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CLAY MINERALOGICAL COMPOSITION OF ALLUVIAL SOILS

FROM DIFFERENT RIVER SYSTEMS/AGRO-ECOLOGICAL REGIONS

IN VIETNAM IN REFERENCE TO ORIGIN, REGIONAL

DISTRIBUTION AND SOIL QUALITY

NGUYEN QUANG HAi' and KAZUHIKO EGASHIRA2

Department of Plant Resources, Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University,

Fukuoka 811-8581, Japan 2 Department of Plant Resources, Faculty of Agriculture, Kyushu University, Fukuoka 812-8581, Japan
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ABSTRACT

Sixteen profiles of alluvial soils of Vietnam were collected throughout the country and subjected to
clay mineral analysis. Alluvial soils from different river systems/agro-ecological regions had different clay
mineralogical compositions due to differences in sediment sources. Mica and kaolinite were found to be
predominant clay minerals in alluvial soils. Other major minerals detected were vermiculite, smectite,
chlorite, and the mica/vermiculite/smectite•`mica/smectite mixed-layer mineral, depending on the river
systems. The clay mineralogical composition was remarkably similar within soil units belonging to the
same river system and in a profile. However, the clay mineralogical composition greatly varied with river
systems; therefore, the regional variation existed and was mainly controlled by the mineralogical features
of the sediment sources. Mica was found to be altered to mixed-layer minerals in some soils under
specific conditions. The soil quality was assessed from the viewpoint of inherent potentiality based on the
type and amount of clay minerals as plant-nutrient sources. Alluvial soils distributed in the Red River
and Mekong River systems were evaluated to be in the high level of inherent potentiality. Those from
the Trakhuc River and Ba River systems were classified to have low inherent potentiality, while those
from the remaining ones were to be at an intermediate level.

Key words: Alluvial soils, Clay mineralogical composition, Soil quality, Agro-ecological region, River
system, Vietnam

INTRODUCTION

Vietnam is situated within 8•K10' to 23•K24' N latitude
and 102•K09' to 109•K30' E longitude ranges in the
Indochina Peninsula. This location makes it own trop-
ical to subtropical monsoons with two distinct seasons:
rainy (April to October) and dry (November to March)
seasons. Although it is narrow in wide, Vietnam has a
very complicated topography and diversified geology.
Based on the topography, geology, climate, and vege-
tation, the whole country is divided into 9 agro-
ecological regions (Fig. 1) . The total land area of
Vietnam is 331,000 km2, of which 3.5 million ha are
alluvial soils distributed throughout the country but
mainly in the Red River Delta region (Red and Thai-
binh River systems) with around 600 thousand ha, and
in the West of the South region (Mekong River system)
with approximately 850 thousand ha. Small areas of

alluvial soils are distributed along the seashore, belong-ing to the North of Central (Ma and Lam River systems), the Coastal Area of Southern Central (Trakhuc and Ba River systems), and the East of the South (Dongnai River system) regions (NISF and DSTPQ, 2002). Because of their high soil fertility, flat topogra-phy, and favorable irrigation condition, alluvial soils have been used for intensive cultivation of paddy rice and cash crops, leading to the regional or national socio-economic development (Pham et al., 2003).
It has been well-known that clay mineral represents the smallest mineral substance in the soil; it plays an important role in determining soil fundamental physical and chemical properties and soil potential fertility. Es-pecially, it takes an active part in the adsorptive process and nutrient exchange (cations and anions) with soil solutions. A good understanding of the clay mineral can help scientists not only to diagnose the genetic, forma-

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FIG. 1. Soil sampling sites on the map of agro-ecological regions of Vietnam.
I. Northwest region; II. Northern region; III. Northeast region; IV. Red River Delta region; V. North of Central region; VI. Coastal Area of Southern Central region; VII. High Plateau Tay Nguyen region; VIII. East of the South region; IX. West of the South region.

tion and development processes of a soil but also to
manage the soil effectively and to propose measures in
order to improve and sustain soil fertility (Dao, 1987).
Until now, only a few studies have been done on the
clay mineralogy of soils in Vietnam including alluvial
soils. There was a work by Nguyen and Tran (1978) on alluvial soils of the Red River and Ma River systems, but they did not carry out it in detail and not estimate percentages of the composing clay minerals. They stated that main clay minerals of the alluvial soils of the Red River and Ma River systems were kaolinite and hydro-

mica and that those were not much dependent on the soil type. Dao (1987) conducted some researches on the mineralogy of alluvial soils of the Red River system but did the clay mineral analysis not with the oriented clay fraction but with the whole soil powder. Recently, Ho et al. (1998) and Nguyen and Egashira (2000) carried out some detailed studies on the clay mineralogical composition of alluvial soils but their works were con-centrated on the two biggest river systems: Red River and Mekong River systems.
Based on the above review, the purposes of the

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TABLE 1. General information on alluvial soils in Vietnam

present study are: (1) to examine the clay mineralogical composition of alluvial soils from important river sys-tems throughout Vietnam; (2) to clarify the factors controlling the clay mineralogical composition of alluvial soils of the respective river systems; and (3) to assess the soil quality of alluvial soils in terms of clay mineralogy.

MATERIALS AND METHODS

Soils

Sampling sites of 16 profiles of alluvial soils are shown on the map of agro-ecological regions of Vietnam in Fig. 1, and general information on soil profiles is given in Table 1. No sample was collected from the Northwest, Northern, Northeast, and High Plateau Tay Nguyen regions, because of limited distribution of al-luvial soils in these regions. All soil samples analyzed in the present study were taken in the following two projects: (1) Surveying and Evaluating Soil Quality to Establish Soil Reference, Database and Information; and
(2) Study in Establishing the Data Guidelines on Envi-ronmental Quality of Vietnam Fluvisols. Seven out of 16 profiles belong to the Red River Delta region, of which 5 are from the Red River system (RD1 through RD5) and 2 from the Thaibinh River system (TB1 and TB2). Profiles MA1 (Ma River system), and LM1 and LM2 (Lam River system) belong to the North of Central region. Profiles TK1 (Trakhuc River system) and BA1 (Ba River system) are distributed in the Coastal Area of Southern Central region. Profile DN1 from the Dongnai River system is in the East of the South region, while profiles MK1 through MK3 from the Mekong River system are in the West of the South region. All of these soils are distributed on the flat plain and have been subjected to intensive paddy rice cultivation (two or three times of rice cropping in a year) except profile DN1 which is used for cultivation of fruit trees.

Soil samples were taken vertically with profile depth based on the genetic horizons, air-dried and gently

ground to pass through a 2-mm sieve in Hanoi, Viet-
nam, followed by clay mineral analysis in Kyushu
University, Japan.

Clay mineral analysis
The <2 gm clay fraction separated in the particle-size
analysis and preserved as a flocculated sol was used to
examine the clay mineral composition by X-ray diffrac-
tion (XRD) method. Duplicate clay sols containing 50
mg clay each were taken in l0-mL glass tubes and then
washed twice with 8 mL of an equal mixture of 1M
NaCl and 1 M NaCH3 COO (pH 5.0) by centrifugation
to lower their pH. Of the duplicate sets, one was
saturated with K and the other with Mg by washing
3 times with 8 mL of 1 M KC1 and 0.5M MgC12,
respectively. The excess salt was removed by washing
once with 8mL of water and the clay in the tube was
thoroughly suspended with 1mL of water. An aliquot of
0.4mL of the clay sol was dropped on to a glass slide
(28•~48mm) covering two-thirds of its area, air-dried
and X-rayed (parallel powder mount).The XRD anal-
ysis was made with the air-dried and glycerol-solvated
specimens for the Mg-saturated clay and air-dried and
heated (at 300•~ and 550•~for 2 h)specimens for the
K-saturated clay. In this study, the XRD analysis was
conducted using a Rigaku diffractometer with Ni-filtered
CuKa radiation at 40 kV and 20 mA and at a scanning
speed of 2•K°20 min-1 with a scanning step of 0.02•K and a
continuous scanning mode over a rang of 3 to 30°20.

Semi-quantitative estimates of mineralogical composition
Relative mineral contents in the clay fraction were
semi-quantitatively estimated on the basis of the XRD
peak intensities. In the present estimation, the peak height
was used as the peak intensity by assuming the relative
proportions of the minerals of a sample normalized to
100% and the same proportionality between the peak
intensity and the content of each mineral (Wada et al.,
1981; Nguyen and Egashira, 2000; Ho et al., 2000).

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Reflections of the Mg-saturated and glycerol-solvated
specimen were usually used to calculate peak intensities
of minerals. The contents of mica and smectite were
calculated from the intensities of 1.00 and 1.80nm

peaks, respectively. To calculate the content of chlorite
the 1.42-1.44nm peak intensity of the K-saturated and
550•Ž-heated specimen was used after normalization by
multiplying by the intensity ratio of 0.425 nm peaks of
the Mg-saturated and glycerol-solvated specimen and of
the K-saturated and 550°C-heated specimen. This nor-
malized intensity was then subtracted from the intensity
of the 0.715nm peak of the Mg-saturated and glycerol-
solvated specimen to calculate the kaolinite content. The
intensity used to calculate the vermiculite content was
obtained by subtracting the normalized intensity of the
1.42-1.44nm peak of the K-saturated and air-dried
specimen from the 1.42-1.44nm peak intensity of the
Mg-saturated and glycerol-solvated specimen. The inten-
sity of chlorite-vermiculite intergrade was estimated from
the difference between the normalized 1.42-1.44nm

peak intensities of the K-saturated and air-dried spec-
imen and of the K-saturated and 550°C-heated speci-
men. The content of the mica/vermiculite/smectite•`mica/
smectite mixed-layer mineral was estimated from the
normalized intensity of the 1.00 nm peak of the K-
saturated and 550•Ž-heated specimen after subtracting
the intensities due to mica, vermiculite, smectite and
chlorite-vermiculite intergrade. The intensity of the 1.20
nm peak of the Mg-saturated and glycerol-solvated
specimen was used to calculate the content of the
mica/chlorite or mica/vermiculite mixed-layer mineral.
The contents of goethite, gibbsite, and lepidocrocite were
calculated from the intensities of the peaks at 0.416-
0.417, 0.484, and 0.627nm, respectively. The 0.425nm
peak intensity was used to calculate the quartz content
after multiplication by the coeficient 3, and the sum of
the intensities around 0.32 nm peak was used to estimate
the feldspars content.

RESULTS AND DISCUSSION

Mineral identification and origin of minerals
The XRD patterns of the <2 gm clay fraction from
the surface horizon of a representative of alluvial soils
from the respective river systems are illustrated in FIg. 2,
and the approximate relative mineral contents in the <2
gm clay fraction of all proFIles and horizons are shown
in Table 2. The presence of mica was indicated by the
1.00 nm peak along with its higher-order reflections at
0.498-0.499 and 0.334 nm. Similarly, the presence of
kaolinite was ascertained by the peaks at 0.715 (0.714-
0.719) and 0.357 nm which disappeared by heating at
550°C of the K-saturated specimen. Mica and kaolinite
were detected in all samples and were regarded as the
most abundant layer silicate minerals in the clay fraction
with the contents ranging from 8 to 49% (32% in
average) and from 18 to 68% (34% in average), respec-
tively. Chlorite was identified by the peaks at 1.42-1.44,
0.715, 0.472 and 0.354 nm and was present in some

samples of the Red, Thaibinh, Lam, and Mekong River
systems with the content ranging form 1 to 17% (5% in
average). Ho et al. (2000) found considerable amounts
of chlorite, in addition to mica and kaolinite, in the soils
derived from alluvium in the Red River system. They
mentioned that the original sediment transported by the
river contained mica, kaolinite and chlorite as major
minerals. This is the case for alluvial soils from some
other river systems in Vietnam.
Vermiculite was identified by the decrease in the
intensity of the 1.42-1.44 nm peak with the correspond-
ing increase in the intensity of the 1.00 nm peak by K-
saturation and air-drying and contributed to 1 to 16%
(6% in average) of the total mineral content in the clay
fraction. The occurrence of vermiculite was generally
noticed in the soils having high pH values such as RD1,
RD2, MA1, LM1 and MK1 (refer to Nguyen et al.
(2005)). The highest values of the vermiculite content
were observed in alluvial soils of the Ma River system.
It has been recognized that upon complete replacement
of K occupying the interlayer of mica by hydrated
divalent cations such as Mg and Ca, the basal spacing
changes from 1.00 nm for mica to 1.42 nm for vermic-
ulite, the hydrated product (Sumner, 2000). Limestone
rich in CaCO3 is the dominant rock in the drainage
basin of the Ma River system, so that the transforma-
tion of mica into vermiculite under affection of Ca may
be highly probable in this area. It made alluvial soils of
the Ma River system have the high vermiculite content
in comparison with those of the remaining river systems.
On the other hand, vermiculite was also found in some
Gleyic Fluvisols having low pH values such as RD4 and
RDS from the Red River system. According to Nguyen
et al. (2005), the low pH values of them are rather
artificial and would be resulted from oxidation of iron

(Fe) and manganese (Mn) compounds during air-drying
of soil samples. Therefore, it was considered that pH
values of these soils were not so low under field condi-
tion as those of air-dried samples and did not prevent
the formation of vermiculite.
Smectite was noticed by the 1.80nm peak in the Mg-
saturated and glycerol-solvated specimen with the con-
tent ranging form 1 to 15% (4% in average). Smectite
occurred with an insignificant amount of normally lower
than 2% in most soil samples, but in the soil from the
Ba River system, the smectite content was relatively high
throughout the profile (11 to 15%). The smectite would
be created from basic magmatic rocks (basalt) which is
dominant in the riverhead of the Ba River (High Plateau
Tay Nguyen region). Dao (1987) and Ho et al. (2000)
reported that semectite (montmorilonite) was very com-
mon in the black soils derived from basaltic deposited
products and subjected to paddy rice cultivation.
The mica/vermiculite/smectite•`mica/smectite mixed-
layer mineral (abbreviated as Mx thereafter) was noticed
on the XRD pattern by poorly defined diffraction effect
between 1.0 and 2.0nm in the Mg-saturated and
glycerol-solvated specimen and by the increase in the
intensity of the 1.00 nm peak after K-saturation and air-

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RD3

MA1

TK1

DN1

TB2

LM1

BA1

MK1

FIG. 2. The XRD patterns of the <2 gm clay fraction from the surface horizon of a profile representing alluvial soils from the respective river
systems. Spacing is in nm. RD3: Red River system; TB2: Thaibinh River system; MA 1: Ma River system; LM1: Lam River system; TK1:
Trakhuc River system; BA1: Ba River system; DN1: Dongnai River system; MK1:Mekong River system. Treatments: a, Mg-saturation and
glycerol-solvation; b, Mg-saturation and air-drying; c, K-saturation and air-drying; d, K-saturation and heating at 300•Ž; e, K-saturation
and heating at 550•Ž.

drying. Mx was detected with a large amount in almost
all samples, except those from the Red River system and
the Coastal Area of Southern Central region. The con-
tent of Mx in the samples having it varied from 8 to
26% (17% in average). Origin and formation of Mx will be discussed later.
Both the mica/chlorite and mica/vermiculite mixed-

layer minerals were noticed by the 1.20 nm peak in the Mg-saturated and glycerol-solvated specimen which exists in all five treatments for the former and shifts to 1.00 nm by K-saturation for the latter. Chlorite-vermiculite inter-grade is a mineral that does not collapse readily when K-saturation but its 1.42-1.44 nm reflection becomes diffuse and shifts toward 1.00 nm after heating at 300

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TABLE 2. Approximate relative mineral contents (%) in the clay fraction of alluvial soils in Vietnam

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TABLE 2 (continued)

Abbreviations: Mc, mica; Ch, chlorite; Vt, vermiculite; St, smectite; Mx, mica/vermiculite/smectite—mica/smectite mixed-layer mineral; Mc/Ch, mica/chlorite mixed-layer mineral; Mc/Vt, mica/vermiculite mixed-layer mineral; Ch-Vt, chlorite-vermiculite intergrade; Kt, kaolinite; Gt, goethite; Lp, lepidocrocite; Gb, gibbsite; Qr, quartz; Fd, feldspars; tr., trace.

and 550•Ž. These minerals were observed only in a few
samples with an insignificant amount of normally lower
than 5%.
Minerals other than layer silicate minerals were
regarded to inherit from parent rocks/materials. Goe-
thite and gibbsite were identified by the peaks at 0.416-
0.417 nm and at 0.484 nm, respectively; their contents
ranged from 1 to 10 or 12% and the average was 4% in
each. Lepidocrocite was noticed by the small peak at
0.627 nm with the content normally lower than 3%.
Quartz was detected by the peaks at 0.425 and 0.334 nm
and was present in almost all samples with the average
of 9%. Feldspars were detected by the peaks around 0.32
nm and its content ranged from 1 to 3%.

Clay mineralogical composition and distribution pattern
in a profile
Characteristics of alluvial soils are closely related to
geology of the riverhead from which sediments were
transported, especially for soils distributed in a river
system having the small drainage basin. Within a river
system, alluvial soils would have the similarity in the
clay mineralogical composition. To test this idea, the
distribution pattern of clay minerals in the clay fraction
was plotted for all profiles of alluvial soils by taking
averages of major clay minerals for all horizons in a
profile. Mica, kaolinite, Mx, chlorite, vermiculite and
semectite were chosen as the major clay minerals for the
pattern analysis because of presence with considerable
amounts and with the large variability among the river
systems.
As illustrated in Fig. 3, the distribution pattern of
clay minerals in the clay fraction of a profile was
grouped into 4 patterns for alluvial soils examined in
the present study. The pattern (a) showed the very high
mica (around 43%) content with being higher than the
kaolinite (around 26%) content; there was some chlorite
and vermiculite (both around 8%) and an insignificant
amount of smectite; Mx was not detected. All profiles
from the Red River system (RD1 through RD5) fitted
well with this pattern. Ho et al. (1998) and Nguyen and
Egashira (2000) have reported the high mica content in
the area of the Red River system. The formation of

alluvial soils in the Red River system is quite complex and results in the distribution of many soil units. However, the present research results clearly showed that their clay mineralogical composition was compara-ble with one another, demonstrating that the soil form-ing processes have not strongly affected the clay min-eralogical composition of alluvial soils in the Red River system.
The pattern (b) is representative of the profiles from the Thaibinh River and Mekong River systems (TB1 and TB2, and MK1 through MK3). The kaolinite content (around 29%) was as high as that of profiles from the Red River system (pattern (a)), but the mica content (around 31%) was much lower, and a remark-able content of Mx (20 to 24% except TB1) was detected. It is probable that a part of mica has been altered to Mx in these soils (discussed further below). Chlorite and vermiculite were present with an insignif-icant amount. Alluvial soils from the Ma River and

Lam River systems (MA1, and LM1 and LM2) showed the pattern (c) similar to the pattern (b) for soils from the Thaibinh and Mekong River systems but with the lower Mx (8 to 10%) and higher kaolinite (around 36%) contents in profiles from the Lam River system while the lower mica (24%) and higher vermiculite (12%) and kaolinite (34%) contents in a profile from the Ma River system. Some mica in a profile from the Ma River system might have been altered to form some vermic-ulite, and the pattern (c) showed a tendency of transition to the pattern (d).
Alluvial soils from the Trakhuc, Ba and Dongnai River systems were grouped into the same pattern, pattern (d). This pattern showed a very high kaolinite content (63 to 65% for the two formers and 52% for the latter) while the mica content was relatively low (8 to 12% for the two formers and 18% for the latter). The Mx content was nothing for profiles from the Trakhuc and Ba River systems and around 11% for a profile from the Dongnai River system. Chlorite and vermic-ulite were not detected in these soils but a considerable

amount of smectite was observed in a profile from the Ba River system as discussed above.
In the analysis of the distribution pattern of clay

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(a)

(c)

(b)

(d)

FIG. 3. Distribution patterns of clay minerals in the clay fraction of a profile for profiles from (a) Red River system,(b) Thaibinh and Mekong River systems,(c) Ma and Lam River systems, and (d) Trakhuc, Ba and Dongnai River systems. Note: Only upper three horizons of profile
TB 1 were included for plotting, because the lower two horizons are mainly derived from marine sediments.
Abbreviations: Mc, mica; Kt, kaolinite; Mx, mica/vermiculite/smectite•`mica/smectite mixed-layer mineral; Ch, chlorite; Vt, vermiculite;St,
smectite.

minerals in the clay fraction of a profile, we found that
profiles from the same river system showed the same
pattern. Profiles from the same agro-ecological region
generally belonged to the same pattern, like profiles
from the Ma and Lam River systems representing the North of Central region and from the Trakhuc and Ba River systems representing the Coastal Area of Southern Central region. Therefore, it can be strongly suggested that the clay mineralogical composition of alluvial soils from a river system in Vietnam closely related to the mineralogical properties of the sediment sources. It was also recognized that the clay mineralogical composition has not been highly affected by the soil forming pro-cesses which produce different soil units within the area of a river system; alluvial soils from the Red River system is a good example for this statement. As a result, the clay mineralogical composition in a profile was kept constant with depth (Table 2). In the previous paper

(Nguyen and Egashira, 2005), we concluded that the vertical distribution of the clay content in a profile of alluvial soils was controlled by the soil forming pro-cesses; and many profiles manifested the clay loss at surface or in upper horizons. The remarkable similarity in the composition of clay minerals throughout the profile observed here demonstrated that the clay loss was hardly accompanied with the clay mineral decom-position and dissolution processes for the alluvial soils examined in the present study. Therefore, it is possible to state that the clay loss would be principally attributed to the migration and erosion of clay particles from surface or upper horizons.

Regional distribution
Clay mineralogical composition in the clay fraction of alluvial soils was remarkably similar within soils in a river system and was nearly constant throughout the

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1. Red River Delta region

FI G. 4. Regional distribution of mica, kaolinite and Mx contents in the clay fraction of alluvial soils in Vietnam. Abbreviations: Mc, mica; Kt, kaolinite; Mx, mica/vermiculite/smectite•`mica/smectite mixed-layer mineral.

profile in a soil. However, variability in the clay min-eralogical composition was large among the soils from different river systems and agro-ecological regions. As illustrated in fig. 3, the main factors causing differen-tiation in the distribution pattern of clay minerals were the relative contents of mica and kaolinite and the

presence of Mx in some profiles. All of these three minerals occupied a large proportion in the clay fraction and showed the regional variation from the north to the south of Vietnam. It is illustrated in fig. 4.
The mica content in the clay fraction averaged for all profiles of a river system (dashed line) decreased grad-ually from the north to the south, from the Red River Delta region (43-35%) to the North of Central region (30-25%) and to the Coastal Area of Southern Central region (12-8%). Then it increased to the south to 30% in the West of the South region through the East of the South region (18%). In contrast, the average of the kaolinite content in the clay fraction (solid line) increased from the north to the south, from the Red River Delta region (25-30%) to the North of Central region (about 35%) and to the Coastal Area of Southern Central region (65%). It was still high in the East of the South region (52%) but decreased to 30% in the West of the South region. The statistical analysis showed that the mica and kaolinite contents of all profiles had a signif-icant and negative relationship with a correlation coef-fi cient of -0.814** (fig. 5). Mica and kaolinite were

n= 71
r=- 0.814**

FI G. 5. Correlation between mica and kaolinite contents in the clay fraction of alluvial soils in Vietnam.

two predominant clay minerals in alluvial soils of Viet-nam. The content of kaolinite once was increased due to any reasons, the content of mica correspondingly was decreased, and vice verse.
Under the tropical to subtropical monsoon climate characterized by high temperature and very heavy rain-fall, weathering of rocks and minerals strongly takes place and some basic cations and SiO2 are leached out,

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and under such conditions kaolinite is found to be a

predominant clay mineral in soils. In Vietnam, ferralitic
soils thus formed are distributed widely over almost
midland and mountainous areas of the country and
cover the largest area (approximate 20 millions ha) of
upland soils (NISF and DSTPQ, 2002). The high kaolinite content in ferralitic soils has been reported by Nguyen and Tran (1978), Dao (1987) and Ho et al. (2000). The drainage basins of the river systems dis-tributed in the North of Central, the Coastal Area of Southern Central and the East of the South regions are small in area and surrounded by upland soils composed of ferralitic soils. Weathered materials rich in kaolinite

are transported from surrounding upland areas to the basin by water erosion and mixed with river sediments. Because of such formation process, alluvial soils from those river systems had the high kaolinite content in comparison with alluvial soils from the Red River Delta and the West of the South regions.
In the small river systems, the kaolinite content in the clay fraction was found to be related to the area of the river drainage basins. The drainage basin was smallest for the Trakhuc River (5.700 km2) and increased in the order of the Ba, Lam, and Ma Rivers (13.900, 27.200, and 28.400 km2, respectively) (NISF and DSTPQ, 2002). The kaolinite content in the clay fraction of soils decreased in the increasing order of the drainage-basin area of the Trakhuc > Ba > Lam > Ma Rivers. The

Dongnai River has a relatively large drainage basin (44.100 km2) but the sampling site was in the riverhead part where the basin was narrow and has been subjected to fruit cultivation; that would be a reason for the comparatively high kaolinite content of soil from this river system.
Beside the increase of the kaolinite content in the

small river systems, the decrease of the mica content in the clay fraction of soils might be caused by the transformation of mica into Mx under the specific conditions. The formation of Mx is expected to be fairly extensively occurring in tropical soils. Egashira (1988) pointed out that the mixed-layer minerals in the Terrace Soils of Bangladesh were weathering products of mica with the following overall transformation sequence: micamica/vermiculite/smectitekaolinite/smectite

→kaolinite. Such transformation may be occurring in

alluvial soils in Vietnam, leading to the presence of Mx in most samples of the current study. Among the small river systems, the average of the Mx content in the clay fraction (the white bars) was found to be 19% in alluvial soils of the Ma River system and then it decreased to about 9% in the Lam River system and disappeared in both the Trakhuc River and Ba River systems. In the Dongnai River system, Mx occurred again with an amount of about 11%. The variation in the Mx content

might result from the extent or intensity of the trans-formation of mica. Because of the severe weathering conditions (so-called semi-arid region) in alluvial soils from the Coastal Area of Southern Central region, the mica transformation might progress to the end product

of kaolinite via Mx, resulting in the highest kaolinite and lowest mica contents and the absence of Mx in these

soils. But, the factors controlling the transformation process of mica into Mx in alluvial soils from the small river systems is still dubious.
The mineral weathering process in soil is somewhat dependent on soil pH. In soil showing an acidic reaction, the mineral weathering normally takes place stronger because H+ is a small ion and can easily enter the interlayer of 2 : 1 layer silicate minerals to accelerate alteration of them. Mica weathers more easily to ver-miculite, smectite, or Mx under acidic conditions. In the Mekong River system, distribution of alluvial soils is associated with acid sulfate soils, resulting in lowering the pH of soil (Nguyen et al., 2005). This would sup-port the occurrence of Mx in a large amount, as a result of the transformation of mica into Mx, and the mica was transported by the river from the upstream region very far from the Mekong Delta. Distribution of meta-morphic rocks in the sediment source regions of the Mekong River is a reason for the relatively high mica content in alluvial soils from the Mekong River system. Mx was similarly observed in alluvial soils from the Thaibinh River system where alluvial soils are distrib-uted in association with acid sulfate soils. This explains why soils from these two river systems had the same clay mineral composition or distribution pattern of clay minerals in the clay fraction in spite of the very large geographical distance of them.
Different from other river systems, alluvial soils from the Red River system are distributed partially with coexistence of both original sediments and acid sulfate soils and naturally have the slightly alkaline reaction, especially for "young" soils. In addition, exchangeable cations such as Ca2+ and Mg2+ in these soils are high in comparison with alluvial soils from the other river systems (Nguyen et al., 2005), keeping soils resistant to acidification and suppressing the mineral weathering. Under these conditions, transformation of mica may hardly proceed and Mx was not detected in all profiles from the Red River system. The highest mica content in the clay fraction of alluvial soils from the Red River system is an indication of the domination of mica in the sediment source regions of the Red River far from the delta.

Clay mineralogy in reference to soil quality
In general speaking, clay minerals play an important role in soil potential fertility and plant nutrition. How-ever, an individual mineral acts a different role. Mica is generally considered a source of the macronutrient K for plants (Thompson and Ukrainczyk, 2002). Kaolinite is an inactive mineral in terms of a nutrient source or

nutrient retention but it may moderate the influence of more reactive minerals such as smectite by lowering the plastic properties, and water and cation holding capacity of smectitic soils (White and Dixon, 2002). Vermiculite plays important roles in the selective sorption, fixation, and release of both essential macronutrients of NH4+

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TABLE 3. Estimated clay mineral contents in soil of surface horizons averaged for profiles of the respective river systems in Vietnam

Abbreviations: Mc, mica; Kt, kaolinite; Mx, mica/vermiculite/smectite•`mica/smectite mixed-layer mineral; Ch, chlorite; Vt, vermiculite; St, smectite; CL, clay loam; HC, heavy clay; LiC, light clay; SiC, silty clay.

and K+ for plant growth in soil, thereby contributing to
their availability to plants or retention by soil particles,
especially in paddy field where N exists mostly in a
NH4+ form (Malla, 2002). Smectite has high physico-
chemical or surface-chemical activity but may limit the soil fertility because of its fixation of NH4+ and K+; and smectite-dominated soil has sticky and plastic consis-tency when wet, and hard consistency when dry (Reid-Soukup and Ulery, 2002). Chlorite may not act as a nutrient source for plants but play a significant role in soil environment protection. The presence of chlorite may result in the partial neutralization of acidic com-ponents and lowering the concentration of toxic heavy metals such as Fe and Al in soil (Kohut and Warren, 2002). The interstratification of mica, vermiculite and smectite in Mx may lead to decline of their fixation capacity of plant nutrients. The fixed K content of mica is negatively correlated with the proportion of smectite and/or vermiculite layers in Mx (Thompson and Ukrainczyk, 2002). Therefore, one unit layer of Mx may function as plant nutrient sources with much lower rate than one unit layer of individual mica, vermiculite or smectite.

The soil quality in terms of clay mineralogy is the inherent potentiality of soil, which is controlled by the type and amount of clay minerals in soil. Because alluvial soils in Vietnam have been mainly subjected to paddy rice cultivation, the evaluation of inherent potentiality of soil was done for the surface horizon, the root concentrated region. The clay mineral contents in soil were calculated from the clay mineral contents in the clay fraction (according to the data obtained in the present study) and the clay content in soil (according to the data quoted from Nguyen and Egashira (2005)). The clay minerals in soil of the surface horizon were aver-aged for the profiles of the respective river systems; and then they were divided into three levels depending on their abundance, as represented in Table 3. Mica and kaolinite were the two clay minerals occupying the highest proportions in soil but kaolinite is an inactive one, therefore the mica content was considered a main factor controlling the inherent potentiality of soil.

Due to the high mica content in the clay fraction for the Red River system and due to the high clay content for the Mekong River system, alluvial soils from both river systems were found to have the high mica content in soil (>15%) and hence were evaluated to be of the high level of inherent potentiality among the alluvial soils in Vietnam. The more diversification of the clay mineralogical composition for alluvial soils from the Red River system than for alluvial soils from the Mekong River system, along with their medium-texture, suggests the possibility that the inherent potentiality of the former is a little higher than that of the latter. The inherent potentiality is displayed effectively under the favorable weather condition, so that the heavy-texture of alluvial soils from the Mekong River system may have an adverse effect on rice production under the unfavor-able weather condition (Nguyen and Egashira, 2000). Ranging from 5 to 15% of the mica and Mx contents in soil for alluvial soils from the Thaibinh, Ma, Lam, and Dongnai River systems coupled with the texture of light clay, classified them to the intermediate level of inherent potentiality. Of which, an alluvial soil from the Ma River system had some vermiculite, suggesting its some-what higher inherent potentiality. Alluvial soils from the Trakhuc River and Ba River systems characterized by the high kaolinite and low mica contents in soil were evaluated to have the low inherent potentiality. Beside the type and amount of clay minerals in soil, the organic carbon content also contributes to the soil quality. By examining 211 surface layers of alluvial soils throughout the country, Pham et al. (2003) concluded that the organic carbon content was a little higher for alluvial soils from the Mekong River system and a little lower for those from the Red River system. However, the organic carbon content of all samples were evaluated to be of the intermediate level, because the organic carbon content of 95% samples examined fell between a rang of 1.9 and 2.1%. It suggested that the soil quality contributed by the organic carbon content was almost the same for alluvial soils from different river systems. Based on the results of inherent potentiality assess-ment, the appropriate management measures should be

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done for alluvial soils having different levels of inherent potentiality in order to take advantages and to improve limitations of them. For example, soils having high inherent potentiality, with CEC ranging from 10 to
16 cmolc/kg (Nguyen et al., 2005), are considered to
have high plant-nutrient and water retention capacity, and they can be applied a large amount of chemical fertilizers at once. In contrast, for soils having low inherent potentiality, with CEC below 10 cmolc/kg (Nguyen et al., 2005), application of chemical fertilizers should be separated into several times with a small amount in each time, and in combination with large amounts of organic amendments as basic fertilizers.

CONCLUSIONS

Alluvial soils from different river systems/agro-ecological regions in Vietnam had different clay miner-alogical compositions due to differences in the sediment sources. In alluvial soils from the same river system, the clay mineral composition was remarkably similar with one another and has not been affected by the soil forming processes leading to differentiation of soil units in a river system. Mica and kaolinite occupied the largest proportions in the clay fraction and showed the regional variation mainly controlled by the miner-alogical features of the sediment sources. Weathering of mica has taken place under the specific conditions and lead to the formation of mixed-layer minerals.
The soil quality of alluvial soils was assessed from the viewpoint of inherent potentiality based on the type and amount of clay minerals. Alluvial soils from the Red River and Mekong River systems were evaluated to be of the high level of inherent potentiality among the alluvial soils in Vietnam. Those from the Trakhuc River

and Ba River systems were classified to have the low inherent potentiality and those from the remaining river systems were at an intermediate level.

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