

COMPARATIVE MINERALOGY AND CHEMISTRY OF LOWLAND SOILS IN THAILAND

INTRODUCTION

Lowland soils in the Tropics are an important soil resource for food production because they are suitable for lowland agriculture, especially rice growing (Kupkanchanakul *et al.*, 2001; Kyuma, 2001). The large majority of rice is cultivated under submerged conditions in Asia, the word paddy implicitly means aquatic rice. Lowland rice means the soil is under water. Submergence, or waterlogging, is a key factor that brings about many of the distinct properties and processes of paddy soils, some of the characteristics of paddy soil are products of a cyclic process of submergence and drying (or draining) and are not just the result of submergence (Eswaran *et al.*, 2001).

Thailand has a total land area of about 51.4 of million hectares. The topography consists of 25 percent lowlands, 46 percent uplands and 29 percent highlands (>500 m MSL) with slopes being higher than 35 percent (Changprai, 1987). The total area for rice cultivation is estimated to be approximately 10 million hectares with lowland rice soils comprising 9 million hectares (Kupkanchanakul *et al.*, 2001). Rice is the most important food crop in Thailand and clearly it is dominantly grown on lowland soils.

Paddy soils used for the intensive cultivation of rice in Thailand vary considerably in mineralogy which is a component of soil composition that is important to plant growth (Yoothong *et al.*, 1997; Kyuma, 2004). The types of clay minerals and their proportions significantly control physical and chemical properties of soils (Yoothong *et al.*, 1997).

Obviously, climate can have a very significant effect on the clay composition of a soil. Many tropical soils in equilibrium with their environment contain kaolinite

as the principal component of the clay fraction (Kanket *et al.*, 2005; Trakoonyingcharoen *et al.*, 2006). It is often said that low activity, variable charge clays dominate in tropical soils but this does not apply to paddy or lowland soils. Typically soils in poorly drained conditions where the basic cations, calcium, magnesium, potassium and sodium, as well as silicon, are not rapidly removed, contain clays dominated by 2:1 type layer silicates (Borchardt, 1989; Brady and Weil, 2002). Smectite forms under brackish conditions because of a high pH and a soil solution enriched in dissolved silicon, magnesium and calcium (Dabbakula *et al.*, 1992). Consequently lowland soils have various clay minerals both in kind and quantity. A better understanding of clay minerals in lowland soils may lead to the improvement of lowland crop production through more effective soil management.

This research investigates variations in mineralogy in relation to other properties of lowland soils in Thailand.

Hypothesis

Due to the various types of development of lowland soils, the minerals in lowland soils vary both in kinds and properties which will affect soil use and management.

Objectives

The objectives in this research are:

1. To determine morphological, chemical, physical, mineralogical and micromorphological properties of lowland soils.
2. To identify pedological features relating to the mineralogy and environment of these soils.

LITERATURE REVIEW

Nature of Lowland Soils

Lowlands naturally form in places on the landscape where surface water periodically collects for some time and/or where groundwater discharges (Tiner, 1999). Common lowlands include relatively flat low-lying areas (floodplains) along major waterbodies (e.g. oceans, rivers, lake and estuaries) usually with fluctuating water levels (Tiner, 1999; Zhang and Gong, 2003). Lowland soil may be defined as soil occurring where drainage is poor and where part or all of the soil profile is waterlogged. The water table is at, near or above, the soil surface for long enough to create waterlogged soil (Cowardin *et al.*, 1979; National Research Council, 1995; Zhang and Gong, 2003).

Soil Forming Factors of Lowland Soils

Formation and properties of the soil are the result of pedogenic processes induced by five key factors namely parent material, climate, organisms, topography and time (Jenny, 1941). These factors influence the physical and chemical properties, clay mineralogy, morphology and development of the soil. Development of lowland soils depends directly on topographic position, parent material and periodic saturation (Markewich and Pavich, 1991; Tiner, 1999).

Kheoruenromne and Suddhiprakarn (1984) found that the type of parent material and variation in landform were major factors causing differences of soils in the Mae Klong Basin. Time and climate may be regarded as constant factors and have only very little influence on the variation in soils in the Basin.

For lowland soils of Northeastern and Eastern United States, Ultisols, Spodosols and Alfisols are the dominant soil orders (Ciolkosz *et al.*, 1989; Markewich *et al.*, 1989). In this region, lowland soils have developed along two different pathways. One is dominated by the dissolution and movement of oxyhydroxides and

the accumulation of organic matter and the other by the accumulation of clays and oxyhydroxides. The first pathway has resulted in the formation of Spodosols, the second, in the development of Ultisols. No clearly distinguishable age trends have been identified in the Spodosols, but the properties of Ultisols have evolved through time (Markewich *et al.*, 1989). Alfisols are less common but are present on the younger terraces of rivers as well as coastal plains. Markewich and Pavich (1991) found that Alfisols are not extensive on the coastal plain of the Eastern United States except on younger low-altitude fluvial sediments north of 36°N. Alfisols are uncommon on the coastal plain because they are probably part of a genetic sequence leading to Ultisols due to intense leaching (Ciolkosz *et al.*, 1989).

Topography is the major factor, when the parent materials are indifferent. For lowland soils developed from alluvial deposits in India, Entisols occur in the floodplain, whereas Alfisols are common on high terraces (Sidhu and Gilkes, 1977). In Northern Taiwan, Alfisols occur on terraces that are used intensively for lowland rice culture includes the Aqualfs (Hseu and Chen, 1996). Similarly, the lowland rice soils on floodplains in Bangladesh are classified as Inceptisols, whereas Alfisols have developed on terraces (Karim, 1984; Egashira *et al.*, 2004). In summary, more highly developed lowland soils occupy relatively higher positions than poorly developed lowland soils (Egashira *et al.*, 2004).

Pedogenic Processes in Lowland Soils

The dominant lowland soil processes are oxidation-reduction, gleization, organic matter accumulation, clay illuviation, clay formation and transformation and ferrolysis (Schlesinger, 1991; Hobson and Dahlgren, 1998).

1. Oxidation-Reduction

Oxidation-reduction processes are the most important chemical reactions in waterlogged soils. These reactions control soil colours, organic matter contents and the amounts of oxygen, nitrate, iron, manganese and sulfate in the water (McBride, 1994).

2. Gleization

The reduction of iron under anaerobic soil conditions, with the production of bluish to greenish gray matrix colours, with or without yellowish brown, brown, and black mottles, and ferric and manganiferous concretions (Buol *et al.*, 2003).

3. Organic Matter Accumulation

The seasonally anaerobic conditions of lowlands inhibit organic matter decomposition. These environmental conditions result in relatively slow decomposition rates and the accumulation of organic matter in the surface layers (Schlesinger, 1991).

4. Clay Illuviation

Clay illuviation is the dominant process in lowland Ultisols and Alfisols. Illuviation was not so influential in translocating clays and other materials in lowland Mollisols and Inceptisols (Thompson and Bell, 1996; Bahmaniar and Mirnia, 2002). Clay illuviation can induce profile differentiation in lowland soils (Ducloux *et al.*, 1998, Zhang and Gong, 2003). The mobility of the fine fraction can be related to drainage conditions (Boixadera *et al.*, 2003). Clay illuviation has been described for climates where the soils become thoroughly or partially dry at some season. Translocated clay forms coatings of oriented clay particles, and an argillic horizon develops at several decimeters below the soil surface, due to the fluctuation of groundwater (Ducloux *et al.*, 1998; Pimentel, 2002). Periodical submergence also leads to fine silt and clay translocation from top to deeper soil layers

(Kanchanaprasert, 1986; Gama-Castro *et al.*, 2000). Clay illuviation may be very quick due to the turbulent flow that occurs as bypass flow along large pores during the floods (Boixadera *et al.*, 2003). Clay illuviation in lowland soils can give rise to clay coatings, which are different in appearance from those developed in upland soils (Fedoroff, 1973; Bullock and Thompson, 1985). Particularly in lowland soils, clay coatings are grayer and have lower birefringence (Bullock and Thompson, 1985; Elless and Rabenhorst, 1994).

Cutans are common fabric features in soil and are the foci of chemical and biological reactions. In general, the cutans will experience greater fluctuations in wet/dry and redox conditions than matrix soil (McBurnett and Franzmeier, 1997; Venugopal, 1998). The influence of cutans on potassium forms and their transformations was investigated for lowland soils in Western Australia. Cutans and matrix soil had a similar clay minerals, but were different in some chemical properties. The mean value of K concentration in cutans is greater than in matrix, and the K concentration decreases with distance from cutan to matrix because cutans are in closer contact with K in the soil solution compared to matrix soil where water movement is greatly restricted (Liu *et al.*, 2002).

Clay Formation and Transformation

The formation of silicate clays occurs by alteration of existing primary or secondary minerals or by precipitation from soil solution due to over saturation. As the weathering intensity increases in a leaching environment, 2:1 layer silicates are progressively altered to 1:1 layer silicates and finally to oxides of iron and aluminum (Bohn *et al.*, 1985; Brady and Weil, 2002). For example, lowland soils on terraces in Southwestern Oregon appear to have seasonal wetting and drying that have led to the breakdown of clays in the upper part of the profile and formation of gibbsite in the subsoil (Bockheim *et al.*, 1996). The type of clay minerals produced is dependent upon the geologic nature of the parent material (Bohn *et al.*, 1985; Evans, 1992; Buol *et al.*, 2003) as well as climate, biota, relief and time (Jenny, 1941). The products of mineral weathering consist of secondary clay minerals, bases (Ca, Mg, K and Na),

metal cations (Fe and Mn) and aqueous silica or silicic acid (H_4SiO_4) (Brady and Weil, 2002).

Bahmaniar and Mirnia (2002) found that the dominant clay mineral of lowland soil in Iran is illite. They concluded that the amount of illite decreased and montmorillonite increased when the soils have been under long and continuous rice cultivation because of transformation of clay mineral. Similarly, Naskręt and Długosz (1996) reported that illite transforms to smectite via mixed-layer illite/smectite in lowland soils in Poland. When subjected to wetting and drying, illite may begin to neoform smectite, through intermediate illite-smectite mixed-layer clays (Madhavaraju *et al.*, 2002). Bonifacio *et al.* (1997) explained the presence of smectite in poorly drained soil as being due to precipitation from soil solution or transformation from a precursor mineral after its translocation through the profile. Once in the deeper horizons with reduced drainage, low charge vermiculite may transform directly into smectite or may dissolve. Golesefidi *et al.* (2001) found that clay minerals of lowland soils in Iran have high amounts of smectite. Galán *et al.* (2002) reported that at progressively greater depths in soils in the Mexican Basin, where there is decreasing permeability and flow, and higher alkalinity, kaolinite was transformed to kaolinite/smectite. The type of layer silicate formed clearly depends on environmental conditions, predominantly on soil drainage (Ducloux *et al.*, 1976; Madhavaraju *et al.*, 2002).

Ferrolysis

The ferrolysis process occurs under a tropical climate where dry and wet periods alternate (Ducloux *et al.*, 1998). It is the process, which decomposes clay and causes interlayering in clay minerals in acid, seasonally wet soils, under the influence of the periodic reduction and oxidation of iron (Kyuma, 2004). In the wet season, reduction of ferric oxides produces dissolved ferrous iron, which displaces and mobilizes exchangeable bases. The bases (and dissolved ferrous iron) are partially removed by leaching. In the dry season, oxidation of exchangeable ferrous iron produces ferric oxide and hydrogen ion and takes the place of adsorbed ferric to the

extent that formerly adsorbed base cations have been leached and then the unstable hydrogen ion dissolves the clay to provide exchangeable Al. During a later waterlogging period, ferric iron is reduced to ferrous iron which can displace adsorbed Al^{3+} and Al hydroxide can form. Al-hydroxy interlayers between plates of 2:1 clay mineral together with trapped ferrous iron and other cations, further decreases cation exchange capacity of clay (Brinkman, 1970). The effects of ferrolysis include the release of bases, metal cations and silicic acid into soil solution for plant utilization, leaching of soluble constituents downward from the reduced soil and upon drying and oxidation of the soil creating redoximorphic features or redox concentrations (Soil Survey Staff, 1999). Ferrolysis causes coarsening of texture, because it destroys clays during the reduction and oxidation cycle (Brinkman, 1970). In conclusion, the low pH associated with oxidation of iron creates a harsh weathering environment (Brinkman, 1970).

Classification of Lowland Soils

Lowland soils exhibit various states of development (Markewich and Pavich, 1991). For example, some lowland soils in Eastern New South Wales have a progressive increase in soil development from low alluvial benches to floodplains to terraces (Walker and Coventry, 1976). Similarly, lowland soils in Thailand have variable development and have aquic condition. Lowland soils in Thailand are classified into Entisols, Histosols, Spodosols, Inceptisols, Mollisols, Vertisols, Alfisols and Ultisols (Kheoruenromne, 1990). Verapattananirund (1986) reported that most of the rice soils in Thailand are Ultisols, Alfisols, Vertisols and Inceptisols. Small areas of Entisols and Mollisols are also found in the lowlands.

Characteristics of Lowland Soils

1. Morphology

Seasonal flooding and draining cycles control saturation and reduction conditions in lowland soils but reduction does not necessarily correspond to

periods of saturation (Singleton, 1991; Hseu and Chen, 1996). Previous studies have indicated that reducing conditions in poorly drained soils result in low chroma colours and oxidizing conditions are responsible for concentrations of brighter colours in better drained soils (Brinkman, 1977; Evans and Franzmeier, 1988; Singleton, 1991). Alternate wetting and drying leads to the development of other unique soil properties. The degree of flooding and/or soil saturation affects the amount of leaching, reduction-oxidation and the accumulation of precipitates of iron (Richardson and Daniels, 1993). Soils experiencing saturation and reduction display morphological evidence such as redoximorphic features (Bushnell, 1945; Kanno, 1956; Tiner, 1999).

2. Soil Colour

The waterlogged soils are usually bluish-gray, greenish-gray or even neutral gray in colour (Vepraskas *et al.*, 1994). Many of the characteristics of lowland soils are due to waterlogging, reduction of iron and iron accumulation (Stolt *et al.*, 1994; Thompson and Bell, 1996). Under anaerobic condition, bacteria obtain their oxygen from the oxygen-containing compounds.

Soil colours are commonly associated with the presence or absence of iron (Schwertmann, 1993; Osher and Buol, 1998). Fialips *et al.* (2002) found that soil colour depends on a ratio of ferrous iron to total Fe. After re-oxidation, almost all ferrous iron was converted back to ferric iron, but the colour of the re-oxidized sample differed from that of the original (unaltered) clay by various degrees. The obvious colour difference between unaltered and re-oxidized samples suggested a change in crystal structure during reduction, and indicated the irreversibility of the process (Fialips *et al.*, 2002). Gleying occurs when lowland soils develop reducing conditions, involving the reduction and mobilization of iron, manganese and other elements. Whereas, the oxidized zones have a brighter, reddish-brown colour, related to the accumulation of iron compounds (Singleton, 1991; Vepraskas, 1992).

Many workers (Daniels *et al.*, 1973; Kheoruenromne, 1990; Darmody *et al.*, 2000; Schafer and Kirchof, 2000; Liu *et al.*, 2002) have studied soil colours in lowland soils. They found that low chroma of ≤ 2 colours is induced by a long saturation period and reduction cycle. However, the presence of gray soil colours is not a conclusive evidence of saturated conditions and gives no indication of the duration of saturation (Singleton, 1991).

3. Redoximorphic Features

Redoximorphic features consist of reduced matrixes, redox depletions and redox concentrations (Vepraskas, 1992; Tucker *et al.*, 1994). They are formed by the processes of reduction, translocation and oxidation of Fe and Mn oxides. These features form in soils when iron or manganese oxides are reduced, dissolved and moved through the soil to accumulate in other places. Their formation occurs in the portions of the soil that become anaerobic because microbes are respiring and utilizing oxygen with iron and manganese as their electron acceptors. The reduction generally occurs at microsites in the soil where the reduction processes are most intense. The microsite will generally become a gray colour following reduction and diffusion of iron out of the microsite. Iron oxidizes at points where oxygen penetrates the soil. The interpretation of redoximorphic features is straightforward: redox depletions (gray colours) show where reduction has occurred via bacterial respiration, while redox concentrations (red or yellow colours) show where oxidation has occurred (Vepraskas, 2001). Vepraskas and Guertal (1992) reported that, as soils were saturated and reduced for longer periods, the amount of Fe depletion increased while the amount of Fe concentration decreased. The pattern of the redoximorphic features may reveal information on variable saturation within the soil profile (Tucker *et al.*, 1994; Soil Survey Staff, 1999; Buol *et al.*, 2003).

Reduced Matrixes: When the reduced compounds are completely removed from the soil, the soil usually takes on a grayish colour (Tiner, 1999). The soil matrix has a low chroma *in situ* because of the presence of ferrous iron, but undergoes a change in hue or chroma within 30 minutes after the soil material has been exposed to

air. The gray colour reflects the natural colour of soils particles (Elless and Rabenhorst, 1994; Vepraskas, 1996; Tiner, 1999).

Redox Depletions: Depletions are zones of low chroma (2 or less) where either Fe-Mn oxides alone or both Fe-Mn oxides and clay have been stripped out, including:

1. Iron depletions, i.e., zones that contain low amounts of Fe and Mn oxides but have a clay content similar to that of the adjacent matrix (often referred to as albans or neoalbans); and

2. Clay depletions, i.e., zones that contain low amounts of Fe, Mn and clay (often referred to as silt coatings or skeletans) (Elless and Rabenhorst, 1994; Vepraskas, 1996).

Redox Concentrations: Redox concentrations are zones of apparent concentration of Fe/Mn oxides (Stolt *et al.*, 1994; Tucker, 1994; Rabenhorst and Parikh, 2000). The redox concentrations of high chroma Fe mottles and neutral Mn stains, concretions and masses are generally due to the oxidation of Fe and Mn (Hobson and Dahlgren, 1998). There are three types of redox concentrations: nodules and concretions (hard bodies), masses (soft bodies), pore linings (coatings of Fe or Mn along cracks and root channels) (McDonald *et al.*, 1990; Stolt *et al.*, 1994).

Mottles are essentially soil matrix with spots, blotches or streaks of subdominant colours that are different from the matrix colour and also different from the colour of ped surface (McDonald *et al.*, 1990). Mottles are commonly continuous with soil matrix in respect of fabric and strength (Singh and Gilkes, 1996).

In Northwestern Wisconsin, the development of maximum iron mottling in somewhat poorly drained environments was compared to well-drained environments by Richardson and Hole (1979). The iron in well drained soils was concentrated in the clay fraction and was more crystalline whereas in poorly drained soils iron was

concentrated in the fine sand fraction and was dominantly amorphous or poorly crystalline (Singh, 1991; Cravero *et al.*, 1997). Singh and Gilkes (1996) reported that the most significant difference in mineralogy for lowland soils of Southwestern Australia between mottles and their associated soil matrix was the presence of higher amounts of goethite in most mottles and of hematite in a few of them. These iron oxides give rise to the distinct yellowish orange to reddish brown colours of mottles. McDaniel and Buol (1991) reported that in North Carolina manganese stains, concentrations and masses are distributed deeper within the soil profiles than Fe mottles as Mn^{2+} is more mobile in the soil solution than Fe^{2+} . These redox features are diagnostic for identifying lowland soils (Collins and Buol, 1970; Vepraskas, 1996).

Redox concentrations and redox depletions can be used as indicators of poorly drained soils and degree of wetness of the soil (Ruhe *et al.*, 1955; Elless and Rabenhorst, 1994; Vepraskas, 1996; Kraus, 1997). For example, reddish colours on ped exteriors and gray colours in the ped interior suggest extended wetness in the interior and better drained ped surface (Richardson and Daniels, 1993). A saturated soil layer above a restrictive layer may have redox depletions around large pores (macropores). Reddish to orangish colours (redox concentrations) in the ped interiors may indicate water movement along the pores leading to reduction along the pores (Vepraskas, 1996).

Mineralogical Properties

1. Clay Minerals

Lowland soils exhibit various levels of development which are indicated by various types and different quantities of clay minerals. Clay minerals are an indicator of the degree of soil development.

The minerals present in young alluvium-derived soils are generally related closely to the composition of source parent rocks. If the source area contributing sediments is from rocks exhibiting various degrees of metamorphism, the young

lowland soils have a wide range of mineralogical composition (Sidhu and Gilkes, 1977). For young lowland rice soils in Thailand, soil properties are much influenced by their parent materials. Soils are dominated by different types of clay minerals (Kanchanaprasert, 1986; Chainaronk, 2001). The parent materials of some young lowland rice soils in Philippines and Indonesia are mafic rocks, therefore the dominant minerals of lowland rice Vertisols and Inceptisols are smectite and kaolinite. However, illite is the minor mineral only of lowland rice Inceptisols (Schafer and Kirchhof, 2000).

Cravero *et al.* (1997) studied lowland soils in the Neuquen Basin of Argentina. They found that kaolinite in these soils comes from a weathered area; it was then transported and deposited in a fluvial environment, whereas illite/smectite in this area was formed by *in situ* illite degradation. Viani *et al.* (1983) studied lowland soils in the central basin of Saudi Arabia. They suggested that kaolinite might be transported from soils situated in the upland areas. In the case of Laos, kaolinite is the predominant clay minerals in lowland rice soils because these soils are derived from local kaolinitic sandstone (Egashira *et al.*, 1997).

Smectite is the dominant clay mineral in the Calatayud Basin (NE Spain) because this area has moderately concentrated soil solutions which have rather high pH and high soluble silica activity. This condition favours formation and preservation of smectite (Tardy *et al.*, 1987; Mayayo *et al.*, 2000). The dominant clay minerals in central basin soils, Saudi Arabia, are smectite and illite. Smectite in these soils may have originated from (i) transportation from highland areas, (ii) alteration of primary layer silicates, and (iii) neoformation via precipitation from an aqueous phase (Viani *et al.*, 1983). In poorly drained saline soils, relatively large K concentrations in soil solution would be effective in keeping mica sheets closed, therefore illite is the dominant clay mineral in these soils (Fanning and Keramidas, 1977). In Iran, the dominant mineral in lowland rice Mollisols and Inceptisols is smectite, whereas the dominant clay mineral of lowland non-paddy soils is illite (Bahmaniar and Mirnia, 2002).

Boonsompoppunth (1984) studied lowland soils on low terraces in Nakhon Ratchasima Province, Thailand. He found that smectite is generally appears to be dominant. Kheornenromne and Suddhiprakarn (1984) investigated major Alfisols in the Mae Klong basin, Western Thailand. They found that all of these soils have a “mixed” mineralogy class. Similar to lowland Alfisols in the Punjab region, India, illite dominates followed by smectite and other clay minerals are kaolinite, vermiculite and chlorite (Sharma *et al.*, 1998). Clearly, these soils have been developed by weathering to some extent. The dominant mineral of lowland Alfisols soils in Punjab region, India, is illite followed by smectite. Other clay minerals present are kaolinite, vermiculite and chlorite (Sharma *et al.*, 1998).

2. Iron Oxides

Generally, iron contents of lowland soil are not high and the low content of iron oxides in these soils detected by XRD may be because some iron is present as amorphous oxides or hydroxides (Cravero, *et al.*, 1997). Different forms of iron as determined by extraction agents are thought to correspond with different soil environments and may also indicate relative soil ages (Arduino, 1984; Schwertmann, 1985; Jacob *et al.*, 1990). McFadden and Hendricks (1985) found that the crystallinity of pedogenic Fe oxides increased with soil age in soils formed on lowland areas in southern California. For paddy soils, the change of soil moisture regime from that in the original soils is very critical for the transformation of iron and manganese minerals (Yu, 1985).

The frequency of soil reduction may affect the crystal size of iron oxide minerals (Singh, 1991; Cravero *et al.*, 1997). For example, lepidocrocite formed in paddy soils by oxidization during drainage may dissolve by reduction during flooding, as evidenced by the observation that reddish iron oxide coatings appears only when paddy soils are more oxidized. Therefore, much of the lepidocrocite in the paddy soils may not grow into coarse crystals because the paddy soil is more intensely reduced seasonally than soils in drier areas (Wang *et al.*, 1993).

Some iron oxide minerals can be more resistant to reduction than others (Stolt *et al.*, 1994). Goethite is the most stable form under hydromorphic conditions (Brown *et al.*, 2004). The most common iron oxide minerals in lowland soils and sediments, which experience seasonally reduced and oxidized conditions, are goethite, ferrihydrite and lepidocrocite (Birnie and Paterson, 1991; Wang *et al.*, 1993). These minerals are thus indicative of soil drainage status. Laboratory synthesis experiments have shown that the formation of goethite from ferrous solutions is favoured at low rates of aeration and/or higher ferrous concentrations whereas lepidocrocite formation requires higher aeration rates and/or lower ferrous concentrations. At a very high aeration rate and a higher pH (pH 7.0) only ferrihydrite formed (Taylor and Schwertmann, 1978; Birnie and Paterson, 1991).

Macro- and Micromorphological Features Indicating an Aquic Condition

The water regime can induce important soil characteristics. Commonly, lowland soils have an aquic condition. Soils with aquic moisture regimes are those that are saturated for periods of time long enough for dissolved oxygen to be removed from the water by microbial respiration (Bullock and Thompson, 1985; Boixadera *et al.*, 2003). Aquic moisture regimes may occur in soils of any order (Soil Survey Staff, 1999). Changes in the frequency, duration and depth of soil saturation produce soil characteristics that affect lowland soil morphology (Tiner, 1999). Some macro- and micromorphological features can be indicative of aquic moisture regimes (Veneman *et al.*, 1976; Bullock and Thompson, 1985) as follows:

a) Saturation for only short periods: Periods of saturation not exceeding one day were sufficient to cause reduction of manganese but not iron (Veneman *et al.*, 1976). In this condition, manganese would be more mobile than iron (Acquaye *et al.*, 1992). The main morphological features associated with this regime were ped mangans and manganese nodules. High chroma ped interiors and some black manganese coating on ped surface could be present (Richardson and Daniel, 1993).

b) Saturation for periods of several days: Soil saturated for periods of several days and also had a high matric potential for several months produced some chroma 2 inside the ped, few black manganese coatings. Iron oxide nodules, ferrans and neoferrans were common (Bullock and Thompson, 1985). There were few

manganese segregations and it was assumed that manganese had been leached from the profile (Tiner, 1999; Boixadera *et al.*, 2003).

c) Saturation for periods of several months: Soil saturated continuously for several months created chroma 1 ped interiors. Low chroma zones could also occur along pore wall. Iron was reduced adjacent to the large pores and migrated towards more aerated ped interiors where it became oxidised (Elless and Robenhorst, 1994; Boixadera *et al.*, 2003).

MATERIALS AND METHODS

Soil Samples Collection

Soil samples are subdivided into sets with respect to type of samples and sample collection. One is samples from an exposed soil profile. The other type of sampling was by augering.

For soil profiles, seventeen soil profiles (Figure 1) were sampled and can be divided into four groups of soils.

1. The Northeastern part of Thailand: six soil profiles, namely Roi Et series (Re), Tha Tum series (Tt), Phimai series (Pm1 and Pm2), Kula Ronghai seires (Ki) and Udon series (Ud) (Figure 2).

2. The Northern part of Thailand: five soil profiles, namely Mae Sai series (Ms), Hang Dong series (Hd), San Sai series (Sai), Chiang Rai series (Cr) and Chum Saeng series (Cs) (Figure 3).

3. The Eastern part of Thailand: two soil profiles, namely Chon Buri series (Cb) and Klaeng series (Kl) (Figure 4).

4. The Central Plain of Thailand: four soil profiles, namely Lop Buri series (Lb), Tha Rua series (Tr), Khok Krathium series (Kk) and Bang Phae series (Bph) (Figure 5).

For samples obtained by augering, the samples represent three depth intervals, the first part is the topsoil (A horizon usually about 0-10 cm). The second part is from base of topsoil to 60 cm and the last one is 60-100 cm. Sample information, soil classification and parent materials are given in Appendix Table 1.

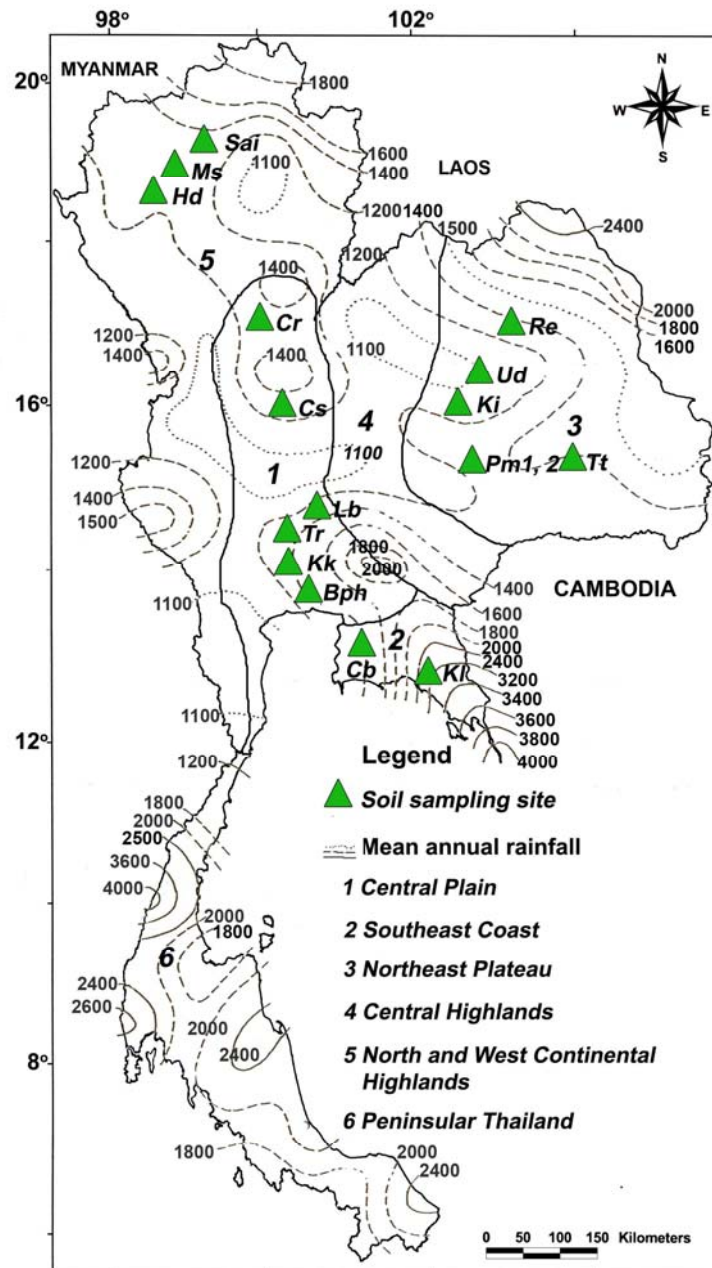


Figure 1 Soil sampling sites of the study.

(The key to the abbreviated soil series names is in Appendix Table 1).

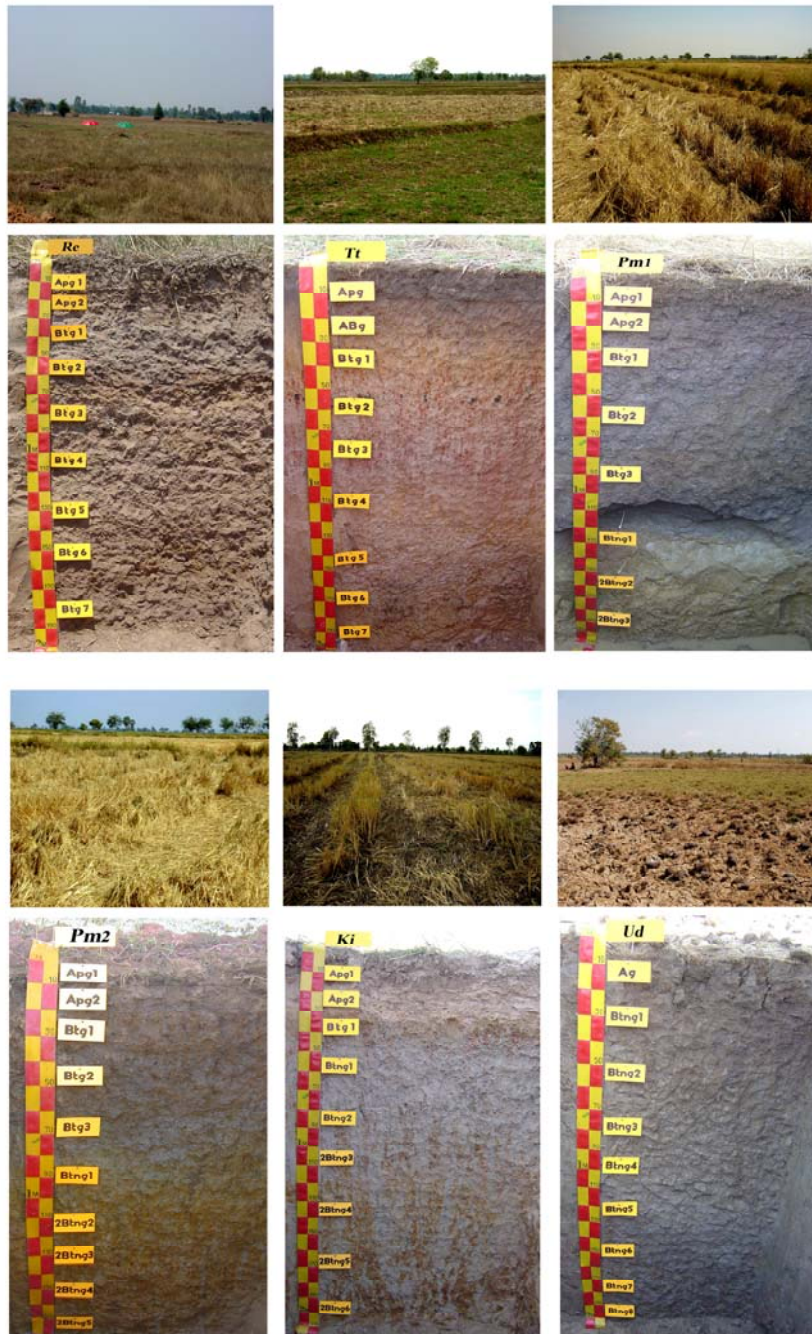


Figure 2 Representative paddy soil profiles in Northeastern Thailand.

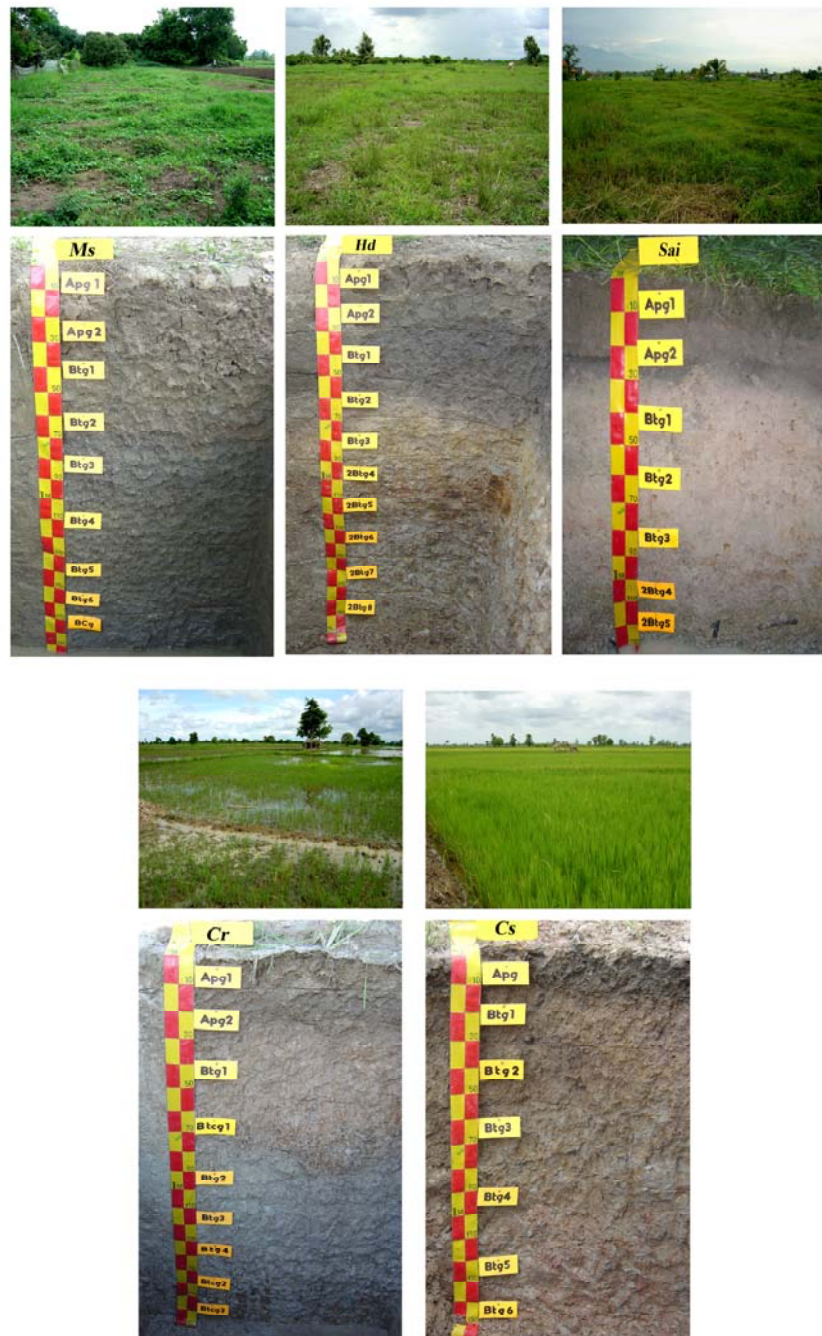


Figure 3 Representative paddy soil profiles in Northern Thailand.

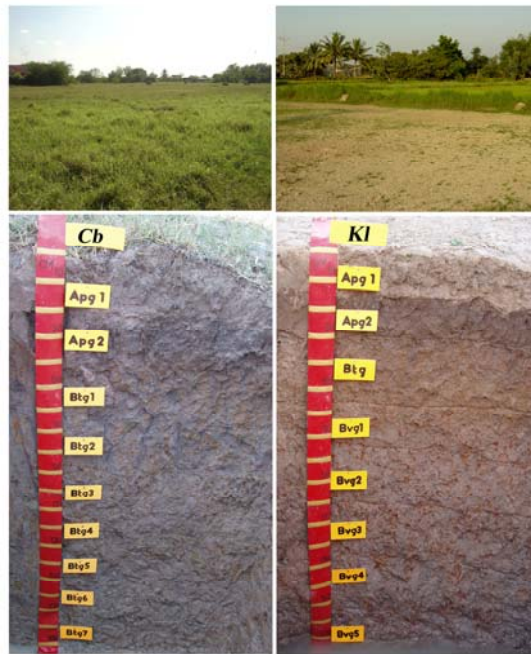


Figure 4 Representative paddy soil profiles in Eastern Thailand.

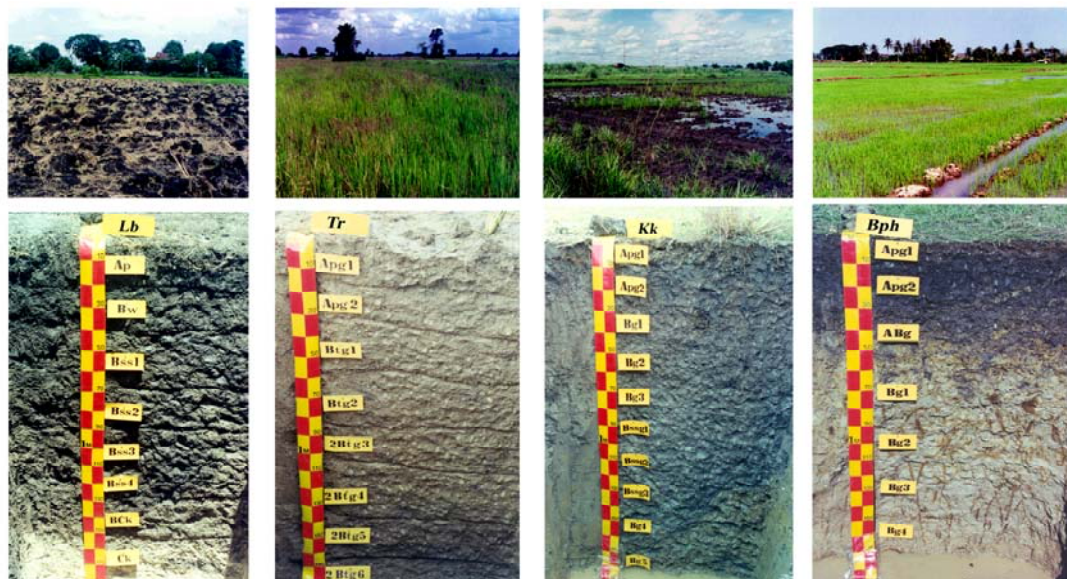


Figure 5 Representative paddy soil profiles in the Central Plain of Thailand.

Geological Setting

Thailand is located in Southeast Asia between latitudes 5°37' N and 20°27'N and longitudes 97°22'E and 105°37'E and covers an area of 518,000 km². It is bounded to the west by Myanmar, to the north by Myanmar and Laos, to the east by Laos and Kampuchea, and to the south by Malaysia.

The soils examined in this research have formed on alluvial and colluvial deposits derived from a diverse suite of rock types. The geologic setting of Thailand reflects a long and complex evolution, with regional differences in geological history. Physiographically, the country can be divided into six regions; 1) Central Plain 2) Southeast Coast 3) Northeast Plateau 4) Central Highlands 5) North and West Continental Highlands and 6) Peninsular Thailand (Figure 1).

The Northeast Plateau is generally underlain by extensive Mesozoic rocks. The Plateau is rimmed by an escarpment of mostly steeply dipping sediments which form *cuestas* rising from 600-1000 m above sea level on its western and southern margins. It has a “saucepan morphology”, covering an area of about 170,000 km². All of the sampled soils in this region developed on the rocks of Khorat Group that comprises continental red and gray sandstone, siltstone and shale with some paralic and thick rock salt layers and gypsum beds with total thickness of more than 600 meters, ranging in age from the Late Triassic to the Cretaceous period (Ward and Bunnag, 1964). The Roi Et (Re), Kula Ronghai (Ki) and Udon (Ud) series were developed on materials derived from Pre-Himalayan Megasequences including the Maha Sarakham and Phu Tok Formations (Late Cretaceous). Phimai (Pm1 and Pm2) series were developed on Quaternary alluvium, whereas the Tha Tum (Tt) series developed on the Khok Kruat and Phu Phan Formations (Middle Cretaceous) (Charusiri *et al.*, 2006).

Northern Thailand is mainly in the North and West Continental Highlands dominated by Paleozoic rocks, including low to high grade metamorphic rocks (Dheeradilok *et al.*, 1992), with small, deformed outliers of Mesozoic strata, and

occasional small Tertiary basins. The soil parent materials in this region are highly variable. Parent materials of the paddy soils sampled are generally mixed alluvium from various depositional episodes and are derived from these rocks (Dheeradilok *et al.*, 1992).

The Eastern region of Thailand has diverse rocks ranging from the Precambrian igneous rocks to Quaternary sediments (Bunopas, 1983; Dheeradilok *et al.*, 1992). Granites occupy a relatively large area in this region and have exerted a strong influence on the parent material of the Chon Buri (Cb) and Klaeng (Kl) series.

The Central Plain of Thailand is occupied by the Chao Phraya, Bang Pakong and Mae Khlong rivers and is a broad, flat, low-lying area of Thailand (Nutalaya and Rau, 1984; Dheeradilok, 1986; Sinsakul, 2000). The Lop Buri (Lb) series occur on limestone of the Upper Paleozoic Saraburi Group whereas the Tha Rua (Tr), Khok Krathium (Kk) and Bang Phae (Bph) series developed on Quaternary sediments of the Lower Central Plain that represent a complex sequence of alluvial, fluvial and deltaic sediments (Dheeradilok *et al.*, 1992; Sinsakul, 2000).

Methods

Pedon analysis in a soil pit was carried out at each site including detailed profile description and sampling of soil from each genetic horizon by standard field study methods (Soil Survey Division Staff, 1993; Kheoruenromne, 1999).

Soil samples were collected for various laboratory analyses as follows: (i) Bulk soil samples will be collected for physical, chemical and mineralogical analyses. (ii) Undisturbed soil samples were collected by coring and in a Kubeina box for physical and micromorphological analyses, respectively.

Bulk samples were aired-dried, gently crushed and then passed through a 2 mm sieve. The resultant <2 mm samples were used for general laboratory analysis. The clod samples were used for bulk density measurement. A summary of analytical methods used in this study is shown in Table 1 and the associated details of each method are summarized in Appendix.

Table 1 Research methods.

Analysis	Method	Reference
<i>Physical analysis</i>		
Particle size analysis	Pipette method	Kilmer and Alexander, 1949
Bulk density	Clod method	Blake and Hartge, 1986
<i>Chemical analysis</i>		
Soil reaction (pH)	1:1 soil:solution in H ₂ O and 1 N KCl by pH meter	National Soil Survey Center, 1996
Organic carbon (OC)	Walkley and Black method	Nelson and Sommers, 1982
Organic matter (OM)	Organic carbon concentration x 1.724	
Total N	Kjeldahl method	Bremner, 1996
Extractable bases Ca ²⁺ , Mg ²⁺ , K ⁺ and Na ⁺	1 N NH ₄ OAc at pH 7 and measured by atomic absorption spectrophotometer and flame emission spectrophotometer	Thomas, 1987a

Table 1 (Continued).

Analysis	Method	Reference
<i>Chemical analysis</i>		
Extractable acidity (EA)	Barium chloride-triethanolamine pH 8.2 extraction	Thomas, 1987b
Available P	Bray II	Bray and Kurtz, 1945
Cation exchange capacity (CEC)		
-CEC by NH ₄ OAc	Saturating the exchange site and displacing by 1 N NH ₄ OAc pH 7.0	Chapman, 1965
-By summation	Sum of cations (CEC-8.2) (Sum bases+EA)	National Soil Survey Center, 1996
Base saturation percentage (For classification)	The sum of bases extracted by NH ₄ OAc pH 7.0 divided by CEC-7 and multiplied by 100	National Soil Survey Center, 1996
	The sum of bases extracted by NH ₄ OAc pH 7.0 divided by the CEC-8.2 and multiplied by 100	National Soil Survey Center, 1996
Extractable Fe, Al, Mn and trace elements	Extraction in dithionite-citrate-bicarbonate (DCB) and measured by ICP-MS	Mehra and Jackson, 1960
	Extraction in 0.2 M ammonium oxalate (pH 3.0) and measured by ICP-MS	McKeague and Day, 1966
	Extraction in 0.1 M sodium pyrophosphate (pH 10.0) and measured by ICP-MS	McKeague, 1967
Total analysis of major elements	X-ray fluorescence spectrophotometry (XRF) using pressed powder pellets	Jones, 1982
Trace element content	Aqua regia digestion and measured by ICP-MS using a Perkin Elmer Elan 6000	Lynch, 1999
<i>Micromorphological analysis</i>		
Micromorphological feature	Polarizing microscope technique	Bullock <i>et al.</i> , 1985
Chemical composition of the micromorphological features	Scanning electron microscopy (SEM) on JEOL 6400 SEM	Stoops, 1970

Table 1 (Continued).

Analysis	Method	Reference
<i>Mineralogical analysis</i>		
Mineralogical characterization	X-ray diffraction (XRD) analysis	Brown and Brindley, 1980
Chemical composition of clay fraction	Transmission electron microscopy (TEM 3000)	Stoops, 1970
Specific surface area	BET nitrogen sorption method (N ₂ -BET)	Brunauer <i>et al.</i> , 1938
Types of smectite	Li-saturation method	Greene-Kelly, 1955
Layer charge characterization of smectite	Alkylammonium method	Lagaly, 1994
<i>Data analysis</i>		
Principal components	Statistical methods	Statsoft Inc., 2003
Correlation matrices	Statistical methods	Statsoft Inc., 2003
Histograms	Statistical methods	Statsoft Inc., 2003

RESULTS AND DISCUSSION

Soil Characteristics

Environmental settings of Thai paddy soils are shown in Appendix Table 1. The field morphology features of Thai paddy soils are shown in Table 2. The typical appearance of Thai paddy soils profiles is shown in Figures 2 to 5 and representative analytical data are presented in Figures 6 and 7. All the soil profiles are deep with no rocks encountered within 1 m depth. The moisture condition of all soils is aquic. All of the soils are poorly drained exhibiting a 2.5Y to 10YR hue with low chroma colour (≤ 2) resulting from the annual reduction/ oxidation cycles imposed over many years. Redox generated concentrations occur in the form of iron oxide mottles in all profiles. Field evidences suggest that endosaturation is responsible for most of the redoximorphic features exhibited by these soils. The distribution of redoximorphic features indicates that the soils are saturated with water in all layers to a depth of at least 200 cm (limit of soil pits). In the Central Plain, marl and limestone play an important role in the soil formation. It is interesting to note that the soils developed in association with marl and limestone are relatively dark in colour.

The Apg horizon of all soils is relatively rich in organic matter. Most soil structure is angular to subangular blocky structure, except for Ki which has prismatic and columnar structure in subsoil horizons due to the high exchangeable sodium. The entire soil profile for Sai, Cb, Kl and the topsoil of Re, Tt, Ki soils have a relatively coarse texture (loam to sandy clay loam), whereas the subsoils of Re, Tt and Ki have a sandy clay texture. The soils, Pm1, Ud, Ms, Hd, Cr, Cs, Lb, Tr, Kk and Bph, have a heavier texture throughout (silty clay to clay). Profile Pm2 has a clay topsoil and sandy clay loam in the subsoil. In some profiles, clay concentration increases with depth possibly due to clay illuviation. Most Thai paddy soils contain clay coatings which occur on void walls and grains and which increase in abundance with increasing depth in all of the soils except for Lb, Kk and Bph.

Table 2 Morphology of Thai paddy soils.

Horizon	Depth (cm)	Colour	Mottle	Structure ^{1/}	Consistence ^{2/}	Coat	Pore
Roi Et (Re): Typic Paleaquult, fine loamy, mixed, semiactive, isohyperthermic							
Apg1	0-14	10YR 6/3	-	2 SBK	SH, SF, SS/MP	-	common
Btg1	32-45	10YR 5/2	10YR 5/6	2-3 ABK	H, F, MS/MP	few	common
Btg7	169-200+	10YR 7/1	5Y 5/2	2 SBK	H, F, MS/MP	common	common
Tha Tum (Tt): Plinthic Endoaqualf, fine loamy, mixed, subactive, isohyperthermic							
Apg	0-12	10YR 3/1	-	2 SBK	SH, SF, SS/SP	-	few
Btg1	26-43	10YR 7/2	10YR 5/8	2 SBK	SH, SF, SS/MP	common	common
Btg5	123-157	10YR 7/1	2.5Y 7/8	3 ABK	VH, VF, SS/MP	common	common
Phimai (Pm1): Vertic Endoaqualf, very fine, kaolinitic, isohyperthermic							
Apg1	0-12	10YR 3/2	5YR 5/8	2 SBK	SH, F, MS/VP	-	few
Btg1	32-43	10YR 5/2	5YR 5/8	2 SBK	VH, VF, MS/VP	few	very few
2Btg5	140-170	7.5YR 7/1	10YR 6/8	1 ABK and semi-massive	VH, VF, VS/VP	few	common
Phimai (Pm2): Aerice Vertic Natraqualf, fine, kaolinitic, isohyperthermic							
Apg1	0-10	10YR 4/3	2.5YR 4/8	2 SBK	SH, F, MS/MP	-	common
Btg1	22-38	7.5YR 4/3	10YR 5/8	2 ABK	SH, F, MS/MP	common	common
2Btg2	102-121	2.5Y 6/2	2.5Y 6/8	2 ABK	H, F, MS/MP	few	common
Kula Ronghai (Ki): Typic Natraqualf, fine, kaolinitic, isohyperthermic							
Apg1	0-18	10YR 6/4	10YR 4/4	2 ABK	SH, Fri, SS/SP	-	common
Btg	30-48	10YR 7/2	10R 4/4	3 Pri and Col	VH, VF, VS/VP	common	common
Btng1	48-73	10YR 7/1	10R 4/4	3 Pri and Col	VH, VF, MS/MP	common	few
2Btg3	91-188	10YR 7/1	2/5YR 4/6	3 semi-ABK	VH, VF, VS/VP	common	common
Udon (Ud): Vertic Natraqualf, fine, mixed, active, isohyperthermic							
Ag	0-21	10YR 4/2	7.5YR 5/6	1 ABK, semi- massive	VH, VF, VS/VP	-	common
Btng1	21-41	10YR 4/2	10YR 5/8	2 ABK	VH, VF, MS/MP	few	common
Btng5	108-132	2.5Y 6/1	10YR 5/8	2 ABK	VH, VF, VS/VP	few	few
Mae Sai (Ms): Aerice Endoaqualf, fine, illitic, isohyperthermic							
Apg1	0-15	10YR 4/3	5YR 4/4	3 semi-ABK	H, F, SS/MP	-	common
Btg1	33-54	2.5Y 6/2	10YR 5/6	2 SBK	H, F, SS/MP	common	common
BCg	168-200+	2.5YR 6/1	10YR 5/6	1 ABK and semi massive	H, F, SS/MP	few	few
Hang Dong (Hd): Aerice Endoaqualf, fine, illitic, isohyperthermic							
Apg1	0-15	10YR 3/2	7/5YR 5/6	3 SBK	H, F, MS/MP	-	common
Btg1	29-50/53	2.5Y 5/1	10YR 5/6	2 ABK	SH, F, MS/MP	common	common
Btg3	68-88/90	10YR 6/2	2.5Y 6/6	2 semi-ABK	VH, F, SS/MP	common	common
2Btg4	90-102/105	2.5Y 6/1	10YR 5/6	2 semi-ABK	VH, F, MS/MP	common	common
2Btg6	124-148	2.5Y 7/1	10YR 6/6	2 SBK	H, F, MS/MP	few	few

Table 2 (Continued).

Horizon	Depth (cm)	Colour	Mottle	Structure ^{1/}	Consistence ^{2/}	Coat	Pore
Chiang Rai (Cr): Plinthic Paleaqualf, fine, illitic, isohyperthermic							
Apg1	0-12	5Y 6/1	10YR 5/4	2 SBK	H, F, MS/MP	-	few
Btg1	30-53	10YR 6/2	10YR 6/8	2 SBK	H, F, MS/MP	common	common
Btg3	106-123	2.5Y 7/2	10R 6/8	2 semi-ABK	H, F, MS/MP	common	few
Btcg2	144-166	10YR 7/1	2.5Y 6/6	2 semi-ABK	H, F, MS/MP	common	few
Chum Seang (Cs): Plinthic Paleaqualf, very fine, kaolinitic, isohyperthermic							
Apg	0-12	10YR 4/1	10YR 5/6	2 SBK	H, F, MS/MP	-	common
Btg1	12-32	10YR 6/6	10YR 5/6	2 SBK	SH, F, MS/MP	common	common
Btg3	55-82	10YR 6/1	10YR 5/8	2 SBK	H, F, MS/MP	common	few
Btg6	131-152+	10YR 6/1	10R 4/6	2 SBK	VH, VF, VS/VP	common	few
San Sai (Sai): Typic Endoaqualf, coarse loamy, siliceous, subactive, isohyperthermic							
Apg1	0-13/17	10YR 3/2	-	2 SBK	S, SF, SS/SP	-	common
Btg1	40-50	7.5YR 7/3	7.5YR 5/6	2 SBK	SH, SF, SS/NP	common	common
Btg2	50-70	7.5YR 7/2	7.5YR 4/6	2 SBK	SH, Fri, SS/NP	few	common
2Btg4	90-115	7.5YR 7/2	7.5YR 5/8	2 SBK	SH, SF, SS/SP	few	common
Chon Buri (Cb): Typic Endoaqualf, fine loamy, mixed, semiactive, isohyperthermic							
Apg1	0-20	10YR 4/1	-	3 ABK	VH, F, SS/SP	-	very few
Btg1	38-65	10YR 4/1	10YR 5/8	3 ABK	VH, F, MS/MP	common	common
Btg3	87-110	10YR 5/1	10YR 2/1	3 semi-ABK	VH, VF, MS/MP	common	few
Btg5	130-150	10YR 6/1	10YR 5/8	3 SBK	VH, F, MS/MP	common	very few
Btg7	175-192+	10YR 5/1	10YR 5/8	3 semi-ABK	VH, F, MS/MP	common	very few
Kleang (KI): Typic Plinthaquult, fine loamy, mixed, subactive, isohyperthermic							
Apg1	0-13/15	10YR 5/2	7.5YR 5/6	2 SBK	SH, SF, SS/SP	-	common
Btg	30-57	10YR 6/2	7.5YR 5/8	2 SBK	VH, F, MS/MP	common	very few
Bvg1	57-72	10YR 6/2	7.5YR 5/8	2 SBK	SH, F, MS/MP	common	common
Bvg3	100-125	7.5YR 6/3	7.5YR 5/8	2 SBK	H, F, SS/MP	few	common
Bvg5	155-180+	7.5YR 7/2	2.5YR 4/8	2 SBK	H, F, SS/MP	common	few
Lop Buri (Lb): Typic Haplustert, very fine, smectitic, isohyperthermic							
Ap	0-23	10YR 3/1	-	2 SBK	H, F, MS/VP	-	few
Bss1	42-70	10YR 4/1	-	2 ABK	VH, VF, VS/VP	-	few
Bss4	110-130	10YR 3/2	10YR 5/4	2 ABK	VH, VF, VS/VP	-	common
BCK	130-155	10YR 4/2	10YR 5/6	2 ABK	H, F, VS/VP	-	common
Ck	155-182+	10YR 3/1	-	2 ABK	H, F, MS/MP	-	few
Tha Rua (Tr): Chromic Vertic Endoaqualf, very fine, smectitic, isohyperthermic							
Apg1	0-18	10YR 4/1	10YR 5/6	2 SBK	VH, VF, VS/VP	-	common
Btg1	35-60	10YR 3/2	-	2 SBK	VH, VF, VS/VP	few	few
2Btg3	88-110	10YR 4/2	10YR 2/2	2 SBK	H, F, MS/VP	common	few
2Btg6	170-180+	10YR 3/2	10YR 2/2	2 SBK	H, F, VS/VP	common	few

Table 2 (Continued).

Horizon	Depth (cm)	Colour	Mottle	Structure ^{1/}	Consistence ^{2/}	Coat	Pore
Khok Krathium (Kk): Ustic Endoaquert, very fine, smectitic, isohyperthermic							
Apg1	0-10	10YR 4/1	7.5YR 4/4	1 ABK	VH, VF, VS/VP	-	few
Bg1	27-45	10YR 4/2	7.5YR 4/4	2 SBK	VH, VF, VS/P	-	common
Bg3	63-82	10YR 5/1	10YR 5/8	2 semi-ABK	VH, VF, VS/VP	-	few
Bssg1	82-100	10YR 5/1	10YR 5/8	2 semi-ABK	VH, VF, VS/P	-	common
Bang Phae (Bph): Typic Endoaquoll, fine, smectitic, isohyperthermic							
Apg1	0-6	10YR 3/2	7.5YR 3/4	3 semi-ABK	VH, F, MS/MP	-	common
Bg1	55-80	10YR 8/1	10YR 3/6	1 ABK	H, F, MS/VP	-	common
Bg4	150-180+	5Y 6/2	10YR 3/6	1 ABK	SH, F, MS/MP	-	common

^{1/} 1 = weak, 2 = moderate, 3 = strong, ABK = angular blocky, SBK = subangular blocky, Pri = prismatic, Col = columnar

^{2/} dry: SH =slightly hard, H = hard, VH = very hard, moist: Fri = friable, SF = slightly firm, F= firm, VF = very firm, wet: SS =slightly sticky, MS = moderately sticky, VS = very sticky, NP = non plastic, SP = slightly plastic, P = plastic, MP = moderately plastic, VP = very plastic

Physical and Chemical Properties

The complete chemical and physical properties are shown in Appendix Table 2. Textural class was determined by plotted the relative proportion of sand, silt and clay particles of the fine earth fraction (<2 mm) of the soil as textural triangle classes in Figure 6 (Soil Survey Staff, 1999). Depth functions of physical and chemical properties of Thai paddy soils are summarized in Figure 7. Soil texture varies from clay to loamy sand. The large range of textures of the soils extends from 7-96% clay. The clay content of Re, Ms, Hd, Sai, Cr, Cb and Kl shows a clear accumulation with depth. Pm1, Ud, Cs, Lb, Tr, Kk and Bph have a clayey texture with a slight increase of clay content in subsoils. Texture of Tt, Ki and Pm2 differs between topsoil and subsoil due to the presence of depositional layers.

Soils with parent materials consisting of alluvium from a sedimentary province, including Re, Tt, Ki, and granite province, including Sai, Cb and Kl, have a coarse texture with sandy loam to clay loam in topsoil and loamy sand to clay in subsoil, while alluvium from a metamorphic province has a medium texture with clay loam to silty clay in topsoil and silty clay to clay in subsoil (Ms, Hd and Cr). The texture is clay throughout the profile where the parent material is alluvium derived from quaternary sediments.

Soil pH in 1:1 H₂O varies between 4.6-8.2 for topsoil and 5.4-8.8 for subsoil. The highest pH (ranging 7.8-8.8) is present in Lb and Tr series because their parent materials include limestone. Values of pH KCl are substantially lower than pH H₂O with an average difference of 1.1 units and the range of this increment is 0.2-2.3 units. Therefore, these soils generally have net negative charges in the systems which favor cation exchange (Beery and Wilding, 1971; Soil Survey Staff, 1999).

The organic matter content also varies greatly and decreases with depth, being 3.7-33.2 g kg⁻¹ for topsoil, 0.3-18.5 g kg⁻¹ for subsoil. The differences in the amount of organic matter are probably due to differences in waterlogging and plant production (Sanchez, 1976; Brady and Weil, 2002). Total N, available P and K are high in the topsoil and decreasing greatly with depth. These trends indicate that organic matter content can be the main source of nitrogen in soils and organic matter may contribute to available phosphorous. The available P in the Sai soil is distinctly higher than for other soils due to excessive application of fertilizer.

The cation exchange capacity is 3.1-34.2 cmol(+) kg⁻¹ for topsoil and 12.0-40.6 cmol(+) kg⁻¹ for subsoil. The CEC of subsoils is ≥ 10 cmol(+) kg⁻¹ for almost all of the soils (Pm1, Pm2, Ki, Ud, Ms, Hd, Cr, Cs, Lb, Tr, Kk and Bph). Although, kaolin is the dominant clay mineral in some profiles, it commonly consists of very small, structurally disordered crystals with moderate values of CEC (Hart *et al.*, 2003; Kanket *et al.*, 2005). The CEC of Central Plain Thai paddy soils has the highest values due to the greater clay and smectite content. Consequently, exchangeable bases in Central Plain Thai paddy soils are higher than in other soils.

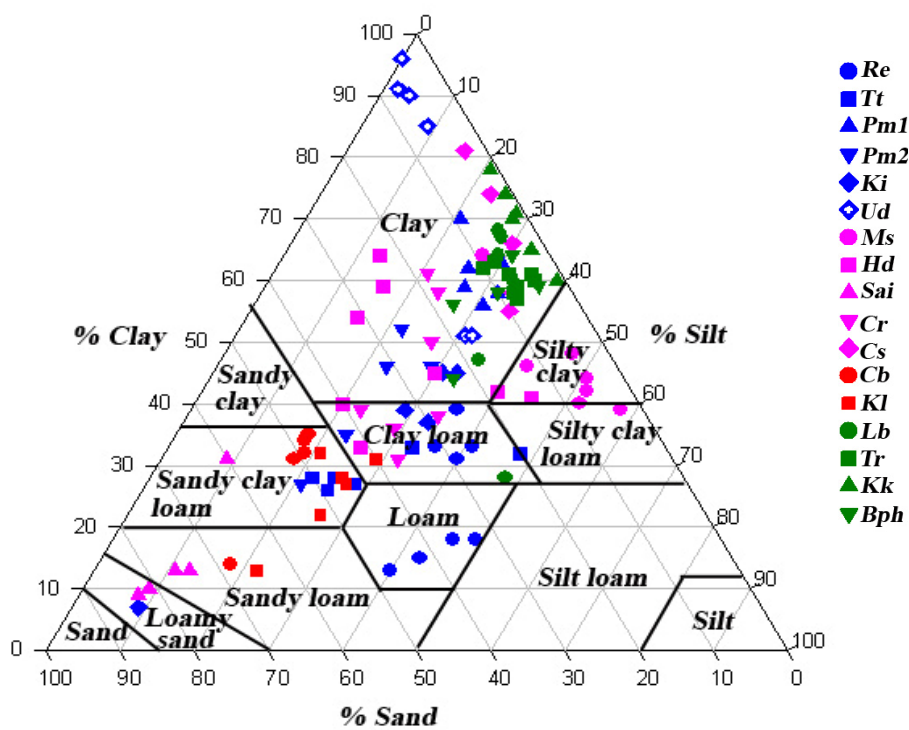


Figure 6 Textural classes of <2 mm fraction of Thai paddy soils.

Geochemical Properties

The complete chemical analyses of the soils are shown in Appendix Table 2. The median and range of elemental concentrations are given in Table 3. Silicon, Al, and Fe are the only major elements in the paddy soils, except for the C horizon of Lb, where Ca is also abundant due to the presence of calcite.

The median concentrations of Si, Al, Fe, K, Ca, Mg, Na, Mn, Ti, S, V, P, Li, Ni, Cu, Ga, Co, Be, U and Ag in Thai paddy soils are comparable to those for worldwide normal soils (i.e. within the range of published values for noncontaminated soils) (Kabata-Pendias, 2001) whereas the median concentrations of Zn, Rb, Sr, Pb, As and Cd are lower than for most normal soils.

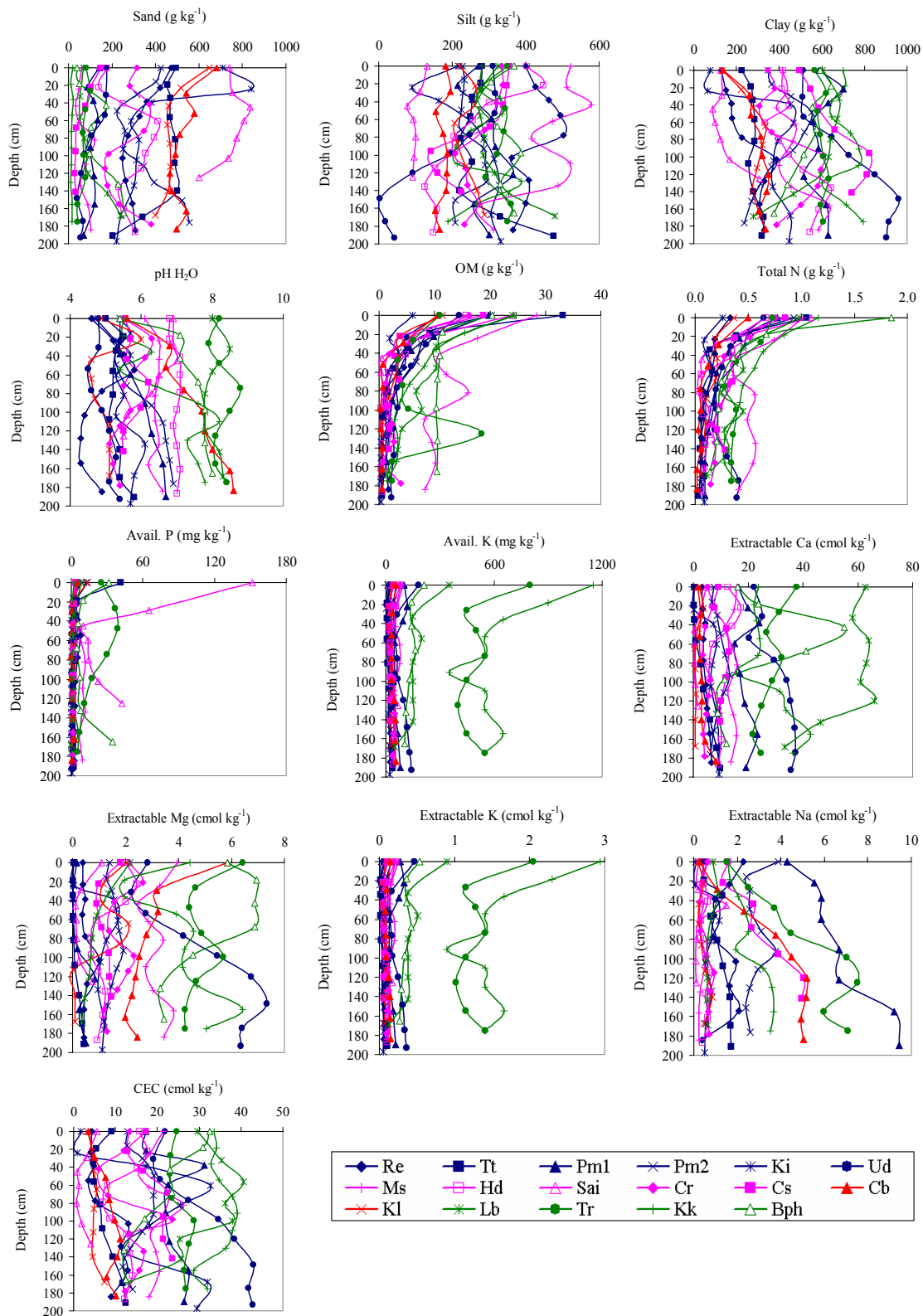


Figure 7 Depth functions of physical and chemical properties of Thai paddy soils.

Only Cr concentrations are above the values for normal worldwide soils (Table 3) and as Cr is mainly present in chromium magnetite (Figure 9) which is extremely stable this elevated concentration does not represent an environmental hazard (Alloway, 1995). All other elements are not present at hazardous concentrations.

In comparison to published values for other uncontaminated paddy soils, the median concentrations of Zn, Ni, Cu, Ga, Pb, U and Cd are lower and Mn, Ti and Co are comparable to values for uncontaminated paddy soils. The median concentrations of Cr and As are higher than for other uncontaminated paddy soil values (Table 3).

Factor analysis and principal component analysis were used to determine elements of similar geochemical behavior and also to group soil samples on the basis of their geochemical affinity (Bellehumeur, *et al.*, 1994). Factor analysis of standardized raw data was used to identify affinity groups of elements, with texture, pH and CEC being included in the data set (Davis, 1986). Only 56% of the variation in data for the soils is explained by the first two factors which is a consequence of the diverse nature of these soils (Figures 8a and 8b). Two affinity groups of properties are recognized. The first group consists of sand, Si and Cr which simply relates to the texture of the soils. The sand fraction is mainly quartz (SiO_2) and Cr is mostly present as sand-size grains of chromium magnetite as indicated by SEM/EDS analysis (Figure 9), however Cr is not statistically associated with Fe (Figure 8) because Fe in this diagram is total iron which can be present in diverse Fe compounds including sesquioxides and clay minerals that represent more Fe than that present in chromium magnetite (Kabata-Pendias, 2001).

The second group is diffuse and consists of clay, silt, CEC, pH H_2O , pH KCl, Al, Fe, K, Ca, Mg, Na, Mn, Ti, S, V, P, Zn, Rb, Li, Ni, Sr, Cu, Ga, Pb, Co, As, Be, U, Ag and Cd. This group of properties relates to the clay content as these elements are constituents of clay minerals and oxides or occur as adsorbed species (Kabata-Pendias, 2001; Sterckeman *et al.*, 2006). The plot of soil samples in the factor diagram (Figure 8b) shows that only profile profile Ms has a tight grouping of samples.

Table 3 Median, minimum and maximum concentrations of elements in paddy soil samples (n=146), mean values for uncontaminated paddy soils, mean values for normal surface soils worldwide and critical concentrations for contaminated soils.

Element	Median	Minimum	Maximum	Mean value for paddy soil ^{1/}	Mean value for normal surface soil worldwide ^{2/}	Critical soil concentration ^{3/}
(g kg ⁻¹)						
Si	332	84	467		250-410	
Al	84.2	3.7	132		10-300	
Fe	29.3	2.1	67.3		2-550	
K	5.7	nd	24.3		0.08-37	
Ca	3.0	nd	276		0.7-500	
Mg	2.8	nd	9.6		0.4-9	
Na	2.1	nd	10.2		0.15-25	
Mn	0.34	0.03	3.30	0.39	0.27-0.53	1.5-3
Ti	5.4	0.9	7.9	5.4	2.3-26	
(mg kg ⁻¹)						
Cr	91	45	516	64	12-83	75-100
S	65	nd	21200		30-1600	
V	56.2	11	144		18-115	50-100
P	38	6.1	359		35-5300	
Zn	29.0	1.8	89	61	45-100	70-400
Rb	25.0	1.5	96.9		30-120	
Li	23.3	0.6	76.9		1.3-56	
Ni	20.0	7.1	57.2	25.5	13-34	100
Sr	19.7	1.4	236		87-210	
Cu	14.9	2.8	44.3	20.7	13-24	60-125
Ga	13.9	1.0	26.8	23.2	1-70	
Pb	13.7	2.4	84.6	23.3	22-44	100-400
Co	10.2	1.4	42.8	10.2	4.5-12	25-50
As	2.0	nd	21.9	1.7	4.4-9.3	20-50
Be	1.6	0.02	5.5		0.35-3.52	
U	1.3	0.2	14.3	2.3	0.8-11	
Ag	0.05	nd	0.4		0.03-0.4	2
Cd	0.03	nd	0.3	0.34	0.37-0.78	3-8

nd = not detectable

^{1/} Mean of total concentration of elements in uncontaminated paddy soils. Data are from Wong *et al.* (2002); Wang *et al.* (2003); Chandrajith *et al.* (2005).

^{2/} Mean of total concentrations of elements in the surface horizon of normal worldwide soil, normal means that the data do not include contaminated or mineralized soils. Data are from Kabata-Pendias (2001); Essington (2004).

^{3/} Higher concentrations may be toxic to plants depending on speciation (Alloway, 1995).

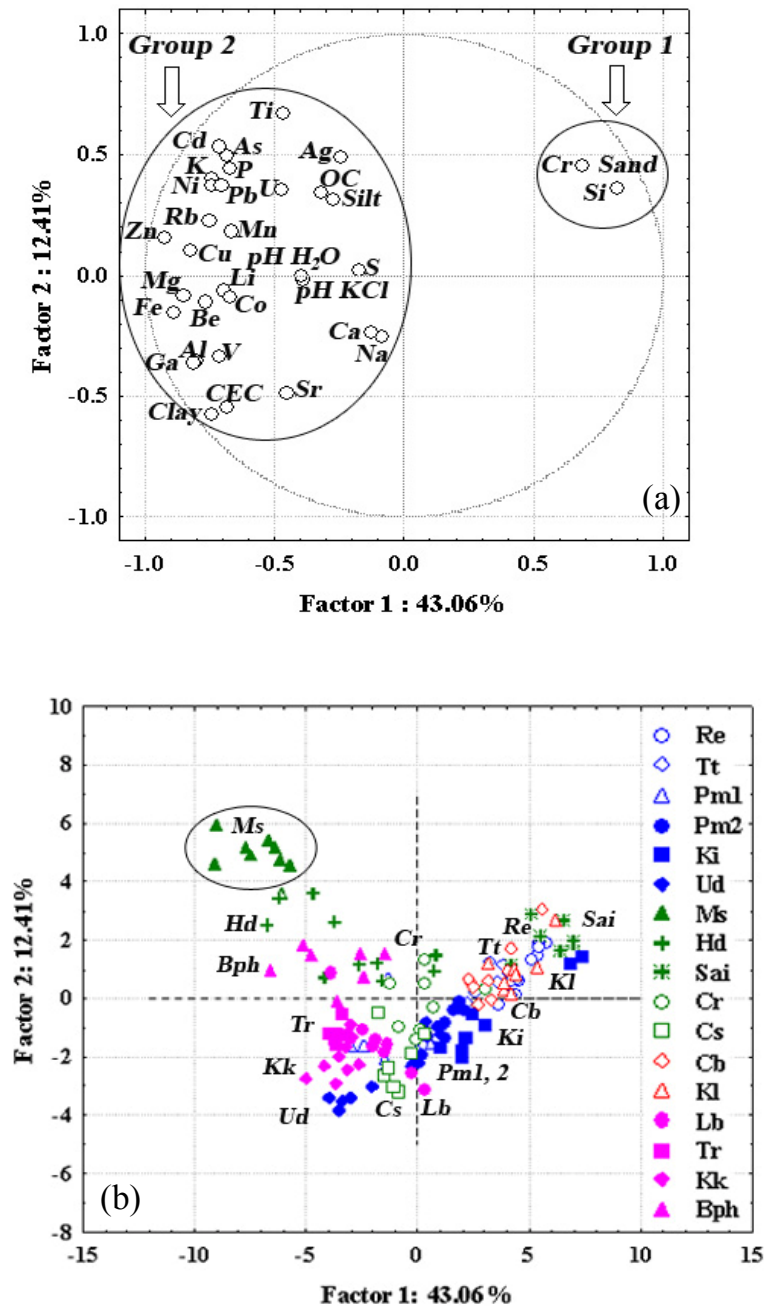


Figure 8 Factor analysis for the chemical composition and some additional properties for whole soil materials (a) distribution of chemical and other soil properties (variables) (b) distribution of soil samples (cases).

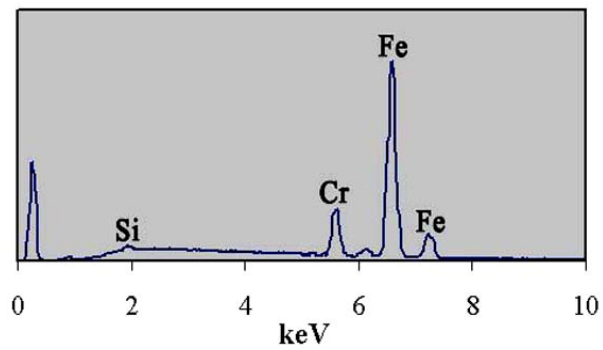
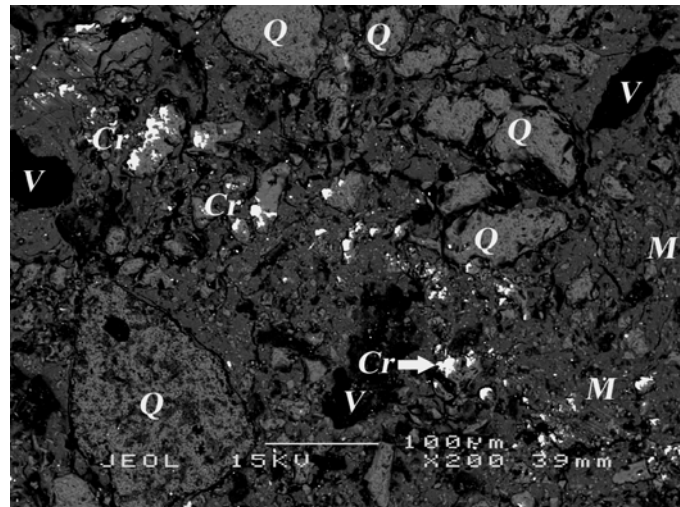


Figure 9 Photograph of a thin section of the 2Btng5 horizon (150-185 cm) of the Kula Ronghai (Ki) series: EDS spectrum of a point within a chromium magnetite grain (M = matrix, Q = quartz, V = void, Cr = chromium magnetite).

Data for horizons in individual soil profiles tend to be grouped together in this diagram but they also overlap with data for other soils to various extents demonstrating the diversity of materials both within and between soil profiles. The large variation in chemical composition within and between paddy soils in Thailand reflects the presence of distinctly different depositional layers within soil profiles, with differences in texture controlling the chemical composition. Clearly pedoturbation, eluviation and other pedogenic processes have not erased the strong influence of depositional layering.

According to the literature concentrations Mn, Ti, Cr, Zn, Ni, Cu, Ga, Pb, Co, As, U and Cd in other uncontaminated paddy soils are also quite varied, presumably reflecting differences in parent material composition and possibly the application of fertilizers (Wong, *et al.*, 2002, Wang *et al.*, 2003, Chandrajith *et al.*, 2005).

1. Specific Elemental Relationships

Within the broad affinity group, there exist some very close relationships between elements, examples of some bivariate plots are shown in Figure 10 (Ga vs Al, Ga vs Fe, V vs Al, K vs Rb, P vs As and Sr vs Ca). Aluminum, Fe, Ga and V are closely associated because these elements occur in clay mineral and oxide structures (Marques *et al.*, 2004; Sterckeman *et al.*, 2006). Lithium, Co and Mn are also closely associated as they occur in manganese oxides (Figure 8) (Tessier, 1992; Wong *et al.*, 2002). Phosphate and As are quite closely associated as both exist as oxyanions in soils which are similarly adsorbed by soil constituents, particularly sesquioxides (Shahandeh *et al.*, 2003; Gordeev *et al.*, 2004).

For some pairs of elements, there is not a simple single bivariate relationship for the complete data set. For example in the case of Sr vs Ca, there is a close statistical relationship between Sr and Ca ($r = 0.71$), which is commonly observed as these divalent elements have similar ionic radii and crystal chemical behaviour (Kabata-Pendias, 2001). However, closer examination of the data shows that three distinct relationships between Sr and Ca exist for different parent materials.

Thus, in the present study the soils can be separated into three groups according to their distinct Sr to Ca ratios (Figure 10f). Group 1, soils consist of Re, Tt, Pm1, Pm2, Ki, Ud, Ms, Hd, Sai, Cr, Cs, Cb and Kl, where the average Sr to Ca ratio is 0.0093 for which the parent materials are alluvium deriving from a sandstone, siltstone, granite and metasedimentary province. The second group consists of Tr and Kk soils with an average Sr/Ca ratio of 0.0070 for which parent materials are riverine and marine sediments which are quite rich in Sr (Yang *et al.*, 2002). The third group consists of Lb and Bph soils where calcite has crystallized within the soil profile so the lower Sr/Ca ratio (0.0025) may reflect the lower capacity of calcite to retain Sr relative to silicate minerals, which is where most Sr and Ca reside in the other soils (Mayayo *et al.*, 1996).

Global average Sr/Ca ratios for limestone, granite and metasedimentary rocks are 0.0020, 0.0046 and 0.0075, respectively (Fralick and Kronberg, 1997; Faure, 1998; Yang *et al.*, 2002; Chaudhri *et al.*, 2003). The Sr/Ca ratio of soil carbonate ranges from 0.0014-0.0030 (Mayayo *et al.* 1996; Jacobson *et al.* 2002). The values for paddy soils on the various parent materials discussed above are consistent with the values from the literature.

2. Depth Variation in Chemical Composition

Depth functions of factor scores for the paddy soils were plotted to determine the uniformity of soil profiles (Figure 11). Values of factor 1 mainly reflect soil texture being positive for more sandy materials (Figure 8). Values of factor 1 are quite constant with depth for Pm2, Ms, Cb, Kl, Tr and Bph profiles and decrease systematically with depth for Ud and Sai, reflecting the increasing clay content, which is probably due at least partly to clay illuviation. In contrast, factor 1 exhibits considerable variation within some soil profiles. Thus, profiles Re, Tt, Ki, Cs and Kk have two distinct layers, whereas profiles Pm1, Hd and Cr have several distinct layers indicating that these profiles contain discrete depositional layers. Factor 2 is associated with properties of the clay fraction (Figure 8) so that variations in factor 2 show similar trends to factor 1, except for profile Lb where an opposite trend occurs.

Factor 2 for Lb becomes highly negative with increasing depth because the Ca content increases greatly with depth reflecting the abundance of pedogenic calcite.

Extractable Iron

Extractable Fe by dithionite-citrate-bicarbonate (Fe_d), ammonium oxalate (Fe_o) and pyrophosphate (Fe_p) are also given in Appendix Table 5. The variation of these properties with depth is shown in Figure 12. Crystalline iron oxides as estimated by DCB extraction (Fe_d) are the dominant form of iron oxide in these soils and amounts differ greatly between soils (Figure 12). The Fe_d in Thai paddy soils ranges from 1.45 to 24.73 g kg⁻¹ for topsoil and 1.14 to 32.38 g kg⁻¹ for subsoil. Differences in the composition of parent materials appear to be responsible as the Fe_d content of alluvial soils from a metamorphic province (Ms, Hd, Cr and Cs) is higher than for soils on other parent materials.

The concentration of Fe_d is quite uniform with depth in Pm1, Pm2, Ki, Ms, Cr, Cs, Cb, Lb and Tr. The Fe_d concentration decreased from topsoil to subsoil in Ud while Fe_d increased from topsoil to subsoil in Kl and Kk. Iron oxides have accumulated in some horizon in Re, Tt, Hd, Sai and Bph. Fe_d and Fe_o have positive relationships with Al_d and Al_o , respectively. There is a highly significant relationship between Fe_p and Al_p (Table 4, Figure 13).

The concentration of Fe_p and Fe_o generally decreased from topsoil to subsoil (Figure 12). The concentration of Fe_o ranges from 22 to 874 mg kg⁻¹ for topsoil and 7 to 1173 mg kg⁻¹ for subsoil. The Fe_p concentration ranges from 10 to 508 mg kg⁻¹ for topsoil and 5 to 398 mg kg⁻¹ for subsoil. The pyrophosphate-soluble iron concentration of topsoil is higher than for subsoil, probably because of Fe complexing with more abundant organic matter (Schuppli *et al.*, 1983; Dahlgren *et al.*, 1997).

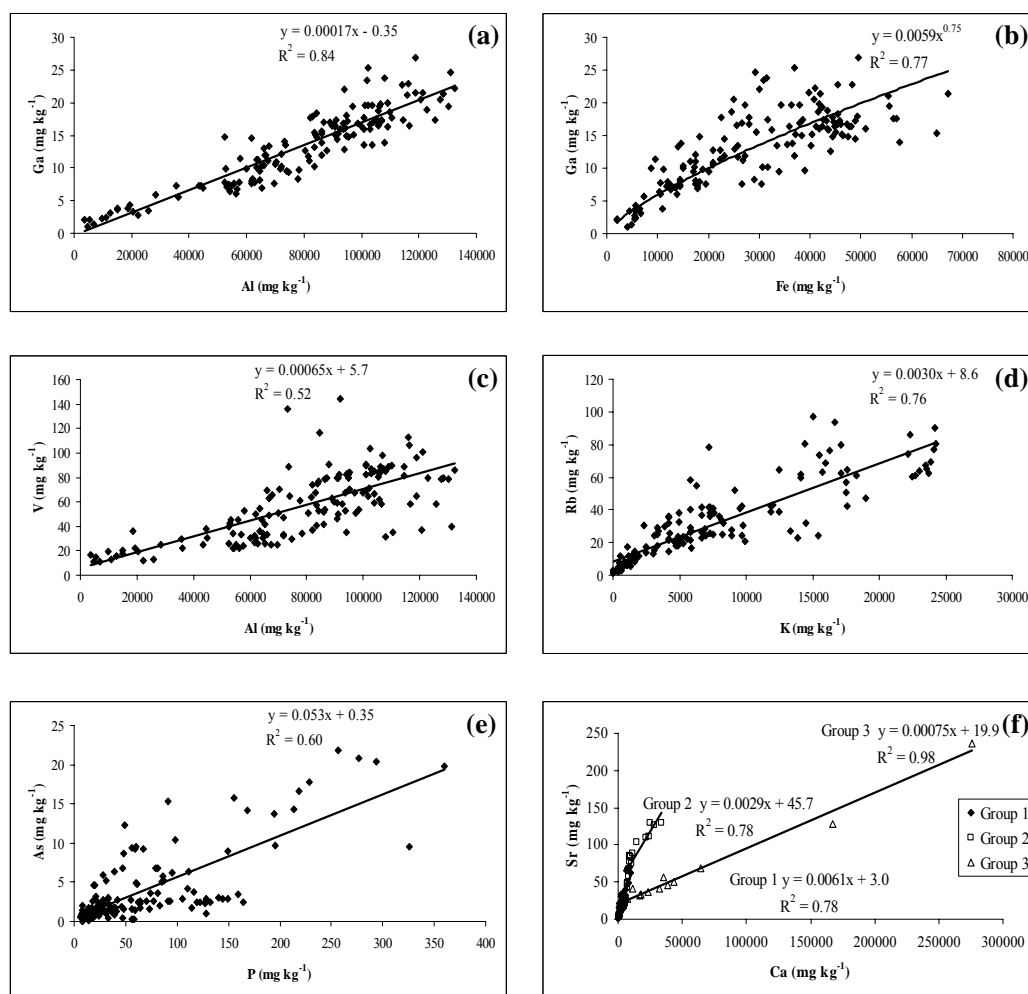


Figure 10 Some highly significant bivariate relationships between the concentrations of elements in the 17 Thai paddy soils.

The Fe_o/Fe_d ratio can be used to provide an indication of the degree of crystallinity of free iron oxides. A low ratio (<0.1) indicates a high degree of crystallinity (Blume and Schwertmann, 1969; Agbenin, 2003). The Fe_o/Fe_d ratio of all soils decreases with increasing soil depth. This trend may be related to the drying of soils, with the topsoil experiencing more severe variation in pedoclimate than subsoils.

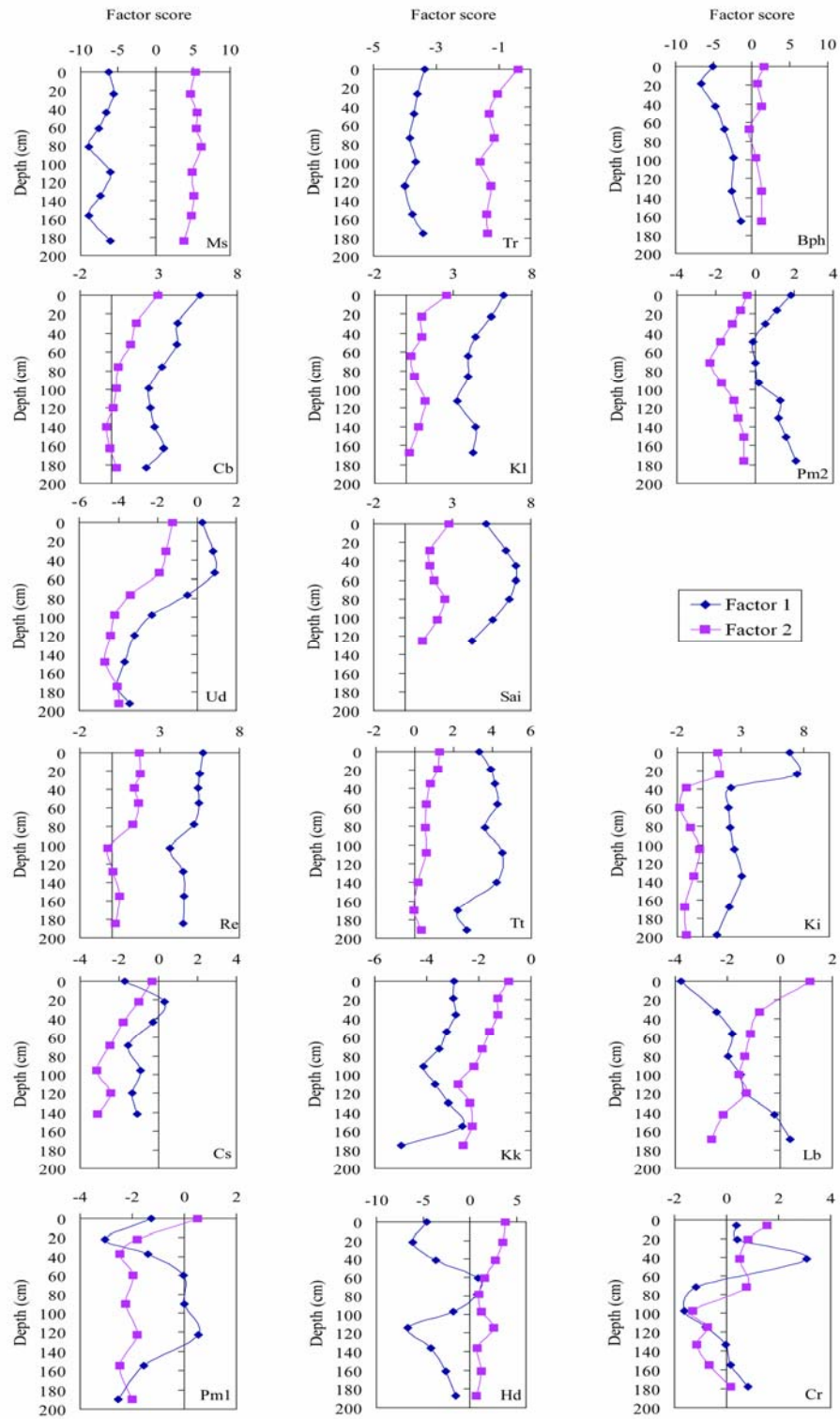


Figure 11 Depth functions for factors 1 (Cr, Si, sand) and 2 (other parameters) for the 17 Thai paddy soils.

1. Extractable Iron and Elemental Associations

The median total P concentration is 232 mg kg⁻¹ for topsoil and 130 mg kg⁻¹ for subsoil (Appendix Table 4). The various forms of Fe (Fe_t, Fe_d, Fe_p and Fe_o) were correlated positively with the total phosphorus concentration in soils (Table 4, Figure 14). This association is consistent with the observations of Krairapanond *et al.* (1993) that phosphorus interacts with all forms of Fe in soil. The concentration of poorly crystalline iron compounds in soils as estimated by oxalate extraction (Fe_o) has the strongest positive relationship with phosphorus content ($r = 0.82$, $n=146$), possibly because poorly crystalline iron compounds are more effective for phosphorus sorption due to their high specific surface area and reactivity (Sah and Mikkelsen, 1986; Shahandeh *et al.*, 2003).

In the profiles studied, concentrations of Mn, Co, Ni, Cu, Zn, As and Cd, are significantly related (+) to iron oxides, especially Fe_t, Fe_d and Fe_o forms (Table 4) presumably because iron oxides play an important role in the retention of cations in their structures and anions by adsorption (Manceau *et al.*, 1992; Palumbo *et al.*, 2001).

Mineralogical Properties

The mineralogical composition of the soils is listed in Table 5. Smectite is a dominant mineral in the clay fraction of soils in the Central Plain (Lb, Tr, Kk and Bph) with traces of illite in Tr, Kk and Bph. The paddy soils in Northeastern Thailand (Re, Tt, Pm1, Pm2, Ki and Ud), contains much kaolin, traces of vermiculite in Pm1, Ki, Ud and traces of illite in Pm1 and Ud. Smectite is a minor constituent of Pm1 and is present in the deeper horizons of Re and Tt. Kaolin is the major clay mineral of soils from Northern (Ms, Hd, Sai, Cr and Cs) and Eastern (Cb and Kl) Thailand with illite also being present, except for the Kl soil. Traces of smectite occur in Ms, Cr, Cs, Kl, the topsoil of Hd and in the subsoil of Cb.

Table 4 The correlation coefficients for four forms (total, dithionite citrate bicarbonate, oxalate and Na pyrophosphate) of Fe, Al and Mn versus concentrations of elements in whole soils ($p < 0.05$, $n=146$).

	Fe _t	Fe _d	Fe _o	Fe _p	Al _t	Al _d	Al _o	Al _p	Mn _t	Mn _d	Mn _o	Mn _p
Fe _d	0.70				0.38				0.41			
Fe _o	0.48	0.59			0.32	0.26			0.41	0.38		
Fe _p	0.37		0.49				0.19		0.17			
Al _t	0.61											
Al _d	0.44	0.73			0.46				0.19			
Al _o	0.44	0.18	0.23		0.40	0.46			0.26	0.23		
Al _p	0.16		0.18	0.87			0.20					
Mn _t	0.63				0.50							
Mn _d	0.58	0.43			0.49	0.22			0.98			
Mn _o	0.51	0.37	0.31		0.42	0.18			0.95	0.97		
Mn _p	0.52	0.64	0.72	0.26	0.41	0.33			0.71	0.74	0.69	
Li _t	0.52	0.31			0.47	0.26	0.34		0.42	0.39	0.35	0.31
Be _t	0.57	0.23	0.21	0.32	0.22		0.31	0.25	0.42	0.37	0.32	0.24
P _t	0.57	0.50	0.82	0.51	0.31		0.24	0.17	0.52	0.46	0.38	0.59
Ti _t	0.31	0.58	0.66		0.26	0.31			0.43	0.42	0.36	0.60
V _t	0.86	0.63	0.39	0.45	0.38	0.46	0.44	0.34	0.41	0.36	0.32	0.40
Cr _t	-0.65	-0.28		-0.27	-0.33		-0.40	-0.24	-0.39	-0.35	-0.33	-0.22
Co _t	0.69	0.53	0.36	0.28	0.46	0.30	0.26		0.62	0.64	0.62	0.57
Ni _t	0.64	0.57	0.69	0.22	0.50	0.34	0.33		0.54	0.49	0.40	0.55
Cu _t	0.84	0.58	0.64	0.46	0.68	0.36	0.40	0.23	0.64	0.58	0.50	0.58
Zn _t	0.82	0.52	0.65	0.48	0.65	0.21	0.35	0.22	0.73	0.67	0.59	0.64
Ga _t	0.78	0.46	0.24	0.26	0.48	0.38	0.53	0.24	0.49	0.44	0.39	0.36
As _t	0.61	0.65	0.70		0.39	0.31	0.27		0.54	0.52	0.42	0.63
Rb _t	0.54	0.46	0.46	0.34	0.39			0.22	0.47	0.44	0.41	0.55
Sr _t	0.42			0.30	0.18	-0.18	0.17	0.27	0.35	0.28	0.27	
Ag _t		0.19	0.33		0.53	0.20		-0.25	0.24	0.24	0.19	0.27
Cd _t	0.36	0.29	0.47	0.33	0.30				0.38	0.36	0.27	0.40
Pb _t	0.51	0.49	0.43		0.45	0.22	0.17		0.59	0.59	0.55	0.58
U _t	0.28	0.42	0.29		0.35	0.30			0.40	0.41	0.38	0.47

t = total (by XRF), d = dithionite citrate bicarbonate extraction, o = oxalate extraction,
p = Na-pyrophosphate extraction

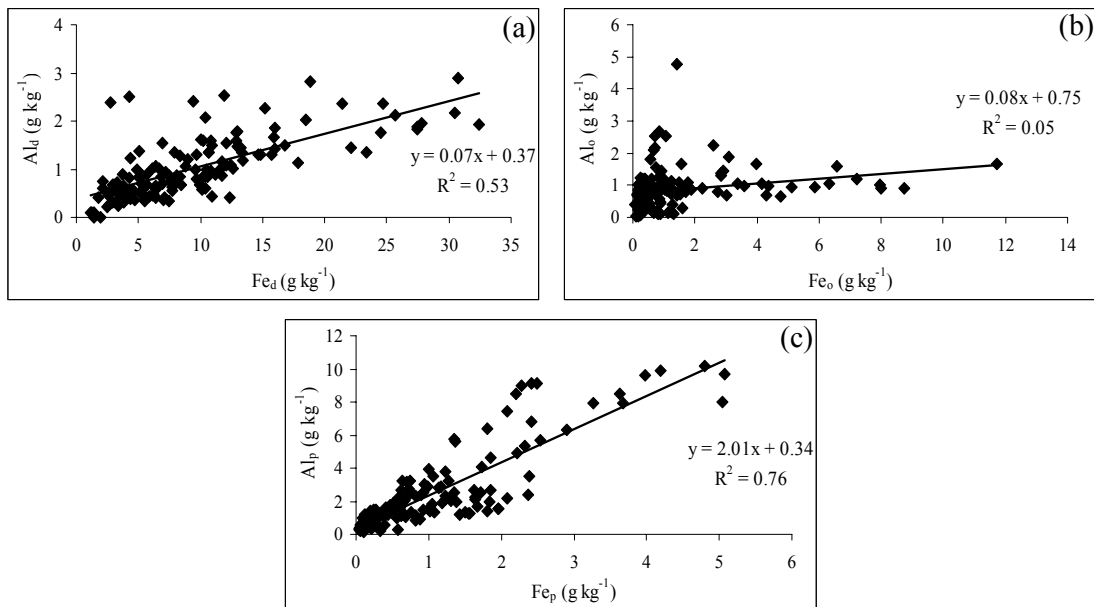


Figure 13 Bivariate relationships between the concentrations of extractable iron and aluminum (a) Fe_d and Al_d , (b) Fe_o and Al_o and (c) Fe_p and Al_p .

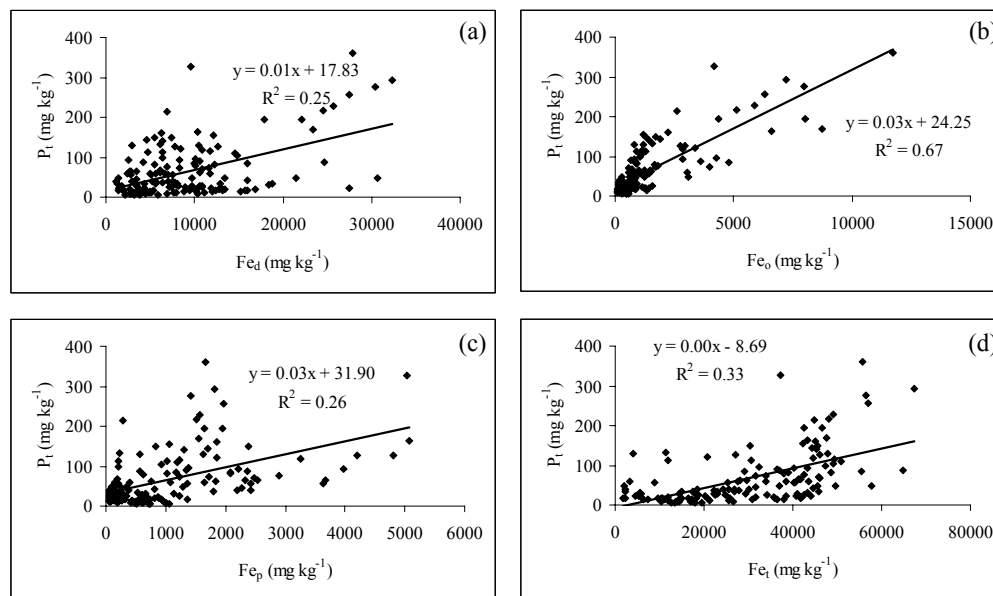


Figure 14 Bivariate relationships between the concentrations of extractable iron and total phosphorous.

Kaolin is a major constituent of all Thai paddy soils, except for the Central Plain where smectite is the dominant clay mineral. For Northern Thailand, illite is a minor constituent of the clay fraction.

The Central Plain is a fault bounded basin that developed in the Plio-Pleistocene epoch. The basin has been filled with Quaternary fluvial and swamp sediments reaching a thickness of almost 2000 m (Sinsakul, 2000). This area is naturally poorly drained and was saturated for a long period each year prior to drainage and agricultural development. Under this condition, some iron was reduced and dissolved ions including Si, Al and Mg were introduced from the adjacent leached uplands enabling the neoformation of smectite (Borchardt, 1989). Calcite is present in some paddy soils in the Central Plain due to authigenesis in this environment where dissolved ions accumulate. In contrast, most paddy soils in other part of Thailand are on terraces where leaching of Si and basic cations has occurred in the humid tropical climate. This condition favours formation of kaolin (Milot, 1970; Tardy *et al.*, 1973; Trakoonyingcharoen *et al.*, 2006).

Quartz is the dominant mineral of the silt fraction for all the paddy soils (Table 5). A little feldspar is present in Pm1, Pm2, Ki, Ms, Cr, Cs, Cb, Kl, Tr, Kk and Bph whereas a moderate amount of feldspar is present in Hd. The SEM results show that the mineralogy of the sand fraction of the soils is similar to that of the silt fraction with minor amounts of resistant primary minerals being present, particularly zircon, ilmenite, and chromium magnetite. Silt-size calcite is present in some soils on the Central Plain.

Characterization of Dominant Minerals in Thai Paddy Soils

1. Smectite

Smectite is the dominant clay mineral in the Central Plain. The parent materials of these soils are associated with limestone derived alluvium and a deltaic environment. A favorable condition for smectite precipitate exists close to dissolving limestones and in the lower positions of landscape that receives alkaline seepage water from uplands (Borchardt, 1989). In addition, smectite occurs under brackish conditions and the soil solution is enriched in silicon, magnesium and calcium (Dabbakula *et al.*, 1992).

Selected clay fractions of Central Plain Thai paddy soils have been studied by XRD. Glycerol solvated, Mg saturated clays gave a very distinct and strong 1.8 nm diffraction peak for all samples. Thus, smectite is the dominant clay mineral in all samples. A 0.72 nm peak, indicating the presence of kaolin, was observed for all clay samples and minor illite occurred in most samples; only the clay fractions of samples from the Lop Buri (Lb) soil are almost pure smectite (Table 6).

XRD patterns of random powder of the clays gave a strong 060 reflection at 0.150 nm indicating that the smectite is dioctahedral (Nemecz, 1981; Badraoui and Bloom, 1990). With one exception the lithium-saturated and heated at 300°C samples gave an approximately 1.4 nm diffraction peak which on glycerol solvation expanded to 1.8 nm (Table 7). After saturation of smectite with lithium ions and heating, the lithium ions migrate to vacant sites in the octahedral sheet to correct charge imbalance consequently montmorillonite loses its capacity to expand after Li saturation and heating.

Table 5 Mineralogical composition of clay and silt fractions (based on XRD).

Soil series	Horizon	Depth (cm)	Clay fraction						Silt fraction		
			Sme	Ill	Ver	Kao	Qtz	Fel	Qtz	Fel	Cal
Re	Apg1	0 - 14	-	-	-	xxxx	x	-	xxxx	-	-
	Btg4	90 - 116	tr	-	-	xxxx	x	-	xxxx	-	-
	Btg6	140 - 169	tr	-	-	xxxx	x	-	xxxx	-	-
Tt	Apg	0 - 12	-	-	tr	xxx	xx	x	xxxx	-	-
	Btg4	93 - 123	x	-	-	xxxx	x	tr	xxxx	-	-
	Btg6	157 - 182	xx	-	-	xxx	x	tr	xxxx	-	-
Ki	Apg1	0 - 18	-	-	tr	xx	x	-	xxxx	tr	-
	Btng1	48 - 73	-	-	tr	xxxx	tr	-	xxxx	tr	-
	2Btng3	91 - 118	-	-	tr	xxxx	tr	-	xxxx	tr	-
Ud	Ag	0 - 21	-	tr	x	x	x	-	xxxx	-	-
	Btng1	21 - 41	-	tr	tr	x	xx	-	xxxx	-	-
	Btng7	165 - 184	-	tr	tr	x	x	-	xxxx	-	-
Pm1	Apg1	0 - 12	x	-	-	xxxx	x	-	xxxx	tr	-
	Btg3	76 - 105	x	-	-	xxxx	x	tr	xxxx	tr	-
	2Btg5	170 - 210	x	x	-	xxx	x	-	xxxx	x	-
Pm2	Apg1	0 - 10	-	-	tr	xx	x	-	xxxx	tr	-
	Btg2	38 - 60	-	-	tr	xxx	tr	-	xxxx	tr	-
	Btng1	83 - 102	-	-	x	xxx	tr	-	xxxx	tr	-
	2Btng2	102 - 121	-	-	x	xxx	x	-	xxxx	tr	-
Ms	Apg1	0 - 15	tr	xx	-	xx	x	x	xxxx	tr	-
	Btg1	33 - 54	tr	xx	-	xx	x	x	xxxx	tr	-
	Btg3	70 - 94	tr	xx	-	xx	x	x	xxxx	tr	-
	BCg	168 - 200+	tr	xx	-	xx	xx	x	xxxx	tr	-
Hd	Apg1	0 - 15	tr	xx	-	xx	x	tr	xxxx	xx	-
	Btg3	68 - 88/90	-	xx	-	xx	x	tr	xxxx	x	-
	2Btg7	148 - 174	-	x	-	xxx	x	-	xxxx	x	-
Sai	Apg1	0 - 13/17	-	x	-	xxxx	x	-	xxxx	-	-
	Btg1	40 - 50	-	x	-	xxx	x	x	xxxx	-	-
	Btg3	70 - 90	-	x	-	xxx	x	x	xxxx	-	-
	2Btg4	90 - 115	-	x	-	xxxx	x	tr	xxxx	-	-
Cr	Apg1	0 - 12	tr	xxx	-	xx	x	tr	xxxx	tr	-
	Btcg1	53 - 80/90	tr	xx	-	xx	x	tr	xxxx	tr	-
	Btg3	106 - 123	tr	x	-	xxxx	x	tr	xxxx	tr	-
	Btcg3	166 - 190+	tr	x	-	xxx	xx	-	xxxx	tr	-
Cs	Apg	0 - 12	tr	x	-	xxxx	x	-	xxxx	-	-
	Btg2	32 - 55	tr	-	-	xxxx	x	-	xxxx	-	-
	Btg4	82 - 109	tr	-	-	xxxx	x	-	xxxx	-	-
	Btg6	131 - 152+	tr	x	-	xxxx	x	-	xxxx	tr	-
Cb	Apg1	0 - 20	-	xx	-	xxx	x	tr	xxxx	tr	-
	Apg2	20 - 38	-	x	-	xxxx	x	tr	xxxx	tr	-
	Btg3	87 - 110	x	tr	-	xxxx	x	-	xxxx	tr	-
	Btg7	175 - 192+	tr	x	-	xxxx	x	-	xxxx	tr	-
Kl	Apg	0 - 13/15	x	-	-	xxxx	tr	tr	xxxx	-	-
	Apg2	15 - 30	tr	-	-	xxxx	xx	-	xxxx	-	-
	Bvg2	72 - 100	tr	-	-	xxxx	x	tr	xxxx	-	-
	Bvg5	155 - 180+	x	-	-	xxxx	x	-	xxxx	tr	-

Table 5 (Continued).

Soil series	Horizon	Depth (cm)	Clay fraction						Silt fraction		
			Sme	Ill	Ver	Kao	Qtz	Fel	Qtz	Fel	Cal
Lb	Ap	0 - 23	xxxx	-	-	tr	tr	-	xxxx	-	x
	Bss3	90 - 110	xxxx	-	-	tr	tr	-	xxxx	-	x
	Ck	155 - 182+	xxxx	-	-	tr	x	-	x	-	xxxx
Tr	Apg1	0 - 18	xx	x	-	xx	tr	-	xxxx	tr	x
	2Btg4	110 - 140	xx	x	-	xx	tr	tr	xxxx	tr	x
	2Btg6	170 - 180+	xx	x	-	xx	tr	tr	xxxx	tr	x
Kk	Apg1	0 - 10	xxx	-	-	xx	tr	-	xxxx	tr	x
	Bssg2	100 - 120	xx	x	-	xx	tr	-	xxxx	tr	x
	Bg5	170 - 180+	xx	x	-	xx	tr	-	xxxx	tr	x
Bph	Apg1	0 - 6	xxx	x	-	xx	tr	tr	xxxx	tr	tr
	Bg2	80 - 115	xxx	x	-	x	tr	tr	xxxx	tr	tr
	Bg4	150 - 180+	xxx	x	-	xx	tr	tr	xxxx	tr	tr

xxxx = dominant (>60%) xxx = large (40-60%) xx = moderate (20-40%)
x = small (5-20%) tr = trace (<5%) - = not detected
Sme = smectite Kao = kaolin Ill = illite
Ver = vermiculite Qtz = quartz Cal = calcite
Fel = feldspar

Table 6 Semiquantitative mineralogical composition of the clay fraction of the Thai paddy soils†.

Sample	Depth (cm)	Sme	Ill	Kao	Qtz	Fel
Lb_Ap	0 - 23	xxxx	-	tr	tr	-
Lb_Bss3	90 - 110	xxxx	-	tr	tr	-
Tr_Apg1	0 - 18	xx	x	xx	tr	-
Tr_2Btg4	110 - 140	xx	x	xx	tr	tr
Kk_Apg1	0 - 10	xxx	-	xx	tr	-
Kk_Bssg2	100 - 120	xx	x	xx	tr	-
Bph_Apg1	0 - 6	xxx	x	xx	tr	tr
Bph_Bg2	80 - 115	xxx	x	x	tr	tr

† Based on integrated areas under the diffraction peaks and the use of mineral standards, xxxx = dominant (>60%), xxx = much (40-60%), xx = moderate (20-40%), x = little (5-20%), tr = trace (<5%), - = not detected, Sme = smectite, Ill = illite, Kao = kaolin, Qtz = quartz, Fel = feldspar

Table 7 The d_{001} spacing for Li saturated and heated (300°C) smectites before and after glycerol solvation.

Sample	d001 interlayer spacing (nm)		
	Li300°C	Li300°C/G	Smectite type†
Lb_Ap	1.52	1.92	B
Lb_Bss3	1.44	1.86	B
Tr_Apg1	1.41	1.98	B
Tr_2Btg4	1.43	1.45	M
Kk_Apg1	1.43	1.89	B
Kk_Bssg2	1.47	1.88	B
Bph_Apg1	1.43	1.94	B
Bph_Bg2	1.43	1.85	B

† B = beidellite; M = montmorillonite

Li300°C = Li-saturated, heated at 300°C

Li300°C/G = Li-saturated, heated at 300°C and glycerol solvated

However, beidellite has dominantly tetrahedral charge and lithium ions cannot migrate to tetrahedral sheets therefore beidellite continues to expand after Li saturation, heating and glycerol solvation. Thus the charge on smectite in these Thai paddy soils is more tetrahedral than octahedral in origin so that in most or all samples the smectite phase resembles beidellite, not montmorillonite (Greene-Kelly, 1955).

The XRD patterns for the various alkylammonium derivatives of the smectites provided evidence for the existence of (1) monolayer forms which had a 1.4 nm basal spacing, (2) bilayer forms which had a 1.9 nm basal spacing, and (3) monolayer-bilayer transition forms which had irrational sequences of basal reflections with values of $d(001)$ between 1.5 to 2.0 nm. For example, the basal spacings for alkylammonium-clay complexes of the smectite in Apg1 of the Tha Rua series are shown in Figure 15 where $d(001)$ interplanar spacing is plotted against the number of C atoms in the alkyl chain. The ~1.45 nm reflection persists up to C7 and possibly up to C8 or C9 (not evaluated in this work) corresponding to an interlayer charge of 0.33 mol of charge per half unit cell formula if layer charge is calculated from the end of the monolayer plateau ($n_c = 7$). The monolayer-bilayer transition (C7-C10) gives a

range of calculated charge of 0.33 to 0.43 with a mean value of 0.38 charge units per half unit cell. Values of the charge for all smectite samples calculated from the mono to bilayer transition are similar averaging around 0.37 charge per half unit cell (Table 8) (Calvet and Prost, 1971). These results are within the range of typical montmorillonite of 0.25-0.40 charge per half unit cell formula (Malla and Douglas, 1987; Laird *et al.*, 1988; Lagaly, 1994; Reid *et al.*, 1996; Mermut and Lagaly, 2001). Natural beidellite typically has a layer charge near 0.33 charge per half unit cell (Ross and Hendrick, 1945) whereas the layer charge of beidellite in Vertisols and Mollisols from Morocco ranged from 0.36-0.55 charge per half unit cell (Badraoui and Bloom, 1990) and beidellite in a Vertic Haplaquoll from Northwestern Minnesota ranged from 0.37-0.50 charge per half unit cell (Badraoui *et al.*, 1987).

The results of chemical analysis of two almost pure smectites from the Ap and Bss3 horizons of Lop Buri soil (Table 9) are consistent with the interpretation of a beidellitic character based on the Li saturation procedure (Table 7). Satisfactory structural formulae can be calculated from the chemical composition of the Lop Buri smectites by assuming the ideal anion composition of smectite and that almost all Fe is present as Fe^{3+} and omitting the elemental contributions of the minor impurity minerals.

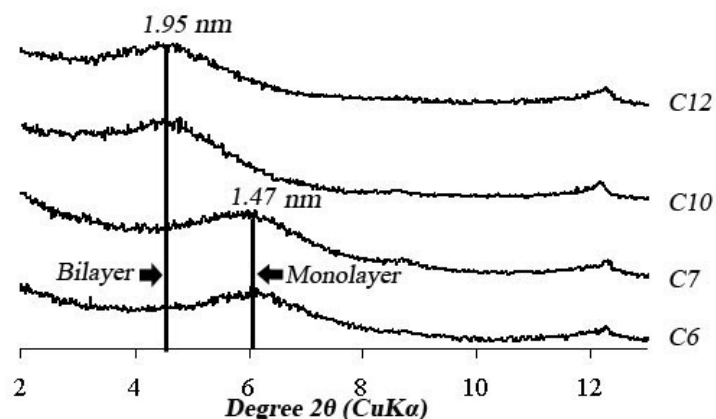


Figure 15 X-ray diffraction patterns of smectite from Apg1 horizon of Tha Rua series (Chromic Vertic Endoaqualf) and treated with various chain length (carbon number) of alkylamine (carbon chain length specified at right). The range for the monolayer to bilayer transition is indicated by the arrows.

Table 8 Interlayer charge characterization of Thai soil smectites determined from the mono/bilayer transition.

Sample	Xmin	Xmax	Xmean
	(-----Charge per half unit cell-----)		
Lb_Ap	0.33	0.43	0.38
Lb_Bss3	0.28	0.48	0.38
Tr_Apg1	0.33	0.43	0.38
Tr_2Btg4	0.28	0.48	0.38
Kk_Apg1	0.28	0.48	0.38
Kk_Bssg2	0.28	0.48	0.38
Bph_Apg1	0.33	0.43	0.38
Bph_Bg2	0.28	0.33	0.31

$$X = \frac{\lambda 23.25}{5.67n_c + 14}$$

- n_c = number of C atoms in the alkyl chains
 λ = number of alkylammonium layers
 X = charge (mol of charge/ (Si, Al) $O_{10}OH_2$)
 X_{max} = beginning of the transition
 X_{min} = end of the transition
 X_{mean} = (Xmax + Xmin)/2

The structural formulae of smectite in the Ap and Bss3 horizons of Lop Buri series are almost identical, being an average $(Ca_{0.38}K_{0.01})(Si_{6.83}Al_{1.17})(Al_{3.20}Fe^{3+}_{0.80}Fe^{2+}_{0.01}Mg_{0.19})O_{20}(OH)_4$. This formula indicates that negative charge originates only in the tetrahedral layer.

The above formula is quite different from that of smectite in Vertisols in New South Wales, $(Ca_{0.30}K_{0.06})(Si_{7.75}Al_{0.25})(Al_{2.92}Fe^{3+}_{0.80}Mg_{0.23})O_{20}(OH)_4$ (Singh and Heffernan, 2002) which has less total layer charge, considerable octahedral charge and little tetrahedral charge. It is also very different from the smectite in the Bt1 horizon of the Zwingle pedon in Iowa, $(Ca_{0.34})(Si_{8.02})(Al_{2.72}Fe^{3+}_{0.12}Ti_{0.02}Li_{0.32}Mg_{1.18})O_{20}(OH)_4$ which has no tetrahedral charge (Laird *et al.*, 1989). Smectite in the fine clay fraction of Chaouia Vertisols and Mollisols $(Na_{1.08}K_{0.15})(Si_{7.18}Al_{0.82})(Al_{2.55}Fe^{3+}_{0.76}Mg_{0.84})O_{20}(OH)_4$ also has a less beidellitic character than Lop Buri smectite (Badraoui and Bloom, 1990).

Table 9 Elemental composition of smectites from a Lop Buri soil (ignited basis).

	Lb_Ap Horizon	Lb_Bss3 Horizon
	(-----g kg ⁻¹ -----)	
SiO ₂	557.0	556.2
Al ₂ O ₃	307.8	309.9
Fe ₂ O ₃ †	85.3	84.9
TiO ₂ *	10.8	11.0
MgO	10.2	9.5
K ₂ O	0.5	0.3
CaO	28.4	27.9
MnO	0.7	0.6

† All Fe expressed as Fe₂O₃, * Anatase impurity

As is commonly the case with calculated structural formulae some uncertainty exists regarding the allocation of minor TiO₂ which is probably free anatase and also very minor amounts of FeO may be present (Brown *et al.*, 1978) but this will not greatly affect the formula. The calculated layer charge of the Lop Buri smectites of 0.38 charge per half unit cell is identical with the value of 0.38 obtained by solvation with alkylammonium ions (Table 8).

A representative TEM micrograph of beidellite from Thai paddy soils is presented in Figure 16 together with the corresponding EDX spectrum. The crystal is an irregular, thin plate as has been observed by other workers (Nadeau *et al.*, 1985; Inoue *et al.*, 1987; Badraoui and Bloom, 1990; Beaufort *et al.*, 2001). The chemical composition of the crystal is indicated by the EDX spectrum and is consistent with the calculated formula.

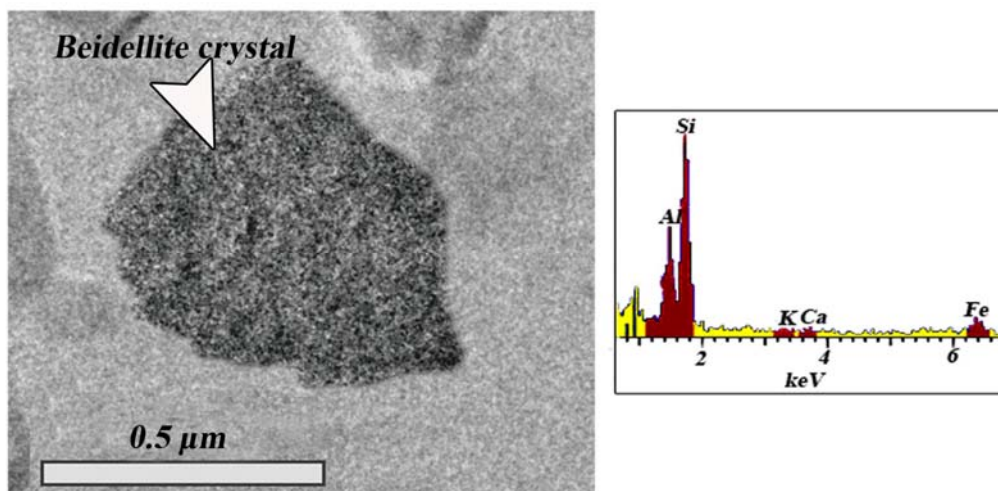


Figure 16 Irregular, platy morphology and EDX spectrum of a smectite crystal from the Bg2 horizon (80-115 cm) of the Bang Phae series.

2. Kaolin

Some paddy soils have kaolin as the dominant clay mineral. Fourteen representative kaolin rich clay fractions of paddy soils from Northern, Northeastern and Eastern Thailand are shown in Table 10. Properties of the kaolin-group minerals derived from XRD patterns (CSD and HB index) together with SSA and CEC of clay fractions are presented in Table 11. Most Thai paddy soil kaolins have a small crystal size. The CSD size calculated from the width at half height (WHH) of (001) XRD reflections using the Scherrer equation indicates that the soil kaolins range in size from 5.9 to 19.5 nm which is less than reported values for most soil kaolins from several other locations and similar to kaolins from Indonesia soils (Table 12).

The HB “crystallinity” index of Thai paddy soil kaolins ranges from 1.3 to 4.8 with a mean value of 3.0 that is smaller than the HB index for Thai upland soil kaolins (range 3.3-11.4, mean 5.6) (Table 12). In comparison to soil kaolin in other country, the HB index for Thai paddy soil kaolins is very different from soil kaolin from W. Australia (range 4.8-6.2 mean 5.5), Indonesia (range 4.1-7.1, mean 5.6), Nigeria (range 4.3-13.7, mean 8.0) and Queensland (range 3.4-8.6, mean 5.9) showing that Thai paddy soil kaolins have the largest defect structure (Hughes and Brown, 1979; Koppi and Skjemstad, 1981; Singh and Gilkes, 1992; Hart, *et al.*, 2002).

Table 10 Mineralogy of Thai paddy soils.

Soil series	Geological Province	Depth (cm)	Clay fraction			
			Very much	Much	Moderate	Little
Tt1	S	43 - 70	Kaolin	-	Qtz, Ver	Fel
Tt2	S	15 - 60	Kaolin	-	Qtz	Fel, Sme
Tt3	S	23 - 60	Kaolin	-	Qtz	Fel, Ver
Ki	S	22 - 60	Kaolin	-	Qtz	Sme
Ms	M	33 - 54	-	Kaolin, Ill	Qtz	Fel, Sme
Hd	M	68 - 88/90	-	Kaolin, Qtz	Ill, Fel	
Cr1	M	106 - 123	Kaolin	-	Qtz, Ill	Fel, Sme
Cr2	M	60 - 100	Kaolin	-	Qtz, Ill	Fel, Sme
Sai	G	70 - 90	-	Kaolin, Qtz	Ill	Fel
Cs1	G	32 - 55	Kaolin	-	Qtz	Sme
Cs2	G	40 - 60	Kaolin	-	Qtz	Sme
Cs3	G	20 - 60	Kaolin	-	Qtz	Fel, Sme
Cb	G	20 - 38	Kaolin	-	Qtz, Ill	Fel
Kl	G	15 - 30	Kaolin	-	Qtz	Sme

S = sedimentary rock, M = metasedimentary rock, G = granite

Ill = illite, Ver = vermiculite, Sme = smectite, Qtz = quartz, Fel = feldspar

Very much = >60%, Much = 20-60%, Moderate = 5-20%, Little = ~2-5%

Table 11 Some properties of Thai paddy soil kaolins.

Soil series	Geological Province	Depth (cm)	CSD ₀₀₁ nm	HB index	SSA (m ² g ⁻¹)	CEC (cmol kg ⁻¹)	Width TEM (nm)±SD	An %	Sub %	Eu %
Tt1	S	43 - 70	5.9	4.3	82.7	19.3	39±13	62	34	4
Tt2	S	15 - 60	7.2	3.0	81.6	26.9	40±13	55	39	6
Tt3	S	23 - 60	8.1	4.8	65.4	13.7	49±16	71	28	1
Ki	S	22 - 60	7.2	3.0	90.0	29.7	54±17	60	38	2
Mean			7.1	3.8	79.9	22.4	45±16	62	35	3
Ms	M	33 - 54	19.5	1.5	35.5	23.8	88±37	69	28	3
Hd	M	68 - 88/90	19.5	1.3	55.2	42.7	65±22	60	35	5
Cr1	M	106 - 123	7.1	2.8	65.9	23.7	55±15	40	49	11
Cr2	M	60 - 100	6.9	3.3	62.6	18.7	81±30	74	26	0
Mean			13.2	2.2	54.8	27.2	72±31	61	34	5
Sai	G	70 - 90	16.0	2.9	46.1	15.9	109±42	47	50	3
Cs1	G	32 - 55	8.0	3.0	72.8	24.5	62±26	55	40	5
Cs2	G	40 - 60	7.0	2.5	69.4	28.0	89±38	58	37	5
Cs3	G	20 - 60	7.2	3.1	73.6	23.6	67±26	57	39	4
Cb	G	20 - 38	11.2	3.7	71.0	19.4	81±35	60	34	6
Kl	G	15 - 30	11.5	3.3	55.8	16.7	81±32	56	33	11
Mean			10.2	3.1	64.8	21.3	85±37	55	39	6

S= sedimentary rock, M = metasedimentary rock, G = granite

CSD₀₀₁ = coherently scattering domain size for 001 reflection, HB index = Hughes and Brown crystallinity index, SSA = specific surface area, CEC= cation exchange capacity, An = anhedral crystal, Sub = subhedral crystal, Eu = euhedral crystal

Table 12 Comparative data for soil kaolins.

Location	CSD ₀₀₁		HB index		SSA (m ² g ⁻¹)		CEC (cmol _c kg ⁻¹)	
	range	mean	range	mean	range	mean	range	mean
Thai paddy soils	5.9-19.5	10.2	1.3-4.8	3.0	35.5-90.0	66.3	13.7-42.7	23.3
Thai upland soils ¹	9.1-43.7	16.8	3.3-11.4	5.6	9.0-67.8	40.7	4.4-23.4	12.5
W Australia ²	19.3-27.7	22.9	4.8-6.2	5.5	33.6-67.8	50.8	2.9-7.6	5.0
Indonesia ³	8.1-13.7	10.8	4.1-7.1	5.6	59.0-88.0	72.8	5.2-12.9	9.4
Nigeria ⁴	-	-	4.3-13.7	8.0	-	-	-	-
Queensland ³	-	-	3.4-8.6	5.9	-	-	9.3-30.5	-
Georgia kaolin code MP5 ⁵	-	37.5	-	28.2	-	18.0	-	2.3

¹Hart *et al.* (2003); ¹Kanket *et al.* (2005); ¹Trakoonyingcharoen *et al.* (2006); ²Singh and Gilkes (1992); ³Hart *et al.* (2002, 2003); ⁴Hughes and Brown (1979); ⁵Kanket *et al.* (2005)

2.1 Size and Shape of Kaolin Crystals

Transmission electron micrographs (TEM) of representative kaolins are shown in Figure 17 which clearly demonstrates the small size and diverse morphologies for different samples. These observations were quantified by determining the morphology of ~100 crystals for each sample. Most Thai paddy soil kaolins consist of large anhedral crystals and small subhedral and euhedral crystals (Table 11). The crystal size of Thai paddy soil kaolins as indicated by the width of crystals in micrographs varies from 19-306 nm with a mean value of 69 nm. Thai paddy soils kaolins in alluvium from a sedimentary province have the smallest crystal size (45±16 nm), whereas kaolins in alluvium from a metamorphic province have higher crystal sizes (72±31) and kaolins in alluvium from a granite province have the largest crystal sizes (85±37 nm). The mean values of the shape ratio (Sr = length/width) for Thai paddy soil kaolins (1.38-1.52) were quite different from Georgia kaolin (1.17) (Singh and Gilkes, 1992). To calculate the proportions of lath shaped and equant particles, Sr value = 2.0 was taken as the boundary between the two shapes. Thus Sr>2.0 identifies a lath and Sr<2.0 identifies an equant crystal. Histograms of the frequency of values of the shape ratio (Sr) derived from TEM micrographs are shown in Figure 18 which identifies that equant crystals are dominant for Thai paddy soil kaolins. Figure 19 indicates that there is a large range of crystal sizes for most kaolins.

2.2 Specific Surface Area and Cation Exchange Capacity

The specific surface area of Thai paddy soil kaolins is large, ranging between 35.5 and 90.0 m² g⁻¹ with a mean value of 66.3 m² g⁻¹. The large surface area is due to the small crystal size. Consequently, specific surface area is inversely related to crystal size (CSD₀₀₁) (Figure 20 and Table 13).

The cation exchange capacity of the Thai paddy soil kaolins ranges from 13.7 to 42.7 cmol(+) kg⁻¹, with a mean of 23.3 cmol(+) kg⁻¹. The CEC of all the soil kaolins is higher than for Georgia kaolin (2.3 cmol(+) kg⁻¹) and most Thai upland soil kaolins (Kanket *et al.*, 2005; Trakoonyingcharoen *et al.*, 2006) (range 4.4 to 23.4 cmol(+) kg⁻¹, mean 12.5 cmol(+) kg⁻¹). CEC is not systematically related to SSA but has strong negative relationship with HB index (Table 13). These relationships are likely to be degraded by the presence of minor smectite, illite and vermiculite in the kaolin concentrates, their impurities will contribute to values of CEC and SSA (Hart *et al.*, 2002; Trakoonyingcharoen *et al.*, 2006).

2.3 Chemical Composition

Electron micrographs and EDS on single crystals of representative kaolins are shown in Figure 21. Al/Si and Fe/Si X-ray intensity ratio of the kaolins as determined by EDS on single crystals are shown in Table 14. The Al/Si ratio of Thai paddy soil kaolins ranges from 0.7-0.8 which is different from Al/Si ratio of Indonesia kaolin samples (0.96-1.04) and Western Australian kaolin samples (0.96-1.00) (Hart *et al.*, 2002). The Al/Si ratio of Thai paddy soil kaolins are <1.00 which may be due to Fe substitution for Al. There is high Fe incorporated into kaolin formed under wet conditions which effect to the kaolin structure. In addition, the presence of iron in the structure of kaolin with the amount of Fe substitution is possibly depending on parent material. Thai paddy soil kaolins in alluvium from a sedimentary province has the lowest iron content (100 Fe/Si = 3.0), kaolins in alluvium a metamorphic province have higher iron content (100 Fe/Si = ~5.8) and kaolin in alluvium from a granite province has the highest iron content (100 Fe/Si = ~9.8).

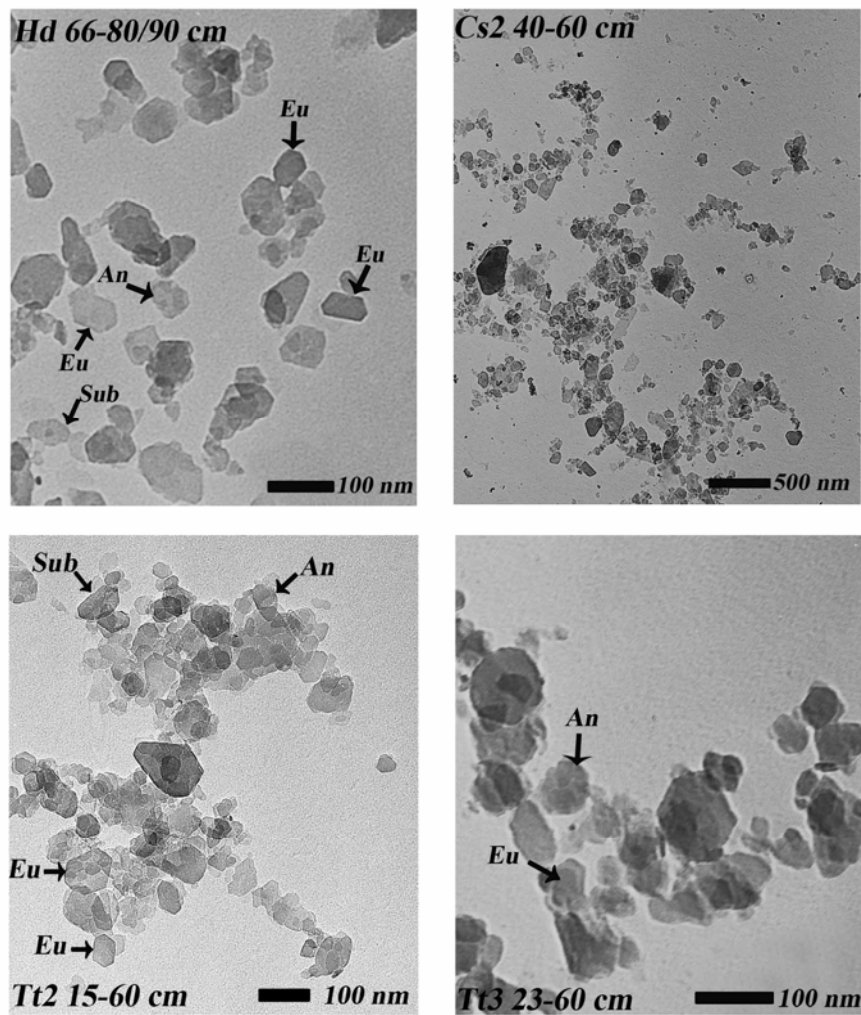


Figure 17 Transmission electron micrographs (TEM) of representative soil kaolins showing the wide ranges of crystal morphology and size. Various morphologies are indicated in the figure: An = anhedral crystal; Sub = subhedral crystal; Eu = euhedral crystal.

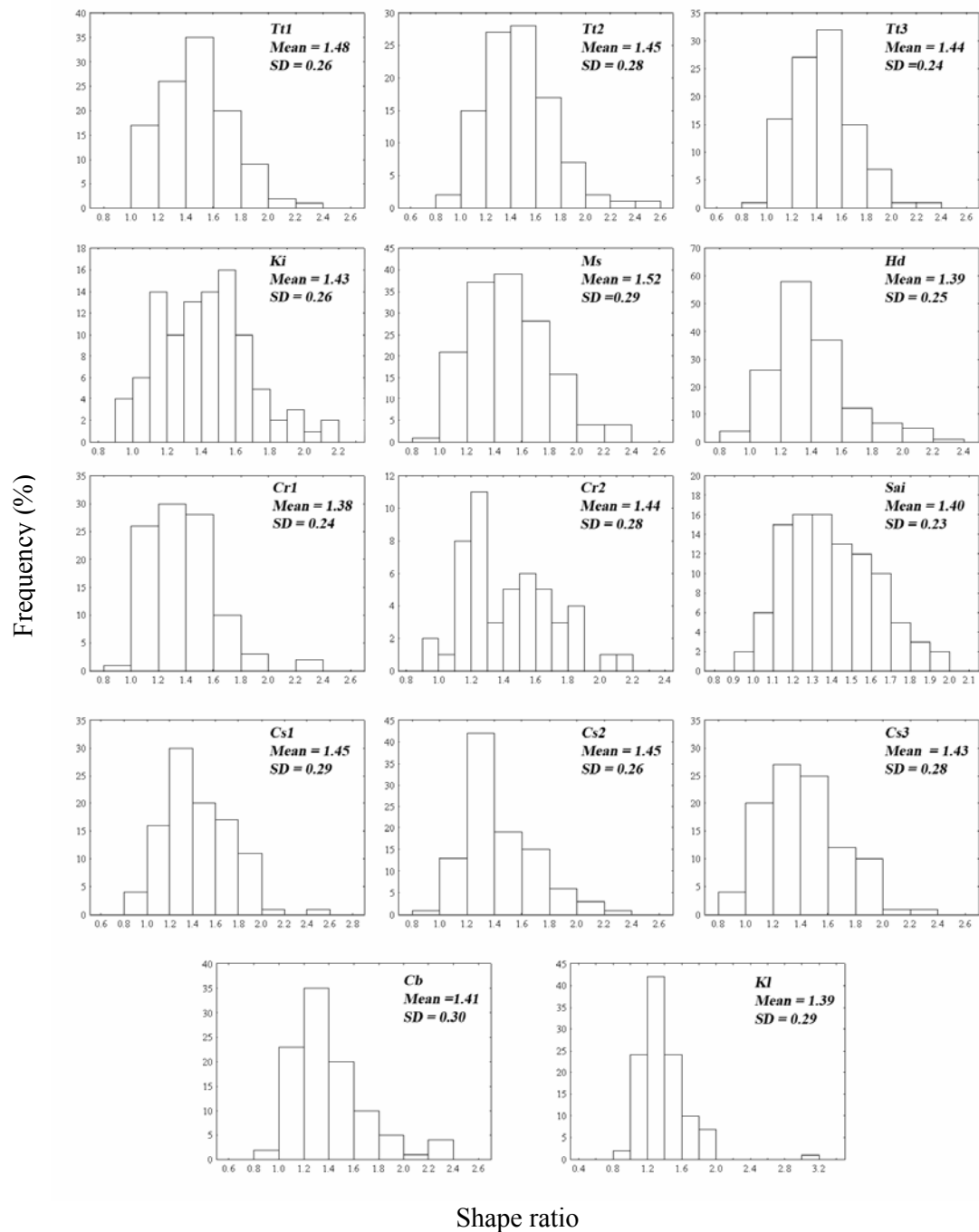


Figure 18 Histogram of the frequency of occurrence of crystals with various values of shape ratio (length/width) determined by TEM for Thai paddy soil kaolins.

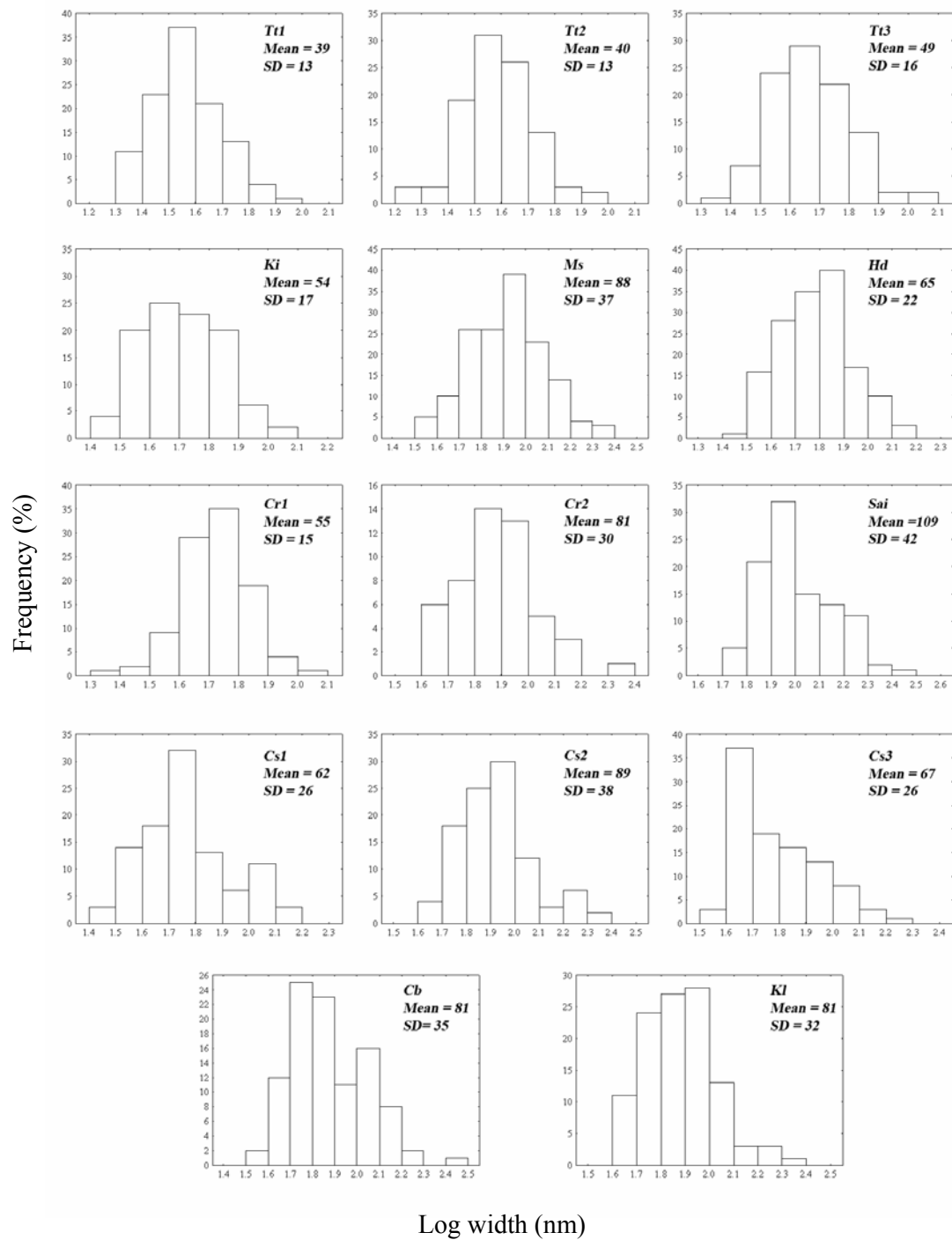


Figure 19 The frequency distribution of values of log width (nm) of kaolin crystals determined by TEM for Thai paddy soil kaolins. Mean and SD values are expressed in nanometres.

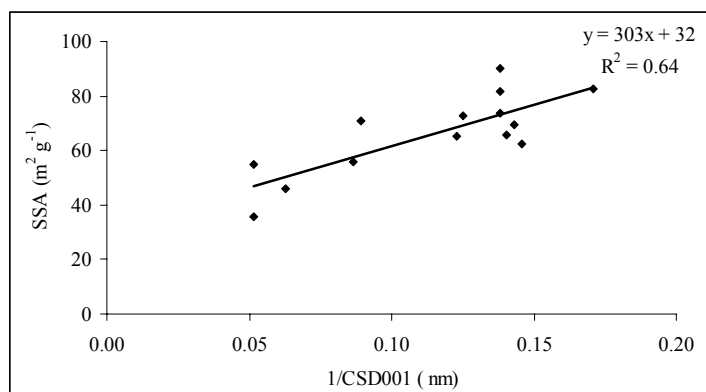


Figure 20 Bivariate relationship of specific surface area with the reciprocal of coherently scattering domain (CSD) size for Thai paddy soil kaolins.

Table 13 Correlation matrix (R values) for properties of kaolin in Thai paddy soils (n = 14, p < 0.01).

	CSD ₀₀₁	CSD ₀₀₂	SSA	CEC	HB index	Eu	L/W	Mean L	Mean W
CSD ₀₀₁	1.00								
CSD ₀₀₂	0.88*	1.00							
SSA	-0.81*	-0.78*	1.00						
CEC	0.29	-0.05	0.11	1.00					
HB index	-0.66*	-0.41	0.49	-0.73*	1.00				
Eu	0.34	0.35	-0.44	0.12	-0.43	1.00			
L/W	-0.29	-0.30	0.49	0.21	0.13	-0.50	1.00		
Mean L	-0.21	-0.13	0.29	0.21	-0.12	-0.10	-0.02	1.00	
Mean W	-0.18	-0.11	0.24	0.20	-0.13	-0.06	-0.12	1.00*	1.00

CSD = coherently scattering domain size, SSA = specific surface area, CEC = cation exchange capacity, HB index = Hughes and Brown crystallinity index, Eu = euhedral face, L/W = length/width

Table 14 Mean values (N = 23) of Al/Si and Fe/Si X-ray intensity ratios of single kaolin crystals determined by EDS.

Sample	Geological province	Al/Si*	100 Fe/Si*
Tt2	Sedimentary rock	0.8	3.0
Hd	Metasedimentary rock	0.7	5.7
Cr1	Metasedimentary rock	0.7	5.8
Cs1	Granite	0.8	9.8

* Note: some Si counts may originate from Si contamination of the carbon support film

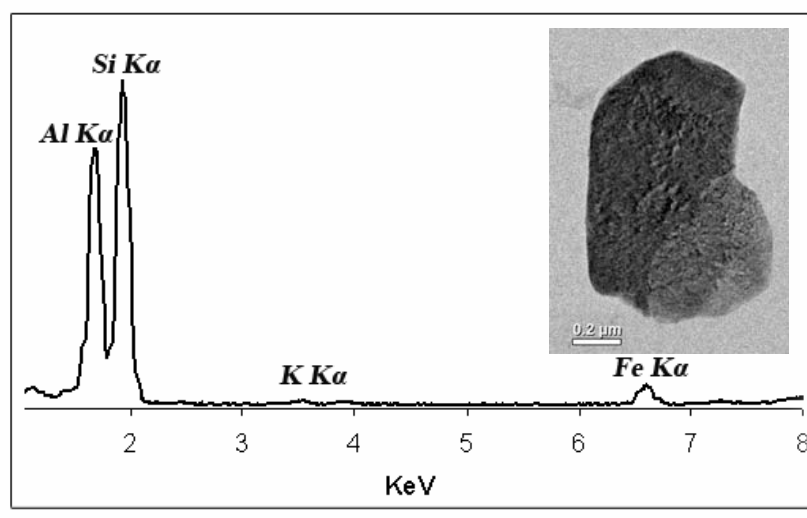


Figure 21 EDX spectrum for a representative soil kaolins, Btg3 horizon (106-123 cm) of Chiang Rai series.

Micromorphological Properties

1. Microstructure

The main micromorphological features of Thai paddy soils are illustrated in Figure 22 and listed in Table 15. The micromorphological properties of the soils

are affected by their parent materials and genesis. The macroporosity of Thai paddy soils containing much clay and with the dominant being smectite decreases with depth, while it tends to increase with depth in other soil profiles (Figure 23). The fine texture soils, including Hd, Cr and Cs are apedal, while the coarser textured soils, consisting Ki, Kl, Sai and Cb, have single grain, bridged grain and compact grain structures, respectively. Vughy structure dominates in the topsoil of Re, Tt, Pm1, Pm2 and Ms whereas angular blocky structure dominates in Ud. The crack structure dominates in the smectite-rich soils (Lb, Tr, Kk and Bph). The formation of crack microstructures is caused by shrinking and swelling of soil materials as a result of drying and wetting (Fanning and Fanning, 1989; Pal *et al.*, 2001). In dry conditions, these soils crack deeply but these cracks close when the soils become wet either due to rain or irrigation water.

2. Basic Mineral Components

The fine materials of all soils have grayish brown to light gray colour and yellowish brown to brownish yellow colour. The basic mineral components are closely related to their parent materials. In all of the soils of coarse materials consist mainly of single quartz grains. Quartz is the major constituent in all soils due to quartz being a highly resistant mineral in soils. Sericite (fine mica) is present and disseminated throughout s-matrix of Ms (Figure 24a) and the carbonate is present and distributed throughout s-matrix of Lb (Figure 24b). In both instances the occurrence of these minerals is related to specific parent materials.

3. Basic Organic Components

The abundance of organic materials visible in thin sections decreases with depth. The organic components of the topsoils from the Northern, Northeastern and Eastern areas are quite similar. They consist of the living plant tissues of various shapes and sizes, while relatively more amorphous organic fine material and punctuations are present in subsoil, except for the San Sai profile.

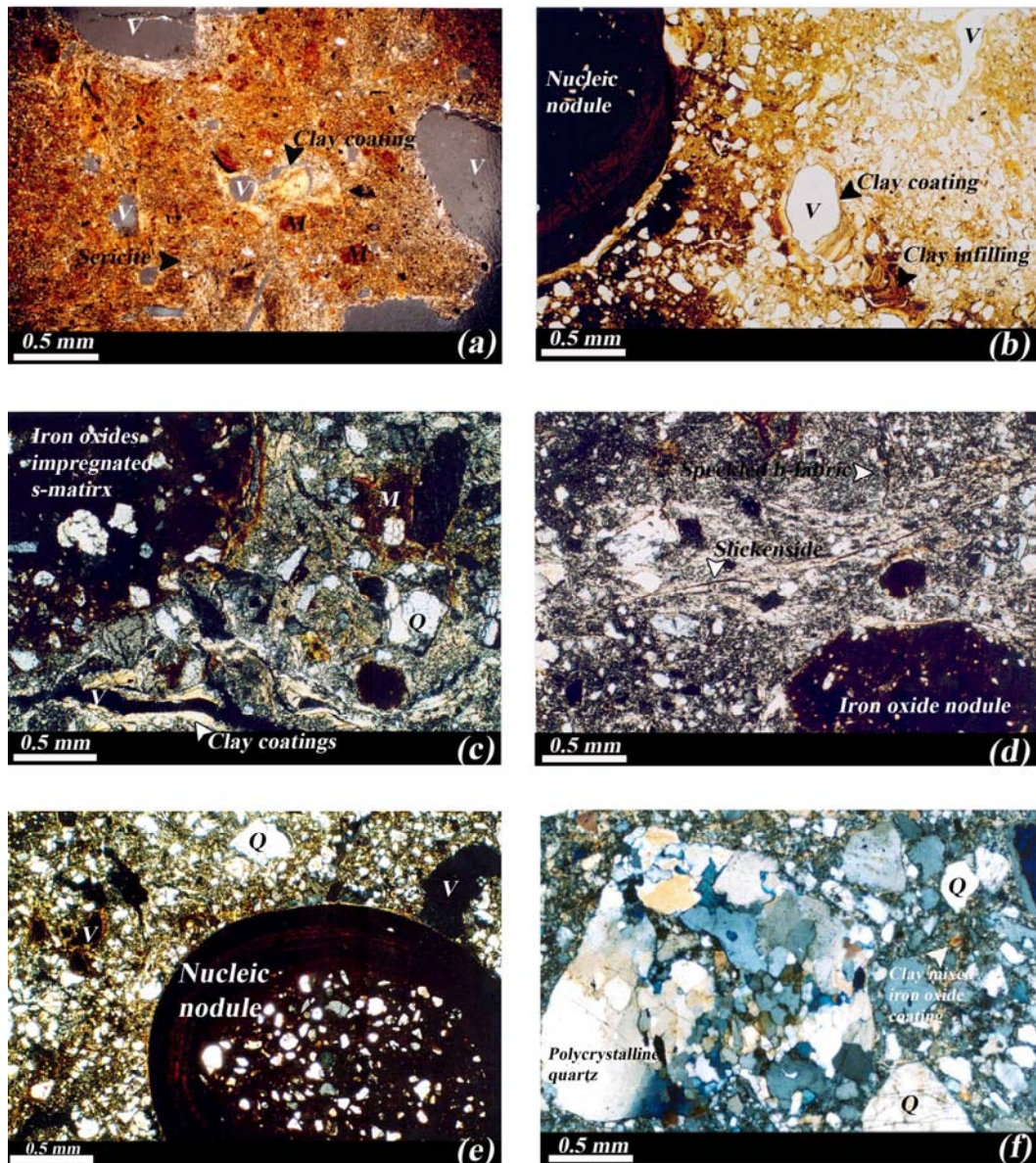


Figure 22 Micromorphology of the soil horizons: (a) Btg4 horizon (94-125 cm) of Mae Sai series; (b) 2Btng5 horizon (108-132 cm) of Kula Ronghai series; (c) 2Btg7 horizon (148-174 cm) of Hang Dong series; (d) Btcg3 horizon (166-190 cm) of Chiang Rai series; (e) Btg1 horizon (22-38 cm) of Phimai 2 series; (f) Btg7 horizon (175-192 cm) of Chon Buri series (M = mottle, Q = quartz, V = void).

Table 15 Micromorphology of Thai paddy soils.

Soil series	Microstructure	Total porosity (%)	c/f ratio	Pedofeature
Roi Et (Re) Apg1 (0-14 cm)	Vughy	15	30:70	Excrement, some impregnative ferruginous nodules
Btg4 (90-116 cm)	Subangular blocky	25	30:70	Clay coatings and infilling; impregnative ferruginous nodules
Tha Tum (Tt) Apg1 (0-12 cm)	Vughy	15	30:70	-
Btg2 (43-70 cm)	Subangular blocky	25	30:70	Manganiferous impregnative nodules
Phimai (Pm1) Apg1 (0-12 cm)	Vughy	15	5:95	Transported ferruginous nodules
Btg3 (76-105 cm)	Subangular blocky	15	20:80	Clay coatings; transported ferruginous nodules
Phimai (Pm2) Apg1 (0-10 cm)	Vughy	30	40:60	Impregnative ferruginous nodules; concentric nodules
Btg2 (38-60 cm)	Channel	25	20:80	Clay coatings and infillings; impregnative ferruginous nodules; concentric nodules
Kula Ronghai (Ki) Apg1 (0-18 cm)	Single grain	25	80:20	Iron oxide nucleic nodules
Btg (30-48 cm)	Vughy	20	60:40	Clay mixed iron oxide coatings; nucleic nodules and iron oxide impregnative nodules
Udon (Ud) Ag (0-21 cm)	Angular blocky	5	20:80	Impurity cryptocrystalline halite; iron oxide typic nodules
Btng1 (21-41 cm)	Angular blocky	5	30:70	Clay coatings
Mae Sai (Ms) Apg1 (0-15 cm)	Vughy	10	2:98	-
Btg3 (70-94 cm)	Vughy	10	2:98	Clay coatings and infillings
Hang Dong (Hd) Apg1 (0-15 cm)	Apedal soil material	2	5:95	Transported ferruginous nodules
Btg1 (29-50/53 cm)	Apedal soil material	7	20:80	Impregnative manganiferous nodules; clay coatings
San Sai (Sai) Apg1 (0-13/17 cm)	Compact grain	20	90:10	Impure carbonate coatings and infillings
Btg3 (40-50 cm)	Compact grain	5	90:10	Clay infilling

Table 15 (Continued).

Soil series	Microstructure	Total porosity (%)	c/f ratio	Pedofeature
Chiang Rai (Cr)				
Apg1 (0-12 cm)	Apedal soil material	2	20:80	Few iron oxide transported impregnative nodules
Btg1 (30-53 cm)	Vughy	10	20:80	Clay coatings; iron oxide transported concentric nodules
Chum Seang (Cs)				
Apg1 (0-12 cm)	Apedal soil material	5	10:90	Iron oxide transported typic and concentric nodules
Btg1 (12-32 cm)	Vughy	20	15:85	Clay coatings and dense complete clay infilling; iron oxide transported typical and concentric nodules
Chon Buri (Cb)				
Apg1 (0-20 cm)	Bridged grain	10	90:10	-
Btg2 (65-87 cm)	Bridged grain	10	75:25	Clay mixed with iron oxide coatings; iron oxide impregnative s-matrix
Klaeng (Kl)				
Apg1 (0-13/15 cm)	Compact grain	25	90:10	-
Btg (30-57 cm)	Compact grain	5	90:10	Ferruginous nodules; clay coatings and infillings
Lop Buri (Lb)				
Ap (0-23 cm)	Crack	10	3:97	Cryptocrystalline calcite; iron oxide concentric and typic nodules
Bss (70-90 cm)	Crack	10	5:95	Iron oxide diffuse boundaries
Tha Rua (Tr)				
Apg1 (0-18 cm)	Crack	20	2:98	Cryptocrystalline calcite; iron and manganese oxide impregnative nodules
Btg1 (35-60 cm)	Crack	10	2:98	Cryptocrystalline calcite; iron and manganese oxide impregnative nodules
Khok Krathium (Kk)				
Apg2 (10-27 cm)	Crack	20	2:98	-
Btg2 (45-63 cm)	Crack	10	2:98	Clay coatings
Bang Phae (Bph)				
Apg2 (6-30 cm)	Crack	10	10:90	Cluster of prismatic gypsum; iron mixed with manganese oxide moderately impregnative nodules
Bg1 (55-80 cm)	Crack	10	20:80	Cluster of prismatic gypsum

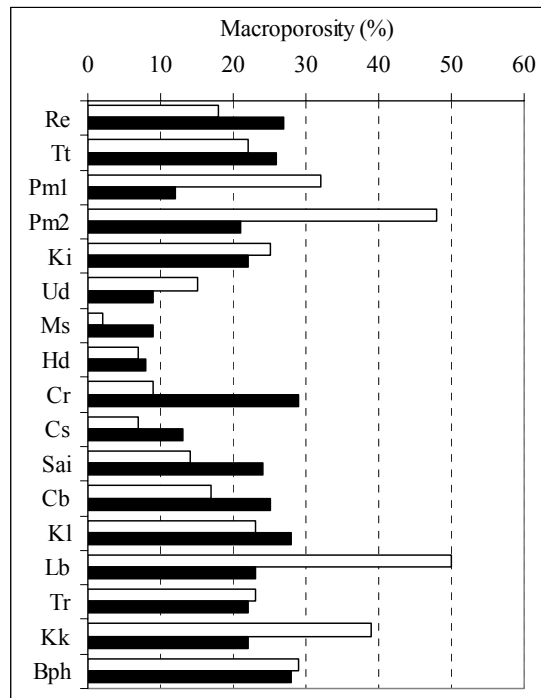


Figure 23 Mean values of macroporosity (%) of soil profiles (□= topsoil, ■ = subsoil).

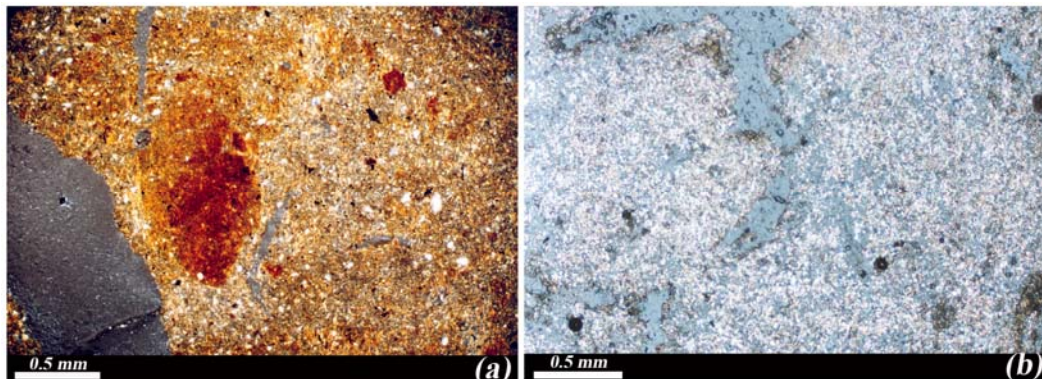


Figure 24 Soil matrix of some Thai paddy soils (a) sericite (fine mica) disseminated throughout the s-matrix of Mai Sai series (Btg4 horizon; 94-125 cm) and (b) carbonate is disseminated throughout the s-matrix of Lop Buri series (BCk horizon; 130-155 cm).

The organic components of the San Sai soil are abundant organic pigment associated with clay and silt fractions forming soil aggregates (500-2100 μm width) (Figure 25) which occupy about 25% of the total area of the thin section and very few fragments of lignified tissue. The soils of the Central Plain have similar organic components comprising moderately to highly decomposed plant tissue residues which occur in voids and decrease in abundance with depth.

4. Pedofeature

Obviously, lowland soils have distinct wet and dry seasons. These soils will consequently have features that depend on both prolonged soil-wet and soil-dry conditions. The important pedofeatures include amorphous and textural pedofeatures.

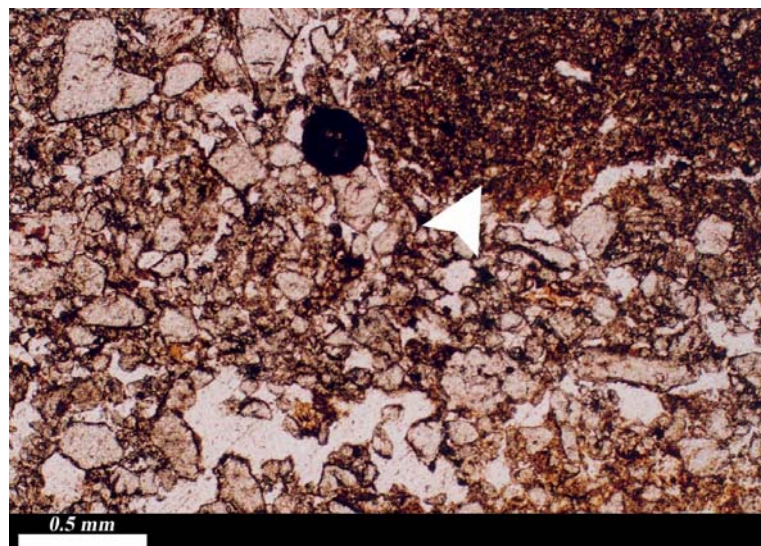


Figure 25 Organic pigment associated with clay and silt fractions forming soil aggregates in the Apg1 (0-13/17 cm) horizon, San Sai series.

4.1 Amorphous Pedofeatures

The amorphous pedofeatures of all soils are quite similar. They include impregnative ferruginous nodules and the yellowish brown to strong brown clay with iron oxide mottles present as coating, hypo-coating and diffuse material in the s-matrix (Figure 26). The impregnative ferruginous nodules present in the topsoil are due to transportation (Bullock *et al.*, 1985). Iron oxide coatings and hypo-coatings present in these soils have resulted from combination of groundwater fluctuation and seasonal flooding giving rise to cycles of reducing and oxidizing conditions (Vepraskas, *et al.*, 1994). Moreover the extent of development of these features depends upon the intensity of the dryness. Coatings indicate restricted drying with only the surface of peds experiencing an oxidizing environment, whereas hypo-coatings suggest intense drying with oxidation conditions prevalent at a short distance from the surface (Boixadera *et al.*, 2003).

Iron oxides coating in topsoil may occur as a result of oxygen diffusion from root plants when these soils experience anaerobic conditions (Figure 26d). Upon draining, some areas around pores, voids and root channels become dry and are aerated more quickly than the rest of the soil, causing precipitation of ferric iron. Both iron and manganese oxides present in these soils result from seasonal water table fluctuations giving rise to cycles of reducing and oxidizing conditions.

Prolonged saturation of soils results in anaerobic conditions leading to the formation of mobile ferrous iron by dissolution of iron oxides. The migrating soil water and diffusion redistribute the iron throughout the soil profile. In the case of mottles, not only are long periods of saturation needed to cause a sufficient mobility of Fe and Mn, but also periods of intense oxidization to produce the accumulation (Kemp *et al.*, 1998). These mottles horizons coincide with the zones of fluctuation of the water table.

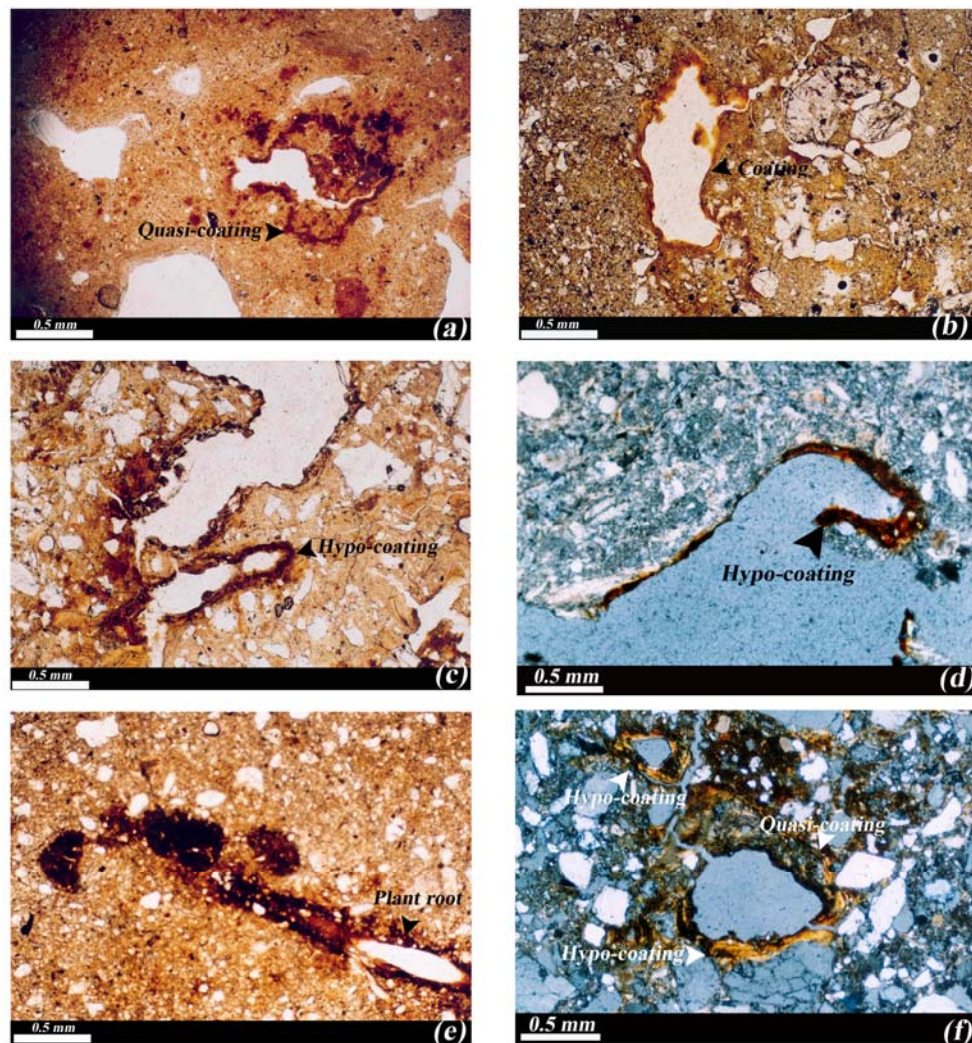


Figure 26 Optical micrographs of Thai paddy soils (a) iron oxide quasi-coating in Mae Sai series (Btg3 horizon, 70-93 cm); (b) iron oxide coatings in Roi Et series (Btg6 horizon, 140-169 cm); (c) iron oxide hypo-coatings in Chon Buri series (Apg2 horizon, 20-38 cm); (d) iron oxide hypo-coating in Chiang Rai series (Btcg3 horizon, 166-190 cm); (e) iron oxide along plant root in Hang Dong series (Apg1 horizon, 0-15 cm) and (f) clay mixed with iron oxide coating and hypo-coating in Chon Buri series (Apg2 horizon, 20-38 cm).

4.2 Textural Pedofeatures

The soils micromorphological feature related to the mobility of the fine fraction due to drainage include clay coatings. Most of the soils examined have clay coatings, hypocoatings and infillings in the subsoil horizons. The presence of illuvial clay indicates that water has percolated through the soil and also that the soil has a periodically dry period when it cracks. This causes a regular arrangement of oriented clay particles. The clay particles are in continuous parallel orientation along channel walls demonstrating that accumulation was due to percolating clay suspensions in cracks (Boixadera *et al.*, 2003). Some pedofeature are due to human activity such as the impure carbonate coatings and infilling present about 1-2% of the area of the thin section of Apg1 of Sai which are due to amelioration with lime.

All studied horizons are composed mostly of fine materials, which have mainly a grayish brown to light gray colour. The fine fraction of Ud, Ms, Tr, and Kk is rather uniform throughout the profiles. The fine fraction of some soils decreases in abundance with depth (Hd, Lb and Bph), while it increases with depth in Sai, Cr, Cs, Re, Tt, Pm1, Pm2, Ki, Cb and Kl. Most Thai paddy soils have a speckled fabric which is generated by suspension settling or flocculation of fine alluvial material during sedimentation (Fitzpatrick, 1993). The textural pedofeature most clearly related to the mobility of the fine fraction is the presence of clay coatings.

4.3 Crystalline Pedofeatures

Cryptocrystalline calcite impregnative nodules of 20-2000 μm size are present in the lower horizons of Lb and Tr indicating the effect of the calcareous parent material. Prismatic gypsum (grain size ranges from 10-100 μm) and clusters of prismatic gypsum have accumulated in some voids of Bph possibly as a consequence of oxidation of pyrite in sediments formed in a deltaic environment. Impure cryptocrystalline halite is present in the topsoil of Ud but not in the subsoils, it has probably formed by capillary rise of saline soil solution from deeper layers and subsequent precipitation as the soil dried.

7. SEM/EDS Analysis

Numerous SEM-EDS single point analyses of mottles, concretion and soil matrix were carried out and indicate that the iron concentration of mottles and concretion varies considerably and is mostly greater than in the associated soil matrix. Calcium is a major constituent of Lb (Figure 27) whereas the major constituents of the matrix of other soils are mainly Si with lesser Al and Fe. The relatively high Si concentration in the ternary diagram is partly due to very fine quartz distributed in the soil matrix and also to the presence of the 2:1 phyllosilicate minerals, including smectite and illite. Important pedofeatures in Thai paddy soils are textural and amorphous pedofeatures with clay coatings and clay coating mixed with iron-oxide coatings in subsoil horizon. The chemical compositions of the clay coatings are quite similar to the compositions of associated soil matrix (Figure 28). The element mapping shows that the weak to moderate iron oxide impregnated mottles contain quartz grains with the same shape and size as quartz in the matrix and also have an $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio similar to that of the matrix, both observations indicate that the iron oxide impregnated mottles have simply formed *in situ* (Figure 29) (Tawornpruek *et al.*, 2006).

In some soils, the normalized chemical compositions of iron oxide nodules and concretions fall on the kaolin composition line (Figure 30), whereas the chemical composition of the matrix reflects the smectite or illite-rich composition. Thus the iron oxide nodules and concretions present in these Thai paddy soils are exogenous and did not form *in situ*. Data points deviating from the kaolin line towards the Al_2O_3 apex mass indicate that gibbsite is present in the nodules and concretions (Tawornpruek *et al.*, 2006) (Figure 31).

The soils of upland regions adjacent to the paddy soil site include Oxisols and other soils that contain concretions composed of iron oxides, kaolin and sometimes gibbsite, that therefore provide a proximate source for iron oxide nodules and concretions (Trakoonyingcharoen *et al.*, 2006).

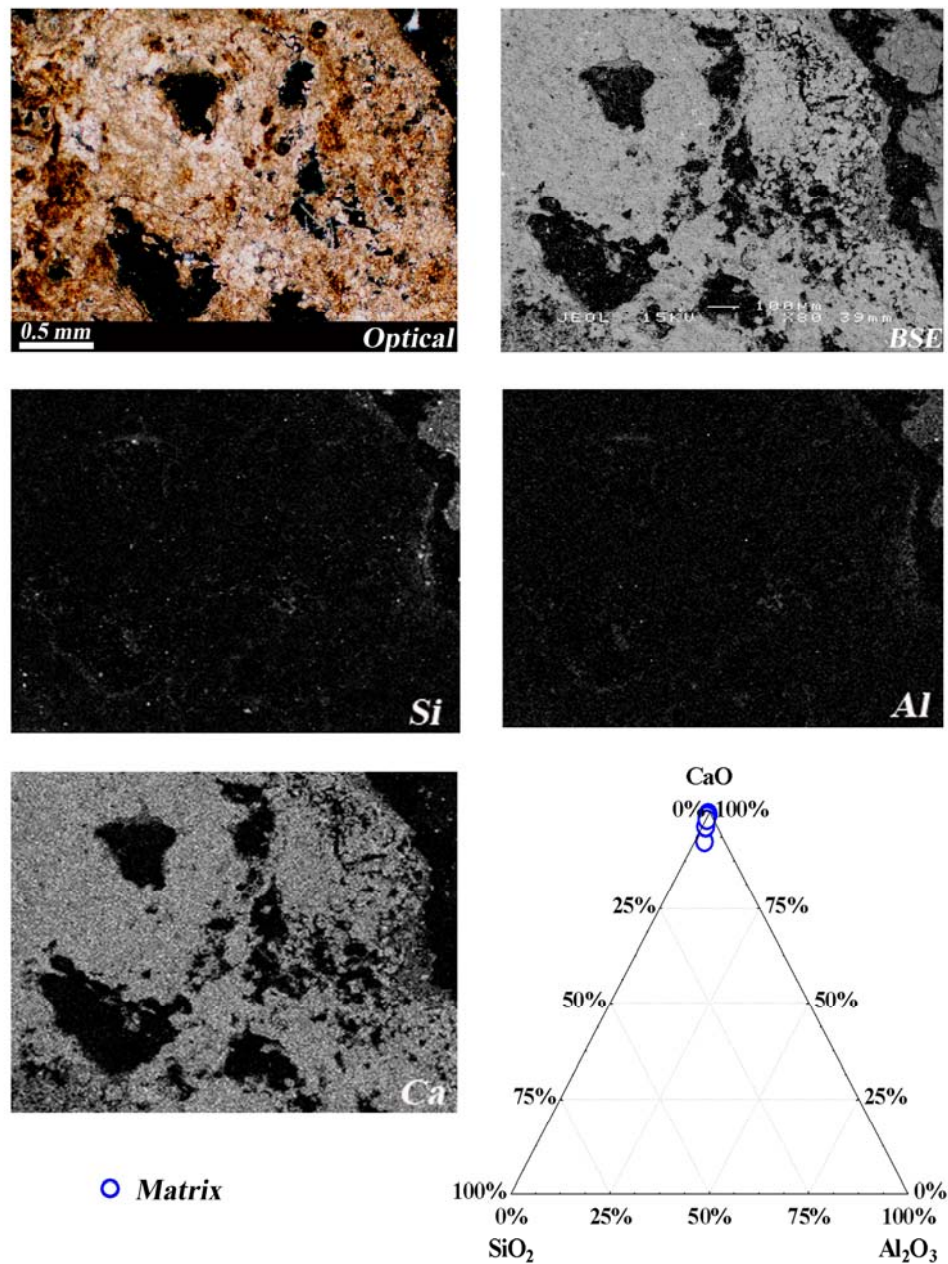


Figure 27 Optical, backscattered electron micrograph and element maps (Si, Al and Ca) and normalized composition triangular graph for the Ap (0-23 cm) horizon of Lop Buri series where the matrix consists of smectite, minor other clay minerals and lesser disseminated calcite. The nodules consist of almost pure calcite (V = void, C = CaCO₃ nodule, M = matrix).

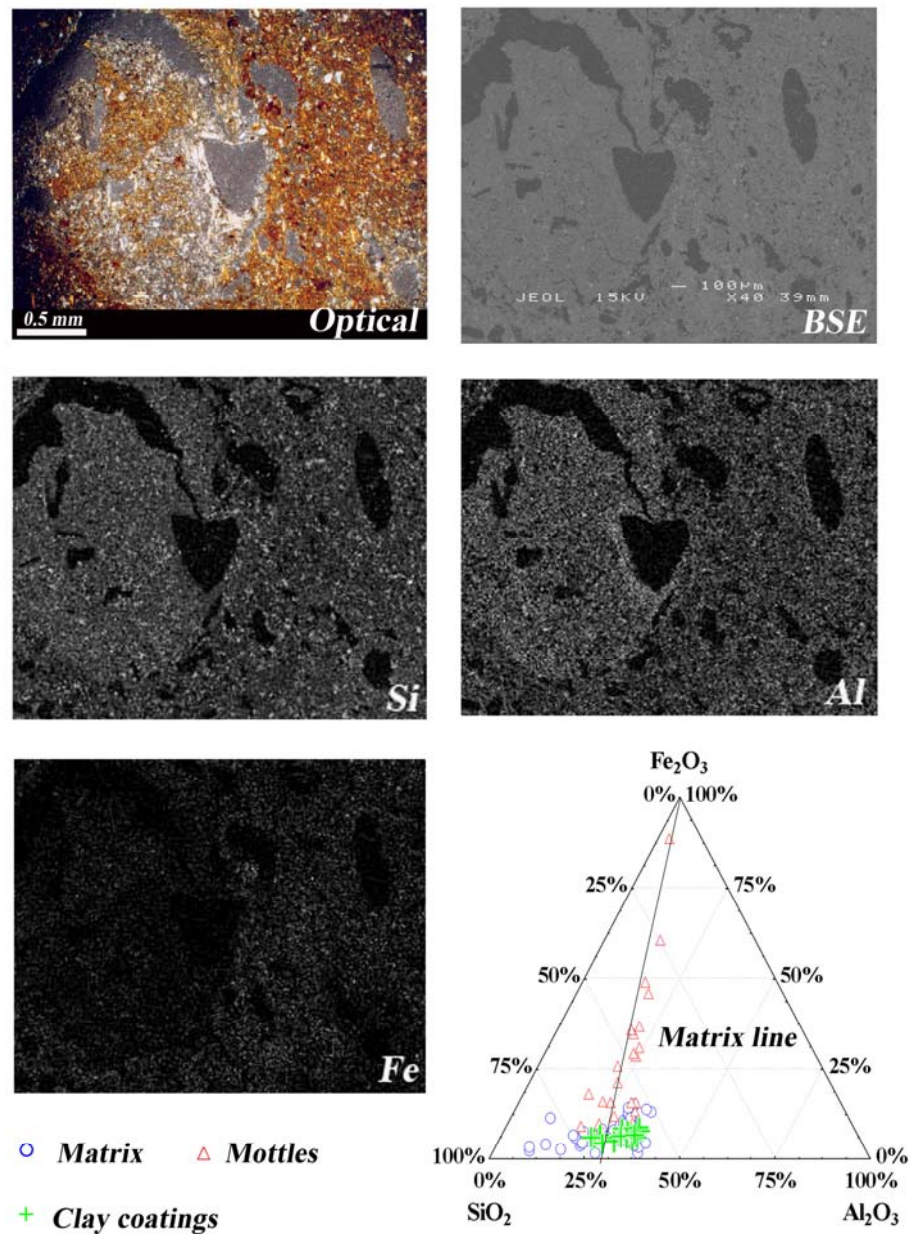


Figure 28 Optical, backscattered electron micrograph and element maps (Si, Al and Fe) and normalized composition triangular graph for the Btg4 (94-125 cm) horizon of Mae Sai series. The matrix consists mostly of approximately equal amounts of kaolin and illite (30% Al₂O₃, 70% SiO₂) and the compositions of clay coatings and iron oxide mottles mostly fall close to the line for this Al₂O₃/SiO₂ ratio.

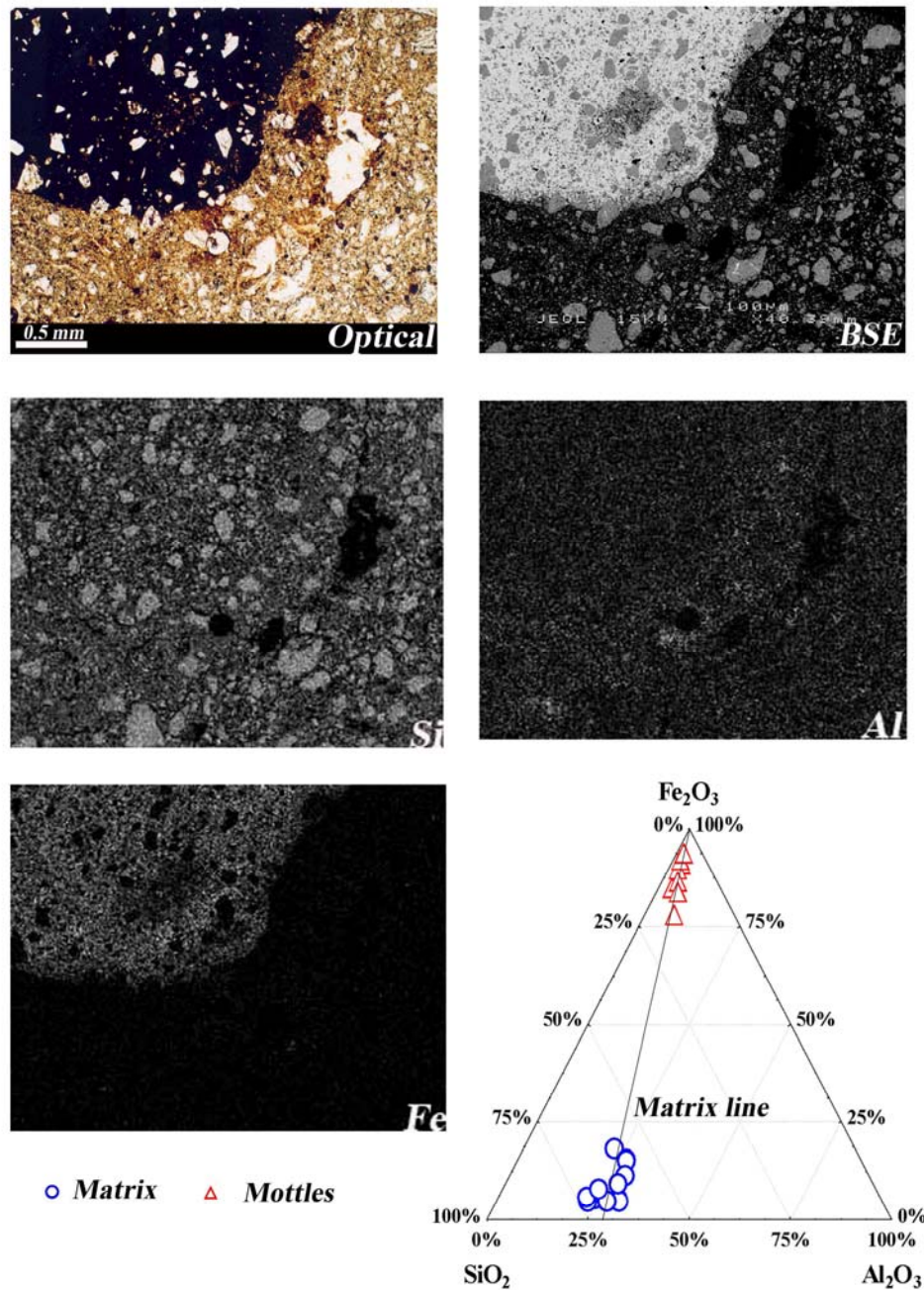


Figure 29 Optical, backscattered electron micrograph and element maps (Si, Al and Fe) and normalized composition triangular graph for the Apg1 (0-14 cm) horizon of Roi Et series. The matrix consists mostly of approximately equal amounts of kaolin and smectite (29% Al_2O_3 , 71% SiO_2) and the composition of iron oxide mottles falls on the line for this $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratio.

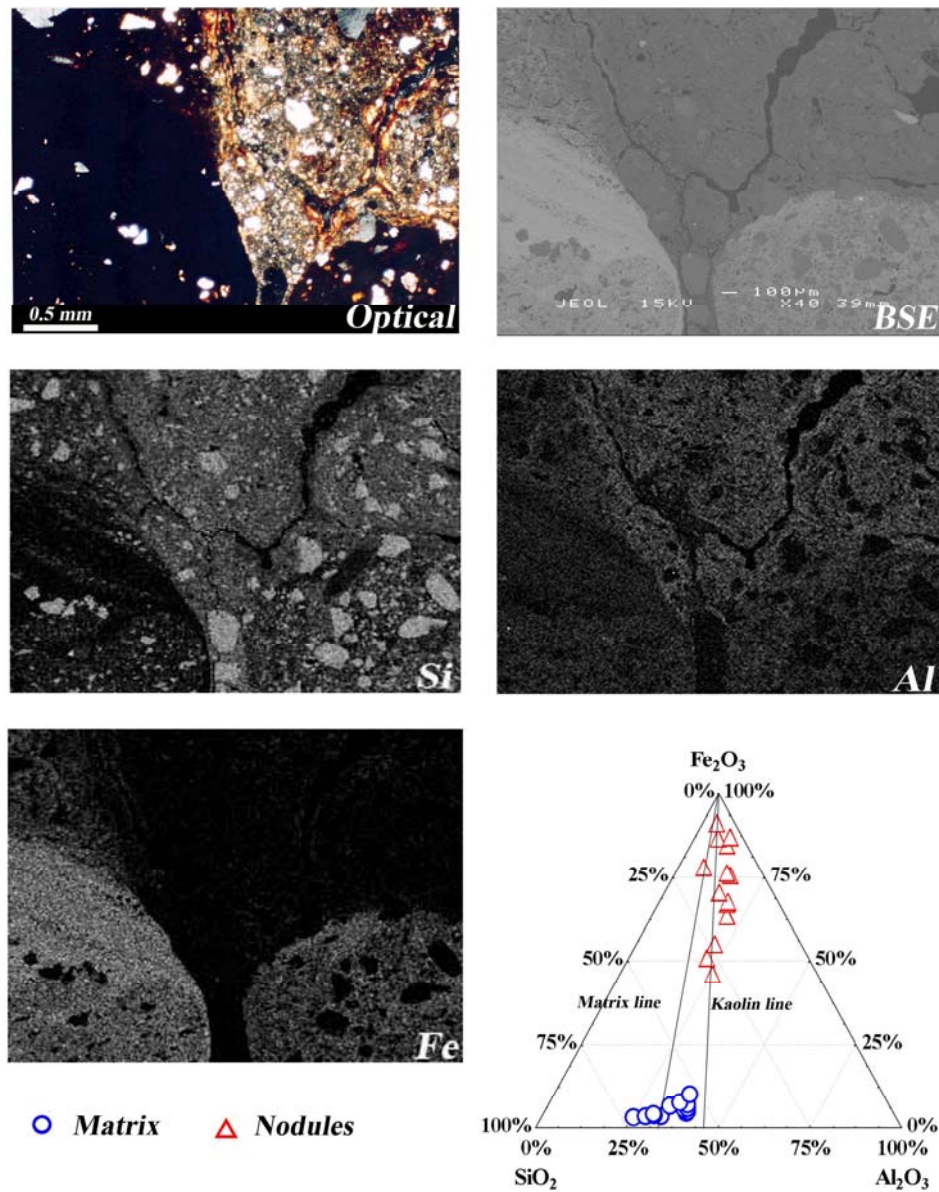


Figure 30 Optical, backscattered electron micrograph and element maps (Si, Al and Fe) and normalized composition triangular graph for the Bteg1 (53-80/90 cm) horizon of Chiang Rai series. The matrix consists of various mixtures of kaolin and lesser illite with a Al₂O₃/SiO₂ ratio of about 36%/64% whereas the composition of ferruginous nodules falls on the kaolin line (46% Al₂O₃/ 54% SiO₂).

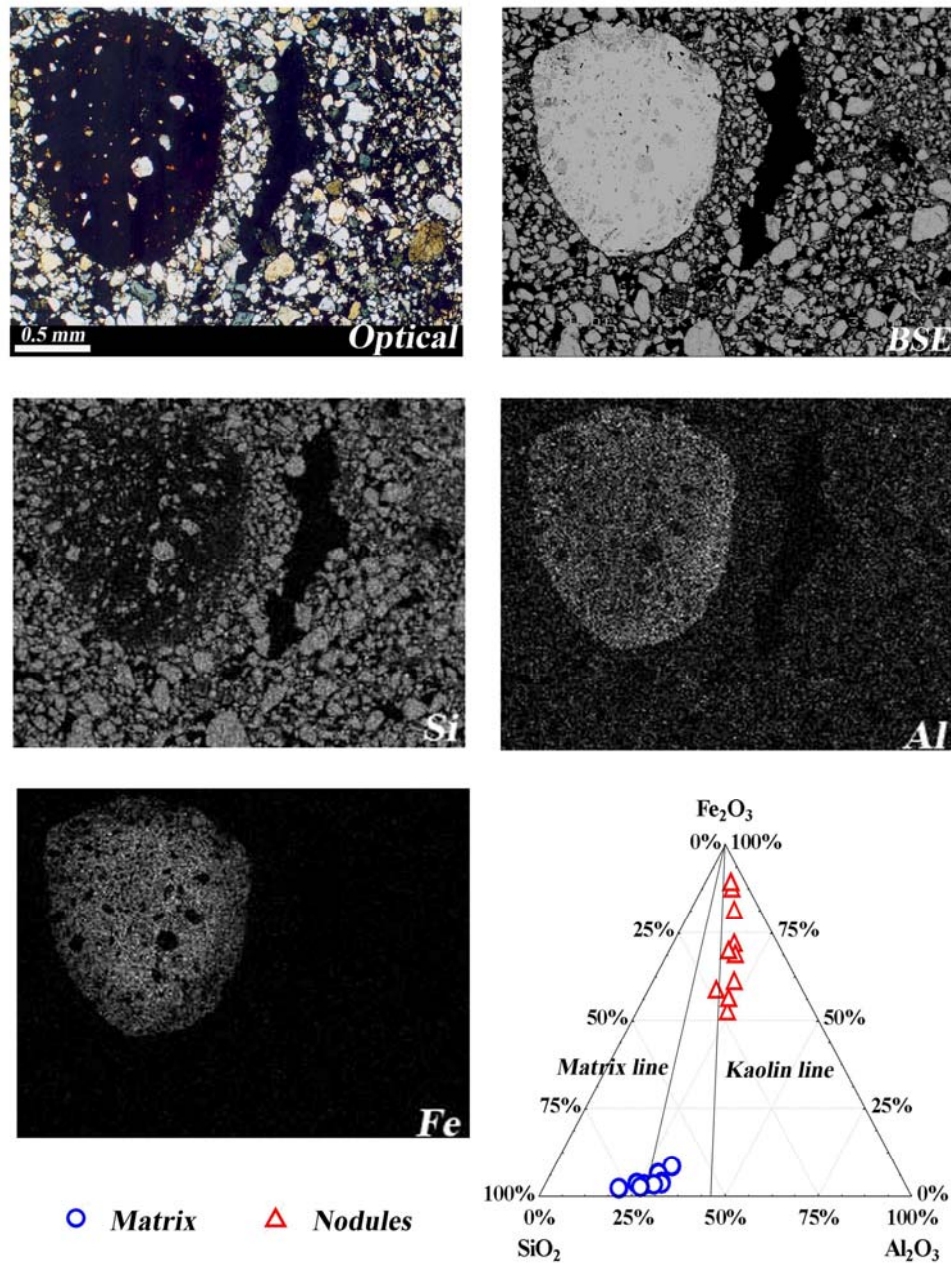


Figure 31 Optical, backscattered electron micrograph and element maps (Si, Al and Fe) and normalized composition triangular graph for the Apg1 (0-18 cm) horizon of Kula Ronghai series. The matrix consists of various mixtures of kaolin and lesser smectite with a Al₂O₃/SiO₂ ratio of about 29%/71% whereas the composition of ferruginous nodules indicates that they contain high amounts of aluminum (54% Al₂O₃/ 46% SiO₂).

Element mapping and analysis by EDS combined with SEM indicate that aggregates in the Apg2 horizon of the Bang Phae series consist of gypsum, a common calcium sulfate mineral in soils (Doner and Lynn, 1989). The EDS spectrum, recorded of the point indicated in Figure 32, demonstrates a clear enrichment of Ca and S (Figure 32c). In soils, lenticular crystals such as these are the most common morphology of gypsum (Jafarzadeh and Burnham, 1992).

For the Bang Phae series, the lenticular is the dominant shape of gypsum crystals with minor tabular and granular shapes (Figure 33). The lenticular habit of gypsum indicates high Ca/SO₄ ratios in soil solution and relatively high temperatures during crystal growth (Cody and Cody, 1988; Rosen and Warren, 1990). Gypsum occurs in significant quantities in soils where the parent material is derived from evaporites or some other geological material of marine, estuarine or lacustrine origin. Oxidized acid sulphate soils commonly contain gypsum (Velasco *et al.*, 2005).

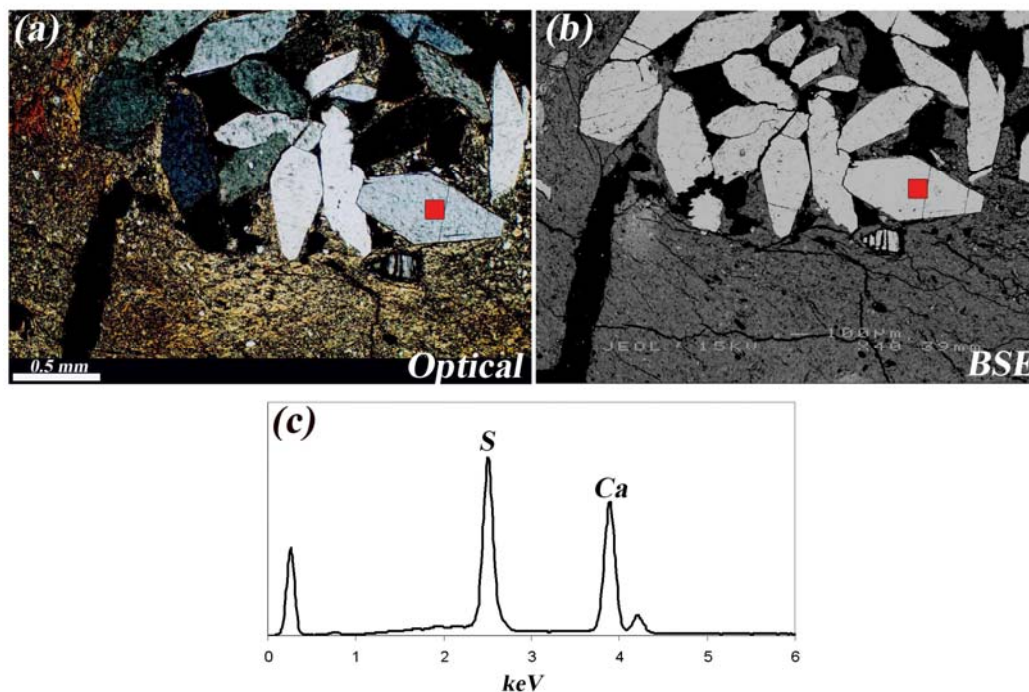


Figure 32 (a) Optical image of gypsum crystals in soil of the Bang Phae series, (b) SEM image and (c) EDS spectrum.

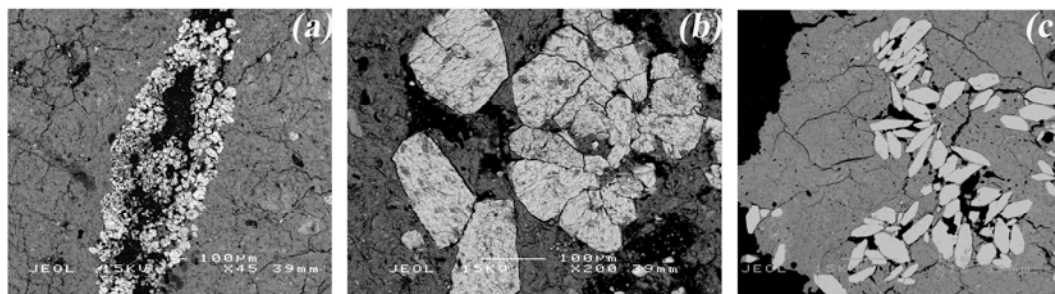


Figure 33 Backscattered electron images of gypsum crystals in soil of the Bang Phae series (a) Apg2 horizon (6-30 cm): an aggregate of gypsum crystals in a void, (b) Apg2 horizon (6-30 cm): an aggregate of granular and tabular gypsum crystals, (c) Bg1 horizon (55-80 cm): large accumulation of lenticular gypsum crystals in a pore.

Classification

Thai paddy soils have been classified based on their morphology, physical, chemical and mineralogical properties according to procedure described in Soil Taxonomy (Soil Survey Staff, 1999). All soils show clay accumulations in the subsoil. The base saturation of Phimai 1, Phimai 2, Tha Tum, Kula Ronghai, Udon, Mae Sai, Hang Dong, San Sai, Chiang Rai, Chum Saeng, Chon Buri and Tha Rua soils is more than 35 percent and have an Aquic soil moisture regime, so these soils are Aqualfs, whereas the base saturation of Roi Et and Klaeng is less than 35 percent, therefore they are Aquults. Only Lop Buri has ustic soil moisture regime because it is at a toeslope position. Lop Buri and Khok Krathium series have large cracks on the surface, common slickensides throughout the B-horizon and 30 percent clay or more between the soil surface and a depth of 18 cm, therefore they are classified to Vertisols. Bang Phae has mollic epipedon therefore it is classified to Mollisols.

Roi Et, Phimai 1 and Tha Tum are Typic Paleaquult, Vertic Endoaqualf and Plinthic Endoaqualf, respectively. Phimai 2, Kula Ronghai and Udon have a natric horizon, they are classified to Natraqualfs. Phimai 2, Kula Ronghai and Udon are Natraqualfs because the underlying rocks provide salts and the tropical savanna

climate where annual evaporation is higher than precipitation for a long period retarding leaching. There is an accumulation of salts in these soils under the present land utilization.

Mae Sai and Hang Dong series have a hue of 10YR and with value and chroma more than 3 within 75 cm from the soil surface so they belong to an aeric subgroup. They are Aerice Endoaqualfs, whereas San Sai is a Typic Endoaqualf. Chum Seang and Chiang Rai are Plinthic Paleaqualfs.

Chon Buri is a Typic Endoaqualf, while Klaeng has a plinthic horizon, hence, it is a Typic Plinthaquult. Lop Buri, Tha Rua, Khok Krathium and Bang Phae are consequently classified to Typic Haplustert, Chromic Vertic Endoaqualf, Ustic Endoaquert and Typic Endoaquoll, respectively.

The mineralogy of soils is known to be useful in making predictions about soil behavior and response to management (Bajwa, 1981; Singh and Heffernan, 2002; Trakoonyingcharoen *et al.*, 2006). Obviously, the mineralogy of Thai paddy soils is highly variable. Phimai 1, Phimai 2, Kula Ronghai and Chum Seang have more than 50 percent kaolin and less than 10 percent smectite, therefore their mineralogy class is kaolinitic. Lop Buri, Tha Rua, Khok Krathium and Bang Phae have more smectite than other clay minerals, so their mineralogy class is smectitic. The mineralogy of San Sai is siliceous. Mae Sai, Hang Dong and Chiang Rai have more than 50 percent illite, therefore their mineralogy class is illitic whereas the mineralogy classes of Roi Et, Thu Tum, Udon, Chon Buri and Klaeng is mixed (Soil Survey Staff, 1999). The classification of all soils are as follows:

- Re: Typic Paleaquult, fine loamy, mixed, semiactive, isohyperthermic
- Tt: Plinthic Endoaqualf, fine loamy, mixed, subactive, isohyperthermic
- Pm1: Vertic Endoaqualf, very fine, kaolinitic, isohyperthermic
- Pm2: Aerice Vertic Natraqualf, fine, kaolinitic, isohyperthermic

- Ki: Typic Natraqualf, fine, kaolinitic, isohyperthermic
- Ud: Vertic Natraqualf, fine, mixed, active, isohyperthermic
- Ms: Aeric Endoaqualf, fine, illitic, isohyperthermic
- Hd: Aeric Endoaqualf, fine, illitic, isohyperthermic
- Sai: Typic Endoaqualf, coarse loamy, siliceous, subactive, isohyperthermic
- Cr: Plinthic Paleaqualf, fine, illitic, isohyperthermic
- Cs: Plinthic Paleaqualf, very fine, kaolinitic, isohyperthermic
- Cb: Typic Endoaqualf, fine loamy, mixed, semiactive, isohyperthermic
- Kl: Typic Plinthaquult, fine loamy, mixed, subactive, isohyperthermic
- Lb: Typic Haplustert, very fine, smectitic, isohyperthermic
- Tr: Chromic Vertic Endoaqualf, very fine, smectitic, isohyperthermic
- Kk: Ustic Endoaquert, very fine, smectitic, isohyperthermic
- Bph: Typic Endoaquoll, fine, smectitic, isohyperthermic

CONCLUSIONS

Thai paddy soils vary in the types of clay minerals they contain. Smectite is a dominant mineral in the Central Plain, where a high water table has persisted and ions leached from adjacent uplands have accumulated resulting in the authigenesis of smectite and calcite (Borchardt, 1989). Illite is dominant in soils of Northern part of Thailand due to the mica bearing parent rocks. Kaolin is the major clay mineral constituent of soils in other regions. Trace of small amounts of smectite are present in several kaolinitic soils which may indicate that smectite has formed under the current land management regime where leaching is retarded (Reid *et al.*, 1996).

For the Central Plain, dioctahedral smectite is the dominant clay mineral in soils used for paddy rice cultivation. The clay fraction of four Thai paddy soils in Central Plain was investigated in details. These contain moderate to abundant amounts of smectite with minor amounts of kaolin and illite. The Greene-Kelly test shows that most of the charge originated in the tetrahedral sheet for seven of the eight smectites examined so most smectites are beidellitic. The CEC of the clay fraction ranges between 32-88 cmol(+) kg⁻¹ with the Lop Buri soil clay having the highest CEC (84-88 cmol(+) kg⁻¹) because it consists mostly of smectite. The swelling behaviour of heated Li-saturated soil smectites demonstrated that considerable tetrahedral charge is present, thus the smectites are mostly beidellitic. The layer charge of the smectites was estimated from the monolayer to bilayer transition associated with the exchange with n-alkylammonium ions and ranges from 0.31 to 0.38 charge units per half unit cell. The mean layer charge is about 0.38 charge units per half unit cell. The structural formula of calcium saturated soil smectite from the Lop Buri series was determined by total chemical analysis to be $(\text{Ca}_{0.38}\text{K}_{0.01})(\text{Si}_{6.83}\text{Al}_{1.17})(\text{Al}_{3.20}\text{Fe}^{3+}_{0.80}\text{Fe}^{2+}_{0.01}\text{Mg}_{0.19})\text{O}_{20}(\text{OH})_4$.

These soil smectites differ from those described by some other workers that are less beidellitic in nature. The availability, release and fixation of major elements in soils are sometimes dependent on the clay mineral species and layer charge characteristics of 2:1 phyllosilicate. Nitrogen and potassium are among the most important nutrients that are considered in the fertilization of paddy soils. Smectite

minerals have the ability to fix both ammonium (NH_4^+) and potassium (K^+) ions. The location of layer charge in smectite is important in the release and fixation of K^+ and NH_4^+ (Horvath and Novak, 1976; Chen *et al.*, 1989). For example, beidellite clay (with substitution charges in the tetrahedral sheet) in lowland Philippine rice soils fixed more than 90 percent of the applied NH_4^+ under hydromorphic conditions, while a montmorillonite clay (with substitution charges mainly in the octahedral sheet) fixed 50 percent of the applied NH_4^+ (Bajwa, 1982). In addition, the differentiation between montmorillonite and beidellite is important with respect to the K dynamics of the soils. Soils dominated by beidellite will fix K much more readily than montmorillonite soils (Badraoui *et al.*, 1987). Under the alternate wetting and drying condition, clays with more than 50 percent beidellite are significant fixers of K from fertilizers, but not clays containing montmorillonite (Bajwa, 1981). Beidellite is the dominant clay mineral in some Thai paddy soils therefore special fertility management practices need to be adapted if efficiency of potassium and ammonium fertilizers is to be increased. For example the use of slow-release K and NH_4 fertilizer may help increase fertilizer efficiency on beidellitic soils. From a classification point of view the smectite-rich Thai paddy soils should be more definitive as beidellitic instead of only smectitic. Soil Taxonomy (Soil Survey Staff, 1999) presently does not include beidellitic in the mineralogy class but it would be useful to consider for modification.

For the kaolin rich Thai paddy soils, the kaolins have a low degree of structural order (crystallinity) together with small crystal size and large specific surface area. Thai paddy soil kaolin properties may relate to parent material and pedogenesis. Structural order may decrease due to the long wet period experienced by these paddy soils (Hart *et al.*, 2002, 2003; Kanket *et al.*, 2005; Trakoonyingcharoen *et al.*, 2006).

The concentrations of elements and other properties of Thai paddy soils mostly depend upon soil parent materials and in particular on the texture of the depositional layers. Factor analysis allowed the properties and chemical composition of the soils to be compared both within and between profiles. Two affinity groups were recognized, the first group (sand, Si and Cr) are closely correlated and reflecting

the present of sand size quartz and chromium magnetite. The second much broader group consists of Al, Fe, K, Ca, Mg, Na, Mn, Ti, S, V, P, Zn, Rb, Li, Ni, Sr, Cu, Ga, Pb, Co, As, Be, U, Ag and Cd are associated with the clay content. In the factor diagram, soil samples from different soil profiles overlap because of the diversity of materials within and between soil profiles, only profile Mae Sai (Ms) is discrete and homogenous. Depth functions of factors show considerable variation for Re, Tt, Pm1, Ki, Hd, Cr, Cs and Kk soils due to the presence of contrasting depositional layers. It is concluded that Thai upland paddy soils have properties that mostly reflect the nature of parent materials and that depositional layering is common. The paddy soils of the Central Plain are different in that authigenesis of smectite and calcite has occurred however here too depositional layering persists.

The chemical composition of clay coatings is quite similar to the matrix for all soils. The chemical composition of matrix in transported nodules for Chiang Rai soil is located along the kaolin line in triangular plots rather than being the same as the matrix, whereas the Si to Al ratio of mottles that have formed *in situ* in this and other soils is similar to that of the matrix. The Apg2 horizon of the Bang Phae series contains gypsum with various crystal habits depending on the action of roots, porosity and shape of voids (Dultz and Kühn, 2005).

The classification of soils in this study in general is relatively similar to the classification of the typical profile data obtained from the Land Development Department. However, some soil classification units that are rather different is a consequence of the higher clay accumulation than that of the typical profile in the databases. According to the mineralogical properties classification of these soils, the soils that have smectitic mineralogy class, which are Lop Buri, Tha Rua, Khok Krathium and Bang Phae soil series, are the best with respect to the current paddy rice land use.