

CLIMATIC FACTORS

Climatic factors are traditionally the prime "active" factors of soil formation. The clay mineralogy of soil, in time, responds sensitively to climatic factors, as reviewed elsewhere (Jenny, 1941, pp. 118-191; Jackson and Sherman, 1953). Thus for example, rainfall and temperature are climatic intensity factors that interact with permeability of parent rock (a capacity factor) reviewed above. Long times of course invariably introduce possible changes in climatic intensity factors. Yet broad geographic ranges in present climate tend to give corresponding mineral sequences in different hemispheres (Hseung and Jackson, 1952; Jackson and others, 1948; Fieldes and Swindale, 1954), progressing from primary minerals in cool dry climates through layer silicates, to abundant $\text{Al}(\text{OH})_3$, Fe_2O_3 and TiO_2 in warm moist climates. Authigenic kaolinite and halloysite make up 80 percent of clay in soils from granite and basalt in western Australia (Hosking, Neilson and Carthew, 1957). High temperatures of warm temperate and tropical climates bring out the red and brown colors indicative of the accumulation of free iron oxides, hematite and goethite, sometimes in large amounts (15-60 percent). Ten to 15 percent hematite occurs in the Red-Yellow Podzolic soils of Southeastern United States, in soils such as the Cecil (Coleman and Jackson, 1946). Rainfall need be only a moderate 40 in. (not unlike temperate regions) to give 20-30 percent free iron oxide in the Humic Latosols of Hawaii under tropical temperatures (Tamura, Jackson and Sherman, 1953). Accumulation of much iron and titanium oxide is favored by a wet-dry seasonal distribution of rainfall, as in the Ferruginous Humic Latosol and the Latosolic Brown soil of Hawaii which have 35-50 percent hematite, goethite and magnetite, and 20 or more percent of anatase and ilmenite (Tamura, Jackson and Sherman, 1955). Gibbsite or kaolinite occurs in the *C* horizons, in amounts up to 30-50 percent.

RELIEF FACTORS

Relief or topography affects soil clay mineralogy through concentrating water (causing hydrolysis and leaching), seepage (bringing in cations in solution), and by affecting oxidation or reduction (through water and air supply). Leaching is more severe when the waters are acid or neutral than when high in metallic cations. Leaching is greatly affected by the permeability of the parent material, making relief interact with the parent material factors (discussed above).

Abundance of divalent cations, in seepage or runoff water has been reported by many workers to favor montmorillonite formation, as in the Dark Magnesium Clays of Hawaii, and in Wiesenboden and Planosol soils (reviewed by Jackson and Sherman, 1953). Iron is accumulated by seepage on to Ferruginous Humic Latosol areas (Tamura, Jackson and Sherman, 1953, 1955). Poor drainage and its associated oxidation or reduction concentrated 70 percent goethite in Ortstein concretions of a Ground Water Podzol of Wisconsin (Whittig and Jackson, unpublished), and 85 percent hematite in concretions of Tropical Savannah Podzol of Haiti (Tamura and Jackson, unpublished).

Relief also acts by supplying alluvial soil parent material, as noted from montmorillonite sediments (above), but once a soil material is moved, clarity of nomenclature requires its mineralogy to be a parent material factor rather than a relief factor.

BIOTIC FACTORS

Plant residues return large amounts of metallic cations and silica to soils and the literature suggests that these substances may contribute greatly to clay formation. A most conspicuous biotic effect on soil mineralogy is under mor-forming type of vegetation. For example, Kauri trees of New Zealand give a thick A_2 horizon consisting of more than 90 percent free SiO_2 (quartz and cristobalite) (Swindale and Jackson, 1956), while nearby soils under grass and other type of trees show little podzolization. The silica is residual from the parent material, while the other minerals have weathered out. Layer silicates and gibbsite are found in still deeper horizons. The organic A_0 horizon supplies organic compounds to leaching waters which are able to chelate Fe and Al, and this accelerates the dissolution of primary and secondary silicates and oxides and their subsequent eluviation, the combined process being termed cheluviation (Swindale and Jackson, 1956). Similar but less extreme effects operate in forming zonal Podzol and Gray Wooded A_2 horizons of North America, so that illite, vermiculite, chlorite and montmorillonite and other layer silicate clays are left after cheluviation of the iron oxides.

ACKNOWLEDGMENTS

This contribution from the Department of Soils, University of Wisconsin, an invited paper for the Conference session on Genesis of clays, was supported in part by the University Research Committee through a grant of funds from the Wisconsin Alumni Research Foundation, for equipment, materials, and graduate student assistantships which made possible many of the mineralogical analyses referred to.

REFERENCES

- Aguilera, N. H. and Jackson, M. L. (1953) Iron oxide removal from soils and clays : *Soil Sci. Soc. Amer. Proc.*, v. 17, pp. 359-364 ; v. 18, pp. 223, 350.
Alexander, L. T., Hendricks, S. B. and Faust, G. T. (1942) Occurrence of gibbsite in some soil-forming materials : *Soil Sci. Soc. Amer. Proc.*, v. 6, pp. 52-57.

142 SIXTH NATIONAL CONFERENCE ON CLAYS AND CLAY MINERALS

- Alexander, L. T., Hendricks, S. B. and Nelson, R. A. (1939) Minerals present in soil colloids II. Estimation in some representative soils : *Soil Sci.*, v. 48, pp. 273-279.
- Barshad, Isaac (1948) Vermiculite and its relation to biotite as revealed by base exchange reactions, x-ray analyses, differential thermal curves, and water content : *Amer. Min.*, v. 33, pp. 655-678.
- Beavers, A. H. (1957) Source and deposition of clay minerals in Peorian loess : *Science*, v. 125, p. 1285.
- Bidwell, O. W. and Page, J. B. (1951) The effect of weathering on the clay mineral composition of soils in the Miami Catena : *Soil Sci. Soc. Amer. Proc.*, v. 15, pp. 314-318.
- Bray, R. H. (1937) Chemical and physical changes in soil colloids with advancing development in Illinois soils : *Soil Sci.*, v. 43, pp. 1-14.
- Brown, B. E. and Jackson, M. L. (1958) Clay-mineral distribution in the Hiawatha sandy soils of northern Wisconsin, in *Clays and Clay Minerals*, Natl. Acad. Sci.-Natl. Res. Council pub. 566, pp. 213-226.
- Chang, S. C. and Jackson, M. L. (1958) Soil phosphorus fractions in some representative soils : *J. Soil. Sci.*, v. 9, pp. 109-119.
- Coleman, N. T., Jackson, M. L. and Mehlich, A. (1950) Mineral composition of the clay fraction : II. of several coastal plain, Piedmont, and Mountain soils of North Carolina : *Soil Sci. Soc. Amer. Proc.*, v. 10, pp. 81-85.
- Coleman, R. and Jackson, M. L. (1946) Mineral composition of the clay fraction of several coastal plain soils of southeastern United States : *Soil Sci. Soc. Amer. Proc.*, v. 10, pp. 381-391.
- Ferguson, J. A. (1954) Transformations of clay minerals in black earths and red loams of basaltic origin : *Austral. J. Agric. Res.*, v. 5, pp. 98-108.
- Fieldes, M. and Swindale, L. D. (1954) Chemical weathering of silicates in soil formation : *New Zealand J. Sci. Tech.*, v. 36, pp. 140-154.
- Goldman, M. I. and Tracey, J. L., Jr. (1946) Relations of bauxite and kaolin in the Arkansas bauxite deposits : *Econ. Geol.*, v. 41, pp. 567-575.
- Hosking, J. S., Neilson, M. E. and Carthew, A. R. (1957) A study of clay mineralogy and particle size : *Austral. J. Agric. Res.*, v. 8, pp. 45-74.
- Hseung, Y. and Jackson, M. L. (1952) Mineral composition of the clay fraction : III. of some main soil groups of China : *Soil Sci. Soc. Amer. Proc.*, v. 16, pp. 294-297.
- Jackson, M. L., Hseung, Y., Corey, R. B., Evans, E. J. and Vanden Heuvel, R. C. (1952) Weathering sequence of clay-size minerals in soils and sediments : II. Chemical weathering of layer silicates : *Soil Sci. Soc. Amer. Proc.*, v. 16, pp. 3-6.
- Jackson, M. L. and Sherman, G. D. (1953) Chemical weathering of minerals in soils : *Advances in Agronomy*, Academic Press, v. 5, pp. 219-318.
- Jackson, M. L., Tyler, S. A., Willis, A. L., Bourbeau, G. A. and Pennington, R. P. (1948) Weathering sequence of clay-size minerals in soils and sediments : I. Fundamental generalizations : *J. Phys. Coll. Chem.*, v. 52, pp. 1237-1260.
- Jackson, M. L., Whittig, L. D., Vanden Heuvel, R. C., Kaufman, A. and Brown, B. E. (1954) Some analyses of soil montmorin, vermiculite, mica, chlorite, and interstratified layer silicates, in *Clays and Clay Minerals*, Natl. Acad. Sci.-Natl. Res. Council pub. 327, pp. 218-240.
- Jeffries, C. D., Rolfe, B. N. and Kunze, G. W. (1953) Mica weathering sequence in the Highfield and Chester soil profiles : *Soil Sci. Soc. Amer. Proc.*, v. 17, pp. 337-339.
- Jenny, H. (1941) *Factors of Soil Formation* : McGraw-Hill Book Company, Inc., New York, 281 pp.
- Kelley, W. P., Woodford, A. O., Dore, W. H. and Brown, S. M. (1939) Comparative study of the colloids of a Cecil and Susquehanna soil profile : *Soil Sci.*, v. 47, pp. 175-193.
- Klages, M. G. and White, J. L. (1957) A chlorite-like mineral in Indiana soils : *Soil Sci. Soc. Amer. Proc.*, v. 21, pp. 16-20.
- Kunze, G. W. and Templin, E. H. (1956) Houston Black clay, the type grumusol : II Mineralogical and chemical characterization : *Soil Sci. Soc. Amer. Proc.*, v. 20, pp. 91-96.

- MacEwan, D. M. C. (1948) A trioctahedral montmorillonite derived from biotite : *18th Int. Geol. Cong., vol. of titles and abstracts*, p. 128, abstract 386.
- Muckenhirn, R. J., Whiteside, E. P., Templin, E. H., Chandler, R. F., Jr. and Alexander, L. T. (1949) Soil classification and the genetic factors of soil formation : *Soil. Sci.*, v. 67, pp. 93-105.
- Murray, H. H. and Leininger, R. K. (1956) Effect of weathering on clay minerals : in *Clays and Clay Minerals*, Natl. Acad. Sci.-Natl. Res. Council pub. 456, pp. 340-347.
- Peterson, J. B. (1946) Effect of Pennsylvanian sediments on the properties of a Gray-Brown Podzolic soil of Iowa : *Iowa J. Sci.*, v. 20, pp. 195-211.
- Retzer, J. L. (1956) Alpine soils of the Rocky Mountains : *J. Soil Sci.*, v. 7, pp. 22-32.
- Rich, C. I. and Obenshain, S. S. (1955) Chemical and clay mineral properties of a Red-Yellow Podzolic soil derived from muscovite schist : *Soil Sci. Soc. Amer. Proc.*, v. 19, pp. 334-339.
- Rolfe, B. N. and Jeffries, C. D. (1952) A new criterion for weathering of soils : *Science*, v. 116, pp. 599-600.
- Ross, C. S. and Hendricks, S. B. (1945) Minerals of the montmorillonite group, their origin and relation to soils and clays : U.S. Geol. Survey Prof. Paper 205-B, pp. 23-79.
- Sawhney, B. L. and Jackson, M. L. (1958) Soils montmorillonite formulas : *Soil Sci. Soc. Amer. Proc.*, v. 22, pp. 115-118.
- Schmehl, W. R. and Jackson, M. L. (1957) Mineralogical analyses of soil clays from Colorado surface soils : *Soil Sci. Soc. Amer. Proc.*, v. 21, pp. 373-380.
- Swindale, L. D. and Jackson, M. L. (1956) Genetic processes in some residual podzolised soils of New Zealand : *Proc. 6th Int. Congr. Soil Sci.*, v. 5, pp. 233-239.
- Tamura, T., Jackson, M. L. and Sherman, G. D. (1953) Mineral content of Low Humic, Humic and Hydrol Humic Latosols of Hawaii : *Soil Sci. Soc. Amer. Proc.*, v. 17, pp. 343-346.
- Tamura, T., Jackson, M. L. and Sherman, G. D. (1955) Mineral content of a Latosolic Brown Forest soil and a Humic Ferruginous Latosol of Hawaii : *Soil Sci. Soc. Amer. Proc.*, v. 19, pp. 435-439.
- Tanada, T. (1951) Certain properties of the inorganic colloidal fraction of the Hawaiian soils : *J. Soil Sci.*, v. 2, pp. 83-96.
- Thorp, James and Smith, G. D. (1949) Higher categories of soil classification : Order, suborder, and great soil groups : *Soil Sci.*, v. 67, pp. 117-126.
- Walker, G. F. (1949) The decomposition of biotite in the soil : *Min. Mag.*, v. 28, pp. 693-703.
- Walker, G. F. (1950) Trioctahedral minerals in the soil-clays of north-east Scotland : *Min. Mag.*, v. 29, pp. 72-84.
- White, J. L. (1951) Transformation of illite into montmorillonite : *Soil Sci. Soc. Amer. Proc.*, v. 15, pp. 129-133.
- White, J. L. (1956) Reactions of molten salts with layer-lattice silicates : in *Clays and Clay Minerals*, Natl. Acad. Sci.-Natl. Res. Council pub. 456, pp. 133-146.
- Whittig, L. D. and Jackson, M. L. (1955) Interstratified layer silicates in some soils of northern Wisconsin : in *Clays and Clay Minerals*, Natl. Acad. Sci.-Natl. Res. Council pub. 395, pp. 322-336.
- Whittig, L. D. and Jackson, M. L. (1956) Mineral content and distribution as indexes of weathering in the Omega and Ahmeek soils of northern Wisconsin, in *Clays and Clay Minerals*, Natl. Acad. Sci.-Natl. Res. Council pub. 456, pp. 362-371.