Nature of Clayey Natraqualfs on a Semi-Recent Terrace under Tropical Savanna Climate

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Abstract

A study on nature of Clayey Natraqualfs on a semi-recent terrace under tropical savanna climate was carried out on a salt affected area in Nakhon Ratchasima Province, Northeast Thailand. Five profiles were sampled along a linear traverse that included the soils with highest and lowest levels of salt accumulation. Soil profiles were described, sampled and analyzed using physico-chemical, geochemical, mineralogical under XRD and TEM, micromorphology under optical microscope and SEM/EDS techniques.

All soils are deep, poorly drained, moderately to highly developed and with various salinity levels. They are four Natraqualfs and one Endoaqualf. Most soils have high values of electrical conductivity (EC) and exchangeable sodium percentage (ESP). These soils are four saline sodic soils and one saline soil. Field morphology and micromorphology are quite comparable between each profile along the linear traverse line reflecting the same parent material, physiographic condition and land use. These soils have clayey texture, dark and gray color with high percentage of mottles with blocky and massive structures. Field morphology, optical micromorphology and SEM/EDS analysis results show clear accumulation of salt in some profiles particularly in the highest salt affected one. Crystalline halite in voids, coated in voids, coated on grain and mixed in soil matrix is abundant in Pedons 1 and 2 where surface salt patch exists. The EDS spectra indicate the presence of halite (NaCl) and barite ($BaSO_4$) that have crystallized in voids and mixed in soil matrix in some of the soils. The element composition of the soil matrix in a triangle graph of SiO_2: Al_2O_3: Fe_2O_3 is displaced from the 'kaolin line' towards the SiO_2 apex, indicating that a Si-rich is present in the matrix, but the XRD results indicated high percentage kaolin minerals. So, the Si-rich soil matrix are probably due to the partial resilication that can occur in salt affected soils.

The chemical composition of the soils is highly diverse and being interpreted as the effects of salinity. Four main chemical affinity groups can be recognized; Group 1 consists of elements associated with clay minerals and oxides (Al, Ga, Cs, Fe, Li, U, Pb, Rb, V and Be). Group 2 consists of Si and Cr. Group 3 consists of Cl, I, Br and S represents the only distinct effect of salinity on soil composition and group 4 consists of Mg and K. These Natraqualfs consist predominantly of quartz and clay minerals. Clay fractions consist predominantly of kaolin, smectite and trace of illite and interstratified minerals in various proportions. The smectite species of these soils include beidellite and montmorillonite. Kaolin consists mainly of platy crystals. The median size of crystals tends to be smaller than that of kaolin crystals in several other soils in Thailand.

Keywords: clayey Natraqualfs, salt affected soils, soil properties, tropical savanna

Introduction

The Clayey Natraqualfs soil is one group of salt affected soils distributed in the Northeast Thailand (Department of Land Development, 1991), particularly in the Khorat and the Sakon Nakhon basins in the Northeast Plateau where salt bearing rocks are common (Department of Mineral Resources, 1982). Salts are mainly derived from the rock of the Maha Sarakham Formation of the Mesozoic Khorat Group with beds and lens of halite (rock salt) up to 250 m thick (Piancharoen, 1973). Soil salinity generally occurs in discharge areas where the water table is high including edges of closed depressions and low lying areas where evaporation is high and high salt concentrations develop (Caballero et al., 2001).

Salts precipitate at the surface or accumulate in the soil profile as diverse minerals. Where Na^+ is introduced sodic properties develop with consequent loss of soil structure causing crusted surfaces, dispersion of both clay and organic matter and the development of prismatic and/or columnar structure in the B horizon (Arshad and Pawluk, 1966; Ivanava and Bol'Shakov, 1972). The salt affected soils normally have different colors and textures depend on soil forming factors and their pedogenic processes (Seelig et al., 1990; Heck and Mermut, 1992; Radogna and Padovano, 1992). Normally, these soils have poor physical properties. The damage of soil structure can be due to salinity and sodium accumulated conditions (Karimpour, 2002). Bulk densities of the salt affected soils are generally high (>1.6 Mg m^{-3}). The reduction of the hydraulic conductivity depends on the sodium adsorption ratio and concentration of soluble salt (Shainberg and Singer, 1985; Samani, 1992; Karimpour, 2002). These soils have high soluble salt in soil solution (Heck and Mermut, 1992; Suddhiprakarn and Kheoruenromne, 1998). The exchange complex of saline soil is dominated by calcium and magnesium. As a consequence, the ESP can be lower than 15. The exchange complex of saline sodic and sodic soils are dominated by sodium (Brady and Weil, 2002). Clay fractions of some salt affected soils are dominated by smectite, with smaller amounts of mica, kaolinite and chlorite (Abder-Ruhman, 1980; Dudas and Plwluk, 1982). However, kaolinite is the dominant mineral in the salt affected soils in Thailand and with variable amounts of smectite. The amounts of smectite in some Thai salt affected soils may be higher than that of kaolinite (Vichiansinpa, 1992; Suddhiprakarn and Kheoruenromne, 1998). This may be the result of salinity effect increasing solubility of silica that induces resilication in the soils (Buol et al., 2003). The dissolution of common silicate minerals such as kaolinite, muscovite, quartz and feldspars increases with increasing pH in the soil solution (Jenny, 1980; Buol et al., 2003). In saline condition the rate of quartz dissolution increases due to it has high electrolyte content in soil solution (Kohut and Dudas, 1994). The result of previous studies indicate accumulation of salt or salt crystals in the soil profile and in voids of salt affected soils (Kooistra, 1983; Rojanapremsuk, 1990; Vichiansinpa, 1992). Salt affected soils show a special kind of salt efflorescence on void-wall. This salt efflorescence on void-wall is halite, and can be observed with the scanning electron microscope (SEM) (Kooistra, 1983). Vichiansinpa (1992) studies salt affected soils in Khorat Basin, Thailand and reported that salt affected soils show the accumulation of salt or chloride salt crystal and carbonate in soil pores.

According to soil survey reports and provincial soil maps of Northeast Thailand the salt affected soil can be both sandy and clayey textured. The sandy textured salt affected soils have been studied in more extensively than the clayey textured salt affected soils. Moreover, the detailed study on nature and properties of Clayey Natraqualfs have not been reported. This paper aimed at investigating the salinity effect on nature and properties of Clayey Natraqualfs developed on a semi-recent terrace under tropical savanna climate in the Khorat Plateau basin.

Materials and Methods

Sampling

The study area was located in Nakhon Ratchasima Province, Northeast Thailand (Figure 1). Five pedons were collected from linear traverses that included the highest and lowest levels of salt accumulation. Pedons were separated by about 60 m within the distance of 240 m from the first profile to the last one. The study site was on flood-

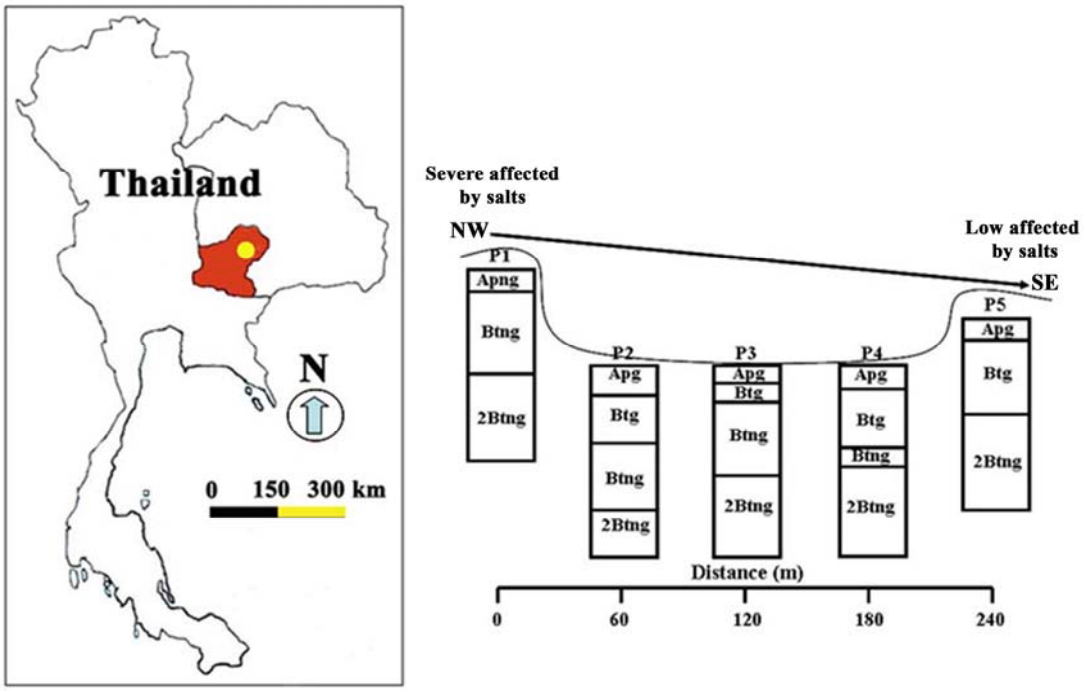

Figure 1. The location of the Clayey Natraqualfs site at Amphoe Phimai, Nakhon Ratchsima Province, Northeast Thailand including the direction of sampling and horizonation of the soil profiles.

plain of semi-recent terrace with an elevation of 151-153 m above sea level. This area has a tropical savanna climate with mean annual precipitation of about 1000 mm, and mean annual temperature of 27°C (Meteorological Department, 2002). Pedon analysis in soil profile pits was carried out at each site including detailed profile description and sampling of soil from each genetic horizon using standard field study methods (Soil Survey Division Staff, 1993; Kheoruenromne, 1999). Disturbed bulk samples from genetic horizons, soil clods, soil core, and Kubiena samples were collected for laboratory analysis.

Laboratory Work

Kubiena samples were transferred to impregnation mould containers, oven dried at 60-70ºC, and impregnated with a 40:60 resin:monostryrene mixture and 5 g of the catalyst benzoyl peroxide before slicing to prepare uncovered thin sections on glass slides for optical microscopy and scanning electron microscopy. The thin sections were analyzed under a polarizing microscope using standard micromorphological techniques as described by Bullock et al. (1985). In addition, the thin sections were investigated under a VPSEM ZEISS 1555 scanning electron microscope with energy dispersive spectrometer (EDS) operated at 15 kV electron beam accelerating voltage, 5 nA beam current and the beam diameter is 1-2 µm to determine the morphology of the composition, elements mapping and quantitative microanalysis of distinct micromorphological features such as soil plasma matrix, nodules and salt crystals (White and Dixon, 1995). Only fine fractions (e.g. clay coat, clay matrix, nodules and salt crystals) were pointed for EDS analysis. The EDS detector was a Be-window Oxford Instruments Link Analytical detector running ISIS software and the analysis results were standardized based on standard natural minerals, metals and synthetic compounds (Briggs et al., 2000; Fandrich et al., 2007).

Clod samples for bulk density were determined by clod method (Blake and Hartge, 1986). Core samples for hydraulic conductivity (Ksat) were determined by falling-head method (Klute and Dirksen, 1986). Bulk samples were air-dried and crushed to pass through a 2 mm sieve for laboratory analysis. The particle size distribution was determined by a combination of sieve and pipette analysis (Gee and Bauder, 1986). Soil pH was determined for a saturation paste, 1:1 soil:water mixture with a pH-meter (National Soil Survey Center, 1996). Organic carbon was determined by the Walkley-

Black wet oxidation (Nelson and Sommers, 1996). The extractable acidity was determined by barium chloride-triethanolamine solution buffer ($BaCl_2$-TEA) method at pH 8.2 (Thomas, 1987b). Cation exchange capacity (CEC) was determined by saturating the exchange sites with an index cation (NH_4^+) using 1 M NH_4OAc at pH 7.0 and measuring the amount of index cation displaced. The exchangeable Na, K, Ca and Mg were determined by using atomic absorption spectrometry (AAS) and the results were used to calculate the exchangeable sodium percentage (ESP) by dividing the exchangeable sodium (ES) by the CEC-7 and multiplying by 100 (U.S. Salinity Laboratory Staff, 1954; Rhoades, 1982; Thomas, 1987a). The satururation extracted cations Ca^{2+}, Mg^{2+} and Na^+ measured by atomic absorption spectrophotometer were used to compute the SAR by dividing the molar concentration of the monovalent cation Na^+ by the square root of the molar concentration of the divalent cations Ca^{2+} and Mg^{2+} (cmol kg^{-1}) (U.S. Salinity Laboratory Staff, 1954; National Soil Survey Center, 1996).

The chemical composition of soil samples was determined by a combination of X-ray fluorescence spectrometry (XRF) of pressed powder pellets (Norrish and Hutton, 1969) and aqua regia digestion (HCl and H_2CO_3) followed by inductively coupled plasma-mass spectrometry (ICP-MS) (Lynch, 1999; Soltanpour et al., 1996). Aluminum, Si, Fe, Na, Mg, K, Ca, S and Cl were determined by XRF. Lithium, Be, P, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, As, Br, Rb, Sr, Mo, Ag, Cd, I, Cs, Pb and U were determined by ICP-MS. The concentrations of elements in soil were statistically analysed after standardization using factor analysis and principal component analysis with the Statistica Program (Version 6.1) (Stat Soft, Inc., 2003). Factor analysis was used to interpret the analytical data as it is commonly used to identify geochemical and lithogeochemical affinities for sediments and soils (Evans et al., 1996; Kumru and Bakac, 2003).

Semi-quantitative determination of mineral abundance in whole soil was done on random powders by X-ray diffraction analysis using mono-chromatised CuKα radiation with a Philips PW-3020 diffractometer (50 kV, 20 mA). The XRD scans extended from 3^o to 70^o 2θ with a step size of 0.02^o and scan speed of 1.2^o per minute. Relative proportions of minerals were calculated by comparing the random powder XRD peak intensity of major reflections with the intensities for a mixture of standard minerals (Brindley and Brown, 1980). Clay minerals percentages were determined from the intensity of their 001 reflection. The total clay mineral abundance (smectite, illite and kaolin) was determined from the intensity of their common reflection at 0.445 nm. The quartz reflection at 0.334 nm d-spacing was used.

Minerals in the clay fraction were identified using XRD of oriented clay pretreated by Mg^{2+} and K^+ saturation on ceramic plates, ≈50% glycerol on the Mg^{2+} saturation plates, and K^+ saturated plates heated to 550^oC (Brindley and Brown, 1980). The XRD of the clay samples was carried out using a monochromatised CuKα radiation with a Philips PW-3020 diffractometer (50 kV, 20 mA). Clay fractions were scanned respectively from 4 to 45° 2θ, using a step size of 0.02° 2θ and a scan speed of 0.04° 2θ sec^{-1}. Relative proportions of various minerals were calculated by comparing the XRD peak intensity with the intensity for standard minerals (Brindley and Brown, 1980).

Greene-Kelley test was used for smectite group identification. A 001 spacing of about 0.95 nm indicates a monmorillonite, and a spacing of 1.78 nm as beidellite (Greene-Kelley, 1953; Brindley and Brown, 1980; Singh and Gilkes, 1991).

For analytical transmission electron microscopy (TEM), specimens were prepared by dispersed samples. A drop of the suspension was deposited on a carbon-coated supported on a Cu grid and examined using a Jeol 2000 FX II electron microscope operated at 80 kV.

Results and Discussion

Morphological Properties

The Clayey Natraqualfs have developed on alluvium over residuum derived from fine grained clastic sedimentary rock. All soils occupy the same area of flat to almost flat with 1-2% sloping surface. All soils are deep and well developed soils indicated by clay-illuviated horizon (Bt) (Figure 2). The natric horizons are present in most of the soil profiles at varying depths (except Pedon 4) and showing several markedly different textural horizons which are probably discrete depositional

Figure 2 Profile development and morphology of the Clayey Natraqualfs in Northeast Thailand. Structure: ABK = angular blocky, SBK = subangular blocky, se-M = semi-massive, G = granular, Texture: C = clay, SC = sandy clay, SCL = sandy clay loam, SiC = silty clay, F = Fine.

layers. In addition, the surface soil of Pedon 1 that is severely affected by salt shows salt patch and bare surface with some halophytic plants. General land use and natural vegetation in the area are paddy rice. Furthermore, a nearby area was used for salt mining.

Moist colors of their A-horizons range from brown to dark brown. Their B-horizons have mixed colors with low chroma (≤ 2) and high percentage of mottles. The mottles and low chroma indicate their poor drainage and development under long period of waterlogging condition sufficiently for reduction

process (Suddhiprakarn and Kheoruenromne, 1998; Buol, et al., 2003). Topsoil colors are darker than subsoil colors due to the amount of organic matter (Buol, et al., 2003). Most of these soils have texture ranges from silty clay to clay with fine sandy clay loam to fine sandy clay in some of the lower horizons (Figure 2). The dominant structures are angular blocky structure and massive structure. The subangular blocky structures are present in A-horizons of Pedons 1, 4 and 5 whereas the angular blocky parting to granular structure present in only Btg1 horizon in Pedon 3. Generally, structures of their subsoils are stronger than their topsoil structures.

Micromorphological Properties

Optical analysis

Micromorphological characteristics was described separately for representative topsoils and subsoils horizons. The microstructures of topsoils horizon are mainly channel and subangular blocky structures (Figure 3a, c, e, g, and i). Quartz and runiquartz grains are common as skeleton materials. The coarse:fine quartz ratio with a lower size limit at 10 μm is 40:60. Quartz grain shapes are subangular to subrounded. The fine fraction consists of variously colored clay to fine silt materials with a dotted appearance. Impure halite coated in voids, coated on quartz grain and mixed locally in the soil matrix are common crystalline pedofeatures for Pedons 1 and 2 (Figure 3a and c). The impure halite crystallized in voids is present only in Pedon 1 (Figure 3a), whereas the impure halite coated in voids are also present in Pedon 4 (Figure 3g). The impure halite is distinct in Pedons 1 and 2 that have a severe effect of salt with salt crust surface and high EC. The crystalline halite is not clearly present in topsoils of Pedons 3-5 (Figure 3e, g and i) where no evidence of salt was observed in field morphology.

The channel and subangular blocky structure are common microstructure of subsoil horizons (Figure 3b, d, f, h and j). The minerals in the coarse fraction are the same as those in the topsoil horizons. The fine fraction of the soils has various colors with the clay to fine silt size materials having a dotted and speckled appearance. Impure halite crystallized in voids, coated in voids and coated on quartz grain and mixed locally in the soil matrix are present in Pedons 2 and 4 (Figure 3b and h), whereas Pedon 5 also shows the impure halite coated in voids and coated on quartz grain and mixed locally in the soil matrix (Figure 3j). Prismatic gypsum cluster present in Pedons 1 and 3 may be the influence of management practices (Figure 3b and f).

The micromorphological features of halite and gypsum accumulation in these soils are shown in Figure 4. The different depths of halite accumulated in soils reflect their clayey texture. All subsoils have clay coatings on the walls of voids and on quartz and bridged grains. This is the characteristic of an argillic horizon where illuvial clay has been introduced. Sand grain shapes are subrounded over subangular indicating long distance water transported sediments over residuum. Runi-quartz grains are an indicator of water transported materials (Buol et al., 2003). The amorphous pedofeatures in these soils are manganiferrous impregnative nodules. The former indicates wetting and drying cycles with associated oxidation-reduction (James and Bartlett, 2000).

Spatial distribution of elements and salt in soils

The SEM images (Figure 5) and element maps show that the major element in the soils are Si and Al. Silicon is present as quartz and a lesser amount is present in clay together with Al. The amount of Al increases in B horizons and is present as the fine fraction including clay coatings, clay infillings and clay matrix. Iron is a relatively minor element being present partly as local concentrations as mottles, concretions or nodules. The high Fe matrix in the Fe mapping are consistent with the presence of manganiferrous impregnative s-matrix or nodules that were observed in the field and under optical analysis of thin section samples (Figures 3 and 5). The element maps of Na and Cl clearly show the widespread distribution of halite in these soils (Figure 5). Sulfur mapping clearly indicates areas of prismatic gypsum but some sulfur containing crystals are barite ($BaSO_4$) (Figure 5). The EDS spectra indicate crystals of halite and barite in these soils (Figure 6).

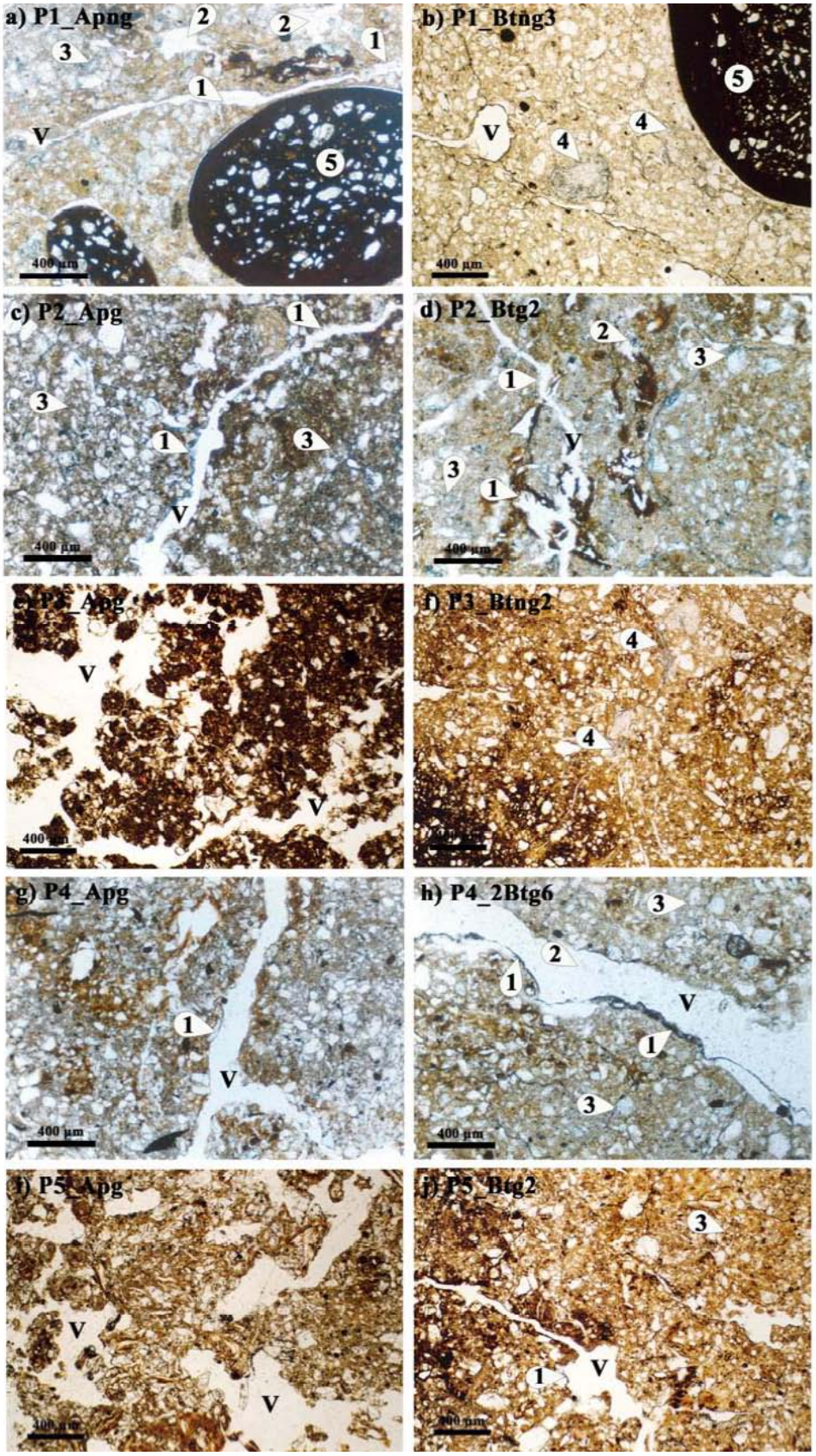

Figure 3 Some micromorphological features of Clayey Natraqualfs in Northeast Thailand; 1=impure halite coated in voids; 2= impure halite crystallized in voids; 3=impure halite coated on quartz grain and mixed locally in soil matrix; 4=prismatic gypsum cluster and 5=manganiferrous impregnative nodules.

The data points for the matrix of these soils are mostly located off the kaolin line (Figure 5) towards the SiO_2 apex due to the presence of Si-rich clay. XRD analysis indicates a moderate percentage of smectite and interstratified 1.0 nm and 1.4 nm minerals in soils but the amount of these minerals in clay fraction is mostly less than 40 % (Table 3) indicating that fine quartz or amorphous silica be present. The normalized element composition of the matrix in the triangle graph between SiO_2: Al_2O_3: Na_2O+CaO+MgO (Figure 5) indicates that the combined salts of Na, Ca and Mg have mostly indurated the soil matrix as most points fall on the matrix line and consistent with optical observations of halite accumulated in these soils.

Micromorphologically, the clearest evidence of salt effect in these soils are the impure halite and the halite coatings in voids or mixed in s-matrix (Figures 3 and 4). The high salt effect also induces the conditions found in the SEM/EDS analysis of the samples as shown in Figures 5 and 6. These micromorphological analysis results on salt effect and the data on minerals in clay fraction in Table 3 along with the lowland condition where soils have extended period of water stagnancy and low leaching under tropical savanna climate the accumulation of silica can induce the crystallization of some smectite from kaolinite in the soils. The condition is interpreted as an evidence of resilication that started with salinization of the soils creating a high pH condition for silica dissolution (Jenny, 1980; Buol et al., 2003). The low leaching environment promotes the accumulation of dissolved silica leading to the addition of silica into the kaolinite forming smectite structure (Tan, 1982). Nevertheless, this resilication, as indicated by the analytical data is generally limited and occurring only in the highly salt affected soils with very poorly drained situation.

Physico-Chemical Properties

The summarized physico-chemical and mineralogical properties of Clayey Natraqualfs are given in Table 1. These soils contain low to medium amounts of sand particles and have medium to high clay contents in all horizons except for subhorizons that are depositional layers of alluvium over in situ residuum derived from clastic sedimentary rocks. Most soils have high bulk density of more than 1.6 Mg m^{-3} (except Apg horizon of Pedon 5). Most of these soils have hydraulic conductivity rating as very slow to moderately slow (Table 1). The soils

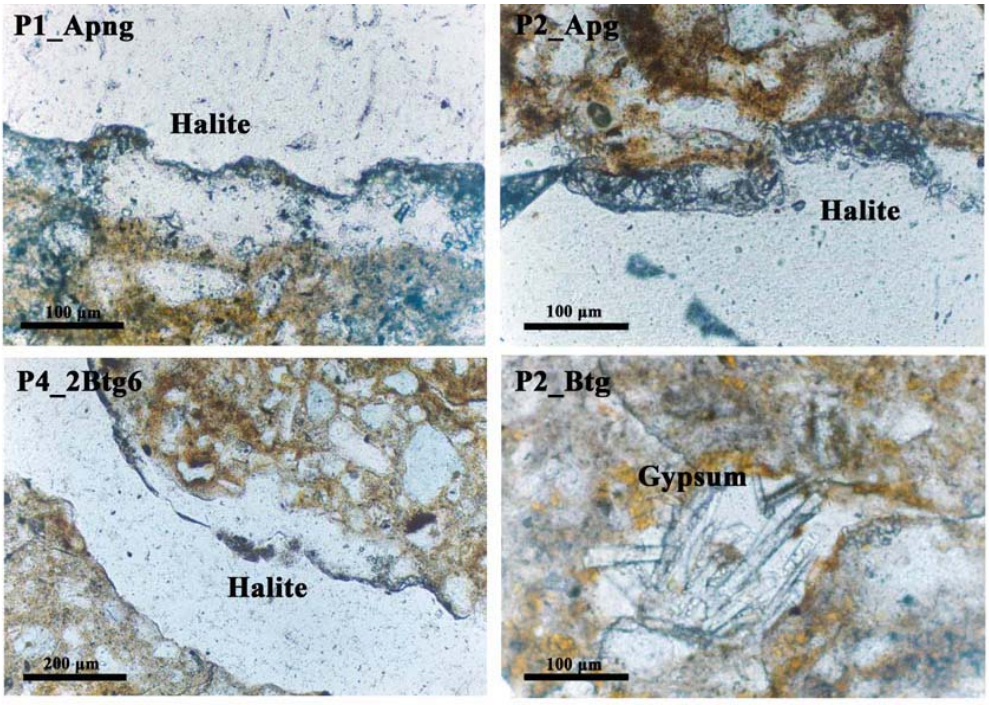

Figure 4 High magnification of micromorphological features showing the salt accumulations in Clayey Natraqualfs in Northeast Thailand.

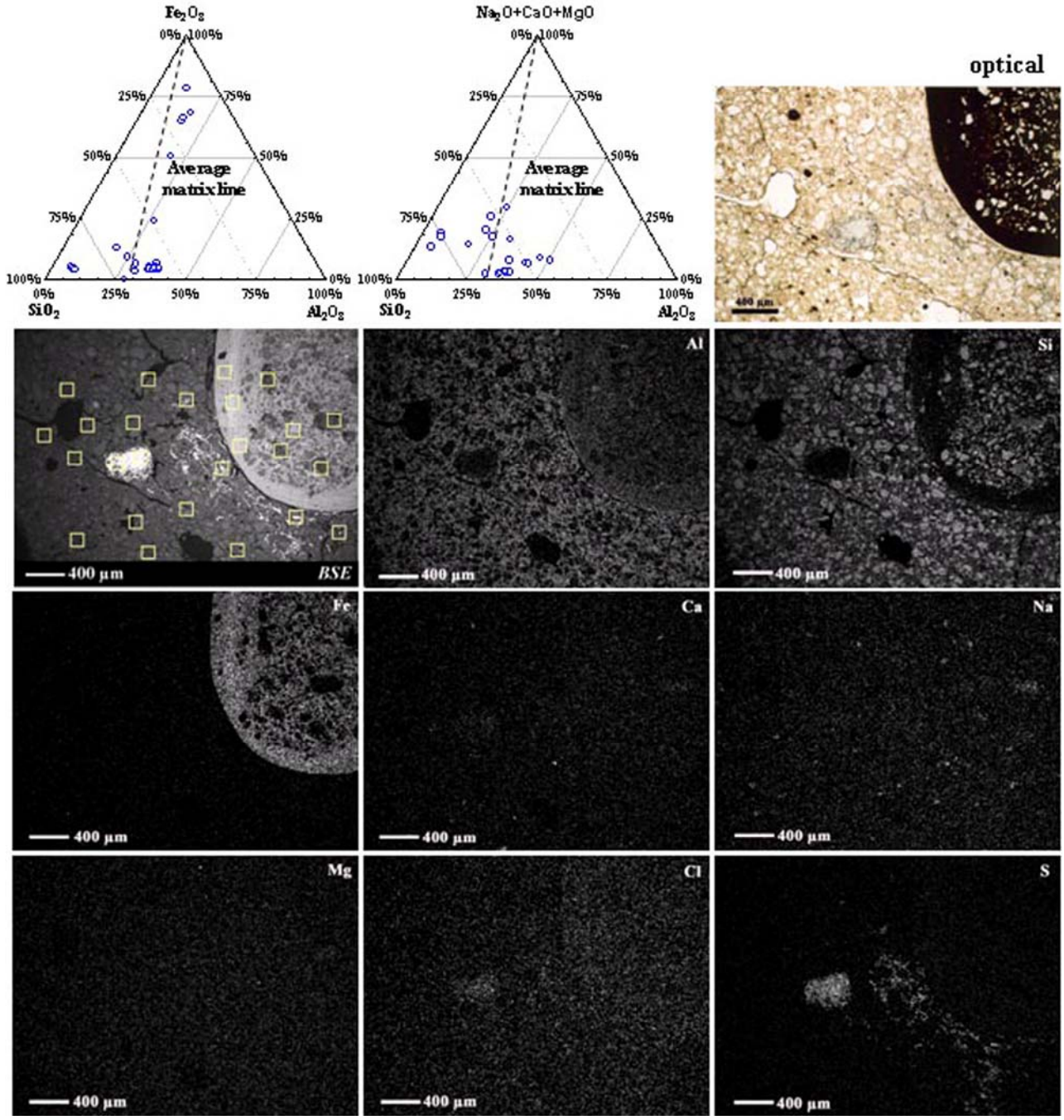

Figure 5 Normalized composition triangular graphs (SiO_2: Al_2O_3: Fe_2O_3, SiO_2: Al_2O_3: Na2O+ CaO+ MgO), Optical image, backscattered electron micrograph and EDS element (Al, Si, Fe, Ca, Na, Mg, Cl, S) maps for the Btng3 horizon of soil in Pedon 1.

show a wide range of pH values from very strongly acid to neutral (ranges 4.9-7.2). The low pH values in some of these soils are consistent with the soil pH of tropical soils that experience leaching (Van Wambeke, 1992). The organic carbon content in these soils are highest in the surface soil and decrease with depth. Most of these soils have medium to high CEC (CEC >10-30 cmol kg^{-1}) as the soils contains more clay. All soils have electrical conductivity (EC) of more than 4 dS m^{-1} at least in one horizon in the soil profile and can be considered as salt affected (Brady and Weil, 2002). Most of soils have high ESP of more than 15 at least in one horizon except for Pedon 4. The soils have SAR value lower than 13 with lower than ESP indicated that sodium ion is higher in the exchange

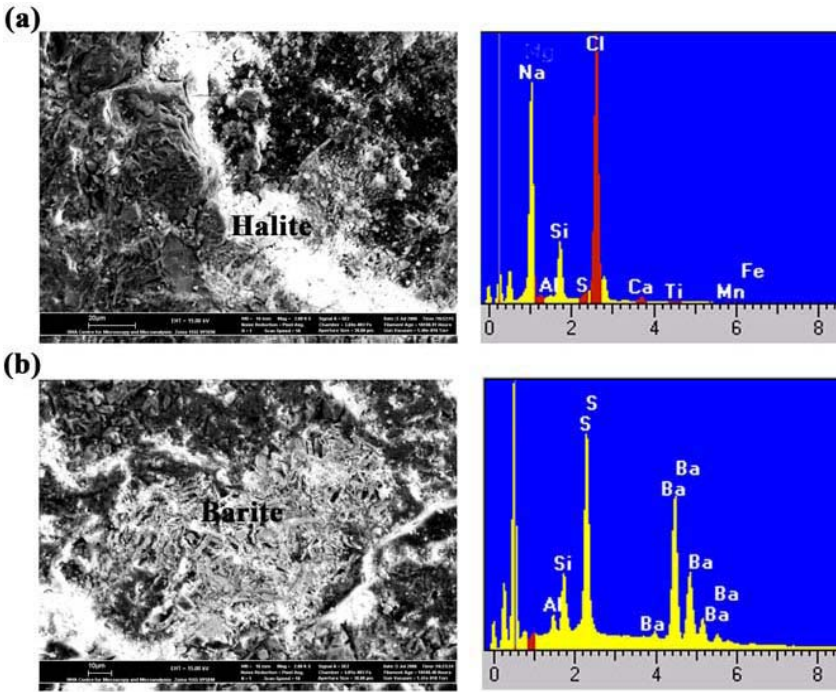

Figure 6 Secondary electron image of a thin section and EDS spectra showing (a) halite accumulations in the Apng horizon of Pedon 1: (b) barite accumulation in Btng3 horizon of Pedon 1.

site or exchange complex than in soil solution. Based on EC and ESP values and the categories of Brady and Weil (2002), these soils can be allocated into two groups of salt affected soils. Pedons 1-3 and 5 are saline sodic soils, whereas Pedon 4 is a saline soil (Brady and Weil, 2002).

Geochemical Properties

Table 2 gives the median and SD values of element concentrations for all Pedons and for each Pedon to provide an indication of the values observed in this research. Silicon is the major component of these soils (median, SD =327, 27). Aluminum and Fe are important constituents of soils in all Pedons. High Cl concentrations exist in many samples due to the influence of salinity (median, SD =2.37, 1.55 g kg^{-1}). Median concentrations of Al, Si, Mg, K, Ca, Li, P, V, Cr, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Pb and U in salt affected soils are similar to the average values for Thai soils whereas the median concentration of Mn and Cs in salt affected soils is above the average value for some Thai soils (Thanachit, 2006). The median of Fe, Ti and Mo are smaller than average values for Thai soils (Thanachit, 2006) (Table 2). In comparison to worldwide soils the median concentrations of S and Cl in salt affected soils are above normal values reflecting the salt affected nature of these soils. Median concentrations of Al, Fe, Na, Mg, K, Li, Be, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, As, I, and Pb in salt affected soils are similar to those of worldwide soils. Sodium concentrations in these salt affected (high NaCl) soils are similar to those of worldwide soils because many soils elsewhere contain much Na in feldspar. Median concentrations of P, Ti, Br, Rb, Sr, Mo, Ag and Cd are smaller than for worldwide soils (Lindsay, 1979) (Table 2).

Distribution of Elements and Properties in Soils

Results on factor analysis of standardized chemical analyses are given in Figure 7a and b. Two factors explain only 57.2 % of the variation in the data when the complete data set is analyzed. This poor explanation of the data and the absence of a limited numbers of close associations of elements or samples may be due to the variable impact of salinity. In the attribute factor diagram four groups of attributes are recognized (Figure 7a). Group 1 consists of clay and elements that are commonly associated with clay minerals and oxides (Al, Ga, Cs, Fe, Li, U, Pb, Rb, V and Be). Group 2 consists of Si which is mostly in quartz and Cr which is mostly in sand within the resistant spinel minerals chromiferous magnetite and chromite (Alloway,

Table 1 Summarized properties of Clayey Natraqualfs in Northeast Thailand.

Horizon	Depth	pH 1:1 H_2O	OC	EA	CEC	EC[1/]	ESP	SAR	Particle size distribution			BD	HC
									Sand	Silt	Clay		
	(cm)		(g kg^{-1})	(--- cmol kg^{-1} --)		(dS m^{-1})	(%)		(---------- g kg^{-1} --------)			(Mg m^{-3})	
Pedon 1: Typic Natraqualf, fine, kaolinitic, isohyperthemic													
Apng1	0-10	5.4	7.1	8.34	16.48	60.5	13.25	10.4	352	245	403	1.78	8.75×10^{-2}
Apng2	10-20	5.5	4.6	9.20	20.09	11.3	20.96	5.4	287	168	545	1.76	1.95×10^{-3}
Btng1	20-33	6.1	2.6	5.98	16.61	9.6	25.93	7.7	332	178	490	1.87	4.3×10^{-3}
Btng2	33-48	6.6	1.9	3.13	13.82	8.6	30.76	8.0	406	192	402	1.84	
Btng3	48-70	6.8	1.1	3.10	15.45	9.0	28.20	8.3	381	200	419	1.94	
Btng4	70-88	7.0	0.8	3.09	14.69	7.2	25.03	8.4	423	216	361	1.90	
2Btng5	88-114	7.1	0.4	2.45	13.09	8.2	29.48	9.1	477	200	323	1.87	
2Btng6	114-135	7.2	0.3	3.08	12.86	14.2	24.84	12.6	514	201	285	1.77	
2Btng7	135-156	7.2	0.4	2.42	9.42	12.4	31.48	8.7	580	178	242	1.75	
2Btng8	156-190	7.2	0.1	2.13	7.41	16.2	28.48	10.3	699	97	204	1.80	
Pedon 2: Typic Natraqualf, very fine, kaolinitic, isohyperthemic													
Apg1	0-18	5.2	12.8	12.41	19.69	10.3	13.66	4.8	235	261	504	1.87	1.10×10^{-3}
Apg2	18-30	4.9	9.0	13.57	21.74	8.7	8.50	5.1	190	290	520	1.75	1.44×10^{-3}
Btg	30-42	4.9	6.0	12.46	19.57	7.2	10.41	5.1	234	267	499	1.68	1.21×10^{-3}
Btng1	42-53/64	5.3	4.8	12.01	25.89	7.1	16.38	5.6	135	226	639	1.84	
Btng2	64-79	5.8	3.8	9.45	25.55	6.5	19.36	6.3	155	201	644	1.86	
Btng3	79-100	6.0	3.1	8.18	22.72	7.3	23.49	7.0	135	219	646	1.82	
Btng4	100-124	6.3	1.6	6.89	19.23	7.6	23.53	7.6	172	272	556	1.87	
Btng5	124-151	6.6	0.5	4.97	19.59	6.4	27.19	7.5	234	275	491	1.94	
2Btng6	151-176	6.7	0.3	3.71	15.10	8.6	28.05	8.1	363	242	395	1.88	
2Btng7	176-200	6.8	0.2	2.46	9.56	13.2	25.53	9.3	628	104	268	1.81	
Pedon 3: Typic Natraqualf, fine, kaolinitic, isohyperthemic													
Apg	0-11	5.1	12.5	10.06	21.49	13.4	9.18	4.2	213	264	523	1.80	1.04×10^{-3}
Btg1	11-32	5.4	5.5	10.52	23.82	5.5	10.30	3.8	132	206	662	1.78	9.51×10^{-3}
Btg2	32-56	5.9	3.9	6.60	21.23	5.3	10.08	4.3	164	228	608	1.82	2.11×10^{-2}
Btng1	56-65/85	6.3	2.4	2.81	19.94	4.7	15.64	4.5	180	253	567	1.85	
Btng2	85-110	6.5	1.6	2.81	20.72	5.0	16.74	5.0	167	265	568	1.92	
Btng3	110-124	6.4	0.7	3.15	20.85	5.8	19.71	5.2	181	211	608	1.93	
2Btng4	124-152	6.7	0.5	5.80	31.14	7.5	19.84	5.8	80	71	849	1.85	
2Btng5	152-180+	6.7	0.3	4.12	24.44	8.4	21.50	6.2	174	186	640	1.92	
Pedon 4: Typic Endoaqualf, fine, kaolinitic, isohyperthemic													
Apg1	0-10	5.4	11.7	6.72	12.84	11.1	6.25	4.0	424	229	347	1.62	3.84
Apg2	10-22	5.7	5.7	6.48	12.70	3.4	10.90	3.1	403	234	363	1.88	1.53×10^{-3}
Btg1	22-38	5.3	4.4	7.72	16.44	3.6	8.16	3.0	315	229	456	1.68	2.81×10^{-2}
Btg2	38-60	5.3	3.9	8.18	19.17	3.7	6.19	3.1	224	225	551	1.79	
Btg3	60-83	5.6	2.2	6.85	18.99	3.9	8.43	3.3	259	222	519	1.93	
Btg4	83-102	6.3	1.3	4.93	19.01	3.7	12.32	3.4	250	285	465	1.91	
2Btg5	102-121	6.6	1.0	3.09	16.46	3.0	9.86	2.9	346	289	365	1.87	
2Btg6	121-140	6.7	0.4	1.84	13.50	4.1	9.34	3.2	395	292	313	1.84	
2Btg7	140-162	6.8	0.2	1.21	11.77	5.9	8.28	3.9	522	208	270	1.81	
2Btg8	162-190	6.9	0.1	0.91	14.09	5.5	7.04	3.6	556	208	236	1.75	
Pedon 5: Typic Natraqualf, fine, kaolinitic, isohyperthemic													
Apg	0-16	5.1	9.1	8.60	13.69	9.0	4.89	3.9	363	290	348	1.51	2.4
Btg1	16-31	5.0	6.1	13.63	21.45	3.3	5.95	3.0	254	283	463	1.74	2.76×10^{-3}
Btg2	31-52	4.9	4.6	11.56	19.43	3.6	7.73	3.4	202	282	516	1.78	3.25×10^{-2}
Btg3	52-69	5.0	3.7	10.98	21.84	2.8	8.23	3.4	203	244	553	1.83	
Btg4	69-95	5.3	3.8	9.36	21.64	3.5	9.67	4.0	130	274	596	1.79	
2Btng1	95-128	5.9	1.9	6.24	16.98	2.9	14.58	3.8	164	302	534	1.84	
2Btng2	128-161	6.6	0.6	3.76	18.27	3.0	16.63	4.3	180	285	535	1.93	
2Btng3	161-187	6.8	0.5	3.12	21.55	3.8	17.72	5.5	223	291	486	1.96	
2Btng4	187-210+	7.0	0.2	3.07	16.39	4.6	16.52	5.7	294	325	381	1.92	

[1/] Saturation paste.

Table 2 Median (±SD) values for element concentrations for Clayey Natraqualfs in Northeast Thailand.

Element	All samples n=47		Pedon 1 n=10		Pedon 2 n=10		Pedon 3 n=8		Pedon 4 n=10		Pedon 5 n=9		Thai soils[1/]		Worldwide Soils[2/]
	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Median	SD	Mean	SD	Range
Major element (g kg^{-1})															
Si	327	27	734	62	692	49	659	45	738	45	700	32	220-463	0.8-39	230-350
Al	90	19	145	40	174	28	207	20	146	33	170	21	3-157	0.6-24	10-300
Fe	27.0	7.5	25.0	9.3	44.2	12.0	43.6	9.9	33.8	6.5	39.9	5.3	100-176	0.5-30	7-550
Na	4.20	2.24	8.49	4.50	5.93	1.27	5.53	1.20	4.72	1.90	3.77	1.87	-	-	0.75-7.5
Mg	3.40	0.68	5.56	0.83	5.80	0.82	5.06	1.46	5.47	1.01	5.31	1.63	0-8.5	0-3.9	0.6-6
K	4.30	1.33	5.00	0.76	5.54	1.17	4.82	1.85	5.18	1.45	5.66	2.53	0.4-17.3	0-9.4	0.4-30
Ca	3.60	0.79	4.13	0.86	5.18	0.95	5.46	1.03	5.53	1.01	4.76	1.10	0.1-8.3	0-4.2	7-500
S	90	102	157	107	177	81	97	90	25	117	25	83	-	-	0.03-10
Cl	2.37	1.55	3.66	2.21	3.23	40.44	1.97	1.31	1.07	0.59	0.97	0.39	-	-	0.02-0.9
Minor element (mg kg^{-1})															
Li	26.4	8.9	19.5	5.9	31.3	9.9	36.0	5.1	20.0	6.6	26.4	7.0	0.7-29	0.4-17	5-200
Be	1.46	0.49	1.04	0.33	1.68	0.56	1.89	0.40	1.20	0.28	1.64	0.29	-	-	0.1-40
P	40.2	39.8	25.9	48.4	58.6	40.5	36.6	36.8	38.4	30.3	53.8	45.4	30-544	12-335	200-5000
Ti	163	40	153	29	174	28	143	29	164	63	166	34	900-24000	0.1-2.6	1000-10000
V	67.6	19.0	49.0	15.0	85.3	25.2	75.0	11.5	55.3	13.3	70.2	8.9	10-311	3.3-80	20-500
Cr	224	73	296	77	215	71	169	34	253	51	183	60	5-354	1-160	1-1000
Mn	223	202	304	129	185	68	228	174	232	261	198	293	8.4-26	2-11	20-3000
Co	9.4	3.7	7.2	1.5	9.9	1.8	9.8	7.0	9.6	0.84	9.1	3.4	0.2-80	0.1-25	1-40
Ni	25.2	3.1	25.8	4.6	26.4	2.9	27.6	2.6	24.9	1.7	24.7	1.2	20-147	4-32	5-500
Cu	10.4	3.2	7.0	2.3	11.2	2.8	11.3	4.5	10.1	1.1	13.1	1.9	1.4-76	0.4-17	2-100
Zn	24.7	6.0	22.5	6.0	25.9	6.4	26.0	5.6	24.9	5.1	27.9	6.8	12-101	2-41	10-300
Ga	16.7	4.0	15.2	5.0	16.7	4.2	20.7	2.9	15.0	2.1	16.7	2.4	1.3-36	0.2-8	5-70
As	1.5	0.78	1.2	0.87	1.4	0.73	1.1	0.48	1.8	0.78	2.1	0.91	0.5-6	0.2-13	1-50
Br	0.97	1.6	1.5	1.7	0.65	0.96	0.46	0.70	0.00	0.87	2.6	1.7	-	-	1-10
Rb	30.0	9.0	22.4	9.1	37.1	9.7	36.1	7.9	27.1	4.1	32.9	6.4	3-54	0.5-6	50-500
Sr	18.2	4.6	16.6	3.8	17.9	4.2	20.6	4.1	20.4	4.9	17.8	4.7	2-80	1.1-29	50-1000
Mo	0.00	0.17	0.00	0.33	0.00	0.13	0.00	0.00	0.00	0.02	0.00	0.05	0.3-2	0.2-2.8	0.2-5
Ag	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	-	-	0.01-5
Cd	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.02	-	-	0.01-0.7
I	0.69	1.2	0.88	1.6	0.64	0.20	0.74	0.21	0.37	0.17	2.1	1.5	-	-	0.1-40
Cs	5.0	1.5	3.6	1.3	5.3	1.2	6.4	0.95	3.0	1.1	5.4	1.0	0.3-4.4	0-2.3	0.3-25
Pb	11.9	4.3	7.1	2.4	13.9	3.5	13.7	6.4	9.4	1.3	12.8	1.7	8.8-23.7	0.5-18	2-200
U	1.6	0.64	0.62	0.53	1.9	0.62	2.1	0.29	1.2	0.43	1.6	0.45	0.2-1.6	0-1.3	-

[1/] Mean and SD of total concentration of element in soils of Northeast Thailand (Thanachit, 2006).
[2/] Range of total concentration of element in normal worldwide soils (Lindsay, 1979).

1995). Group 3 consists of Cl, I, Br and S that are associated salt properties and group 4 consists of Mg and K. The soil samples are widely distributed in the corresponding factor diagram (Figure 7b).

Mineralogical Properties

Minerals in soils and in clay fraction

The soils consist predominantly of quartz and kaolin. Small amount of feldspar and goethite is found in some samples (Table 3). The clay fraction of these soils consists predominantly of kaolin. Smectite is present as a minor clay mineral with trace of illite. Quartz is also present in clay fraction (Table 3). The high amounts of smectite present in some of the soils may be resulted from the salinity effect increasing solubility of silica inducing the synthesis of 2:1 clay minerals under high salt affected condition (Dixon and Darrell, 2002). The interstratified 1.0 nm and 1.4 nm minerals are

Table 3 Minerals in soil and clay fraction of Clayey Natraqualfs in Northeast Thailand[1/].

Depth	Horizon	Minerals in soil					Minerals in clay fraction			
(cm)		qtz	kao	other clay	fel	goe	kao	smec.	Ill	qtz
Pedon 1 : Typic Natraqualf, fine, kaolinitic, isohyperthemic										
0-10	Apng1	xxx	xx	x	-	-	xxxx	x	tr	x
20-33	Btng1***	xxx	xxx	tr	-	-	xxxx	x	tr	tr
48-70	Btng3**	xxx	xx	x	-	-	xxxx	x*	tr	tr
70-88	Btng4	xxx	xx	x	tr	tr	xxxx	x	tr	x
88-114	2Btng5	xxx	xx	x	tr	tr	xxxx	xx	tr	tr
135-156	2Btng7**	xxxx	x	x	tr	tr	xxx	xx	tr	x
Pedon 2 : Typic Natraqualf, very fine, kaolinitic, isohyperthemic										
0-18	Apg1	xx	xxx	x	-	tr	xxxx	x	tr	x
30-42	Btg	xx	xxx	x	-	-	xxxx	x	tr	x
42-53/64	Btng1	xx	xxx	x	-	-	xxxx	x	tr	x
64-79	Btng2	xx	xxx	x	-	-	xxxx	x	tr	x
100-124	Btng4	xx	xxx	x	-	-	xxxx	x*	tr	x
151-176	2Btng6	xxx	xx	x	tr	-	xxxx	x	tr	x
Pedon 3 : Typic Natraqualf, fine, kaolinitic, isohyperthemic										
0-11	Apg	xx	xxx	x	-	-	xxxx	x	tr	x
11-32	Btg1	xx	xxx	x	-	-	xxxx	x	tr	x
56-65/85	Btng1	xx	xxx	tr	tr	-	xxxx	x	-	x
85-110	Btng2***	xx	xxx	tr	tr	-	xxxx	x	-	tr
124-152	2Btng4	x	xxxx	x	-	tr	xxxx	x	tr	tr
Pedon 4 : Typic Endoaqualf, fine, kaolinitic, isohyperthemic										
0-10	Apg1	xxx	xx	x	tr	-	xxxx	x	tr	x
22-38	Btg1	xxx	xx	x	-	-	xxxx	x	tr	x
38-60	Btg2	xx	xxx	x	tr	-	xxxx	x	tr	tr
83-102	Btg4	xx	xxx	x	tr	tr	xxxx	xx	tr	tr
102-121	2Btg5	xxx	xx	x	tr	tr	xxxx	xx	tr	x
140-162	2Btg7**	xxxx	x	x	tr	tr	xxx	xx	tr	x
Pedon 5 : Typic Natraqualf, fine, kaolinitic, isohyperthemic										
0-16	Apg	xxx	xx	x	tr	-	xxxx	x	tr	x
31-52	Btg2**	xxx	xx	x	-	-	xxxx	xx*	tr	x
69-95	Btg4	xx	xxx	x	-	-	xxxx	xx*	tr	x
95-128	2Btng1*****	xx	xxx	x	-	-	xxxx	x	-	x
161-187	2Btng3	xx	xx	x	tr	tr	xxxx	x	tr	x

[1/] xxxx = dominant (>60%), xxx = large (40-60%), xx = moderate (20-40%), x = small (5-20%), tr = trace (<5%), - = not detected, qtz = quartz, kao= kaolin, other clay=2:1 clay mineral, fel=feldspar, goe=goethite, smec=smectite, Ill=Illite, * Interstratified 1.0 nm and 1.4 nm, ** high smectite, selected for Greene-Kelly test, *** high kaolin, selected for the TEM for size and shape of kaolin crystal.

found in some soil horizons (Table 3). Smectite is not present in the horizons containing the interstratified minerals. It is possible that the interstratified mineral is the intermediate product from the development of 1:1 to 2:1 clay minerals, but the process is not complete (Brindley and Brown, 1980).

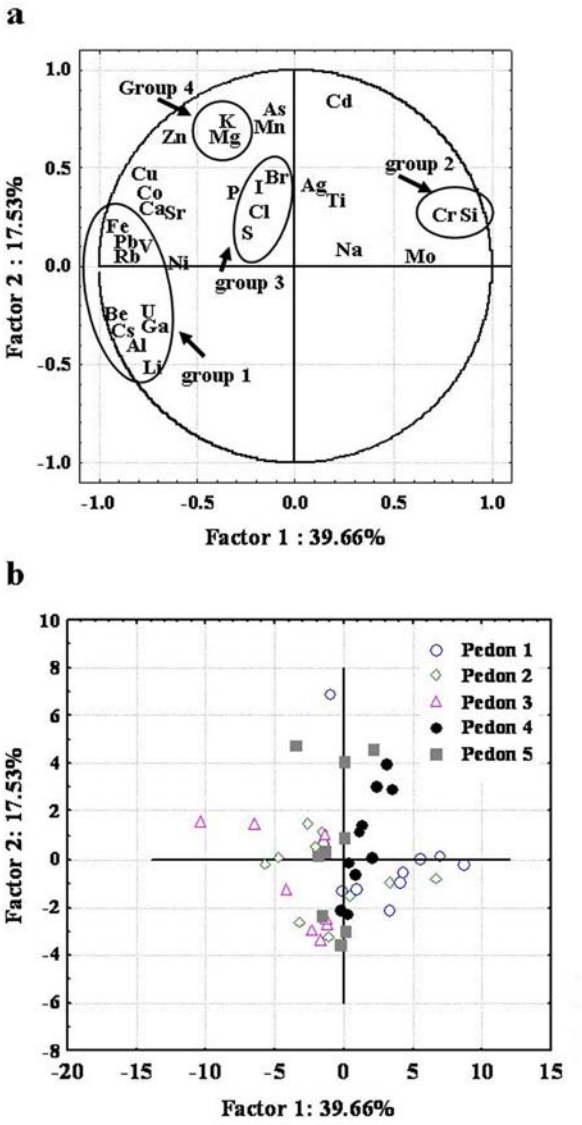

Figure 7 Factor analysis for element concentrations in whole soil of the Clayey Natraqualfs: (a) Distribution of elements; (b) Distribution of soil samples.

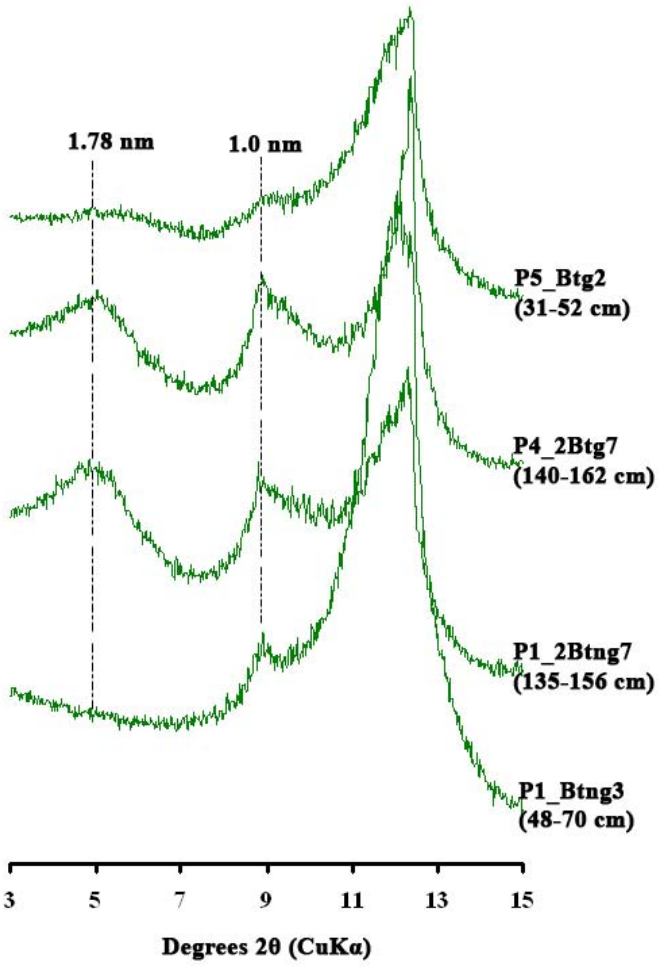

Figure 8 XRD patterns of oriented clay of Clayey Natraqualfs showing the distinction between beidellite and montmorillonite provided by the Green-Kelly test. Samples were Li- saturated, heated at 250ºC and glycerol solvated which results in the following basal spacings ~1.8 nm (beidellite) and 1.0 nm (montmorillonite).

Identification of smectite species

The samples contain high percentage of smectites were selected for identification of smectite species. Figure 8 shows the XRD patterns distinguishing beidelite and montmorillonite by Greene-Kelly test (Brindley and Brown, 1980). The 001 spacing of about 1.0 nm indicates a montmorillonite, and the spacing range of 1.70-1.78 nm indicates a beidellite. The two samples are beidelite dominant (P1_2Btng7 and P4_2Btng7) whereas in the other two samples (P1_Btng3 and P5_Btg2) beidelite is also present along with montmorillonite.

Properties of kaolins

The electron micrographs of kaolin are shown in Figure 9. The dominant morphologies of kaolins in different samples include anhedral, subhedral and euhedral faces of platy crystals. The tubular crystal is not present. Figure 10 shows the bar graph of percentages among three shapes of kaolin minerals. The median size of kaolin crystal ranges from 47-52 nm with the standard deviation range of 13.0-15.8 and the crystals size does not have a normal distribution (Figure 11). The sizes of kaolin crystals in these soils tend to be smaller than those Thai kaolin crystals reported by Trakoonying-

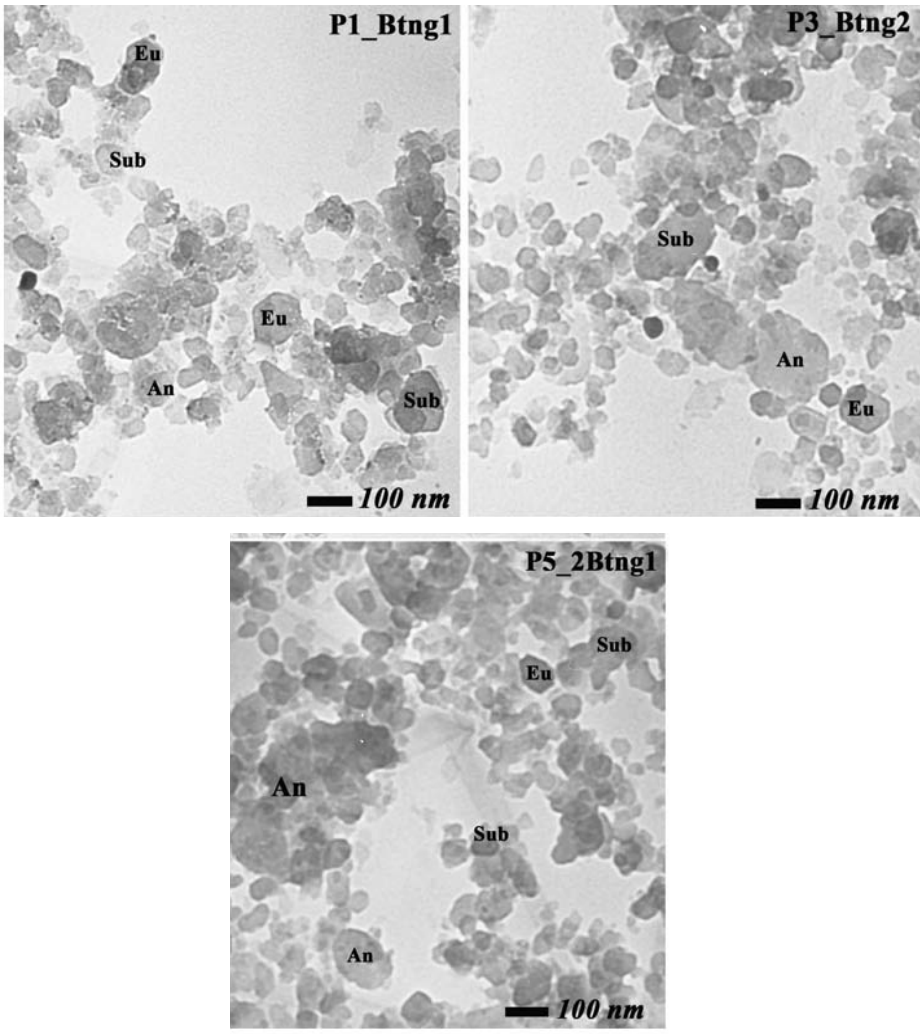

Figure 9 Transmission electron microscope (TEM) micrographs of kaolin from Clayey Natraqualfs showing the wide ranges of crystal morphology and size. Various morphologies are indicated in the Figure: Eu=euhedral crystal, Sub=subhedral crystal and An=anhedral crystal.

charoen et al. (2006). The crystal sizes of kaolin ranging from 50-200 nm are also smaller than platy kaolin particles in soils from tropical and Mediterranean climates observed by Singh and Gilkes (1992) and Hart et al. (2002). Figure 12 shows no relationship between the number of euhedral face and kaolin crystal size. The coherently scattering domain (CSD) sizes derived from the width at half height (WHH) of XRD reflections using the Scherrer equation indicate that the CSD size of these soil kaolin crystals ranges from 5.2-8.4 nm for 001. The particle size determined by TEM is larger than values derived by XRD. A major cause of this discrepancy is that XRD measurement is from the c-axis direction which is much smaller that the width of the platy crystals (a, b directions) measured by electron microscopy (Hart et al., 2002).

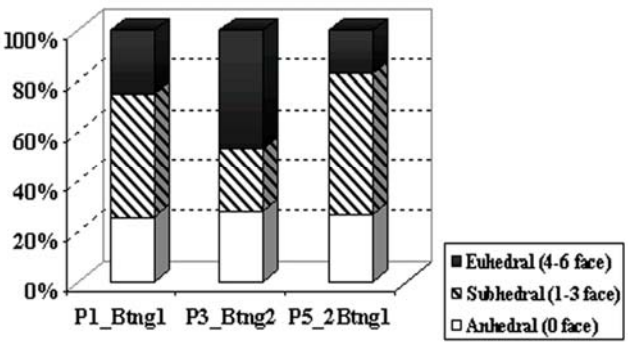

Figure 10 Graph showing the percentages of kaolin crystal shape from some Clayey Natraqualfs.

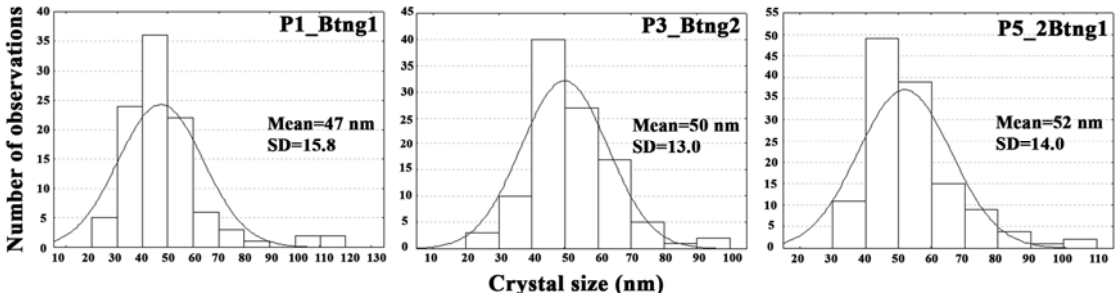

Figure 11 Histograms of the crystal size of the individual kaolin crystal from Clayey Natraqualfs in Northeast Thailand.

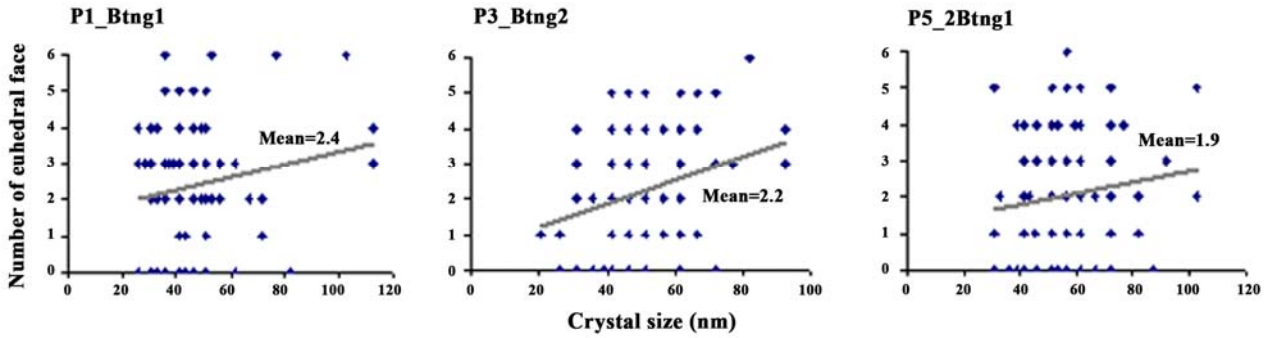

Figure 12 Graph showing the relationship between the frequency of the number of euhedral face and kaolin crystal size from Clayey Natraqualfs, Northeast Thailand.

Conclusions

The Clayey Natraqualfs have a salt patch, bare surface and halophytic plants as environmental indicators. On the basis of chemical properties the soils could be classified into two groups of salt affected soils: saline sodic soil (Pedons 1-3 and 5), and saline soil (Pedon 4). The salinization and alkalization are the most important pedogenic processes in these soils. However, the desalinization and dealkalization are also active.

Field morphology and micromorphology are quite comparable among profiles along the linear traverse line due their similar parent material, physiographic condition and land use. Optical micromorphology and SEM/EDS analysis results clearly show the accumulation of salt in some profiles. Crystalline halite in voids, coated in voids, coated on grains and mixed in the soil matrix is abundant in Pedons 1 and 2 where salt patches surface exist. The EDS spectra indicate the presence of halite (NaCl) and barite ($BaSO_4$) that have crystallized in voids and mixed in the soil matrix in some of the soils. The element composition of the soil matrix in a triangle graph of SiO_2: Al_2O_3: Fe_2O_3 is displaced from the 'kaolin line' towards the SiO_2 apex, indicating that a Si-rich is present in the matrix, but the XRD results indicated high percentage kaolin minerals. So, a Si-rich in soil matrix are probably due to the resilication that can occur in salt affected soils where the solubility of silica is promoted by the high pH. The chemical composition of the soils is highly diverse attribute the effects of salinity. Salt affected soils consist predominantly of quartz and clay minerals. Clay fractions consist predominantly of kaolin, smectite and trace of illite and interstratified minerals. The smectite species of these soils are beidellite and montmorillonite. Kaolin consists of platy crystals. The median size of crystal tends to be smaller than the size of kaolin crystals in several other soil types in Thailand.

The presence of salinity has affected some soil properties generating salt patch, prismatic or columnar structure, high EC, and elevated concentrations of Na and halides. The trend of salinity effect on mineral alteration exists but needs be explored in more details.

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