PEDOGENIC FORMATION OF MONTMORILLONITE FROM A 2:1-2:2 INTERGRADE CLAY MINERAL*

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Abstract—Montmorillonite was found to be the dominant clay mineral in surface horizons of certain soils of the North Carolina Coastal Plain whereas a 2:1-2:2 intergrade clay mineral was dominant in subjacent horizons. In all soils where this clay mineral sequence was found, the surface horizon was low in pH (below 4.5) and high in organic matter content. In contrast, data from studies of other soils of this region (Weed and Nelson, 1962) show that: (1) montmorillonite occurs infrequently; (2) maximum accumulation of the 2:1-2:2 intergrade normally occurs in the surface horizon and decreases with depth in the profile; (3) organic matter contents are low; and (4) pH values are only moderately acid (pH 5-6).

It is theorized that the montmorillonite in the surface horizon of the soils studied originated by pedogenic weathering of the 2:1-2:2 intergrade clay mineral. The combined effects of low pH (below 4.5) and high organic matter content in surface horizons are believed to be the agents responsible for this mineral transformation. The protonation and solubilization (reverse of hydrolysis) of Al-polymers in the interlayer of expansible clay minerals will occur at or below pH 4.5 depending on the charge and steric effects of the interlayer. A low pH alone may cause this solubilization and thus mineral transformation, but in the soils studied the organic matter is believed to facilitate and accelerate the transformation. The intermediates of organic matter decomposition provide an acid environment, a source of protons, and a source of watersoluble mobile organic substances (principally fulvic acids) which have the ability to complex the solubilized aluminum and move it down the profile. This continuous removal of solubilized aluminum would provide for a favorable gradient for aluminum solubilization.

The drainage class or position in a catena is believed to be less important than the chemical factors in formation of montmorillonite from 2:1-2:2 intergrade, because montmorillonite is present in all drainage classes if the surface horizon is low in pH and high in organic matter.

INTRODUCTION

A 2:1-2:2 aluminum intergrade clay mineral with 14 Å spacing having some of the properties of vermiculite, chlorite, and montmorillonite has been studied intensively during the last decade. The mineral has also been referred to as di-octahedral vermiculite (Brown, 1953; Rich and Obenshain, 1955), chloritized montmorillonite (Sawhney, 1958; Frink, 1965), aluminum interlayered vermiculite (Douglas, 1965), intergrade chlorite-vermiculite-montmorillonite (Jackson,
1960), and chlorite-like intergrade (Weed and Nelson, 1962). This mineral, or perhaps more properly this series of similar clay minerals, is formed when aluminum, iron, magnesium, and perhaps other ions are precipitated in the interlayer space or when hydroxy polymers of these ions are adsorbed into the interlayer space of expanding 2:1 layer silicates. This process has been called "chloritization" because the end product of the phenomenon is chlorite, a 2:2 layer silicate. According to Sawhney (1958), a continuous chloritized montmorillonite series may exist in soils. The diversity of the reports concerning the character and composition of the mineral are a result of variation in the degree of chloritization, composition of the interlayer polymers, and layer charge characteristics of the parent mineral.

The 2:1-2:2 aluminum intergrade was first reported in soils by Brown (1953) and has been reported to occur in many soils of the eastern United States (Rich and Obenshain, 1955; Klages and White, 1957; Tamura, 1958; Sawhney, 1960; Weed and Nelson, 1962; Dixon and Jackson, 1962; Nash, 1963). The accumulation and heat stability (of characteristic X-ray diffraction peaks) of the intergrade normally is at a maximum in surface horizons and decreases with depth in the profile. Exceptions to this generalization have been attributed to poor drainage (Weed and Nelson, 1962; Sawhney, 1960) and to low pH (Sawhney, 1958). A possible inhibition of intergrade formation due to the complexing ability and other properties of organic matter has been suggested (Sawhney, 1960; Jackson, 1960; Weed and Nelson, 1962).

In this paper the clay mineralogy of certain soils in North Carolina with montmorillonite in surface horizons and 2:1-2:2 intergrade clay minerals in subsurface and subsoil horizons is examined and a mechanism is theorized for the pedogenic origin of the montmorillonite from 2:1-2:2 aluminum intergrade clay minerals.

**METHODS AND MATERIALS**

*For more detailed soil descriptions, organic matter characterization and additional soil chemical and physical properties, refer to Unpublished Ph.D. Theses of R. L. Malcolm and W. D. Nettleton, N. C. State University, 1964 and 1966, respectively.*

**Soil sampling and characterization**

Soil samples from two areas of the North Carolina Coastal Plain were used in this study. Three soils (Lakewood, Leon, and Wando soils) were sampled in Brunswick County, approximately one mile from the ocean along the inland waterway. Two catenas of four soils each were sampled in Wilson County, one on the lower Coastal Plain and the other on the middle Coastal Plain. The soils of each catena include moderately well to very poorly drained soils. Some pertinent chemical, physical, and classification data of representative soils are given in Table 1. Soil pH was determined on samples with a soil:water ratio of 1:1, free iron by the citrate-dithionite method of Mehra and Jackson (1960), CEC<sub>K+</sub> and exchangeable aluminum by the method of Coleman, Weed, and McCracken (1959), total nitrogen by standard Kjeldahl, total carbon by the wet-combustion method of Mebius (1960), and particle size analysis by the sedimentation-pipette method of Kilmer and Alexander (1949).

**Mineralogical analysis**

The bulk soil samples were air dried and passed through a 2 mm sieve. The methods of Kunze and Rich (1959) were used with minor modifications to obtain K- and Mg-saturated silt and clay fractions. After organic matter was destroyed by hydrogen peroxide, the soil samples were dispersed in a mixing cup for 10 min with 1 per cent sodium hexametaphosphate as dispersant. Selected clay samples were fractionated into coarse clay (2.0-0.2 μ) and fine clay (<0.2 μ) by high speed centrifugation. After saturation, a 2 ml suspension containing 50 mg of clay was allowed to dry on a glass slide to attain parallel orientation. Expansive properties of the Mg-saturated series were determined after ethylene glycol or glycerol solvation. The slides were irradiated by the X-ray beam of a GEXRD-5 diffractometer, using copper Kα radiation. All X-ray diffraction patterns in Figs. 1-4 are for the whole clay fraction (<2 μ).

**RESULTS**

A most striking mineralogical sequence occurs in the Lakewood Soil in Brunswick County (Fig. 1). Montmorillonite and swelling intergrade are the predominant clay minerals of the dark-gray Al horizon which has a low pH (3.9) and high organic matter content (2.2 per cent carbon). The term montmorillonite is defined operationally in this paper as the clay mineral component or smectite which exhibits a 14 Å spacing upon Mg-saturation at room temperature and expands to 17-18 Å upon ethylene glycol or glycerol solvation. A portion of the 14 Å clay fraction, a low stability 2:1-2:2 intergrade, did not expand with ethylene glycol solvation but readily collapsed with the montmorillonite to 10 Å upon K-saturation and heating at 350°C. At room temperature the major portion of the K-saturated clay sample collapsed to 11-12 Å with some low intensity broad peaks between 12-14 Å. A small amount of vermiculite may also be present in the sample.
Table 1. General chemical and physical properties of representative soils

<table>
<thead>
<tr>
<th>Soil horizon</th>
<th>Depth (in.)</th>
<th>pH</th>
<th>Exchangeable CEC&lt;sub&gt;8-H&lt;/sub&gt;</th>
<th>Free iron</th>
<th>Nitrogen</th>
<th>Carbon</th>
<th>Sand</th>
<th>Clay</th>
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<tbody>
<tr>
<td>Wando (Typic Quartzipsamment, well drained) (Brunswick County, lower Coastal Plain)</td>
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<tr>
<td>A2</td>
<td>0-2</td>
<td>4-7</td>
<td>4-1</td>
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<td>0-044</td>
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<td>2-8</td>
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<td>—</td>
<td>1-21&lt;sup&gt;a&lt;/sup&gt;</td>
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Unnamed (Typic Fragiaquult, somewhat poorly drained) (Wilson County, middle Coastal Plain)

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<th>Depth (in.)</th>
<th>pH</th>
<th>Exchangeable CEC&lt;sub&gt;8-H&lt;/sub&gt;</th>
<th>Free iron</th>
<th>Nitrogen</th>
<th>Carbon</th>
<th>Sand</th>
<th>Clay</th>
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<td>17-2</td>
<td>3-6</td>
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<td>—</td>
<td>2-60&lt;sup&gt;a&lt;/sup&gt;</td>
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<td>10-9</td>
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<td>1-21&lt;sup&gt;a&lt;/sup&gt;</td>
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Portsmouth (Typic Umbraquult, very poorly drained) (Wilson County, lower Coastal Plain)

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<th>Soil horizon</th>
<th>Depth (in.)</th>
<th>pH</th>
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<td>13-9&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3-6</td>
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<td>2-5&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>B2&lt;sub&gt;gt&lt;/sub&gt;</td>
<td>18-24</td>
<td>4-8</td>
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<td>10-0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6-6</td>
<td>0-39</td>
<td>—</td>
<td>0-1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>45-7</td>
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</table>

<sup>a</sup> Determined by dry combustion.
<sup>b</sup>c of exchangeable Ca, Mg, and K exchange acidity.
<sup>c</sup>Determined by wet combustion (Peech et al., 1947).

The white bleached A 2 soil horizon was essentially devoid of crystalline clay minerals.

The mineralogy changes abruptly in the dark-brown Bh horizon which has a pH of 5-2 and 0-3 per cent carbon. The 2:1-2:2 intergrade is the dominant clay mineral. No traces of montmorillonite were found. The maximum formation of the intergrade, as indicated by heat stability, occurs in the Bh horizon where heat treatment at 550°C resulted in a sharp peak at approximately 12 Å with no resolution of a 10 Å peak.

The abundance of the intergrade clay mineral gradually decreases and the amount of montmorillonite increases with depth from the lower B in the C horizon. The clay in the C horizon, which expands with ethylene glycol, is believed to be a mixture of montmorillonite and an expanding, poorly-formed 2:1-2:2 intergrade mineral. With increasing depth the 2:1-2:2 intergrade is less heat stable as indicated by increased resolution of the 10 Å peak and increased low intensity smudging of the diffuse peak between 14 and 10 Å. A small amount of vermiculite and mica are also present in the horizon. There is also the possibility that the clay fraction contains randomly inter-stratified vermiculite and mica in addition to the montmorillonite.

A relatively constant amount of kaolinite (approximately 25 per cent) and minor amounts of gibbsite and quartz are present in the clay fraction of all horizons.

The precursor of the 2:1-2:2 intergrade could
be montmorillonite, vermiculite, or mica because all three minerals are present in the C horizon.

The well-drained Wando soil is a less well-developed soil which was sampled near, and is commonly associated with, the Lakewood soil. In contrast to the Lakewood soil, the Wando soil does not have a thin mat of organic matter covering the mineral soil, a low pH (below 4-5) in the surface horizon, a thick bleached A₂ horizon, a Bh horizon, or montmorillonite in the surface horizon (Fig. 2). A 2:1-2:2 aluminum intergrade is the predominant clay mineral in all horizons, with maximum intergrade formation in the B horizon. The intergrade also is well formed in the thin incipient A₂ horizon where the dealumination of the intergrade is beginning to occur. The pH of the A₂ horizon was 4-7 at the time of summer sampling and would probably approach pH 4-5 at some season(s) of the year. The intergrade is less well formed in the C horizon than A or B horizons as more of the 14 Å peak shifts toward 10 Å upon heating. Small amounts of vermiculite may be present in all horizons. Appreciable amounts of kaolinite are present in all horizons along with minor amounts of gibbsite and quartz.

The poorly drained soils of the catena in the middle Coastal Plain in Wilson County have clay mineralogy similar to the Lakewood soil with maximum relative accumulation of montmorillonite in the surface horizons and 2:1-2:2 intergrades in the subsurface and subsoil horizons. The surface horizons of the soils are below pH 4-5 and the subsurface and subsoil horizons near or above pH 4-5. The poorly drained soils of the catena in the lower Coastal Plain in Wilson County have a more diverse mineralogy but appear to have a mineral assemblage intermediate between the Lakewood and Wando mineral assemblages, i.e., the surface horizons contain both montmorillonite and a 2:1-2:2 intergrade clay mineral while B horizons are mostly 2:1-2:2 intergrade clay minerals with some montmorillonite. All horizons of the poorly drained soils of this catena from the lower Coastal Plains have a pH near or above 4-5. The poorly drained soils of this area. An unnamed somewhat poorly-drained soil and the Portsmouth soil representative of the respective conditions found in the wetter soils will be discussed.

The A₁ horizon of a somewhat poorly-drained unnamed soil from the middle Coastal Plain with a low pH (4-0) and 2-6% organic carbon is predominantly montmorillonite (Fig. 3). Almost all of the 14 Å peak expanded to 18 Å upon glycerol solvation and readily collapsed to 10 Å upon K-saturation at room temperature. Heat treatment at 350°C produced a strong-sharp 10 Å peak. The
14 Å clay in the B22 gt horizon was a mixture of montmorillonite and a swelling poorly-formed intergrade. Upon glycerol solvation the 14 Å peak expanded to a broad peak from 14–18 Å and collapsed only to approximately 13 Å after K-saturation at room temperature. After heating to 350°C the 14 Å peak collapses to a broad 10 Å peak. The C horizon clays were kaolinite and illite with no montmorillonite or intergrade.

The clays of the solum of the very poorly-drained Portsmouth soil are predominantly of intergrade type (Fig. 4). The AI horizon with a pH of 4.5 and 2-5% organic carbon contained a small amount of expansible 14 Å material, presumably montmorillonite. The major portion of the 14 Å peak was an intergrade which gave a diffuse peak between 10 and 14 Å upon K-saturation and heating. The mineralogy of the B horizon was very similar to the A horizon except that the intergrade was slightly more heat stable. A small amount of vermiculite may also be present. Moderate amounts of kaolinite and small amounts of illite were present in the A and B horizons, with kaolinite becoming the predominant mineral in the C horizon. A moderate amount of illite was present in the C horizon also, with small amounts of quartz and montmorillonite. No intergrade mineral was present in the C horizon.

The presence of a swelling 2:1-2:2 aluminum intergrade in addition to montmorillonite is indicated in the surface horizon of the Lakewood and the B22 gt horizon of the unnamed soil by the weak broad 10 Å peak after K-saturation and heat. This peak is very weak when compared to the 18 Å after Mg-saturation and glycol or glycerol solvation. The swelling intergrade did not collapse to a uniform 10 Å spacing, but random collapse between 10 and 12 Å results in little reinforcement of the X-ray beam and poor resolution of the 10 Å peak. The strong sharp 10 Å peak after K-saturation and heating the clay from the surface horizon of the somewhat poorly drained wet unnamed soil suggests that the major portion of the 14 Å peak is montmorillonite with very little swelling intergrade clay.

DISCUSSION

The monomeric aluminohydronium ion is the fundamental acid ion in soil below pH 4.5. If the pH of the soil rises to 4.5, aluminum hydrolysis begins and is almost complete at pH 5. There is some evidence (Jackson, 1960) that hydrolysis may occur at a slightly lower pH when aluminum is held on exchange sites of expansible layer silicates due to a steric pinching effect. When aluminum precipitates as polymers in the interlayer of expansible minerals, the resultant mineral is called a 2:1-2:2 aluminum intergrade. Several inves-
tigators have synthesized aluminum and iron inter-
grades in laboratory experiments from mont-
morillonite and vermiculite (Rich, 1960; Shen and
Rich, 1962; Hsu and Bates, 1964). These inter-
grades are heterogeneous in character as discussed
previously, and loss of expansibility can be
achieved when less than 10 per cent of the inter-
layer surface is covered with polymer (Frink, 1965).

Chlorite as well as montmorillonite and vermi-
culite have been postulated (Jackson, 1963) to
be the precursor of aluminum intergrades in soil
under conditions of natural weathering. In soil
studies, Tamua (1958) and Douglas (1965) re-
ported montmorillonite and vermiculite, respec-
tively, to be the precursors of the intergrade. Mica
was suggested as the precursor of the intergrade
by Weed and Nelson (1963). It is now known if
mica can weather directly to the intergrade or if
intermediary phases of montmorillonite or ver-
miculite are necessary. In this study, montmoril-
onlite is believed to be the dominant precursor
in the Lakewood and Wando soils, although ver-
miculite and mica are minor possibilities because
they are present in small amounts. Mica and/or
montmorillonite is the precursor of the intergrade
in the Wilson County soils.

The process of intergrade formation from
montmorillonite or vermiculite is reversible in the
laboratory and is believed to be so in soils. When
synthetic interlayers are removed by chemical
means such as acids or complexing agents, the
parent expansible mineral is obtained. In soils
or the laboratory, protonation (the reverse of
hydrolysis) of the interlayer polymer would occur
when the pH dropped below 4.5. This protonation
would result in the solubilization or dealumination
of the interlayer, and the mineral would once again
become expansible.

The mineralogical sequence and associated
chemical conditions in the soils studied support
many of Jackson's postulates. The intergrade is
apparently formed in the B and C horizons from
montmorillonite or vermiculite where the pH
is favorable for hydrolysis and then the intergrade
is transformed back to montmorillonite in the
surface where the low pH and high organic matter
favor protonation or dealumination of the inter-
layer polymer.

Low pH and organic matter are probably of
equal importance in the pedogenic formation of
montmorillonite from 2:1-2:2 intergrades in the
soils studied because the intermediates of organic
matter decomposition (primarily fulvic acids)
are the most common source of soil acidity (pH
4-5 and below), and because the properties of
high organic matter and high hydrogen ion activity
environments in soils are closely interrelated.

It is difficult to assess if low pH alone (below
4-5) without the influence of organic matter is an
important or extensive mechanism in the pedo-
genic transformation of 2:1-2:2 intergrades to
montmorillonite because few low pH environments
are created in soils without the dominant influence
of organic matter. Theoretically a source of protons
at the low pH (below 4-5) and the 2:1-2:2 inter-
grade clay are all that is needed for the dealumina-
tion reaction and transformation to occur. At this
low pH the aluminum polymer is thermodynam-
ically unstable and protonation of the interlayer
aluminum polymer would result in the formation
of exchangeable aluminum species, subject to
leaching, and an expansible aluminosilicate. This
mechanism may also be functional in certain local
or micro environments where sulfur oxidation
is prevalent, as in oxidized soil materials from
costal marshes or in stripmine soil.

Likewise, organic matter alone above the critical
pH of 4-5 may not bring about the transformation
of 2:1-2:2 intergrade to montmorillonite. In
most soils both the 2:1-2:2 intergrade and organic
matter increase in amount with proximity to the
surface, the maximum intergrade occurring where
maximum accumulation of organic material is
found. The critical point is that in such soils the
pH is always above the critical pH for solubiliza-
tion of the interlayer polymer.

Poor drainage alone is not responsible for the
transformation because the process occurs in
the well-drained Lakewood soil and the trans-
formation does not occur in all poorly drained soils.
For example, the poorly drained Plummer soil,
a low Humic Gley with high organic matter
content, exhibited a high degree of interlayering
throughout the profile (Weed and Nelson, 1963).
The critical point here again is that nowhere in
the solum of the Plummer soil was the pH below
the critical pH of 4-5.

Organic matter is believed to facilitate the re-
moval of aluminum interlayers in several ways
in addition to providing the acid environment or
the source of protons for the protonation reaction.
It is well established that organic matter, especially
fulvic acids, form water-soluble complexes with
Al, Fe, and other metals. The product of the
protonation reaction, aluminum ion species in
solution or on exchange sites, would be subject
to complexation by fulvic acid and other mobile
soil organic matter constituents. These water-
soluble complexes would move downward in the
profile in percolating water, thus removing the
product of the protonation reaction. The con-
tinuous removal of product would keep the equili-
rium shifted to the right, favoring the production
of more aluminum ions at a maximum rate, $K_1$.
The rate $K_1$ of this protonation reaction is believed to be very slow.

The organic matter may take a more active role in the solubilization of aluminum in a manner similar to the solubilization of iron from Triassic sands as reported by Coulson, Davies and Lewis (1960). The rate of iron solubilization by the polyphenols was ten times greater than with buffer solution at the same pH without polyphenols. The mechanism of this reaction is not known, but complex formation seems to be essential. Fulvic acids have phenolic carboxyl, and other reactive groups capable of complex formation and would be expected to act in a manner similar to complex polyphenols in solubilization of iron and aluminum sesquioxides.

By either mechanism the aluminum polymer would be readily accessible to fulvic acids or mobile soil organic matter. Other workers have shown that much of the aluminum interlayer polymer is near the edge of the clay particle. Electron micrographs of some of the clays in this study (Fig. 5)* show that clumps of amorphous material are on the surface and edges of the clay plates. These surface clumps of aluminum polymer would be expected to be readily available to fulvic acids in soil solution because the clay is dispersed throughout the sandy soils studied. In the surface horizons having montmorillonite the clay plates have fewer clumps of amorphous material and the edges of these are practically free of the material (Fig. 6).

The aluminum polymer within the interlayer would not be protected from solubilization by fulvic acids, because the fulvic acid-montmorillonite clay complex has a 14 Å spacing (Schnitzer and Kodama, 1966) which is essentially the same as the intergrade. The remaining portion of the polymer in the intergrade and the hydration of the portion of the platlet where the polymer was removed would prop the interlayer open for free movement of fulvic acids within the interlayer.

If organic matter is such an integral part of the dealumination process, there should be considerable amounts of organic matter in the soil and evidence of organic matter, aluminum, and iron movement. The composition of the O1, A2, and Bh horizons in the Lakewood and Leon soils provide strong evidence that a supply of organic matter is available and that considerable eluviation has occurred. The organic matter of the Bh horizon is readily extractable with acetylacetone or sodium hydroxide and is composed of over 85% fulvic acids. The Bh horizon also has maxima of free iron and exchangeable aluminum suggesting that metal movement was associated with fulvic acid movement.

Soil water collected periodically from the Wilson County soils contained up to 0.07% organic matter, 0.2 ppm aluminum, and 3.4 ppm iron. The highest concentrations of aluminum and iron in soil solution occurred when the concentration of organic materials was highest. By paper chromatography it was determined that the water-soluble or mobile organic matter consisted of sugars, organic acids and polyphenols—all of which are capable of complex formation with aluminum, iron and other metals.

Soil conditions such as low pH or high organic matter content may prevent or inhibit intergrade formation. Such inhibition may well have occurred in certain instances and is surely preventing additional formation of intergrade in soils where the pH drops below 4.5. However, the dealumination theory is supported in this investigation because all the soil conditions necessary for the process to occur are present and the inhibition theory does not explain the presence of some intergrade in the surface horizon with a pH 3-9 or the apparent mineralogical sequence with decreasing pH and increased weathering.

Intergrade formation should be completely inhibited at a pH of 3-9, but a small amount of intergrade is present in the A1 horizon of the Lakewood soil. Aluminum hydrolysis should not occur at this low pH, therefore no intergrade could be formed. The swelling intergrade must be the last remnant of a well-formed intergrade which is undergoing dealumination because the pH dropped below 4.5 in the process of soil development.

In these soils weathering must have occurred over a long period of time before the formation of low pH conditions. During this initial weathering period, the inhibition theory could not apply and the intergrade which is a stable weathering product for the region probably would have formed in all horizons.

In support of these statements, there seems to be a sequence or evolution of soils and mineralogy with increased time on the coastal plain. Old soils or very youthful soils with a pH between 5 and 6 have maximum intergrade formation in the surface horizon. With decreasing pH and incipient A2 formation, such as is found in the Wando soil on the coastal dunes, dealumination apparently begins in the surface horizon. With time an acid litter mat forms on the soil surface, pH consequently drops to below 4.5 during the entire year, and the
intergrade is transformed into montmorillonite in the acid soil surface. This situation occurs in the Lakewood soil which is approximately 1 mile back from the ocean.

With more time and lowering of the pH to below 4.0 in a Leon soil 50 miles inland (Duplin County), montmorillonite is weathered from the soil surface and only small amounts of crystalline clay mineral remain (Weed and McCracken, 1963). The weathering boundary moves downward in the soil and montmorillonite or poorly formed intergrade is in the upper B with maximum formation of intergrade in the middle to lower B horizon.

CONCLUSIONS

The decision table (Table 2) summarizes some of the evidence which support the conclusion that organic matter and low pH (<4.5) are jointly the principal agents responsible for the conversion of intergrade to montmorillonite. The surface horizon of the first four soils, which are predominantly montmorillonitic, have only high organic matter and low pH in common. Organic matter alone is not responsible for the conversion because many soils in addition to those listed in the table have high organic matter contents, but do not have montmorillonite in the surface horizon. From the table, it might be concluded that low pH alone could bring about the conversion, and may do so in some rare soil environments; but because organic matter is the agent responsible for the low pH in the soil studied, it is believed that organic matter and low pH are intimately associated in the conversion.

A pH of 4.5 seems to be the critical pH below which dissolution of the Al (Fe?) interlayer polymers occurs within the intergrade clay mineral. All horizons above this pH are devoid of montmorillonite and contain the intergrade; all horizons with a lower pH are predominantly montmorillonitic; and the Portsmouth surface horizon of 4.5 is mixed intergrade and montmorillonite. This Portsmouth surface horizon is believed to be a manifestation of incipient montmorillonite formation from the intergrade.

The critical amount of organic matter or mobile fulvic acids in the soil necessary for the conversion is not known, except that the organic matter must provide a pH of <4.5. Organic matter contributes to the conversion in many ways, in addition to providing an acid environment. These include a readily available supply of protons, the complexation of Al and Fe, and perhaps the active solubilization of Al and Fe polymers.

Drainage is not believed to be an important factor, because the conversion occurs in both well-drained and poorly-drained soils.

The theorized mechanism of intergrade de-alumination is believed to be occurring and has occurred in the soils studied. It is believed to be a more common pedogenic phenomenon responsible for the occurrence of montmorillonite than montmorillonite resulting from prevention of interlayer polymer formation.

Table 2. Decision table

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Poor drainage</th>
<th>PH &lt; 4.5</th>
<th>High organic matter</th>
<th>Predominantly montmorillonite</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Lakewood</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>2. Leon</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>3. Leon</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>4. Unnamed soil</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>5. Portsmouth</td>
<td>yes</td>
<td>yes-no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>6. Wando</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>7. Plumer</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>8. Norfolk</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

REFERENCES

Fig. 5. Electron micrograph, 2-0.2μ clay fraction of B22t horizon of somewhat poorly drained unnamed soil of the middle Coastal Plain.

Fig. 6. Electron micrograph, 2-0.2μ clay fraction of Al horizon of the somewhat poorly drained unnamed soil of the middle Coastal Plain.


**Résumé** — Le montmorillonite s'est révélé le minéral d'argile dominant dans les horizons superficiels de certains sols dans la Plaine Côtière de la Nouvelle Caroline, tandis qu'un minéral d'argile interstratifié 2:1–2:2 dominait dans les horizons sousjacents. Dans tous les sols où on trouvait cette séquence de minéral d'argile, l'horizon superficial avait un pH bas (inférieur à 4,5) et une teneur élevée en matière organique. Par contraste, les données obtenues dans les études d'autres sols de cette région (Weed et Nelson, 1962) montrent que: (1) le montmorillonite est rare; (2) l'accumulation maximum de l'interstratifié 2:1–2:2 a généralement lieu dans l'horizon superficial et décroît avec la profondeur dans le profil; (3) la teneur en matière organique est basse, et (4) le pH n'est pas fortement acide (pH 5–6).

On présente la théorie que le montmorillonite dans l'horizon superficial du sol a son origine dans le vieillissement pédogénique du minéral d'argile interstratifié 2:1–2:2. Les effets combinés de bas pH (inférieur à 4,5) et de la teneur élevée en matière organique dans les horizons de surface sont considérés être responsables de cette transformation minéralogique. La protonation et solubilisation (inverse de l'hydrolyse) des polymères Al dans la couche intermédiaire des minéraux d'argile expansibles ont lieu à un pH égal ou inférieur à 4,5 selon la charge et les effets stériques de la couche intermédiaire. Un bas pH peut à lui seul provoquer cette solubilisation et de là la transformation minéralogique, mais dans le cas des sols étudiés, on considère que la matière organique facilite et accélère la transformation. Les produits intermédiaires de la décomposition de la matière organique fournissent un milieu acide, une source de protons et une source de substances organiques mobiles et solubles dans l'eau (surtout les acides fulviques) qui ont la capacité de rendre complexe l'aluminium solubilisé et de le déplacer vers le bas du profil. Cet enlèvement continu de l'aluminium solubilisé tend à fournir une pente qui favorise la solubilisation de l'aluminium.

La catégorie d'assèchement et la position dans la chaîne semblent être moins importantes que les facteurs chimiques en ce qui concerne la formation de montmorillonite à partir d'un intergrade 2:1–2:2, parce que le montmorillonite est présent dans toutes les catégories d'assèchement si l'horizon de surface a un pH bas et une teneur élevée en matière organique.

**Kurzreferat** — Montmorillonit wurde als vorherrschendes Tonmineral in den Oberflächenhorizonten gewisser Böden der Küstenenebene von North Carolina gefunden, während in den darunter liegenden Horizonten ein 2:1–2:2 Übergangstonmineral vorherrschte. In allen Böden, wo diese Tonmineral-
folge festgestellt wurde, war das pH niedrig (weniger als 4,5) und der Gehalt an organischen Bestandteilen hoch. Im Gegensatz dazu erweisen die Ergebnisse der Untersuchungen anderer Böden dieser Gegend (Weed und Nelson, 1962) folgendes: (1) Montmorillonit tritt nur spärlich auf; (2) eine maximale Anhäufung des 2:1-2:2 Übergangsminerals tritt normalerweise im Oberflächenhorizont auf und nimmt mit der Tiefe des Profils ab; (3) die Gehalte an organischen Bestandteilen sind niedrig; und (4) die pH Werte sind nur schwach sauer (pH 5–6).
