RESULTS AND DISCUSSION

1. Minerals in clay fractions of Alfisols and Ultisols in Thailand

1.1 Alfisols

1.1.1 Types and abundance of minerals in the clay fraction

Results obtained from XRD analysis revealed that kaolin is the dominant silicate clay mineral conforming with typical situation of the soils in the Tropics. Smectite and illite in small amounts can also be detected in these soils. Quartz is present in the clay fraction in all soils. Anatase and vermiculite are also found in trace amounts in some soils (Appendix Table 3). The XRD patterns of basally oriented specimens of representative Alfisols (Pran Buri=Pr, Muak Lek= Ml, Phak Kat= Pak, Phan= Ph and San Sai= Sai), are given in Figure 3 and electron micrographs of representative kaolin are shown in Figure 4.

1.1.2 Nature of minerals in the clay fraction

A summary on mineral species in the clay fraction and some fertility parameters of these Alfisols are shown in Table 6. The presence of kaolin in the clay fraction is reflected well in the XRD pattern of these soils. The XRD pattern also shows quartz and anatase in most of these soils that due to the effect of their parent materials. Iron oxides are present in most soils and are the most abundant metallic oxides in most soils. Goethite (α-FeOOH) which gives yellow to brown colours and hematite (α-Fe_2O_3) which gives red colours are the only two Fe oxides are present. They are important constituents of the highly weathered soil of tropical region that kaolin as the major clay mineral (Schwertmann and Taylor, 1989).

Kaolin: Kaolin is evidently the major clay mineral in these soils and is present in all of samples (Figure 5a). About 80 percent of these soils have more than about 40 percent kaolin in the clay fraction. The presence of kaolin is consistent with the quite highly weathered condition of most of these soils (Dixon, 1989).

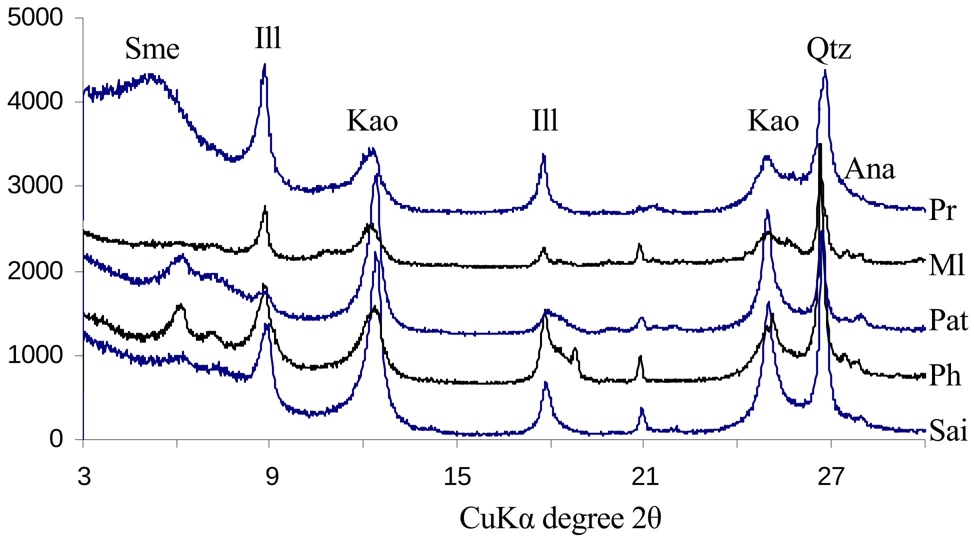


Figure 3 XRD patterns of the basally oriented clay fraction on representative Alfisols. The clay consists much of kaolin (Kao) and illite (Ill) but also has a small amount of smectite (Sme). (Pran Buri= Pr, Muak Lek= Ml, Phak Kat= Pak, Phan= Ph and San Sai= Sai).

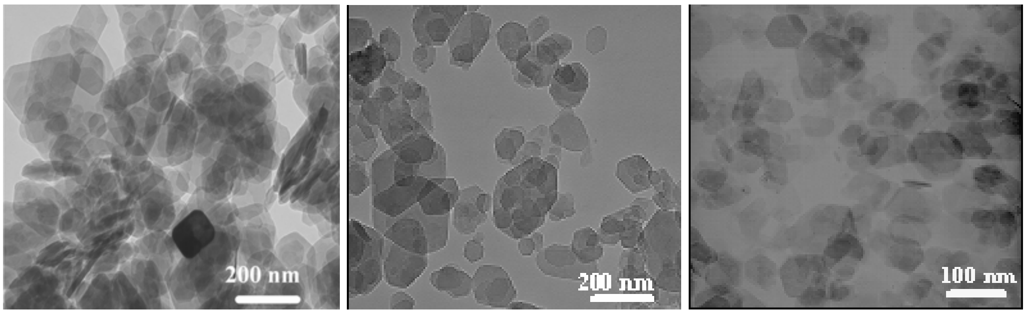


Figure 4 Transmission electron micrographs (TEM) of Alfisols illustrating the dominantly sub-micron, platy, euhedral to subhedral morphologies and the wide variation of crystal morphology and size.

Table 6 Minerals in the clay fraction and some properties of Alfisols

Soil series	Mineral species in clay fraction						pH	CEC	Clay
	Ver	Sme	Ill	Kao	Qtz	Ana	(1:1) H_2O	(cmol kg^{-1})	(g kg^{-1})
Land condition: Lowlands									
Doem Bang (Db)	-	-	tr	xxx	xxx	tr	7.2	11.40	188
Khao Yoi (Kyo)	-	x	x	xxx	x	tr	6.1	16.90	224
Manorom (Mn)	-	-	x	xxx	x	tr	6.0	12.10	244
Nakhon Pathom (Np)	-	tr	x	xx	x	tr	7.8	20.00	268
Hang Dong (Hd)	-	xxx	-	xx	tr	tr	7.9	27.20	368
Phan (Ph1)	-	tr	x	xx	x	tr	4.8	13.90	216
Phan (Ph2)	-	tr	tr	xx	x	-	5.3	7.83	248
Phan (Ph3)	-	tr	tr	xx	xx	tr	4.8	12.90	300
San Sai (Sai)	-	tr	x	xx	x	tr	6.5	4.13	128
Mae Sai (Ms)	-	tr	x	xx	x	tr	5.7	23.98	448
Lampang (Lp)	-	-	tr	xxx	x	tr	5.4	8.91	268
Tha Tum (Tt)	-	x	tr	xx	x	tr	5.0	21.81	420
Langu (Lgu)	-	tr	tr	xxx	tr	tr	5.6	10.58	272
Land condition: Uplands									
Pran Buri (Pr)	-	x	x	x	x	-	7.2	6.90	188
Thap Khwang (Tw)	-	tr	-	xxx	x	-	8.3	14.61	168
Kamphaeng Sean (Ks)	-	-	x	xx	x	tr	7.7	19.91	352
Phetchaburi (Pb)	-	-	x	x	xxxx	-	5.9	5.36	96
Wichain Buri (Wb)	-	x	tr	xx	xx	tr	5.6	3.30	60
Muak Lek (Ml)	tr	-	x	xx	x	tr	6.2	19.50	268
Kamphaeng Phet (Kp)	-	tr	x	xx	x	tr	5.7	20.75	136
Li (Li)	tr	-	-	xxxx	tr	-	4.6	25.23	500
Phayao (Pao)	-	x	tr	xxx	tr	-	4.9	7.01	212
Khambong (Kg)	-	-	tr	xxx	x	tr	6.0	3.24	64
Wang Hai (Wi)	-	tr	tr	xxx	x	tr	5.5	5.40	108
Loei (Lo)	-	-	-	xxxx	tr	tr	5.3	12.73	360
Wang Saphung (Ws)	-	-	x	xx	x	-	7.0	22.35	408
Chatturat (Ct)	-	-	x	xxx	x	-	7.8	14.02	220
Nam Pong (Ng)	-	-	tr	xxx	x	-	5.6	0.90	52
Sikhio (Si)	-	tr	xx	xx	x	tr	7.3	23.67	512
Phak Kat (Pat)	-	tr	tr	xxx	x	tr	4.6	17.75	264

Ver = Vermiculite, Sm = Smectite, Ill = Illite, Kao = Kaolin, Qtz = Quartz, Ana = Anatase
tr= trace (<5%), x= small (5-20%), xx= moderate (20-60%), xxx= large, xxxx= dominant (>60%)

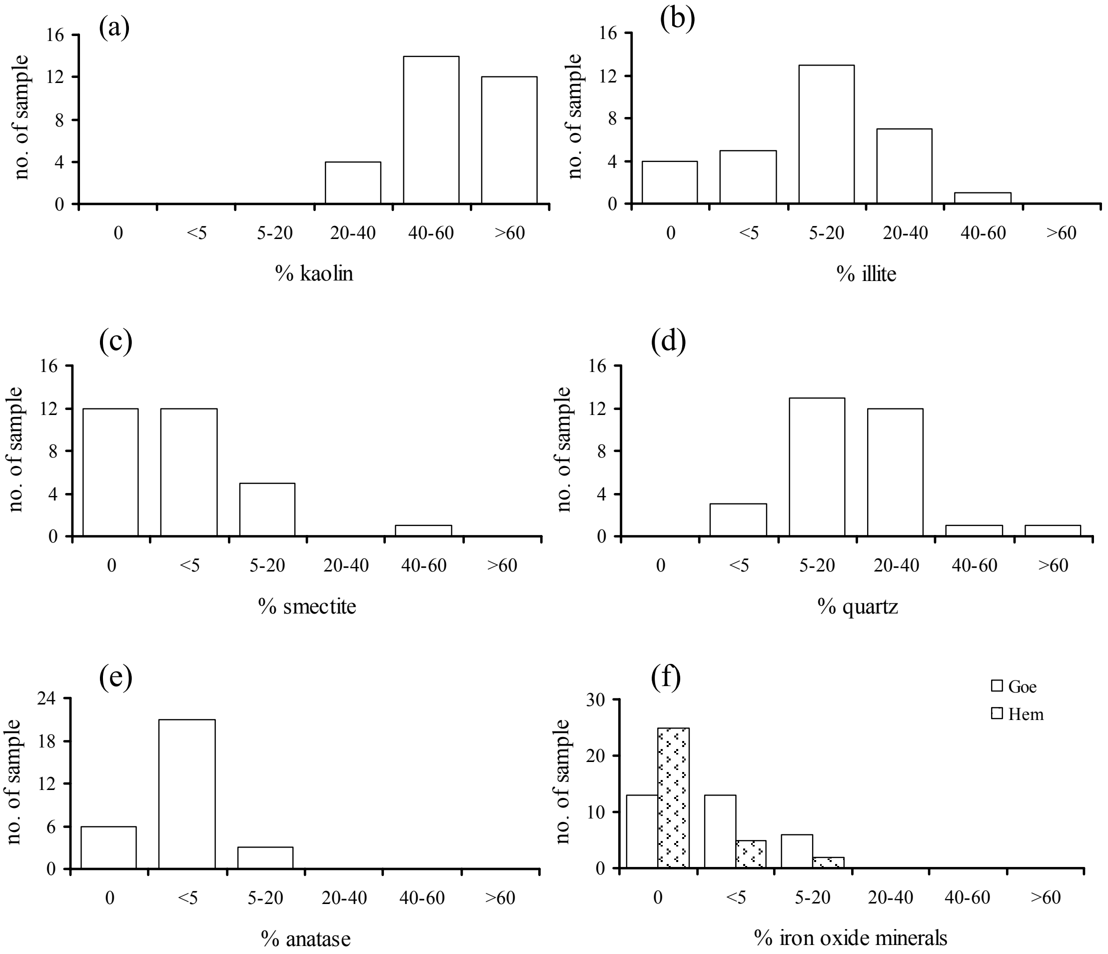


Figure 5 Frequency distribution of the abundance of clay mineral species in the clay fraction of 30 samples of Thai Alfisols; (a) kaolin, (b) illite, (c) smectite, (d) quartz, (e) anatase and (f) iron oxide minerals (Goe=goethite and Hem=hematite).

Similar observations have been made for highly weathered soils from various parts of the world (Juo, 1980; Suddhiprakarn *et al.*, 1985; Singh and Gilkes, 1992; Yoothong *et al.*, 1997; Hart *et al.*, 2003; Tragulyingjaroen *et al.*, 2006).

San Sai (Sai) and Phan (Ph) series represent soils under aquic moisture regime and Phak Kat (Pat) series for the udic moisture regime have more dominant kaolin than Pran Buri (Pr) and Muak Lek (Ml) (ustic moisture regime) (Kheoruenromne and Suddhiprakarn, 1984).

It may be expected that, with current soil forming processes, soil under udic moisture regime should have more advanced development stage due to a more continuous condition of leaching and oxidation (Kheoruenromne and Suddhiprakarn, 1984).

Electron micrographs of representative kaolin are shown in Figure 4. Kaolin in the clay fraction has relatively poor crystal order and quantitative electron microscopy has clearly shown that kaolin in these soils has small crystal size (100 to 218 nm) as compared to Georgia reference kaolins (280 and 370 nm) and other Thai soils (20 to 750 nm) (Hart *et al,* 2003) and with euhedral to subhedral platy shape.

Illite: Illite is present in 26 out of 30 samples, and some soils have moderate amounts of this clay mineral (Figure 5b). Illite can be formed in the saprolite zone of lateritic profiles from the weathering of K-feldspar or biotite (Gilkes *et al*., 1973; Singh, 1991).

Smectite: Smectite is present in 18 samples. The corresponding frequency distribution is givien in Figure 5c. Smectite occurs in soils developed from alluvial deposits, in relatively young soils (Borchardt, 1989; Singh, 1991; Dabbakula *et al.,* 1992; Yoothong, 1997). Pran Buri (Pr), Phak Kat (Pat), Phan (Ph) and San Sai (Sai) series developed on alluvium have smectite in their clay fraction.

Quartz: Quartz is present in all samples (Figure 5d). Phetchaburi (Pb) series has a dominance of quartz that maybe due to its parent material. The presence of quartz is consistent with the quite highly weathered condition of most of these soils (Allen and Hajek, 1989; Drees *et al*., 1989; Kabata-Pendias and Pendias, 2001).

Anatase: Anatase is present in most of samples but in trace amounts (Figure 5e). Anatase is the most common TiO_2 mineral in soils (Walker *et al.,* 1969; Milnes and Fitzpatrick, 1989). It is a major constituent in some highly weathered soils in the Tropics (Anand and Gilkes, 1984).

Goethite: Goethite is present in 19 samples but in trace amounts (Figure 5f). The low temperature, humid climate, pH near 4, high water activity, and high organic matter are among the conditions that favour goethite formation (Schwertmann and Taylor, 1989).

Hematite: Hematite is present in only 7 samples (Figure 5f). Hematite is the most abundant iron oxide of these Alfisols. Hematite forms in relatively dry, warm soils more slowly than in moisture environments (Ibanga *et al.*, 1983).

1.1.3 The effect of minerals in clay fraction on soil fertility parameters

The pH values of most of these soils in water (1:1) range from very strongly acid to moderately alkaline (4.6-8.3). The results show that the dominance of kaolin is consistent with high leaching and acid conditions. Hang Dong (Hd) and Thap Khwang (Tw) series have high pH so that they have smectite in the samples. The high pH is required to stabilize the smectite initially present in the soils (Singh, 1991). CEC of these soils ranges from 0.9 to 27.2 cmol kg^{-1} (Table 6). The CEC is quite variable within and between mineral groups. For example, the CEC of the kaolin and illite is relatively low, whereas the CEC is high for smectite and vermiculite. Hang Dong (Hd) series has the highest CEC because of this soil contains large amounts of smectite, whereas Loei (Lo) series has lower CEC because it is dominated by kaolin (Schwertmann and Herbillon, 1992; Hart *et al.,* 2003). While Li series also dominated by kaolin but the CEC is high that may be due to the small size and defect structure of kaolin in this sample (Singh and Gilkes, 1992c; Hart *et al.,* 2002, 2003; Trakoonyingcharoen, 2006).

These soils consist of kaolin as the dominant species whereas smectite and illite can also be found in some samples in variable quantity depending on the parent materials. This dominance of kaolin is consistent with the highly weathered condition of these soils and similar observations have been made for highly weathered soils from other parts of the world (Juo, 1980; Suddhiprakarn *et al.,* 1985; Singh and Gilkes, 1992c; Yoothong *et al.,* 1997; Hart *et al.*, 2003; Trakoonyingjaroen *et al.*, 2006). The large surface area and chemical reactivity of soil kaolin, which results from the small size and defect structure will be important for sorption reactions in some of these soils (Singh and Gilkes, 1992c; Hart *et al.*, 2003) which are often sandy and containing little organic matter to adsorb plant nutrients and other ions.

Consequently, kaolin may provide a substantial part of the capacity of some soils such as Li series (Table 6) to retain cations and anions (Hart *et al.*, 2002, 2003).

1.2 Ultisols

1.2.1 Types and abundance of clay minerals

Three clay minerals (kaolin, illite and inhibited vermiculite) were identified in the clay fraction of these soils (Appendix Table 4). Representative XRD patterns of basally oriented specimens after various diagnostic treatments (magnesium saturated air-dried, magnesium saturated, ethylene glycol, potassium saturated air-dried and potassium saturated, heated at 550°C) obtain from Klaeng (Kl) series are given in Figure 6.

The clay fraction of Thai Ultisols consists mostly of kaolin with lesser inhibited vermiculite, illite and anatase (Table 7). The relative abundance of clay mineral and species and other minerals such as quartz, iron oxide minerals were determined semi quantitatively by XRD, amounts of a clay minerals are expressed as a percentage of all clay minerals in the clay fraction. Percentages were determined by reference to XRD patterns of standard minerals. Although these estimates are semi-quantitative they do permit the comparison of a large number of samples and help identify substantial differences between soils. Frequency histograms of the relative amounts of clay and the others minerals in the clay fraction of all soils are shown in Figure 7.

1.2.2 Nature of minerals in the clay fraction

A summary on mineral species in the clay fraction and some soil fertility parameters of these Ultisols are shown in Table 7.

Kaolin: About 80 percent of these soils have more than about 40 percent kaolin in the clay fraction (Figure 7a).

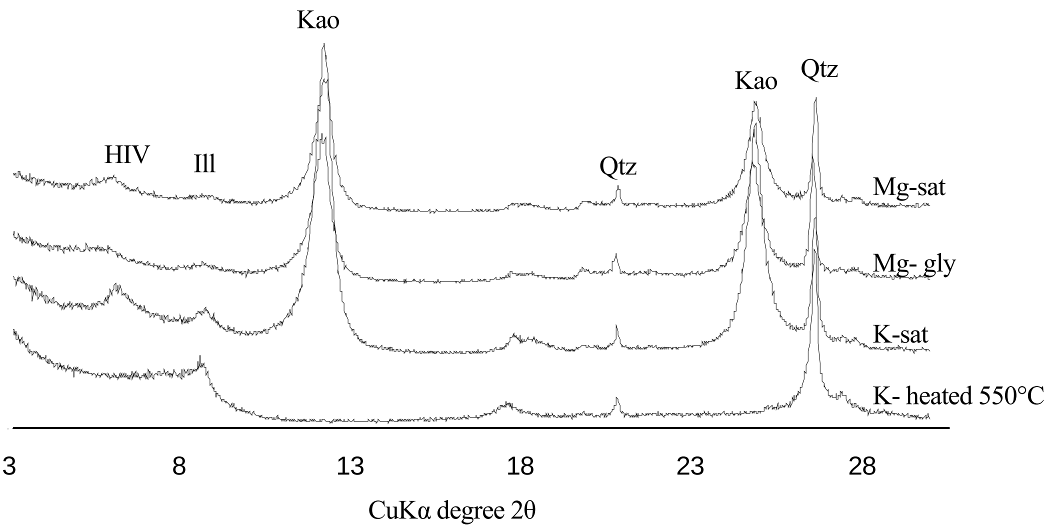


Figure 6 XRD patterns of the basally oriented clay fraction of Klaeng (Kl) series (Typic Plinthaquults; Very-fine, kaolinitic) after various pre-treatments. The clay consists much kaolin (Kao) and has small amount of inhibited vermiculite (HIV).

Illite: Illite is present in 79 out of 150 samples, and some soils have moderate amount of this clay mineral (Figure 7b). Pedogenic illite can be formed in the saprolite zone of lateritic profiles from the weathering of K-felspar or biotite (Gilkes *et al.,* 1973, Bettenay *et al.,* 1980; Singh, 1991), although much illite in soils originates in sedimentary rocks. Pak Tho (Pth), Sri Thep (Sri) and Chiang Rai (Cr) series are the representative Ultisols that have illite minerals which form from lateritic profile.

Inhibited vermiculite: Inhibited vermiculite is present in 36 samples and in most of these samples it comprises less than 5 percent of the clay mineral suite (Figure 7c). This mineral is most abundant in more acidic and highly weathered soils (Carlisle and Zelazny, 1973; Harris *et al.*, 1980; Norrish and Pickering, 1983; Barnhisel and Bertsch, 1989; Singh, 1991). The association of inhibited vermiculite with abundant kaolin can be related to the occurrence of mica and feldspar in the deeper horizons of the soil (Douglas, 1989; Singh, 1991).

Table 7 Minerals in the clay fraction and some soil properties of Ultisols

Soil series	Mineral species in clay fraction					pH	CEC	Clay
	Ver	Ill	Kao	Qtz	Ana	(1:1) H_2O	(cmol kg^{-1})	(g kg^{-1})
Land condition: Lowlands								
Hin Kong (Hk)	tr	x	xxx	xx	-	6.0	7.66	120
Pak Tho (Pth)	-	x	xxx	xx	-	5.9	7.44	240
Si Thep (Sri)	tr	x	xxx	xx	-	6.2	8.84	168
Klaeng (Kl)	x	tr	xxx	x	-	5.1	5.74	24
On (On)	tr	tr	xxx	xx	tr	5.5	5.13	112
Chiang Rai (Cr1)	x	x	xx	x	tr	5.3	7.62	168
Chiang Rai (Cr2)	x	x	xx	x	tr	6.8	11.47	240
Phen (Pn)	tr	-	xx	xxx	tr	5.1	5.89	140
Renu (Rn1)	tr	-	xxx	xx	tr	4.6	2.85	80
Renu (Rn2)	tr	-	xxxx	tr	-	5.6	3.71	148
Roi Et (Re)	tr	-	xxx	xx	tr	5.7	2.38	92
Bang Nara (Ba)	tr	x	xxx	x	tr	5.5	14.02	484
Khok Khain (Ko)	tr	tr	xxx	xx	tr	4.9	8.04	144
Phatthalung (Ptl)	x	tr	xxx	x	-	4.8	10.72	280
Sungai Padi (Pi)	tr	tr	xxxx	tr	tr	5.1	4.94	208
Visai (Vi)	x	tr	xxx	xx	tr	4.5	4.85	68
Yan Ta Khao (Yk)	xx	tr	xxx	x	tr	5.2	11.93	192
Land condition: Uplands								
Bang Khla (Bka)	tr	-	xxxx	tr	-	4.9	3.57	120
Don Rai (Dr)	tr	-	xxxx	tr	tr	4.5	3.15	128
Lat Ya (Ly)	tr	xx	xx	x	tr	5.7	7.42	120
Tha Yang (Ty)	tr	xx	xx	x	tr	5.2	6.97	68
Kabin Buri (Kb1)	tr	-	xxxx	tr	tr	5.4	15.61	396
Kabin Buri (Kb2)	tr	-	xxxx	tr	tr	4.7	8.17	228
Khlong Chak (Kc)	x	tr	xxx	x	tr	5.5	13.68	408
Mab Bon (Mb)	tr	-	xxx	xx	tr	6.0	1.70	20
Ban Chong (Bg)	-	x	xxx	x	tr	5.2	17.16	393
Ban Chong-high bases (Bg-hb)	-	x	xxx	x	-	4.9	11.26	324
Doi Pui (Dp)	-	-	xxxx	tr	tr	5.5	15.02	240
Hang Chat (Hc)	tr	-	xxxx	x	-	5.9	8.73	168
Chiang Khan (Ch1)	tr	-	xxxx	tr	tr	4.9	12.90	300
Chiang Khan (Ch2)	tr	-	xxxx	tr	tr	5.5	10.65	264
Korat (Kt1)	-	-	xx	xxxx	tr	6.0	1.29	120
Korat (Kt2)	-	-	xx	xxxx	tr	5.7	1.21	40
Dan Sai (Ds)	-	x	xxx	x	-	6.3	5.57	12

Table 7 (Continued)

Soil series	Mineral species in clay fraction					pH	CEC	Clay
	Ver	Ill	Kao	Qtz	Ana	(1:1) H_2O	(cmol kg^{-1})	(g kg^{-1})
Land condition: Uplands								
Korat (Kt3)	tr	x	xx	tr	tr	6.6	1.90	40
Mae Rim (Mr)	-	tr	xx	xx	tr	5.9	3.17	112
Mae Taeng (Mt)	-	tr	xxxx	tr	-	4.7	9.72	256
Nong Mot (Nm)	tr	-	xxxx	x	-	4.7	4.40	104
Pak Chong (Pc)	tr	-	xxx	tr	tr	7.8	23.37	452
Phu Sana (Ps)	-	tr	xxxx	x	tr	6.5	3.86	16
Sakon (Sk)	x	x	xx	xx	tr	6.9	4.21	60
Satuk (Suk1)	-	-	xx	xxx	tr	5.9	1.55	56
Satuk (Suk2)	-	-	xxx	xx	tr	6.0	1.37	40
Satuk (Suk3)	tr	-	xx	xxx	tr	6.4	2.00	64
Satuk (Suk4)	-	x	xx	xxx	tr	5.3	1.90	56
Sung Noen (Sn1)	-	-	xxxx	x	-	7.8	18.12	224
Sung Noen (Sn2)	tr	-	xxx	xx	-	5.8	1.43	28
Warin (Wn)	tr	-	xxxx	x	tr	5.3	1.26	40
Yasothon (Yt1)	-	-	xx	xxx	tr	5.1	0.95	40
Yasothon (Yt2)	-	-	xxx	xx	tr	6.0	2.20	56
Chalong (Chl)	tr	-	xxxx	x	tr	4.6	6.45	148
Fang Daeng (Fd)	tr	-	xxxx	tr	tr	5.9	5.17	120
Hat Yai (Hy)	-	x	xxx	x	tr	4.4	5.09	124
Huai Pong (Hp)	-	-	xxx	xx	tr	4.1	4.45	80
Khao Khat (Kkt)	tr	x	xxx	xx	tr	4.3	0.70	252
Khlong Teng (Klt)	tr	xx	xx	x	-	4.8	10.74	264
Khlong Thom (Km1)	-	-	xxxx	x	tr	4.6	5.67	44
Khlong Thom (Km2)	-	-	xxxx	x	-	5.4	0.70	68
Kho Hong (Kh1)	tr	tr	xxx	x	tr	4.2	3.82	240
Kho Hong (Kh2)	-	-	xxx	xx	tr	4.2	1.31	52
Klong Nok Krathung (Knk)	-	x	xxx	x	-	4.7	4.32	92
Krabi (Kbi)	x	tr	xxx	x	tr	4.7	14.76	436
Na Tham (Ntm)	tr	-	xxxx	tr	-	3.8	6.46	148
Nong Khla (Nok)	x	tr	xxx	x	tr	5.4	17.98	380
Padang Besar (Pad)	-	-	xxxx	tr	-	5.1	2.43	76
Pak Chan (Pac)	x	tr	xx	xx	-	4.8	11.40	248
Pathio (Ptu)	tr	-	xxxx	x	tr	6.8	5.28	84
Phangnga (Pga)	-	tr	xxxx	x	tr	4.3	3.70	108
Phato (Pto)	x	-	xxx	x	-	5.4	0.76	32

Table 7 (Continued)

Soil series	Mineral species in clay fraction					pH	CEC	Clay
	Ver	Ill	Kao	Qtz	Ana	(1:1) H_2O	(cmol kg^{-1})	(g kg^{-1})
Land condition: Uplands								
Phuket (Pk)	tr	tr	xxxx	x	-	4.5	8.80	152
Sawi (Sw)	x	tr	xxx	x	-	4.5	7.25	32
Tha Sae (Te)	tr	-	xxxx	x	-	5.9	8.86	132
Wang Tong (Wat)	xx	-	xx	x	tr	5.5	13.15	216
Yala (Ya)	tr	tr	xxxx	x	tr	4.2	4.15	136

Ver = inhibited vermiculite, Ill = illite, Kao = kaolin, Qtz = quartz, Ana = anatase,
tr= trace (<5%), x= small (5-20%), xx= moderate (20-60%), xxx= large, xxxx= dominant (>60%).

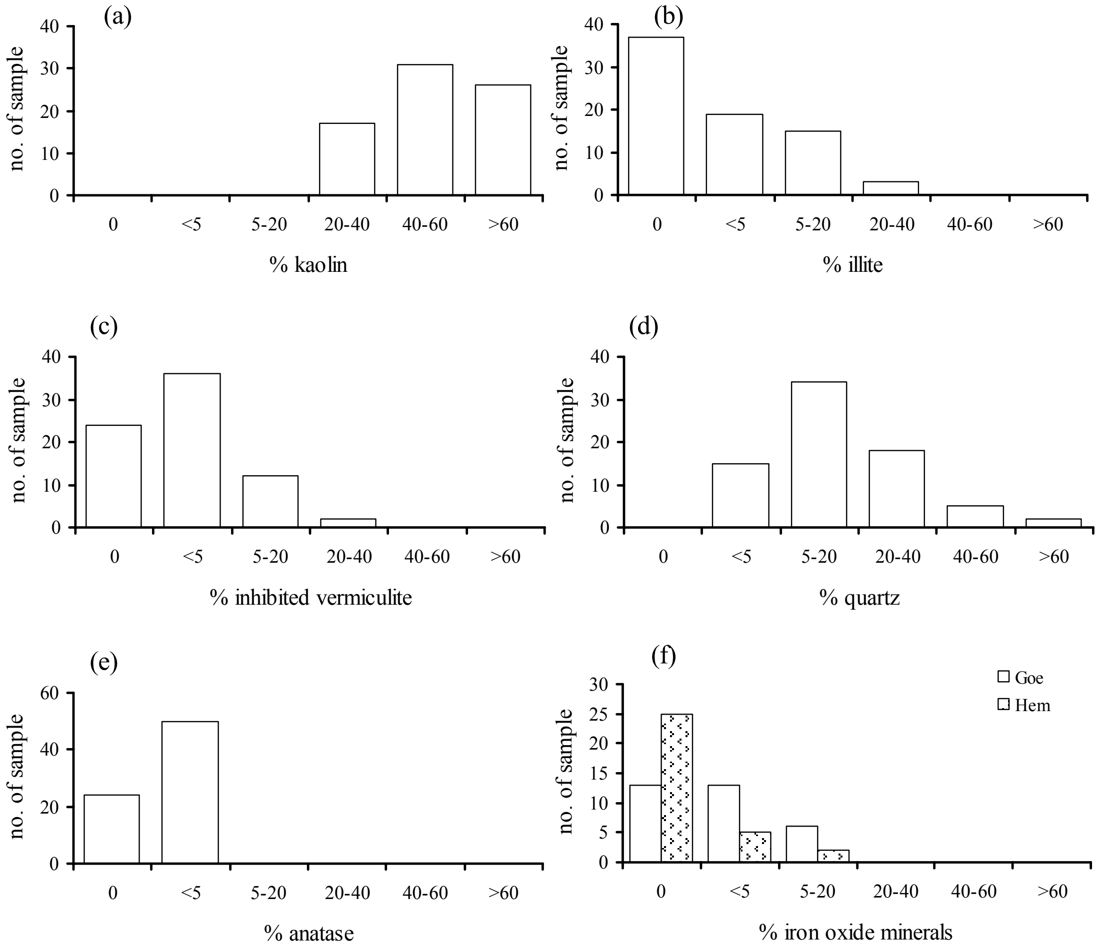


Figure 7 Frequency distribution of the abundance of clay mineral species in the clay fraction of 75 samples of Thai Ultisols; (a) kaolin, (b) illite, (c) smectite, (d) quartz, (e) anatase and (f) iron oxide minerals (Goe=goethite and Hem=hematite).

In the more acidic surface soil horizons the interlayer K has been removed from mica by exchange and replaced by aluminum hydroxide polymers (Norrish and Pickering, 1983) while feldspar weather to kaolin. In the present study amounts of inhibited vermiculite were similar in the topsoil (mean = 0.35%) and subsoil (mean= 0.3%of clay).

Quartz: Quartz is present in all samples (Figure 7d). The presence of quartz is consistent with the quite highly weathered condition of most of these soils (Dress *et al.*, 1989; Kabata-Pendias and Pendias, 2001).

Anatase: Anatase is present in most of samples but in trace amounts (Figure 7e). Anatase is the most common TiO_2 mineral in soils. It is a major constituent in some highly weathered soils in the Tropics (Anand and Gilkes, 1984; Milnes and Fitzpatrick, 1989).

Goethite: Goethite is present in 45 out of 75 samples for Thai Ultisols (Figure 7f). Low temperature, humid condition, high water activity, pH near 4 and high OM favor goethite formation (Velde, 1992).

Hematite: Hematite is present in 30 samples (Figure 7f). High temperature, arid climate and pH near 7-8 favor hematite formation (Velde, 1992).

1.2.3 The effect of minerals in clay fraction on soil fertility parameters

Ultisols have an acidic reaction for most samples with pH values in water (1:1) ranging from extremely acid to slightly alkaline (pH 3.-7.8) (Table 7). The mineralogical results revealed that minerals in their clay fraction are kaolin and inhibited vermiculite. And these minerals are consistent with high leaching and acid conditions. The CEC of these soils ranges from 0.76-23.37 cmol kg^{-1} (Table 7). The CEC can vary within and between mineral groups. For example, kaolins have variable CEC depending on their member minerals. The CEC of the kaolin and illite is relatively low, whereas the CEC is high for smectite and vermiculite (Bain and Smith, 1987; Orlov, 1992; Richard *et al.*, 1997). Pak Chong (Pc), Krabi (Kbi), Nong Khla (Nok) and Wang Tong (Wat) series have high CEC because of these soils contain inhibited vermiculite (Bertsch and Thomas, 1983), whereas Korat (Kt), Yasothon (Yt) and Kho Hong (Kh) series have low CEC because they are dominated by kaolin and quartz (Hart *et al.,* 2003).

The wide variety of soil in Thailand is the result of the interaction among climate, parent rocks and physiographic regions of the country. This is reflected in the wide variety of clay minerals. Kaolin is the most common and abundant clay mineral in Alfisols and is present in all samples. About 80 percent of the samples has more than 40 percent of kaolinite in the clay fraction. Variable amounts of illite and smectite are also constituents of these soils along with quartz, anatase and trace amounts of iron oxides.

The clay fraction of Thai Ultisols consists mostly of kaolin. The dominance of kaolin is consistent with the high development stage of the soil since kaolin is the most stable clay mineral in highly weathered soil condition (Allen and Hajek, 1989; Yoothong *et al.,* 1997; Schulze *et al.,* 1999; Hart *et al.*, 2003; Tragulyingjaroen *et al.*, 2006). Illite and inhibited vermiculite are also present in clay fraction in minor quantities for some samples. Quartz, goethite and hematite are present in most clay samples in minor amounts. Goethite is highly stable and can be found in tropical zone (Schwertmann and Taylor, 1989; Schwertmann, 1993; Brennan and Lindsay, 1998). In Thai Ultisols, goethite can be found mixed with hematite (Schwertmann, 1988; Schwertmann, 1993; Anjos *et al.*, 1998). The present of hematite in these Ultisols indicates their high degree of development (Torrent *et al.*, 1983; Schwertmann and Kämpf, 1985; Torrent and Schwertmann, 1987; Cornell and Schwertmann, 2003).

Kaolin is the most common and abundant clay mineral in these Alfisols and Ultisols and is present in all samples. The presence of kaolin is consistent with the quite highly weathered condition of most of these soils (Dixon, 1989; Yoothong *et al.,* 1997; Schulze *et al.,* 1999; Hart *et al.*, 2003)

Smectite is present in only Alfisols. It is a weatherable mineral (Dabbakula *et al.,* 1992; Olsen *et al.*, 2000). During formation, smectites require an environment high in Si and alkaline earth cations (Borchardt, 1989; Olsen *et al.*, 2000). Smectite becomes unstable as soil leaching increases. In a soil-leaching environment with low organic matter and moderate acidity (pH~5), smectite weathers to pedogenic chlorite (Borchardt, 1989), or, with sufficient Al or Fe, forms hydroxy interlayers (Barnihisel and Bertsch, 1989). Smectite indicates lower degree of development of Alfisols as compared to that of Ultisols (Kheoruenromne, 1991; Velde, 1992; Soil Survey Staff, 1999; Brady and Ray, 2002). The presence of smectite could increase the CEC of the soils (Foster, 1955; Harris, 1980; Olsen *et al*., 2000), so the fertility status of these soils is moderate.

Illite is present in both Alfisols and Ultiosls. Illite in most soils originates mainly from soil parent materials. They are generally more prevalent in the clay mineralogy of younger, less weathered soils such as Alfisols than in that of the more weathered soils (Ultisols) (Fanning *et al*., 1989). But for some of these Thai Ultisols, illite still persist in their clay fraction. This indicates differential development and variability of parent materials and forming condition of these soils (Singer, 1993; Bryant and Aenold, 1994; Churchman, 2000).

Inhibited vermiculite is abundant in more acidic highly weathered soils (Norrish and Pickering, 1983, Barnhisel and Bertsch, 1989; Soil Survey Staff, 1999). It tends to be most abundant in Ultisols (Soil Survey Staff, 1999). In this study inhibited vermiculite can be found only in Thai Ultisols.

2. Kaolin minerals

2.1 General properties of selected Thai Ultisols

Properties of the investigated soils are given in Table 8. Their texture ranges from loamy sand to clay with most soils being sandy in texture. In some soil profiles there is a substantial increase in clay content in subsurface horizons, indicating that some of the Ultisols are duplex (texture contrast) soils (Stace *et al.,* 1965).

The soils are all acidic, with pH values in water mostly range from extremely to moderately acid (4.1-6.0). The Pathui (Ptu) series has a near neutral pH in the topsoil that is possibly due to addition of colluvial limestone. The CEC of these soils is low to very low which is consistent with the mostly small OM content, low pH, sandy texture and kaolin dominated clay.

Table 8 Locations, soil parent materials and some soil properties of samples from selected Thai Ultisols for kaolin study

Soil series	Parent material	Horizon	pH (H_2O)	CEC ($cmol_c$ kg^{-1})	Total Fe	Sand	Silt	Clay
					(------------g kg^{-1}	-------------		-------------)
Typic Kandiudults, fine*								
Hoi Pong (Hp)	Colluvium and alluvium	topsoil	4.1	1.09	8.4	756	164	80
	from granite and quartzite	subsoil	4.5	1.50	12.0	604	316	80
Pathui (Ptu)	Sandstone, limestone	topsoil	6.8	2.89	16.7	718	198	84
		subsoil	5.0	3.10	40.0	500	152	348
Typic Kandiudult, coarse-loamy								
Kho Hong (Kh)	Alluvium	topsoil	6.0	1.18	5.0	787	161	52
		subsoil	5.1	1.42	6.9	728	140	132
Typic Kandiustult, fine-loamy								
Don Rai (Dr)	Old alluvium on middle	topsoil	4.5	1.26	9.2	669	243	88
	terraces	subsoil	4.8	2.29	10.4	552	244	204
Rhodic Kandiudult, fine-loamy								
Fang Daeng (Fd)	Granite, quartzite and	topsoil	5.9	1.55	18.5	680	200	120
	phyllite	subsoil	5.1	1.17	27.7	534	346	120
Typic Palehumult, fine								
Doi Pui (Dp)	Residual soils derived from	topsoil	5.5	5.53	95.4	119	641	240
	granite, gneiss or schist	subsoil	5.5	5.97	107	103	547	440
Typic Plinthudult, clayey-skeletal								
Krabin Buri (Kb)	Residual soils derived	topsoil	5.4	3.44	79.9	360	260	380
	from shale	subsoil	5.2	3.58	104	200	190	610
Typic Kandiustult, fine-loamy								
Warin (Wn)	Old alluvium	topsoil	5.3	0.44	3.9	480	480	40
	(middle and high terrace)	subsoil	5.1	1.98	12.1	670	130	200
Typic Paleustult, fine-loamy								
Satuk (Suk)	Old alluvium	topsoil	5.9	1.28	3.1	850	94	56
	(middle and high terrace)	subsoil	4.7	3.18	13.7	648	76	276
Mean			5.2	2.38	3.2	553	250	197
SD			0.6	1.49	3.6	218	145	154

2.2 Properties of the soil kaolins

2.2.1 Clay mineralogy

From powder patterns the approximate abundance of kaolin in the samples was calculated based on the relative peak areas of the 001 kaolin reflection for soil kaolin and reference Georgia kaolin (MP#5). The approximate amounts of the impurities quartz, vermiculite and anatase were also calculated from the XRD patterns, by comparing peak areas from powder patterns with those of patterns of standard quartz (101 reflection), vermiculite (001) and anatase (101). It was assumed that errors due to differences in X-ray absorption coefficients would be small because all samples and standards had similar X-ray absorption coefficients (Klug and Alexander, 1954). The properties of kaolin derived from the XRD patterns together with their specific surface area are given in Table 9.

The 001 spacing of the kaolins range from 0.716 to 0.725 nm with a median value of 0.719 nm. The range of values of the 002 spacing was narrower than for the 001 reflection with a median value of 0.357 nm. The basal spacings are slightly higher than those for the Georgia kaolin (Table 9). The spacing of the 001 reflection increases with decreasing CSD due to displacement of the 001 reflection towards smaller 2θ as CSD decreases (Trunz, 1976) (Figure 8a). There is no corresponding relationship for d_{002} (Figure 8b).

The asymmetry of the 001 reflection was higher than for the 002 reflection. Perfectly symmetrical reflections would have an asymmetry index of zero whereas the 001 reflections for the soil kaolins, excluding the Satuk (Suk) series, are greater than zero which is a consequence of small crystal size and to the rapid increase of the angular Lorentz-Polarization factor towards small 2θ values in the region of d_{001} (McEwan and Wilson, 1980).

Table 9 Properties of the soil kaolins

Soil series	Kaolin	CEC	SSA	CD	HB	*d*-value (nm)		Asymmetry index		CSD (nm)	
	(%)	(cmol$_c$ kg^{-1})	(m^{2}g^{-1})	(C m^{-2})	index	001	002	001	002	001	060
Typic Kandiudults, fine											
Hp-top[1/]	95.7	16.2	36.5	0.44	6	0.716	0.357	0.33	0.14	19.6	21.4
Hp-sub[2/]	94.4	9.6	37.1	0.26	7	0.719	0.358	0.33	0.33	20.1	19.9
Ptu-top	91.7	17.5	44.0	0.40	7	0.718	0.358	0.33	0.00	29.2	18.5
Ptu-sub	91.4	10.1	50.9	0.20	5	0.716	0.357	0.33	0.00	24.8	19.2
Typic Kandiudult, coarse-loamy											
Kh-top	99.1	11.8	59.8	0.20	6	0.717	0.356	0.14	0.00	11.4	17.2
Kh-sub	99.3	12.5	61.4	0.21	6	0.724	0.357	0.17	0.00	11.3	15.3
Typic Kandiustult, fine-loamy											
Dr-top	99.6	20.7	53.1	0.38	5	0.720	0.356	0.00	0.33	14.2	19.2
Dr-sub	97.9	19.3	50.8	0.39	4	0.718	0.356	0.18	0.00	12.8	18.7
Rhodic Kandiudult, fine-loamy											
Fd-top	95.4	15.7	15.9	0.99	4	0.717	0.357	0.20	0.20	18.6	19.7
Fd-sub	93.7	15.7	22.7	0.69	4	0.717	0.357	0.27	0.00	19.5	21.6
Typic Palehumult, fine											
Dp-top	97.7	23.4	45.7	0.57	5	0.719	0.357	0.00	0.11	10.0	10.4
Dp-sub	93.3	20.1	42.9	0.47	5	0.724	0.357	0.11	0.11	9.6	18.5
Typic Plinthudult, clayey-skeletal											
Kb-top	96.1	18.9	40.8	0.46	9	0.720	0.357	0.43	0.14	16.1	14.7
Kb-sub	94.8	9.3	39.5	0.24	8	0.717	0.356	0.25	0.14	13.9	21.0
Typic Kandiustult, fine-loamy											
Wn-top	91.2	7.2	44.4	0.16	4	0.723	0.357	0.41	0.14	13.0	14.7
Wn-sub	91.1	10.1	48.9	0.21	5	0.721	0.357	0.25	0.14	11.3	19.9
Typic Paleustult, fine-loamy											
Suk-top	95.1	20.1	59.8	0.34	6	0.721	0.357	0.00	0.00	10.7	15.6
Suk-sub	92.1	15.1	54.0	0.28	6	0.725	0.358	0.11	0.11	10.4	15.9
Mean	95.0	15.2	44.9	0.38	6	0.719	0.357	0.21	0.11	15.4	17.8
SD	2.9	4.7	12.1	0.21	1	0.003	0.001	0.14	0.11	5.5	2.9
Georgia kaolin (MP#5)	-	2.3	18.0	0.18	28.2	0.715	0.356	0.26	0.03	37.5	31.5
Thai soils	-	8.3	47.4	0.17	6.7	0.721	-	-	-	19.3	17.9
W. Australian soils	-	5.0	50.8	0.09	5.6	0.721	-	-	-	22.9	34.5
Indonesian soils	-	9.4	72.8	0.13	5.6	0.721	-	-	-	10.8	11.9
Nigerian soils	-	-	-	-	8.0	-	-	-	-	-	-
Brazilian Ultisols	85.4	-	45.8	-	14.1	0.719	0.358	-	-	-	-

Abbreviation: SSA= specific surface area, CD=surface charge density; HB=Hughes and Brown (HB) index; CSD=coherently scattering domain size. [1/]=Topsoil (0-50 cm); [2/] =Subsoil (50-100 cm).

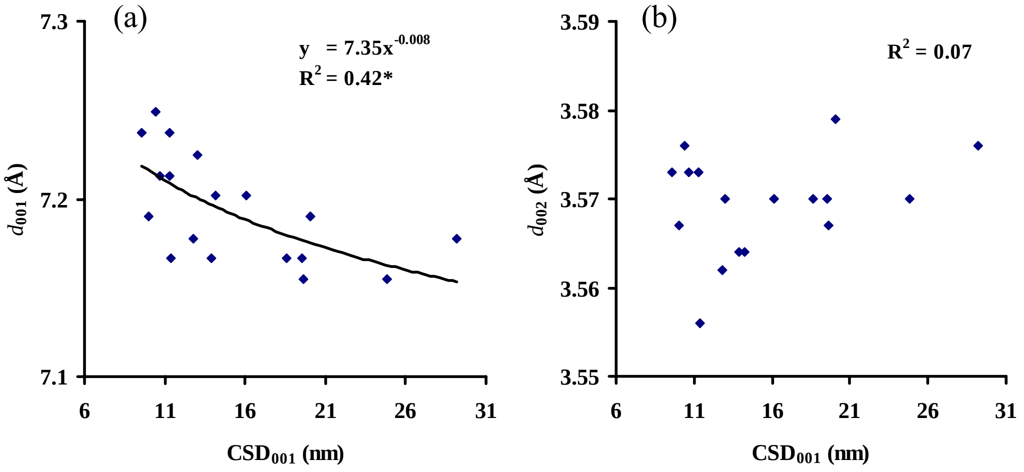


Figure 8 Relationships between crystal size (CSD) and other properties of the soil (a) *d*-value of 001 and (b) *d*-value of 002 reflection.

Some asymmetry could also be due to interstratification of kaolin with a small proportion of other clay minerals such as smectite, vermiculite or illite but the extent of such interstratification must be small as there is little or no displacement of d_{001} to higher spacings and no sensitivity to glycerol solvation or K saturation and heating. The kaolins show a very large range of asymmetry values but there is no significant difference between the mean values of the AI for soil kaolins and those for the reference kaolin for both 001 and 002 reflections. The asymmetry index for the 002 reflection is near zero as angular variations in both Lorentz-Polarization and structure factor are small at this 2θ angle (McEwan and Wilson, 1980).

The CSD calculated from the 001 reflections of the soil kaolins (Table 9) range from 9.6 to 29.2 nm, with a mean value of 15.4 nm and are similar to values for soil kaolins from other Thai soil (mean = 19.3) (Hart *et al.,* 2003), Western Australia (mean = 22.9 nm) and Indonesian soils (mean = 10.8 nm) (Singh and Gilkes, 1992c; Hart *et al.,* 2002). There is an inverse exponential relationship between CSD_{001} and Fe_2O_3 concentration as was also observed by Hart *et al.* (2003). The CSD values for the 060 reflection (mean = 17.8 nm) are larger than for the 001 reflection which is consistent with the platy morphology of kaolin crystals.

Values of CSD determined for the kaolin 060 reflection must be treated with caution as several kaolin reflections occur at about 0.15 nm and may coalesce. These reflections are also split into Kα1 and Kα2 components and the relative intensities of these reflections also depend on the extent of three dimensional order as several of the reflections are prism ($h, k, l \neq 0$) reflections that are highly sensitive to defects. Consequently the measured Width of Half Height (WHH_{060}) is often too large so that the calculated CSD_{060} is much smaller than the true plate dimension of crystals observed by TEM (Hart *et al.,* 2003).

The HB "crystallinity" index for soil kaolins ranges from 4 to 9 with a mean value of 6 which is indicative of kaolin with a high-defect structure. The values are similar to those for other Thai soils that range from 4.1 to 11.4 with a mean of 6.7 (Hart *et al.,* 2003), 4.5 to 7.1 with a mean of 5.6 for Indonesian soils, 3.1 to 10.7 with a mean of 5.6 for Western Australian soils (Singh and Gilkes, 1992c), 4.3 to 13.7 with a mean of 8.0 for soils from Nigeria (Hughes and Brown, 1979) and 10.1 to 18.5 with the mean of 14.1 for Brazilian Ultisols (Melo *et al*., 2001). Generally, structural order in kaolin is inversely related to the amount of structural iron. For these soil kaolins the range of values of both the HB index and structural Fe (13.1 to 44.8 g kg^{-1}) are too small and error of measurement too large to exhibit a clear relationship between these parameters.

2.2.2 Morphology of kaolin crystals

The size and shape of the kaolin crystals in representative samples were determined by TEM, and typical micrographs are shown in Figure 9 which clearly demonstrate the small size and diverse morphologies of kaolin crystals in these Ultisols.

These observations were quantified by determining the morphology of about 200 crystals for each sample (Table 10). Most of the kaolins consist of mixtures of particles with very different morphologies including large euhedral crystals (common in Hoi Pong (Hp) and Fang Deang (Fd) series), small subhedral-euhedral crystals (Pathui (Ptu) series) and small anhedral platy crystals (Kho Hong (Kh), Don Rai (Dr), Krabin Buri (Kb), Warin (Wn) and Satuk (Suk) series); a few samples also contain tubular halloysite crystals (0 to 34% for Dp subsoil).

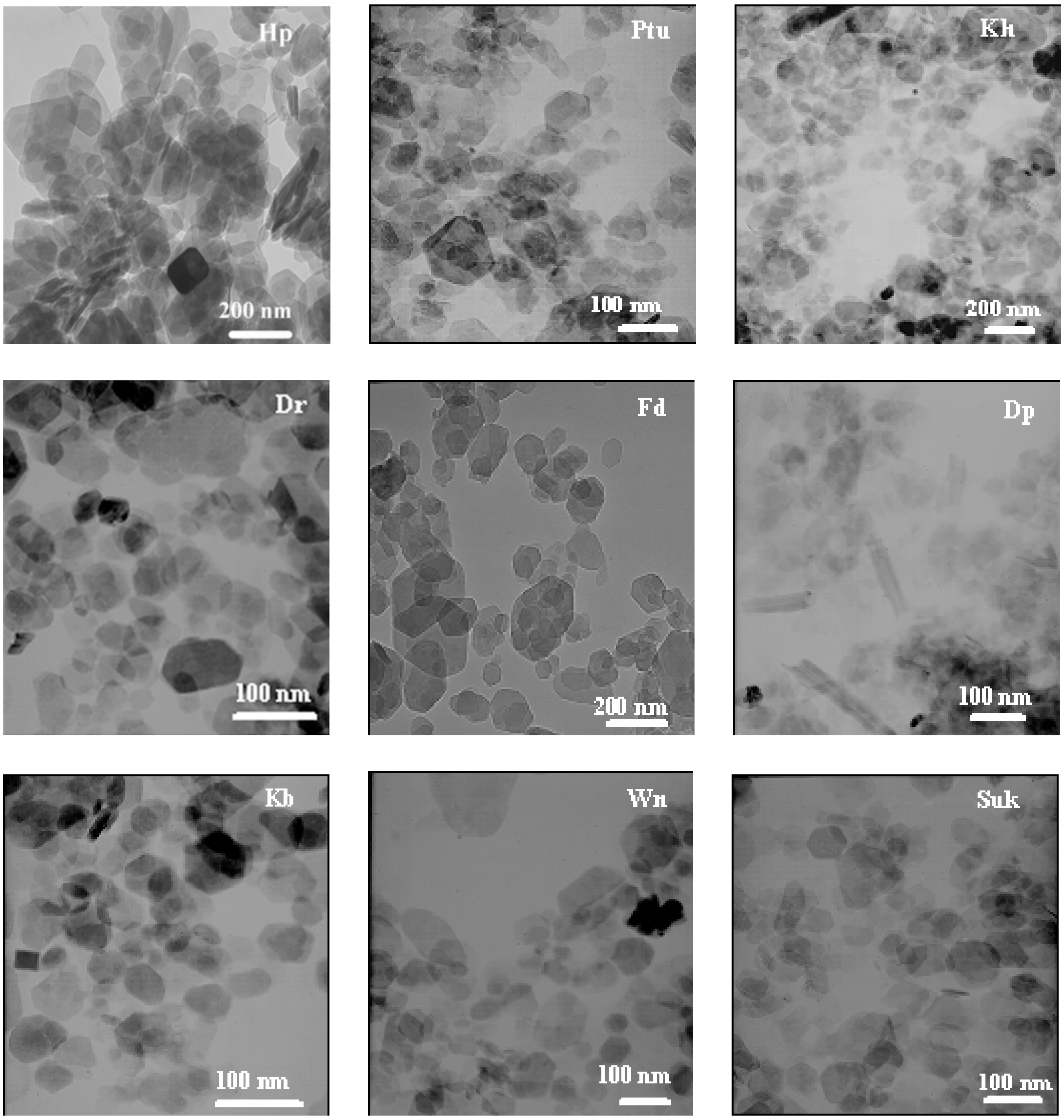


Figure 9 Transmission electron micrographs (TEM) of the soil kaolins illustrating the dominantly sub-micron, platy, euhedral to subhedral morphologies and the wide variation of crystal morphology and size within a single kaolin concentrate (Hp=Hoi Pong; Ptu= Pathui; Kh=Kho Hong; Dr= Don Rai; Fd= Fang Daeng; Dp=Doi Pui; Kb=Krabin Buri; Wn=Warin and Suk=Sasuk).

Table 10 Distribution of various crystal forms and particle dimensions of soil kaolin crystals determined by TEM

Soil series	% of platy crystal with euhedral faces							% Total plates	% Tubes	Crystal length (l) (nm)			Crystal width (w) (nm)			Axial ratio
	0 face	1 face	2 faces	3 faces	4 faces	5 faces	6 faces	Platy	(length, diameter, nm)	Max	Min	Mean	Max	Min	Mean	(l/w)
Typic Kandiudults, fine																
Hp-top[1/]	9	6	17	19	7	4	29	90	10 (112, 29)	392	29	133	373	29	110	1.20
Hp-sub[2/]	13	9	24	23	9	2	19	99	1 (250, 50)	475	24	135	350	24	114	1.19
Ptu-top	24	9	9	21	12	6	18	97	3 (96, 41)	373	24	110	353	24	89	1.23
Ptu-sub	24	9	9	21	12	6	18	97	3 (101, 44)	373	24	110	353	24	89	1.23
Typic Kandiudult, coarse-loamy																
Kh-top	27	1	2	5	16	11	39	100	0	275	30	100	235	30	83	1.20
Kh-sub	26	5	9	14	4	5	39	100	0	471	39	141	392	20	114	1.24
Typic Kandiustult, fine-loamy																
Dr-top	26	14	16	16	9	5	15	100	0	324	28	103	269	19	78	1.34
Dr-sub	28	11	15	21	10	1	16	100	0	293	24	110	220	24	90	1.22
Rhodic Kandiudult, fine-loamy																
Fd-top	18	17	21	21	7	4	14	100	0	667	48	218	524	48	180	1.24
Fd-sub	11	16	20	28	7	3	14	100	0	451	59	162	373	39	134	1.21
Typic Palehumult, fine																
Dp-top	10	5	7	17	19	13	31	100	0	317	37	110	256	24	94	1.18
Dp-sub	12	3	7	12	12	7	12	66	34 (125, 40)	275	29	123	235	29	100	1.23
Typic Plinthudult, clayey-skeletal																
Kb-top	80	10	10	0	0	0	0	100	0	183	61	107	152	55	87	1.22
Kb-sub	36	36	18	0	9	0	0	100	0	183	69	119	171	56	92	1.32
Typic Kandiustult, fine-loamy																
Wn-top	40	10	20	10	10	0	10	100	0	244	73	124	232	49	98	1.34
Wn-sub	20	40	20	10	0	0	10	100	0	130	74	103	130	60	90	1.15
Typic Paleustult, fine-loamy																
Suk-top	20	5	6	18	6	7	39	100	0	294	37	114	235	37	93	1.23
Suk-sub	21	2	3	4	6	20	47	100	0	294	29	115	255	29	96	1.20

[1/] =Topsoil (0-50 cm); [2/] =Subsoil (50-100 cm).

All samples contain some rounded platy particles with no euhedral (hk) faces (9 to 80% of crystals). The percentage of platy kaolin crystals with six euhedral (hkl) faces varies from 0 to 47 percent. The dimensions of the kaolin crystals vary greatly both within and between samples. The longest axis (henceforth called the length or l dimension) and the shortest axis (the w dimension) were measured for about 200 platy crystals in each sample (Table 10). The ratio l/w is defined as the axial ratio (AR) and a regular hexagonal crystal would have an axial ratio of 1.12. The mean values of AR for the kaolins (1.18 to 1.34) are similar to the value for Georgia kaolin (1.17) (Singh and Gilkes, 1992c) and indicate that substantially elongated crystals (*i.e.* laths) are rare. The mean l dimension of the platy crystals of the soil kaolins varies from 100 to 218 nm, compared with 20 to 750 nm for other Thai soil kaolins (Hart *et al.*, 2003; Trakoonyingcharoen *et al.*, 2006), 60 to 120 nm for Western Australian soil kaolins, 20 to 70 nm for Indonesian soil kaolins and 57 to 80 nm for kaolins in Brazilian Ultisols (Melo *et al.*, 2001; Hart *et al.,* 2003). The median size of platy crystals of three Georgia reference kaolins determined by Hart *et al.* (2003) using the same procedure as followed here are 180, 280 and 370 nm. The size of soil kaolin crystals in these Ultisols is inversely related to their specific surface area (Figure 10a). Kaolin in the Kho Hong (Kh) series topsoil has the smallest mean crystal size (100x83 nm) which is consistent with its large SSA (59.8 m^2 g^{-1}). As cation exchange positions are located on the crystal, surfaces exchange capacity is expected to increase with decreasing crystal size (Suraj *et al.,* 1997) but there is not a systematic statistical relationship between these two attributes for these soil kaolins (Figure 10b).

2.2.3 Chemical composition

The major elemental concentrations for the kaolins are given in Table 11. The mean concentrations of 403 g kg^{-1} Al_2O_3 and 550 g kg^{-1} SiO_2 differ substantially from those of ideal kaolin which contains 459 g kg^{-1} Al_2O_3 and 541 g kg^{-1} SiO_2. The SiO_2/Al_2O_3 ratio for soil kaolins ranges from 1.20 to 1.76 with a mean of 1.38 which is higher than the values of 1.17 for ideal kaolin and 1.20 for the reference Georgia kaolin, due mostly to the presence of quartz and to some Al in soil kaolin being replaced by Fe.

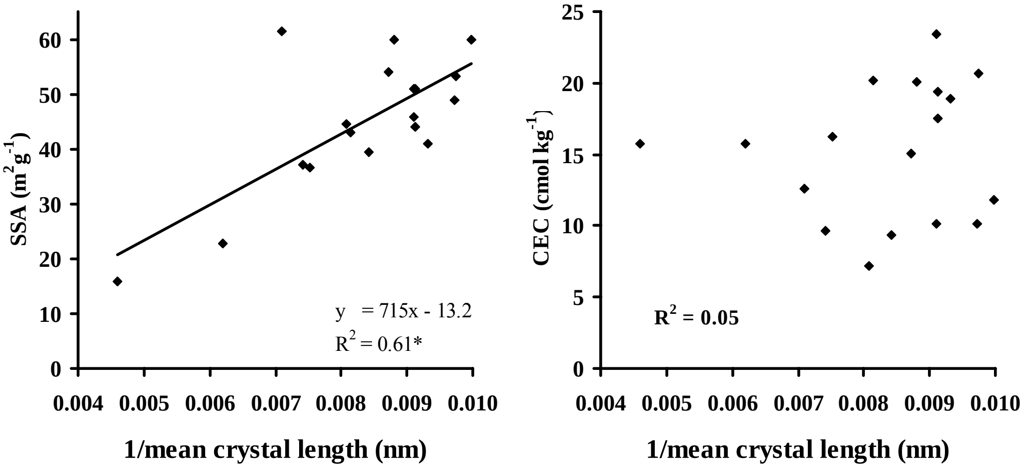


Figure 10 Relationships between the reciprocal of mean crystal size (length) determined by electron microscopy and (a) SSA and (b) CEC.

Minor inhibited vermiculite of unknown composition but probably containing interlayer Al-OH polymers are present in most samples and may have affected the SiO_2/Al_2O_3 ratio. Although, as pointed out by Hart *et al.* (2002, 2003), the SiO_2/Al_2O_3 ratio of inhibited dioctahedral vermiculite with aluminous interlayers is similar to that of kaolin.

The deferrated clay from the two horizons in profile Doi Pui (Dp) contained no quartz or vermiculite and the two samples have a SiO_2/Al_2O_3 ratio of 1.32 and 1.38, respectively which are higher than the value for ideal kaolin, it is likely that this kaolin contains structural Fe (Singh and Gilkes, 1992c). Small amounts of anatase are present in all samples as indicated by a distinct XRD reflection at 0.352 nm and anatase crystals observed by TEM.

The kaolin clay concentrates contain small amounts of potassium (mean = 4.65 g kg^{-1}) but there are no mica or feldspar reflections in the XRD patterns. Each sample would have less than about 5 percent illite as a discrete impurity or as interstratified layers in kaolin (Ma and Eggleton, 1999). A consistent difference between the soil kaolins and standard kaolins (Georgia kaolin, MP#5) is the much higher amounts of iron in the former with a mean value of 25.3 g kg^{-1} relative to 6.9 g kg^{-1} or less for most standard kaolins (Hart *et al.,* 2002, 2003). The Fe_2O_3 concentration of the soil kaolins (Table 11) ranges from 13.1 to 44.8 g kg^{-1}.

Table 11 The major element composition of kaolin concentrates from 9 Thai Ultisols (ignited, exchangeable cation free basis)

Soil series	Al_2O_3	SiO_2	TiO_2	Fe_2O_3	CaO	K_2O	MgO	P_2O_5	SiO_2/Al_2O_3
	(---------------------------------g kg^{-1}------------------------------------)								
Typic Kandiudults, fine									
Hp-top[1/]	422	535	15.8	23.8	0.24	3.11	0.00	0.46	1.27
Hp-sub[2/]	431	530	13.2	23.3	0.00	2.61	0.00	0.32	1.23
Ptu-top	368	596	18.1	13.1	0.12	3.85	0.00	0.68	1.62
Ptu-sub	404	566	13.6	12.4	0.58	2.88	0.00	0.00	1.40
Typic Kandiudult, coarse-loamy									
Kh-top	374	563	11.5	44.2	1.86	4.89	0.12	0.31	1.51
Kh-sub	377	559	10.8	44.6	3.85	4.43	0.00	0.14	1.48
Typic Kandiustult, fine-loamy									
Dr-top	370	576	22.4	27.6	0.41	4.19	0.00	0.24	1.56
Dr-sub	392	557	16.2	30.0	0.13	4.28	0.00	0.23	1.42
Rhodic Kandiudult, fine-loamy									
Fd-top	421	540	20.9	16.8	0.14	0.82	0.00	0.31	1.28
Fd-sub	434	531	17.2	17.0	0.13	0.52	0.00	0.25	1.22
Typic Palehumult, fine									
Dp-top	407	536	7.1	44.8	0.12	3.29	2.07	0.00	1.32
Dp-sub	396	548	6.9	42.1	0.12	5.47	1.07	0.00	1.38
Typic Plinthudult, clayey-skeletal									
Kb-top	429	529	17.3	17.4	0.24	5.59	0.48	0.44	1.23
Kb-sub	438	525	15.6	15.9	0.35	4.90	0.00	0.07	1.20
Typic Kandiustult, fine-loamy									
Wn-top	427	520	21.1	20.3	5.05	6.16	0.49	0.46	1.22
Wn-sub	415	538	19.5	19.3	0.47	5.82	0.70	0.58	1.30
Typic Paleustult, fine-loamy									
Suk-top	342	602	19.5	20.7	2.63	10.5	2.03	0.66	1.76
Suk-sub	404	546	14.4	23.0	0.00	10.3	2.00	0.36	1.35
Mean	403	550	15.6	25.3	0.91	4.65	0.50	0.31	1.38
Ideal kaolin	459	541	-	-	-	-	-	-	1.17
Georgia kaolin (MP#5)	442	532	16.4	6.9	1.30	1.20	0.10	0.80	1.20
Thai soil	355	452	19.9	19.6	0.40	2.80	6.00	-	1.27
W. Australian soils	-	-	-	25.7	-	-	-	-	0.96
Indonesian soils	-	-	-	25.4	-	-	-	-	0.98
Brazilian Ultisols	360	417	3.2	19.6	-	0.70	0.80	-	1.16

[1/] =Topsoil (0-50 cm); [2/] =Subsoil (50-100 cm).

The values are similar to those for kaolins from other Thai soils (5.4 to 31.2 g kg^{-1} with a mean value of 19.6 g kg^{-1}) (Hart *et al*., 2003), kaolins from Western Australian soils, with a mean value of 25.7 g kg^{-1} and smaller range from 21.6 to 33.4 g kg^{-1}. Indonesian soil kaolins exhibited similar Fe_2O_3 concentrations with a mean of 25.4 g kg^{-1} and a range of 15.2 to 37.2 g kg^{-1} (Hart *et al*., 2002). The Fe_2O_3 concentrations in the soil kaolins are also similar to those from Nigeria, 18.6 g kg^{-1}; Rwanda, 23.2 g kg^{-1} and Cuba, 15.2 g kg^{-1} (Mestdagh *et al*., 1980).

Data also indicate that an increasing iron concentration in kaolin is commonly related to reduced crystal size (CSD_{001}) as is also indicated by the present data (Figure 11a).

2.2.4 Cation exchange capacity

The CEC of the kaolins ranges from 7.2 to 23.4 cmol$_c$ kg^{-1} (Table 9). These values are similar to those for other Thai and for Indonesian soil kaolins (range 4.4 to 17.4 cmol$_c$ kg^{-1} and 5.2 to 12.9 cmol kg^{-1}, respectively), and are approximately twice those for Western Australian soil kaolins (range 2.9 to 7.6 cmol$_c$ kg^{-1}) (Hart *et al.,* 2002, 2003). Koppi and Skjemstad (1981) reported values of 9.3 to 30.5 cmol$_c$ kg^{-1} for Queensland soil kaolins and Ma and Eggleton (1999) values of 16 to 34 cmol$_c$ kg^{-1} for thin (15 nm) high defect kaolins. Kaolins in Warin series (Wn) has the lowest CEC, possibly because of the relatively high quartz content of these samples, although Hoi Pong (Hp) and Pathui (Ptu) soil clays also have high quartz contents. The CEC of kaolin is considered to be primarily due to pH-dependent charge arising from broken bonds along the edges of crystals (Yong *et al.,* 1992). The abundance of this charge should therefore increase as the size of kaolin crystals decreases (Ma and Eggleton, 1999). However, no systematic relationship exists for the present data (Figure 11b). The presence of small amounts of inhibited vermiculite, could have increased the CEC of some of the clays (Yong *et al.,* 1992) *e.g.* kaolin from Krabin Buri series (Kb) contains the most inhibited vermiculite (~5%) and has the highest CEC.

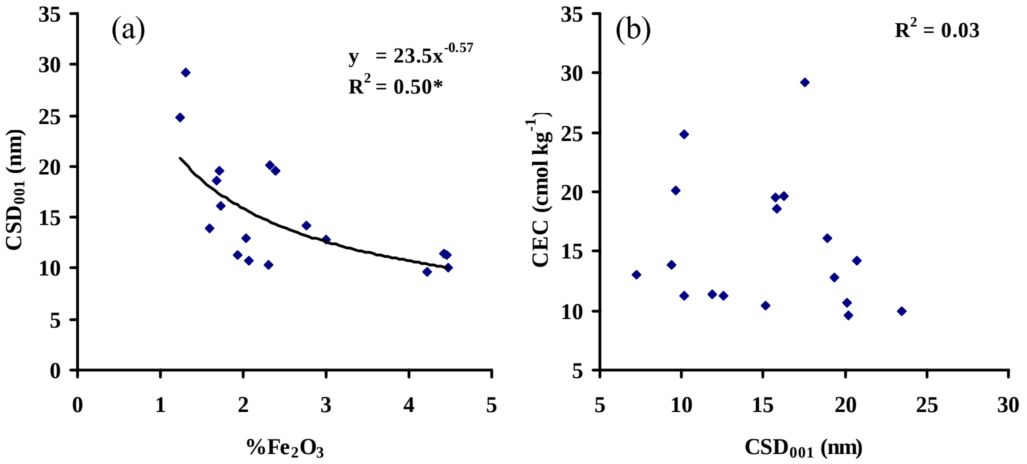


Figure 11 Relationships between crystal size (CSD) and other properties of the soil kaolins (a) % Fe_2O_3 and (b) CEC.

2.2.5 Specific surface area

Values for the specific surface area of the kaolins are large, ranging between 15.9 and 61.4 m^2g^{-1} with a mean value of 44.9 m^2g^{-1} (Table 9). These kaolins have higher surface areas than most standard kaolins (5 to 28 m^2g^{-1}) (Hart *et al.,* 2002) but are similar to soil kaolins from Brazil, Western Australia, and Thailand (44.0 to 56.0 m^2g^{-1}, 33.6 to 67.8 m^2g^{-1} and 35.3 to 80.6 m^2g^{-1}, respectively) (Melo *et al.*, 2001; Hart *et al.,* 2002; 2003). Values of SSA are mostly smaller than for Indonesian soil kaolins on volcanic tuff (59.0 to 88.0 m^2g^{-1}; Hart *et al.*, 2002). Values of the surface density of charge (CD) calculated from CEC and SSA range from 0.16 to 0.99 C m^{-2} in comparison to 0.18 C m^{-2} for the Georgia kaolin (Table 9).

The higher values of CD for soil kaolins are likely to reflect the presence of small amounts of impurities (*e.g.* inhibited vermiculite) which contribute to high CEC values (Hart *et al.*, 2003).

2.2.5 Trace element concentrations

The concentrations of trace elements in the clay fraction of the Ultisols were determined before (whole clay fraction) and after removal of free iron oxides by DCB treatment (kaolin concentrate) as shown in Table 12.

Table 12 Trace element concentrations in soil and kaolin concentrates of the 9 Ultisols and their percentage retention (ret.) by the kaolin concentrates

Soil	Mn			Co			Ni			Cu			Zn			As			Pb		
series	soil	kao	ret.	soil	kao	ret.	soil	kao	ret.	soil	kao	ret.	soil	kao	ret.	soil	kao	ret.	soil	kao	ret.
	(mg kg^{-1})		%	(mg kg^{-1})		%	(mg kg^{-1})		%	(mg kg^{-1})		%	(mg kg^{-1})		%	(mg kg^{-1})		%	(mg kg^{-1})		%
Typic Kandiudults, fine																					
Hp-top[1/]	56	43	6	0.5	1.2	19	3	54	12	3	17	46	11	39	27	2	2	8	8	45	43
Hp-sub[2/]	20	28	11	0.5	1.5	24	5	38	63	3	16	46	8	29	29	2	1	6	11	27	20
Ptu-top	371	35	1	4.3	4.4	9	7	39	45	6	16	22	10	20	18	28	31	9	7	15	19
Ptu-sub	146	38	9	2.7	3.9	50	14	36	93	9	20	82	16	37	80	58	36	22	9	16	59
Typic Kandiudult, coarse-loamy																					
Kh-top	117	86	4	1.3	5.5	22	1	37	14	2	28	60	4	60	71	0.7	0.4	3	7	71	51
Kh-sub	16	57	48	0.4	2.7	88	3	47	23	3	30	136	5	52	133	0.8	0.1	1	7	27	52
Typic Kandiustult, fine-loamy																					
Dr-top	432	49	1	1.7	4.2	22	3	21	59	4	13	28	6	45	62	2.7	0.8	2	5	31	61
Dr-sub	90	41	9	1.1	3.1	58	5	23	96	5	10	47	8	40	101	1.1	0.5	9	4	17	86
Rhodic Kandiudult, fine-loamy																					
Fd-top	608	80	2	1.3	2.5	23	6	37	76	6	30	61	8	42	62	2.8	2.4	10	7	32	55
Fd-sub	607	93	2	1.9	2.2	14	10	57	69	6	17	34	9	22	28	4.6	2.4	6	9	24	34
Typic Palehumult, fine																					
Dp-top	566	32	1	16.6	5.3	8	49	84	41	42	36	21	123	117	23	16	6	9	48	24	12
Dp-sub	436	28	3	10.6	4.2	18	48	63	58	45	27	26	129	95	32	14	4	12	63	17	12
Typic Plinthudult, clayey-skeletal																					
Kb-top	886	88	4	11.3	4.7	16	15	39	10	27	33	46	28	49	67	13	3	8	9	7	28
Kb-sub	1134	52	3	7.4	4.6	38	17	34	12	34	37	66	28	41	91	11	3	18	7	13	12
Typic Kandiustult, fine-loamy																					
Wn-top	56	92	7	0.3	3.9	52	1	53	16	2	19	42	4	62	63	0.5	0.1	1	3	38	51
Wn-sub	29	29	20	0.4	1.3	63	4	29	15	3	6	34	7	35	106	1.5	1.1	14	9	36	78
Typic Paleustult, fine-loamy																					
Suk-top	78	75	5	0.3	4.7	88	2	39	12	1	33	141	3	49	83	0.4	2.8	39	3	7	13
Suk-sub	20	38	52	0.7	4.6	18	7	34	13	4	37	236	12	41	99	1.2	3.2	75	9	13	39
Mean	315	55	10	3.5	3.6	44	11	42	10	11	24	65	23	49	65	9	6	14	12	26	47
SD	336	24	15	4.8	1.4	43	14	15	51	15	10	55	38	24	34	14	10	18	16	16	29

[1/] =Topsoil (0-50 cm); [2/] =Subsoil (50-100 cm).

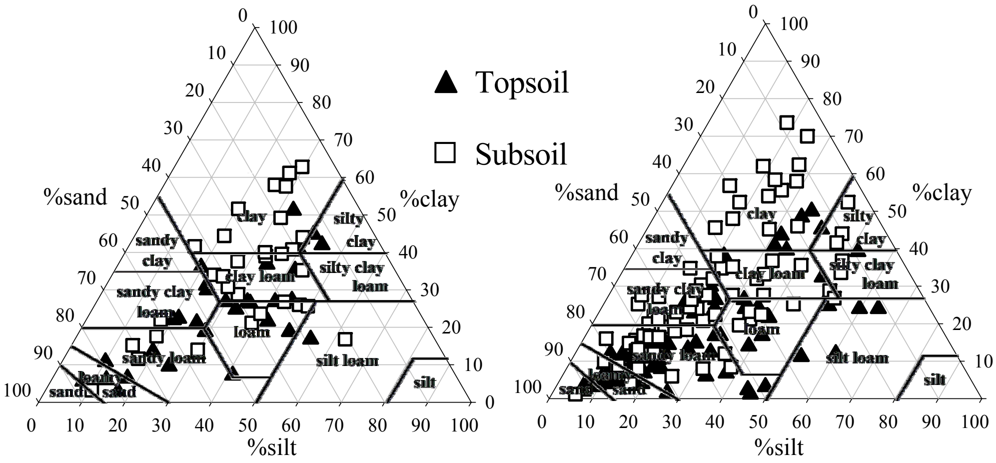
The concentrations of trace elements were determined together with the percentage of trace element retained in deferrated clay after DCB treatment. Concentrations of Mn, Ni, Cu, Zn and Pb in the clay are significant and the average percentage retained by the deferrated clay is >50 percent for Ni, Cu and Zn. Most Mn, Co, Pb and As (>75%) were removed from the clay fraction by DCB treatment so these elements are probably mostly associated with Fe and Mn oxides. The concentrations of trace elements in the soil kaolins are quite small and these elements could be in accessory minerals including anatase or even in sulphides precipitated during the DCB treatment. However, these data are consistent with soil kaolin containing appreciable proportions of the Ni, Cu and Zn and some of the Co and Pb present in these highly weathered soils.

3. Geochemistry of Thai Alfisols and Ultisols

3.1 Physical properties

The textural triangle (Figure 12) shows the wide range in texture of both Alfisols and Ultisols with a similar range of textures for the two soil orders. Their subsoils commonly contain more clay than the topsoils. Texture of Alfisols ranges from loamy sand to clay with most soils having a loam texture. Nearly 50 percent of subsoils and 10 percent of topsoils have a clay texture. Many Ultisols and especially topsoils have a sandy texture, whereas texture of their subsoils ranges from sand to clay. Differences in texture between individual soils are predominantly due to differences in soil parent materials although eluviation of clay from topsoils has played an important role in creating the sandier topsoils (Singh, 1991; Buol *et al.*, 2003).

Bulk density values of Thai Alfisols and Ultisols are shown in Appendix Tables 5 and 6, range from 1.40 to 2.48 Mg m^{-3} (medium to very high) for Alfisols and 1.21 to 2.43 Mg m^{-3} (medium to very high) for Ultisols. Bulk density is generally lower in topsoil as compared to subsoil, due to the high clay content of subsoil.



Alfisols Ultisols

Figure 12 The textural triangle for topsoil and subsoil samples of Thai Alfisols and Ultisols.

3.2 Chemical Properties

In general, Alfisols and Ultisols in Thailand occur under well drained leaching conditions and they are commonly under agricultural use with various soil-fertilizer management practices (Kheoruenromne and Suddhiprakarn, 1984; Kheoruenromne, 1991; Brady and Ray, 2002; Rojanasoonthorn and Kheoruenromne, 2002). Most of the soils sampled in this research have supported agriculture and will have received N, P, K fertilizer and in some instances lime or trace elements. Most of Alfisols have a slightly acidic reaction throughout the soil profile as indicated by their pH values in water (1:1) (mean, 6.15 for topsoil and 6.19 for subsoil). The pH values measured in KCl are consistently lower than those measured in water (Table 13 and Appendix Table 7), thus delta pH of the soils is negative.

Ultisols have an acidic reaction for most samples (Table 13 and Appendix Table 8) with pH values in water (1:1) ranging from extremely acid to moderately alkaline (pH 3.70-8.10). Most of the soils are acidic due to the high weathering and leaching of basic cations during soil development. However, the soil reaction of Sung Noen (Sn) soil is high (pH 8.10 in the topsoil) because its parent material is limestone and colluvial limestone could affect topsoil pH. pH value measured in KCl are consistently lower than those measured in water.

Table 13 The mean values of some properties of Thai Alfisols and Ultisols

	Alfisols		Ultisols	
	Topsoil	Subsoil	Topsoil	Subsoil
pH (1:1 H_2O)	6.15	6.19	5.34	5.31
pH (1:1 KCl)	4.78	4.67	4.32	4.13
Organic matter (g kg^{-1})	14.88	6.09	10.74	4.57
CEC (cmol kg^{-1})	13.75	13.58	6.99	8.11
Clay content (g kg^{-1})	248.00	365.00	156.00	297.00
Total N (g kg^{-1})	0.28	0.16	0.16	0.09
Avail. P (mg kg^{-1})	8.65	2.50	7.19	1.86
Avail. K (mg kg^{-1})	58.16	51.12	19.58	17.58
Extr. Ca (cmol kg^{-1})	6.28	5.22	1.94	1.50
Extr. Mg (cmol kg^{-1})	1.18	1.31	0.47	0.06
Extr. Na (cmol kg^{-1})	0.37	0.16	0.24	0.34
Extr. K (cmol kg^{-1})	0.32	0.22	0.12	0.15

Delta pH (pH_{KCl}-pH_{H2O}) of these soils is negative. Negative pH values indicate the presence of negative net surface charge on the soil colloid (Uehara and Gilman, 1980), which provides some of the cation exchange capacity (Sanchez, 1976). The organic matter concentration in topsoils of Alfisols ranges from 2.71 to 43.47 g kg^{-1} with a mean of 14.88 g kg^{-1}. Cation exchange capacity of these topsoils (mean, 13.75 cmol kg^{-1}) is markedly higher than that for Ultisols (mean, 6.99 cmol kg^{-1}) because of the higher clay and OM contents of the Alfisols (Table 3) (Kheoruenromne, 1991; Brady and Ray, 2002; Rojanasoonthorn and Kheoruenromne, 2002). The profile trends of organic matter for these soils are typical, being higher in the topsoil and decreasing with depth (Agbu *et al.*, 1990). The moderate amount of organic matter (14.88 and 10.74 g kg^{-1} for topsoil against 6.09 and 4.57 g kg^{-1} for subsoil for Alfisols and Ultisols) of these soils is beneficial for crops (Brady and Ray, 2002). Cation exchange capacity (CEC) of these soils is very low due to the advanced stage of weathering and the dominance of kaolin-sesquioxide clay that generally has a low CEC (Barber and Rowell, 1972; Moncharoen and Vijarnsorn, 1978; Brady and Ray, 2002).

3.3 Concentration of elements in Alfisols

Element concentration in Alfisols varies widely. Table 14 compares the median values of major and trace element concentrations in Thai Alfisols and Ultisols with the range of concentrations for worldwide soils not affected by mineralization or contamination (Kabata-Pendias and Pendias, 2001) and the reported critical threshold concentrations for contamination (Alloway, 1995).

Major elements

Silicon, Al and Fe are the major elements which are much more abundant in these Alfisols than other elements (Ca, K, Mg, P and Ti) (Appendix Table 9). Concentrations of Al, Fe, K, Ti, Mg are higher in subsoil than in topsoil. The concentration of Si (365 g kg^{-1} for topsoil and 335 g kg^{-1} for subsoil horizons), largely depends on parent material composition. Much Si is present in quartz which is abundant in these soils. The higher concentration of Si in the topsoil than in the subsoil is due to surface erosion of fine material and eluviation of fine material to accumulate in the subsoil. For P (130 mg kg^{-1} for topsoil and 108 mg kg^{-1} for subsoil) which exhibits the same trend within soil profile as Si, the greater concentrations of P in the topsoil when compared to the subsoil of both soil orders reflects P fertilizer applications and biocycling (Brady and Ray, 2002). These profile trends are in contrast to the concentrations of Al (46.3 g kg^{-1} for topsoil and 67.9 g kg^{-1} for subsoil horizons) and Fe (20.6 g kg^{-1} for topsoil and 25.6 g kg^{-1} for subsoil horizons). Aluminum concentrations tend to be higher in the subsoil than in the topsoil, due to clay accumulation in the subsoil; Al is a major constituent of alumino-silicate clay minerals including kaolin which is the dominant clay mineral in these soils (Grim, 1968; Schulze, 1989; Velde, 1992). Accumulation of the Fe in the subsoil relative to the topsoil reflects the same process operating on iron oxides (Schwertmann and Taylor, 1989).

Table 14 The median values of concentrations of elements in topsoil and subsoil samples of Thai Alfisols and Ultisols compared with concentrations in worldwide soils (topsoil) and critical concentrations for contaminated soils

	Alfisols			Ultisols			Worldwide[+]	Critical
	Topsoil	Subsoil	Median	Topsoil	Subsoil	Median	Normal Soils	Concentration[++]
Si (g kg^{-1})	365	335	343	411	378	388	24-361	-
Al (g kg^{-1})	46.3	67.9	59.0	25.9	45.2	38.6	-	-
Fe (g kg^{-1})	20.6	25.6	23.0	11.1	18.5	12.9	-	-
K (g kg^{-1})	8.13	9.25	9.29	1.73	2.74	2.06	24-83	-
Ti (g kg^{-1})	3.98	4.20	4.09	2.68	3.25	2.97	0.1-15.0	-
Ca (g kg^{-1})	1.34	1.17	1.45	0.35	0.21	0.29	10-22.9	-
Mg (g kg^{-1})	1.17	1.93	1.73	0.18	0.57	0.35	193	-
Mn (g kg^{-1})	0.40	0.47	0.44	0.15	0.07	0.11	-	-
P (mg kg^{-1})	130	108	123	77	72	74	200-600	-
As (mg kg^{-1})	2.89	4.89	3.38	2.82	4.52	3.74	4.4-9.3	20-50
Co (mg kg^{-1})	7.74	9.88	8.74	1.68	2.44	2.08	4.5-12	25-50
Cr (mg kg^{-1})	22.4	30.0	25.4	16.6	24.2	19.4	12-83	75-100
Cu (mg kg^{-1})	11.8	13.1	12.2	4.6	5.2	5.2	13-24	60-125
Ga (mg kg^{-1})	7.9	11.9	9.7	4.3	8.4	6.2	<5-70	-
Li (mg kg^{-1})	12.7	17.1	13.9	3.4	6.2	3.9	13-56	-
Mo (mg kg^{-1})	0.20	0.25	0.23	0.26	0.32	0.28	1.3-2.8	2-30
Ni (mg kg^{-1})	10.3	13.7	12.2	3.4	6.3	4.8	12-34	100
Pb (mg kg^{-1})	12.4	13.5	13.2	8.2	10.1	9.2	22-44	2-300
Se (mg kg^{-1})	0.08	0.04	0.08	0.04	0.08	0.05	0.25-0.37	5-10
V (mg kg^{-1})	19.6	32.8	26.7	14.6	25.9	19.0	18-115	50-100
Zn (mg kg^{-1})	27.0	31.5	30.3	8.2	10.2	9.6	45-100	70-400
Zr (mg kg^{-1})	331	304	314	401	358	375	70-850	-

[+] Means of total concentrations of elements in the surface horizon of normal worldwide soil (Kabata-Pendias and Pendias, 2001), normal means not contaminated or mineralised.

[++] Critical concentration of heavy metals in soils, higher concentrations may be toxic (Alloway, 1995).

Despite their history of fertilization the P concentration in these Thai soils is much lower than has been reported for worldwide soils. This difference being due partly to the low P fertilizer application rates used for crop cultivation, the higher rate of P loss under tropical weathering (Brady and Ray, 2002) and the relatively low degree of weathering exhibited by many soils in temperate and arid regions. Conversely the Si concentration is slightly higher in these Thai soils than values reported for worldwide soils. This is due to the abundance of quartz in the Thai soils due to the siliceous parent materials and the persistence of quartz in soils during pedogenesis. Table 14 indicates that these soils contain small amounts of K with Alfisols which contain illitic minerals having more K than Ulitsols which do not contain illite. Much of the Ti in these soils is present as microcrystalline anatase.

Trace elements and heavy metals

The results shown in Table 14 and Appendix Table 11 indicate that concentrations of trace elements in these Thai soils are within range of the worldwide normal soils and that heavy metals (Ni, Cu, Zn, Pb and Co), Se and As concentrations are not high enough to be considered hazardous (Alloway, 1995).

3.4 Concentration of elements in Ultisols

The relative abundance of trace elements in Ultisols is as follows: Zr>Cr>V>Zn>Pb>Ga>Cu>Ni>Li>As>Co>Mo>Se (median= 375, 19.4, 19.0, 9.6, 9.2, 6.2, 5.2, 4.8, 3.9, 3.7, 2.1, 0.28 and 0.05 mg kg^{-1}, respectively) (Appendix Table 12). The concentrations of these elements are mostly lower than in Alfisols because of the sandier texture higher intensity of leaching and more extreme weathering conditions (Kheoruenromne, 1991; Brady and Ray, 2002). Zirconium is more abundant in Ultisols because it is mostly associated with sand-sized zircon grains. Molybdenum and As may be associated with sesquioxides, especially iron oxides, being adsorbed as oxyanions in acid soils and both trace elements are more abundant in Ultisols (Aubert and Pinta, 1977; Bowen, 1979; Kabata-Pendias and Pendias, 2001).

Compared with published data on other Ultisols, heavy metal (Co, Ni, Cu, Zn and Pb) concentrations in Thai Ultisols are quite low (Holmgren *et al.,* 1993; Fauziah *et al.*, 2001; Zauyah *et al.*, 2004). For example, Zn concentrations for topsoil and subsoil in Thai Ultisols are 8.2 and 10.2 mg kg^{-1} while they are 63 and 76 mg kg^{-1} for Oklahoma Ultisols and 65.7 and 95.6 mg kg^{-1} for general Ultisols in the United States (Lee *et al.,* 1997). These USA soils also have higher Pb concentrations than do Thai Ultisols but show the same trend with depth. Heavy metals in Thai Ultisols increase with depth (3.4 to 6.3 mg kg^{-1}Ni; 4.6 to 5.2 mg kg^{-1}Cu and 8.2 to 10.1 mg kg^{-1}Pb) due to the increasing clay content. However, Marques *et al.* (2003) reported that some heavy metals decrease in concentration with depth (38 to 37 mg kg^{-1}Cu and 26 to 16 mg kg^{-1}Pb) due to different parent materials in Brazilian Cerrado soils.

3.5 Relationship between soil properties and elements concentrations

Results on correlation analysis of major element (Al, Fe, Mg, Mn, P, Si and Ti) and trace element (As, Co, Cr, Cu, Ga, Li, Ni, Pb and Zn) concentrations with soil properties including organic matter content, cation exchange capacity and clay content are shown in Table 15. The correlation between major elements and trace elements is shown in Table 16. The results show that organic matter content, CEC and clay content influence the concentration of major elements (Al, Fe, Mn and Ti) in Thai Alfisols and Ultisols. However, the amounts of clay tend to show the strongest relationship with some major element (Al, Fe and Ti) concentrations in soils of both orders when compared with organic matter and CEC. This can be expected since these elements are the major composition of alumino-silicate minerals in the clay fraction and they also have quite high correlation with the CEC. Similar results were reported by many authors (Pierce *et al.*, 1982; Shuman, 1985; Ma *et al.*, 1997; Kabata and Singh, 2001; Andersen *et al.,* 2002). For the case of P and Mn, the accumulation of both elements in topsoils are highly significantly correlated with organic matter content which normally high in the topsoil for both Alfisols and Ultisols.

Table 15 The correlation coefficients (r) of elemental content (major and trace elements) with soil properties of Thai Alfisols and Ultisols

	OM		CEC		Clay		Iron	
	Alfisols	Ultisols	Alfisols	Ultisols	Alfisols	Ultisols	Alfisols	Ultisols
Si	-0.79*	-0.69*	-0.75*	-0.67*	-0.79*	-0.86**	-0.92**	-0.89**
Al	0.78*	0.61*	0.69*	0.63*	0.78*	0.84**	0.91**	0.82**
Fe	0.78*	0.65*	0.66*	0.60*	0.81**	0.77*	1.00**	1.00**
Ti	0.75*	0.72*	0.54*	0.64*	0.82**	0.83**	0.83**	0.78*
Mg	0.52*	0.53*	0.72*	0.70*	0.44	0.69*	0.62*	0.73*
Mn	0.75*	0.57*	0.52*	0.37	0.50*	0.55*	0.77*	0.63*
P	0.64*	0.56*	0.54*	0.46	0.64*	0.52*	0.69*	0.55*
As	0.48	0.32	0.36	0.47	0.51*	0.42	0.53*	0.46
Co	0.73*	0.45	0.64*	0.53*	0.70*	0.61*	0.90**	0.76*
Cr	0.56*	0.60*	0.23	0.51*	0.56*	0.62*	0.60*	0.67*
Cu	0.56*	0.51*	0.63*	0.54*	0.64*	0.65*	0.65*	0.85**
Ga	0.59*	0.54*	0.60*	0.63*	0.70*	0.70*	0.76*	0.69*
Li	0.46	0.38	0.56*	0.62*	0.58*	0.64*	0.53*	0.59*
Ni	0.67*	0.55*	0.62*	0.61*	0.63*	0.67*	0.73*	0.75*
Pb	0.33	0.37	0.61*	0.55*	0.52*	0.49	0.43	0.57*
Zn	0.81**	0.46	0.66*	0.65*	0.68*	0.53*	0.81**	0.58*

* Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.

Table 16 The elemental correlation coefficients of four major elements with some trace elements of Thai Alfisols and Ultisols (topsoil)

	Al		Si		P		Ti	
	Alfisols	Ultisols	Alfisols	Ultisols	Alfisols	Ultisols	Alfisols	Ultisols
As	0.60*	0.41	-0.53*	-0.46	0.64*	0.24	0.50*	0.31
Co	0.84**	0.71*	-0.85**	-0.73*	0.67*	0.56*	0.71*	0.71*
Cr	0.64*	0.64*	-0.55*	-0.64*	0.62*	0.72*	0.65*	0.69*
Cu	0.61*	0.79*	-0.62*	-0.80**	0.57*	0.64*	0.50*	0.71*
Ga	0.86**	0.87**	-0.82**	-0.82**	0.73*	0.62*	0.70*	0.65*
Li	0.73*	0.76*	-0.70*	-0.73*	0.57*	0.47	0.63*	0.57*
Mn	0.81**	0.61*	-0.80**	-0.62*	0.64*	0.54*	0.64*	0.69*
Ni	0.76*	0.78*	-0.75*	-0.77*	0.69*	0.63*	0.69*	0.67*
Pb	0.62*	0.75*	-0.66*	-0.75*	0.47	0.4	0.54*	0.53*
Zn	0.90**	0.69*	-0.89**	-0.66*	0.78*	0.59*	0.81**	0.51*

* Significant at the 0.05 probability level.
**Significant at the 0.01 probability level.

In the context of trace elements, results indicate a clear link between parent materials and most of trace elements (Co, Cr, Cu, Ga, Ni and Zn) concentrations, which, in turn, those give the large amounts of clay would reflect the positive amounts of these trace elements similarly to those described above. These are in good agreement with other studies (Pardue *et al.*, 1992; Ma *et al.*, 1997; Chen *et al.,* 1999; Burt *et al.,* 2003) which concluded that the concentration of major elements (e.g. Al, Fe, K and Mn) and trace elements (e.g. Co, Cr, Li, Ni, V and Zn) were positively correlated with the clay content. The elemental correlation coefficients of Thai Alfisols and Ultisols (Table 16) indicate a similar trend of relationship between clay content and trace elements (As, Co, Cr, Cu, Ga, Li, Ni, Pb and Zn). As a result, it is clear that the higher the Al and Si in both soil orders, the more the trace elements concentrate in these soils. This is because the Al and Si are the major constituents in all types of clay minerals. As shown in Tables 15 and 16, all kinds of these previously mentioned relationships are slightly better in Alfisols than in Ultisols.

3.6 Principal component analysis

The results of factor analysis of standardized chemical analyses of Thai Alfisols are given in Figure 13. Two factors explain 66 percent and 62 percent of the variation between soil samples for these Alfisol topsoils and subsoils respectively. For topsoils, elements can be allocated to five main groups of similar geochemical behavior (affinity groups), and some elements do not belong to any group. The first group is related to organic matter and clay content and consists of, Al, Fe, Ti, Mn, P, Co, Ga, Li, Ni and Zn, it is opposed in Figure 13a to Si that is an indicator of sand. The second group represents exchange cations and consists of K, Ca, Mg, Cu, Pb and CEC. The third group is As and Se which are commonly present as oxyanions adsorbed by oxide minerals. This group is located close to group 1 which contains Fe, Al the major constituents of soil oxides. The fourth group is Cr and V which maybe present as oxides but are not closely associated with Fe or Ti oxides which commonly contain these elements. For the subsoils, the grouping of elements is somewhat different from that for topsoils with six main groups being identified. The first group includes Al, Fe, Ti, Mn, P, Co, Ga, Ni, Zn and clay as for topsoils but not Li or OM, the second group again includes K, Mg, Ca, Cu, Li, Pb and

CEC, the third group includes As, Mo, Se and OM, the fourth group includes Cr and V as for topsoils.

Factor analysis of topsoil and subsoil analytical data does not identify any discrete groupings of Alfisols as indicated in Figures 13c and 13d. However, for both topsoils and subsoils, the Li series (Ultic Haplustalf; Clayey-skeletal, mixed, semiactive, shallow) (Appendix Table 1) is outlier with a quite different composition from the majority of Alfisols. This may be due to the high concentrations of Cr and V in this soil, presumably reflecting the composition of the parent materials.

The results of factor analysis for Thai Ultisols are shown in Figure 14a. Sixty nine percent of the variation in the data for the topsoil is explained by two factors and there are three groups of elements with similar behavior. The first group consists of Fe, Ti, Mn, Co, Cu, Ni, organic matter, CEC, and clay and is directly opposed to Si. The second group includes Al, Mg, Ga, Li, Pb and Zn. The third group consists of Ca, P, Cr, Mo and V. Selenium, K, As and Zr do not belong to any group. Many topsoils form a closely associated group but as is evident in Figure 14b a number of topsoils are clear outliers. Khlong Chak (Kc) series (Typic Kandihumult; Clayey-skeletal, kaolinitic) and Krabi (Kbi) series (Typic Kandiudult; Fine, kaolinitic) have a very high Mn concentrations in the whole soil when compared with the coherent group. This large diversity of Ultisol compositions may simply be a consequence of the great diversity of parent materials

Groups of elements with similar behavior in the subsoils of Thai Ultisols are shown in Figure 14c and two factors explain 62 percent of the variation between the samples. This result is quite different from that for topsoil. There are three affinity groups of elements with considerable overlap between groups 1 and 2. The first group consists of Al, Fe, Ti, P, Cu, Ga, Ni and clay, the second group includes Ca, Mg, Mn, As, Co, Li, Pb, Zn, OM and CEC, the third group consists of Cr, Mo and V. Potassium, Se, Si and Zr do not belong to any group

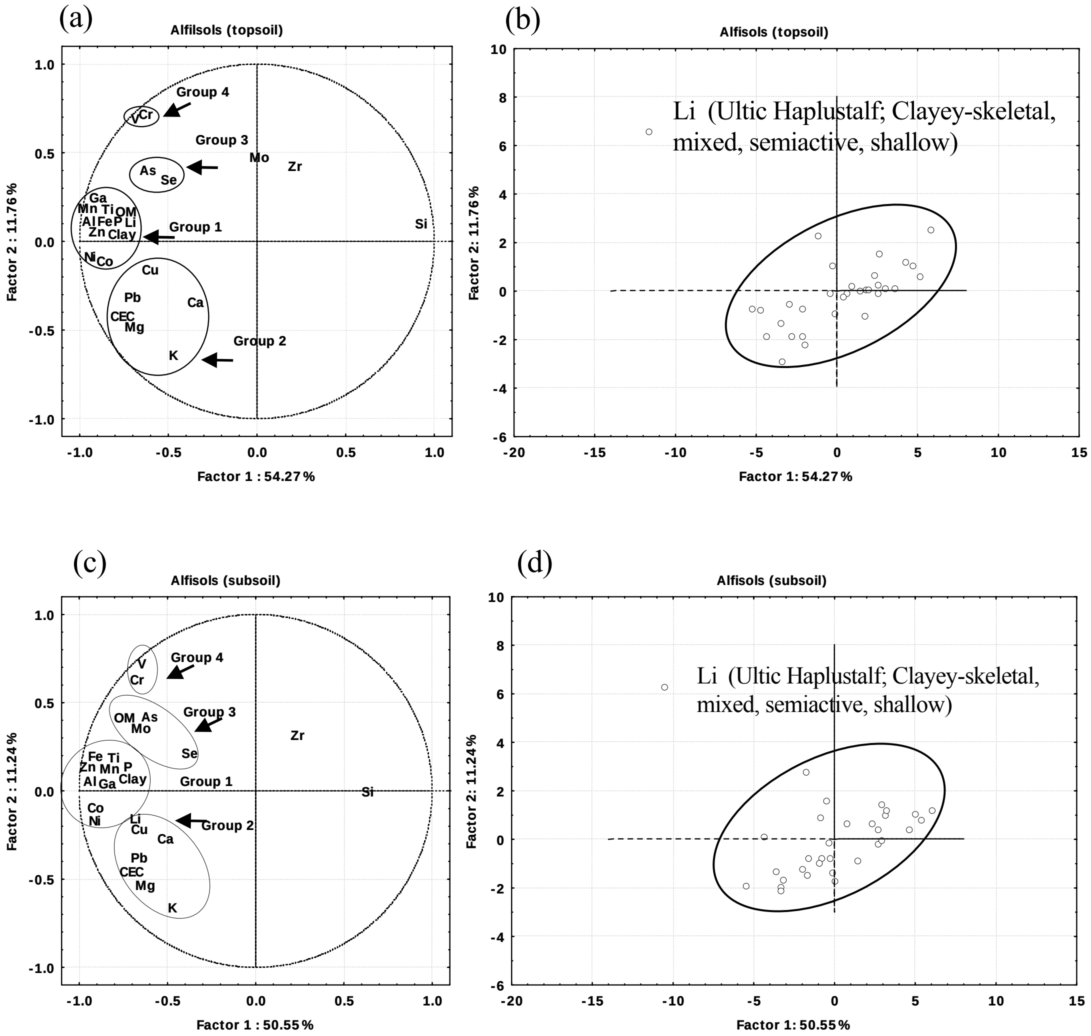


Figure 13 Factor analysis for chemical composition in whole soils of Thai Alfisols: (a) distribution of elements and soil properties, some points have been slightly displaced for clarity (topsoil); (b) distribution of soil samples (topsoil), (c) distribution of elements and soil properties, some points have been slightly displaced for clarity (subsoil); (d) distribution of soil samples (subsoil).

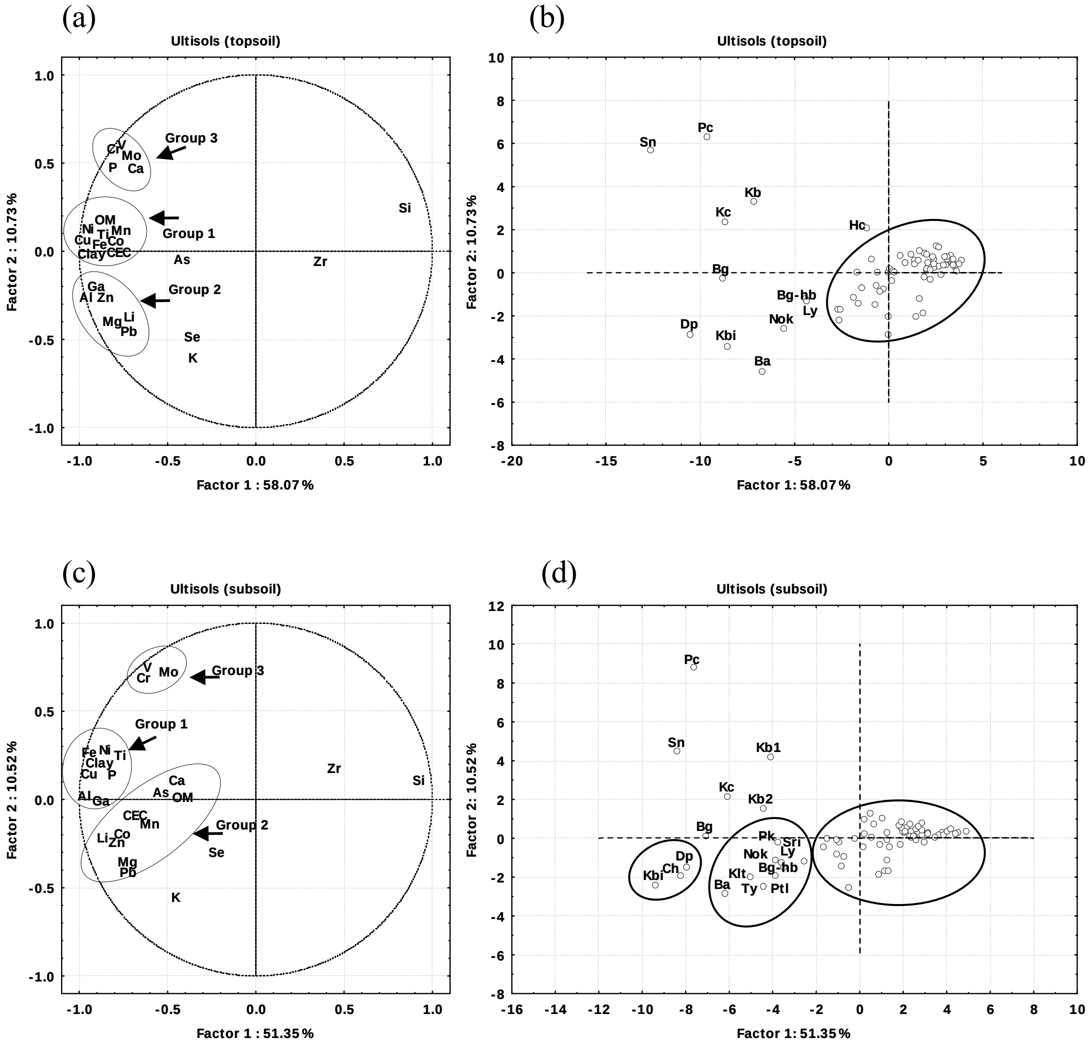


Figure 14 Factor analysis for chemical composition in whole soils of Thai Ultisols: (a) distribution of elements and soil properties, some points have been slightly displaced for clarity (topsoil); (b) distribution of soil samples (topsoil), (c) distribution of elements and soil properties, some points have been slightly displaced for clarity (subsoil); (d) distribution of soil samples (subsoil).

Most trace elements in Ultisols with the exception of Zr are associated with clay and sesquioxide indicating their existence as structural components of layer silicates or as ions that are adsorbed or occluded by Fe-oxides, Mn-oxides or OM (Ma *et al*, 1997). Soil series, parent materials and classification of Thai Ultisols are shown in Appendix Table 2. For the Ultisols Khlong Chak (Kc) series (Typic Kandihumult; Clayey-skeletal, kaolinitic), Krabin Buri (Kb) series (Typic Paleustult; Clayey-skeletal, kaolinitic), Pak Chong (Pc) series (Oxic Paleustult; Clayey, kaolinitic), Ban Chong (Bg) series (Typic (Kandic) Paleustult; Fine, kaolinitic), Sung Noen (Sn) series (Typic Paleustult; Fine, silty, subactive) are outliers (Figure 14d) with the major difference being due to much higher concentrations of Ca, Li, Co and Se.

CONCLUSION

The physical and chemical properties of a soil are controlled to a very large degree by the soil minerals, especially by the minerals constituting the clay fraction. Kaolin is the most common and abundant clay mineral in these Alfisols and Ultisols and is present in all samples. About 80 percent of the samples has more than 40 percent kaolin in the clay fraction. Variable amounts of illite, inhibited vermiculite and smectite are also constituents of these soils along with quartz and anatase. Results of semi-quantitative study on minerals in clay fraction of Thai Alfisols and Ultisols correspond well with their chemical properties. With kaolin, illite, inhibited vermiculite and smectite as the major clay mineral species in the clay fractions, the fertility status of these soils is moderate. In addition, the large surface area and chemical reactivity of soil kaolin, which resulted from the small size and defect structure are also important for sorption reactions in these soils which are often sandy and containing little organic matter to adsorb plant nutrients and other ions. Consequently, kaolin alone may contribute a substantial part to the capacity of some soils to retain cations and anions. The nature of the dominant minerals in these soils therefore, should be considered carefully in soil-fertilizer management for intensive crop production on these soils.

The deferrated clay fraction of Thai Ultisols consists mostly of kaolin with lesser inhibited vermiculite, illite and anatase and so resembles other tropical soils including those Thai soils investigated by Hart *et al.* (2003). The large surface area and chemical reactivity of soil kaolin, which results from the small size and defect structure will be important for sorption reactions in these soils which are often sandy and containing little organic matter to adsorb plant nutrients and other ions. Consequently, kaolin may provide a substantial part of the capacity of the soil profile to retain anions and cations. This study has also identified a possible role for kaolin as a host for minor elements as structural ions which has significant implications for soil fertility and geochemical exploration. Although not investigated in this study the physical properties of Ultisols may also reflect their kaolin dominated clay mineralogy. There is a need to identify the properties of kaolin in all the major soils of tropical regions where this mineral is dominant as it has the potential to play an important role in determining soil chemical and physical properties.

Concentrations of trace elements in Alfisols tend to be greater than in Ultisols, even when parent materials are the same. This is possibly due to the Alfisols being developed under less intense weathering conditions than the Ultisols. Soils derived from alluvium have slightly higher concentrations of trace elements than those formed from sandstone regardless of their degree of development.

Concentrations of major and trace elements in these uncontaminated and nonmineralised Thai Alfisols and Ultisols are similar to those in comparable worldwide soils. Many elements in these soils, especially heavy metals, are associated with clay in subsoils and some elements are associated with organic matter. Ultisols have lower concentrations of many elements, especially Mg, K, Ca, Co, As, Se and Mo, possibly because of their more heavily weathered nature. Only Si and Zr concentrations are higher in Ultisols than in Alfisols, presumably because of the high resistance to weathering of quartz and zircon. Total trace element concentrations in these Thai topsoils are generally much lower than those in contaminated soils. The only exception is the high As concentrations in some soils which are above the values for uncontaminated worldwide soils and need be explored further for an explanation of this observation. The generally low elemental concentrations in these Thai Alfisols and Ultisols soils reflect the dominantly siliceous soil parent materials and soil formation in a strongly weathering tropical situation.

The characteristic geochemistry of Thai soils is inherently complex because they vary widely in composition across landscape, bioclimatic gradients and soil depth. And also, the separation of natural form anthropogenic sources of trace elements is not clear-cut in soils. Factor analysis does not support the hypothesis that there would be systematic differences in element composition in the whole soil samples among the several Alfisols and Ultisols.

The results of geochemical analysis related to various soil processes affecting amounts and distribution of elements in these Thai Alfisols and Ultisols and their relationships with other soil properties should be further explored for each different affinity group to enhance the understanding of the fate and transport of major and trace elements in light of the environmental implication in agricultural practices on these tropical Alfisols and Ultisols.